

Deployment of passenger car technology in Europe and the United States

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1. Summary

A key objective of this paper is to compare the uptake of a range of vehicle technologies in the United States (U.S.) and the European Union (EU) in recent years. Technologies under assessment include variable valve timing (VVT), gasoline direct injection (GDI), turbocharging, and stop/start, as well as transmission and hybridization technologies.

For both markets, rapid technology diffusion is found in recent years, largely as a response of vehicle manufacturers to increasingly stringent regulatory standards. Yet there are differences in the mix of technologies in both regions. In the U.S., manufacturers tend to focus more on VVT, GDI, hybrids, and continuously variable transmissions (CVTs) or transmissions with six or more gears, whereas in the EU there is stronger growth of diesel engines, stop/start, and turbocharging.

Vehicle characteristics in both regions differ as well. Passenger cars in the U.S. are generally heavier, bigger, and more powerful than in Europe, which results in higher average fuel consumption and carbon dioxide (CO₂) emission levels in the U.S. However, in both regions vehicles have tended to become more powerful and heavier while deploying increasingly high levels of technology and reducing official type-approval CO₂ emissions and fuel consumption. As a result, both regions met their respective 2015 CO₂ standards ahead of time. Some technologies seem to be driven not only by CO₂/fuel efficiency regulations, but also by other influencing factors, such as complementary regulations and incentives, differences in the enforcement of vehicle test procedures, and marketing efforts, as can be seen, for example, in the markedly different deployment of diesel and

hybrid electric cars in the U.S. and the selected EU member states.

In retrospect, the amount of technology deployment required to meet the EU's 2015 vehicle CO₂ target and in particular the associated cost increment is found to be significantly lower than expected at the time when the respective regulation was developed. Additional manufacturing costs to comply with future CO₂ standards are as of yet uncertain, but it is concluded that rigorous bottom-up methods should be the preferred approach for estimating future technology potential and costs.

1. Introduction

1.1. Background and objectives

Vehicle carbon dioxide (CO₂) and fuel efficiency standards for light-duty vehicles have been introduced in the United States (U.S.), the European

ABBREVIATIONS

AFV	Alternative fuel vehicles	FCA	Fiat-Chrysler	NHTSA	National Highway Traffic and Safety Administration
BEV	Battery electric vehicle	FCV	Fuel cell vehicle	PHEV	Plug-in hybrid electric vehicle
CAFE	Corporate average fuel economy	FTP	Federal test procedure	SUV	Sport utility vehicle
CNG	Compressed natural gas	GDI	Gasoline direct injection	VVT	Variable valve timing
CVT	Continuously variable transmission	GHG	Greenhouse gas	WLTP	Worldwide Harmonized Light Vehicles Test Procedure
EPA	Environmental Protection Agency	GM	General Motors		
		mpg	Miles per gallon		
		NEDC	New European Driving Cycle		

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Union (EU), Japan, China, Canada, India, South Korea, Brazil, Saudi Arabia, and other regions, covering approximately 80% of global new vehicle registrations in 2014. These standards are becoming increasingly stringent, driving car manufacturers to reduce their average fleet CO₂ emissions and to improve their fuel economy. This paper takes a closer look at the technology deployment in response to the U.S. and EU standards.

The U.S. and the EU are forerunners in the adoption of policies and standards to increase light-duty vehicle efficiency and to reduce CO₂ emissions.¹ The EU established 2015 CO₂ requirements in 2009 and has standards through 2021, as well as complementary policies such as relatively high fuel taxes and taxation fees indexed to CO₂ emissions in most member states. In addition, the EU is in the process of extending the vehicle CO₂ standards beyond 2021, with a regulatory proposal for extension expected in 2017. The U.S. introduced 2012–2016 fuel economy and greenhouse gas (GHG) standards for the light-duty vehicle fleet in 2010. The regulation was extended to include mandatory targets up to 2025, with an ongoing review of the 2022 to 2025 standards.

Technology forecasting is critical for setting the stringency level of future standards. Accurate analyses of the availability of additional technology, the rate at which new technology is being developed and used, and the benefits and cost of the various technologies are the basis for properly crafting standards. The design of the standards and complementary policies can also influence the technological development and technology deployment. For example, lower diesel fuel taxes and high fuel prices in most countries in Europe have resulted in a large increase of the light-duty diesel vehicle market share in Europe over

the past two decades. This has not occurred in the United States.

There are two overall objectives in this paper. The first is to evaluate the historic and current market deployment of various technologies in response to the standards in the U.S. and the EU. This includes an evaluation of the speed at which technologies have been implemented. In addition, differences in technology use between manufacturers, vehicle segments, and EU member states are considered. The second goal is a brief assessment of the accuracy of previous studies that forecasted the technology deployment deemed necessary to comply with the CO₂ standard in the EU.

The remainder of the introduction discusses the data sources used for the technology analyses in this report. Section 2 discusses the technology deployment in the EU and U.S. and where there are differences and similarities. Subsections discuss technology deployment by vehicle segment, by manufacturer, and by EU member state. Section 3 compares previous assessments of expected technology penetration and cost with actually observed developments in recent years. Section 4 summarizes the findings and briefly discusses implications on future policies and standards.

1.2. Data sources

The analyses for the U.S. are based entirely on the 2015 Fuel Economy Trends report by the U.S. Environmental Protection Agency (EPA) (U.S. EPA, 2015). The primary advantage of this report is that the EPA is in possession of the reports directly submitted by manufacturers for compliance with the fuel economy and GHG standards. These reports include detailed vehicle sales,

allowing for accurate sales-weighted assessments of fuel economy and technology market shares. Appendix K of the EPA report provides technology deployment estimates by manufacturer and vehicle type.² A limitation is the fact that the results are restricted to the assessments conducted by the EPA. For example, the EPA publishes data by manufacturer, but not by state (Table 1). Technologies reported by the EPA include type of fuel injection, variable valve timing (VVT), cylinder deactivation, turbocharging, stop/start, hybrid power trains, alternative fuel vehicles (AFVs), diesels, number of engine cylinders, automatic transmission, number of transmission gears, and continuously variable transmission (CVT), but do not include technologies such as variable valve lift, the type of hybrid system, the type of automatic transmission (e.g., conventional versus dual-clutch automated manual), or electric power steering. Data on AFVs is not available by segment or state.

Data for the EU comes from an ICCT internal database (Mock, 2015b) and additional data from KM77.com.³ KM77 is a car website that publishes independent vehicle reviews and maintains a comprehensive database with detailed vehicle specifications for passenger cars available in the Spanish market. The data is available for different manufacturers, EU countries, and car segments. Similarly to the U.S. data source, available data includes type of fuel injection, turbocharging, stop/start, hybrid power trains, AFVs, diesel, number of engine cylinders, automatic transmission, number of transmission gears, and CVT, but not the type of hybrid system or the type of automatic transmission. Cylinder

1 Given the direct link between fuel consumption and CO₂ emissions, a reduction in fuel consumption/increase in fuel economy goes hand in hand with a reduction in CO₂ emissions.

2 Appendix K does not include all of the technologies summarized in the main fuel economy trends report. The EPA provided an updated spreadsheet with all technologies to ICCT for this report. Also, the vehicle type classification in Appendix K only includes cars, two-wheel-drive compact sport utility vehicles (SUVs), all other SUVs, vans, and pickup trucks. Thus, the EPA also provided a further breakdown by small, medium, and large cars to the ICCT.

3 Available from <http://www.km77.com> (Spanish-language website).

Table 1. Available data for this report.

Technology	By country/state		By segment		By manufacturer	
						
Hybrid power train	✓	X	✓	✓	✓	✓
Diesel engine	✓	X	✓	✓	✓	✓
Fuel injection type	✓	X	✓	✓	✓	✓
Number of cylinders	✓	X	✓	✓	✓	✓
Variable valve timing (VVT)	X	X	✓	✓	X	✓
Turbo	✓	X	✓	✓	✓	✓
Start/stop	✓	X	✓	✓	✓	✓
Automatic transmission	✓	X	✓	✓	✓	✓
Continuously variable transmission (CVT)	✓	X	✓	✓	✓	✓
Transmission gears	✓	X	✓	✓	✓	✓
Alternative fuel vehicles (AFVs)	✓	X	✓	X	✓	✓

deactivation and variable valve lift are not included in the EU dataset and are therefore excluded from the analysis. VVT is only available by segment in the EU. However, EU data is available by member state, which allows a comparison of technology deployment between different EU member states.

Note that for the analysis as part of this paper, for hybrids, VVT, gasoline direct injection (GDI) and turbocharging, the technology penetration is put in perspective to the total number of gasoline vehicles only, as those technologies largely apply to gasoline vehicles and thereby allow for a more meaningful comparison with the situation in the U.S. The overall market shares of those technologies, when also taking into account diesel vehicles, differ from the figures provided here.

2. Efficiency and Technology Trends

2.1. Standard stringency in the U.S. and the EU

Two regulatory agencies are responsible for issuing and implementing GHG and fuel efficiency standards in the United States, namely the EPA and the National Highway Traffic and Safety Administration (NHTSA) under the U.S. Department of Transportation. The first Corporate Average Fuel Economy (CAFE) standard was introduced in 1975 and GHG emissions requirements were added in 2009. CAFE fuel economy testing is done

on the combined U.S. federal test procedure (FTP) driving cycle and highway cycles. The first significant tightening of the CAFE standards since the early 1980s was issued by NHTSA in 2003 and applied to light trucks manufactured between 2005 and 2007 (NHTSA, 2003). The next revision applied to the manufacturing years 2008 to 2011, introduced a higher stringency and broadened vehicle categories to include heavy sport utility vehicles (SUVs). In addition, the vehicle footprint (a measure of vehicle size: wheelbase x track width) has been established as a utility parameter.⁴ Thus, starting with the 2011 standards, mass has been superseded as a utility parameter (NHTSA, 2006).

The 2012–2016 CAFE (NHTSA) and GHG (EPA) standards for passenger cars and light-duty vehicles were announced in May 2009 and issued one year later (German & Bandivadekar, 2010; NHTSA, 2010). They target a GHG emissions reduction of the average 2009 passenger car vehicle fleet down

to 36.2 mpg (158 g CO₂/km)⁵ by 2015 and 37.8 mpg (151 g CO₂/km) by 2016. The 2017–2025 CAFE/GHG standards for light-duty vehicles, including passenger cars, light-duty trucks, and medium-duty passenger vehicles, were issued in August 2012. They further restricted CO₂ emissions of passenger cars down to an equivalent of 97 g CO₂/km (U.S. EPA, 2012b).

Battery electric vehicles (BEVs), fuel cell vehicles (FCVs), and plug-in hybrid electric vehicles (PHEVs) are counted as 0 g/km toward the U.S. fleet average CO₂ level. In addition, multiplier credits are granted for BEVs, FCVs, PHEVs, and vehicles that run on compressed natural gas (CNG) (U.S. EPA, 2012a). These multiplier credits allow manufacturers to account for these vehicles more than for other vehicle types, thereby reducing the overall CO₂ average of a manufacturer's vehicle fleet (Table 2).

Table 2. U.S. credits for alternative vehicles as a function of time.

Year	BEV and FCV	PHEV and CNG vehicles
2017–2019	2.00	1.60
2020	1.75	1.45
2021	1.50	1.30
2022–2025	1.00	1.00

4 Utility parameter is defined as a standardized measure that is used as the basis to determine a manufacturer CO₂ target value. In the U.S., the utility parameter is the footprint of a vehicle (i.e., the larger a vehicle, the more CO₂ emissions it is allowed to emit). In the EU, the utility parameter is the weight of a vehicle (i.e., the heavier a vehicle, the more CO₂ emissions it is allowed to emit).

5 The U.S. CAFE standard is converted to CO₂ emissions in g/km on the New European Driving Cycle (NEDC), applying a set of conversion factors described in more detail in (Kühlwein et al., 2014).

The European Commission is the regulatory body responsible for proposing CO₂ standards for motor vehicles in Europe, with the European Parliament and the Council (the EU member states) voting on the final regulatory proposal. The EU standard applies to new passenger vehicles and light commercial vehicles (with lower targets for passenger vehicles). Voluntary targets were introduced in the mid-1990s, requiring each manufacturer to reduce the average CO₂ emissions for new passenger vehicles down to 140 g CO₂/km (as measured over the NEDC) until 2008 (Mock, 2014).

Initially, manufacturers successfully reduced emission levels, but did not meet the voluntary targets anymore from 2004 onwards. As a result, mandatory targets were introduced in 2009, stipulating a passenger car fleet average target of 130 g CO₂/km by 2015. The 2015 target has been phased in over four years, beginning in 2012. An additional long-term target of 95 g CO₂/km was introduced for 2020, by which date only 95% of the fleet actually has to comply with the target. Full compliance is not required until 2021 (EC, 2016). The official emissions testing procedure in the EU is the NEDC, which will be in place until the end of 2019. In parallel, the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) will be introduced in 2017, and a simulation model will help with translating NEDC into WLTP CO₂ targets during the interim phase in which both test procedures will be in place in the EU.

Additionally, BEVs and FCVs are counted as 0 g/km toward the CO₂ fleet average, and vehicles that emit less than 50 g CO₂/km on the NEDC receive multiplier credits (so-called super credits) until 2023 (Table 3), facilitating formal compliance with the 2020 target. Each of these vehicles has been counted as several cars between 2012 and 2015. In addition, the credits will be reintroduced in 2020 for a second phase

(EC, 2016). Also, fleet-average CO₂ emissions are reduced by 5% for flex-fuel cars that run on a mix of 85% ethanol and gasoline (E85). In case of noncompliance, penalties apply, depending on the amount of CO₂ emitted above the threshold.

Table 3. EU super-credit values as a function of time.

First phase		Second phase	
YEAR	CREDIT VALUE	YEAR	CREDIT VALUE
2012–2013	3.50	2020	2.00
2014	2.50	2021	1.67
2015	1.50	2022	1.33
2016–2019	1.00	2023	1.00

A 2025 target value range of 68–78 g CO₂/km has been proposed by the European Parliament and both the review and impact assessment are expected to take place mostly in 2017 (Mock, 2014). In addition, the European Parliament suggested introducing the vehicle footprint as an additional utility parameter and as an alternative to vehicle mass from 2020 onwards (ibid.). The footprint-based system has the advantage that emission reductions from vehicle weight reduction are fully taken into account, leading to a lower compliance cost for manufacturers (Mock, 2013).

Both regions, the U.S. and the EU, met their respective 2015 CO₂ standards ahead of time. In the EU, the official car fleet average was already below 130 g CO₂/km in 2013; in the U.S. the official fleet average was below the 158 g CO₂/km target (expressed in NEDC terms) by 2014. Note that both the U.S. and EU standards are based on official type-approval measurements on the FTP and highway test cycles (U.S.), respectively the NEDC (EU). Real-world fuel consumption and CO₂ emissions in the EU are typically around 40% higher when looking at new cars in 2014 (Tietge et al., 2015). The discrepancy in U.S. test cycles is expected to be smaller (Greene et al., 2015).

2.2. Vehicle segmentation in the U.S. and the EU

The U.S. light-duty vehicle fleet as defined under the GHG/fuel economy regulation includes not only cars and two-wheel drive SUVs with a gross vehicle weight up to 2,700 kg, but also light trucks that include two-wheel drive SUVs from 2,700 kg to 4,500 kg, all of the four-wheel drive SUVs and passenger vans up to 4,500 kg, and all cargo vans and pickup trucks up to 3,900 kg (U.S. EPA, 2015). In the EU, according to Directive 70/156/EC, as amended by Directive 2007/46/EC,⁶ light-duty vehicles include passenger cars with a gross vehicle weight up to 3,500 kg (M1) and light-commercial vehicles up to 3,500 kg (N1). Most of the light trucks per the EPA's definition are regulated as N1 vehicles in the EU and are subject to a different CO₂ target. Therefore, it is more appropriate to directly compare U.S. passenger cars and two-wheel drive SUVs up to 2,700 kg with EU passenger cars up to 3,500 kg (M1).

As illustrated in Table 4, U.S. passenger cars are about 14% heavier than EU cars and have a power-to-mass ratio that is about 29% higher. The impact of mass on fuel economy during constant performance is generally considered to be about a 6%–7% change in fuel consumption for a 10% change in mass (Mock, 2011). Thus, the U.S. passenger car fleet would have about 14 g or 9% lower CO₂ emissions if its mass were reduced to the EU average, or about 143 g CO₂/km (in NEDC terms). While the trade-off between performance and fuel economy is more uncertain, the U.S. passenger car fleet has a power-to-mass ratio roughly 30% higher than

6 <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007L0046&from=en>

7 As discussed in more detail in (Mock, 2011), there are some inconsistencies with respect to the vehicle weight definitions in vehicle markets around the world. As the focus of the analyses within this paper is on trends over time, these differences in definitions are expected to have only a minor effect on the overall observed trends.

Table 4. Comparison of 2014 U.S. and EU new passenger car characteristics and 2015 standards.

Region	Mass (kg) ^(a)	Footprint (m ²)	Power (kW)	Power/ mass (kW/kg)	Diesel (%)	Auto (%) ^(b)	Average CO ₂ (g/km) ^{(c)(d)}	2015 CO ₂ standard (g/km) ^(c)
	1,614	4.3	148	0.092	1	96	157	158
	1,392	4.0	90	0.065	53	23	123	130

^(a) Mass in running order⁷; ^(b) Auto = automatic transmission; ^(c) U.S. figures normalized to NEDC; ^(d) Excluding credits

the EU fleet, arguably reflecting the adoption of more powerful engines than the use of lightweight materials. This large discrepancy, along with a much higher proportion of automatic transmissions (96% vs. 23%) and differences in the enforcement in vehicle testing regulations, likely account for the remaining difference between the fleets' average CO₂ levels.

2.3. Technology trends in the U.S. and the EU

The latest data from the U.S. EPA fuel economy trends report shows that

the rate of technology adoption is increasing for the fuel-saving technologies under study. Even without policy intervention, automakers never stop innovating new technologies, re-designing vehicles, and retooling their manufacturing facilities to remain competitive (not all technological improvements necessarily go toward improving fuel economy, though). U.S. data from the past two decades shows that once applied for the first time, new technologies can be deployed to a large fraction of the fleet quickly, thanks to platform sharing and improved manufacturing

flexibility in the modern auto industry (Lutsey, 2012).

Stringent technology-forcing policies such as performance standards increase the innovation capacity of manufacturers in the competitive automotive markets (ibid.) and further drive the deployment of advanced technologies. This has been observed in the U.S. for the past decade. Figure 1 shows the evolution of several major power train technologies since 2001 and the regulatory timeline in the United States and in the EU.

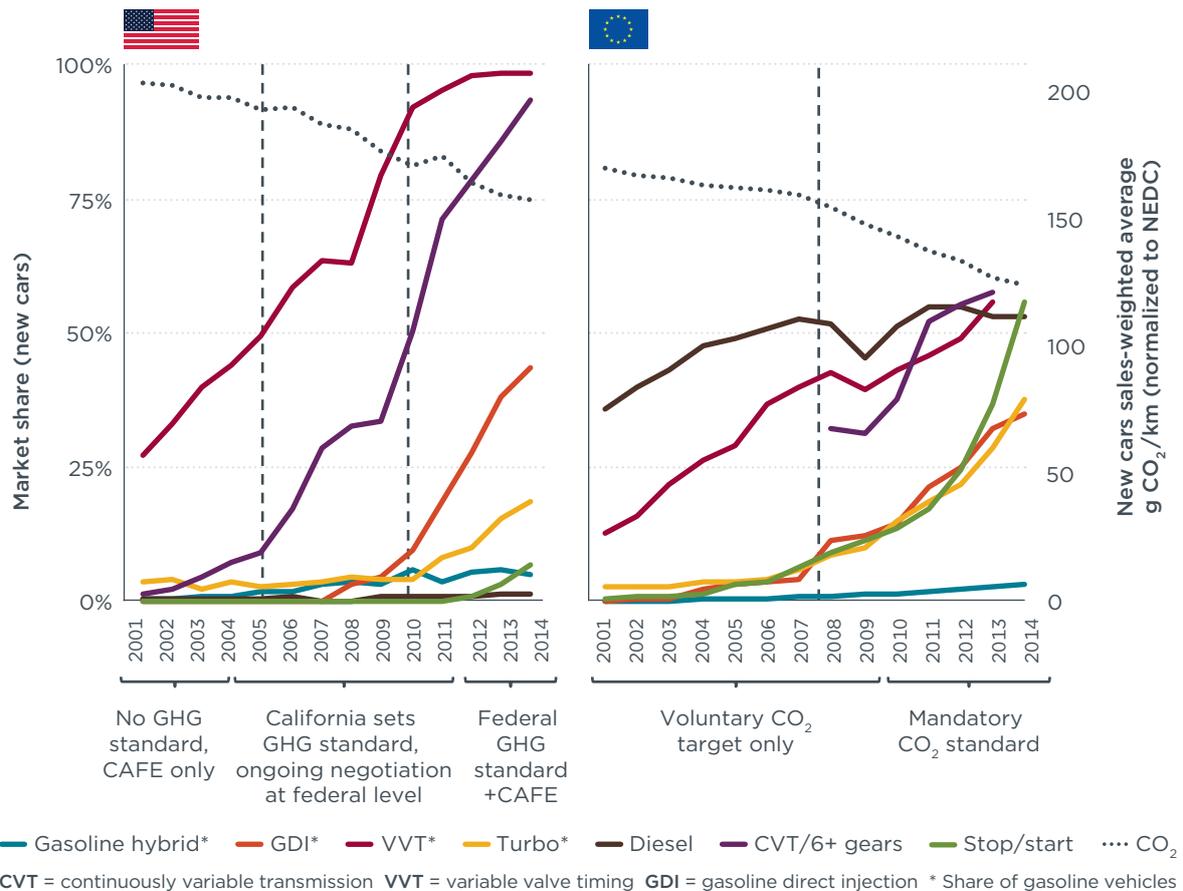


Figure 1. Trends of technology deployment for the U.S. and EU passenger car fleet during 2001-2014, the sales weighted type-approval CO₂ average (on secondary axis), and regulatory timeline. The U.S. CAFE standard is converted to CO₂ emissions in g/km on the NEDC.

In contrast to the slow uptake of these technologies in the U.S. before 2004, the market share of few fuel-saving technologies rose significantly between 2004 and 2009, and more technologies took off after 2009. The increasing pace of technology deployment is correlated with the U.S. light-duty vehicle CAFE/GHG emissions regulation. The U.S. fuel economy standard had stagnated for nearly two decades until California adopted the first regulatory GHG standards for the manufacturing years 2009–2016 of light-duty vehicles in 2004 (CARB, 2013). In addition, NHTSA began tightening light-truck CAFE standards, starting with the 2005 model year (NHTSA, 2003). As manufacturers often share power trains between cars and light trucks, this contributed to the increasing technology adoption in cars after 2005. Then the federal government, California, and the industry reached an agreement in 2009–2010, and the regulatory process formally adopted the manufacturing year 2012–2016 standards nationwide in 2010 (German & Bandivadekar, 2010).

U.S. manufacturers made substantial technology investments over the 2004–2010 period for anticipated compliance with the California GHG standards and the NHTSA light-truck standards (ibid.), which is evident in accelerated deployment of key efficiency technologies during that time frame. This was followed by adoption of the 2012–2016 standards in 2010, which was a signal to the industry that the standards would continue to be tightened in the long term. During development of the 2017–2025 rule, the industry reached another agreement with the federal government and California to support the long-term standards until 2025 (U.S. EPA & NHTSA, 2011). This has driven faster diffusion of technologies beyond 2010 (Lutsey, 2012).

A similar pattern was observed for the EU new passenger car fleet. Since the mandatory standards were adopted in 2008/2009, advanced engine and

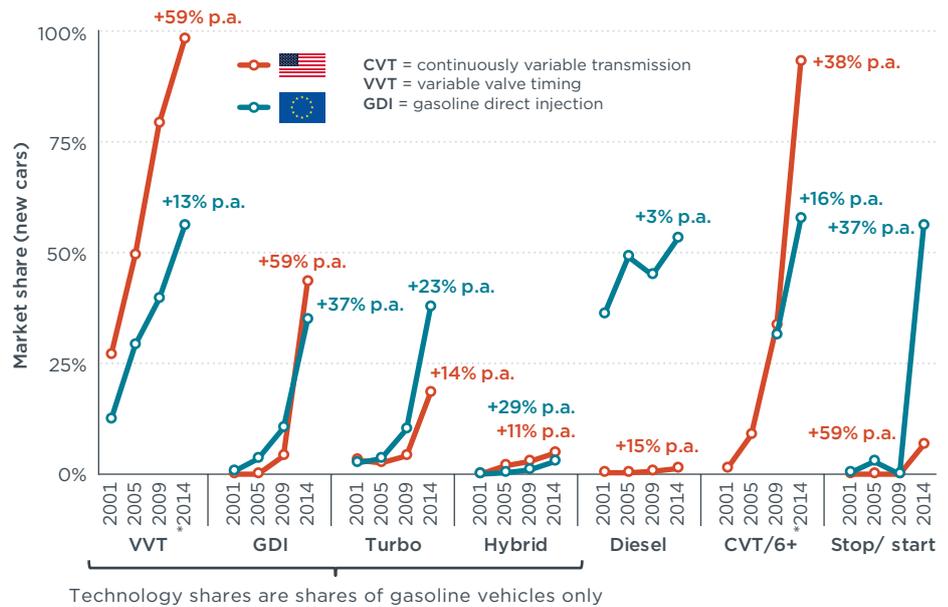


Figure 2. Power train technology adoption rates in new U.S. and EU passenger cars 2001–2014. Red values show average annual technology growth rates for the U.S.; blue values for the EU; *EU figures up to 2013.

transmission technologies have been introduced to the market at a faster pace. Specifically, from 2009 to 2014, deployment rates of GDI and turbocharged/supercharged gasoline engines approximately tripled from about 10% to 38%. Similarly, stop/start increased from 11% to 56% and gasoline hybrid market shares (excluding plug-in hybrids) grew from 1% to 3%. Diesel engines saw an increase from 45% to 53%, due to lower diesel fuel taxes and high fuel prices in most European countries, but also due to technical improvements and increased marketing efforts (Neumaier, 2010). In addition, VVT increased from 39% to 56% of gasoline engines and CVT/transmissions with six speeds and more increased from 31% to 58% between 2009 and 2013.

Stop/start has been one of the fastest-growing technologies in the EU with an average growth rate of 37% per year between 2001 and 2014 (Figure 2). This trend can be explained by the high share of idling time on the NEDC compared with the FTP. The NEDC is characterized by an idle time of 294 seconds or 24.9%. Idle time is 262 seconds or 19.1% on the FTP and only 0.5% on the

highway cycle. The combined time-weighted average used for CAFE/GHG regulations is 10.7%. Start/stop technology allows the motor to shut down during idling times to optimize for fuel consumption and thus to reduce CO₂ emissions. With the introduction of the new WLTP in the EU, scheduled for 2017, idle time during vehicle testing will decrease to 235 seconds or 13.1% (Mock et al., 2014).

Even though both regions have seen rapid growth in GDI and gasoline turbocharging, the U.S. has higher GDI and lower turbocharging deployment, suggesting that the U.S. has many naturally aspirated engines with GDI while in Europe manufacturers are primarily matching GDI with turbocharged engines, the combination of both usually associated with a reduction of cylinder capacity. These strongly downsized engines have recently become popular in Europe while, also for marketing reasons, they are not as popular in the U.S. (Neumaier, 2010).

2.4. Technology trends by vehicle segment

Trends are also tracked by vehicle segment. This is challenging,

Table 5. Comparison of 2014 U.S. and EU new passenger car characteristics by segment.

Segment	Region	Mass (kg) ^(a)	Footprint (m ²)	Power (kW)	Power/mass (kW/tonne)	Diesel (%)	Auto (%) ^(b)	CO ₂ (g/km) ^(c)
Small		1,171	3.7	65	56	28.0	9	113
Small		1,487	4.0	144	97	2.6	87	156
Lower-medium		1,391	4.1	90	65	59.5	18	116
Midsize		1,601	4.3	142	89	1.7	97	152
Medium		1,624	4.4	118	73	83.0	44	127
Large		1,722	4.5	185	107	0.1	98	184
Upper-medium		1,849	4.6	156	84	87.9	83	138
Car SUV		1,750	4.3	155	89	0.0	99	185
Off-road		1,585	4.2	107	68	71.5	30	142

^(a) Mass in running order; ^(b) Auto = automatic transmission; ^(c) U.S. figures normalized to NEDC

though, as the U.S. applies different vehicle classifications than the ones commonly used in the EU. As a consequence of the different classification schemes, for example, the Volkswagen (VW) Golf and similar vehicles are classified as small cars in the U.S., while they are lower-medium cars in Europe.

For this assessment, the EPA classification⁸ is used for U.S. cars. For EU cars a classification in line with ICCT’s European Vehicle Market Statistics Pocketbook (Mock, 2015b) is used. U.S. and EU segments are then matched based on best judgement, as shown in Table 5. Regarding average mass and footprint, the U.S. small-car segment is best comparable to the EU lower-medium segment. Similarly, U.S. midsize cars are matched with EU medium cars, large U.S. passenger cars with upper-medium cars in the EU, and European off-road vehicles with U.S. American SUVs. Small EU cars do not have a direct equivalent in the U.S. and are therefore excluded from the analysis.

The footprint by segment is slightly higher for the EU. Power, power-to-mass ratio, and drive-cycle CO₂ emissions are lower in the EU for comparable segments. Consistently through all segments, U.S. passenger

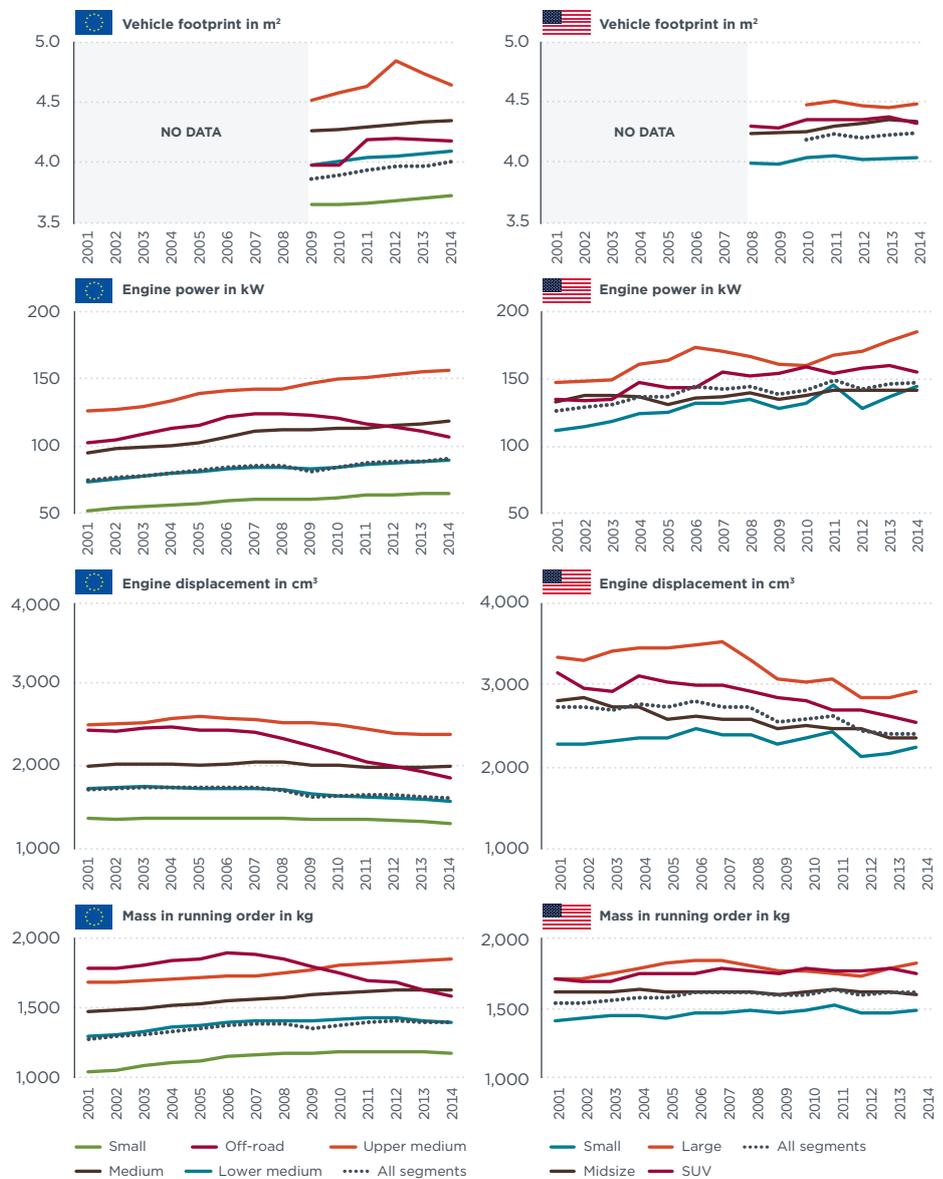


Figure 3. EU and U.S. new passenger car trends, by segment.

⁸ <http://www.fueleconomy.gov/feg/info.shtml#sizeclasses>.

cars have a lower share in diesel but a higher share in automatic transmissions. The small-car segment in the U.S. is characterized by a high engine power (144 kW) as this segment includes a lot of high-performance sports cars. Figure 3 illustrates the development of EU and U.S. passenger car characteristics by segments between 2001 and 2014.

In the United States, vehicle footprint remained stable across all segments with moderate growth between 0.2% for large cars and 2% for midsize cars. Meanwhile, engine power increased considerably between 6% for midsize cars and 22% for small cars, whereas engine displacement decreased between 1% (small) and 19% (SUV) in the same time period. This can be explained by the fact that the share of gasoline turbocharging and GDI increased (compare with Figure 4).

Turbocharging permits a higher amount of air and fuel to be injected into the cylinders, generating more power per unit of engine displacement. As a result, turbocharging allows for engine downsizing while maintaining or increasing performance. The highest increase in engine power can be found in the small-car segment (22%) where the share of turbo is the highest (27%). The second-highest increase in engine power can be observed in the large-car segment (21%), which is characterized by a high share of GDI (58%).

Similar to the United States, the passenger car footprint remained relatively constant across segments in the EU, with a moderate increase between 2% (medium) to 5% (off-road) (Figure 3). Also, engine power increased, in general by 21% to 24% for the lower- to upper-medium segments, whereas engine displacement decreased by 0.3% (medium) to 8% (lower medium). An exception is the off-road segment where engine power increased until 2007 but then declined, resulting in an overall

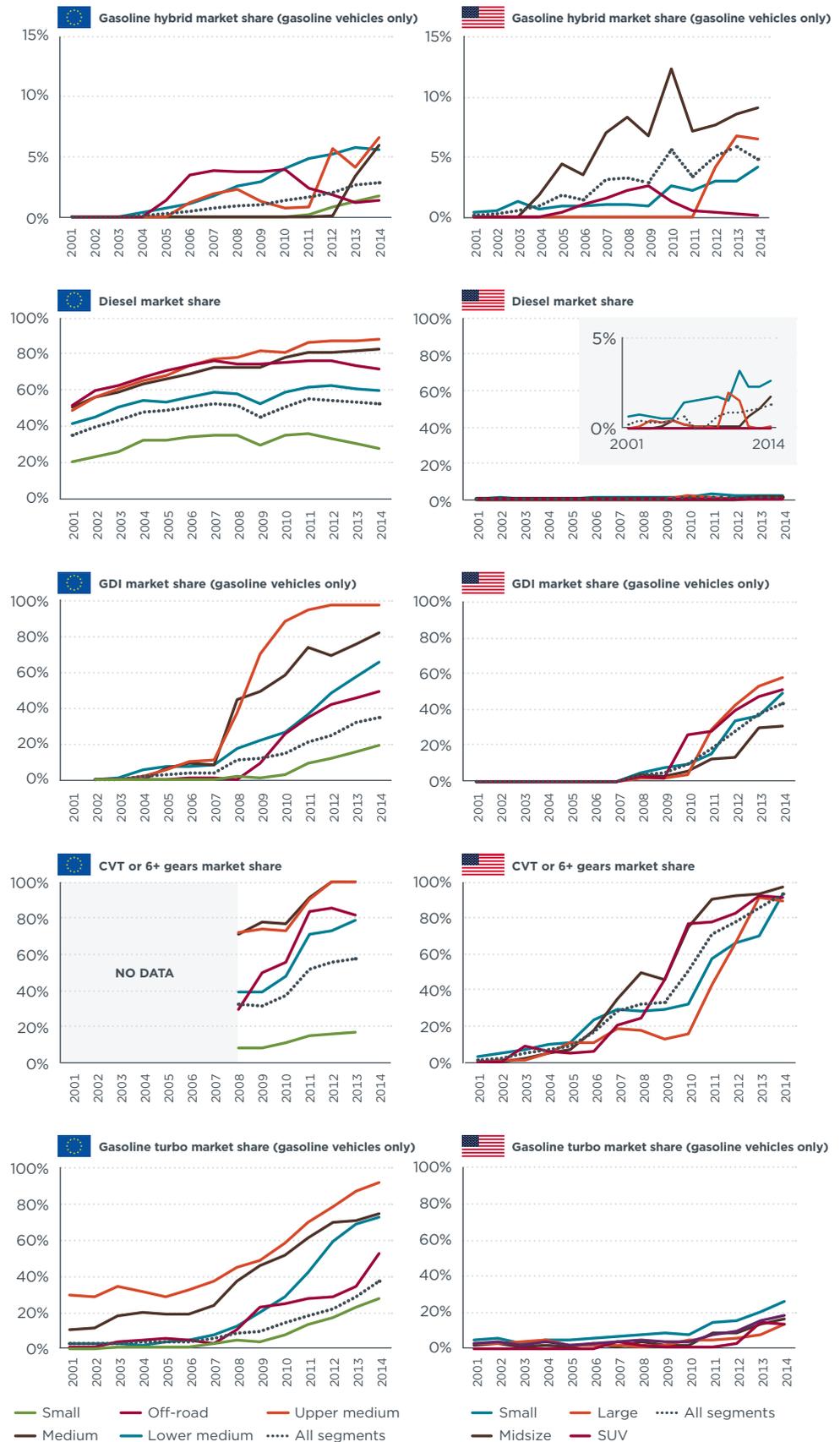


Figure 4. EU and U.S. new passenger car technology trends, by segment. Figure continued on next page

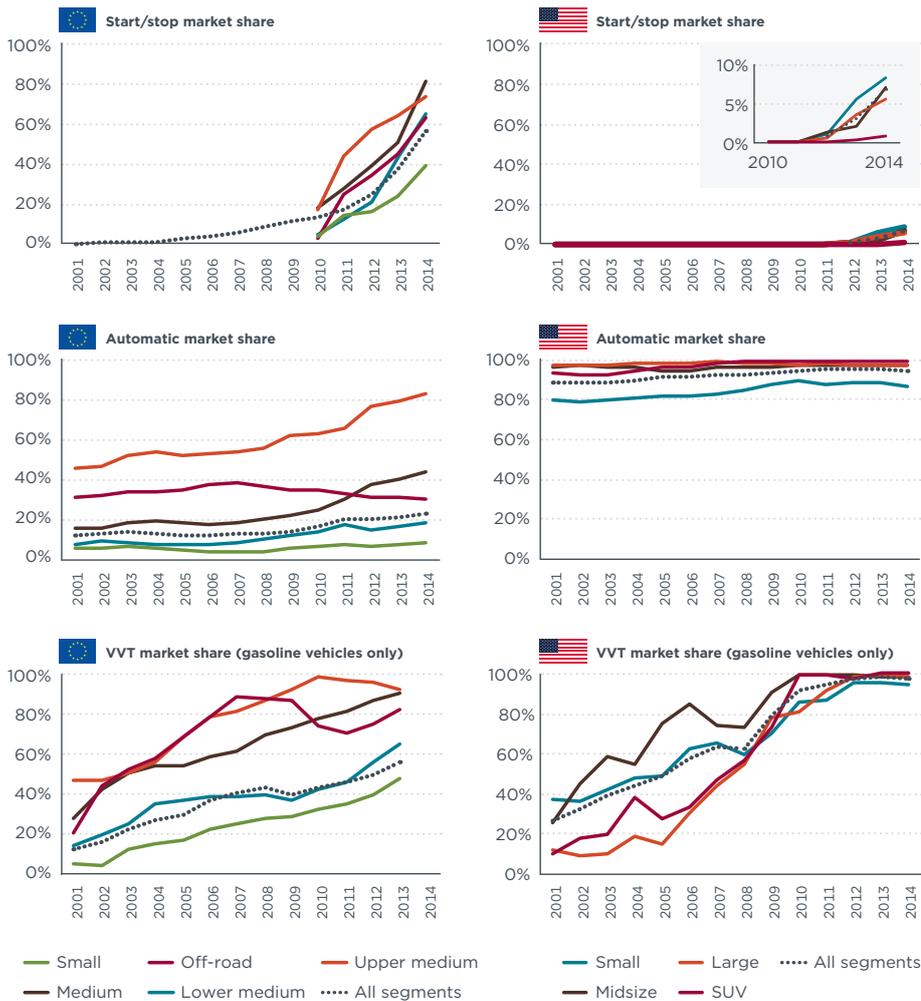


Figure 4. EU and U.S. new passenger car technology trends, by segment.

moderate increase of 5%. In the same time, engine displacement decreased by a notable 24%. This could be explained by the increasing popularity of subcompact SUVs such as the Opel Mokka and the Renault Captur in Europe. Also termed mini-SUVs, these are lighter and less powerful than conventional SUVs and are usually not equipped with an all-wheel drive system. Similarly, the average mass of the SUV segment increased until 2006 and then declined, leading to an overall reduction of 11%. The other segments increased in mass between 8% and 14%.

One of the main differences between the EU and U.S. markets is that—although compact SUVs such as the Ford Escape or Toyota’s RAV-4 and

subcompact SUVs such as Fiat’s 500X or the Mini Countryman became increasingly popular in the U.S. as well—the observed impact on mass, engine power, and vehicle footprint is not as striking as in the EU.

In addition, the overall European average engine power, engine size, and mass match quite closely those of the lower-medium segment, whereas in the United States, average vehicle characteristics correspond more to the medium-sized segment. This reflects the high popularity of not only the lower-medium but also the small-car segment in Europe. Most vehicles registered in Europe are small- or medium-sized; for instance, the lower-medium VW Golf was the top-selling car in Europe between

2008 and 2014. Other popular models are Ford’s Fiesta, Renault’s Clio, and VW’s Polo, which are all found in the small-car segment. In the U.S., the medium/upper-sized Honda Accord and Toyota Camry are very popular. Note that the three highest-selling vehicles in 2014 were all pickup trucks (Dodge Ram, Chevrolet Silverado, Ford F-150) which are not reflected here (Cain, 2015).

In the U.S., gasoline hybrids are increasingly found in the midsize-car segment (Figure 4) but the share is also growing in the large-car segment. Between 2004 and 2010, federal, state-level, and/or local financial and nonfinancial incentives have been in place for hybrid vehicles, which helped to increase their share during that time. Financial incentives included direct subsidies for customers, usually in the form of a rebate on the purchaser price, and tax exemptions. At a federal level, the 2004 Tax Relief Act provided a US\$2,000 (~€1,800) taxable income deduction for the purchase of an alternative fuel vehicle, which included hybrids. The 2005 Energy Policy Act granted a direct tax credit for the purchase of a hybrid. In addition, the 2009 Car Allowance Rebate System gave a tax credit for the trade-in of less efficient cars for more efficient cars, such as hybrids (Jenn, Azevedo, & Ferreira, 2013). Nonfinancial incentives included access to carpool lanes, also referred to as high-occupancy vehicle (HOV) lanes. These have different stringency levels, requiring between one to three passengers in the vehicle besides the driver.

Lately, the diesel share has been growing among smaller U.S. car segments with better fuel economies; up to 2.6% in the small-car segment and up to 1.7% in the midsize-car segment in 2014 (see figure inlet). The high diesel shares are due to the VW group, which dominated the car diesel market in the United States up

until 2015, so their market segments dictate the overall industry market segments for diesels. In the light of the recent uncovering of VW's illegal defeat device usage, however, the future of diesel vehicles in the U.S. is uncertain.

Start/stop technology has been increasing since 2011, and higher shares are found in the smaller segments (see figure inset). Also, turbo is mainly deployed in the small-car segment.

CVT/6+ gears experienced significant market share growth across all segments but especially in the midsize segment. Also, hybrids are especially found in the midsize segment. Automatic and VVT shares are in general very high among all segments but especially in the larger ones.

In the EU, gasoline hybrids were characterized by strong growth in the off-road segment between 2004 and 2006 before the growth stagnated and declined after 2010 (Figure 4). Nowadays, the technology is predominantly found in the lower- to upper-medium vehicle segments. This development relates to high sales numbers of different Toyota/Lexus models, and especially of Prius models (Mock, 2015b, p. 40), which are found in this segment range. Different EU member states provide incentives for hybrid vehicles; see Section 2.6 for details.

In general, diesel technology in the EU has been growing, with an exception between 2008 and 2009. During this time, several member states granted a scrappage incentive. These incentives diminished sales of diesel cars (see Section 2.6 for more details). Between 2010 and 2012, diesel shares in the lower-medium segment first recovered but then declined again. A similar trend can be observed in the off-road car segment. However, the diesel share across the medium and

Table 6. Newly registered U.S. and EU passenger cars by manufacturer group, 2014.

Manufacturer group	Main brands/affiliated companies	Market share in 2014	
			
VW	VW, Audi, SEAT, Škoda, Porsche, Bentley, Bugatti, Lamborghini	25%	6%
Renault-Nissan	Renault, Dacia, Nissan, Infiniti	14%	11%
Groupe PSA	Peugeot, Citroën, DS	10%	0%
Ford	Ford, Lincoln, Mercury	7%	10%
GM	Chevrolet, Cadillac, Buick, GMC, Opel, Vauxhall	7%	14%
BMW	BMW, Mini, Rolls-Royce	6%	4%
Hyundai/Kia	Hyundai, Kia	6%	13%
FCA	Fiat, Chrysler, Dodge, Jeep, Ram, Alfa Romeo, Lancia, Ferrari, Maserati	6%	6%
Daimler	Mercedes-Benz, Smart	5%	3%
Toyota	Toyota, Lexus, Daihatsu, Scion	4%	16%
Others		7%	7%

upper-medium segments has been constantly growing since 2010.

Start/stop, turbo, VVT, GDI, and CVT/6+ gears technology grew substantially between 2001 and 2014 in all segments. Most technology (start/stop, turbo, VVT, GDI, CVT/6+, diesel, and automatic) is found in the European medium and upper-medium segments. This is related to the fact that these segments are among the higher-selling segments in combination with relatively high CO₂ emissions. Thus, in order to comply with fleet-average CO₂ standards, manufacturers deploy most technology in these segments as the effect on reducing official fleet-wide CO₂ emissions is higher. Also, the price sensitivity of the customers tends to be lower in these segments (Baltas & Saridakis, 2009).

One of the key differences between the EU and U.S. market is that gasoline hybrid shares are generally higher (on average about twice as high as in the EU) in the U.S. market. This is true for all segments except for the off-road/SUV segments where the share is somewhat higher in the EU (but low in both regions when compared with the overall market averages). In the EU, if diesel vehicles are taken into account, the resulting overall

market share of hybrid electric vehicles is significantly lower than in the U.S. The diesel market share in the U.S. is very low (1% versus 53%) because diesel fuel prices are relatively high compared with gasoline fuel prices in the U.S. and diesel refueling stations are less common than in the EU. In addition, negative customer perception of diesel has been observed in the U.S. (Neumaier, 2010).

2.5. Technology trends by manufacturer

The manufacturer groups chosen for comparison are major automobile makers that are successful in both the EU and U.S. markets, and for which detailed data is available. These are VW, General Motors (GM), Ford, Toyota, Fiat-Chrysler Automobiles (FCA), BMW, and Daimler, which—including affiliated brands—accounted for around 13 million newly registered passenger cars or about 60% market share in the EU and U.S. combined in 2014 (Table 6).

Toyota, VW, and GM are the top three global vehicle sellers, each with around nine to 10 million units worldwide in 2015. GM and Toyota are also the highest-selling manufacturers in the U.S., each with around 14%–16% market share) (Marklines, 2016). For Europe, the

Table 7. Comparison of 2014 U.S. and EU new passenger cars by manufacturer group.

Manufacturer group	Region	Mass (kg) ^(a)	Foot-print (m ²)	Power (kW)	Power/ mass (kW/tonne)	Diesel (%)	AFVs (%) ^(b)	Auto (%) ^(c)	CO ₂ (g/km) ^(d)
Ford		1,625	4.3	151	93	0	0.8	94	165
		1,358	4.0	83	61	44	2.0	9	122
GM		1,696	4.3	159	94	1	0.9	97	173
		1,436	4.0	85	59	40	3.2	9	130
FCA		1,741	4.5	178	102	1	0.2	96	195
		1,245	3.6	70	56	33	12.2	4	123
Toyota		1,563	4.2	125	80	0	0.6	99	142
		1,317	3.9	77	58	26	0.0	34	113
VW		1,650	4.2	148	90	19	0.1	91	168
		1,411	4.0	96	68	56	1.4	23	126
BMW		1,749	4.4	191	109	5	2.6	95	166
		1,581	4.3	131	83	81	0.8	57	131
Daimler		1,850	4.3	207	112	1	1.0	100	186
		1,618	4.3	121	75	72	0.8	61	129
All		1,614	4.3	148	91	1	0.7	96	161
		1,392	4.0	90	65	53	2.2	23	123

^(a) Mass in running order; ^(b) AFVs = alternative fuel vehicles; ^(c) Auto = automatic transmission; ^(d) U.S. figures normalized to NEDC

top selling manufacturer group is VW with 25% market share). BMW and Daimler are added to the list of manufacturers for the comparison, as they are leaders in the premium segment in both the U.S. and the European market. Manufacturers of premium brands are often forerunners in technology deployment and are therefore of particular interest for this work.

As it is shown in Table 7, on average, all manufacturers sell heavier, larger, and more powerful vehicles in the U.S. market, when compared to the respective averages for the EU new car fleet.

AFVs include all vehicles that run on fuels other than conventional diesel or gasoline; these fuels include natural gas, liquefied petroleum gas, flex-fuel (conventional fuel blended with biofuel, e.g., BEVs, PHEVs, and FCVs) but exclude non-plug-in hybrids.

In the U.S., the overall share of AFVs is below 1% for all considered manufacturers. Only BMW reaches a share above 2% as a share of their newly registered vehicles in 2014. In the EU, shares of AFVs are relatively low as well but somewhat higher than in the United States. Only FCA reached a significant share of AFVs, mainly caused by the fact that natural gas and liquefied-petroleum-gas-fueled vehicles are eligible for cleaner vehicle subsidies in Italy (ACEA, 2016), the home market of Fiat. Electric vehicles accounted for 0.3% of EU and U.S. passenger car sales in 2014.

In the U.S., there are similar trends by manufacturer as with vehicle segments in the sense that engine power increased whereas engine displacement decreased (Figure 5) due to the growing use of GDI and turbochargers (compare with Figure 6). Vehicle footprint increased between 1% and 5% for most manufacturers.

Only the footprint of Ford vehicles remained constant on average, and GM reduced its footprint by 1%. In addition, most manufacturers increased the average mass of their cars by 2% to 10%.

Similarly, engine power of all manufacturers increased in the EU while engine displacement decreased (Figure 5) due to higher deployment rates of GDI and turbocharging (Figure 6). The reduction in engine displacement was larger for manufacturers that produce vehicles with relatively high engine displacement. Overall, the observed average car characteristics follow the same upward or downward trend in both regions: footprint, engine power, and mass are increasing and engine displacement is decreasing.

Some selected key differences between the U.S. and the EU markets are that manufacturers are selling more powerful, bigger, and heavier vehicles in the U.S. than

in Europe. It is interesting to note that in Europe, BMW and Daimler sell larger and heavier vehicles with bigger and more powerful engines than the other manufacturers, whereas in the U.S. there is less difference between the manufacturers. It is also noteworthy that the vehicle footprint of FCA is much smaller in the EU than in the U.S. This is due to the fact that the European sales of FCA are dominated by Fiat, which produces mostly compact vehicles such as the Fiat 500, whereas the U.S. passenger car market is dominated by larger Chrysler models, and with the two companies merging only recently back in 2014.

In the U.S., Toyota reaches significant shares of gasoline hybrids as a share of the company's yearly registered vehicles (Figure 6). These high shares are reached predominantly through sales of the Prius vehicle family. The only manufacturer that—until recently—has gained significant diesel share is VW.

Market share of automatic transmissions in the U.S. is high across all manufacturers with 88% to 100% in 2014. Only VW and BMW had built a significant share of car models with manual transmission, mainly before 2010. BMW and Daimler transferred start/stop technology from the EU to the U.S. market and are thus the only manufacturers reaching significant shares of start/stop in the U.S. BMW and Daimler reached shares up to 70% and more in 2014, but all other manufacturers reached shares less than 5%.

In the EU, Toyota is the only manufacturer with strong growth of gasoline hybrid vehicles, mainly due to growing sales of the Toyota Prius, Yaris, and Auris, and most Lexus gasoline engines. BMW, Daimler, and VW are the manufacturers with the highest diesel shares in the European market. VW and BMW were early forerunners in deploying GDI

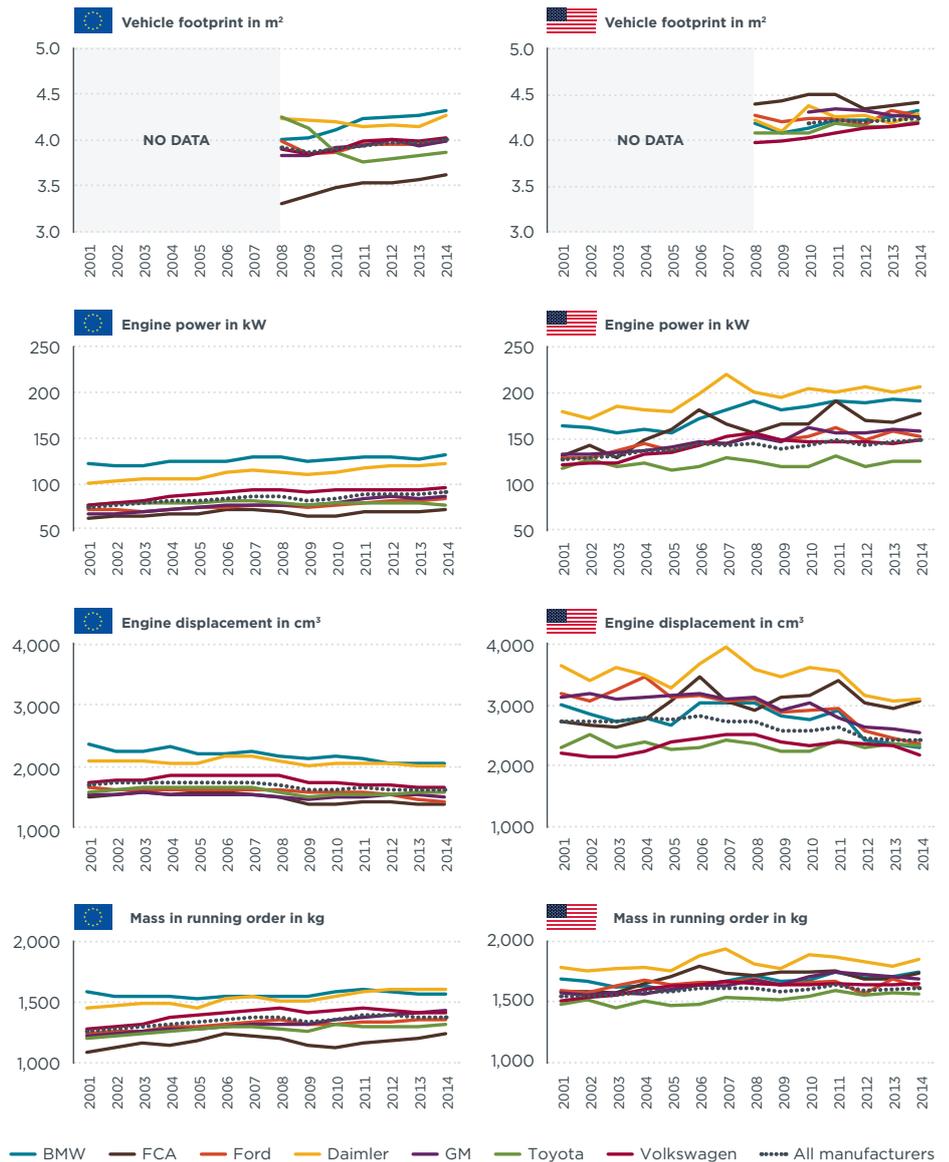


Figure 5. EU and U.S. new passenger car trends, by manufacturer.

technology, whereas Daimler focused on gasoline turbochargers. BMW and Daimler also have the highest share in automatic transmission.

One of the key similarities of both markets is that GDI, CVT/6+ gears, and turbo (and VVT) technology are increasingly deployed among manufacturers in the U.S. and the EU. This is a similar development as per vehicle segments in the U.S. and the EU.

In addition, BMW and Daimler deploy a significant amount of technology in both regions (Figure 6). Specifically,

for GDI, start/stop, turbo, CVT/6+ gears, VVT, and automatic transmissions, BMW reaches market shares of 73% to 97% in the U.S., whereas Daimler reaches 46% to 98% market share. Similarly, EU market shares for these technologies are 84% to 100% for BMW, and 77% to 98% for Daimler (excluding VVT). BMW and Daimler are also the best-selling premium brands in both markets. Premium-segment customers tend to be less price-sensitive than those in mass-market segments (Baltas & Saridakis, 2009). This allows both manufacturers to deploy more technology than their competitors.

2.6. Technology trends by EU member state

In line with the trends by segments (Section 2.4) and manufacturers (Section 2.5), technology deployment also increased among the 28 (formerly 27) EU member states (EU 27/28). The countries chosen for comparison are the major automotive markets in Europe, namely Germany, France, and the United Kingdom (UK). In addition, the Netherlands is chosen due to an especially high share of gasoline hybrid vehicles and a relatively light and low-CO₂-emitting fleet. Sweden is selected as it represents an interesting market in the sense that overall technology deployment is quite high and vehicles are among the heaviest and most powerful in Europe.

Swedish vehicles are the biggest, heaviest, and most powerful among the depicted countries (Figure 7). This is due to the high popularity of the Swedish car manufacturer Volvo (not shown in Figure 6) focusing on the production of relatively powerful and heavy vehicles. Also, the German vehicle fleet is above the European average in terms of vehicle footprint, engine power, engine displacement, and mass. Thus, also CO₂ emissions and fuel consumption in Sweden and Germany are the highest of the considered countries. On the other end of the spectrum, the French and Dutch fleets are below the European average for vehicle mass, footprint, engine power, and engine displacement and reach the lowest fuel consumption and CO₂ values. The British fleet is generally in the region of the European average except for engine power where it lies somewhat above. Besides that, there has been a general trend toward heavier, more powerful, and bigger vehicles across all of Europe.

In the Netherlands, the vehicle purchase tax has been based entirely on type-approval CO₂ emissions since 2013. Until the end of 2015, this tax used to be higher for diesels than for gasoline cars (Kok, 2015), contributing

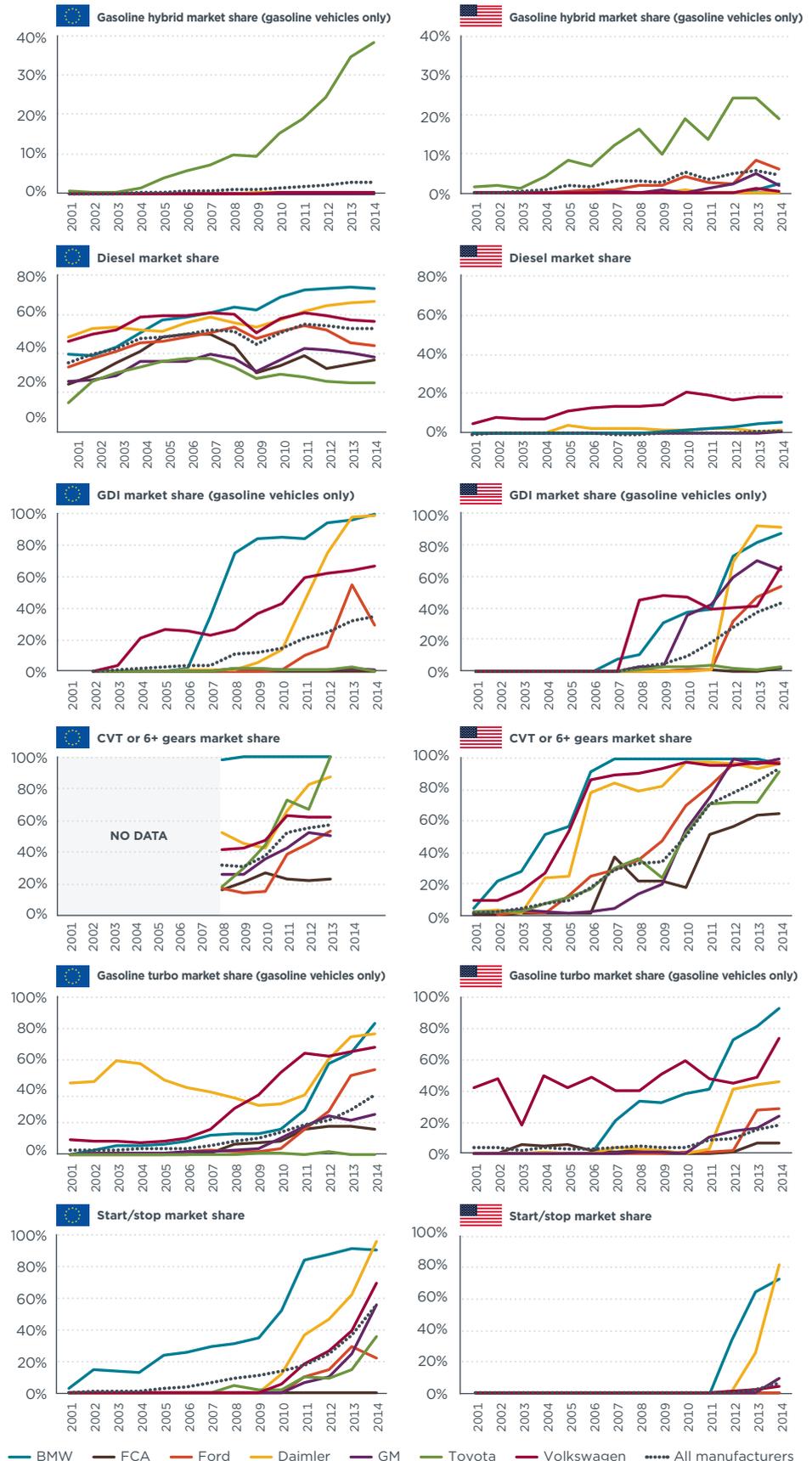


Figure 6. EU and U.S. new passenger car technology trends, by manufacturer.

Figure continued on next page

to a relatively low diesel share with 27% in 2014. Together with an above-average number of hybrid vehicles, this transformational process likely contributed to the Dutch new car fleet achieving the lowest drive-cycle fuel consumption and CO₂ emissions in Europe with 108 g CO₂/km and 4.6 L per 100 km in 2014. Hybrid electric vehicles that emit below 80 g/km of CO₂ pay considerably lower purchase taxes (ACEA, 2016) and are therefore particularly popular (Figure 8). Exceeding the 80 g/km threshold can be expensive: €69 (-US\$80) per g CO₂/km until a threshold of 106 g CO₂/km and €124 (-US\$140) above this threshold for a gasoline car. The threshold decreased from 85 g/km for diesel cars and 88 g/km for gasoline cars in 2015 to a common target of 80 g/km in 2016 (Mock, 2015a). Sales of hybrid vehicles fell in 2014, likely as a result of the phase-out of the registration fee exemption for hybrid and electric vehicles, in particular for company cars.

In addition, France grants a bonus up to €3,300 (-US\$3,800) and a two-year company car-tax exemption for this type of vehicle and has a high share of gasoline hybrids (5%). Sweden grants a five-year exemption from the annual circulation tax, also known as annual road tax. In addition, the UK and Belgium place incentives for vehicles with CO₂ emissions below a certain threshold (e.g., 100 g/km in the UK). Germany currently provides no incentives for hybrid vehicles. Other European member states that do provide such incentives include the Czech Republic, Ireland, and Portugal. In the Czech Republic, hybrids and AFVs are exempt from the road tax when used for business purposes. Ireland provides a registration tax relief up to €1,500 (-US\$1,700). In Portugal, hybrid vehicle owners benefit from a 50% registration tax reduction. In Romania, hybrids are completely exempt from the registration tax and Greece has several tax exemptions in place (ACEA, 2016).

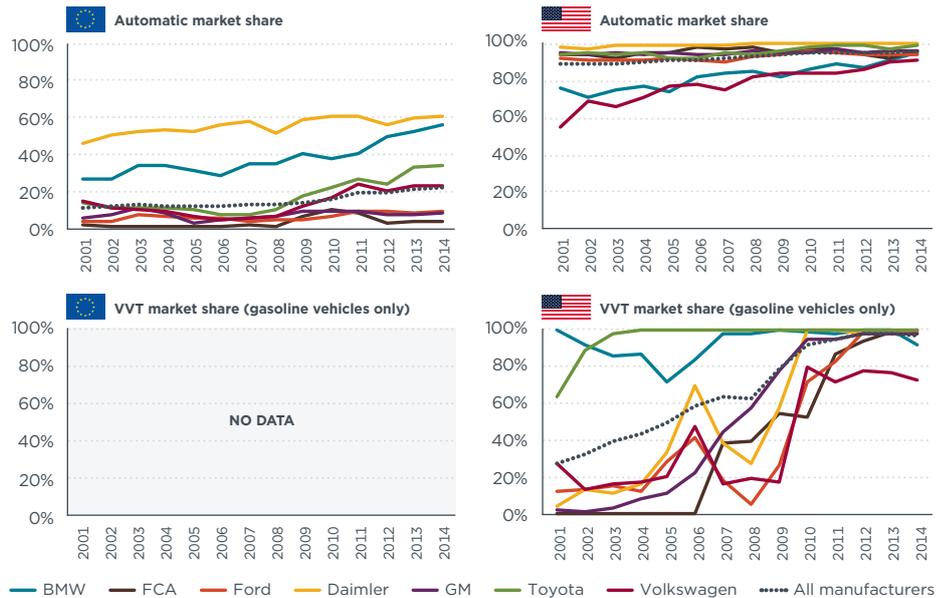


Figure 6. EU and U.S. new passenger car technology trends, by manufacturer.

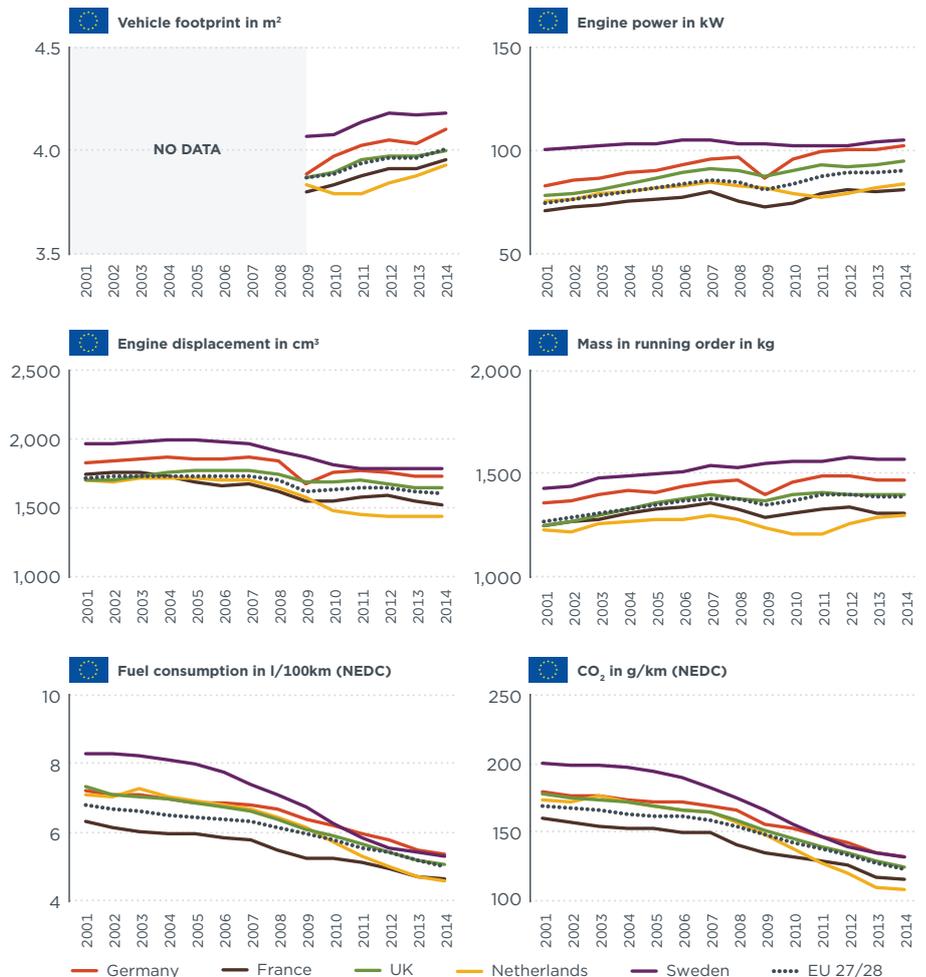


Figure 7. EU new passenger car trends, by country.

Diesel shares are high in most European countries in an international comparison due to lower diesel fuel taxes and high fuel prices in general.

In France, where the gasoline tax is a quarter higher than the diesel fuel tax (0.62 €/L versus 0.47 €/L) (ACEA, 2016), the diesel share is especially high with 63%. In the UK, where diesel and gasoline fuel taxes are identical (0.67 €/L) (ibid.), the share of diesel and gasoline-fueled cars is balanced (Figure 9). However, the diesel tax is not the only explaining variable for a country's diesel share. This becomes apparent when looking at the Netherlands, where the gasoline tax is 37% higher (0.77 €/L versus 0.48 €/L) (ibid.) but the diesel share is only about a third nevertheless. Other factors that influence the diesel share in the different member states include average annual mileage and other taxes such as the registration tax. For instance, the registration tax and also the road tax tend to be significantly higher for diesel cars in the Netherlands (Kok, 2015), which contributes to the low diesel share in this EU member state. Changes to the tax structure for diesel have been recently announced in France (Rosemain, 2015) (as a consequence of the discovery of VW's illegal defeat device usage) and in the UK (due to high nitrogen oxides levels in London and other cities), reducing the tax advantage of diesel over gasoline (Swinford & Collins, 2014).

Several factors have been responsible for a steep decline in the diesel market between 2008 and 2009, notably not only the global economic recession, but also the scrappage premium. France introduced a scrappage premium in January 2009, offering €1,000 (-US\$1,100) for every car older than 10 years. Germany introduced a similar program in the same month and granted €2,500 (-US\$2,800) for the replacement of every car older than nine years. The program covered around 1.3 million vehicles alone in Germany (BAFA, 2009).

The fixed incentive in both countries favored sales of small (gasoline) vehicles because cheap small cars

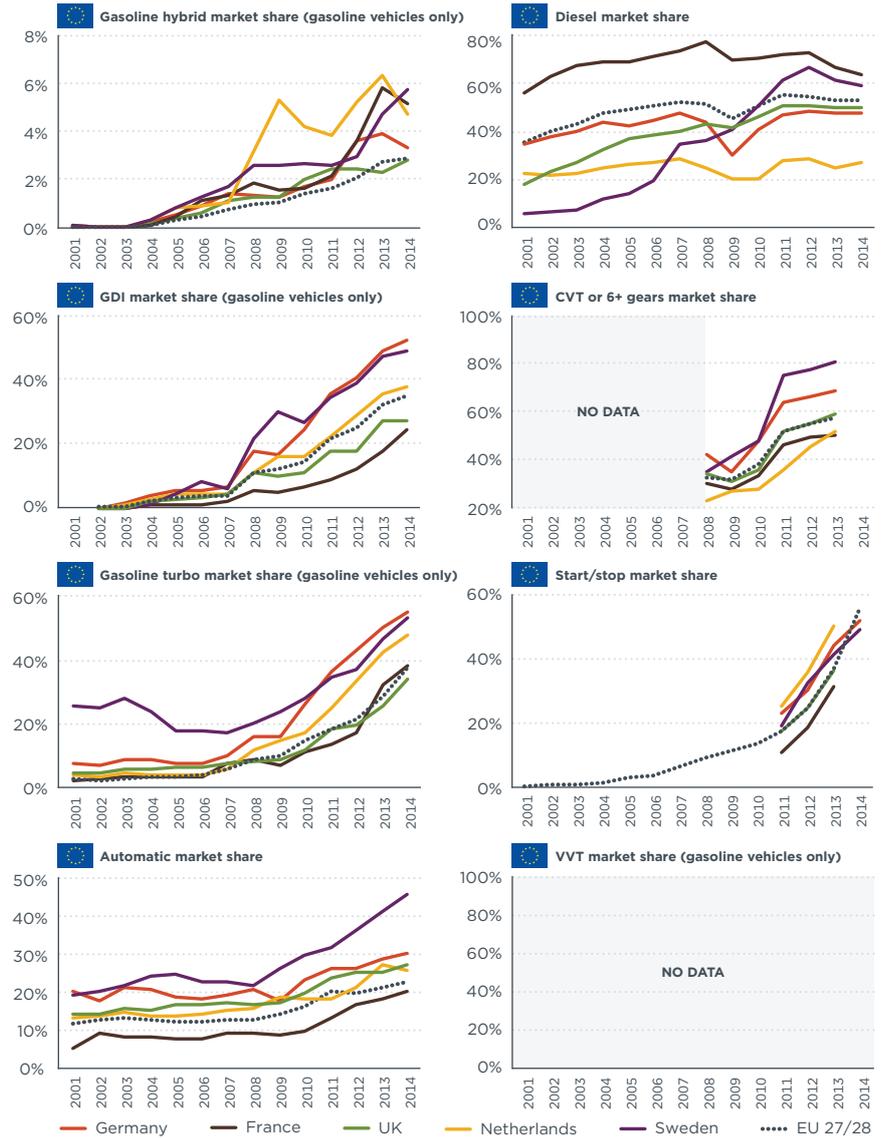


Figure 8. EU new passenger car technology trends, by country.

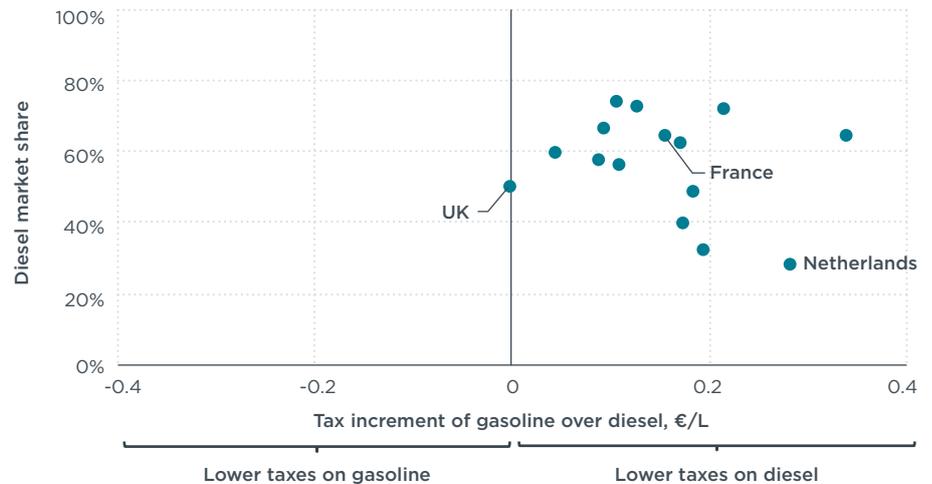


Figure 9. Diesel market shares and tax increments of diesel over gasoline in the EU (data source: ACEA, 2016).

received a bigger discount (in % of purchase price) than more expensive ones. Thus, diesel sales declined in both countries while gasoline sales increased in the same time (not shown in Figure 8). The impact was especially high in Germany as the diesel market fell below the 2001 level but recovered in subsequent years. Since around 2012, the diesel share in Sweden, France, and also to some extent the EU-27/28 average is falling again.

Technology deployment in France tends to be below the EU average, expect for diesel technology penetration, gasoline turbocharging, and gasoline hybrids. In the UK, gasoline hybrids, CVT/6+, and gasoline turbo market shares are at about the European average, whereas other technologies are below average. However, technology deployment is above average in Sweden and also Germany, which reaches the largest deployment for GDI, turbocharging, and start/stop. Meanwhile, the French vehicle fleet is among the lightest and least powerful, whereas the British fleet follows the average mass and engine power in the EU, and the Swedish and German vehicle fleets are among the heaviest and most powerful. Thus, there is an observed trend of higher technology deployment in heavier and more powerful car fleets.

3. Technology deployment and cost increase in retrospect

As previous studies have shown, there is a wide range of technologies available that can be deployed to meet the EU and U.S. vehicle CO₂ emission-reduction targets (Mock, 2013; U.S. EPA, 2012b). For both the EU and the U.S., the majority of technology pathways leading to compliance with the 2021/2025 targets are expected to focus on improving the efficiency of power trains and vehicle accessories that are considered for the laboratory test procedure, and on reducing vehicle mass, and do not require a significant

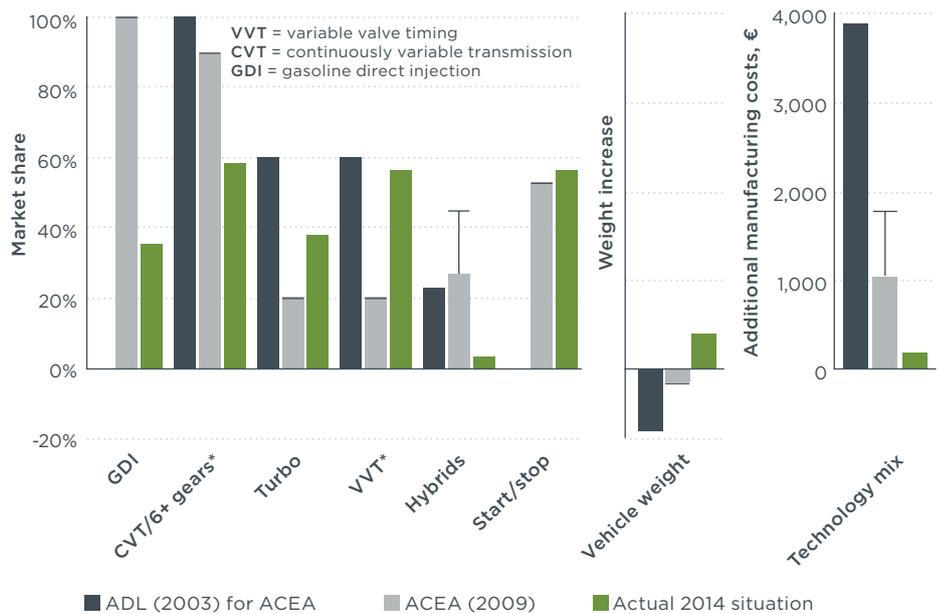


Figure 10. Anticipated technology market shares in order to meet an EU new fleet average target of 120 g CO₂/km and the actual situation in 2014 at a fleet average of 123 g CO₂/km. ADL (2003) provides no data for GDI and start/stop. Error bars indicate range of stated values. *Actual share for 2013.

increase in market share of electric vehicles or other AFVs (ibid.). The associated cost increase is generally offset by fuel savings in the first few years of vehicle ownership (ibid.). For all technologies, incremental costs are expected to decrease over the longer term (U.S. EPA, 2012b) due to manufacturers' learning and economy of scale.

Looking backwards, it can be seen how the amount of technology deployment and cost increase required to comply with anticipated CO₂ standards were often overestimated in previous years. For instance, in a study for the European Automobile Manufacturers' Association (ACEA) back in 2003, high levels of technology deployment were deemed necessary to comply with a CO₂ standard of 120 g/km on the NEDC,⁹ with an expected market share of 60% for turbocharging and VVT for gasoline engines and 100% for CVT (assuming no market share

for six and more gear transmissions) (Figure 10) (ADL, 2003). In addition, an 18% reduction in vehicle mass as well as a market deployment of mild hybrids up to a level of 20% and full hybrids up to a level of 2.5% were deemed necessary to comply with the CO₂ standard. The additional manufacturing costs of this technology mix were projected to total an average of €3,900 (-US\$4,300) per medium-sized baseline car.

Similarly, in 2009 ACEA estimated the following market shares to comply with a CO₂ target of 120 g/km in 2012: 20% turbo, 20% VVT and cylinder deactivation, 90% CVT or six gears for gasoline vehicles (no transmissions with more than six gears assumed), 25%–30% mild gasoline hybrids plus 2%–15% full gasoline hybrids (in total 27%–45%), 60% GDI, and 53% start/stop (ACEA, 2009). Associated costs were expected to add up to around €1,000–1,800 (-US\$1,100–2,100).

In reality, the EU market share of gasoline hybrids is still below 3%, and vehicle mass even increased while fleet average CO₂ emissions declined down to 123 g/km by 2014.

⁹ In 2003, a target value of 120 g/km was expected to be introduced for 2012 but was replaced later on by a target value of 130 g/km for 2015. Against this background, the cost increase provided by ADL (2003) for 2012 was calculated incremental to a 2008 baseline car.

The 2014 share of turbochargers for gasoline cars is 38%, VVT share is 56%, CVT/6+ share is 58% (2013), GDI share is 35%, and start/stop share is 56%. Thus, the actual necessary deployment is lower for several technologies. Also, the actual average cost increase per vehicle was as low as -€200 (-US\$230) and has thus been overestimated in the past (Kollamthodi, 2014).

A key reason for the differences in technology potential and cost estimates is the differences in the approaches applied. The studies presented by ADL and ACEA strongly relied on a survey of representatives of industry associations as well as vehicle and vehicle parts manufacturing companies. As part of the survey, the representatives were asked to share data on CO₂ reduction potentials and costs of fuel efficiency technologies and technology packages. There is a risk that such top-down survey results, although quicker and cheaper to carry out, yield a systematic overestimation of compliance costs, as they generally represent the lowest common denominator within a manufacturing company and/or an industry association. However, studies such as the EPA (2012b) and Mock (2013) rely on in-depth bottom-up analyses using computer simulations to determine CO₂ reduction potentials of technology packages and “tear down” assessments to estimate hardware costs. This time-consuming and relatively expensive bottom-up approach allows for significantly more transparent results, as it provides all detailed assumptions to the interested reader. The methodology has also been subject to an independent peer-review process, with the EPA concluding that “[...] this approach has great potential for determining accurate technology costs, a goal that is of paramount importance in the setting of appropriate greenhouse gas standards” (U.S. EPA, 2009).

Another aspect to be taken into account is the increasing discrepancy

between official drive-cycle and real-world fuel consumption and emission figures in recent years. Manufacturers can lower their official CO₂ figures by exploiting tolerances and flexibilities on the official driving test cycle and therewith reducing their short-term compliance costs (i.e., additional manufacturing costs that are necessary to comply with the respective CO₂ standard). As previous studies have shown, this exploitation of loopholes in the regulatory test procedures has become much more common in recent years and thereby explains some part of the observed drastic reduction in compliance cost (Tietge et al., 2015).

4. Conclusions

A key objective of this paper was comparing the deployment of different technologies for passenger cars in the U.S. and the EU. Both the EU and U.S. data show rapid technology diffusion in recent years. It is indicated that this development is largely a response of vehicle manufacturers to increasingly stringent regulatory standards. Yet there are differences in the mix of technologies in both regions. In the U.S., manufacturers tend to focus more on VVT, GDI, hybrids, and continuously variable transmissions or transmissions with six or more gears, whereas in the EU there is stronger growth of diesel engines, stop/start, and turbocharging.

Vehicle characteristics in both regions differ as well. Passenger cars in the U.S. are generally heavier, bigger, and more powerful than in Europe, which results in higher average fuel consumption and CO₂ emission levels in the U.S. However, in both regions vehicles have tended to become more powerful and heavier while deploying increasingly high levels of technology and reducing official type-approval CO₂ emissions and fuel consumption. As a result, both regions met their respective 2015 CO₂ standards ahead of time. Some technologies seem to be driven not only by CO₂/

fuel efficiency regulations, but also by other influencing factors, such as complementary regulations and incentives, differences in the enforcement of vehicle test procedures and also marketing efforts, as can be seen, for example, in the markedly different deployment of diesel and hybrid electric cars in the U.S. and the selected EU member states.

Most manufacturers that are active on both sides of the Atlantic sell a different mix of vehicles in the U.S. and EU, with generally bigger, heavier, and more powerful vehicles being sold in the U.S. The market share of the start/stop technology is generally higher in the EU (driven by characteristics of the European test cycle, the NEDC) whereas automatic transmission market shares are found to be higher in the U.S. (linked to historical customer preferences/expectations). Toyota is the primary seller of hybrid vehicles in both markets. Manufacturers of premium vehicles, such as Daimler or BMW, are found to have high deployment rates of several technologies, not least due to a generally lower price sensitivity of their customers.

In retrospect, the amount of technology deployment required to meet EU’s 2015 vehicle CO₂ target and in particular the associated cost increment is found to be significantly lower than expected at the time when the respective regulation was developed. Additional manufacturing costs to comply with future CO₂ standards are as yet uncertain, but it is concluded that rigorous bottom-up methods should be the preferred approach for estimating future technology potential and costs.

An important limitation of the analysis is that it focused entirely on the passenger car market in the EU and the U.S., leaving aside the segment of light trucks that is of particular relevance for the U.S. market. Furthermore, it should be noted that it is challenging to compare vehicle segments in the EU and U.S. side by side, given

significant differences in the market structures in both markets. For future studies, it would be desirable to obtain additional market penetration data also for other technologies not included in the current analysis to extend the analysis to a broader range of technological options.

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