WHITE PAPER NOVEMBER 2017

FROM LABORATORY TO ROAD INTERNATIONAL

A COMPARISON OF OFFICIAL AND REAL-WORLD FUEL CONSUMPTION AND CO_2 VALUES FOR PASSENGER CARS IN EUROPE, THE UNITED STATES, CHINA, AND JAPAN

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ACKNOWLEDGMENTS

The authors thank the internal and external reviewers of this report for their guidance and constructive comments, with special thanks to Maya Ben Dror, Liping Kang, and Lanzhi Qin (Innovation Center for Energy and Transportation); Jeff Alson and Roberts French (EPA); Iddo Riemersma; John German, Hui He, and Dan Rutherford (ICCT). The authors are grateful to the following individuals and organizations for contributing data and background information: Rick Goeltz, Janet Hopson (Oak Ridge National Laboratory); Xiong Zhang, Hongbo Sun (XiaoXiongYouHao); Masayoshi Ishihara (e-nenpi.com); and all who provided data for the 2016 update of the *From Laboratory to Road* study.

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Funding for this work was generously provided by the ClimateWorks Foundation and Stiftung Mercator.

EXECUTIVE SUMMARY

The majority of all passenger cars sold in 2015 were subject to carbon dioxide (CO_2) or fuel economy standards. The six largest vehicle markets and nine of the top 11 have implemented such standards to curb fuel consumption and greenhouse gas emissions of light-duty vehicles. Leading markets have set passenger vehicle standards for 2020 and beyond, driving the decarbonization of road transportation and setting clear long-term targets for automakers. As a result, average CO_2 emission values of new cars are declining on a global scale.

While fuel efficiency standards thus sound like a success, there is evidence of a growing divergence (or "gap") between official and real-world CO_2 values in a number of markets, implying that laboratory measurements are increasingly overestimating the fuel efficiency of cars. The ICCT analyzes the gap between official and real-world CO_2 emission values of European passenger cars in a series of studies termed *From Laboratory to Road*. This study extends the analysis beyond the borders of Europe and includes other major vehicle markets.

This study is based on real-world fuel consumption data for more than 1.5 million passenger cars in the European Union (EU), the United States, China, and Japan. Figure ES- 1 indicates that the divergence between the official and real-world CO_2 emission values has increased over time in all regions. The EU, which uses the New European Driving Cycle (NEDC) for vehicle testing, is the market with the steepest annual growth in the gap between 2001 and 2014, while Japan and the United States experienced smaller increases. Japan phased out the 10-15 mode cycle in the 2008–2011 time frame, replacing it with the JC08 cycle. The United States is the only market with two sets of CO_2 values: the more limited two-cycle-based Corporate Average Fuel Economy (CAFE) values are used for regulatory purposes, while the U.S. Environmental Protection Agency (EPA) provides more inclusive five-cycle-based fuel economy label values to inform consumers about the real-world on-road performance of vehicles. The label values were found to offer the most realistic fuel consumption figures in the analysis. The label values are the basis for the adjustment factor used by U.S. regulators to convert CAFE values to real-world estimates during fuel economy standard rulemakings.

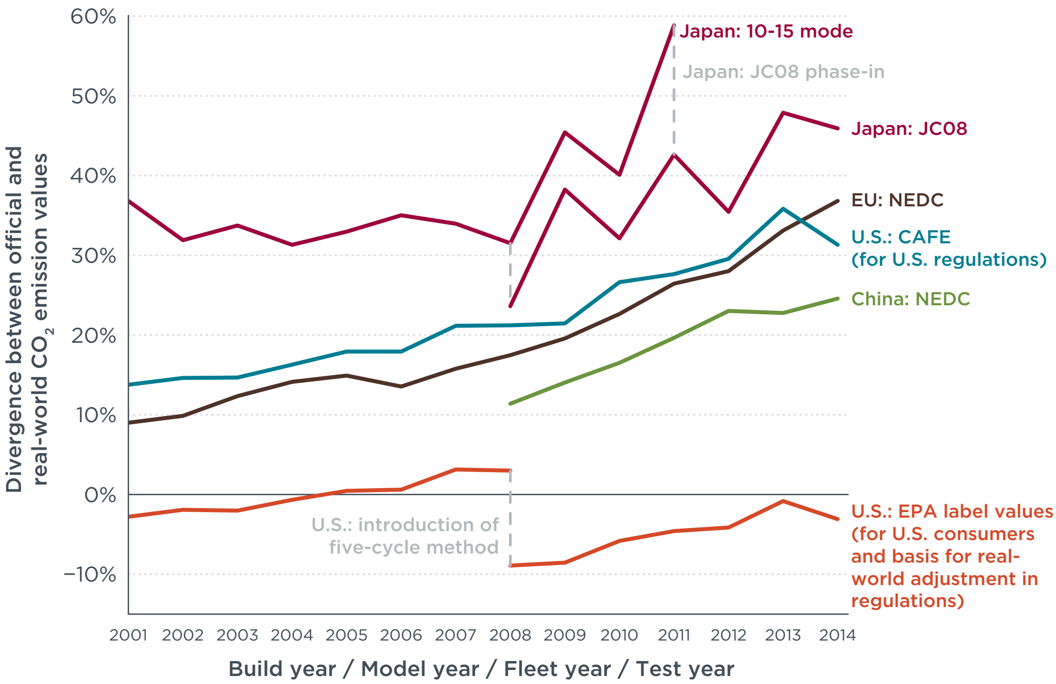

Figure ES- 1. Divergence between official and real-world CO_2 emissions for new passenger cars in the EU, the United States, China, and Japan.

Unless regulators handle the growing gap appropriately, the divergence between official and real-world CO_2 emission values will continue to dilute fuel efficiency policies. Figure ES-2 plots average official and estimated real-world CO_2 emission values of passenger cars in the four regions under study. The EU and China appear to have made little progress in reducing on-road CO_2 emission values after 2008, as the gap rapidly grew in both markets. The United States has the highest on-road CO_2 emission values, but is reducing these values at a faster rate than the EU and China. Moreover, to compensate for the growing gap between CAFE and real-world CO_2 values, U.S. regulators apply and periodically update adjustment factors in the impact assessments that accompany fuel economy rulemakings. Japan stands out with the lowest official and real-world CO_2 emission values due to a light, efficient fleet and a comparatively low growth in the gap. Overall, the decoupling of official and real-world values in Figure ES-2 illustrates that the growing gap is a substantial obstacle to reducing CO_2 emissions on the road, and must therefore be addressed when designing fuel efficiency policies.

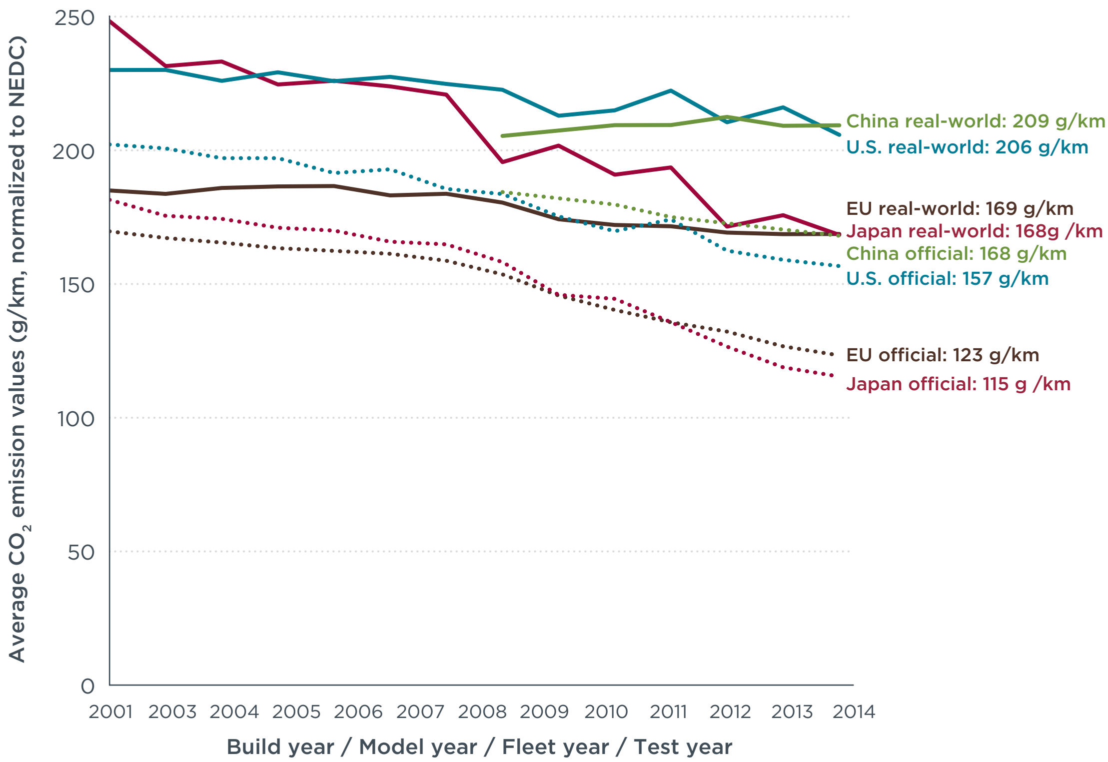

Figure ES-2. Official and real-world CO_2 emission values for new passenger cars in the EU, the United States, China, and Japan.

In addition to studying the gap, this study summarizes vehicles testing procedures and policy frameworks in the four regions. A side-by-side comparison of procedures and divergence estimates highlights some aspects that are key to effective CO_2 or fuel economy standards:

» **Independent retesting:** Independent retesting of laboratory measurements was identified as a best practice. All markets have some form of compliance program in place, but the United States has the most extensive program, covering the full lifetime of vehicles by verifying coastdown measurements, testing production-line vehicles, and conducting in-use surveillance tests.

» **Policy enforcement**: The comparatively low growth in the U.S. gap indicates that stringent policy enforcement, such as levying penalties on manufacturers that misstate fuel economy values, acts as a deterrent to gaming. In contrast, the EU has seen the largest growth in the gap from 2001 to 2014 and lacks a central authority to issue vehicle recalls and to impose financial penalties.

» **Real-world standards:** CO_2 and fuel economy standards should be based on test values that, on average, correspond to real-world measurements. Policies that fail to account for the divergence will overestimate fuel savings and climate change mitigation benefits. Using an adjustment factor to approximate on-road values, as is done in the United States, is an approach that does not require extensive overhauls of vehicle testing procedures to account for real-world CO_2 emissions. Another approach for measuring on-road emissions is using portable emissions measurement system (PEMS) equipment. On-road tests using PEMS are currently only being conducted for nitrogen oxides (NO_x) and particulate number emissions as part of the real-driving emissions (RDE) procedure, but these kinds of measurements could be used to monitor on-road CO_2 emissions and to test the on-road conformity of vehicles in use. More realistic test cycles and more rigorous testing procedures (e.g., including auxiliary equipment, using stock tires, and using standard engine and transmission calibrations) for laboratory testing could also furnish more realistic CO_2 values.

» **Real-world measurements:** Measuring real-world fuel consumption is a key recommendation because these data are needed to evaluate the efficacy of CO_2 and fuel economy standards. Bulk on-road fuel consumption data can be measured using web services. As the only government-run example of such services, the MyMPG tool on FuelEconomy.gov stands out as a best-practice example. These data can be used to estimate fleet-wide real-world CO_2 emission values and gauge policy impacts. Using data loggers connected to vehicles' on-board diagnostics ports is another option for real-world fuel consumption data collection (see Posada & German, 2013).

» **Consumer information:** Consumers need access to realistic fuel consumption values to make informed decisions when buying vehicles. U.S. EPA window label values demonstrate that it is possible to produce fuel consumption values that, on average, are representative of real-world performance. The FuelEconomy.gov website stands out as a best-practice example of consumer information because it combines real-world measurements, realistic fuel consumption values, and information on efficient driving in one portal.

The growing divergence between official and on-road CO_2 emission values is troubling since it represents a decoupling of regulated metrics and real-world impacts. Good practices covered in this study illustrate that solutions are available to close or at least manage the gap. Differences in the development of the gap in Europe and the United States illustrate that effective policies and rigorous enforcement can change the trajectory of the gap: In the EU, the gap started growing at a faster rate after CO_2 standards were introduced in 2009, while the U.S. gap slowed down after fuel economy standards were reintroduced in 2012, largely due to a suite of policy measures including testing of production vehicles and in-use testing. This study aims to facilitate the transfer of such good practices and hard-won policy insights across markets.

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ABBREVIATIONS

2WD	two-wheel drive
4WD	four-wheel drive
B7	diesel blend containing up to 7% biodiesel (volume/volume)
CAFC	Corporate Average Fuel Consumption
CAFE	Corporate Average Fuel Economy
CAGR	compound annual growth rate
CARB	California Air Resources Board
CO_2	carbon dioxide
CoP	conformity of production
CVT	continuously variable transmission
E10	10% ethanol/90% gasoline blend (volume/volume)
E5	5% ethanol/95% gasoline blend (volume/volume)
EEA	European Environment Agency
EU	European Union
EUDC	Extra Urban Driving Cycle
FTP-75	Federal Test Procedure
g	gram
GVW	gross vehicle weight
HEV	hybrid electric vehicle
HWFET	Highway Fuel Economy Test
ICCT	International Council on Clean Transportation
IUCP	In-Use Confirmatory Program
IUVP	In-Use Verification Program
km	kilometer
l	liter
LCV	light commercial vehicle
LDV	light-duty vehicle
m	meter
M1	passenger car with a gross vehicle weight not exceeding 3.5 tons
M1G	off-road passenger cars
M2	light commercial passenger vehicles
METI	Japanese Ministry of Economy, Trade and Industry
MIIT	Chinese Ministry of Industry and Information Technology
MLIT	Japanese Ministry of Land, Infrastructure, Transport and Tourism
mpg	miles per gallon
MPV	multi-purpose vehicle
MY	model year
N1	light commercial vehicle with a gross vehicle weight not exceeding 3.5 tons

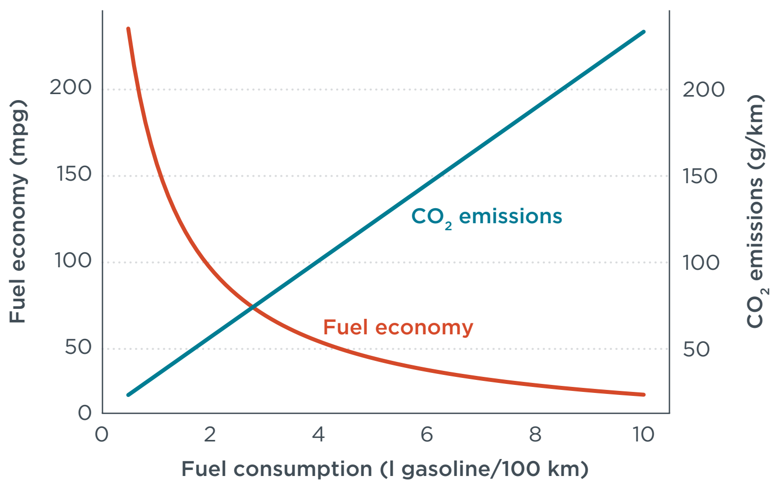
NEDC	New European Driving Cycle
NHTSA	National Highway Traffic Safety Administration
NO_x	nitrogen oxides
NTSEL	National Traffic Safety and Environment Laboratory
PEMS	Portable emissions measurement system
PHEV	plug-in hybrid electric vehicle
RDE	Real-driving emissions
SEA	Selective Enforcement Audit
SUV	sport utility vehicle
U.S.	United States of America
U.S. EPA	United States Environmental Protection Agency
UK	United Kingdom
UNECE	United Nations Economic Commission for Europe
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

1. INTRODUCTION

Most major vehicle markets in the world have carbon dioxide (CO_2) or fuel economy standards in place to curb fuel consumption and greenhouse gas emissions of light-duty vehicles (see Box 1.1 for definitions of metrics). Approximately 78% of all vehicles sold in 2015 were subject to CO_2 or fuel consumption standards (ICCT, 2016a). Leading markets have set passenger vehicle standards for 2020 and beyond, driving the decarbonization of road transportation and setting clear long-term targets for automakers.

BOX 1.1: OVERVIEW OF VEHICLE EFFICIENCY METRICS

Fuel consumption refers to fuel consumed per unit of distance traveled. Fuel economy refers to distance traveled per unit of fuel consumed. The two metrics are therefore inversely related: As fuel consumption decreases, fuel economy increases. CO_2 emissions are directly proportional to fuel consumption and depend on the carbon intensity of the fuel. Fuel economy values are common in the United States, expressed as miles per gallon (mpg), and in Japan, expressed as kilometer per liter (km/l). Fuel consumption values, expressed as liters per 100 kilometers (l/100 km), are common in the EU and in China. All markets use CO_2 emission figures for some purposes, which are expressed either as grams of CO_2 per kilometer (g/km) or grams of CO_2 per mile (g/mi).



As a result of CO_2 and fuel economy standards, greenhouse gas emissions from new light-duty vehicles (LDVs) are declining in major vehicle markets. The United States has a long history of fuel economy targets reaching back to 1975. The most recent fuel economy target requires that average CO_2 emission values of passenger cars fall below approximately 97 g CO_2/km by 2025 (all values normalized to the New European Driving Cycle), which translates to a 4.8% annual reduction. The EU agreed on a 2015 fleet-average target of 130 g CO_2/km in 2008. As a result, average CO_2 emission values of new European passenger cars have declined by roughly 4% per year, up from 1% before the standards were introduced. Major Asian vehicle markets such as China (93 g CO_2/km by 2025) and Japan (122 g CO_2/km by 2020) also have CO_2 standards or fuel economy targets in place (see Figure 1).

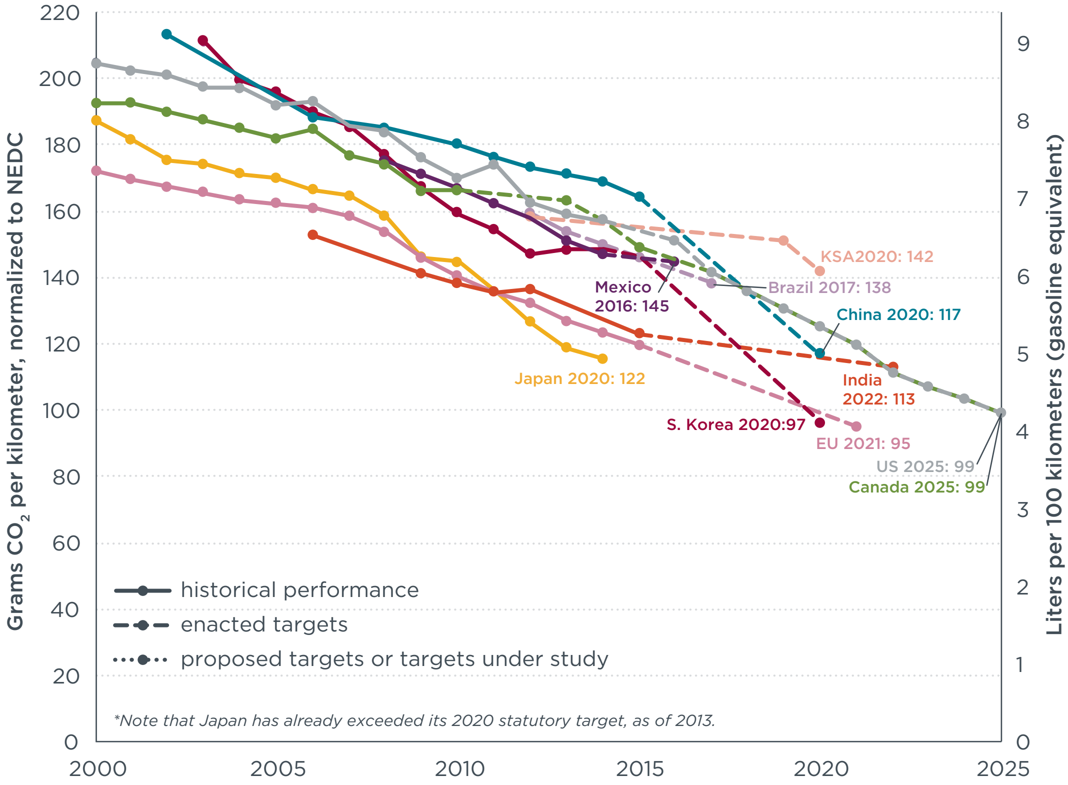


Figure 1. Global new passenger car CO_2 emissions and fuel consumption, normalized to NEDC, including future targets (source: ICCT, 2016b; methodology: Kühlwein, German, & Bandivadekar, 2014).

Although fuel efficiency standards have been successful at reducing declared CO_2 and fuel consumption values, these values are measured in laboratories under controlled circumstances and rarely reflect measurements of average emissions from on-road driving. However, to achieve real-world benefits, official CO_2 values measured in the laboratory must translate into on-road emission reductions and fuel savings.

The International Council on Clean Transportation (ICCT) began to investigate the divergence (or "gap") between European official and real-world CO_2 and fuel consumption values in 2012 (Mock, German, Bandivadekar, & Riemersma, 2012). Results from these investigations are summarized in a series of studies termed *From Laboratory to Road*. These studies have found evidence of a growing divergence between official and real-world CO_2 values for passenger cars in Europe. Based on data for approximately 1 million vehicles from 13 data sources and seven countries, the 2016 study found that the divergence increased from approximately 9% in 2001 to 42% in 2015 (Tietge et al., 2016). The growing divergence counteracts the EU CO_2 standards and dilutes their intended benefits, which include mitigating climate change, reducing oil imports, and reducing consumers' fuel expenses.

This study reaches beyond Europe's borders and takes a global perspective on real-world CO_2 emissions from passenger cars by studying three additional major vehicle markets: the United States, China, and Japan. Roughly two-thirds of new passenger cars in the world in 2015 were registered in one of these four markets. Standards set by the EU and the United States also affect fuel economy and CO_2 standards in other markets, since European and U.S. regulations and test procedures are used elsewhere. For instance, Brazil, Canada, Mexico, and South Korea use U.S. test cycles, while India and China employ test procedures similar to EU regulations. Findings from this study therefore also have implications for other markets.

The objective of this study is to compare the divergence between on-road and official CO_2 values in the four studied markets in order to evaluate the efficacy of different regulations and to distill good practices for policy design. Some studies of regional on-road environmental performance of cars have been conducted before (Ding, Ben Dror, Kang, & An, 2015; Greene et al., 2015; Huo, Yao, He, & Yu, 2011; Ntziachristos et al., 2014; Qin, Ben Dror, Kang, Sun, & An, 2016; Tietge et al., 2015), but studies of global scope have traditionally relied on real-world fuel consumption estimates based on fuel sales (e.g., Schipper, 2008; Schipper & Tax, 1994). This study provides the first global comparison of the divergence between on-road and official CO_2 emission values.

To provide estimates of the divergence between official values and real-world performance, this study compares large samples of on-road fuel consumption measurements. Findings are presented in terms of divergence between official and real-world CO_2 emission values. The *divergence* is defined as the difference between real-world and official values, expressed as a percentage of the official value. In other words, a 30% gap implies that real-world CO_2 emissions are 30% higher than measured in the laboratory. It should be noted that calculating the divergence based on CO_2 emission values yields different results than using fuel economy figures, as is common practice in Japan and the United States (see Section 4.5 for a discussion of the relationship between fuel economy and fuel consumption divergence). Figures using fuel economy are presented in Appendix I to make the findings more accessible to readers from these markets. While findings are presented in terms of CO_2 emission values, the same divergence estimates also apply to fuel consumption as virtually all of the carbon in the fuel is converted to CO_2 during combustion. The terms *fuel consumption* and *CO_2 emissions* are used interchangeably throughout the study.

The remainder of this study is organized in five parts. Section 2 provides an overview of the four vehicle markets and vehicle testing frameworks. Section 3 summarizes findings from previous studies on the real-world gap in the four markets. Section 4 presents real-world fuel consumption data from the four markets, quantifies the divergence between official and real-world values, and compares the findings. Section 5 discusses the relationship between the design of vehicle testing frameworks and the divergence between testing and on-road emissions, and distills good practices identified in the analysis. Lastly, Section 6 summarizes the findings and presents policy recommendations.

2. VEHICLE TESTING AND REGULATORY FRAMEWORKS

BOX 2.1: LABORATORY VEHICLE TESTING

To measure fuel consumption and CO_2 emissions in laboratories, vehicles are placed on chassis dynamometers. Chassis dynamometers can be compared to large treadmills, allowing the vehicle to remain stationary while the wheels spin. The resistance placed on the rollers of the chassis dynamometer by an electronic controller simulates the inertia effects due to the weight of the vehicle and the aerodynamic drag and rolling resistance forces acting on a vehicle during on-road operation. These two effects are commonly referred to as the *road load*. Road load is measured during coastdown testing, where vehicles are accelerated to a certain speed and then coast in neutral. The time it takes for the vehicle to decelerate is used to estimate the road load force acting upon the vehicle.

This section explores the different vehicle markets, testing procedures, and regulatory frameworks in the regions studied in the analysis.

2.1 LIGHT-DUTY VEHICLE DEFINITIONS

The regions covered in this study use varying definitions of LDVs. Definitions vary in terms of vehicle size, vehicle weight, intended use, and body style.

In the EU, LDVs include vehicles classified as passenger cars, referred to as *M1 vehicles*, and light commercial vehicles, referred to as *N1 vehicles*. Passenger cars are intended to carry passengers, do not exceed 3,500 kg gross vehicle weight (GVW), and have no more than eight passenger seats (European Parliament, 2007). Light commercial vehicles are intended to carry goods and do not exceed 3,500 kg GVW. Determining whether a vehicle is intended for passenger or goods transportation is subject to national legislation, so that a certain vehicle model may be registered as M1 in one member state and as N1 in another. See Figure 2 for an overview and market shares of the different vehicle categories in the EU.

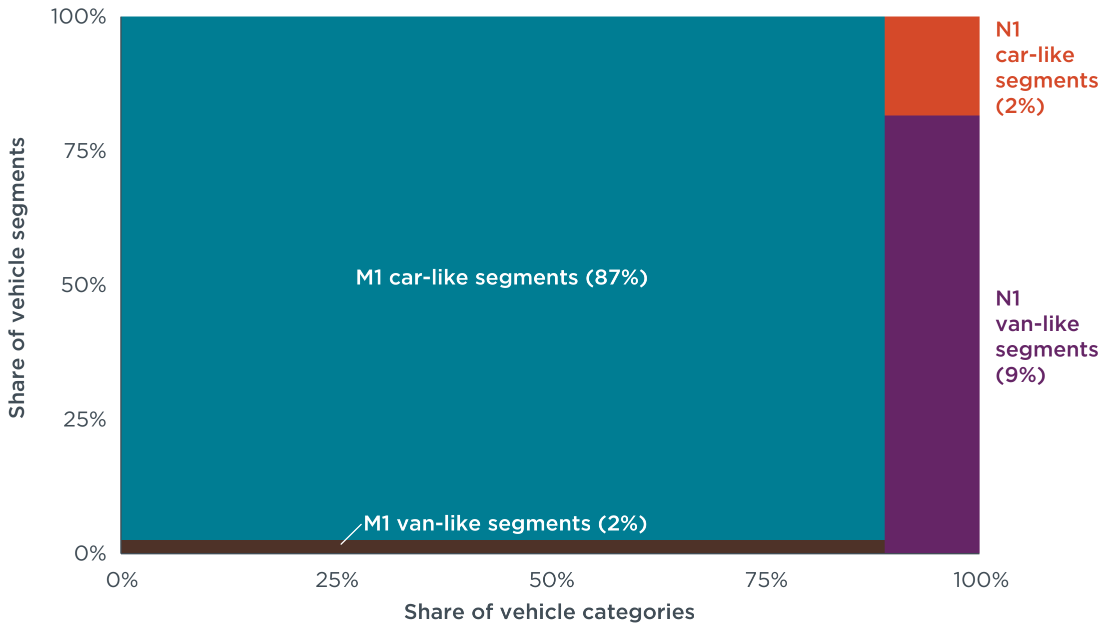


Figure 2. Light-duty vehicle shares of 2014 registrations by vehicle category and segment in the EU (source: Mock, 2015).

In the United States, vehicles are primarily classified not according to their intended use, but rather according to their GVW and body type. For the purposes of fuel economy certification, the U.S. Environmental Protection Agency (EPA) classifies vehicles as light-duty (GVW ≤ 3,900 kg) and heavy-duty (GVW > 3,900 kg), although SUVs and passenger vans with GVW ratings between 3,900 and 4,500 kg (medium-duty passenger vehicles) have recently been added to the light-duty fuel economy regulation (U.S. EPA, 2010a). The U.S. LDV category comprises passenger cars and light-duty trucks. The regulatory definitions of cars and trucks have evolved over time and are currently based on the ability of the vehicle to perform certain functions (e.g., provide temporary living quarters, transport property on an open bed) (U.S. EPA, 2015b). The term *passenger car* refers to vehicles with car-like body types and a GVW up to 3,900 kg, as well as small and mid-size two-wheel (2WD) drive SUVs with a GVW up to 2,700 kg. Light trucks are all vans and four-wheel drive (4WD) SUVs up to 4,500 kg GVW, plus cargo vans and pick-up trucks up to 3,900 kg GVW. See Figure 3 for an overview and market shares of the different vehicle categories in the United States.

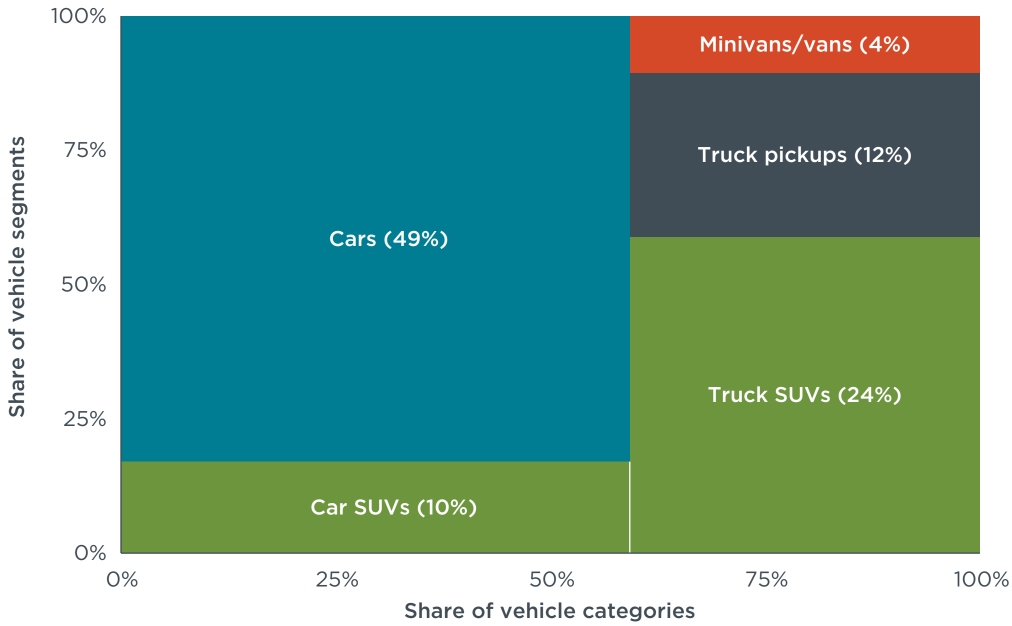


Figure 3. Light-duty vehicle shares of model year 2014 by vehicle category and segment in the United States (source: U.S. EPA, 2015b).

In China, according to the standard GB 15089-2001 introduced in 2001, the LDV category comprises passenger cars, classified as M1, and light commercial vehicles, classified as N1 or M2 (He & Tu, 2012). Similar to the EU M1 definition, China's passenger cars are vehicles whose main function is to carry people, have nine or fewer seats, and weigh no more than 3,500 kg. Fuel consumption standards further divide M1 vehicles into M1 and M1G, where the M1G category refers to off-road-capable passenger cars and M1 comprises the remaining passenger car body types. M1G vehicles were held to a more lenient set of standards than M1 vehicles until 2011. The term *light commercial vehicle* refers to both light commercial passenger vehicles (M2 category) and light commercial cargo vehicles (N1 category) (Tu, Zou, & He, 2014). The M2 category refers to passenger vehicles with more than nine seats and a GVW less than 5,000 kg. However, only lighter M2 vehicles with a GVW below 3,500 kg are considered light commercial vehicles. N1 vehicles are primarily designed for the transportation of goods and, as all LDVs, have a GVW of 3,500 kg or less. See Figure 4 for an overview and market shares of the different vehicle categories in China.

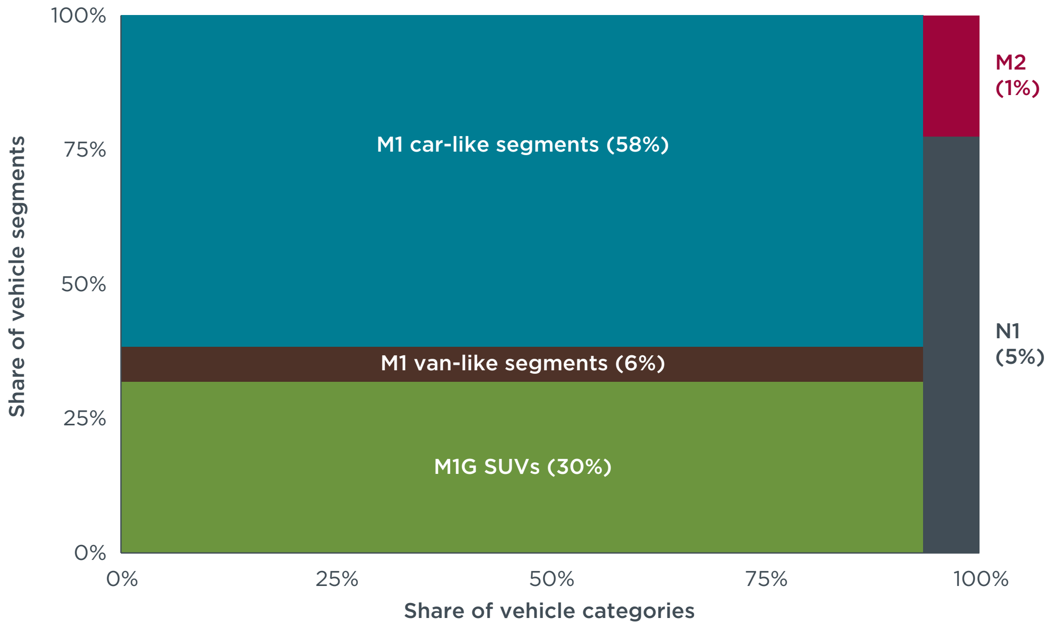


Figure 4. Light-duty vehicle shares of 2014 registrations by vehicle category and segment in China (data provided by Segment Y).

Lastly, Japanese light-duty fuel efficiency standards classify LDVs into the following three categories: passenger cars, small buses, and freight vehicles. *Passenger cars* are defined as vehicles designed to carry 10 passengers or fewer, whereas *small buses* are described as passenger vehicles with a capacity of 11 passengers or more and a GVW below 3,500 kg. Freight vehicles are further divided into three categories: mini, light-weight, and medium-weight. *Mini freight vehicles* are defined as cargo vehicles whose length, width, and height do not exceed 3.4 m, 1.48 m, and 2.0 m respectively, and whose engine capacity does not exceed 0.66 l. Light and medium-weight freight vehicles have a maximum a GVW of 1,700 kg and 3,500 kg respectively. See Figure 5 for an overview and market shares of the different vehicle categories in Japan.

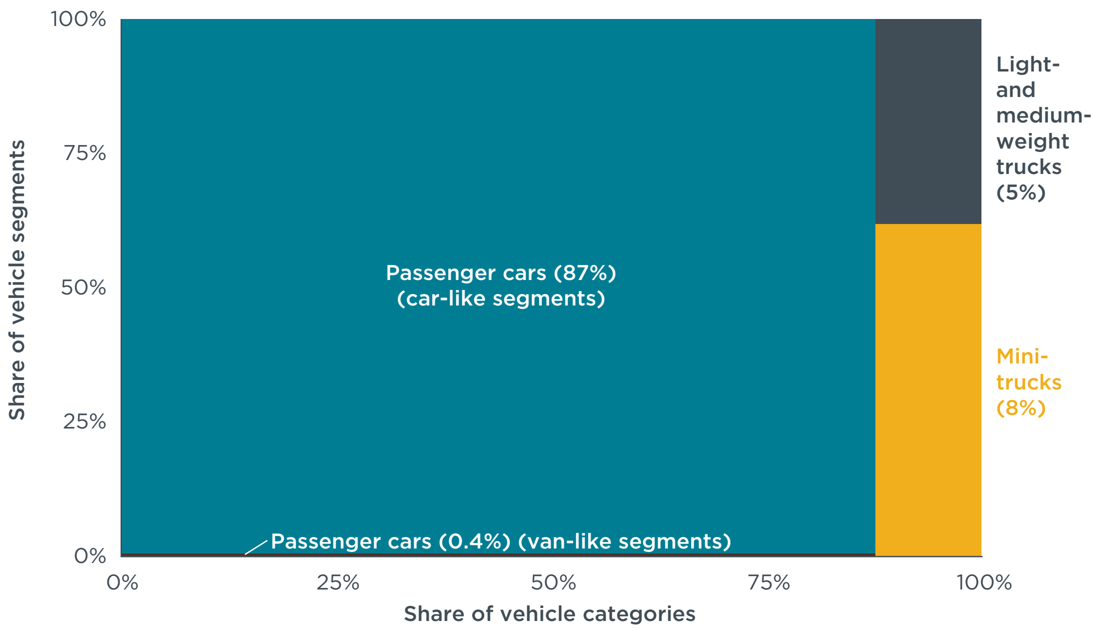


Figure 5. Light-duty vehicle shares of 2014 registrations by vehicle category and segment in Japan. Small buses account for about 0.1% of the market and are therefore not displayed in the figure (source: JAMA, 2015).

While all four regions generally define LDVs by weight (GVW of less than approximately 3,500 kg), light-duty categories or segments are not always comparable across regions. For instance, a 4WD SUV intended for passenger transportation is subject to passenger car regulations in the EU and China, but is subject to light truck standards in the United States.

To produce comparable results, **the scope of this study is limited to passenger cars**. Passenger cars are defined here as follows: M1 car-like segments in the EU; cars plus 2WD SUVs with GVW below 2,700 kg in the United States; M1 car-like segments and M1G vehicles in China; and passenger cars in Japan. Van-like models were excluded from both the EU and China analyses, because it was not possible to determine whether such vehicles were registered as M1 or N1 vehicles. The Japanese on-road fuel consumption data did not contain any information on vehicle category or segment, so it was not possible to ensure that vehicles other than car-like passenger cars were excluded from the analysis. In short, to ensure comparability of results, the analysis focuses on vehicles that are registered as passenger cars and have body types resembling stereotypical cars and SUVs.

2.2 PASSENGER CAR CHARACTERISTICS

Even though the study only focuses on passenger cars, the markets for these cars vary substantially in terms of basic vehicle characteristics. Table 1 provides an overview of average new car parameters in each of the four regions under study. While EU and China fleet specifications refer to new 2014 registrations, the U.S. data refers to model year 2014, indicating when a vehicle was marketed, and the values for Japan to sales year 2011 (more recent data was not available). Vehicle mass is provided as curb weight, which is commonly defined as the weight of the empty vehicle with standard equipment, all necessary operating consumables, and a fuel tank roughly filled to capacity. In the EU, however, vehicle mass is typically given as mass in running order, which includes the mass of the driver in addition to the curb weight. To account for the difference in the definition, a mass of 75 kg has been subtracted from the EU mass in running order value.

The EU and China are similar in terms of vehicle mass and engine power. U.S. passenger cars are the heaviest and most powerful on average, while Japanese cars are on the other end of the spectrum. The United States has the most powerful cars even when accounting for vehicle mass, with a power-to-mass ratio around 40% higher than the rest. Diesel vehicles are only popular in the EU, where they accounted for 53% of new vehicle registrations in 2014. The EU is also an exception regarding transmission types, as it is the only region where vehicles with automatic transmission do not account for the majority of car registrations. In terms of CO_2 emissions, China and the United States stand out with the highest average values, while the EU and Japan average values are around 26% lower.

Table 1. Comparison of new passenger car characteristics. CO_2 emission values normalized to NEDC (sources: Mock, 2015; U.S. EPA, 2015b).

Region	EU	U.S.	China	Japan
Dating convention	Sales year	Model year	Sales year	Fleet year
Year	2014	2014	2014	2011
Curb weight (kg)	1,317	1,478	1,376	1,193
Power (kW)	90	148	101	78
Specific power (kW/kg)	0.070	0.100	0.073	0.065
Diesel (%)	53%	1%	2%	1%
Automatic transmission (%)	23%	96%	56%	99%
CO_2 (g CO_2/km)	123	167	171	126

2.3 EU

2.3.1 Vehicle testing

In the EU, LDV CO_2 emission and fuel consumption figures are determined in laboratories using the United Nations Economic Commission for Europe (UNECE) R101 procedure and the New European Driving Cycle (NEDC), a cycle developed in the 1970s and last updated in 1998 (Kühlwein, 2016). The NEDC consists of four consecutive urban driving cycles, termed ECE-15, followed by an Extra Urban Driving Cycle (EUDC). While the ECE-15 represents urban driving with low vehicle speeds and engine load, the EUDC covers higher speeds, up to 120 km/h (see Figure 6). Before the testing begins, the vehicle is conditioned to an ambient temperature of 20°C to 30°C for at least six hours. During NEDC testing, auxiliary electric devices such as air conditioning or entertainment systems are turned off. Testing conditions (e.g., the high ambient temperature) and a number of tolerances and flexibilities—allowable tolerances for laboratory instruments, testing of so-called “golden vehicles”, special test driving techniques, etc.—provide opportunities to produce particularly low CO_2 emission values during type-approval testing (Stewart, Hope-Morley, Mock, & Tietge, 2015).

Before the chassis dynamometer testing begins, resistance values are determined during coastdown testing. The coastdown procedure used to estimate road loads for NEDC testing also includes technical tolerances and imprecise definitions, indicative of the poor technical standards and imprecise instrumentation of the 1970s, but out of date compared with modern technologies and standards (Kühlwein, 2016). Manufacturers can exploit a number of imprecisions, allowing for pretreatment of tires by baking or shaving them, optimizing aerodynamics, opening brake calipers, or carefully selecting test tracks with smooth and hard road surfaces, among others (Kadijk et al., 2012; Kühlwein, 2016). The problems with the out-of-date requirements are compounded by the lack of any oversight of the manufacturer testing.

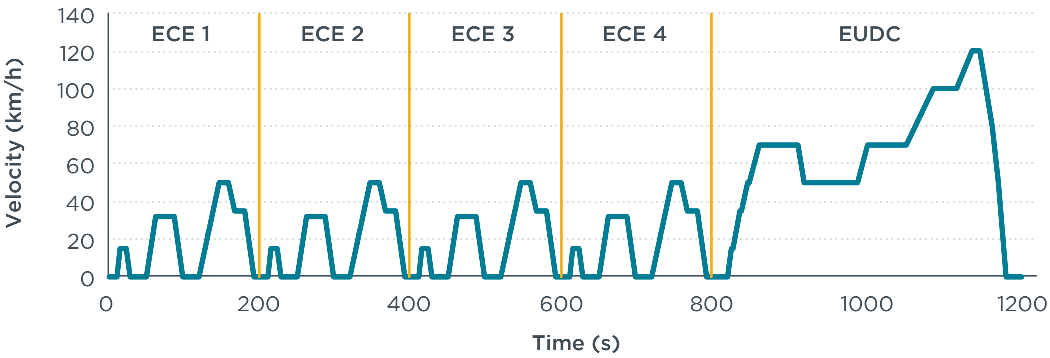


Figure 6. Driving schedule of the NEDC

2.3.2 CO_2 targets

The first binding CO_2 target in the EU was set in 2009 and required average CO_2 emission values of new passenger cars to fall below 130 g/km by 2015 (Regulation (EC) No 443/2009, 2009). A second target of 95 g CO_2/km for 2020, with a 1-year phase-in period, was set in 2014 (European Commission, 2014). The European Commission (2016a) is also working on post-2020 CO_2 standards, including an intermediate target before 2030.

All vehicle manufacturers must comply with CO_2 standards, although targets are adjusted by vehicle mass such that manufacturers of heavier cars are allowed higher CO_2 emissions, whereas manufacturers of lighter cars must meet more stringent targets. The pre-production type-approval test results are weighted by vehicle sales to calculate a manufacturer's fleet average CO_2 emission values. If a manufacturer fails to comply with its CO_2 target, it must pay an excess emissions premium, which can easily amount to multimillion-euro penalties. Up until 2019, the premiums, per vehicle, are: 5 euros for the first g/km of exceedance; 15 euros for the second g/km; 25 euros for the third g/km; and 95 euros for each subsequent g/km (European Commission, 2016c). A number of provisions are in place to help manufacturers meet their targets, and include multipliers ("super-credits") for low-carbon vehicles, emission credits for innovative off-cycle efficiency technologies ("eco innovations"), rules allowing manufacturers to enter pools to jointly meet targets, and separate targets or derogations for smaller manufacturers, among others (for more details, see Mock, 2014).

According to official values, so-called type-approval values[1], CO_2 emissions from new cars in the EU have rapidly decreased from 168 g CO_2/km in 2001 to 120 g CO_2/km in 2015. The rate of reductions increased noticeably after CO_2 standards were introduced in 2009 (see Figure 7), illustrating that the 2015 target was effective at driving down CO_2 emission and fuel consumption values, at least on paper.

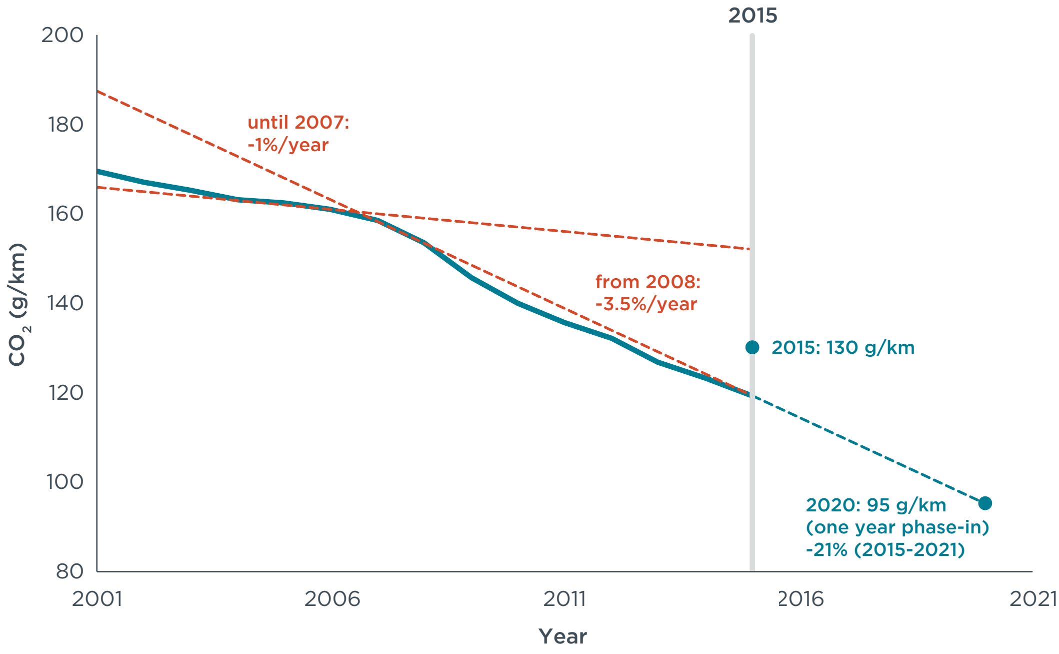


Figure 7. Development of average type-approval CO_2 emission values for new passenger cars in the EU.

2.3.3 Policy framework and enforcement

Type-approval CO_2 emissions testing in the EU is done primarily with laboratory tests of pre-production vehicles based on the NEDC. After laboratory testing is completed, conformity of production (CoP) certification requires manufacturers to demonstrate that each vehicle is manufactured to the approved specifications, which typically can be proven by using quality-management systems (Mock & German, 2015). Manufacturers must also retest randomly chosen vehicles from the assembly line, and CO_2 emissions may not deviate from the type-approval value by more than 8%. On-road tests using portable emissions measurement systems (PEMS) are currently only being conducted for nitrogen oxides (NO_x) and particulate number emissions as part of the real-driving emissions (RDE) procedure (Franco & Mock, 2015). The European Commission (2016a) is investigating the feasibility of measuring real-world CO_2 emissions. The current

1 *Type-approval* refers to the process of vehicle certification, that is, demonstrating the roadworthiness of a vehicle type, in China and in the European Union.

laboratory testing procedure based on the NEDC will be replaced by the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) beginning in 2017. The WLTP will introduce a more dynamic test cycle and more realistic test parameters related to vehicle weight and ambient temperature, among others. It will also introduce improvements to coastdown testing. Nevertheless, the WLTP is not expected to align official and real-world measurements by itself (Stewart et al., 2015).

The current European type-approval framework has systemic flaws related to how different organizations in the type-approval chain interact. First, car manufacturers pay technical services to conduct vehicle tests. Technical services therefore have an incentive to produce favorable test results to attract business from car manufacturers (ICCT, 2016c). Competition between different technical services may also create a "race to the bottom." Second, important test parameters, most notably road-load coefficients, are not independently verified or even publicly available (Kühlwein, 2016). Lastly, European regulators and member states do not have the authority to impose financial penalties for noncompliance, and only the member state that issued the type approval for a particular model variant can revoke the certificate. This market structure and the lack of transparency provide opportunities for car manufacturers to furnish unrealistic CO_2 emission values.

The impact assessment accompanying the 2020 CO_2 standards acknowledges this issue. Some cost scenarios in the impact assessment, including the central scenario, assume that the cost of complying with the 2020 standard would be lower than industry estimates because the decline in average CO_2 emission values from 2002 to 2009 was achieved without significant deployment of new technologies, which are the major driver of compliance costs. The impact assessment also uses a factor of 1.195 (corresponding to a 19.5% gap) to convert type-approval values to real-world estimates. This factor was based on a 2006 study (see Smokers et al., 2006) and underestimates the gap between real-world and official CO2 values, which has grown to a level of 42% for new vehicles in 2015 (see Section 4.1).

A proposal by the European Commission (2016b) aims to overhaul the legal framework of the European type-approval scheme to address some of the aforementioned shortcomings. The proposal would (1) require EU member states to perform market surveillance testing; (2) allow EU member states to take measures, such as recalls and fines, against noncompliant vehicles; (3) create an information exchange for enforcement expertise; and (4) break financial ties between vehicle manufacturers and organizations conducting the type-approval testing and provide funding for market surveillance activities (Franco, 2016; Yang & Muncrief, 2017).

2.4 UNITED STATES

2.4.1 Vehicle testing

Two types of fuel economy values are available for light-duty vehicles in the United States: Corporate Average Fuel Economy (CAFE) values are used for fuel economy standards, while Fuel Economy Label values (here referred to as *U.S. EPA label values*) are presented to consumers at the point of purchase.

CAFE values are based on laboratory measurements of exhaust emissions during two driving cycles, the FTP-75 and the U.S. EPA Highway Fuel Economy Test Cycle (HWFET):

- FTP-75: The FTP-75 is used to estimate urban fuel consumption of vehicles. The cycle consists of three phases (see Figure 9): the cold start phase, the stabilized phase, and the hot-start phase. The hot-start phase is conducted after a 10-minute break following the stabilized phase. The average speed during the test is 34 km/h and ranges up to 91 km/h.

» HWFET: The HWFET was developed to measure fuel economy during highway driving. This is a hot-start test. While the maximum speed (97 km/h) is similar to the FTP-75, average speeds are considerably higher at 78 km/h.

The two test cycles are respectively weighted 55% and 45% in the calculation of the fuel economy value.

U.S. EPA label values are meant to be representative of fuel consumption during real-world driving. The values are presented at the point of purchase so that consumers can compare the fuel economy and fuel costs of different vehicles. Until model year 2007, the label value was based on adjusting the city (FTP) fuel economy value downward by 10% (equivalent to an 11% increase in fuel consumption) and the highway (HWFET) value downward by 22% (equivalent to a 28% increase in fuel consumption) (U.S. EPA, 2006). Since model year 2008, a new procedure, termed the *five-cycle method*, includes additional laboratory fuel consumption tests based on three cycles (see Figure 9):

» US06: The US06 Supplemental Federal Test Procedure was developed to represent more aggressive driving, including higher speeds and higher acceleration rates than the FTP-75 test cycle.

» SC03: The SC03 Supplemental Federal Test Procedure was developed to represent engine load resulting from the use of air conditioning, with vehicles tested at high ambient temperatures (35°C), full sun load, and air conditioning turned on.

» Cold FTP: The cold FTP refers to a FTP-75 test at reduced ambient temperatures, specifically –6.7°C, instead of 20°C–30°C.

The weighting of the five cycles in the calculation of average urban, highway, and combined fuel economy values takes into consideration average vehicle usage patterns and ambient conditions (U.S. EPA, 2006). On top of using the three more demanding cycles in the calculation of U.S. EPA fuel economy labels, the final fuel economy values are adjusted downward by 9.5% (corresponding to a 10.5% increase in fuel consumption) to account for real-world factors that are not measured during laboratory testing, including fuel quality, tire pressure, wind, road gradient, etc. The U.S. EPA (2006) estimated that the five-cycle method reduced urban fuel economy values by 8% to 15% (corresponding to a 9% to 18% increase in fuel consumption) and reduced highway fuel economy values by 5% to 15% (corresponding to a 5% to 18% increase in fuel consumption) for most conventional vehicles compared with the procedure used before 2008.

In practice, the five-cycle values are commonly calculated from the FTP-75 and HWFET fuel economy values (see U.S. EPA, 2015c). This simplified approach can be used for all versions of a vehicle model as long as manufacturers can demonstrate that the derived five-cycle method yields comparable results to those achieved by the full five-cycle method for the certification vehicle (U.S. EPA, 2015b).

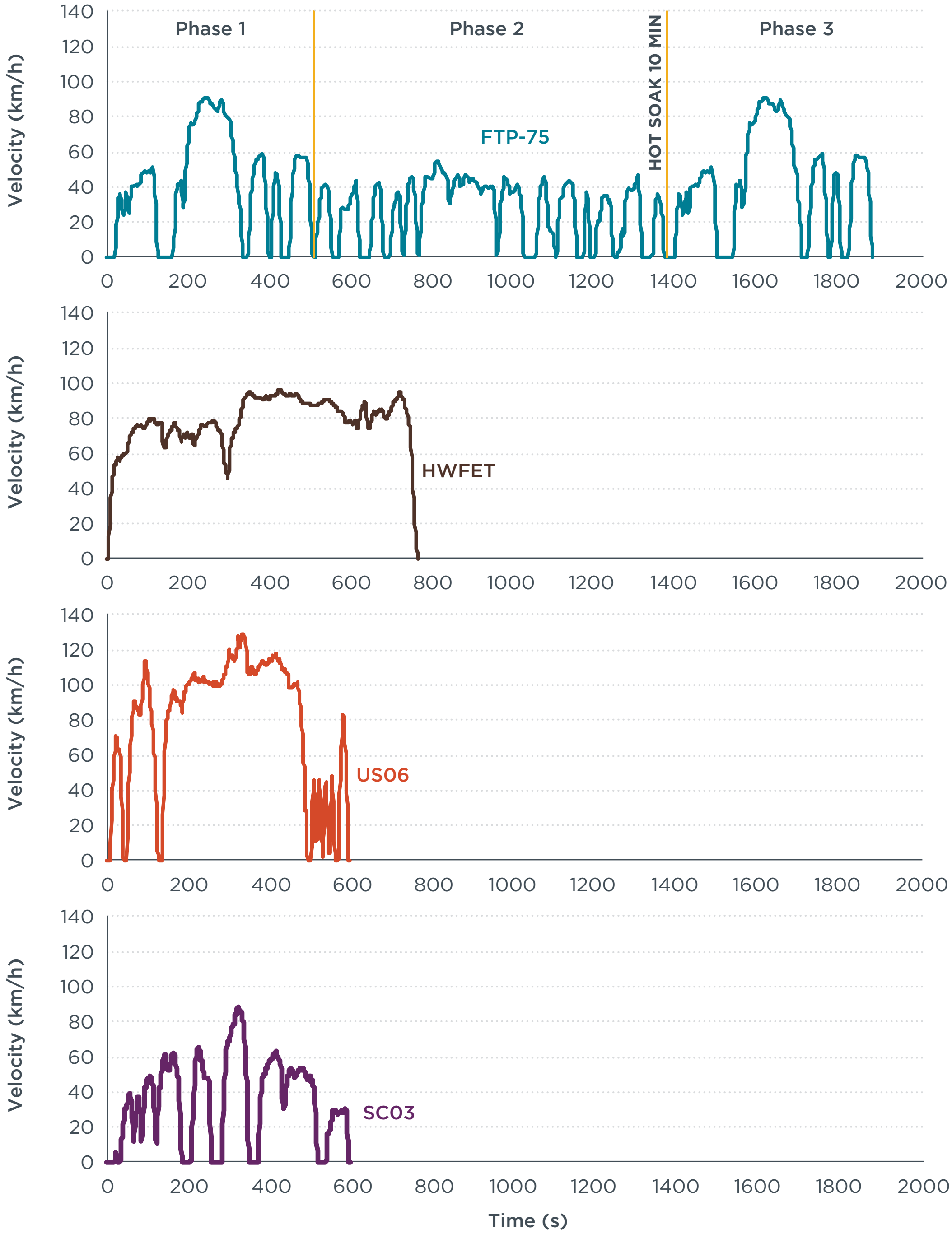


Figure 8. U.S. driving schedules used for the CAFE standards (FTP-75 & HWFET) and EPA label values (all cycles) (source: DieselNet, 2016).

2.4.2 Fuel economy and CO_2 emission targets

The United States set its first fuel economy standard for LDVs in 1975, aiming to roughly double the average fuel economy of cars from 13.6 miles per gallon (mpg) (17.3 l/100 km) in 1974 to 27.5 mpg (8.6 l/100 km) by 1985 using the unadjusted CAFE test results, a target that was met with a one-year delay (DieselNet, 2013; NHTSA, 2014). A second set of standards was set for light trucks only for model years (MY) 2005 to 2011. A third stage required cars to increase fuel economy to 37.8 mpg (6.2 l/100 km or 140 g CO_2/km) and light trucks to meet a target of 28.8 mpg (8.2 l/100 km or 185 g CO_2/km) (ICCT, 2016a) by 2016. This third stage, covering MY 2012 to MY 2016, also adjusted targets for vehicle size, allowing manufacturers with larger vehicle footprints to have lower fuel economy targets. Other flexibilities include credits for improvement in air conditioning systems, electric vehicles, and technologies that reduce CO_2 emissions outside of vehicle testing, among others (DieselNet, 2013; U.S. EPA, 2010b). A fourth stage of standards set targets up to 2025: an estimated 56.2 mpg (4.2 l/100 km or 89 g CO_2/km) for cars and 37.8 mpg (6.2 l/100 km or 126 g CO_2/km) for light trucks (ICCT, 2016a).

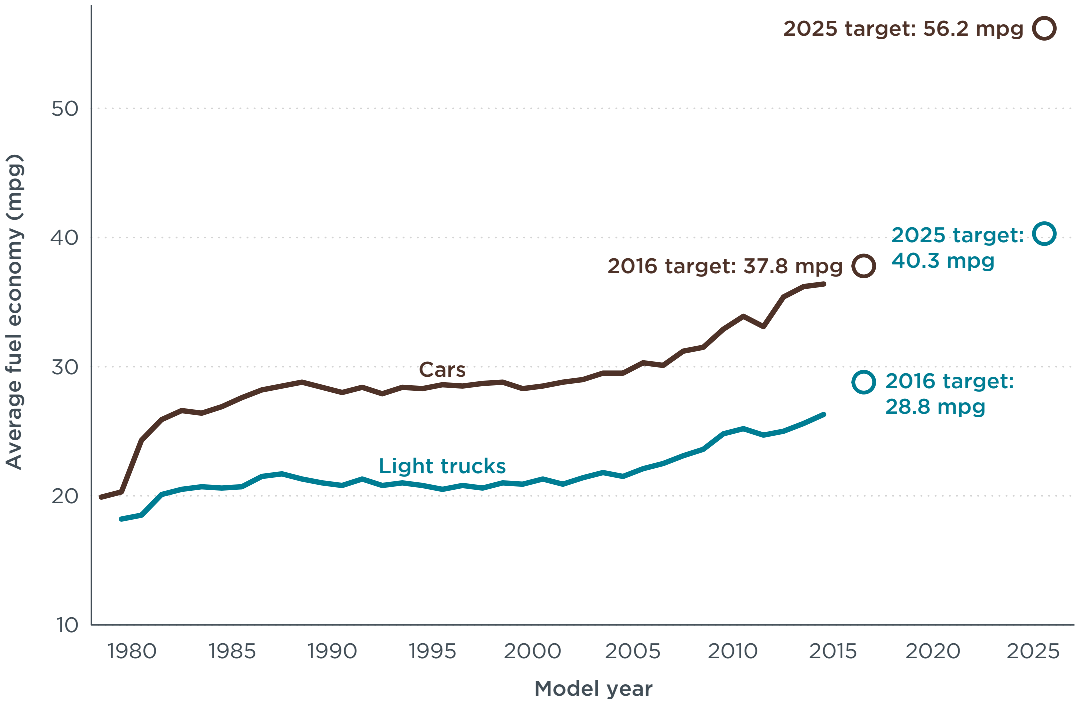


Figure 9. Historical fuel economy values for U.S. cars and light trucks, including 2016 and 2025 targets (source: NHTSA, 2014).

2.4.3 Policy framework and enforcement

A wide variety of policy enforcement measures are in place in the United States to ensure compliance with emission and fuel economy regulations. Figure 10 follows a vehicle through the U.S. EPA compliance program. The unit of analysis for most of this program is a test group, a group of vehicles or engines with similar technical and emission characteristics (for more details, see Mock & German, 2015).

During the preproduction phase to establish fuel economy label values, the U.S. EPA does confirmatory testing of about 15% of the vehicles tested by the manufacturers, who also submit their results to the U.S. EPA. If there is an ongoing offset between the two test results, U.S. EPA will increase the confirmatory testing rate until the manufacturer fixes the problem. The U.S. EPA also has extensive guidance on all aspects of vehicle testing, including defining how to determine the vehicle weight, accessories installed on the vehicle, selection of representative tires (and associated road-load), mileage accumulation adjustments, and how to test vehicles with driver-selectable devices.

During the vehicle design-and-build phase, the U.S. EPA may test vehicles off the assembly line to ensure that they are built in accordance with specifications of prototypes used for certification, so-called Selective Enforcement Audits (SEAs). SEAs have become less common over time: Failed audits were becoming rare by the mid-1980s, as they had triggered manufacturers to conduct extensive tests themselves (Mock & German, 2015). Road-load coefficients, which are also determined during the vehicle design and build phase, are publicly accessible online, and the U.S. EPA conducts confirmatory coastdown tests on vehicles that are in use (Kühlwein, 2016).

For CAFE and CO_2 standard compliance, the U.S. EPA requires testing of vehicle configurations representing at least 90% of each manufacturer's actual production. This means that the manufacturers conduct another round of testing after the model year ends and they have final production numbers, also subject to U.S. EPA confirmatory testing. This eliminates problems with unrepresentative pre-production test vehicles and ensures that the test vehicles properly represent actual production. Note that this means that the final fuel economy values for each model type determined for standard compliance might be significantly different from the fuel economy label values that were based upon prototype vehicles and early calibrations.

Once vehicles enter the market, the In-Use Verification Program (IUVP) requires manufacturers to conduct chassis dynamometer tests on at least one in-use vehicle for each test group at low mileage (10,000 miles, or 16,000 km) and high mileage (50,000 miles, or 80,000 km). Emission exceedances during the IUVP can trigger an In-Use Confirmatory Program (IUCP) test, which requires manufacturers conduct further investigations. Failure of IUCP tests can lead to recalls. To ensure the accuracy of the manufacturers' testing, the U.S. EPA also randomly selects or targets suspicious test groups during in-use surveillance tests, which involve testing three to five vehicles from a test group to ensure compliance with declared values and emission standards.

In addition to monitoring vehicle testing, U.S. authorities account for the gap between regulated CAFE values and on-road measurements: the U.S. EPA uses a real-world adjustment factor in the impact assessment for fuel economy standards. For instance, for the third stage of standards (MY 2012 to MY 2016), CAFE fuel economy targets were adjusted downward by 20% (equivalent to an increase in fuel consumption by 25%), reflecting the average gap at the time (U.S. EPA, 2010c). The midterm evaluation of the fourth stage of standards for 2017 to 2025 increased the adjustment factor to 23% (equivalent to an increase in fuel consumption by 30%), in anticipation of a growing gap due to increased ethanol content in fuels (U.S. EPA, CARB, & NHTSA, 2016). The U.S. fuel economy regulations are thus accompanied by impact assessments that take into consideration the gap between CAFE and real-world values.[2]

Taken together, the U.S. EPA compliance program follows vehicles throughout their useful life and has mechanisms in place to ensure independent testing of vehicles and testing of representative vehicles (see Figure 10). In contrast to the EU, the regulator (the U.S. EPA) also has the power to issue vehicle recalls and to impose fines for non-compliance.

2 It should be noted that the U.S. EPA adjustment procedure for the CO_2 and fuel consumption impact assessments could be improved. The U.S. EPA has found that the "gap" between test and real-world fuel economy is, in part, a function of the fuel economy of the vehicle, such that higher fuel economy vehicles have a higher gap. This is reflected in the fuel economy label adjustment formula, but instead of using this formula for the impact assessment, the U.S. EPA used the same adjustment factor (23% for the latest rule) for both the baseline fleet and the future fleet. When incorporating the average fuel economy, the gap for the average fleet mpg of about 28 in 2008–2010 yields a correction factor of about 23.5%, and the 2025 average fleet mpg of about 49 yields a correction factor of about 26.5%. The impact of this correction is much smaller than incorporating a factor for the gap into the impact assessments, but would still be an incremental improvement.

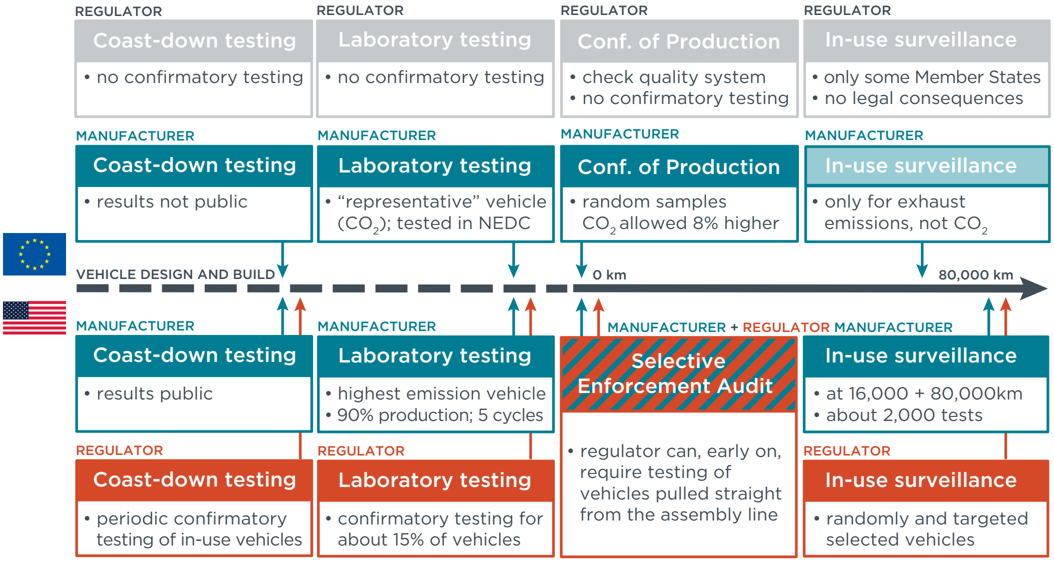


Figure 10. U.S. EPA compliance program for light-duty vehicles (Mock & German, 2015; U.S. EPA, 2008).

2.5 CHINA

2.5.1 Vehicle testing

China has followed the UNECE R101 to determine LDV fuel consumption figures in laboratories since the adoption of fuel consumption standards in 2004. The testing methodology is thus exactly the same as EU testing methods, using the four consecutive ECE-15 (urban) and a EUDC (extra-urban) of the NEDC with the same ambient temperature (see Figure 6).

To estimate road loads for chassis dynamometer testing, manufacturers can refer to predetermined values, so-called *cookbook values*, or conduct coastdown tests following the UNECE R83 procedure (the same as in the EU).

2.5.2 Fuel economy and CO_2 emission targets

China's first fuel consumption standards for passenger vehicles took effect in 2005 and applied only to domestic vehicles. The standards were implemented in two phases: Phase I took effect on July 1, 2005, and Phase II took effect on January 1, 2008, for new models and a year later for continued models. These first two phases set fuel consumption limits for individual vehicle models by weight category.

China then released the Phase III fuel consumption standards to regulate vehicles produced from 2012 on that applied to both domestic and imported vehicles. In contrast to the first two phases, the Phase III standards define corporate-average fuel consumption (CAFC) targets for each manufacturer in addition to per-vehicle targets. Similar to the EU CO_2 regulations, manufacturers were required to meet an average fuel consumption target, which was adjusted by the vehicle curb weight distribution across the manufacturers' fleet, limiting overall fleet-average fuel consumption values to 6.9 l/100km by 2015.

The Phase IV standards, which were released in 2014, follow the same regulatory structure as Phase III, targeting a fleet-average fuel consumption of 5 l/100km in 2020. Phase IV includes a number of flexibility mechanisms, such as multipliers for new energy vehicles and ultra-low fuel consumption vehicles, off-cycle technology credits, and a phase-in period (He & Yang, 2014b). China now is working on future standards with a proposed target of 4 l/100km by 2025.

Figure 11 shows the development of the fuel consumption standards in China over time. The term *special vehicles* refers to vehicles with automatic transmission and three rows of seats or more for Phase I, II, and III standards, and refers to three rows of seats or more for the Phase IV standards.

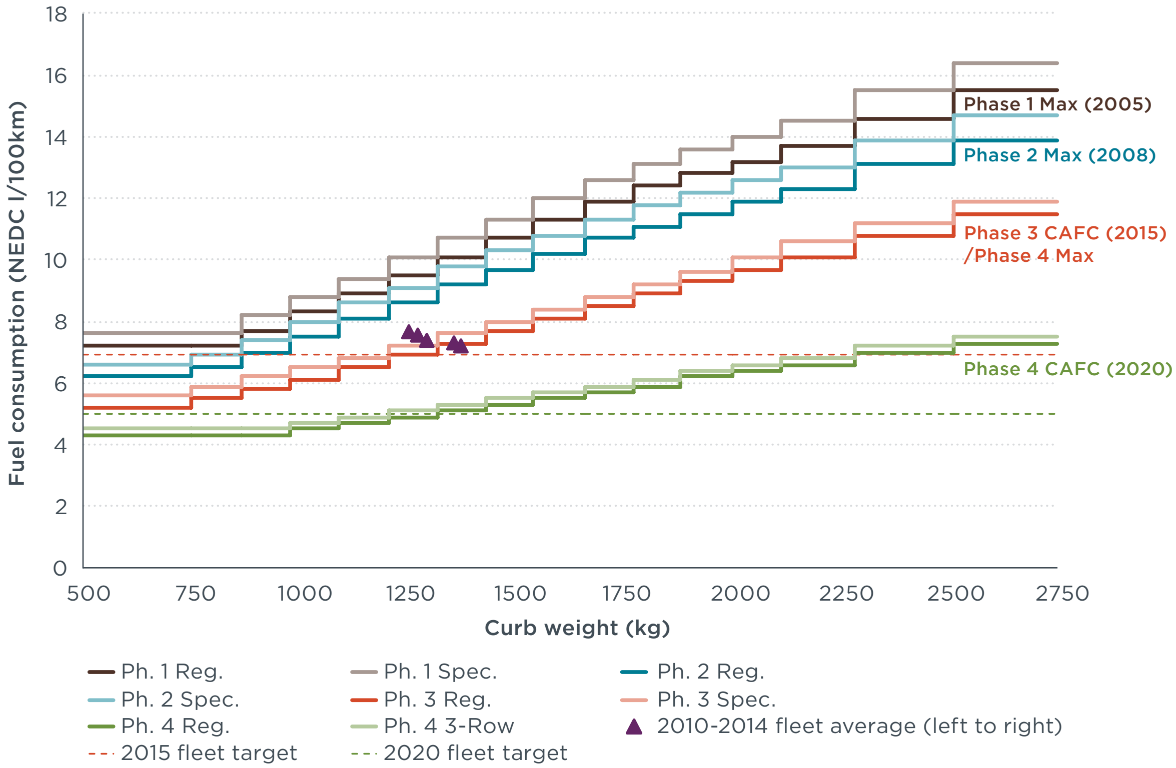


Figure 11. Development of fuel consumption standards and fleet trends in China for regular vehicles (Reg.) and special vehicles (Spec.).

2.5.3 Policy framework and enforcement

The enforcement of vehicle fuel consumption standards differs from the enforcement of conventional pollutant standards. The former is currently regulated by the Ministry of Industry, Information, and Technology (MIIT), whereas the Ministry of Environmental Protection regulates the latter.

The enforcement of fuel consumption standards in China mainly focuses on tests of pre-production vehicles in the laboratory. Manufacturers must test vehicles at a certified laboratory to conduct type-approval testing for LDVs and then submit the data with their application for type approval.

The regulation requires manufacturers to ensure CoP of produced vehicles, but manufacturers are not required to prove that vehicles meet certified fuel consumption levels. The regulatory agency has the authority to select vehicles from the production line to carry out a CoP test, but there is no evidence that proves such tests are carried out on a regular basis, nor that any noncompliance has been discovered by such tests. There is no in-use surveillance testing of vehicles to verify that vehicles meet the certified values throughout their useful life.

China enforces its fuel consumption standards with administrative, rather than financial, penalties. From November 1, 2014, on, if a manufacturer does not meet its CAFC target with only its conventional fuel passenger cars and also cannot meet a uniform 6.9 l/100km corporate fuel consumption target after counting in its New Energy

Vehicles, which include battery electric vehicles and plug-in hybrid electric vehicles (PHEVs), MIIT will "name and shame" the manufacturer. In addition, MIIT can suspend the new type approval (vehicle product catalog) application of noncompliant manufacturers, ban or limit the production of new models that cannot meet their individual fuel consumption targets in the following year, require the manufacturer to submit an improvement plan (He & Yang, 2014a), and suspend the plant expansion application from noncompliant manufacturers. Such enforcement rules have not been updated for Phase IV standards.

The Chinese regulatory framework has a systemic flaw similar to the EU type-approval framework. Manufacturers pay laboratories to conduct tests, so there is a potential conflict of interest and it is difficult to ensure the test result is accurate. Moreover, regulators do not conduct regular independent testing to verify fuel consumption values of new vehicles and in-use vehicles, which increases the opportunities for manipulation and reporting unrealistic fuel consumption values.

2.6 JAPAN

2.6.1 Vehicle testing

Japan has used a number of cycles to test vehicles for emissions and fuel economy. First, a test cycle called "10-mode" was used when emission standards for cars were first developed in 1973. The 10-mode cycle simulates urban driving conditions with a maximum speed of 40 km/h. The 10-15 mode, developed in 1991 and used to compile national fuel economy statistics from 1993, added one 15-mode segment simulating highway driving with speeds up to 70 km/h after three segments of the 10-mode. The JC08 test cycle was introduced in 2005 to determine vehicle fuel economy and was fully phased in by October 2011. Compared to 10-15 mode, JC08 is longer, has higher average and maximum speeds, and requires more aggressive acceleration. Moreover, fuel economy is measured twice, under cold-start and hot-start conditions. The final fuel economy value weighs the cold start by 25% and hot start by 75%. All tests are conducted at an ambient temperature of 20°C to 30°C. According to the Japanese government, the JC08 produces 9% lower fuel efficiency values compared with 10-15 mode (corresponding to a 10% increase in fuel consumption), which has made compliance with standards more difficult since the transition to the JC08.

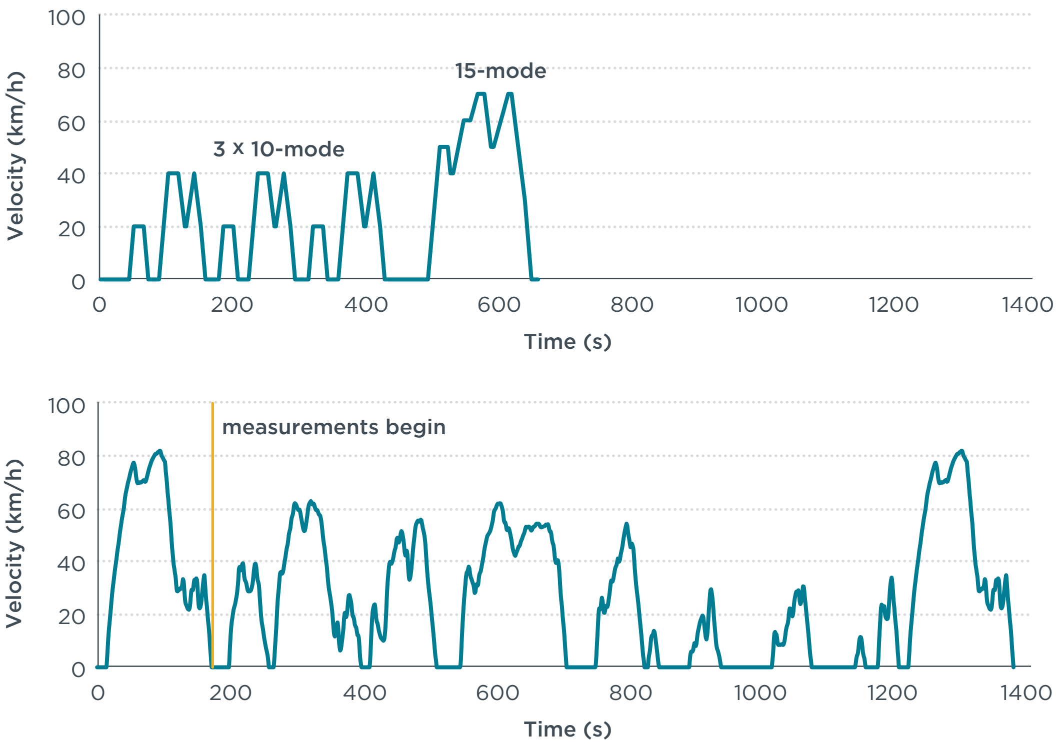


Figure 12. Japanese driving schedules under 10-15 mode and JC08 (source: DieselNet, 2016)

Similar to the other countries, coastdown tests are used in Japan to determine road loads for chassis dynamometer testing. In 2016, Mitsubishi was found to have manipulated coastdown tests for decades. The manipulation led to as much as 5-10% higher fuel economy results than valid measurements (Soble, 2016).

2.6.2 Fuel economy and CO_2 emission targets

The Japanese government first established fuel economy standards for passenger vehicles in 1999 under its "Top Runner" energy efficiency program. Fuel economy targets are based on weight classes, with automakers allowed to accumulate credits in one weight class for use in another, subject to certain limitations. The 2010 target was 15.1 km/l (6.6 l/100 km or 35.5 mpg) under 10-15 mode and 13.6 km/l (7.4 l/100 km or 32 mpg) under JC08.

Because the majority of vehicles sold in Japan in 2002 already met or exceeded the 2010 standards, Japan revised its fuel economy standards in 2006, replacing the 10-15 mode cycle with the stricter JC08 test cycle and setting the 2015 target of 16.8 km/l (6.0 l/100 km or 40.0 mpg). In 2011, Japan released the 2020 standards of 20.3 km/l (4.9 l/100 km or 47.8 mpg) for passenger cars. On average, the new vehicle fleet exceeded its 2015 fuel economy target in 2011 and exceeded its 2020 fuel economy target in 2013.

A substantial share of the rapid fuel economy improvements in Japan can be attributed to the rise of hybrid electric vehicles (HEVs). In 2015, around 20% of passenger cars sold in Japan were HEVs, the highest share of any market. The aggressive fiscal incentives for fuel efficient vehicles have accelerated the growth of HEV shares since 2009 (Rutherford, 2015).

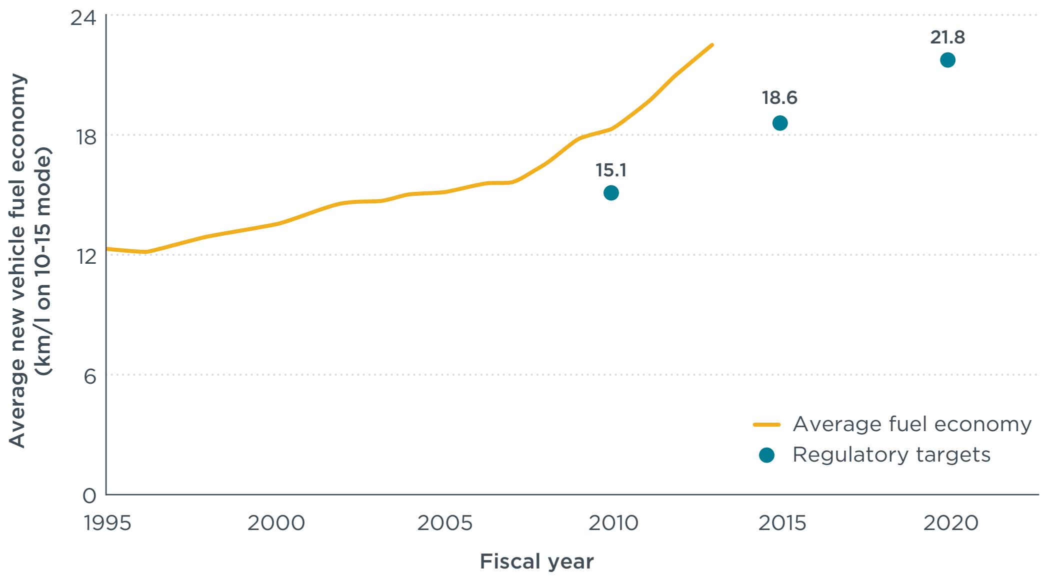


Figure 13. Japanese new vehicle fuel economy and regulatory targets, 1995 to 2020.

2.6.3 Policy framework and enforcement

The Ministry of Economy, Trade and Industry (METI) and Ministry of Land, Infrastructure, Transport and Tourism (MLIT) jointly issue and enforce fuel economy standards.

For the type-approval application, all manufacturers must test the vehicles at National Traffic Safety and Environment Laboratory (NTSEL), the national laboratory owned and operated by government, or conduct testing with a witness from the NTSEL. While the testing is conducted or supervised by the governmental laboratory, manufacturers conduct coastdown tests. After the news broke about manipulation of coastdown tests by Mitsubishi, MLIT announced plans to conduct confirmatory road load tests or witness coastdown tests without previous notice.

For CoP, MLIT requires manufacturers to regularly test fuel economy values and conventional pollutant emissions of vehicles off the assembly line. MLIT investigates production lines to evaluate their capacity to produce qualified vehicles. No CoP testing is conducted by the regulatory agency, and MLIT does not require manufacturers to conduct in-use surveillance tests of any vehicles. MLIT selects some models to conduct in-use tests each year, but only to confirm compliance with conventional pollutant emission standards rather than fuel economy values.

There are minimal penalties if manufacturers fail to meet fuel economy targets. It is unclear how the regulatory agency will penalize manufacturers manipulating vehicles tests.

2.7 SUMMARY OF VEHICLE TESTING AND CO_2 STANDARDS

All four markets under study have fuel economy or CO_2 standards in place (see Figure 14). The EU, United States, and China have similar targets in place, around 95 g CO_2/km (when normalized to NEDC), with the United States and China trailing behind the EU by five years. Japan and the EU currently have the most efficient new car fleets, with roughly 120 g CO_2/km according to official values.

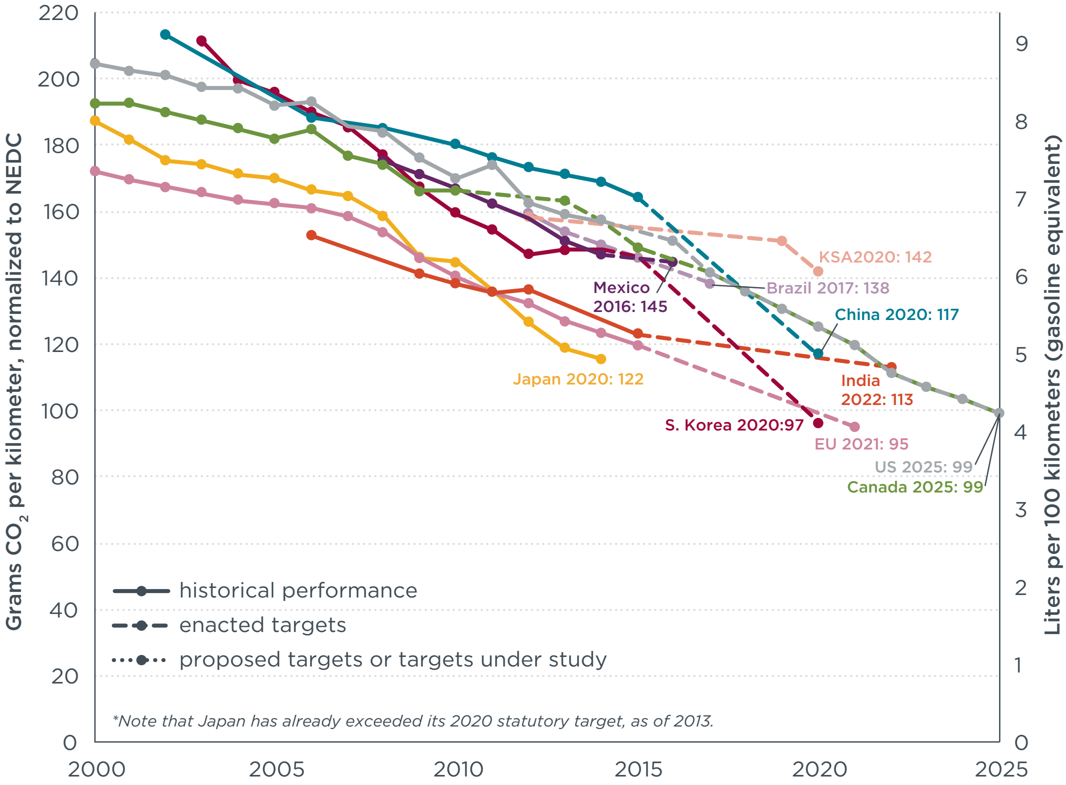


Figure 14. Official passenger car CO_2 and fuel consumption values and targets, normalized to NEDC.

Table 2 compares the driving cycles used in the EU, the United States, China, and Japan. The CAFE procedure stands out with the highest mean velocity, lowest share of idling, and highest share of time accelerating. The Japanese JC08 cycle has the lowest average speed and highest share of idling time and lies between the CAFE and NEDC schedules in terms of most measures of dynamicity. Lastly, the NEDC has the highest share of constant speed driving and a comparatively low average speed, but also has the highest mean positive acceleration.

A comparison of vehicle testing and policy frameworks in the four regions reveals substantial differences. The U.S. has the most extensive vehicle testing practices, with the U.S. EPA compliance program ensuring independent confirmatory tests, testing of vehicle configurations representing actual production, and in-use surveillance testing. In contrast, the other regions primarily rely on CoP to ensure that production vehicles meet type-approval specifications, although the EU's draft proposal to overhaul the type-approval framework would add several other testing components; in addition, introduction of the WLTP (applicable in the EU, Japan, and China) will tighten test conditions during laboratory testing. In terms of official CO_2 values, Japan has the most efficient fleet and the EU has the most ambitious targets. The rest of the study aims to assess how these differences in vehicle testing and policy frameworks affect the on-road efficiency of vehicles.

Table 2. Overview of test cycles used in the EU, the United States, China, and Japan (data source: Kühlwein et al., 2014).

	Units	NEDC	FTP75 weighted	HWFET	CAFE	JC08
Country		EU/China	US	US	US	Japan
Start condition		cold	43% cold / 57% hot	hot		25% cold / 75% hot
Duration	s	1180	1369	765		1204
Distance	km	11.03	11.99	16.51		8.17
Mean velocity	km/h	33.6	31.5	77.7	43.0	24.4
Max. velocity	km/h	120.0	91.2	96.4		81.6
Stop phases		14	18	2		12
Durations						
Stop	s	280	241	4		346
Constant driving	s	475	109	126		21
Acceleration	s	247	544	338		432
Deceleration	s	178	475	297		405
Shares (% of cycle duration)						
Stop		23.7%	17.6%	0.5%	13.3%	28.7%
Constant driving		40.3%	8.0%	16.5%	10.1%	1.7%
Acceleration		20.9%	39.7%	44.2%	40.8%	35.9%
Deceleration		15.1%	34.7%	38.8%	35.7%	33.6%
Mean positive acceleration	m/s^2	0.59	0.50	0.19	0.42	0.42
Max. positive acceleration	m/s^2	1.04	1.48	1.43		1.69
Mean positive velocity x acceleration, acceleration phases	m^2/s^3	4.97	3.86	3.45	3.76	3.34
Mean positive velocity x acceleration, whole cycle	m^2/s^3	1.04	1.53	1.52	1.53	1.20
Max. positive velocity x acceleration	m^2/s^3	9.22	19.19	15.17		11.60
Mean deceleration	m/s^2	-0.82	-0.58	-0.22	-0.49	-0.45
Min. deceleration	m/s^2	-1.39	-1.48	-1.48		-1.19

3. LITERATURE REVIEW

3.1 EU

Several studies have analyzed the growing divergence between type-approval and official CO_2 emissions in the European vehicle market. To arrive at an estimate of the gap, some of these studies have taken a top-down approach by aggregating large sets of in-use fuel consumption data from one or more EU member states. Other studies have followed a bottom-up approach and looked into the underlying causes of the gap in terms of both size and development over time.

The *From Laboratory to Road* series (Mock et al., 2014, 2012, Tietge et al., 2015, 2016) is the most extensive top-down analysis of the divergence between official and on-road CO_2 emissions in the European market to date. The 2016 study aggregated 13 real-world fuel consumption data sources from seven European countries covering a total of 15 years (Tietge et al., 2016). Combining all data sources, the study found that the average CO_2 gap increased from 9% in 2001 to 42% in 2015, and that the increase was particularly steep after 2008, when CO_2 standards were first agreed on in the EU. Section 4.1 summarizes the findings.

Ligterink and Eijk (2014) analyzed real-world fuel consumption data from Dutch company cars covering model years 2004 to 2014.[3] The study found that the average divergence between on-road and official fuel consumption values increased from approximately 10% to 50% from 2004 to 2013. Ligterink and Smokers (2015) also conducted a study of Dutch company car data, focusing on the real-world performance of five top-selling plug-in hybrid electric vehicle models. The study found that drivers on average only covered about 30% of the type-approved electric mileage with electric drive on the road, and observed a decreasing trend in the electric drive share. The CO_2 gap from the PHEV sample increased from 169% to 176% from 2013 to 2015.

Stewart et al. (2015) built upon the top-down approach of Mock et al. (2014) and added a bottom-up analysis of the factors causing the CO_2 gap. Both approaches found that the divergence increased from around 10% in 2002 to about 35% in 2014. The study concluded that the growth was mainly due to manufacturers exploiting flexibilities in testing procedures. Similarly, Kadijk et al. (2012) demonstrated that the application of test flexibilities in the EU increased significantly between 2002 and 2010. The study estimated that the use of flexibilities accounted for around 11 percentage points and 7 percentage points of the on-paper reduction in CO_2 emissions achieved between 2002 and 2010 for passenger cars and LCVs respectively.

Mellios et al. (2011) and Ntziachristos et al. (2014) developed a model to predict on-road fuel consumption of a given vehicle model on the basis of type-approval fuel consumption, engine capacity, and vehicle mass. The studies stated that in-use fuel consumption of gasoline and diesel passenger cars tested between 2009 and 2011 was, on average, 11% and 16% higher than the official value. Other studies (e.g., Ligterink, Smokers, Spreen, Mock, & Tietge, 2016; Tietge, Mock, Franco, & Zacharof, 2017) propose similar models to predict real-world fuel consumption. The former study also provides evidence that the increase in the real-world gap after 2007 is linked to increased exploitation of flexibilities in the test procedure and increased use of technologies that provide disproportionate benefits under laboratory conditions.

3 Company cars are a common job benefit in many European countries and represent roughly half of new car registrations in Europe.

3.2 UNITED STATES

Since fuel economy standards were introduced in the United States in the mid-1970s, the discrepancy between laboratory and real-world fuel economy has been the subject of government studies, industry surveys, and scientific reports. Evidence of an on-road fuel economy shortfall led the U.S. EPA to adjust downward the fuel economy values reported to consumers starting in 1984 (Greene et al., 2015). The original adjustments were 10% for the city test and 22% for the highway test, for an overall adjustment of about 15%. Before introducing updated test methods for the U.S. EPA label values in 2008, the U.S. EPA analyzed several real-world data sources of fuel economy estimates (U.S. EPA, 2006). The studies reviewed provided a snapshot of the on-road fuel economy shortfall at the time, which was roughly 20%.

More recently, Greene et al. (2015) and previously Greene, Goeltz, Hopson, & Tworek (2007), conducted an in-depth statistical analysis of the discrepancy between official and in-use fuel economy based data from the MyMPG service, a fuel economy tracking service on FuelEconomy.gov. The most recent study analyzed a sample of 75,000 submissions and covered model years 1984 to 2015. The study furnishes evidence of a growing divergence between official and real-world CO_2 emissions, but notes that the magnitude and direction of the gap was taken into account by the U.S. EPA. The study also pointed out that U.S. EPA window label values are a reasonable predictor of average on-road fuel economy, but that the considerable variance in on-road fuel economy experienced by different drivers detracts from the usefulness of the U.S. EPA label value in purchasing decisions.

3.3 CHINA

A number of studies investigated the divergence between real-world and type-approval CO_2 emissions in the Chinese vehicle market. Huo et al. (2011) found that the real-world fuel consumption of new cars sold in China in 2009 was about 16% higher than the type-approval value. The study was based on fuel consumption data from 153 vehicle models tracked by Chinese car owners on a local website. The study further used the International Vehicle Emission model to compare the type-approval driving cycle (NEDC) to several real-world city driving cycles and concluded that the NEDC failed to reflect city driving conditions, which was identified as one of the primary reasons for the gap.

Zhang et al. (2014) measured on-road CO_2 emissions from 60 passenger cars in 2013 in Guangzhou, Beijing, and Macao using PEMS equipment. They found that on-road CO_2 emissions normalized to the NEDC were 30% higher than type-approval figures. On-road measurements that were not normalized to the NEDC were 10% higher than the normalized values.

Lastly, Ding et al. (2015) and Qin et al. (2016) analyzed large samples of real-world fuel consumption data collected from XiaoXiongYouHao, a Chinese fuel tracking mobile application. The latter study found that the gap increased from 12% in 2008 to 27% in 2015 based on a set of more than 500,000 drivers' fuel consumption data. The studies investigate variations in the gap by vehicle segment, vehicle make, geographic region, and season.

3.4 JAPAN

A handful of studies have raised concerns about the divergence between type-approval and real-world CO_2 emissions from passenger cars in Japan. Kudoh (2012) observed an on-road fuel economy shortfall of 24% (32% fuel consumption gap) in e-nenpi.com data from fiscal years 2001 to 2004 and cites the inability of the 10-15 mode to reflect urban driving conditions as one of the main reasons for the divergence. Imported vehicles were found to have a lower gap than domestic ones, suggesting that imported vehicles were not optimized for Japanese road conditions and thus had higher laboratory fuel consumption values. Schipper (2008) observed a decrease in Japanese official fuel consumption from 8.1 l/100 km in to 6.5 l/100 km in 2005 (according to 10-15 mode), while real-world values only appeared to decline from 11.3 l/100 km to 10.6 l/100 km in the same period. These values correspond to a 40% gap in 1995 and a 63% gap in 2005, although it should be noted that the real-world values are based on fuel sales rather than measurements from individual vehicles. This method of estimating real-world fuel consumption is prone to errors because it proves difficult to accurately measure the required inputs for the calculation (Schipper, Figueroa, Price, & Espey, 1993).

4. DATA ANALYSIS

4.1 EUROPE: MULTIPLE SOURCES

Data type	User-submitted, vehicle test, and fuel card on-road fuel consumption values
Data availability	Varies between data sources; approximately 90,000 vehicles per year
Data collection	Varies between data sources; fuel consumption data entered by vehicle drivers into a publicly available online database, recorded using a tank card when refueling at gas stations, or measured on the basis of test drives
Fleet structure, driving behavior	Varies between data sources: approximately 73% of vehicles were company cars, 26% private cars, and 1% vehicles selected for testing. Driving behavior varies.

Description

This section summarizes the real-world fuel consumption and CO_2 data analyses conducted in the *From Laboratory to Road* studies focusing on Europe. A condensed version of the results published in the 2016 update of the series is presented here. The 2016 report was based on 13 data sources from seven European markets and included data on approximately 1 million private and company cars. Table 8 provides an overview of the samples used in the report.

The available data sources can be classified into the following three groups based on how data was collected: automatically recorded data from fuel card providers, user-submitted data from online fuel consumption tracking services, and data from on-road tests conducted by auto magazines and car clubs. Data sets from fuel card providers mostly include company cars, while user-submitted data predominantly cover private cars.

There are some sources of bias and transcription errors specific to each sample. Nevertheless, any biases are considered to be consistent over time and should not interfere with the observed trends. For a detailed description of each data source, see Tietge et al. (2016).

Table 3. Summary of data sources used for the 2016 *From Laboratory to Road* report.

Country	Source	On-road data collection	Total vehicles	Vehicles per year	Mostly company cars	Data availability	Dating convention
Germany	Spritmonitor.de	User-submitted; some information on driving style provided	134,463	~9,000		2001–2015	Build year
	LeasePlan	Fuel card system, fuel consumption automatically recorded	~180,000	~20,000	X	2006–2015	Fleet year
	AUTO BILD	Test route, fuel consumption measured before and after test drives	2,242	~280		2008–2015	Test date
	auto motor und sport	Test route, fuel consumption measured before and after test drives	1,885	~150		2003–2015	Test date

Country	Source	On-road data collection	Total vehicles	Vehicles per year	Mostly company cars	Data availability	Dating convention
United Kingdom	Allstar card	Recorded using fuel card	242,353	~24,000		2006–2015	Build year
	honestjohn.co.uk	User-submitted; no details on driving style	97,291	~6,500		2001–2015	Model year
	Emissions Analytics	Test route, Portable Emissions Measurement System testing	674	~170		2012–2015	Test date
Netherlands	Travelcard	Fuel card system, fuel consumption automatically recorded	275,764	~25,000	X	2004–2015	Build year
	Cleaner Car Contracts	Various data collection procedures	24,513	~3,500	X	2010–2015	Fleet year
France	Fiches-Auto.fr	User-submitted	23,559	~1,500		2001–2015	Model year
Spain	km77.com	Test route, fuel consumption measured before and after test drives	273	~45		2010–2015	Test date
Sweden	auto motor & sport	Test route, fuel consumption measured before and after test drives	643	~90		2009–2015	Test date
Switzerland	Touring Club Switzerland	Test route, fuel consumption measured before and after test drives	271	~20		1996–2015	Test date
Total			**~1,000,000**	**~90,000**			-

Methodology

Thirteen data sets were used to estimate the divergence between real-world and type-approval CO_2 emissions in the European market. The analysis of each of sample followed the methodology described in Section 1. A description of the exact methodology used for each data set can be found in Tietge et al. (2016).

A central estimate of the divergence between European type-approval and real-world CO_2 values was constructed by combining the 13 data sets. This process involved calculating the annual average divergence from all private car data sources. The same procedure was applied to company car data sets. Private and company car estimates were then combined with equal weights under the assumption that the European new car market consists of private and company cars in equal parts (Næss-Schmidt & Winiarczyk, 2010).

Results

Figure 15 shows the trend in the divergence between real-world and official CO_2 emission values for each European data source. All data sources— regardless of country, data collection methodology, or whether cars are privately or company owned—show a clear upward trend in the divergence over time. Estimates of the divergence were approximately 9% in 2001, but increased to between 35% and 61% in 2015.

The precise level of the gap varies by data source. Vehicle tests by car magazines and other organizations typically produce internally consistent data due to standardized measurement procedures, but different sources deliver quite dissimilar results due to differing test procedures and small data sets. In addition, despite precise data collection procedures, fluctuations in traffic and weather conditions may affect the consistency of the tests. These inconsistencies are considered to be of minor import when looking at trends. The three data sources that rely on user input produce comparable divergence estimates over the years despite covering different markets, namely Germany (Spritmonitor.de), the UK (honestjohn.co.uk), and France (Fiches-Auto.fr). Estimates of the divergence from web services range from 8% to 11% in 2001 to between 35% and 42% in 2015. Divergence estimates of company cars are typically among the highest because company car drivers have a weaker incentive to drive in a fuel-conserving manner, as employers usually cover fuel expenses. Estimates in 2015 ranged from 41% to 61% in 2015.

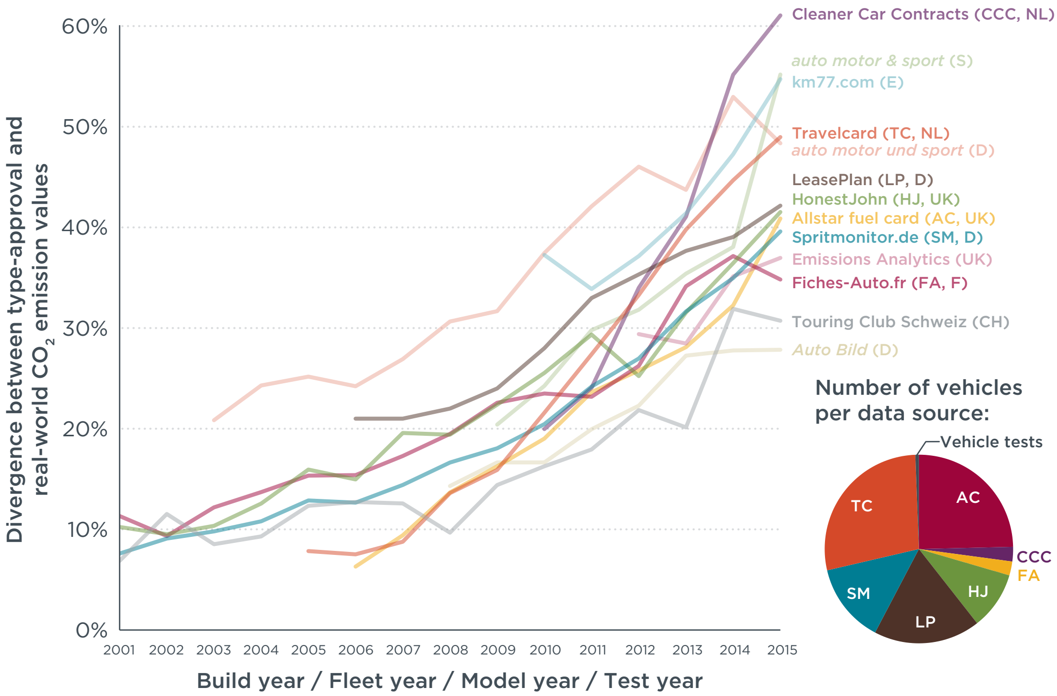


Figure 15. Divergence between type-approval and real-world CO_2 emissions for various European on-road data sources.

Figure 16 combines divergence estimates from different data sources and shows averages for private cars, company cars, and the total new vehicle market. Combining the 13 data sources, the divergence increased from 9% in 2001 to 42% in 2015. Over that time, company cars consistently exhibited a higher average divergence than private cars, as noted above. In 2015, the average estimate of the divergence from company cars amounted to 45%, five percentage points higher than the private car average.

Considering that the data sources cover different European markets, include private and company cars, and follow differing data collection procedures, the central estimate should be viewed as strong evidence of a systemic, growing divergence between real-world and official CO_2 emission values. Estimates of the divergence vary from source to source, but aggregating data on almost 1 million cars reveals a consistent increase in the divergence over time that seems to affect all European markets alike.

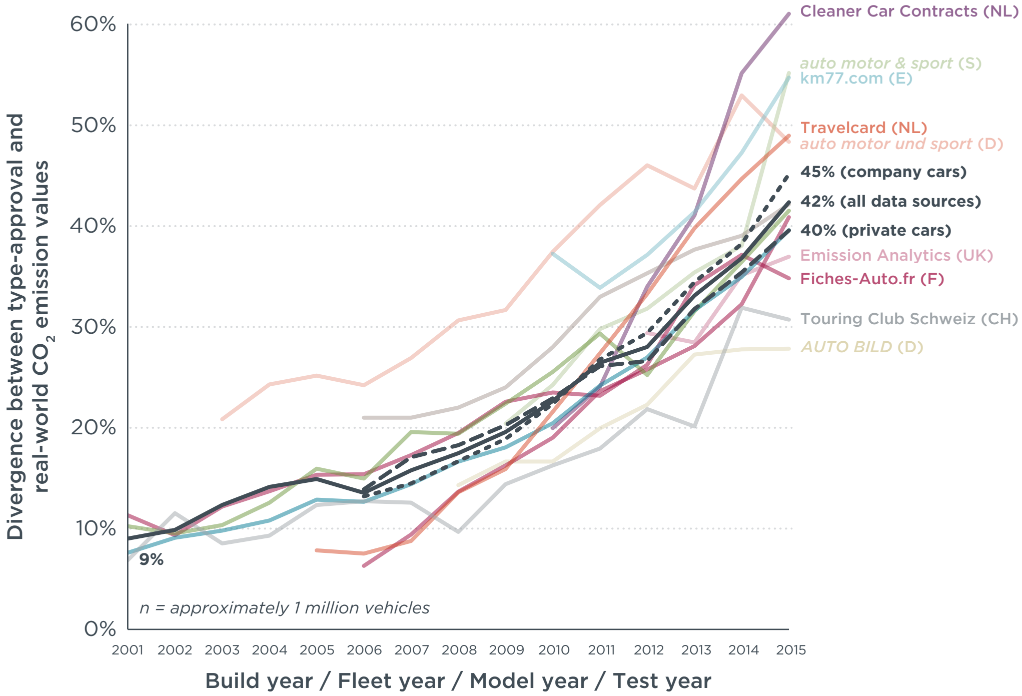


Figure 16. Divergence between type-approval and real-world CO_2 emissions for various European real-world data sources, including average estimates for private cars, company cars, and all data sources.

4.2 UNITED STATES: FUELECONOMY.GOV

Data source	https://www.fueleconomy.gov/mpg/MPG.do
Data type	On-road, user-submitted
Data availability	Model years 2001–2014, approximately 3,000 vehicles per model year
Data collection	Fuel economy data entered by vehicle drivers into a publicly available online database
Fleet structure, driving behavior	City and highway driving, some information on driving conditions and fuel costs

Description

FuelEconomy.gov[4] is the official U.S. government online source for fuel economy information. The site is maintained by the U.S. Department of Energy with data provided by the U.S. EPA. FuelEconomy.gov helps consumers make informed fuel economy choices when purchasing vehicles and advises them on how to drive more efficiently. The website provides EPA fuel economy ratings for passenger cars and trucks, user-provided real-world fuel economy estimates, and extensive information on current fuel and technology trends. Real-world fuel economy estimates are collected through MyMPG, a tool embedded in FuelEconomy.gov that allows users to track their fuel economy and compare it with EPA label values and input from other drivers. The service currently has more than 100,000 active users.

MyMPG enables users to track their fuel economy values using one of two methods. They can enter fuel log data, including odometer readings and fuel quantity, and MyMPG automatically calculates the fuel economy for a driving period. Alternatively, they can directly enter fuel economy estimates calculated by them or obtained from the vehicle's digital dash readout. For the first method, users are requested to fill the vehicle's gas tank completely and write down odometer readings each time they refuel the car. Once two readings are entered, the tool can calculate fuel economy. Users can also add information on fuel cost and driving conditions to each record. Driving conditions are reported as the shares of city and highway driving.

Methodology

The FuelEconomy.gov sample initially consisted of two different real-world fuel economy data sets, reflecting the method chosen by the user to enter the data. The first group consisted of fuel log data from more than 37,000 vehicles. The second group contained fuel economy estimates calculated by users for more than 46,000 vehicles. Fuel consumption values from the first group were estimated by evaluating the longest sequence of valid fuel-up data for each vehicle. After calculating fuel consumption estimates for the first group and converting fuel economy values from the second group to fuel consumption values, both data sets were combined.

For each vehicle in the combined data set, the divergence between real-world and official fuel consumption was calculated using both the CAFE and U.S. EPA label values as denominators. The U.S. EPA changed the methodology used to estimate fuel economy starting with MY 2008 (see Section 2.4), so divergence values for both types of label values are presented in the analysis. Extreme divergence estimates resulting from transcription errors were removed using Peirce's criterion.[5] In total, 43,000 out of 83,000 vehicles remained after removing approximately 14,000 vehicles with invalid fuel log data, roughly 3,000 vehicles with missing fuel economy values, approximately

4 See http://fueleconomy.gov. The complete data set was generously provided by Rick Goeltz and Janet Hopson of the Oak Ridge National Laboratory.

5 For more information on Peirce's criterion, see Tietge, Mock, Franco, & Zacharof (2017).

20,000 vehicles from before model year 2001, and less than 1,000 vehicles with unrealistic divergence estimates.

Because MyMPG users enter fuel consumption data on a voluntary basis, there is a risk of self-selection bias in the data (although any bias should be reasonably consistent over time, so trends should be reasonably accurate). For instance, the service may attract consumers who are particularly concerned about fuel economy. Greene et al. (2015) analyzed the MyMPG data as of mid-2015 and compare MyMPG vehicles to new cars registered in the United States. The comparison provides a rough indication of the sample representativeness. Table 4 presents Greene et al.'s (2015) findings together with a summary of the MyMPG sample at hand. As illustrated in the table, passenger cars (excluding SUVs) appear to be overrepresented in the MyMPG sample, while the remaining vehicle types are somewhat underrepresented.

Table 4. Comparison of MyMPG shares by vehicle type to market shares (based on: Greene et al., 2015).

	New vehicles as a share of production			MyMPG (Greene et al., 2015)	MyMPG (this study)
	MY 2000–2014			MY 2000–2014	MY 2001–2014
Vehicle type	**Mean**	**Min**	**Max**	**Mean**	**Mean**
Car	52.70%	47.70%	60.50%	67.56%	64.48%
SUV	27.70%	18.90%	17.72%	17.72%	22.93%
Pickup	13.40%	10.10%	10.42%	10.42%	8.39%
Minivan/van	6.20%	3.80%	10.20%	4.30%	4.20%

In addition to the comparison based on vehicle types, average vehicle specifications of MyMPG cars are compared with sales data for model year 2014 in Table 5. While the average capacity and number of cylinders of the MyMPG sample are in line with the market average values, diesel and hybrid cars are significantly overrepresented. As a result, average CO_2 emissions of the MyMPG data set are roughly 20% lower than the average of new 2014 cars. These figures indicate that diesel vehicle and HEV owners are more likely to use a web service such as MyMPG.

Table 5. Comparison of average characteristics of MyMPG and new passenger cars in model year 2014 (source of sales data: U.S. EPA, 2015b).

Source	Model year	Capacity (l)	No. cylinders	Diesel (%)	Automatic transmission (%)	HEV (%)	CO_2 (g CO_2/km)
MyMPG	2014	2.2	4.3	8.0%	86%	22.1%	136
Sales	2014	2.4	4.5	1.3%	96%	4.2%	167

Results

Figure 17 shows the trend in the divergence between real-world and official CO_2 emission values based on CAFE and U.S. EPA label values.[6] Taking the former as a reference, the divergence increased from around 16% in MY 2001 to 34% in MY 2015 for all light-duty vehicles, and from 14% to 31% for cars only. U.S. EPA label values more accurately reflect real-world fuel consumption figures, but the divergence between U.S. EPA and real-world fuel consumption also increased over time. Before MY 2008, U.S. EPA label values were calculated using a flat adjustment factor for the city and highway fuel economy values (see Section 2.4). The divergence between real-world fuel consumption and the U.S. EPA label values therefore consistently lies about 17 percentage points below the CAFE divergence, increasing from roughly –1% in MY 2001 to 4% in MY 2007. The new U.S. EPA label methodology, the five-cycle method, produces the most realistic fuel consumption values in recent years, with divergence estimates ranging from approximately –8% in MY 2008 to close to no divergence MY 2015.

6 Results are presented in terms of fuel economy in Appendix I.

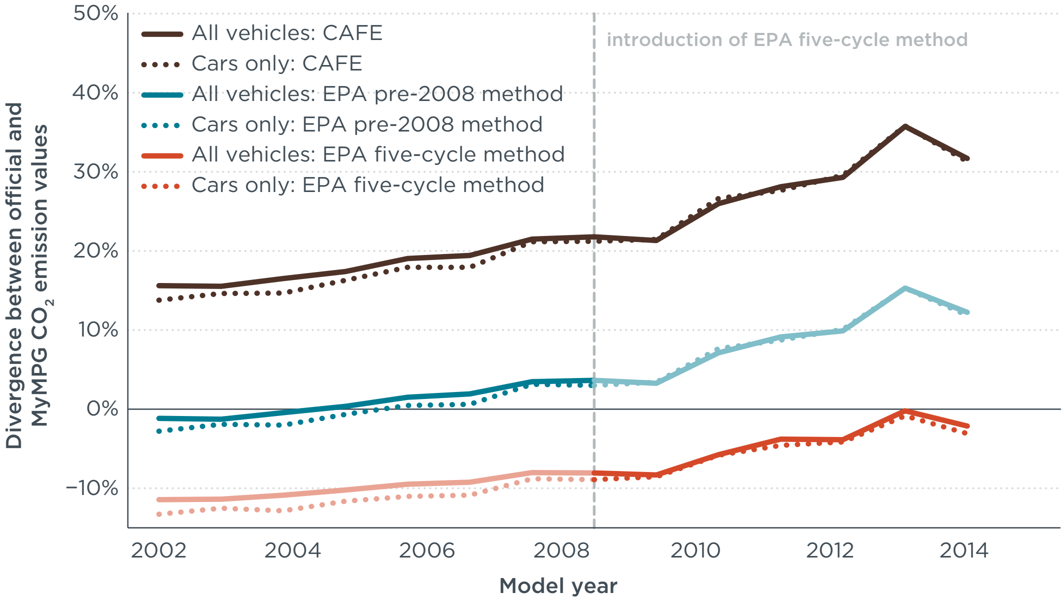


Figure 17. Divergence between MyMPG and official CO_2 emission values for light-duty vehicles and cars. Official CO_2 values include CAFE figures and EPA label values.

Figure 18 shows the development of the divergence between real-world and CAFE values for different powertrains.[7] The lines represent the development of the real-world divergence for cars including and excluding hybrid electric vehicles (HEVs). HEVs consistently have higher average divergence values than conventional powertrains, as witnessed by the higher divergence for both CAFE and U.S. EPA values when including HEVs. For CAFE values, the difference between including and excluding HEVs reached four percentage points in model year 2015, when HEVs accounted for approximately 11% of the cars in the data set. Diesel cars were not plotted separately due to the low share (less than 5% of cars in the sample) and the likelihood of overstated real-world fuel economy due to the VW defeat devices. The results show that the 2008 fuel economy label method significantly reduced the gap for HEVs compared with other vehicles.

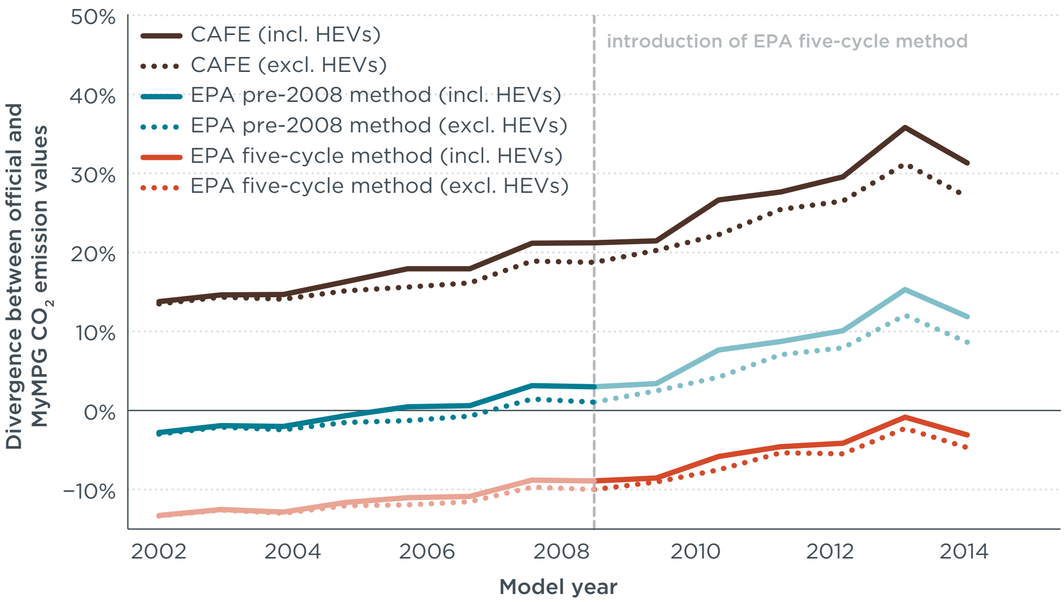


Figure 18. Divergence of MyMPG from official CO_2 emission values by powertrain. Official CO_2 values include CAFE figures and EPA label values.

7 Results are presented in terms of fuel economy in Appendix I.

Figure 19 shows the average divergence between FuelEconomy.gov and CAFE fuel consumption values by data collection method. The first two bars refer to fuel log data, one based on cumulative odometer readings ("odometer"), the other based on incremental distance readings ("trip"). The last two bars show the divergence according to estimates entered directly by users, including fuel consumption values measured by the vehicle's onboard computer ("digital readout") and fuel consumption values calculated by the user ("mathematical"). The figure shows that fuel log data generally provides higher divergence estimates than when users directly input real-world fuel estimates.

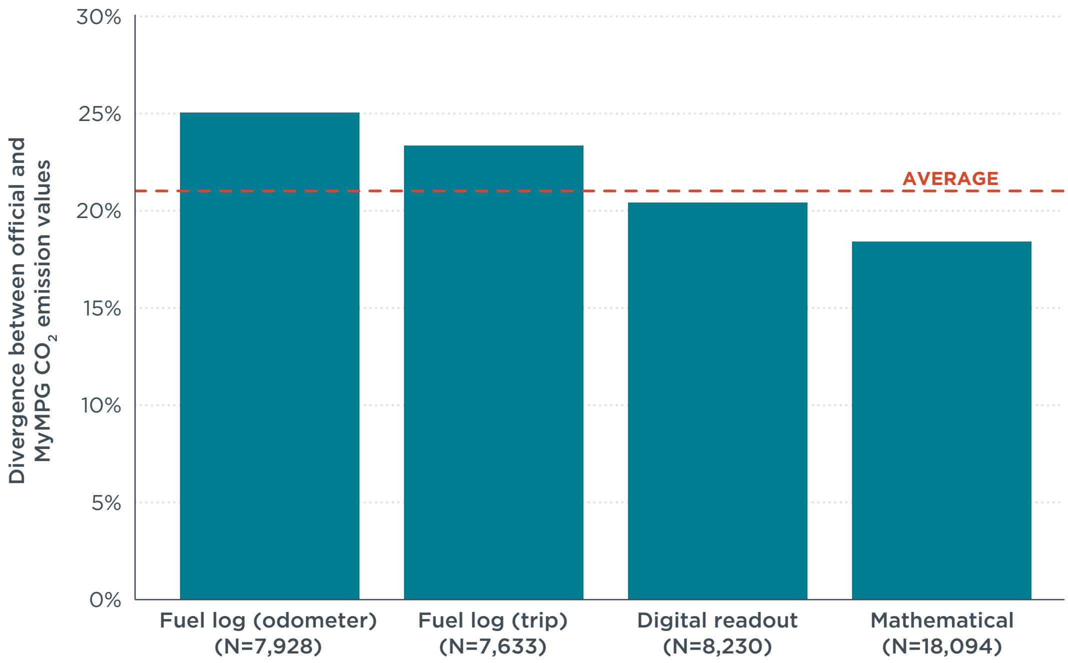


Figure 19. Divergence between MyMPG and CAFE CO_2 emission values by data entry method.

4.3 CHINA: XIAOXIONGYOUHAO

Data source	http://www.xiaoxiongyouhao.com/
Data type	On-road, user-submitted
Data availability	2005–2015, approximately 50,000 vehicles per model year
Data collection	Fuel consumption data entered by vehicle drivers into an online database using a mobile app
Fleet structure, driving behavior	Urban and extra-urban driving

Description

XiaoXiongYouHao[8] is a Chinese mobile application that allows users to track and compare their fuel consumption. The app was launched in 2010 and has more than 2.5 million downloads in China. XiaoXiongYouHao publishes periodic reports analyzing the real-world fuel consumption data to help policy makers and consumers make better-informed decisions.

To start using the XiaoXiongYouHao application, drivers are requested to select their vehicle model version. Users then log fuel volume and odometer readings and indicate whether the tank is full after refueling. The application calculates fuel consumption based on the reported fuel volume and vehicle mileage once sufficient data has been entered. A typical user records more than 20 fueling events.

Methodology

The XiaoXiongYouHao data set included information on approximately 7,000 vehicle model variants with model years ranging from 2003 to 2016. More data points were available for recent years because the Chinese markets for both vehicles and smartphones grew during the measured time frame. For each vehicle model variant, the sample included information on the model year, engine specifications, transmission type, vehicle segment, average on-road and official fuel consumption, and number of vehicles. After filtering the data set for missing values and removing model years 2003 and 2004 as they included fewer than 500 vehicles per year, a sample of about 490,000 vehicles remained, with model years ranging from 2005 to 2015. Outlier removal was not deemed necessary as no erroneous data points were identified using Peirce's criterion.

Because XiaoXiongYouHao users record fuel consumption data on a voluntary basis, there is a risk of self-selection bias. To assess the sample representativeness, Table 6 compares average fleet parameters with the corresponding average values of newly registered passenger vehicles in China in 2014. In addition, Figure 20 compares the XiaoXiongYouHao sample with the 2014 Chinese new car fleet in terms of segment shares. Since the XiaoXiongYouHao data set uses model year, and market data was only available by registration year, 2014 sales data were compared to XiaoXiongYouHao segment shares and fleet specifications averaged over model years 2011 to 2014, under the premise that new registrations mainly consist of vehicle models released during the four years preceding the date of purchase.

As illustrated in Table 6, the average engine power, engine capacity, and type-approval fuel consumption values of the XiaoXiongYouHao sample match the 2014 new fleet average values very closely. The share of automatic vehicles in the sample is slightly higher than the 2014 new fleet share, whereas the opposite is true for the average vehicle mass. The discrepancy in the mass values is consistent with the

8 See http://www.xiaoxiongyouhao.com. The complete data set was generously provided by the data proprietor.

overrepresentation of small and lower medium cars in the XiaoXiongYouHao sample, as shown in Figure 20. The XiaoXiongYouHao sample is generally somewhat skewed toward smaller vehicles, with medium and MPV segments underrepresented. Despite these deviations, on the whole the sample appears to provide a reasonable reflection of the Chinese new vehicle market.

Table 6. Comparison of vehicle characteristics in the XiaoXiongYouHao sample (model years 2011 to 2014) and new passenger vehicles for sales year 2014 (source: data provided by Segment Y).

Source	Year	Engine power (kW)	Engine displacement (l)	Fuel consumption (l/100km)	Curb weight (kg)	Automatic transmission (%)
XiaoXiongYouHao	Model years 2011–2014	99	1.7	7.1	1343	60%
Sales data	Sales year 2014	101	1.7	7.3	1376	56%

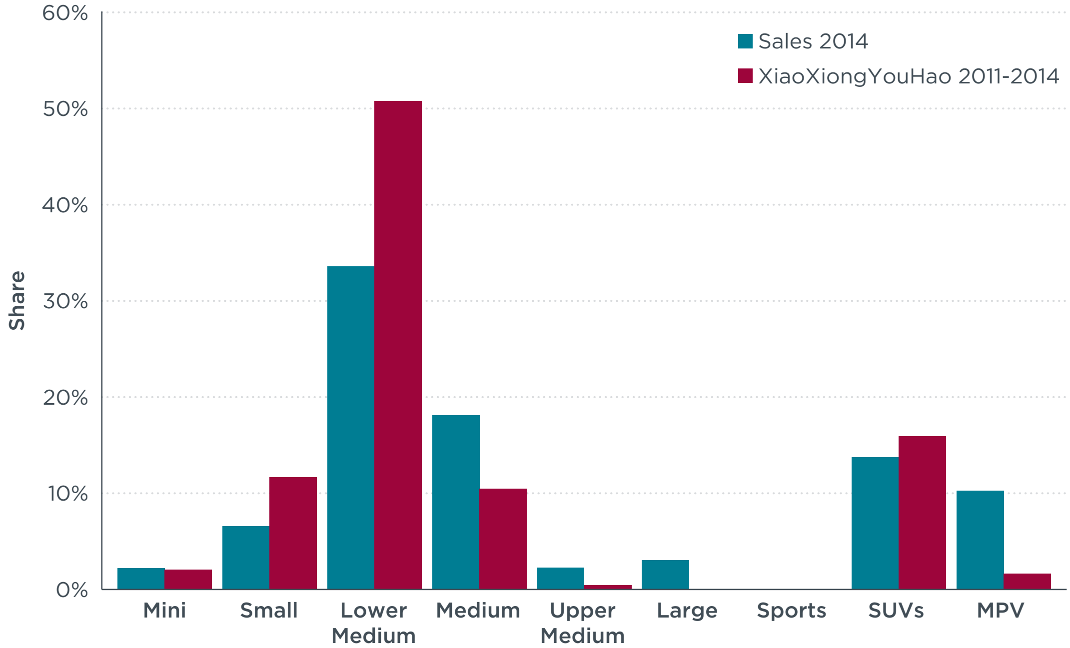


Figure 20. Segment shares in the XiaoXiongYouHao sample (model years 2011–2014) and Chinese vehicle sales for sales year 2014 (source: data provided by Segment y).

Another potential bias should be acknowledged: XiaoXiongYouHao users enter data using smartphones. Use of smartphone apps for fuel expense recording may be more prevalent in urban areas, leading to an overrepresentation of city driving in the XiaoXiongYouHao sample and potential overestimation of real-world fuel consumption. Nevertheless, if such a bias were present in the data, we would expect more pronounced differences between average vehicle characteristics in the XiaoXiongYouHao data and official registration statistics, assuming that average vehicle characteristics differ depending on where they are purchased.

Results

Figure 21 plots the development in the average divergence between XiaoXiongYouHao and official CO_2 emission values by transmission type. Model years with less than 5,000 vehicles are plotted using sparsely dotted lines.

According to the XiaoXiongYouHao sample, the average divergence between real-world and type-approval CO_2 emissions increased by around 15 percentage points between MY 2008 and MY 2015, reaching 27% in model year 2015. As Figure 21 shows, the divergence increased for both automatic and manual transmission cars, and vehicles with automatic transmissions consistently exhibited a higher divergence than vehicles with manual transmissions. Until MY 2013, the shares of automatic and manual transmission vehicles were balanced. From MY 2014 on, automatic vehicles clearly outnumbered those with manual transmission, and in MY 2015 they made up 67% of the XiaoXiongYouHao fleet.

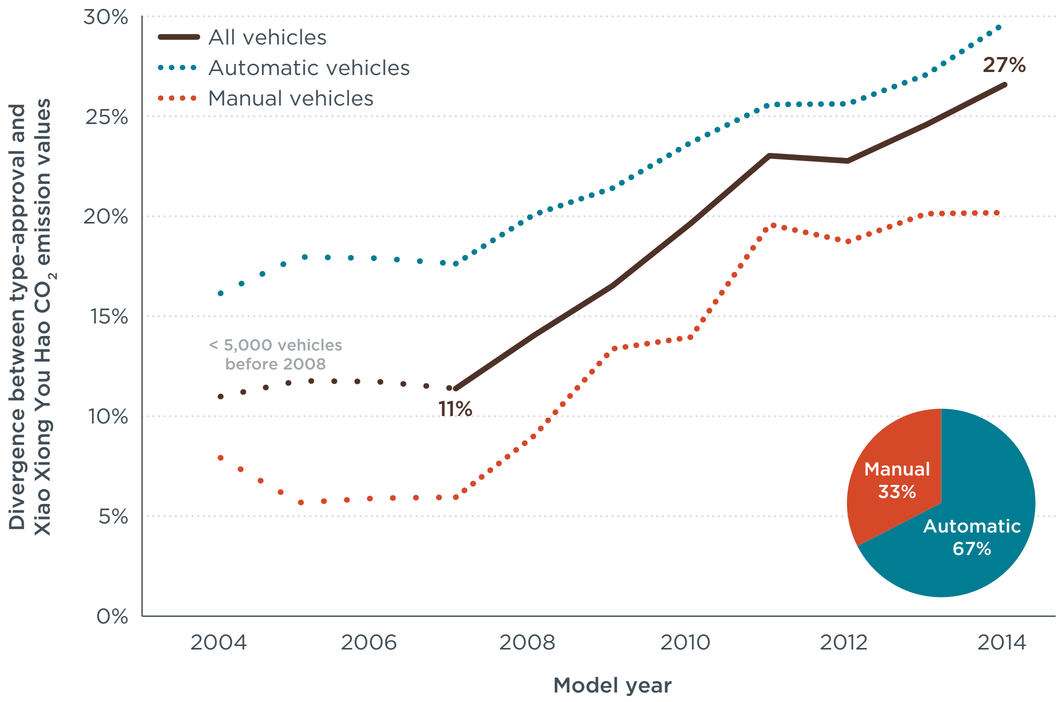


Figure 21. Divergence between XiaoXiongYouHao and official CO_2 emissions by transmission type (pie chart indicates the share of vehicles per transmission type in the data set for model year 2015).

4.4 JAPAN: E-NENPI.COM

Data source	www.e-nenpi.com
Data type	On-road, user-submitted
Data availability	Data from 2001 to 2014, approximately 3,000 vehicles per year
Data collection	Fuel economy data entered by vehicle drivers into a publicly available online database
Fleet structure, driving behavior	Unknown

Description

Data from the Japanese web service e-nenpi.com was used to estimate the gap between official and real-world fuel consumption values in Japan. The web service allows users to monitor their fuel consumption by entering fuel quantity and odometer readings. More than 80,000 vehicles have been added to e-nenpi.com.

Methodology

The e-nenpi.com sample included approximately 20,000 observations. Each observation contains one year of data for a given model version.[9] Because different vehicles of a model version may have entered and left the database over time, and data was delivered aggregated by model version and calendar year, the number of vehicles in the sample was estimated. In total, more than 47,000 cars from model years 2001 to 2014 were analyzed. Since data was delivered in aggregated form, outlier detection was not performed for individual vehicles, but data for vehicle models were validated using Peirce's criterion. A detailed methodology is provided in Appendix II.

To evaluate the representativeness of the e-nenpi.com sample, segment shares of the e-nenpi.com fleet were compared with those of the 2014 new car fleet in Japan. In the absence of market data by model year, which is the dating convention of the e-nenpi.com sample, it was assumed that the new fleet is comparable to e-nenpi.com segment shares averaged over model years 2011 to 2014. In addition, average vehicle specifications of Japan's 2011 passenger vehicle fleet were compared to the specifications provided in the e-nenpi.com data set averaged over model years 2008 to 2011. A comparison for more recent years was not possible due to data availability. Segment information was not provided in the e-nenpi.com data set. Vehicle model names were thus translated from Japanese to English, and the data set was joined with external data that contained the required segment information.

Figure 22 shows that segment shares of new 2014 vehicles decrease as vehicle size increases. The mini segment stands out with a 40% share of new registrations. The mini segment consists mainly of Kei cars, a category specific to the Japanese vehicle market that is strongly incentivized by the government (German, 2015). In the e-nenpi.com data set, however, the share of mini cars only amounts to roughly 20%. While the sample shares of small, upper medium, and large vehicles match with the respective shares of new vehicles sold in 2014, the lower medium and medium segments are significantly overrepresented. These findings are in line with the comparison presented in Table 7. The average capacity and HEV share of the e-nenpi.com data set are higher than those of the 2011 fleet. The share of HEVs in the Japanese market started increasing in 2009 (Rutherford, 2014), and the most popular HEV models, such as the Toyota Prius, belong to the lower medium and medium segments.

9 A model version was defined as a unique combination of vehicle brand, model name, model year, and a number of powertrain characteristics.

Table 7. Comparison of vehicle characteristics in the e-nenpi.com sample (model years 2008-2011) and Japan's 2011 passenger vehicle fleet.

Source	Year	Engine capacity (l)	HEV (%)	Transmission (%)			Driven wheels (%)		
				Man.	Aut.	CVT	All	Front	Rear
e-nenpi	Model year 2008-2011	1.6	27.8%	7%	26%	67%	17%	78%	4%
Sales data	Fleet year 2011	1.4	13.0%	1%	34%	65%	36%	59%	5%

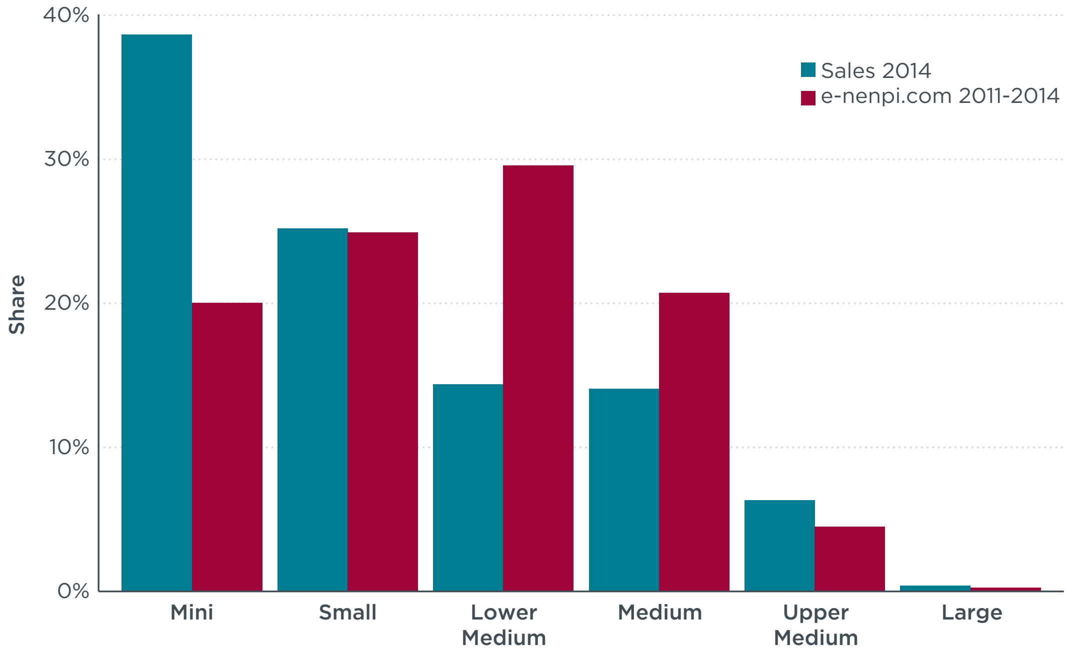


Figure 22. Share of new passenger vehicles in Japan in 2014 by segment vs. segment shares in the e-nenpi data set for model years 2011 through 2014.

In short, the e-nenpi.com sample is skewed towards mid-sized cars, whereas Japan's unique Kei segment is significantly underrepresented. In addition, the size of the sample is relatively small, which further undermines the statistical significance of the analysis. Nevertheless, this study is among the first to tackle the divergence between official and real-world CO_2 emissions in the Japanese vehicle market and serves as a basis for subsequent research.

Results

Figure 23 presents the development of the average divergence between official and e-nenpi.com fuel consumption values over vehicle model years.[10] While the divergence between 10-15 mode values and e-nenpi.com data is more or less constant during the model years 2001 through 2007, there is a noticeable increase after 2007. The increase is also noticeable in the JC08 data. This development followed the introduction of the 16.8 l/km (5.9 l/100 km) fuel economy target for 2015, which was agreed on in 2007, and subsidies for vehicles exceeding the 2010 fuel economy standard by 15% or more, which were introduced in 2009 (see Section 2.6 for details on fuel economy targets).

10 Results are presented in terms of fuel economy in Appendix I.

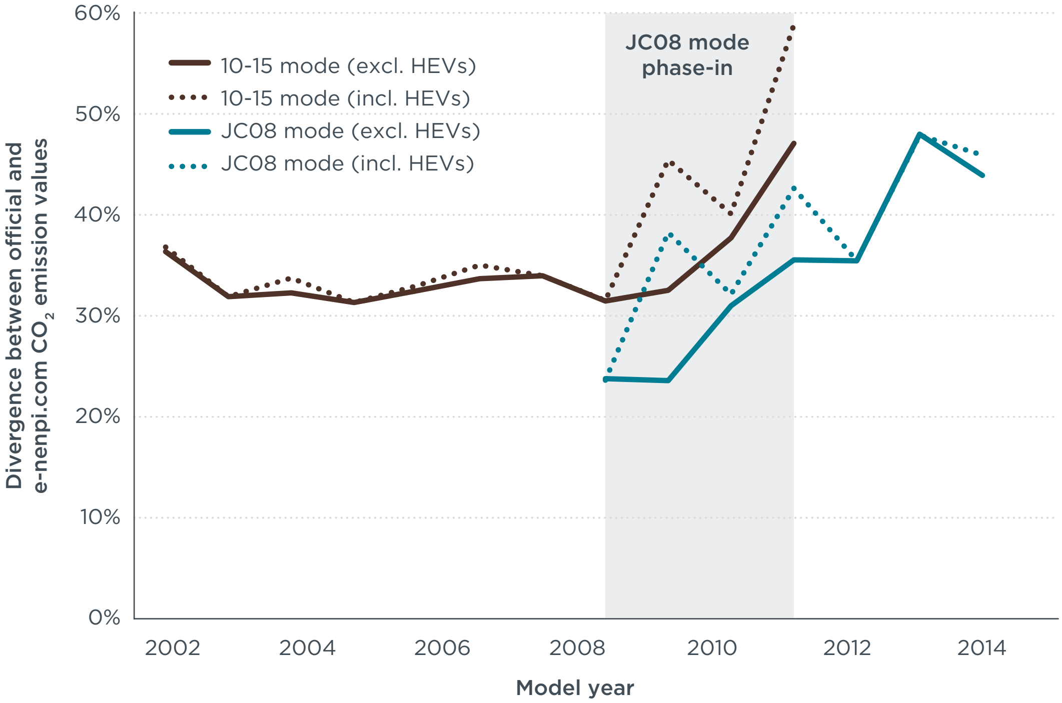


Figure 23. Divergence between official and e-nenpi.com CO_2 emission values for different vehicle model years.

Figure 24 compares the average divergence between e-nenpi.com values and the two test cycles, the 10-15 mode and the JC08, and distinguishes between conventional powertrains and hybrid electric vehicles. Only vehicles with both 10-15 mode and JC08 fuel consumption values were included in the graph, the vast majority of which were of model years 2008 to 2011, so the difference between the different gap estimates is directly attributable to the differences between the two test cycles. The figure illustrates that the 10-15 mode generally delivered less realistic fuel consumption values: for conventional powertrains, the divergence was almost nine percentage points higher using the 10-15 mode. For HEVs, this difference is even more pronounced, with the 10-15 mode gap exceeding the JC08 gap by approximately 20 percentage points.

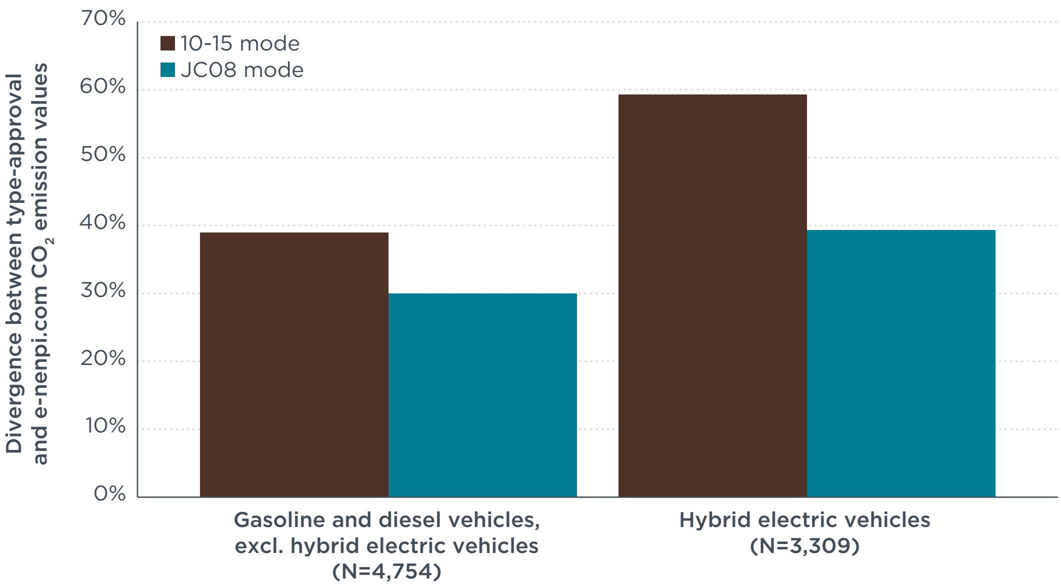


Figure 24. Divergence between official and e-nenpi.com CO_2 emission values for different powertrains.

4.5 DATA COMPARISON

Table 8 provides an overview of the data sources used in the analysis. In total, the analysis covers more than 1.5 million vehicles from 2001 to 2014.

Table 8. Summary of data sources used in the analysis.

Region	Data source	Total vehicles	Vehicles per year	Dating convention
China	XiaoXiongYouHao	~490,000	~50,000	Model year
EU	13 data sources	~1,000,000	~90,000	Various
Japan	e-nenpi.com	~47,000	~3,000	Model year
United States	FuelEconomy.gov	~41,000	~3,000	Model year
Total	-	**~1.6M**	**~146,000**	-

Figure 25 plots the divergence between real-world and official CO_2 emission values of passenger cars in the four regions covered in the analysis, revealing substantial differences between the markets. According to e-nenpi.com data, Japan is the market with the highest divergence. In contrast, EPA label values provide the most realistic CO_2 values. Between these two extremes, U.S. CAFE and EU and China NEDC values all exhibit growing gaps between declared and on-road CO_2 emission values, which increase from an 8% to 14% range in 2001 to a 25% to 40% range in 2014. The growth in the gap is considerably less pronounced in the United States than in the EU and in China.

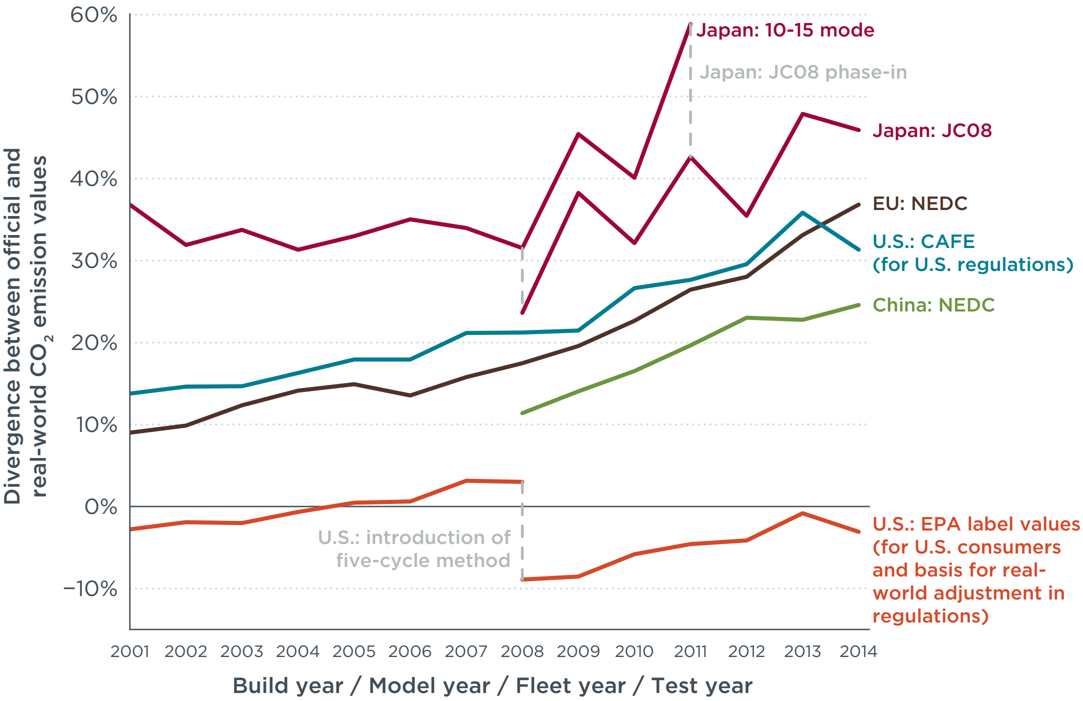


Figure 25. Divergence between official and real-world CO_2 emissions for new passenger cars in the EU, the United States, China, and Japan.

Figure 26 plots the 2014 estimates of the gap. The estimates for the four regions are the same as the 2014 values in Figure 25, but are also presented in fuel economy terms. As fuel consumption and fuel economy are inversely related, the curve representing the relationship between the fuel consumption gap and fuel economy shortfall is convex to the origin.

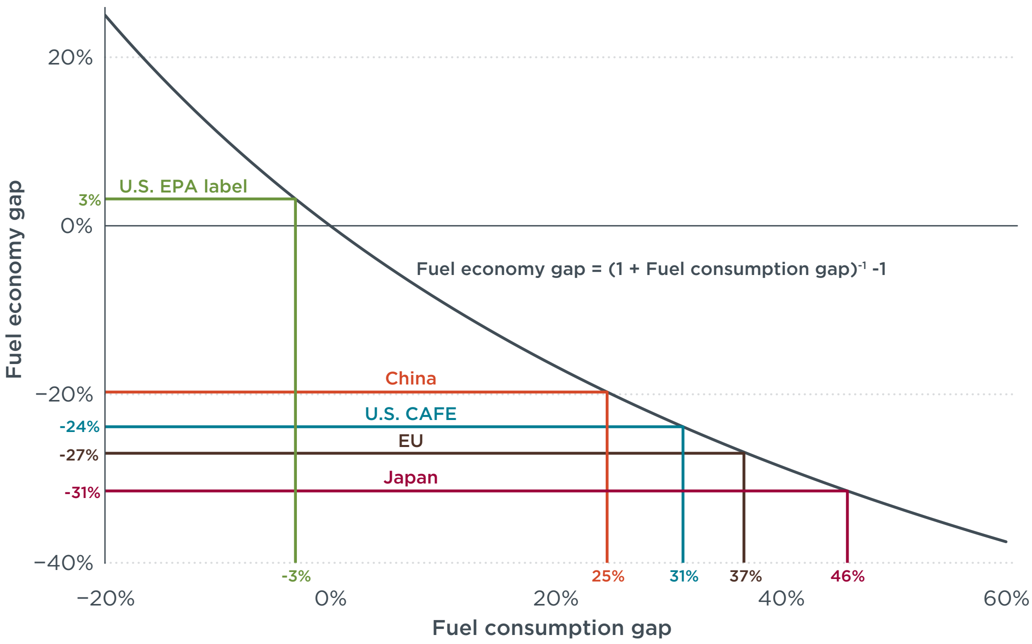


Figure 26. 2014 estimates of the divergence between official and real-world fuel consumption and fuel economy values in different regions.

Figure 27 focuses on the increase in the gap and plots the compound annual growth rate (CAGR) for different regions and time periods. Between 2001 and 2014, the annual growth rate in the EU (13% CAGR) is roughly twice as high the one observed in the U.S. market (7% CAGR). The gap in Japan is the most stable when comparing 2001 and 2014 values (2% CAGR). This metric is not available for China because on-road data only reaches back to 2005.

Focusing on the 2008 to 2014 time frame reveals additional information. China has the highest annual growth in divergence, followed by the EU. Both markets use test procedures based on the NEDC. The EU also exhibits a noticeably higher annual growth rate during the 2008 to 2014 time frame than during the 2001 to 2014 period. This change indicates that the gap grew quicker after the 2008 agreement on the first European CO_2 standards. In contrast, the United States had slightly lower annual growth rates for 2008-2014. As the United States had flat standards for cars from 2001 to 2010 and increasing standards starting in 2011, this means that the gap increased faster when standards were not changing than when they did change—exactly the opposite from Europe. The Japanese JC08 values show a substantial increase between 2008, the year the new test procedure was introduced, and 2014.

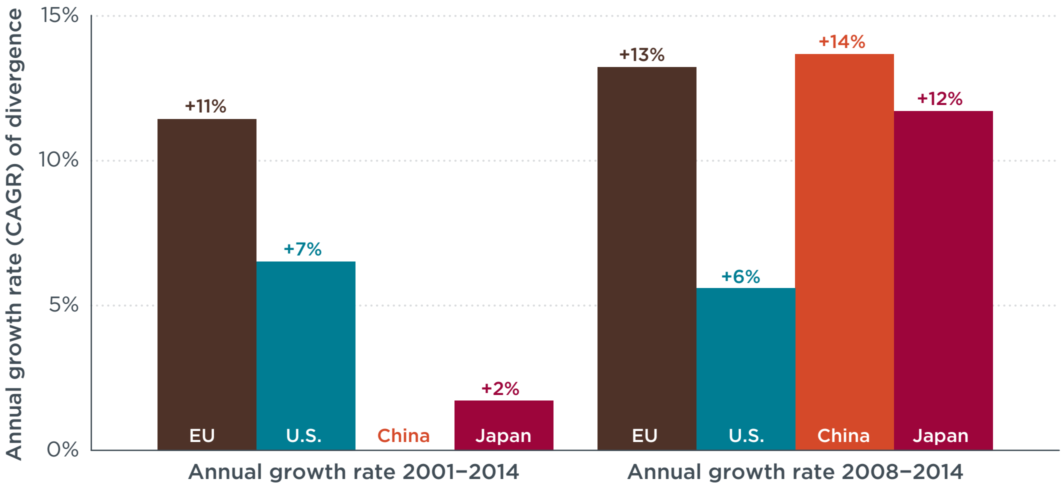


Figure 27. Annual growth rates (CAGR) of the divergence between official and real-world CO_2 emissions for various regions (expressed as % growth of gap).

5. DISCUSSION

5.1 COMPARISON OF RESULTS AND PREVIOUS RESEARCH

This study is not the first attempt to analyze on-road fuel consumption data from the foregoing four vehicle markets. The results for Europe were extracted from previous *From Laboratory to Road* studies by the ICCT (e.g., Tietge et al., 2016), and the analyses for the other regions followed in other researchers' footsteps. For the United States, our results closely match findings by Greene et al. (2015), who also analyzed the MyMPG data from FuelEconomy.gov. Both the level and pattern in the CAFE gap appear congruent. For China, Ding et al. (2015) also analyzed data from XiaoXiongYouHao and gap estimates closely match our results, with the largest difference between annual estimates being three percentage points. Lastly, there is less research to compare to for Japan, but our findings are similar to results from Kudoh (2012), with both studies pointing to a gap of roughly 30% for the 2001 to 2004 time frame. Our results do not match the dramatic increase in the gap, from 40% in 1995 to 63% in 2005, that Schipper (2008) estimated, although it should be noted that these numbers are based on market-wide fuel sales rather than measuring the fuel consumption of individual vehicles. The former method is susceptible to systemic errors in the input data (Schipper et al., 1993). Nevertheless, more research and data is needed to establish reliable real-world fuel consumption values for the Japanese market. Taken together, the findings presented in this study are generally in line with previous research, indicating that the methodological approach and data used in this analysis are sound and confirming results from preceding studies.

5.2 REASONS FOR GROWING DIVERGENCE ESTIMATES

A detailed discussion of the underlying reasons for the growing divergence between official and on-road CO_2 emission values is outside the scope of the study, but some common reasons are discussed below.

5.2.1 Decreasing official CO_2 values

A frequently cited reason for the increasing gap is the global decrease in official CO_2 values, which makes a constant absolute g/km difference between real-world and type-approval values proportionately larger.[11] This factor was determined to be of minor import in the EU, where the decrease in type-approval CO_2 values accounts for less than one-tenth of the increase in the gap between 2001 and 2015 (see Tietge et al., 2016, section 4). Replicating this calculation for the United States indicates that roughly one-fifth of the increase in the gap between model years 2001 and 2014 may be due to declining CO_2 values.[12] In China, this effect may explain roughly one-tenth of the increase in the gap from 2008 to 2014.[13] In Japan, there are some indications that decreasing official fuel consumption values are one of the drivers of the growing gap: The absolute gap in Japan decreased from 2001 to 2014.[14] This development is mainly due to the fact that Japan had a comparatively high divergence to begin with (37%), and saw a drop of more than 40% in official fuel consumption values from 2001 to 2014. Because

11 In reality, while there may be a component of the gap that has a constant absolute g/km difference, most of the gap is proportional. Thus, this methodology overstates the impact of decreasing official CO_2 values on the gap.

12 According to NHTSA data (U.S. EPA, 2015b), average fuel consumption of U.S. cars decreased from 8.2 l/100 km (28.8 mpg) in model year 2001 to 6.5 l/100 km (36.4 mpg) in MY 2014. The absolute gap in MY 2001 was 14% × 8.2 l/100 km ≈ 1.1 l/100 km according to MyMPG data. If this absolute offset had remained constant, the divergence in MY 2014 would have been roughly 17%. Instead, the observed gap that year was 31%.

13 Average official CO_2 values of new passenger cars in China decreased from 185 to 169 g CO_2/km from 2008 to 2014. At the same time, the gap increased from 11% to 25%. The 2014 gap would have been 12% if the absolute offset had remained stable since 2008.

14 Average fuel consumption of cars in Japan decreased from 7.9 l/100 km in 2001 to 4.6 l/100 km in 2014, where both values are normalized to the JC08. According to e-nenpi.com data, the absolute gap in 2001 was 37% × 7.9 l/100 km ≈ 2.9 l/100 km. If this gap had remained constant until 2014, the observed divergence in MY 2014 would have been higher than the observed gap of 46% (or 2.1 l/100 km in absolute terms).

of the limited Japanese real-world data at hand, more study of this development is recommended. On the whole, while these calculations do not provide definitive evidence of the influence of decreasing official CO_2 values on the gap, they indicate that this effect is not the predominant driver of the growing divergence in the EU, the United States, and China, although it may be at least a contributing factor, especially in Japan.

5.2.2 Driver behavior

Driver behavior is also cited as a reason for the growing gap in some markets. Self-reported data on driving behavior is available for two data sources in this study, namely Sprimonitor.de (EU) and FuelEconomy.gov (United States), and both data sets confirm that driving behavior affects on-road fuel efficiency. The Spritmonitor.de data indicates that economical driving reduces the gap by approximately nine percentage points compared with balanced driving, while speedy driving increases the gap by 7 percentage points compared with a balanced driving style. However, different driving styles did not account for the increase in the gap over time, as the share of different driving styles remained fairly constant and all driver types experienced an increase in gap estimates over time (Tietge et al., 2016). An extensive regression model developed by Greene et al. (2015) indicates that driving style significantly affected on-road fuel economy. For gasoline vehicles, cautious drivers improved their fuel economy by 9% to 10% (8% to 9% decrease in fuel consumption) compared with the most aggressive drivers. More importantly, however, the shares of self-reported driving styles remained fairly constant over time (see Figure 28). While it is possible that other developments (e.g., increased speed limits, increased opportunity costs of driving, increased vehicle performance, etc.) may affect all driving styles alike, the self-reported data on FuelEconomy.gov indicates that driving behavior does not account for the increasing gap. Taken together, self-reported data on driving behavior from the EU and United States suggest that changes in driving styles do not account for the growing gap in the two regions.

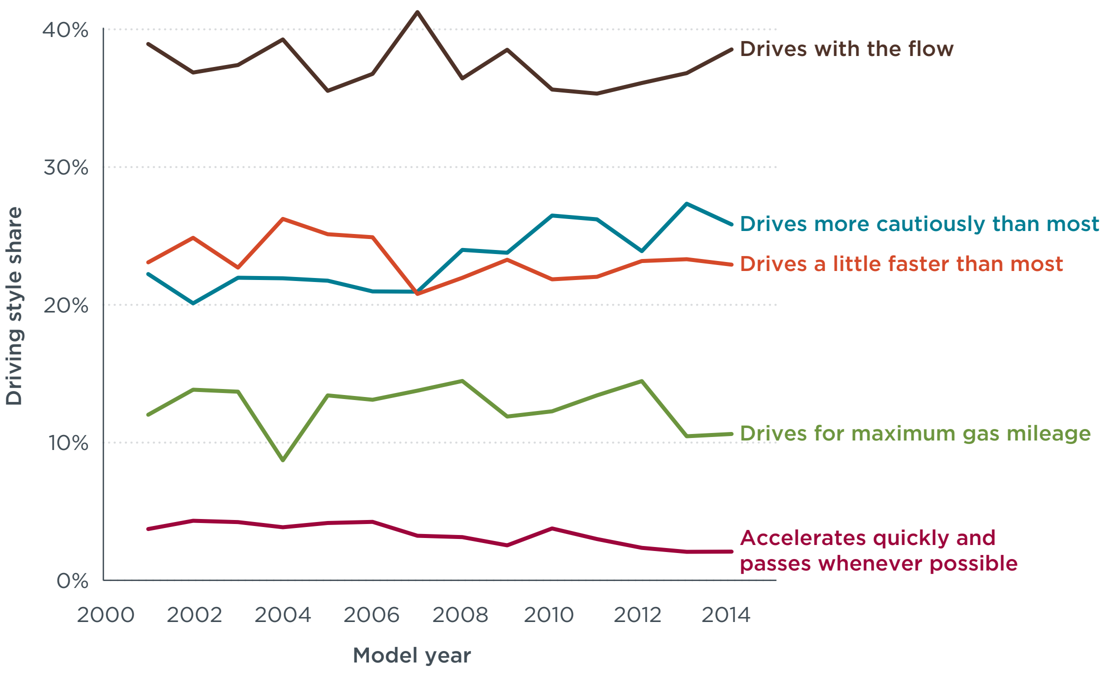


Figure 28. Shares of different driving styles in MyMPG data.

5.2.3 Vehicle technologies

A number of recent developments in vehicle technologies contribute to the growing gap. For instance, air-conditioning systems have become more common in all markets included in the analysis but are turned off during laboratory tests; the only exception to this rule is the SC03 cycle, which forms part of the U.S. EPA five-cycle method. Other vehicle technologies, such as stop/start systems, have been shown to typically provide disproportionate benefits during laboratory testing compared with real-world driving in Europe and China (Qin et al., 2016; Stewart et al., 2015), while hybrid electric vehicles show higher gaps in the EU, United States, and Japan (data for China was not available).

Increased ethanol content of fuels also contributes to the gap since ethanol has a lower energy content on a volumetric basis, so real-world fuel consumption could be inflated if official fuel consumption values fail to consider the increase in ethanol content over time. In the United States, the increase in ethanol accounts for around two percentage points of the divergence between real-world and official CO_2 values (Greene et al., 2015) and three percentage points of the gap between CAFE and U.S. EPA five-cycle values (U.S. EPA et al., 2016). In the EU, biofuels have become more common over time. Ethanol blends E5 and E10 (5% and 10% ethanol share respectively) made up more than 80% of all gasoline sold in 2014, while B7 (7% biodiesel share) accounted for virtually all diesel sold in the same year (EEA, 2015); however, these developments are largely taken into account in the calculation of type-approval fuel consumption figures by means of reference fuels (see UNECE, 2013) and should therefore only increase the gap of older vehicles, for which official fuel consumption figures do not consider biofuel blends.

5.2.4 Vehicle testing and policy frameworks

To what extent manufacturers are optimizing vehicles for testing in order to produce lower CO_2 emission values is a key question for policymakers. This analysis does not attempt to answer that question, but we discuss findings from other studies relative to our results. Since testing procedures and policy frameworks vary by jurisdictions, findings are organized by region.

In Europe, numerous studies indicate that test cycle optimization and the exploitation of flexibilities in the test procedure contribute to—and may be the leading cause of—the growing gap. A detailed summary of findings is beyond the scope of the discussion, but unrealistic road-load coefficients from coastdown testing and leveraging flexibilities and tolerances in chassis dynamometer testing are key culprits (Kadijk et al., 2012; Mellios et al., 2011; Stewart et al., 2015). The European policy framework perpetuates these problems because market surveillance is limited and road-load coefficients are treated confidentially and are not verified by regulators. Moreover, the European Commission currently does not have the power to issue vehicle recalls or impose financial penalties in case of violations.

In contrast to the EU, there is no clear evidence to link the increase in the U.S. CAFE gap to manufacturers optimizing test values. Not only is the increase in the gap considerably lower than in the EU (see Figure 27), but the annual growth in the gap actually slowed somewhat after the United States adopted new standards for cars starting in 2011, indicating that the U.S. policies provide less room for manipulation. Greene et al. (2015) observe that "the timing of the increase in [the U.S. on-road fuel economy] shortfall suggests the possibility that as standards are tightened (or gasoline prices increase) manufacturers increasingly design vehicles to perform well on the test cycle [...], in the process increasing the gap between test cycle and on-road fuel economy" (p. 22). However, the study concludes that more research is needed to establish causality. The regression model presented in the same study also indicates that individual model year effects rarely have significant impacts on real-world fuel economy when accounting for a range of vehicle and external parameters, but that "the pattern of the model year coefficients [...] suggests the possibility of an increasing shortfall in the more recent model years when fuel economy standards have been increasing" (Greene et al., 2015, p. 26).

The U.S. policy framework incorporates a wide range of measures that aim to detect misstated fuel economy values, which may explain the lower growth in the gap compared to other markets. These measures include SEAs, road-load confirmatory testing, and in-use surveillance testing (see Section 2.4.3), which have led to numerous corrections of fuel economy values (U.S. EPA, 2014a). Comparing EU and U.S. road load coefficients, Kühlwein (2016) notes that U.S. coefficients reported by manufacturers are far closer to independent measurements and traces this difference back to rigorous policy enforcement in the United States rather than better coastdown procedures. Fines for violations act as a further deterrent. For instance, Hyundai and Kia paid a civil penalty of $100 million for using inaccurate road load forces, thereby overstating fuel economy of their vehicles (U.S. EPA, 2014b). Taken together, there is no clear evidence linking the increase in the U.S. gap to manufacturers gaming the system, and numerous mechanisms are in place to detect any violations and to deter manufacturers from cheating. This is supported by the fact that the annual increase in the gap in the United States actually slowed down slightly after new car standards were adopted for 2011 through 2016.

There is less literature investigating the growing gap in China and Japan. Chinese studies seem to indicate that the test procedure rather than the test cycle itself is the leading cause of the divergence between official and real-world CO_2 emission values, given that on-road emissions were 30% higher than laboratory measurements, even when the real-world measurements were normalized to the NEDC (Zhang et al., 2014). Another factor that was highlighted by previous studies is the importance of traffic conditions, and particularly traffic congestion, on real-world CO_2 emissions (Qin et al., 2016; Zhang et al., 2014). Similar to findings on the gap in China, Kudoh (2012) links the divergence in Japan to the inability of the 10-15 mode to accurately recreate congested city driving conditions.

5.2.5 Summary

The reasons for the growth of the divergence in several regions of the world are likely to be a complex combination of different developments; however, literature from the EU and China indicates that the exploitation of loopholes in the NEDC is the leading cause. In contrast, there is no clear evidence of systematic manipulation in the United States or Japan.

5.3 POLICY IMPLICATIONS

The divergence between official and real-world CO_2 emission values has important implications for fuel efficiency policies. If on-road CO_2 emissions routinely exceed regulated metrics, policies that are solely based on official CO_2 values will fail to achieve the full real-world benefits in terms of fuel savings, climate change mitigation, and reducing reliance on oil products. This problem is particularly acute when the gap is allowed to grow, since benefits of CO_2 or fuel economy standards will be diluted over time.

In order to reflect the real-world performance of the new vehicle fleet in each region, we applied annual gap estimates to the official laboratory measurements in the past years. Because the real-world gap estimates are based on CO_2 emissions values over the official test cycle used by each region, we apply the divergence estimates to certified CO_2 emission values and then normalize the resulting emission values to NEDC equivalents to ensure comparable results (see Kühlwein et al., 2014).

Figure 29 displays the official and real-world average CO_2 emission values for the four markets under study. The EU and China appear to be making little progress in reducing on-road CO_2 emission values after 2008, when the gap started to rapidly grow in both markets. According to the data at hand, the United States has the highest on-road CO_2 emission values, but is improving at a higher rate (1% annual reduction since 2008) than the EU (<1% annual reduction) and China (0% annual reduction). Japan stands out with the lowest official and real-world CO_2 emission values due to a light, efficient fleet and a comparatively low growth in the gap, although the e-nenpi.com data indicates that the gap has been growing since 2008. On the whole, the figure illustrates that the growing gap is a substantial obstacle to reducing CO_2 emission values in the real world, particularly in the EU and in China, and must therefore be factored in when designing CO_2 or fuel economy standards, a subject that is explored in the next section.

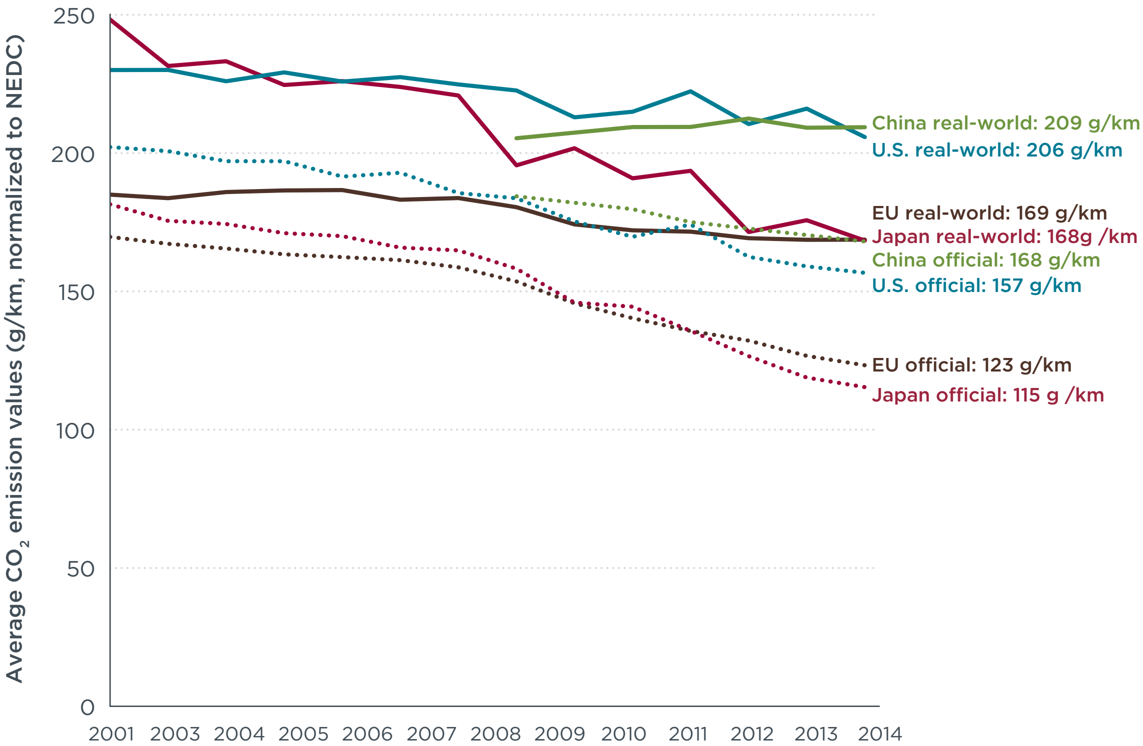


Figure 29. Official and real-world CO_2 emission values for new passenger cars in the EU, the United States, China, and Japan.

Figure 30 shows the development of official and real-world CO_2 values relative to 2008 levels. Japan achieved the highest reduction in official (–27% change) and real-world (–14% change) values. The EU achieved the second highest reduction in official CO_2 values (–20% change), but was outperformed by the United States in terms of real-world performance (–8% change for the United States, –7% change for the EU). Lastly, China achieved a comparatively modest reduction in official values (–8% change) and saw a growth in real-world values (+2% change).

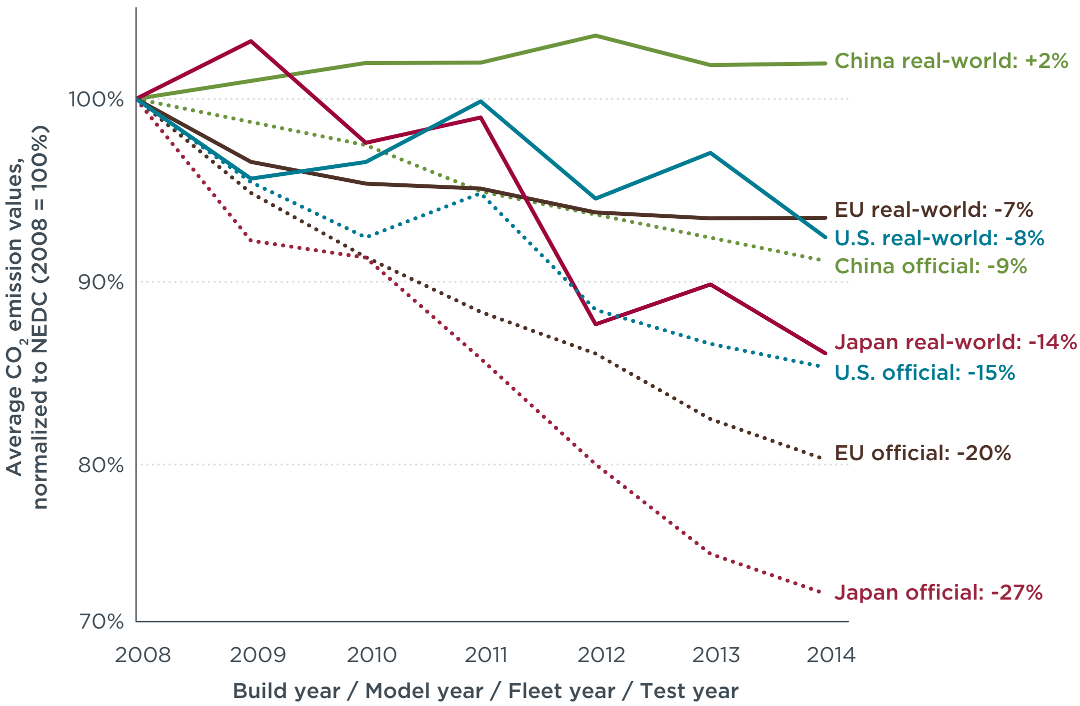


Figure 30. Change in official and real-world CO_2 emission values of new vehicles since 2008 in the EU, the United States, China, and Japan.

5.4 GOOD PRACTICES FOR VEHICLE TESTING AND POLICY FRAMEWORKS

Laboratory tests of vehicles cannot produce a single fuel consumption estimate that is accurate for all drivers, but the analysis indicates that some procedures and policy frameworks are better at ensuring representative and consistent results.

Policy enforcement and continuous monitoring of test results seem to be key to ensure that car manufacturers follow the intent and spirit of regulations rather than exploiting loopholes and technicalities. For instance, as the market with the most rigorous policy enforcement, the United States has seen the smallest increase in the gap over time compared to the other three regions and the annual rate of increase has actually slowed a bit since the government adopted new standards. The United States is the only market to test vehicles throughout their useful lives, conduct confirmatory road-load testing, and independently retest a portion of all vehicle models. In contrast, the EU has made substantial improvement in vehicle efficiency on paper, but there is evidence to suggest that a large portion of these improvements resulted from manufacturers gaming vehicle tests and exploiting systemic faults in the type-approval framework (Kadijk et al., 2012; Stewart et al., 2015). Similarly, in the absence of rigorous market oversight, Japan has seen an increase in the gap after fuel economy standards and incentives for efficient vehicles were introduced around 2008. However, these observations are based on limited data, and Section 5.2.1 indicates that the decrease over time in official fuel consumption values may have contributed to the growing gap in Japan. More research is needed to identify the reasons for that growing gap.

Another key feature of the different policies is to what extent they account for the divergence. The impact assessment (European Commission, 2012a, 2012b) accompanying the 2020 CO_2 standard assumes a 19.5% gap between real-world and official CO_2 emission values. This gap estimate was based on a 2006 study. Since then, empirical evidence points to significant growth in the gap, reaching 42% for new passenger cars in 2015. This development indicates that there is need to limit the growth of the gap or to periodically reassess the adjustment factor. In contrast, the adjustment factor used by the United States has been increasing over time as the gap increased. Greene (2015) observes that “because the rulemaking calculated the benefits of the standards assuming a 20% [fuel economy] shortfall, the implication for the projected benefits is very small provided that the gap does not continue to grow” (p. 22). Factoring in the gap during policy design is a low-cost measure to ensure that policies do not overestimate the benefit of on-paper fuel consumption improvements, and could thus help to set economically efficient CO_2 or fuel economy targets.

Measuring the on-road performance of vehicles enables policy actions to manage or close the divergence between official and real-world CO_2 values. The best practice example is the MyMPG service on FuelEconomy.gov, a tool that collects real-world fuel consumption data from consumers. The United States is the only region that has a governmental website for this purpose; the data from Europe, China, and Japan relies on private services. This kind of service allows regulatory agencies to monitor the divergence without relying on third-party data or research. In addition, FuelEconomy.gov presents MyMPG on-road measurements and U.S. EPA label values to the public and therefore helps consumers make informed vehicle purchase decisions.

The design of test cycles and test procedures also deserves attention. The basically non-existent gap for U.S. EPA label values in 2014 indicates that it is possible to design test procedures that, on average, deliver realistic results. In contrast to all other test procedures studied in the report, the five-cycle method measures fuel consumption during aggressive driving, includes the use of air conditioning systems, and tests vehicles at low ambient temperatures. As a result, these values provide reliable estimates of on-road fuel economy for consumers. Nevertheless, while test cycles are frequently cited as a reason for the existence of a gap (e.g., Ding et al., 2015; Kudoh, 2012; Zhang et al., 2014), the foregoing good practices indicate–perhaps somewhat counter-intuitively–that the level of the real-world divergence of regulated CO_2 values is not essential, as long as (1) the gap and any increase in the gap is taken into account when setting CO_2 or fuel economy targets, and (2) consumers have access to reliable fuel consumption values.

5.5 LIMITATIONS AND FUTURE RESEARCH

This study covers four major global vehicle markets, each with different vehicle characteristics, unique policies, and varying data availability. The analysis used the best possible data to estimate the divergence between official and on-road CO_2 emission values. Results were discussed with experts from each region to ensure that policy descriptions and real-world data represent each market as accurately as possible. Nonetheless, some limitations remain and are acknowledged below.

Different dating conventions were used in the analyzed data. European samples include vehicle build year (the year a vehicle was constructed), model year (the year a model generation was introduced), fleet year (the year of measurements for an entire fleet), and test year (the year a vehicle was tested). The other data sources, covering China, the United States, and Japan, all use model year to date vehicles. The somewhat inconsistent dating conventions impede like-for-like comparisons of samples, but comparisons between European data sources indicate that these differences do not significantly impact the results. For instance, comparing Spritmonitor.de data, a sample covering German cars by build year, and honestjohn.co.uk, a British data source using model year, reveals that gap estimates from model years tend to be more erratic, but that the general levels of the gap are similar. More importantly, the upward trend in divergence estimates is not affected by the dating convention.

Vehicle definitions vary in the four regions. The analysis generally focuses on passenger cars, and other types of vehicles (light-commercial vehicles in the EU, light trucks in the United States, commercial cargo and passenger vehicles in China, and trucks in Japan) were excluded from comparison charts such as Figure 25 and Figure 27. We attempted to select comparable subsets of the light-duty vehicles by selecting vehicles with similar technical characteristics (passenger cars), but this decision inherently compromises the comparability in terms of how vehicles are used. For instance, the majority of light trucks registered in the United States are used for personal transportation, but U.S. vehicle definitions are based on vehicle characteristics rather than the intended use of a vehicle. In contrast, such vehicles could be registered as passenger cars or light commercial vehicles in the EU, depending on the intended use of the vehicle. While these differences would be significant in comparing technical parameters of the national samples, these differences are less important for the comparison of divergence estimates since the samples indicate that all light-duty vehicles generally follow the same trend (see Figure 17 for example). A study on light commercial vehicles in the EU also suggests that light commercial vehicles follow similar trends as passenger cars (Zacharof, Tietge, Franco, & Mock, 2016). The differing vehicle definitions therefore hamper like-for-like comparisons, but these differences are unlikely to substantially change the divergence estimates and the results of the study.

Limitations in the data collection method should also be acknowledged. The majority of the data–with some exceptions in the EU datasets–were based on fuel consumption values entered by users of web services. This sample design may introduce self-selection bias. Nonetheless, comparisons in each region's analysis section indicate that all real-world samples, with the exception of the Japanese e-nenpi.com data, match vehicle registrations data in terms of vehicle characteristics. Moreover, two samples, Spritmonitor.de and FuelEconomy.gov, provide self-reported information on driver behavior. This data indicates that users are not biased toward driving economically or aggressively, but that most users tend to gravitate to balanced driving styles (Greene et al., 2015; Tietge et al., 2015). Nevertheless, because this data is self-reported and not available for all samples, the potential for skewed samples due to self-selection bias remains.

Taken together, the foregoing limitations imply that the data presented in this study are more suitable for gauging long-term trends in the divergence rather than comparing the different markets in terms of the precise level of the gap in a specific year. It is also the upward trend in the gap that deserves attention in future research. In the EU, a number of studies more or less qualitatively discuss the reasons for the increasing divergence, but quantitative models (e.g., Mellios et al., 2011; Ntziachristos et al., 2014) fail to account for the increase in the gap over time (see Tietge et al., 2017). The findings also echo the call of Greene et al. (2015) for further research on reasons for the increase in the gap in the United States, as well as in other markets. There is also a need to collect more real-world CO_2 emissions data, particularly in markets with comparatively small samples sizes in this study. This is most notable for Japan, where the limited sample size, limitations to the representativeness of the data, and the fact that different test cycles were used during the studied time frame, stand in the way of drawing detailed conclusions from the data at hand. More data could address issues of representativeness of the samples and could help validate the findings presented here.

Lastly, this work has implications for ongoing regulatory discussions in U.S. and EU CO_2 regulations on off-cycle credits. U.S. regulations, within the off-cycle credit provisions, allow approved technologies and additional automaker petitions for new technologies to receive additional credits when they provide evidence of real-world benefits. The U.S. EPA continues to receive and approve petitions (e.g., U.S. EPA, 2015a). The EU regulations, under the eco-innovation provisions, similarly allow technology credits for technologies that deliver greater benefits in the real world than on paper. The results from this study suggest that automakers are deploying technologies, for instance stop/start systems, that deliver less real-world benefits than measured during laboratory tests. This calls into question the very logic that automakers can apply for additional credits for the technologies that deliver additional real-world benefits, when a sizeable portion of technologies do not deliver the full extent of benefits during real-world use. We therefore call for more rigorous analyses of how different technologies affect the real-world gap. Moreover, as long as the real-world gap is increasing in some markets, the issuance of off-cycle credits should be reconsidered.

6. CONCLUSIONS AND RECOMMENDATIONS

This study analyzes real-world fuel consumption data for more than 1.5 million vehicles from four major vehicle markets, namely the EU, the United States, China, and Japan. The results indicate that the growing divergence between official and real-world CO_2 emission values is a global problem, but that the causes and management of the gap differ from region to region.

This study does not attempt to provide a comprehensive explanation for the growth in the divergence in different regions, but the results indicate that independent confirmatory testing and policy enforcement affect the gap. Lax enforcement in the EU was accompanied by the largest growth in the divergence among the studied regions. In contrast, the United States has the most rigorous compliance and enforcement programs and experienced the smallest growth in the divergence.

Based on the comparison of the divergence and fuel efficiency policies in the different regions, the following aspects should be considered when designing CO_2 or fuel economy standards:

» **Independent retesting:** Independent retesting of laboratory measurements was identified as a best practice. All markets have some form of compliance program in place, but the United States has the most extensive program, covering the full lifetime of vehicles by verifying coastdown measurements, testing production line vehicles, and conducting in-use surveillance tests.

» **Policy enforcement**: The comparatively low growth in the U.S. gap indicates that stringent policy enforcement, such as levying penalties on manufacturers that misstate fuel economy values, acts as a deterrent to gaming. In contrast, the EU has seen the largest growth in the gap from 2001 to 2014 and lacks a central authority to issue vehicle recalls and to impose financial penalties.

» **Real-world standards:** CO_2 and fuel economy standards should be based on test values that, on average, correspond to real-world measurements. Policies that fail to account for the divergence will overestimate fuel savings and climate change mitigation benefits. Using an adjustment factor to approximate on-road values, as is done in the United States, is an approach that does not require extensive overhauls of vehicle testing procedures in order to account for real-world CO_2 emissions. Another approach for measuring on-road emissions is using PEMS equipment. On-road tests using PEMS are currently only being conducted for nitrogen oxides (NO_X) and particulate number emissions as part of the RDE procedure, but these kinds of measurements could be used to monitor on-road CO_2 emissions and to test the on-road conformity of vehicles in use. More realistic test cycles and more rigorous testing procedures (e.g., including auxiliary equipment, using stock tires, and using standard engine and transmission calibrations) for laboratory testing could also furnish more realistic CO_2 values.

» **Real-world measurements:** Measuring real-world fuel consumption is a key recommendation since this data is needed to evaluate the efficacy of CO_2 and fuel economy standards. Bulk on-road fuel consumption data can be measured using web services. As the only government-run example of such services, the MyMPG tool on FuelEconomy.gov stands out as a best practice example. This data can be used to estimate fleet-wide real-world CO_2 emission values and gauge policy impacts. Using data loggers connected to the on-board diagnostics port of vehicles is another option for real-world fuel consumption data collection (see Posada & German, 2013).

» **Consumer information:** Consumers need access to realistic fuel consumption values to make informed vehicle purchasing decisions. U.S. EPA window label values demonstrate that it is possible to produce fuel consumption values that, on average, are representative of real-world performance. The FuelEconomy.gov website stands out as a best practice example of consumer information since it combines real-world measurements, realistic fuel consumption values, and information on efficient driving in one portal.

The growing divergence between official and on-road CO_2 emission values is troubling because it represents a decoupling of regulated metrics and real-world impacts. Nevertheless, the recommendations presented here illustrate that solutions are available to close or at least manage the gap.

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APPENDIX I: FUEL ECONOMY CHARTS

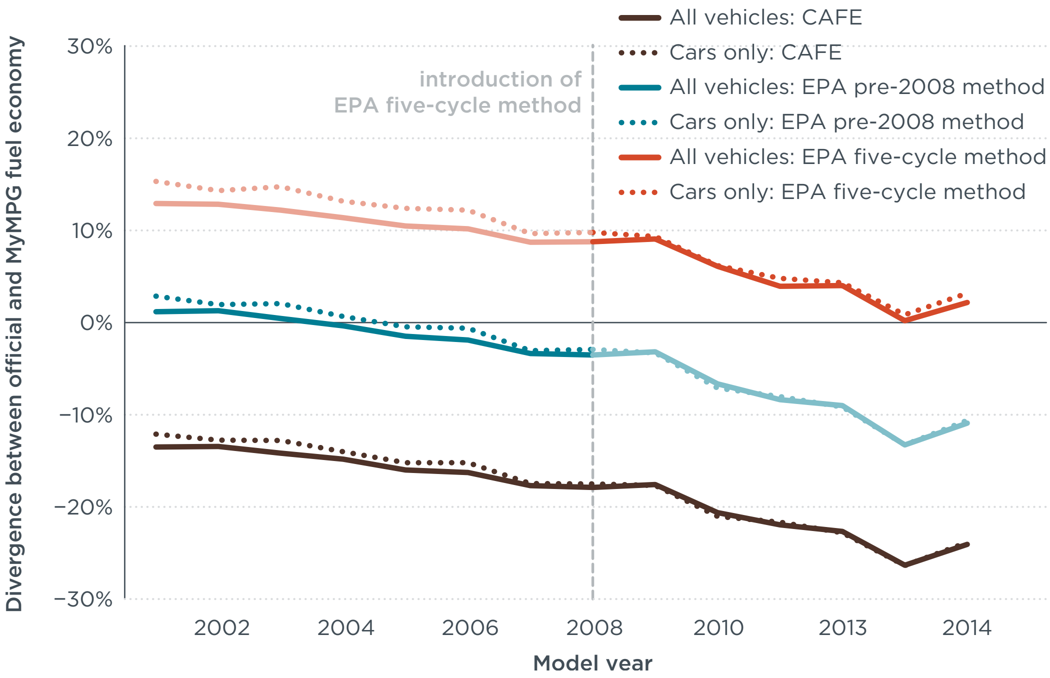

Figure 31. Divergence between MyMPG and official fuel economy values for light-duty vehicles and cars. Official fuel economy values include CAFE figures and EPA label values.

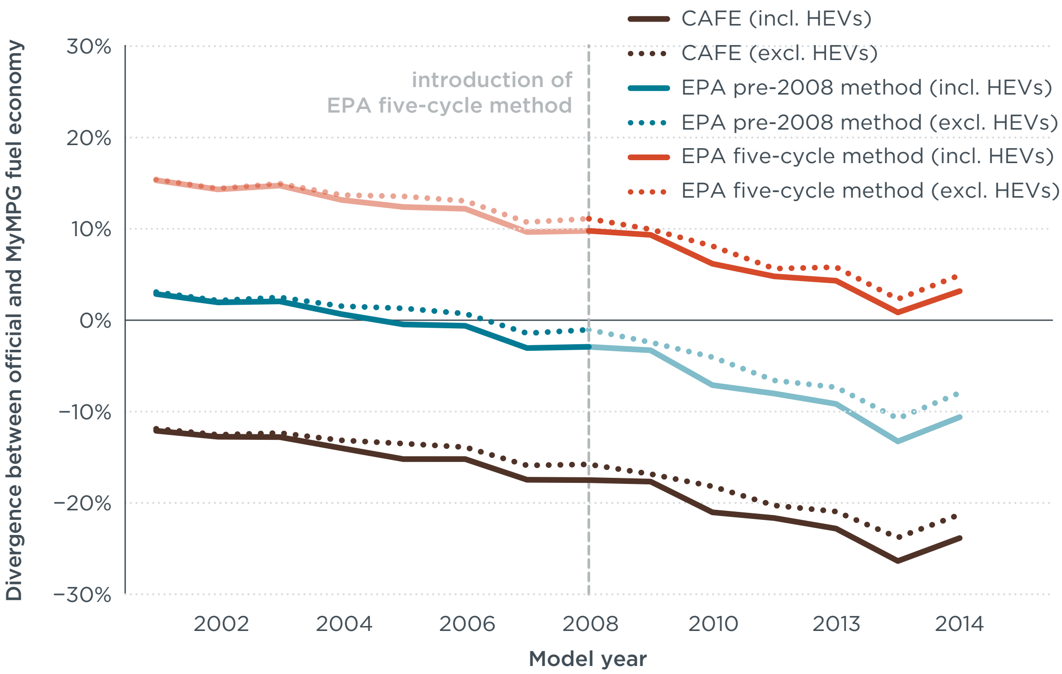

Figure 32. Divergence of MyMPG from official fuel economy values by powertrain. Official fuel economy values include CAFE figures and EPA label values.

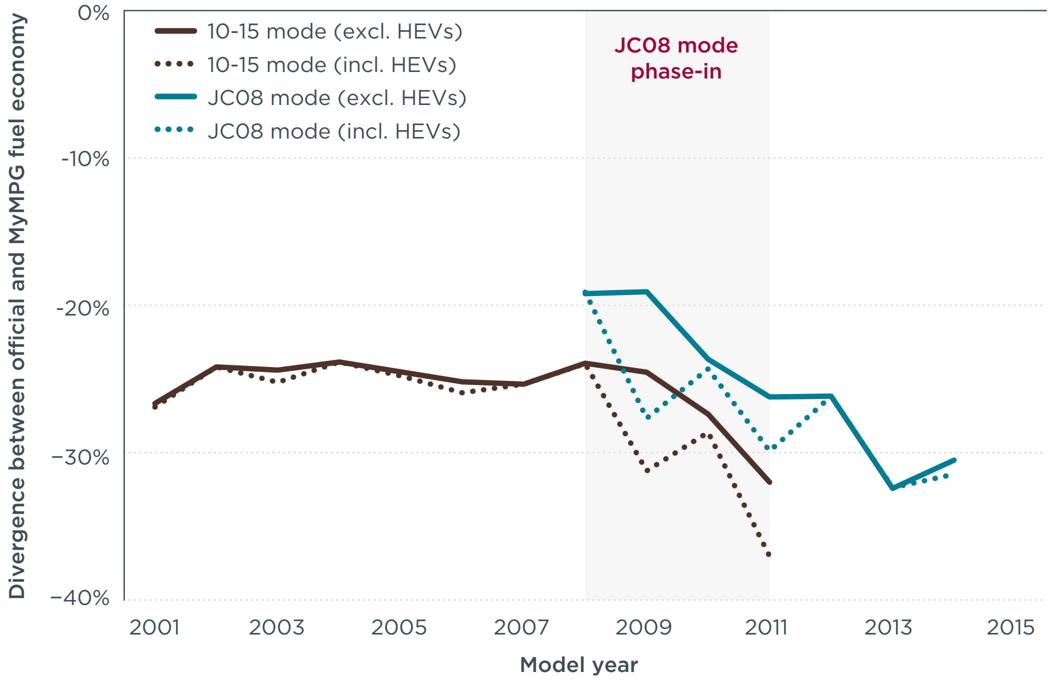

Figure 33. Divergence between official and e-nenpi.com fuel economy values.

APPENDIX II: CALCULATION METHODOLOGY FOR E-NENPI.COM

Each row of the e-nenpi data set described one year of data for one model version, where a model version is defined as a unique combination of vehicle brand, model name, model year, body style, fuel type, engine displacement, transmission type, number of gears, and other powertrain characteristics. Since different vehicles of a given model version may have entered and left the database over time, and data was delivered aggregated by model version and calendar year, the number of vehicles in the sample was estimated as follows:

$n_i = \max(n_{i,t=0}, n_{i,t=1}, \ldots, n_{i,t=t})$, where

n_i = *number of vehicles of model version i*

n_i = *period of data collection*

T = *total number of data collection periods*

Furthermore, only minimum and maximum type-approval fuel consumption values of each model version were delivered by e-nenpi.com. Type-approval fuel consumption values of model versions were thus estimated as:

$$\text{TAFC} = \frac{TAFC_{min} + TAFC_{max}}{2}, \text{ where}$$

TAFC = *type-approval fuel consumption*

The average divergence between type-approval and e-nenpi.com fuel consumption values was calculated as the weighted arithmetic mean of the divergence of all model versions:

$$\delta = \frac{\sum_{i=1}^{V} n_i x \delta_i}{\sum_{i=1}^{V} n_i}, \text{ where}$$

V = *total number of model version*

δ = *divergence*