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The evolution of heavy-duty vehicles in China: A retrospective evaluation of CO_2 and pollutant emissions from 2012 to 2021

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Keywords: Heavy-duty vehicle, CO_2 emissions, trend study

Executive summary

Heavy-duty vehicles (HDVs) consume energy and emit climate and air pollutants. By 2021, diesel-powered HDVs still dominated the Chinese HDV market, accounting for approximately 90% of sales. Over the past decade, Chinese regulatory bodies have adopted various standards to curb fuel consumption and emissions of pollutants that pose health hazards. In 2020, China committed to peaking CO_2 emissions by 2030 and to achieving carbon neutrality by 2060. Since then, the nation has actively considered policies to reduce GHG emissions from road vehicles. In this context, this study reviews the historical development of HDV energy consumption, its corresponding CO_2 emissions and air pollutant emissions, emission-control technologies, and vehicle and fleet characteristics. The study evaluates the effectiveness of policies in curtailing vehicular emissions and lays a foundation for developing future regulations for direct control of CO_2.

Our analysis focuses on the development of heavy-duty vehicles from several perspectives, including key attributes (such as curb weight, engine power, and others), fuel consumption/CO_2 emissions for various HDV segments, and NO_x emissions from tailpipes. We explore development of six vehicle segments: city buses, coaches, dump trucks, medium straight trucks, heavy straight trucks, and tractor trailers.

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Figure ES-1 summarizes trends for key measures of the HDV fleet as a whole in China over the 2012–2021 period. Vehicle attributes such as total weight, power, and engine displacement increased by 15%–50% during the last decade. The development of weight and engine specifications implies ongoing expansion of the HDV fleet in China. Meanwhile, fleet average CO_2 emissions fluctuated and fell gradually since 2015 due to the adoption of increasingly stringent fuel consumption standards. In 2021, a limited improvement (approximately 2%) in fleet-level CO_2 emissions is seen relative to 2013.

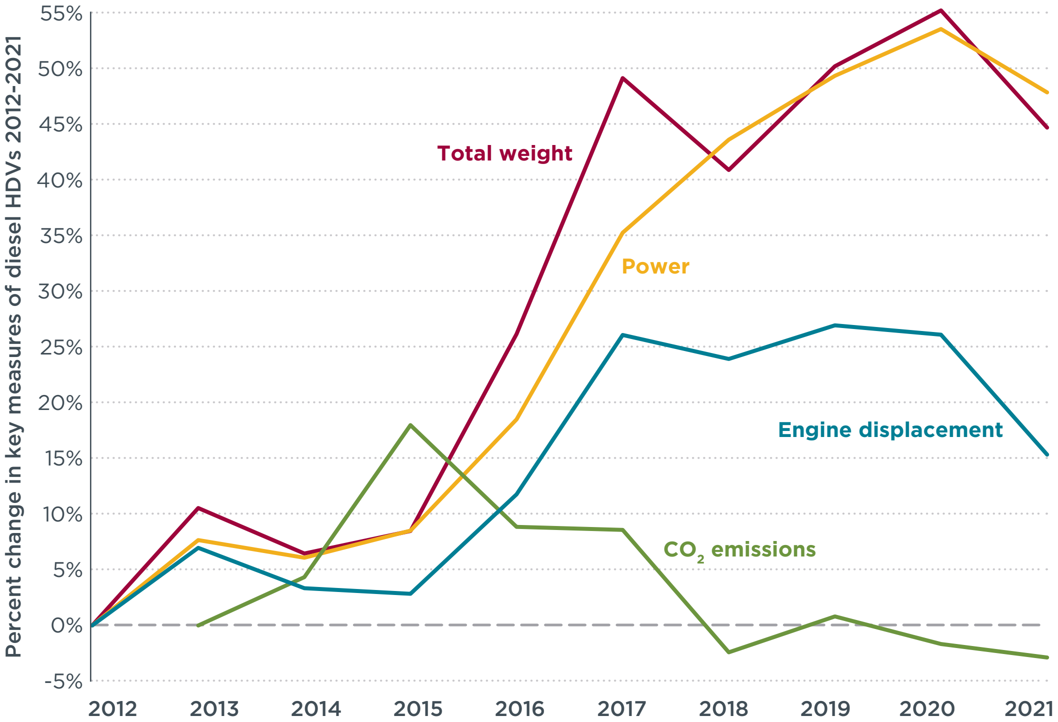


Figure ES-1. Percent change in key measures of diesel HDVs, 2012–2021. The 2012 fleet average CO_2 emission value was not included because of the lack of data for fuel consumption values in 2012.

This study also tracks pollutant and CO_2 emissions throughout the period. **Figure ES-2** illustrates the type approval values of CO_2 and NO_x from diesel engines. China has adopted more stringent limits on NO_x emissions in the past decade, progressing from China IV standards (2012-2016) to China V (2017-2020) and China VI (2021-present). China does not yet control CO_2 emissions at the engine level, and CO_2 emissions do not show a decrease with each update of NO_x emission standards.

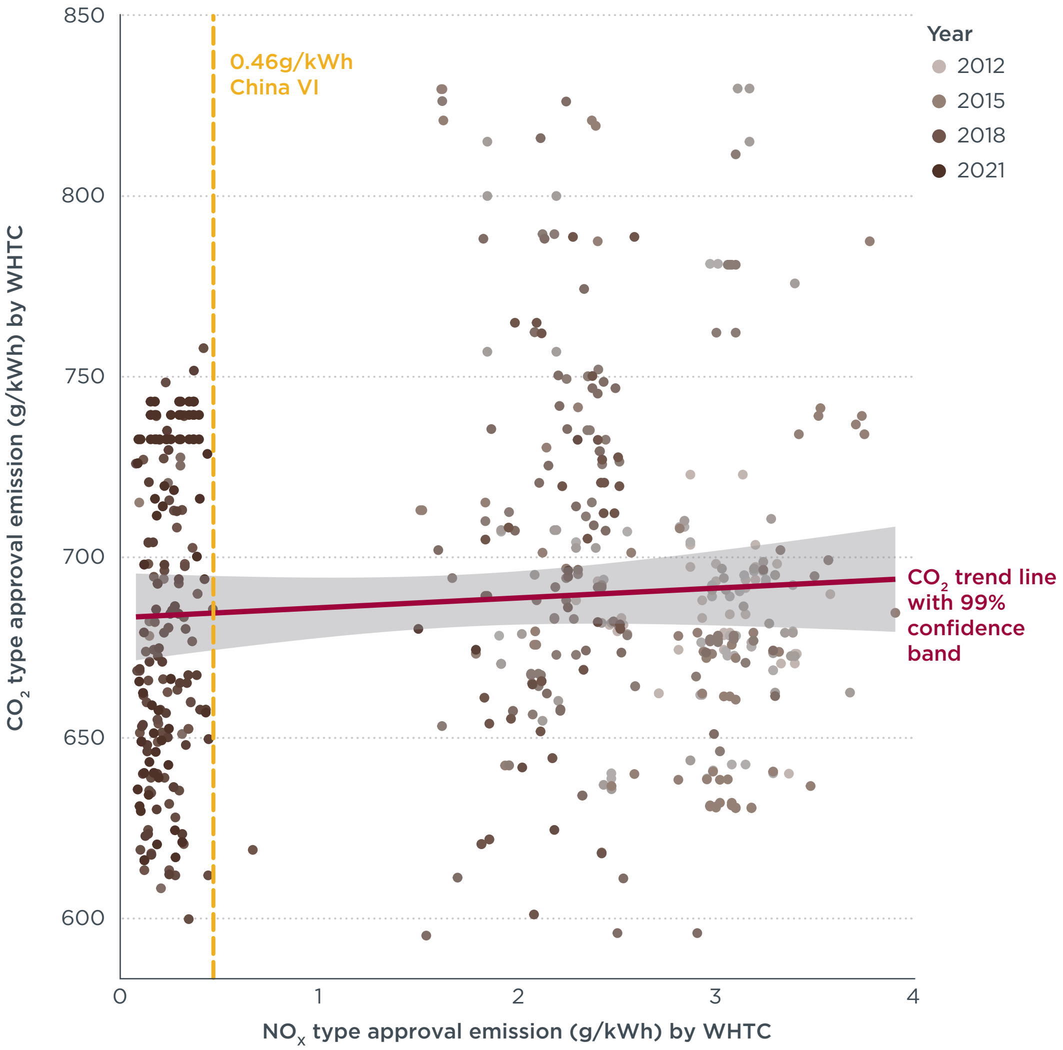


Figure ES-2. Type approval values of CO_2 and NO_x by diesel engines, 2012–2021

The findings in this study yield several policy recommendations:

1. Utility vehicles should be fully included in the next stage of fuel consumption standards to cover a fuller set of energy consumers. China explicitly mandates five segments of HDVs: straight trucks, dump trucks, tractor trailers, city buses, and coaches, but utility vehicles—those used for specific functions such as sanitation, engineering, and others—are not yet regulated. Utility vehicles accounted for about 10% of the total market share in 2021, so stricter regulation of the fuel efficiency of such vehicles is important. Moreover, the boundary between utility vehicles and other segments is vague, which leaves loopholes for interpreting regulations according to one's interests.

2. A more inclusive and integrated emission control regulation for both pollutant and GHG emissions should be enacted to guide development of heavy-duty vehicles. Currently, China does not control GHG emissions at the engine or vehicle level. A switch from the current fuel consumption standard to regulation of GHG emissions will cover more greenhouse gases such as N_2O, CH_4, etc., which can provide greater information on realistic GHG emissions of HDVs. In addition, a complete GHG emission standard will provide the HDV industry with a long-term vision and allow it to balance control of pollutants and GHG emissions under various technology combinations. China launched its nationwide carbon trading scheme in 2021 and is promoting inclusion of more industries. Applying complete

GHG emission regulations on HDVs also helps lay a solid foundation for future work on carbon trading and climate protection.

3. Electrification is key to decarbonizing road transport, although clean diesel engine technologies should still be encouraged. In this report, we have found that China's HDVs are equipped with more advanced engine technologies such as common rail to improve fuel efficiency and cut down on exhaust emissions. We encourage further development of clean diesel engine technologies as a strategy for making the transition to full electrification smoother and more affordable. In addition, China applied a dual-credit policy to promote production of electric passenger vehicles; similarly, we recommend that the upcoming credit policy on HDVs also highlight the effort to improve engine fuel efficiency and performance.

Introduction and policy background

With a booming manufacturing industry and high demand for heavy-duty vehicles (HDVs), China is now the world's largest HDV market (Mao & Rodríguez, 2021). The rapid growth of China's HDV market brought to the country 1.4 million new sales in 2021 (**Figure 1**), deepening concerns over the climate and urban air pollution impact of this large and growing fleet.

In 2020, 78.5% of road fleet NO_x emissions in China came from heavy-duty trucks, while an additional 11.7% was emitted by large buses. Heavy-duty trucks also accounted for 90.6% of the total vehicle PM emissions in 2020, according to the latest official survey on China's mobile sources of pollution (Ministry of Ecology and Environment, 2021). To address the emissions challenge, China's State Council launched a three-year action plan for a "Blue-Sky Defense" in 2018, placing special emphasis on the control of emissions from heavy-duty diesel vehicles (Zhang et al., 2020). China's Clean Diesel Program is another ambitious effort to reduce pollutants from diesel engines and heavy-duty vehicles. China applied a series of strategies to achieve the emissions reduction goal, including newly enacted laws & legislation, in-use vehicle and engine tests, and more stringent CO_2 regulations for new vehicles, among others (Yang et al., 2021). China VI, the most recent and stringent emission standard for heavy-duty vehicles, inherited and built upon legacy standards, and made great changes to testing schemes and methods, all aimed at reflecting emissions more accurately.

At the same time, emissions from heavy-duty vehicles are a threat to the climate. Heavy-duty vehicles emitted about half of GHG emissions across all vehicle types and approximately 3% of total GHG emissions from all industry in China, according to the latest census conducted by the Chinese government in 2019 (Ministry of Ecology and Environment, 2020). China's President Xi Jinping announced that carbon emissions in China will peak by 2030 and that carbon neutrality will be achieved by 2060 (IEA, 2021), GHG emission reductions from the HDV fleet have been identified as an important path for achieving carbon neutrality in the transportation sector before the underlying nationally determined commitments. But unlike pollution control technologies, which reduce engine emissions by more than 95% at an affordable cost, reducing GHG emissions by a similar amount is relatively expensive. Engine improvements, light-weighting technology, and low-resistance tire and aerodynamic devices can all help to reduce energy consumption and GHG emissions, but these reductions are limited (Meszler et al., 2019). The bottom line is that to achieve deep cuts in GHG tailpipe emissions, it is necessary to electrify the fleet.

Vehicle pollutants have been regulated since 2000 by China's vehicle emission standards, with the latest adopted version being China VI[1]. By contrast, China does not have any direct, enforceable regulation for curbing GHG emissions from HDVs, although CO_2 emissions are regulated indirectly through fuel consumption standards, which were introduced back in 2012. In their three stages, the standards have gradually adjusted the upper limit of fuel consumption for HDVs, by segments and weight classes. China's drive to regulate truck fuel consumption is initially aimed at reducing crude oil consumption, given the country's dependence on imports for 72% of oil use (IEA, 2020). Consideration of greenhouse gas emissions (mostly for CO_2, but also for CH_4, N_2O, and so on) and their impact on global warming have not yet led to regulatory action for HDVs. But with an eye on the important goal of carbon neutrality in the coming decades, China is acting to reduce greenhouse gas emissions and energy consumption by several means such as mass promotion of new energy vehicles, application of more advanced technologies (such as high-pressure common rail injection) to HDV internal combustion engines and with light weighting materials.

In a previous paper, ICCT conducted a retrospective assessment of the effectiveness of China's Stage 1 and Stage 2 standards in reducing fuel consumption (Mao et al., 2021). In this paper, we assess the impact of the standards for a wider time frame, i.e., 2012-2021, extending our original scope to include both fuel consumption and air pollutant emissions.

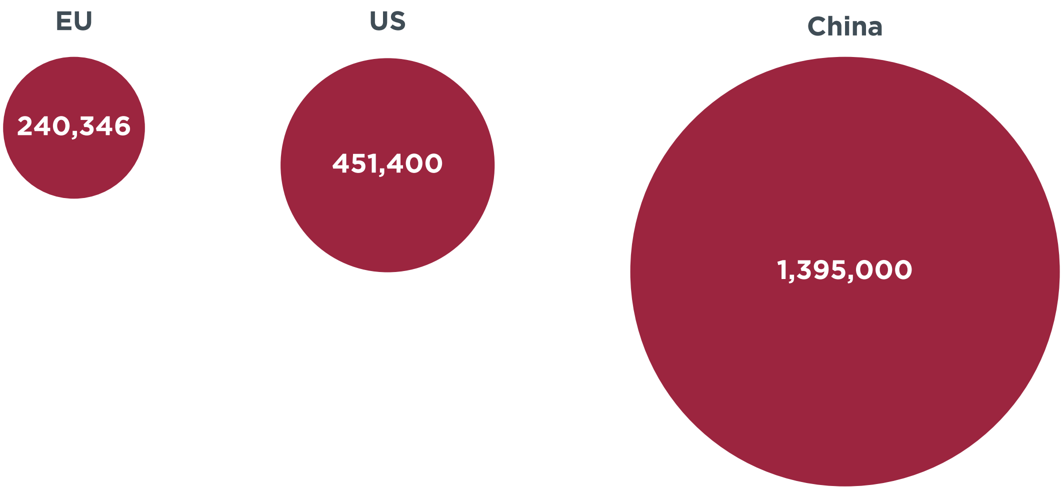


Figure 1. Heavy-duty vehicle sales in the EU, US, and China in 2021

Source: ACEA, 2022; cvworld.cn, 2022; Statista, 2022)

Definition, scope, and segmentation of HDVs in this study

The dataset used in this study is assembled from independent data providers. It includes the type-approval information of heavy-duty vehicles sold during 2012–2021. Only diesel vehicle models with GVW over 3,500 kg will be involved and analyzed; other entries are not considered. The dataset includes for analysis about 21 million available HDV vehicles, of which 19.3 million are diesel vehicles.

The HDV fleet in China consists mostly of diesel-powered vehicles, which is also reflected in our dataset. **Figure 2** presents a breakdown of HDV sales from 2012 to 2021. In the past decade, total sales of the HDV industry have grown from approximately 1.7 million to 3.0 million vehicles per year, of which diesel models increased from 1.63 million to 2.73 million per year. Fossil fuel-powered HDVs still dominate the market as

1 A couple of pollutants are mandated in China VI, such as CO, total hydrocarbon (THC), non-methane hydrocarbon (NMHC), CH_4, NO_X, NH_3, particulate matters (PM) and solid particle number (PN).

a whole, accounting for more than 96.0% of total sales in 2021 (**Figure 3**). New Energy Vehicles (NEVs), which refers to electric and fuel cell electric vehicles, grew from zero to 4% during the evaluation period. This growth can be attributed to the great efforts that government and industry are making to promote low-carbon transportation in China. Nevertheless, NEV models are beyond the scope of this study and will be analyzed in future studies.

The scope of this study almost matches the entire HDV fleet produced since 2012, including the new models introduced each year (**Figure 4**).

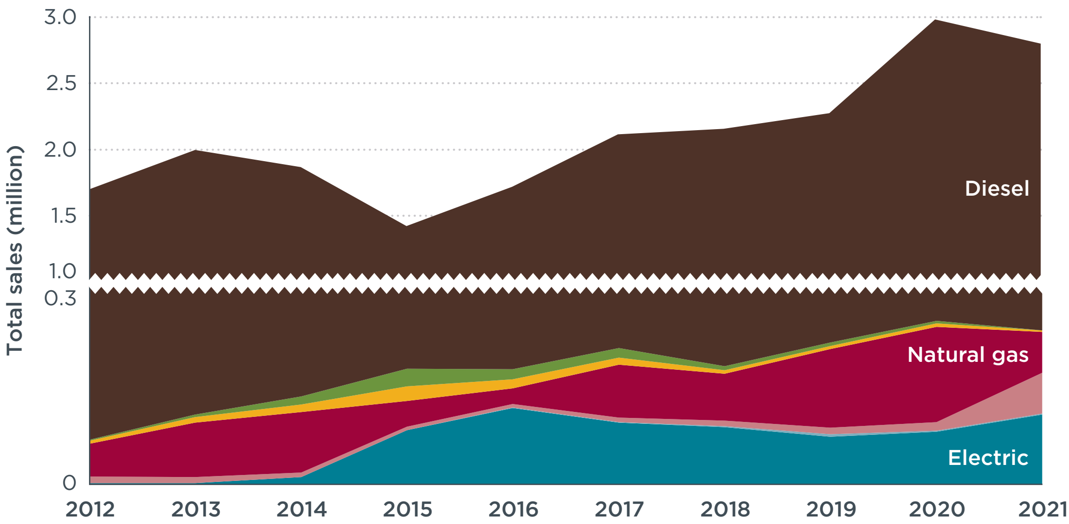


Figure 2. HDV sales by fuel type from 2012 to 2021.

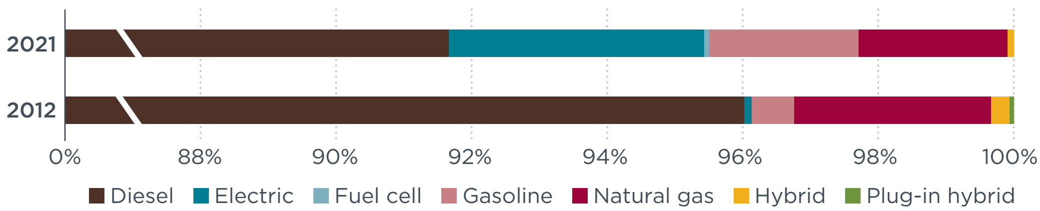


Figure 3. Share of HDV sales by fuel type in 2012 and 2021.

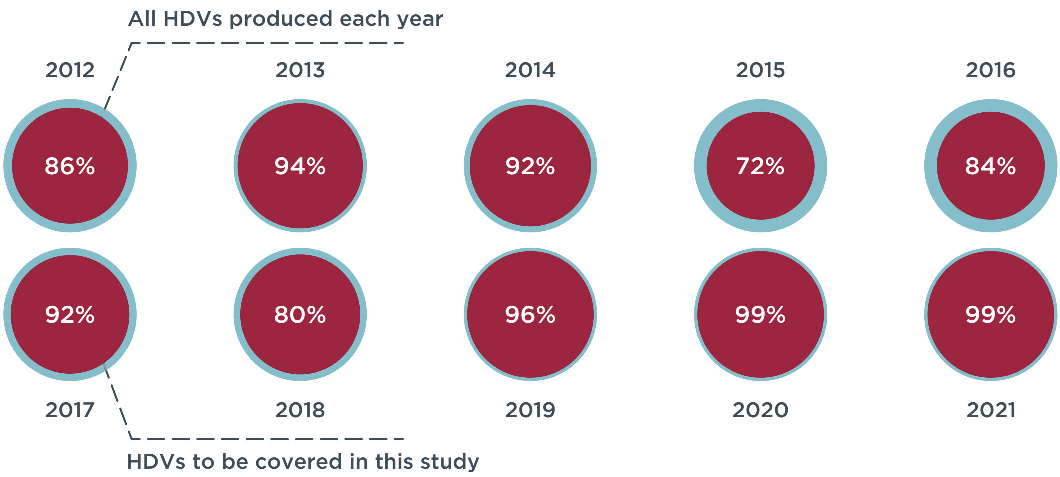


Figure 4. Scope of this study

In this study, five HDV segments with GVW/GCW[2] greater than 3.5 tonnes are investigated, i.e., straight trucks, dump trucks, tractor trailers, city buses, and coaches. This scope is in line with the latest China HDV fuel consumption standard (GB 30510-2018), i.e., Stage 3. Specifically, this study selects the most representative weight class by sales from each segment due to varied regulatory limits on different weight classes. Hence, this study covers six segments (straight trucks of medium and heavy weight will be discussed separately), which are illustrated in **Table 1** and **Figure 5**.

Table 1. Segments and weight classes selected in this study

Segments	Weight class (tonnes)
Medium straight truck	3.5 - 4.5
Heavy straight truck	16 - 20
Dump truck	25 - 31
Tractor trailer	46 - 49
Coach	3.5 - 4.5
City bus	5.5 - 7

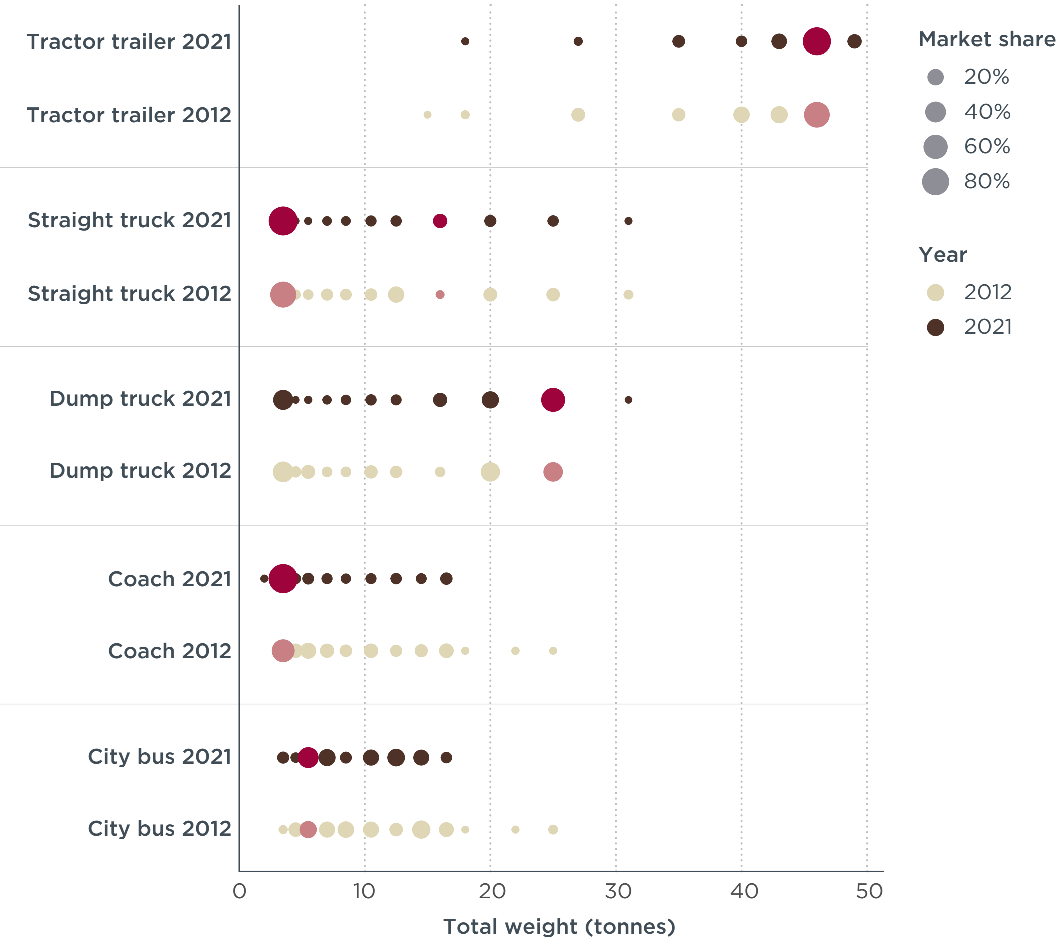


Figure 5. HDV sales by weight, and representative vehicle segments to be studied (red bubbles)

This study analyzes HDV models sold from 2012 to 2021, covering the implementation timeframe of Stage 1 through Stage 3. By each new stage, a more stringent fuel consumption standard is to be applied to all newly registered vehicles. In a previous study (Mao et al., 2021), the ICCT has explored improvement of Stage 2 over Stage 1 and

2 Gross combined weight, or GCW, is an indicator specifically for tractor trailer segmentation.

the potential of Stage 3 with a timeframe of 2012–2017. This work will also refer to key information from that study.

HDV market overview

China's conventional HDV market developed rapidly, with some twists, from 2012 to 2021. After a temporary market contraction in 2015, sales after 2016 quickly climbed and reached 2.8 million in 2021. Total sales in 2021 saw a slight decline of 3.6% compared with 2020.

The HDV market is dominated by key players over the past decade, including Dongfeng Motors, FAW Group, Foton, JAC Motors, JMC Motors, and Sinotruk, which is also shown in the **Figure 6**. The top 4 OEMs held their positions over the period, but Sinotruk replaced JMC Motors as No.5 in 2017.

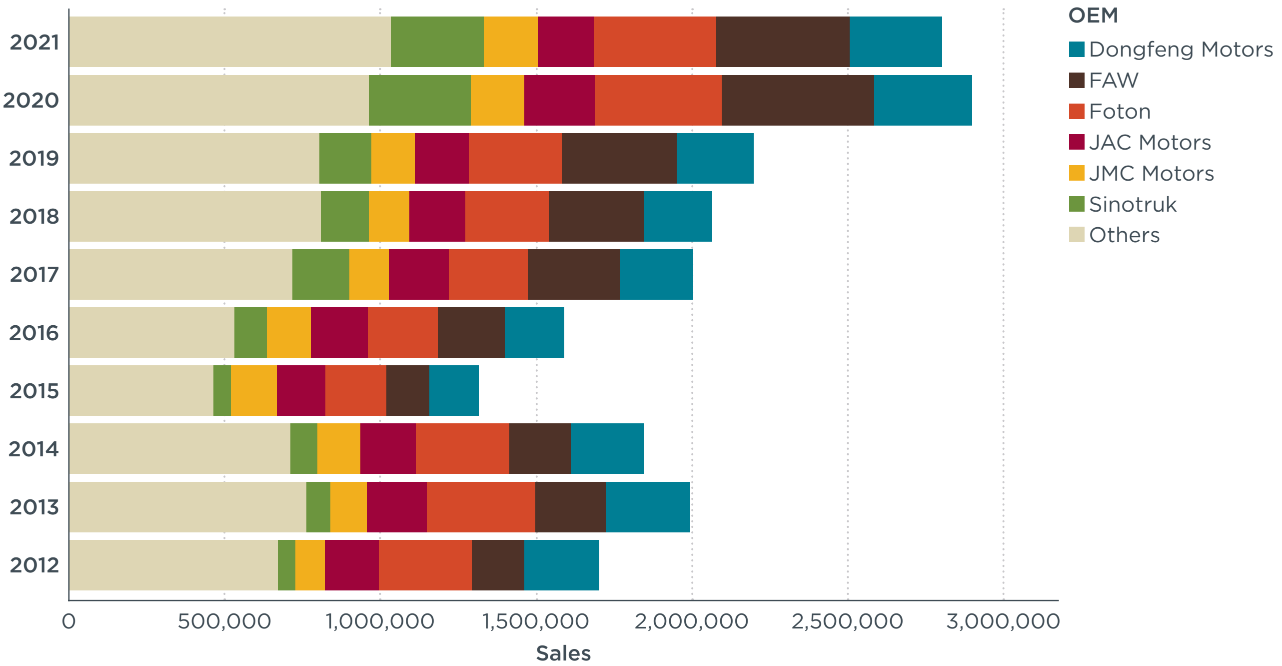


Figure 6. Top OEMs in HDV sales

Evolution of vehicle attributes and technologies

Curb weight

Curb weight refers to the total weight of a vehicle with standard equipment and necessary operating consumables such as fuel (Waring, 2022). For the representative segments and weight classes, on average, new HDVs have similar curb weights. Coaches, tractor trailers, and medium straight trucks saw no observable change over the period. The weight of city buses and dump trucks increased slightly in the second half of the decade but dropped again in 2021. The most notable change is found with heavy straight trucks, whose curb weight declined by 27% between 2012 and 2021, with a peak in 2016 (**Figure 7**). The decline can be explained by a regulatory change applied to trucks by the Ministry of Transportation (MOT) since September 2016 (MOT, 2016). MOT updated the categorization of running heavy-duty freight vehicles by axles and GVW; specifically, new trucks with two axles that in this study are heavy straight trucks with GVW between 16 and 20 tonnes, were now limited to no more than 18 tonnes of GVW; thus heavy straight trucks since 2017 have tended to reduce curb weight to guarantee a minimum level of payload (payload = GVW – curb weight).

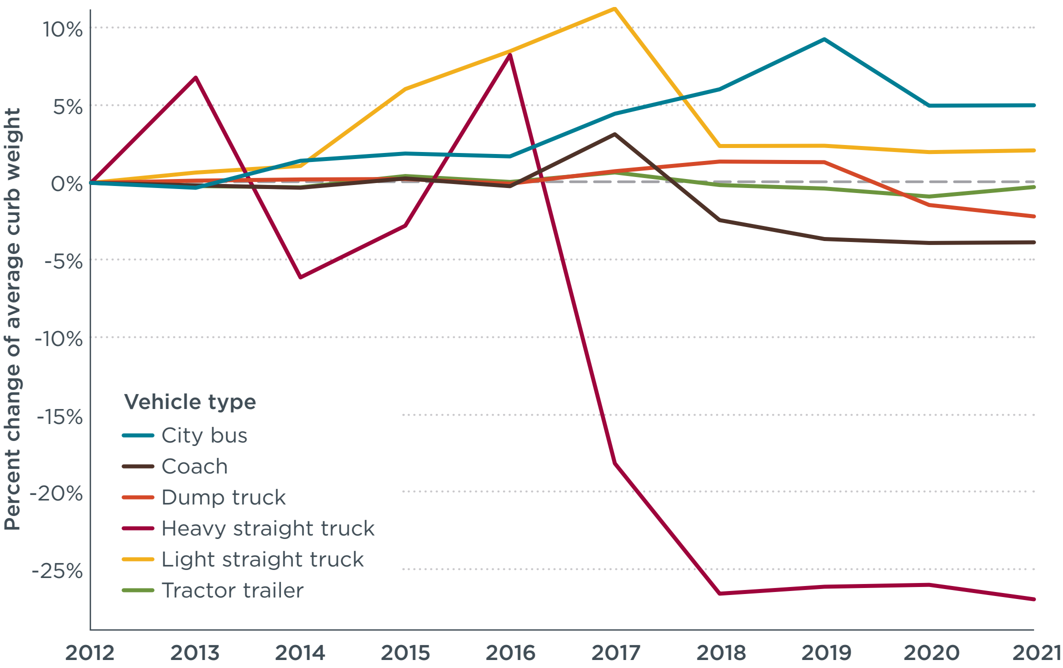


Figure 7. Change in curb weight by segment, 2012–2021

Engine power, energy density, and displacement

Diverse trends are observed for engine power and displacement of different segments. Dump trucks and tractor trailers saw increases of 30% and 28% in engine power, respectively, and 10% growth in engine displacement over the period. Such disparities in growth indicate that engines were increasing in power density over the years. Medium straight trucks, city buses, and coaches showed a binary pattern for both indicators: Approximately a 5–25% increase in engine power can be observed, while all witnessed a 5–10% decrease in engine displacement. Heavy straight trucks are the only segment seeing a significant decrease in power and displacement. Declines of 8% and 32% have been identified for power and displacement change, respectively (**Figure 8**). This fact is mostly driven by the curb weight changes illustrated in **Figure 7**.

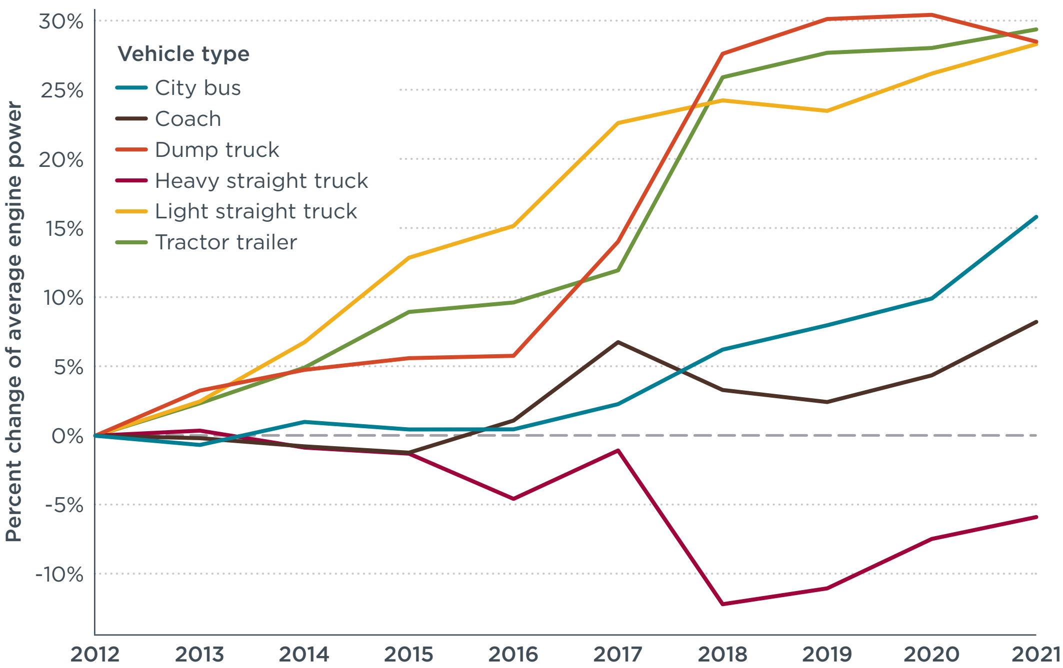


Figure 8. Change in engine power, 2012–2021

Figure 9 illustrates a pattern of change in engine power over the period. The most popular classes by 2021 were still 50-100 kW and 100-150 kW, but an increase in the share of engines with greater power can also be found. More specifically, engine power of 300-350 kW saw rapid growth from 1% (2012) to 18% (2021), and >400 kW from 0.01% (2012) to 5.8% (2021), respectively. On the other hand, engine power of less than 50 kW almost vanished in recent years, which implies a trend of enlargement in size and power for HDVs during the period.

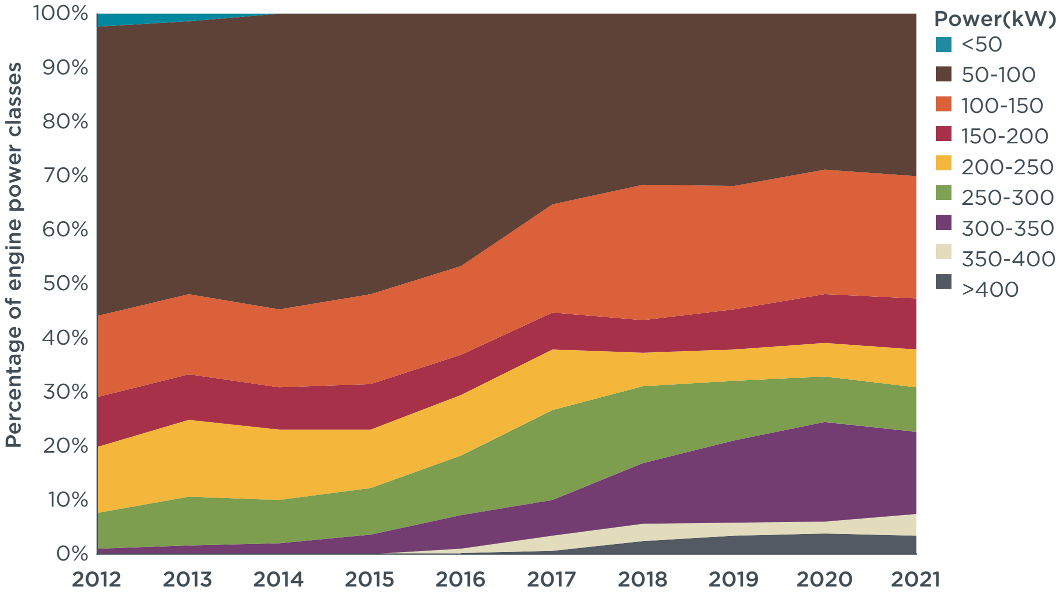


Figure 9. Change in engine power class, 2012–2021

The trends of power density for all segments are trending steadily upward. Over the last decade, power density grew by 45% and 40% for city bus and heavy straight trucks, the best performing segments. Tractor trailers and dump trucks were the most conservative segments, accounting for 15% of the progress throughout the period. Higher power density implies greater power per unit of engine displacement, which also reflects the improvement in and upgrade of engine technologies.

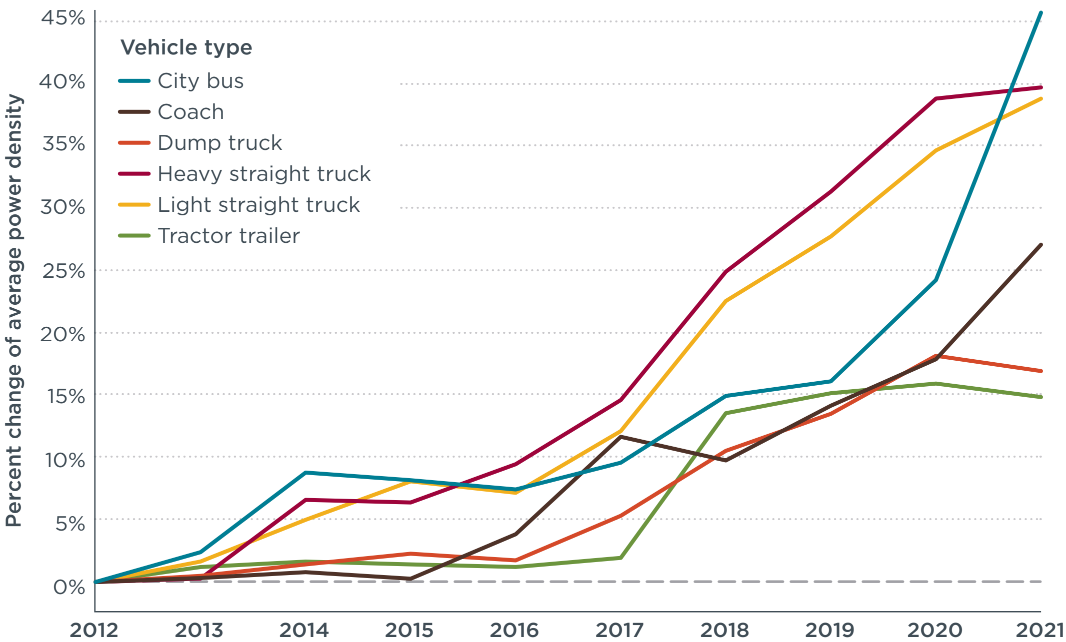


Figure 10. Change in power density, 2012–2021

CO_2 emission trends for mandated vehicle segments

Table 2 illustrates the coverage of mandated vehicle segments by fuel consumption standard. Coaches, straight trucks, and tractor trailers were mandated from Stage 1; city buses and dump trucks were then included starting in Stage 2. In this section, CO_2 trends of the most representative weight class range of each segment will be analyzed.

Table 2. Mandated vehicle segments by fuel consumption standards.

Segment	Stage 1 (2012-2015)	Stage 2 (2015-2019)	Stage 3 (2019-now)
City bus		O	O
Coach	O	O	O
Straight truck	O	O	O
Dump truck		O	O
Tractor trailer	O	O	O

O indicates the segments to be involved.

City bus

The average CO_2 emission rate declined over the past decade despite a brief increase between 2014 and 2017. The median value of the newly registered fleet in each year also witnessed a more significant reduction from 2012 to 2021, by about 13%. With China's prodigious efforts to electrify city bus fleets, sales of diesel-powered city buses with GVW of between 5.5 and 7 tonnes plummeted by about 85%. (**Figure 11**).

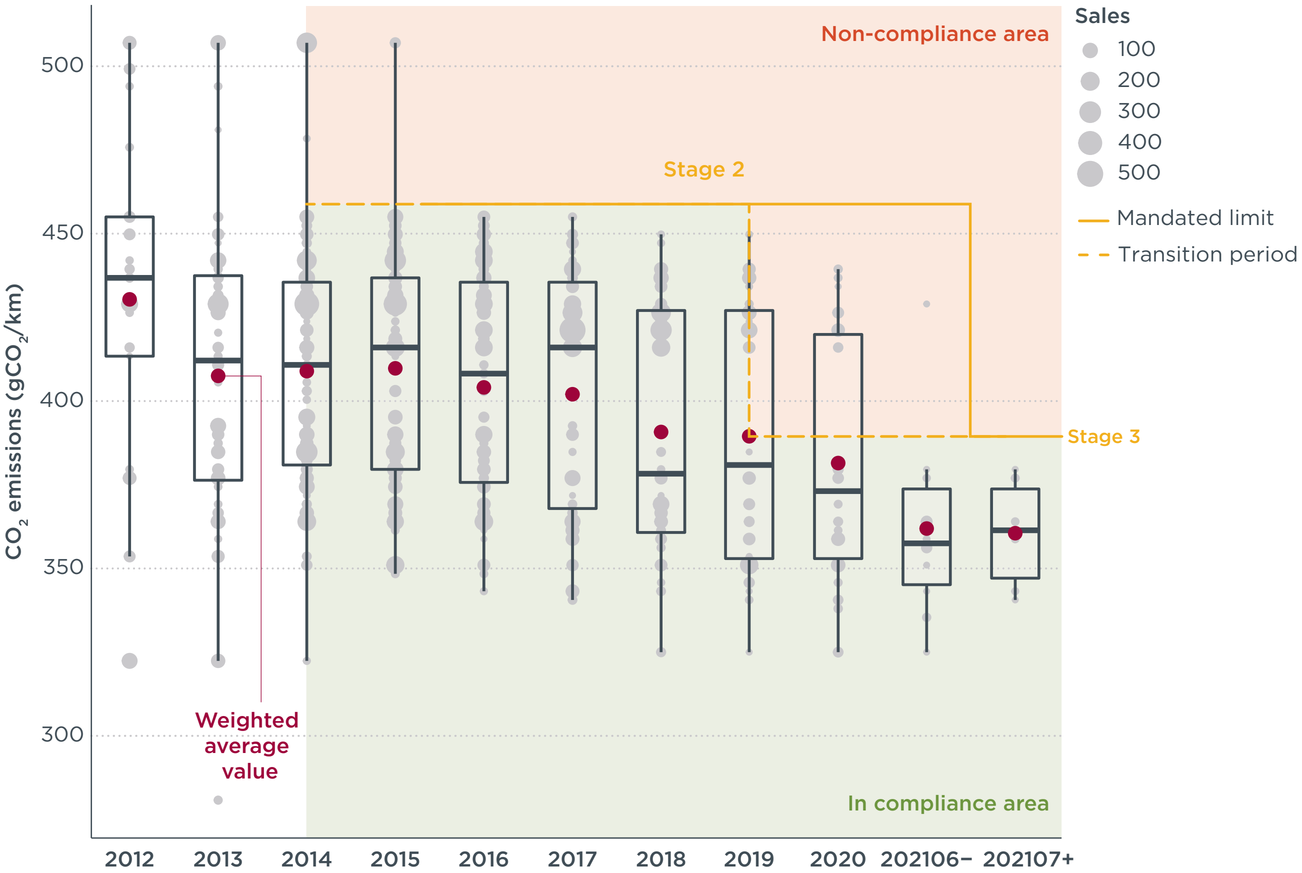
Diesel-powered city buses also experienced more stringent limits on fuel consumption, and thus, declines in their CO_2 emissions,[3] in the last decade. City buses were not involved in Stage 1 of the fuel consumption standard; in a revised standard on HDV fuel consumption (Stage 2), city buses with the GVW class of 5.5–7 tonnes were mandated for the first time to achieve an efficiency standard of 17.5 L/100km (455 gCO_2/km). Since 2019, the latest version of fuel consumption standards tightened the limit to 14.7 L/100km, which is equivalent to about 382 gCO_2/km. As China adopts a per-vehicle limit on type-approval fuel consumption, which is different from the U.S. focus on fleet average, only compliant vehicles can be produced and sold to the market. However, there are still some outliers each year because Stage 2 and Stage 3 came into force in July, and some legacy models produced in the first half of the year failed to catch up with the updated standard limits. In 2020, some legacy models were still sold as Stage 3 leaves 2 years of probation period before all models could be mandated[4]. In 2021, the fuel efficiency of buses improved and 100% of models have met the Stage 3 standard since July of that year.

China is in the early stages of developing the next phase of a fuel consumption standard with a hybrid and flexible regulation on each segment. The transition to China's CHTC driving cycle systems with a brand-new testing procedure will introduce a more stringent requirement on city buses' fuel efficiency performance.

3 Fuel consumption may not be directly convertible into GHG emissions; nevertheless, in this section we apply a conversion factor of 2,600 gCO_2/L, which is in line with the fuel consumption testing standard.

4 Stage 3 mandates that newly registered city buses comply with the new standard by July of 2019, and by July of 2021 for all models.

Table 3 presents manufacturer-average information about CO_2 emissions. The mean value in 2021 is approximately 363 g/km and the lead manufacturer, Ankai, has -0.7% lower performance on average.



Note: The red dot represents the average value of CO_2 emissions in each year; all emissions are converted from fuel consumption with a conversion factor of 2,600g CO_2/(Liter of diesel * 100 km). The yellow dashed line refers to a limit during transition period for newly type approved models with fresh MIIT registry code only, and the solid line indicates the standards for all updated type-approval models (including new type-approvals and variants). Specifically, "202106-" and "202107+" refer to the first (January to June) and second (July to December) half of 2021, respectively.

Figure 11. CO_2 emissions of city buses, 2012–2021

Table 3. CO_2 information about city bus OEMs in 2021

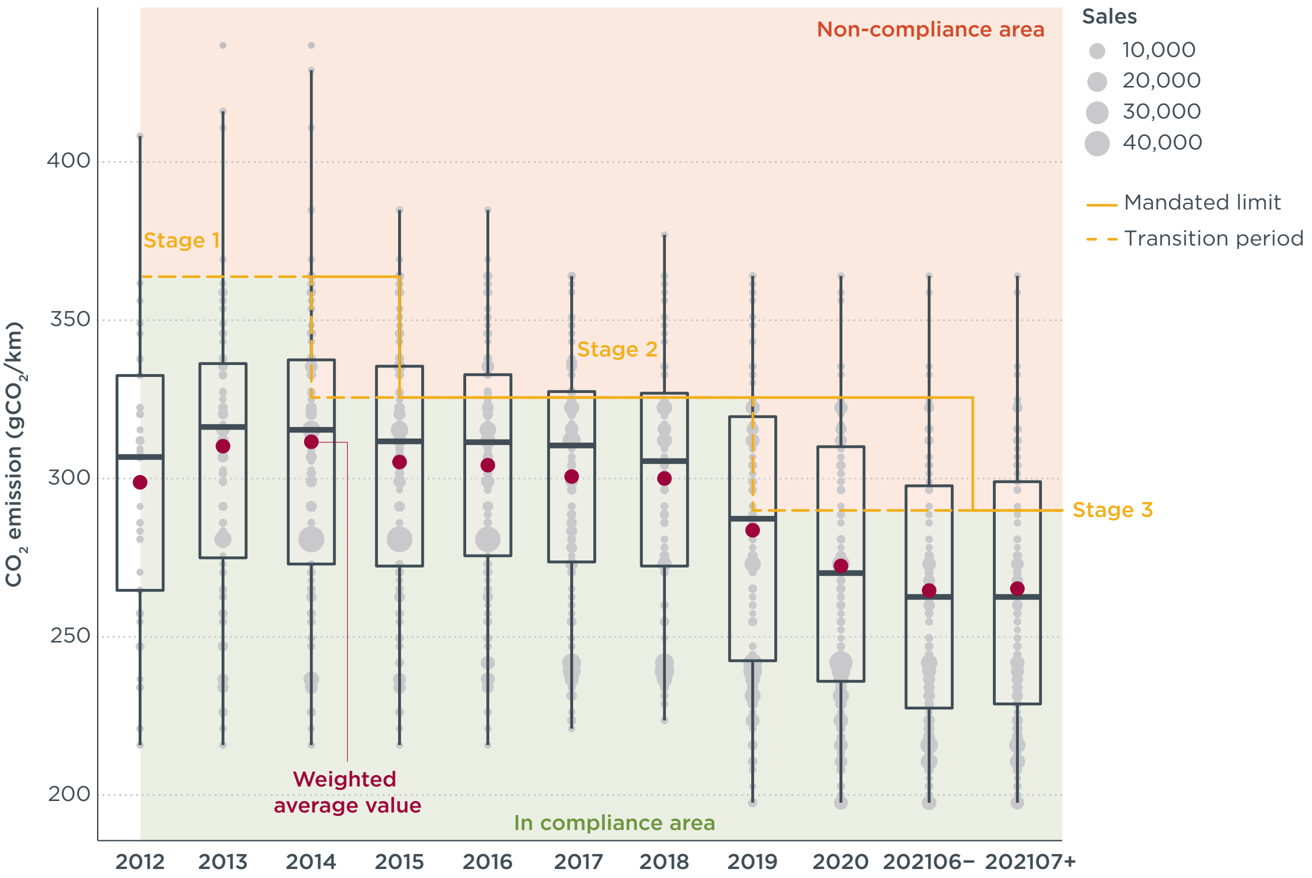
OEM	Average CO_2 emissions in 2021 (g/km)	Deviation from mean (%)	Sales (%)
Ankai	360.9	-0.7	60.4
Yutong	372.8	2.6	16.2
Dongfeng Motors	373.4	2.7	9.0
Zhongtong Bus	353.2	-2.8	6.3
Others	361.1	-0.6	8.1

Coach

Coaches were first regulated in 2012, when Stage 1 of the heavy-duty vehicle fuel consumption standard took effect. The limits on coaches became more stringent in Stages 2 and 3. The fuel consumption limit for the most representative weight class of coaches (3.5–4.5 tonnes) was mandated to be 14 L/100km (Stage 1), 12.5 L/100km (Stage 2) and 10.6 L/100km (Stage 3). By direct conversion with a rate of 2,600g CO_2 / Liter of diesel, CO_2 emission limits for each stage are 364.0, 325.0, and 275.6 gCO_2/km, which are illustrated in **Figure 12**.

Diesel-powered coaches have seen a steady decline in terms of permitted levels of fuel consumption, or CO_2 emissions, in the past decade. Over the past 3 years, average CO_2 emissions declined by approximately 15% because of the Stage 3 standard (see Figure 11). The trend of diesel coaches in the early years was almost flat and Stage 2 failed to have much impact on fuel efficiency improvements for coaches. Approximately 20% of coaches sold during Stage 2 and 3 were above the limit, which suggests that existing models that were type approved in the previous Stage continued to be sold. In other words, there would be a delay in realizing fuel consumption improvements in practice. The actual improvement of increasingly stringent regulations will therefore be weakened.

Table 4 summarizes CO_2 information about coach OEMs in 2021. Leading OEMs such as JMC Motors and SAIC produced coaches with approximately 4.4% lower CO_2 emissions than the mean value; however, smaller OEMs (referred to as "Others") provided inferior models in terms of CO_2 emissions.



Note: The red dot represents the average value of CO_2 emissions in each year; all emissions are converted from fuel consumption with a conversion factor of 2,600g CO_2/(Liter of diesel * 100 km), according to the Chinese Stage 3 HDV fuel consumption testing standard. The yellow dashed line indicates a limit during the transition period for newly type approved models with fresh MIIT registry code only, and the solid line indicates the standards for all updated type-approval models (including new type-approvals and variants). Specifically, "202106-" and "202107+" refer to the first (January to June) and second (July to December) half of 2021, respectively.

Figure 12. CO_2 emissions of coaches, 2012–2021

Table 4. CO_2 information about coach OEMs in 2021

OEM	Average CO_2 emissions in 2021 (g/km)	Deviation from mean (%)	Sales (%)
JMC Motors	223.1	-4.4	38.7
SAIC	222.9	-4.4	33.7
Foton	242.2	3.9	10.3
Dongfeng Motors	255.5	9.6	3.5
Others	273.5	17.3	13.7

Dump trucks

Dump trucks are trucks that deliver raw materials such as ores and sands, and that feature a lifting function. Dump trucks were first regulated in Stage 2 of the HDV fuel consumption standard. The fuel consumption limit of the Stage 2 standard for dump trucks with GVW between 25 and 31 tonnes was set to be 47 L/100km (1,222 gCO_2/km); a more stringent limitation was put into effect in Stage 3, at 41L/100km (1,066 gCO_2/km).

The diagram below illustrates the CO_2 emission trend of dump trucks during the past decade (**Figure 13**). Few improvements on fuel consumption have been observed during this period; the average CO_2 emission of newly type-approved dump trucks remained within a range of 1,100 gCO_2/km to 1,150 gCO_2/km over the 2012-2021 period. Dump trucks sold after July of 2021 failed to meet the newly adopted Stage 3 standard, which is due to a temporary postponement of the new regulation for months, according to a person familiar with the matter.

Table 5 gives summary information about OEM-specific CO_2 emissions for dump trucks ranging in weight from 25 to 31 tonnes. Dongfeng Motors produced dump trucks with a CO_2 emission level 5.2% lower than average; smaller OEMs, labeled "Other", deviated from the mean value by 8%.

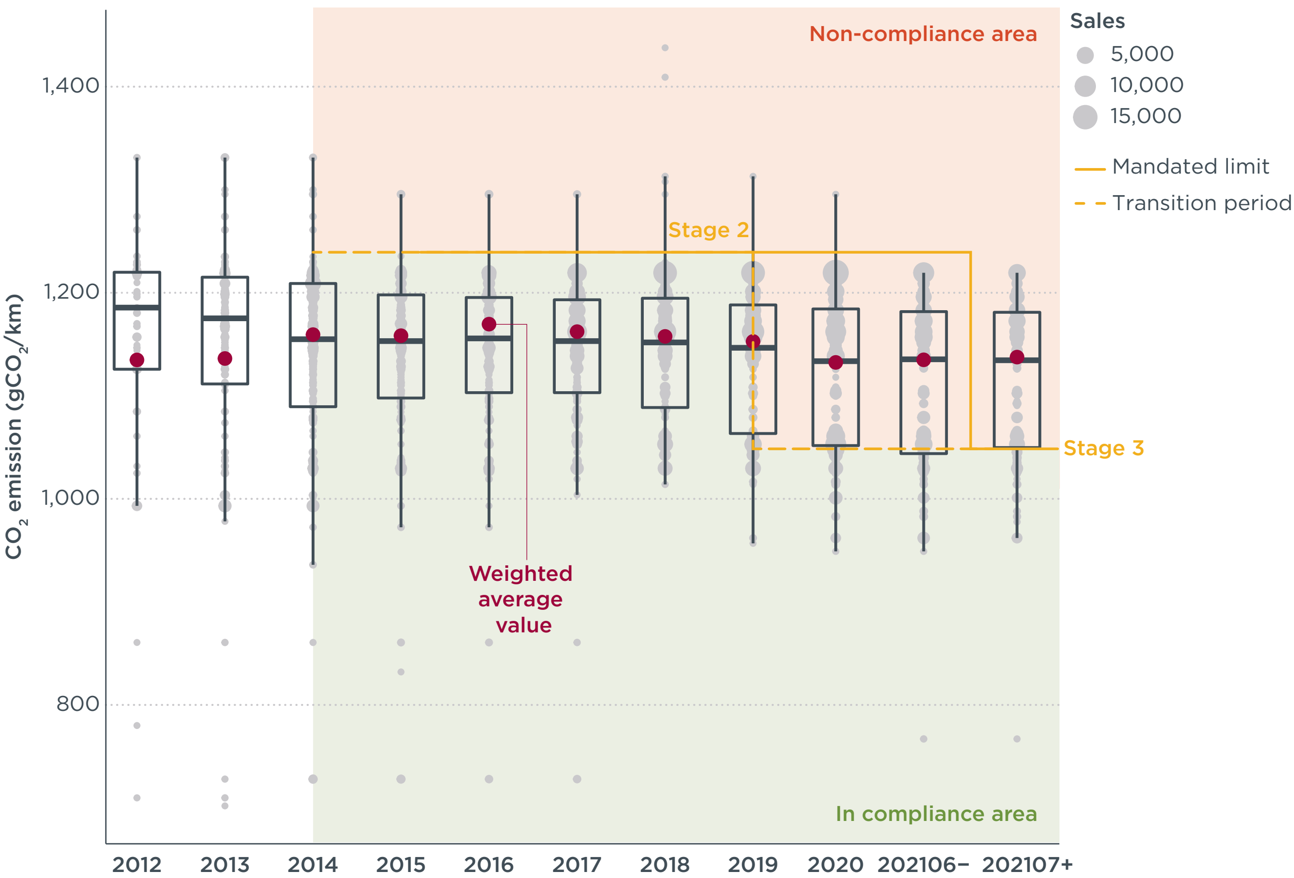


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Figure 13. CO_2 emissions of dump trucks, 2012–2021

Table 5. CO_2 information about dump truck OEMs in 2021

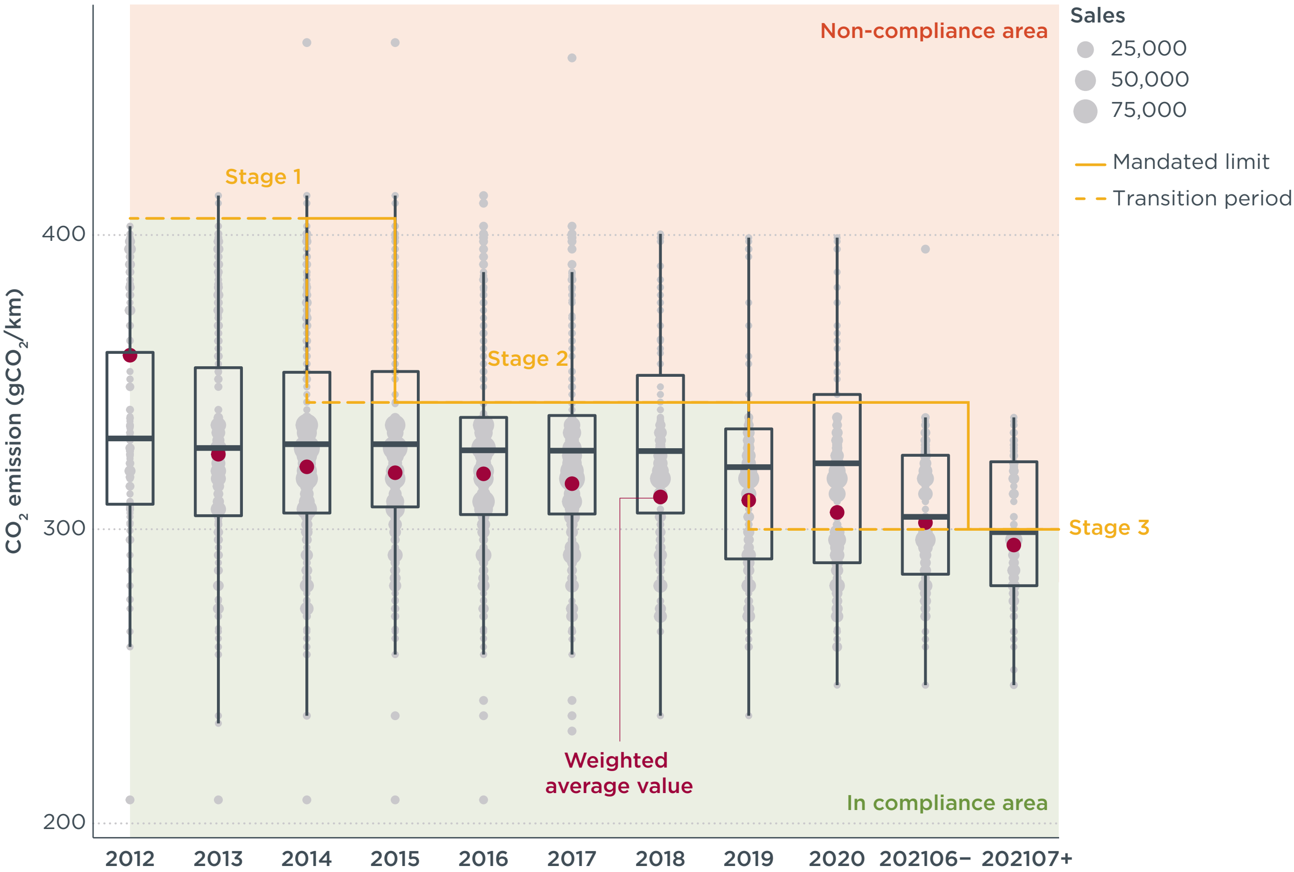
OEM	Average CO_2 emissions in 2021 (g/km)	Deviation from mean (%)	Sales (%)
Shaanxi Auto	1157.0	8.9	17.0
Dongfeng Motors	1007.3	-5.2	15.2
Sinotruk	1041.9	-1.9	14.9
Hongyan	1121.0	5.6	14.0
FAW	1097.5	3.3	13.0
Foton	1026.6	-3.3	8.6
Others	977.5	-8.0	17.3

Medium & heavy straight trucks

Straight trucks were first covered under fuel consumption standards in 2012, i.e., in Stage 1 of the fuel consumption standard for HDVs. In this study, light and heavy straight trucks are examined in **Figure 14** and **Figure 15**, respectively. Fuel consumption limits for medium straight trucks (3.5-4.5 tonnes) were mandated as 15.5 L/100km (403 gCO_2/km), 13 L/100km (338 gCO_2/km) and 11.5 L/100km (299 gCO_2/km); for heavy straight trucks with GVW between 16 and 20 tonnes, the upper bound for each Stage was set to be 35 L/100km (910 gCO_2/km), 31.5 L/100km (819 gCO_2/km) and 27 L/100km (702 gCO_2/km), respectively.

As with other truck segments, medium and heavy straight trucks saw very limited improvement in 2021 relative to 2012. CO_2 emissions of medium straight trucks declined by approximately 10%, but heavy straight trucks saw little progress over the entire period. Specifically, scarcely any new light trucks (less than 1%) failed to meet Stage 2 during 2016-2018, but a majority (50% for the first half of 2021 and 85% for the second half) of newly produced light trucks met the Stage 3 standard; for heavy trucks this pattern can also be observed in the second half of 2021 particularly (approximately 75%), and the weighted average of the heavy-duty fleet fell by 5%. In other words, the newly registered vehicles did not improve as much as the updated standard required, which also implies that more enforcement may be needed to improve the fuel efficiency of straight trucks.

Table 6 and **Table 7** present summaries of CO_2 emissions of medium and heavy straight truck OEMs in 2021. For medium straight trucks, JMC Motors produced models with the best performance in terms of CO_2 emissions among all major players. On the other hand, for heavy straight trucks, Dongfeng Motors, the lead company in this weight class, showed a -3.3% deviation from the mean value.

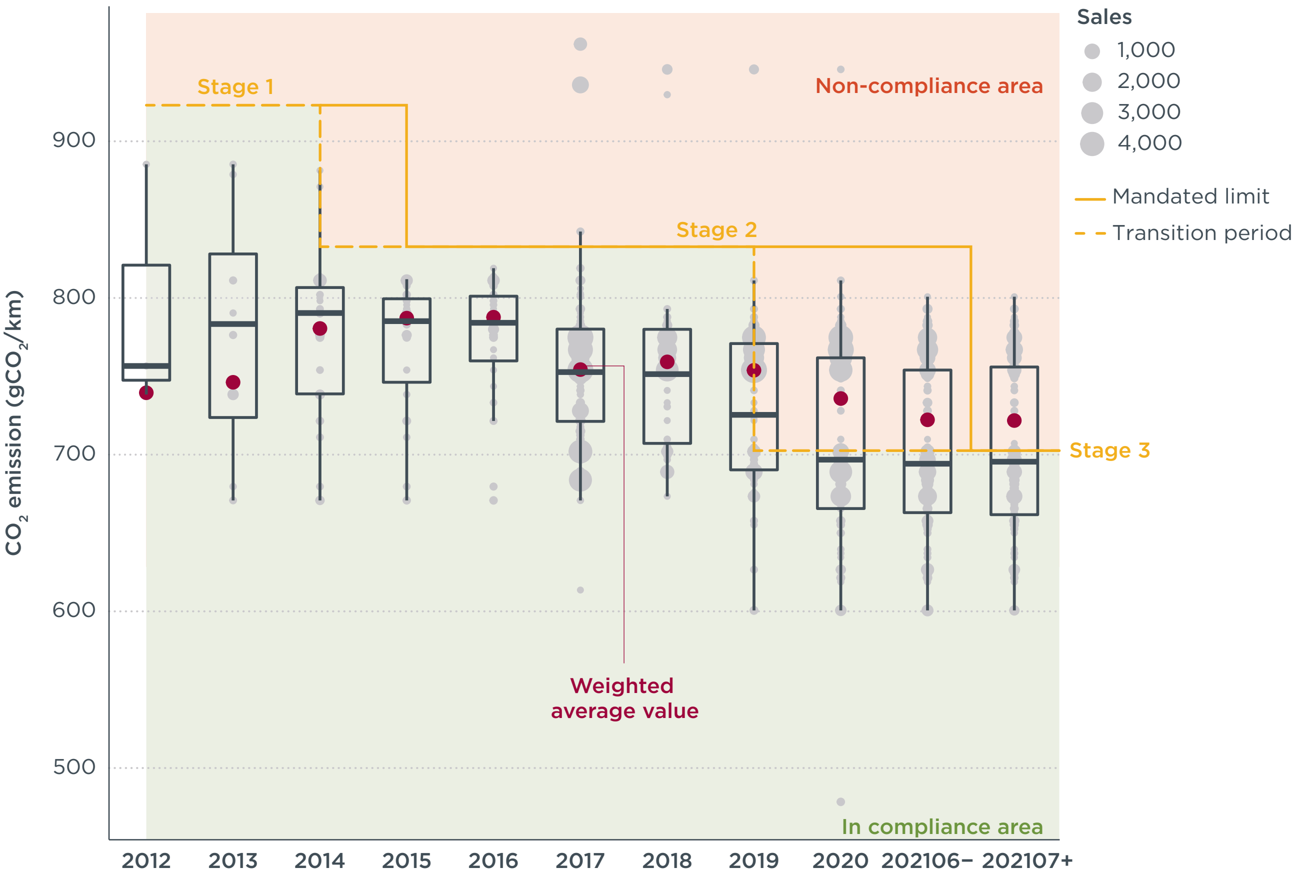


Note: The red dot represents the average value of CO_2 emissions in each year; all emissions are converted from fuel consumption with a conversion factor of 2,600g CO_2/(Liter of diesel * 100 km), according to the Chinese Stage 3 HDV fuel consumption testing standard. The yellow dashed line indicates a limit during the transition period for newly type approved models with fresh MIIT registry code only, and the solid line indicates the standards for all updated type-approval models (including new type-approvals and variants). Specifically, "202106-" and "202107+" refer to the first (January to June) and second (July to December) half of 2021, respectively.

Figure 14. CO_2 emissions of medium straight trucks, 2012–2021

Table 6. CO_2 information about medium straight truck OEMs in 2021

OEM	Average CO_2 emissions in 2021 (g/km)	Deviation from mean (%)	Sales (%)
Foton	299.2	-0.3	22.6
JAC Motors	305.2	1.7	20.4
JMC Motors	284.8	-5.1	12.4
Sinotruk	294.0	-2.0	9.9
FAW	301.8	0.6	7.8
Others	305.7	1.9	26.8



Note: The red dot represents the average value of CO_2 emissions in each year; all emissions are converted from fuel consumption with a conversion factor of 2,600g CO_2/(Liter of diesel * 100 km), according to the Chinese Stage 3 HDV fuel consumption testing standard. The yellow dashed line indicates a limit during the transition period for newly type approved models with fresh MIIT registry code only, and the solid line indicates the standards for all updated type-approval models (including new type-approvals and variants). Specifically, "202106-" and "202107+" refer to the first (January to June) and second (July to December) half of 2021, respectively. Due to missing information of type-approval fuel consumption in 2012, few dots have been plotted.

Figure 15. CO_2 emissions of heavy straight trucks, 2012–2021

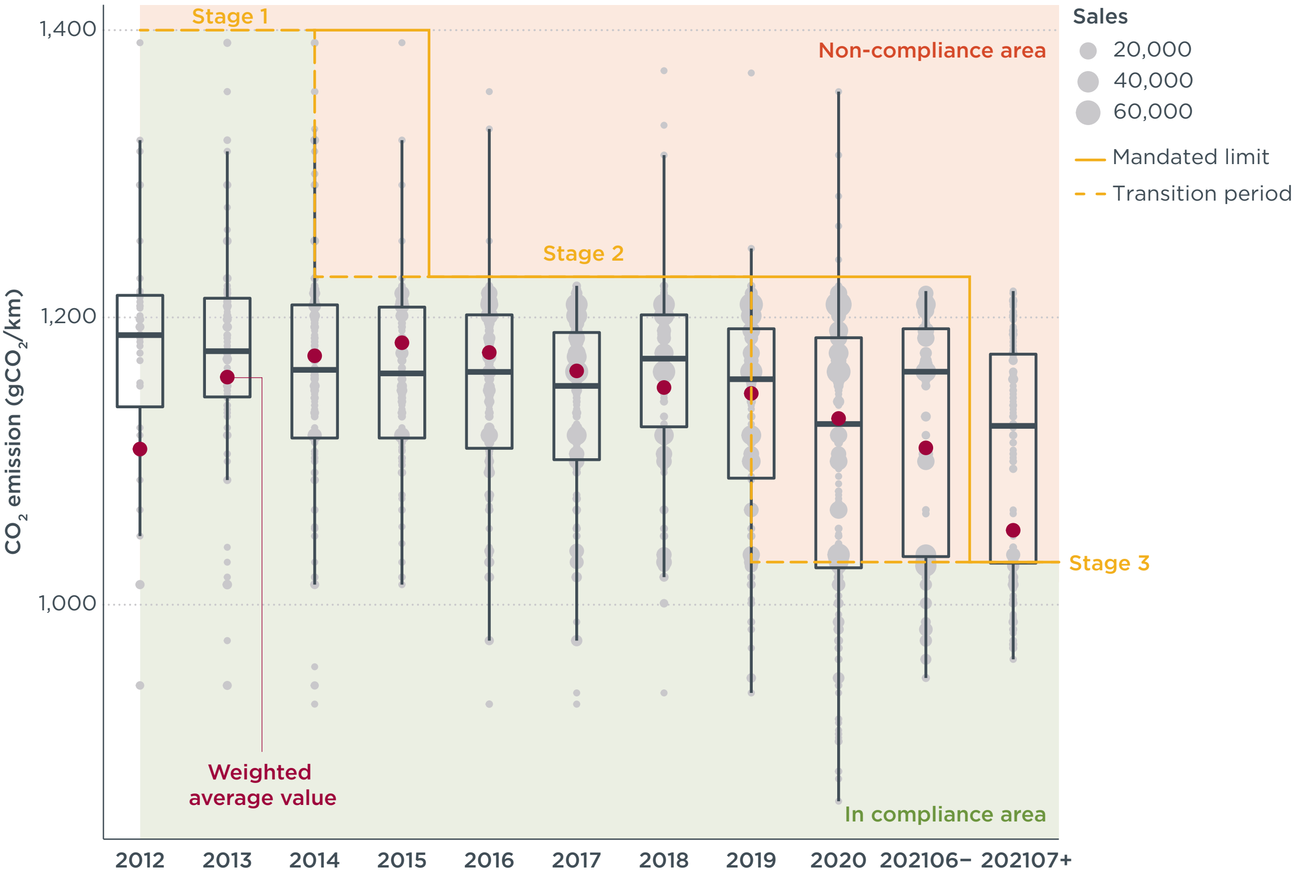
Table 7. CO_2 information about heavy straight truck OEMs in 2021

OEM	Average CO_2 emissions in 2021 (g/km)	Deviation from mean (%)	Sales (%)
Dongfeng Motors	697.8	-3.3	29.9
FAW	740.0	2.4	29.1
Foton	708.3	-1.9	14.1
JAC Motors	743.9	3.0	11.7
Sinotruk	711.1	-1.5	7.2
Others	750.5	3.9	7.6

Tractor trailers

Tractor trailers became one of the most important segments for fuel consumption regulation in the past decade. Regulations for the segment were first mandated by Stage 1 of the fuel consumption standard and requirements became more stringent in the succeeding stages. Specifically, for tractor trailers with GCW between 46 and 49 tonnes, the limit of vehicle fuel consumption was mandated to be 54 L/100km (Stage 1), 47 L/100km (Stage 2) and 40 L/100km (Stage 3), which can also be expressed as 1,404 gCO_2/km, 1,222 gCO_2/km, and 1,040 gCO_2/km of CO_2 emissions (**Figure 16**). Since it was launched, a dominating majority (98%) of newly registered tractor trailers during Stage 1 and Stage 2 complied with both standards, except another 2% of outliers exceeded the limit of the Stage 2 standard. The average fuel consumption performance in 2021, however, significantly lagged behind the regulated value set by Stage 3. According to our datasets, about 50% of tractor trailers sold in the second half of 2021 still exceeded the Stage 3 limit, even though the average emission was improved by 10% compared to the first half. This implies that, like dump trucks, the latest efforts may fail to reduce CO_2 emissions from tractor trailers via more stringent fuel consumption standards. No public change was announced; however, full implementation of the Stage 3 standard for tractor trailers was postponed for months, according to someone familiar with the matter.

Table 8 illustrates CO_2 information of major tractor trailer OEMs in 2021. Dongfeng Motors, Sinotruk and Shaanxi Auto produced models with lower CO_2 emissions than average. Specifically, Dongfeng Motors witnessed a deviation of -4.6% from the mean value.



Note: The red dot represents the average value of CO2 emissions in each year; all emissions are converted from fuel consumption with a conversion factor of 2,600g CO_2/(Liter of diesel * 100 km), according to the Chinese Stage 3 HDV fuel consumption testing standard. The yellow dashed line indicates a limit during the transition period for newly type approved models with fresh MIIT registry code only, and the solid line indicates the standards for all updated type-approval models (including new type-approvals and variants). Specifically, “202106-” and “202107+“ refer to the first (January to June) and second (July to December) half of 2021, respectively.

Figure 16. CO_2 emissions of tractor trailers, 2012–2021

Table 8. CO_2 information about tractor trailer OEMs in 2021

OEM	Average CO² emissions in 2021 (g/km)	Deviation from mean (%)	Sales (%)
FAW	1151.5	2.3	28.2
Sinotruk	1122.7	-0.2	19.3
Dongfeng Motors	1073.5	-4.6	15.4
Shaanxi Auto	1120.4	-0.5	13.9
Foton	1153.2	2.5	12.8
Others	1109.1	-1.45	10.4

Efficiency technology trends by diesel engine

Technologies for HDV efficiency saw great progress during the last decade. Because there is an information gap regarding engine and vehicles when a vehicle is being registered for type-approval, in this section analysis will be based on five distinct engine displacement classes, namely, ≤ 3L, 3-6L, 6-9L, 9-12L and ≥ 12L. Data regarding engines is available until 2020.

Transmission

Four types of transmission are commonly applied on HDVs: manual transmission (MT), automatic transmission (AT), automated manual transmission (AMT), and continuously variable transmission (CVT). MT is still the most popular type of transmission for heavy-duty trucks; this technology requires driver control of the clutch when trucks change speeds. AT is an updated transmission technique that can shift the gearbox automatically by algorithm. Its greatest advantage is to eliminate the need for a driver to focus on shifting, allowing them to be more careful on the road. AMT is a type of hybrid technique with features of both manual and automatic transmissions; typically it is based on a conventional manual transmission but uses automatic actuation to operate the clutch mechanism. CVT provides limitless gear ratios with seamless change by two pulleys and a belt or chain, so that CVT is often more fuel-efficient than other transmission types (Hearst Autos Research, 2020).

Regarding market penetration of each transmission technology (**Figure 17**), MT dominated the market in the 2012 to 2020 period for each engine displacement class, especially for most light and medium trucks with engine displacement of less than 12 L. Alternative transmission technologies such as AT and AMT saw moderate growth in these classes but still accounted for no more than 10% of market share. For the heaviest trucks with engine displacement greater than 12 L, AT and AMT claimed a 27% market share in 2012 but this declined to 18% in 2020. CVT technology has been used in light and medium classes of trucks only, as this technology may not fully support the performance needed in heavier trucks; on the other hand, CVT also entails more maintenance expense than MT, thus such technology is still not popular for HDVs in China (Hearst Autos Research, 2020).

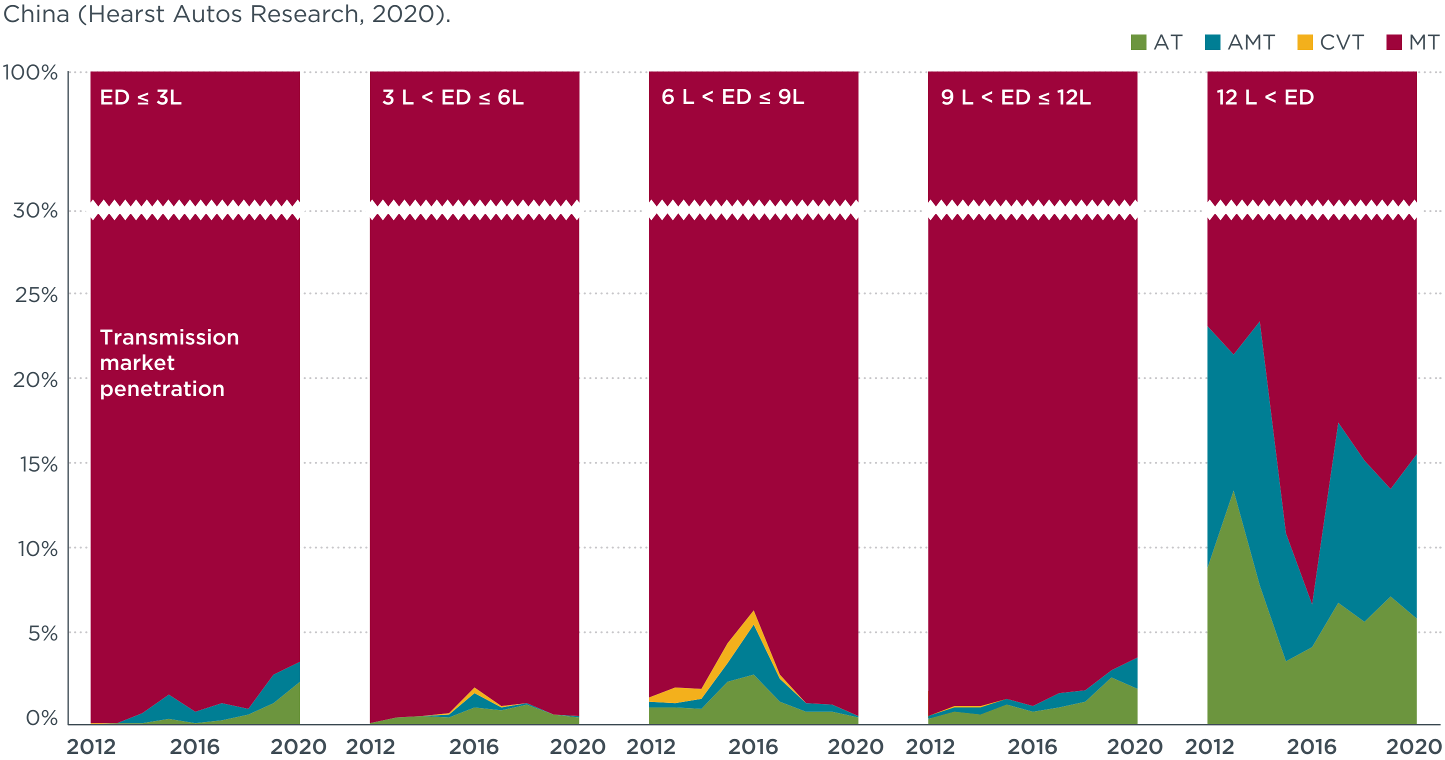


Figure 17. Market penetration by various transmission technologies, 2012–2020. ED refers to engine displacement.

Diesel injection technologies

The performance of diesel engines is greatly influenced by injection system design, not only for fuel efficiency, but emissions as well. Diesel injection technologies are created to supply fuel to the engine cylinder, where diesel is combusted and power is generated. High-pressure common rail is a popular diesel injection technology applied to diesel engines and used in heavy-duty trucks in China. Common rail provides improved vaporization from the surface of fuel droplets, making it more fuel efficient by combining oxygen with vaporized fuel for more complete combustion.

Figure 18 shows the development of market penetration of high-pressure common rail technology during last decade. For each engine displacement class, common rail claims greater market share for lighter vehicles with engine displacement lower than 3L; the common rail market penetration increased to about 99% in 2020. The dominance of common rail technology declined for larger engine displacements, such as those greater than 12L; 38% of engines applied other injection technologies such as intake manifolds and pump nozzles. Because high-pressure common rail technology can improve vehicle output performance on dimensions such as torque, it is reasonably assumed that this technology helped increase combustion efficiency and energy density for commercial fleets during the last decade. However, several key components of the technology, such as injectors and fuel filters, show high sensitivity to diesel quality, which suggests a need for more stringent requirements on fuel quality.

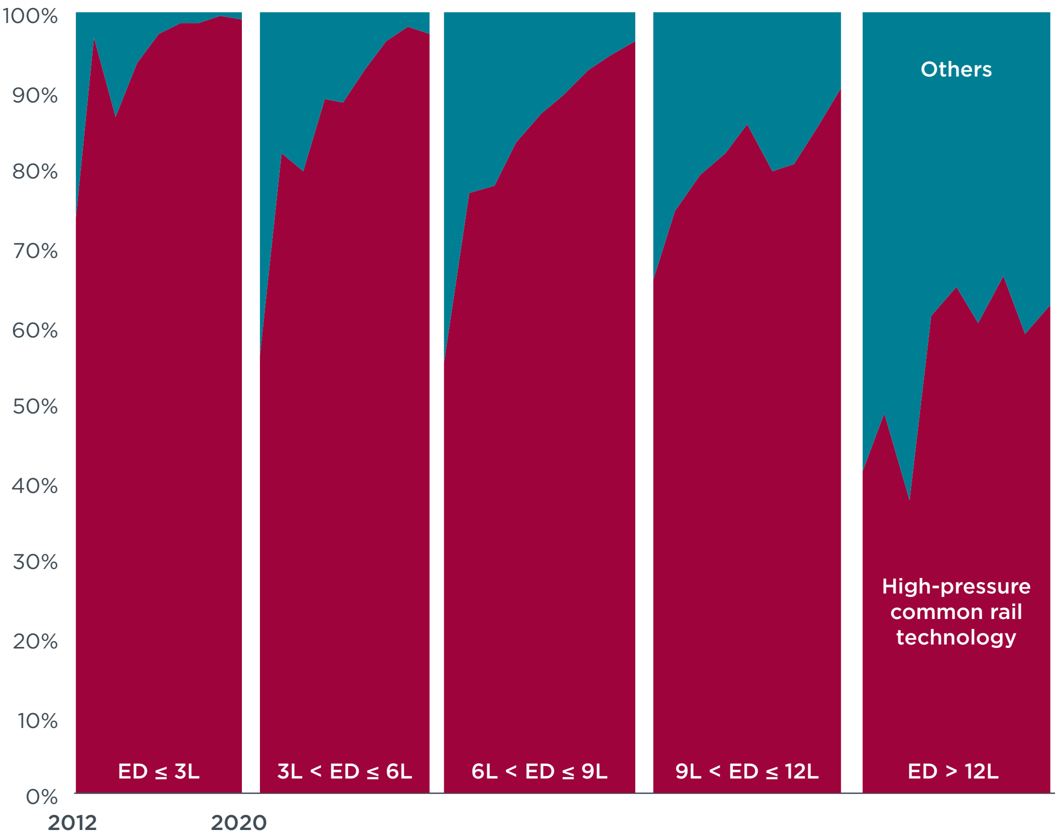


Figure 18. Market penetration by diesel injection technologies 2012–2020, ED refers to engine displacement

Emission control technologies

China adopted China I as its first effort to curb vehicle emissions at the very beginning of the 21st century, with more advanced aftertreatment technologies applied thereafter. During China IV (i.e., 2013-2017), the most commonly applied emission control technologies were selective catalytic reduction (SCR), exhaust gas recirculation (EGR) and diesel oxidation catalyst (DOC). SCR is the most popular technology on board

HDVs in China; it is a specific technology for reducing NO_x emissions by injecting automotive-grade urea, or ammonia for conversion, where nitrogen and a fraction of carbon dioxide will be produced (Majewski, 2005). DOC is a technique applied on board for catalytic reaction to convert carbon monoxide, gas phase hydrocarbons and other diesel particulates into harmless products. Besides, DOC is able to oxidize nitric oxide to nitrogen dioxide, which supports performance of diesel particulate filters and SCR catalysts used for NO_x reduction (Majewski, 2021). EGR is another technology used to reduce nitrogen oxide emission by recirculating the air outflow and then diluting oxygen concentration in the incoming air stream for higher combustion efficiency in the cylinders (Jääskeläinen & Magdi K., 2020).

Diesel particulate filter (DPF) is becoming popular during China V due to its high removal efficiency of particulate matter. DPF is a technique used to capture and remove diesel particulates from tailpipe emissions. After years of development work, diesel particulate filter materials are now able to achieve greater than 90% filtering efficiency (Majewski, 2020). DPF was first used in 2016 and since then has become indispensable as an efficient component of a technology combination. In 2020, DPF was used in 70% of aftertreatment technology combinations. Given stricter requirement on tailpipe emissions from HDVs in recent years, many of these technologies are used in various combinations as a strategy for achieving high levels of emission reduction.

Figure 19 illustrates the market pattern of the most popular combinations of emission control technology from 2012 to 2020. SCR and EGR are the two leading technology combinations during the period. SCR (alone, or in combination with DOC, and blue in the figure) dominated the market early in the period years, but a broader combination of technologies has prevailed since 2019, when China VI took effect. In 2012, 44% of trucks carried no after-treatment technology onboard, but it became indispensable for new models since 2013 when China IV took effect and introduced more stringent emission control requirements. Recently, more exhaustive combinations of technology have been used; since the implementation of China VI-a, for example, the combination EGR+SCR+DOC+ASC[5]+DPF accounted for 48% of the market in 2020. This shift of pattern also suggests that policies are exerting growing pressure on heavy-duty vehicle fleets to cut emissions; OEMs must develop cheaper and more efficient technologies to adapt to increasingly stringent regulations.

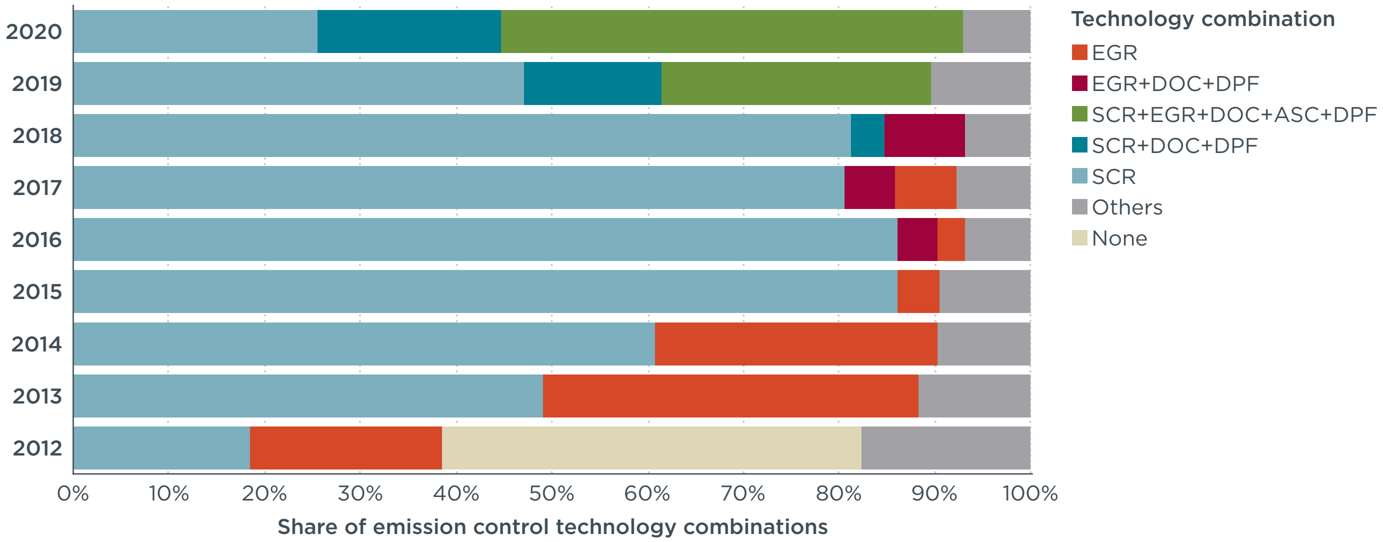


Figure 19. Emission control technology adaptation for HDVs, 2012–2020

5 Ammonia slip catalyst

CO_2 and NO_x emission trends from truck engines

Figure 20 shows CO_2 and NO_x emission trends from truck engines during the 2012-2021 period. In this diagram, hundreds of representative engines with varying displacements are illustrated. China has become increasingly stringent in setting NO_x emission standards in the past decade; the latest regulation is China VI, which went into effect in 2021. China has applied World Harmonized Transient Cycle (WHTC) on NO_x emission testing with a limit of 0.46 g/kWh since China VI; however, China does not yet control CO_2 emissions at the engine level, so CO_2 emissions did not decline significantly along with the decline in NO_x emissions (**Figure 20**). The average value of CO_2 type approval emissions was around 690 g/kWh across the period (**Figure 21**).

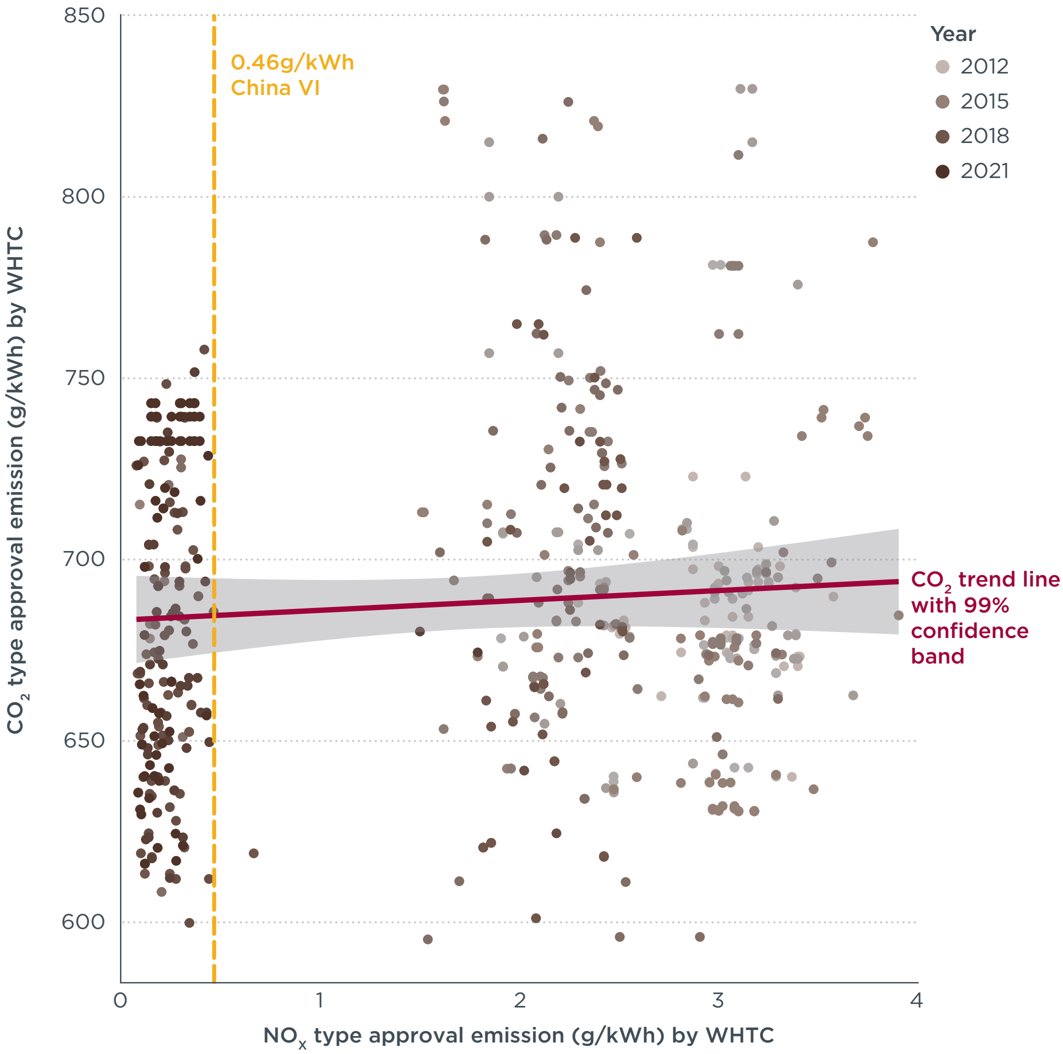


Figure 20. Type approval values of CO_2 and NO_x emissions from diesel engines, 2012-2021

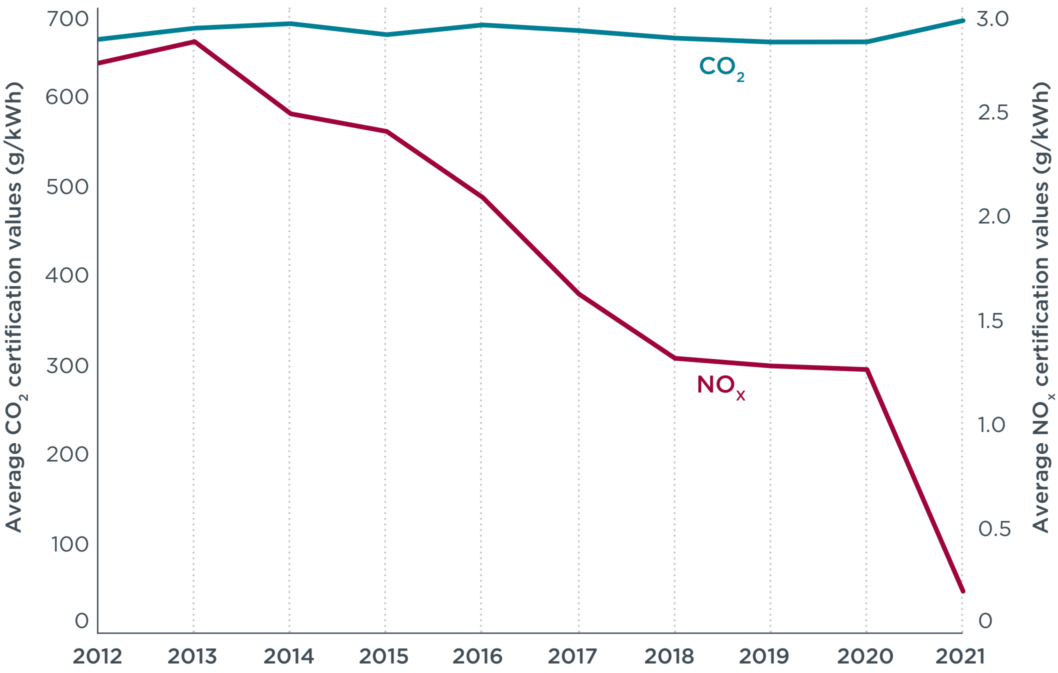


Figure 21. Average type-approval values of CO_2 and NO_x from diesel engines, 2012-2021

Policy recommendations

This study describes in broad strokes how China's diesel-engine HDV market developed in last decade. China's administrative management of the HDV sector, including control of emissions and reductions in fuel consumption, progressed significantly over the years and the evolving standards advanced this transition considerably. However, we also identified some challenges to the HDV industry becoming cleaner and more technologically advanced. Based on our findings, we provide policy recommendations as follows:

1. Utility vehicles should be fully included in the next stage of fuel consumption standards, to cover a fuller set of energy consumers. China explicitly mandates five segments of HDVs—straight trucks, dump trucks, tractor trailers, city buses, and coaches, but utility vehicles—those used for specific functions such as sanitation, engineering, and others—are not yet regulated. Utility vehicles account for about 10% of market share in 2021, so it is important to regulate the fuel efficiency of such vehicles more strictly. Moreover, the boundary between utility vehicles and other segments is still vague, which creates loopholes for avoiding fuel consumption regulation (interpreting regulations according to one's interests).
2. A more inclusive and integrated emission control regulation for both pollutant and GHG emissions should be enacted to guide development of heavy-duty vehicles. Currently, China does not control GHG emissions at the engine or vehicle level. A switch from the current fuel consumption standard to regulation of GHG emissions will cover more greenhouse gases such as N_2O, CH_4, and others, which can provide the public with accurate information regarding GHG emissions from HDVs. In addition, a complete GHG emission standard will provide the HDV industry with a long-term vision and allow it to balance control of pollutants and GHG emissions under various technology combinations. China launched its nationwide carbon trading scheme in 2021 and is working to include more industries. Applying complete GHG emission regulations on HDVs also helps lay a solid foundation for future work on carbon trading and climate protection.
3. Electrification is key to decarbonizing road transport, although clean diesel engine technologies should still be encouraged. In this report, we have found

that China's HDVs are equipped with more advanced engine technologies such as common rail to improve fuel efficiency and reduce exhaust emissions. We encourage further development of clean diesel engine technologies as a strategy for making the transition to full electrification smoother and affordable. In addition, China has applied a dual-credit policy to promote production of electric passenger vehicles; similarly, we recommend that the upcoming credit policy on HDVs also highlight the effort to improve engine fuel efficiency and performance.

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