Commercial Diesel Vehicle Technologies

In the Face of Global Emissions Regulations

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Introduction

Emissions of carbon dioxide (CO_2) from vehicles and nitrogen oxides (NO_X) from diesel engines are a significant contributor to poor air quality, ozone pollution and climate change. According to the International Council on Clean Transportation (ICCT), although heavy-duty vehicles (HDVs) in the US and EU account for less than 5% of the total on-road vehicle fleet, they are responsible for close to 50% of the NO_X emissions from mobile sources. An overwhelming majority of heavy-duty vehicles are powered by diesel engines today.

However, heavy-duty vehicles are also viewed as a lifeline for trade and commerce. Complete electrification of the truck fleet is still decades away. It is, therefore, imperative for countries to regulate NO_X and CO_2 emissions reductions from diesel HDVs to spur innovation in engine and aftertreatment technologies in the industry and incentivize a greener fleet.

Global Heavy-Duty Diesel Emissions Regulations

Heavy-duty diesel NO_X and CO_2 regulations across the world are becoming increasingly stringent (Figure 1). Most countries around the world pattern EU and/or US requirements, although with a delayed timeline. Given that many OEMs are global, synergies in technology development and a reduction in compliance cost can be achieved by harmonizing global standards.

In the US, even though the Environmental Protection Agency's (EPA) 2010 emissions standards for heavy-duty engines were responsible for significantly reducing diesel emissions, there is still a misalignment between certification cycles and real

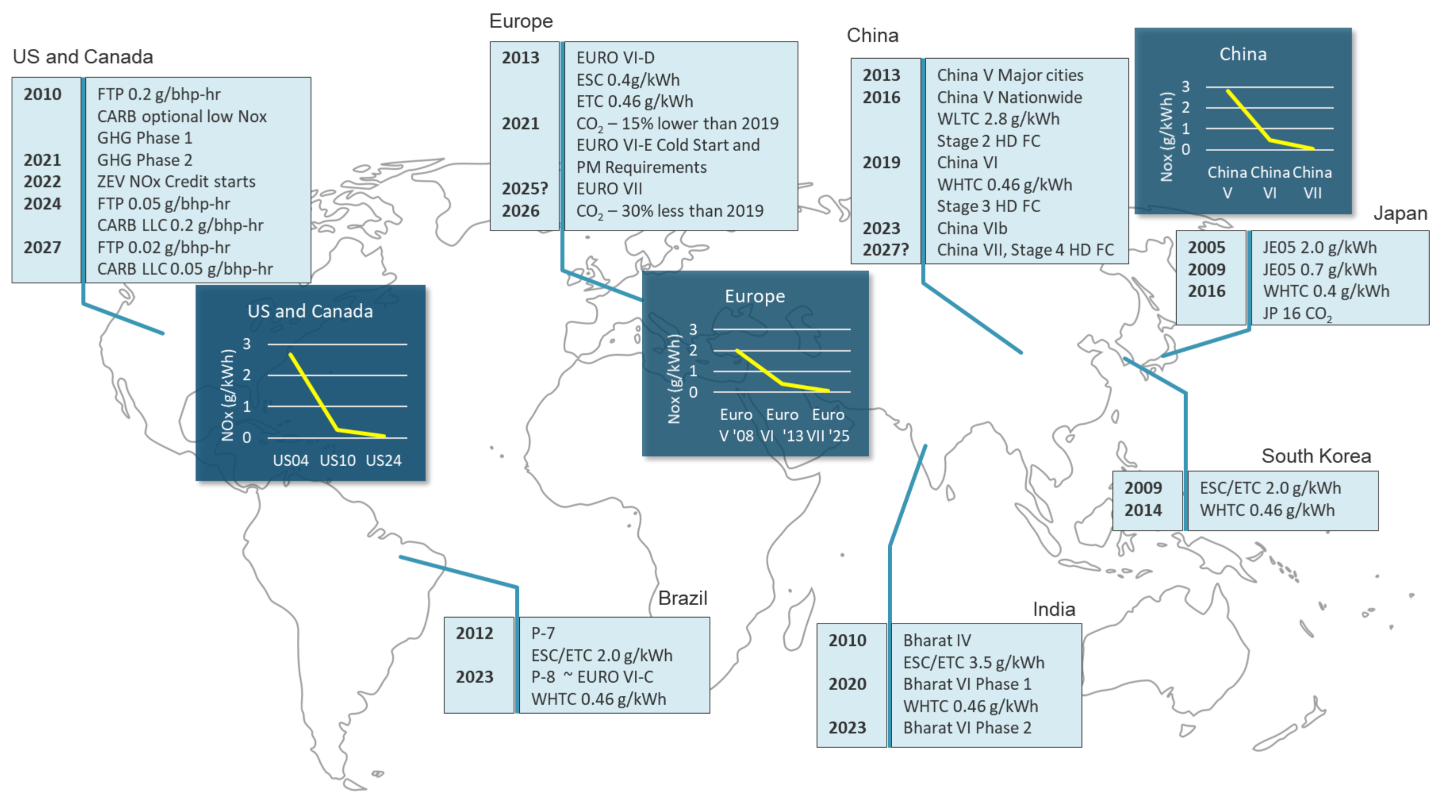

Figure 1: Heavy Duty Diesel NO_X and CO_2 Regulations across the World

world driving profiles. To remedy that, the California Air Resources Board (CARB) has recently approved new low NO_X regulations and the adoption of a low-load cycle (LLC) to supplement the Federal Test Procedure (FTP) protocol to drastically cut NO_X emissions from diesel vehicles (up to 90%). The new regulations also include increasing the full useful life and aftertreatment system warranties for longer HDV operating life and real-world emissions control.

Commercial Vehicles in the US

Figure 2 shows the transportation fuel use in the US in 2016, by mode, according to the US Energy Information Administration (EIA). Nearly a quarter of all transportation fuel use is consumed by commercial trucks and buses.

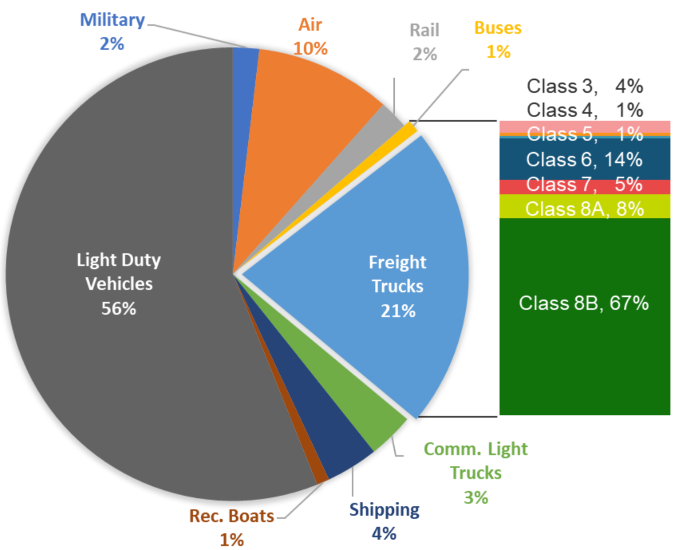

Figure 2: Transportation Fuel Use by Mode and by Class (Source: EIA Energy Outlook 2020 and NRC)

The US Department of Transportation classifies commercial vehicles in one of eight classes according to gross vehicle weight rating (GVWR) with class 1 being light duty vehicles less than 6000 lbs., and class 8b being heavy duty tractor trailers more than 33,000 lbs.

The EIA estimates that Class 3-6 vehicles (minibuses, step vans, utility vans, city delivery trucks and buses) consume between 1,000 gallons per year (light duty) to 7,000 gallons per year (heavier Class 6 applications).

Class 7 and Class 8a trucks include buses, dump trucks, trash trucks, and other hauling trucks and consume typically 6,000–8,000 gallons of fuel per year for Class 7, and 10,000–13,000 gallons of fuel per year for Class 8a.

Class 8b trucks are typically long-haul trucks weighing more than 33,000 lbs. and have one or more trailers. Class 8b trucks **consume two-thirds of the fuel used by all trucks** as can be seen in Figure 2. The high fuel use by these trucks is due to their heavy weight and higher vehicle miles traveled.

The average new Class 8b truck travels over 100,000 miles per year, with some trucks traveling 200,000 miles or more in a year (Figure 3). Therefore, any reduction in fuel consumption in Class 8b trucks has a great impact on overall fuel consumption and CO_2 emission. By 2040, the EIA estimates that the US fleet of freight trucks will use 40% more fuel and, therefore, emit 40% more CO_2 due to increased vehicle miles traveled with economic growth.

Heavy-duty diesel vehicles are a major source of smog forming NO_X emissions. In California alone, HDVs are responsible for more than 70% of NO_X emissions from on-road mobile sources (CARB, 2019).

ICCT analyzed on-road measured test data from eight manufacturers and 26 unique engine families certified between 2010 and 2016. The discrepancy between the EPA 2010 limits and the actual on-road NO_X emissions for different driving conditions were analyzed and the data shows that urban driving is the most impacted (up to seven times the limit) in terms of toxic emissions. Given the population density is much higher in urban areas, the health

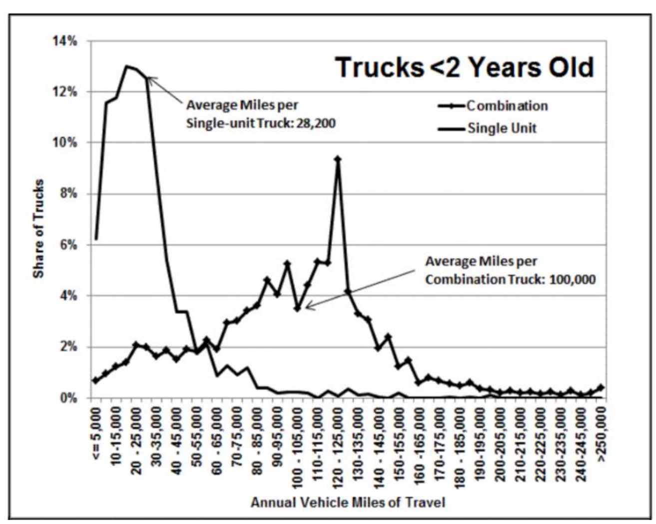

Figure 3: Annual VMT by Trucks over 26,000 lbs. (Source: ORNL – Transportation Energy Data Book – Jan '19)

impacts of NO_X pollution are much greater. Urban driving is characterized by low load and idle cycles. Therefore, by making modest reductions on low load and idle emissions, the toxic effects of NO_X can be significantly reduced.

There are primarily two ways, among others, to reduce NO_X emissions from heavy duty trucks: through improved aftertreatment technologies for emission control, and through engine technologies to lower NO_X emissions.

Emission Control Technologies

Selective catalytic reduction (SCR) systems in the aftertreatment system enable significant reductions in NO_X emissions from trucks. By using a catalyst to convert toxic emissions to more benign compounds, SCRs provide more opportunities for combustion efficiency and CO_2 reduction from the engine. However, SCR systems require high temperatures to function well, which is typically achieved at high load operation. SCRs do not work well at light loads such as at idle, or cold starts and slow speeds. Trucks emit high NO_X in urban areas and stop and go traffic, not because the engine is at high load but because their aftertreatment systems do not get hot enough to work effectively at low engine loads.

Given emission standards now mandate NO_X control at ALL loads, the challenge is to quickly warm-up the SCR system and to keep it warm enough to operate, even under low-load and low-speed operation. Burning more fuel can accomplish the task but at the risk of exceeding the EU's or EPA's Green House Gas (GHG) emission regulations. This is the NO_X vs. CO_2 paradox facing the industry.

To achieve both CO_2 and NO_X reduction targets, technology improvements include close-coupled SCR systems and heated urea injection. Close-coupled SCR systems are used to address NO_X emissions during low-load operation. Heated urea injection reduces the need to heat the exhaust flow and allows for injections at lower temperatures. Electrically heated catalysts are also available, but they depend on the availability of 48V systems or hybrid systems to perform well, with the associated concerns of durability and expense.

To meet future regulations, diesel particulate filter (DPF), diesel oxidation catalyst (DOC), as well as close-coupled SCR, along with sensors and control systems to optimize the operation are needed. However, these systems and technologies come at a significant cost in terms of acquisition and maintenance, as well as warranty costs for the life of the vehicle. The ICCT estimates more than $5,000 for aftertreatment costs alone to meet the 2024 and 2027 CARB low-NO_X regulations. The National Renewable Energy Laboratory (NREL) has a higher $8000+ number which includes higher warranty costs for the aftertreatment system.

Engine Technologies

Improved fuel injection, air handling, and exhaust gas recirculation (EGR) are some of the engine technologies that improve overall combustion and reduce pollutants. In addition, cylinder deactivation (CDA) is a proven light-duty engine technology that is now demonstrating significant simultaneous reductions of both CO_2 and NO_X in heavy-duty diesel engines.

CDA technology can be implemented in either of two options: static CDA and dynamic CDA. Static cylinder deactivation is a technology that disables a fixed number of cylinders during engine operation, effectively forcing the firing cylinders to operate at higher loads and increasing exhaust temperatures. Dynamic CDA, also known as dynamic skip fire (DSF), is an advanced CDA technology that can deactivate individual cylinders dynamically on an event-by-event basis to more fully cover the operating range with deactivation capability. Pioneered by Tula Technology, DSF is already in production on over a million light-duty vehicles primarily to benefit fuel consumption reduction. For diesel engines, diesel dynamic skip fire (dDSF) also increases exhaust gas temperatures due to higher cylinder load operation, to continue to keep the aftertreatment system at operating temperature, especially under low-load conditions. By delivering simultaneous NO_X and CO_2 reduction, the emissions tradeoff is no longer a dilemma.

Figure 4 shows the differences in typical operating regions between static CDA and dynamic CDA, with dynamic CDA providing greater than twice the benefits of static CDA.

Cummins and Tula Technology published a paper at the 41st International Vienna Motor Symposium discussing the results of their collaboration in dDSF. In order to determine the improvement in NO_X and CO_2 emissions control for the US HD FTP and the new CARB low load cycle, transient simulations were conducted by Cummins and Tula. Evaluations

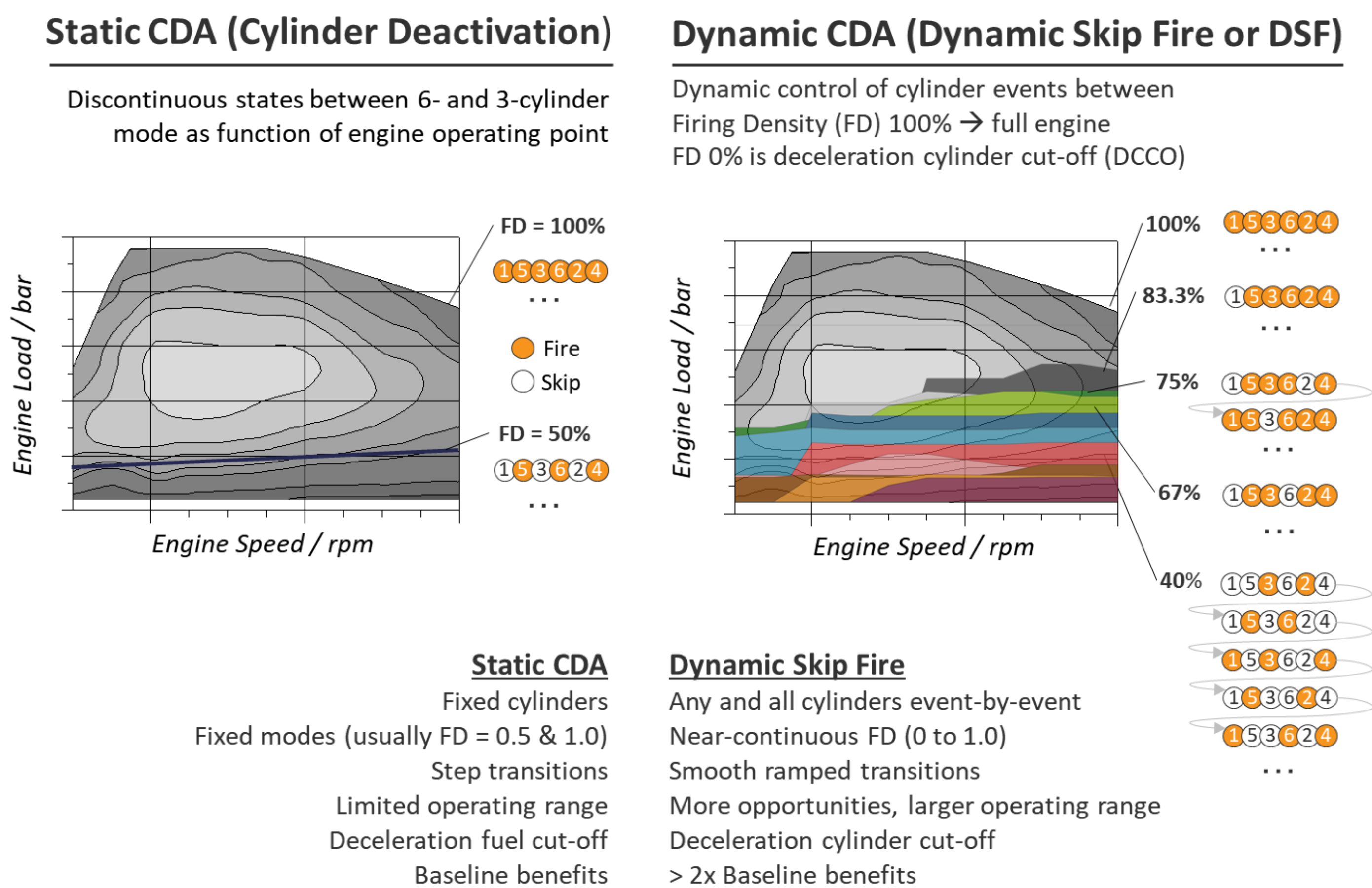

Figure 4: Differences between Static CDA and Dynamic CDA (DSF)

were performed to demonstrate the benefit of dDSF over the baseline 2017 X15 system, using the 6-cylinder CDA system with individual cylinder actuation provided by Jacobs Vehicle Systems, with and without increased conventional thermal management (ICTM). dDSF showed an overall 5% CO_2 reduction benefit along with 74% NO_X emissions reduction compared to the baseline. dDSF expands CDA's operating envelop, providing even more benefits at incremental cost and complexity.

Meeting Future Regulations

CARB's heavy-duty engine and vehicle omnibus rulemaking presentation has specifically called out dynamic cylinder deactivation as one of the technologies that would help OEMs meet low-NO_X and CO_2 regulations. Cylinder deactivation for diesel engines is the only technology that can simultaneously reduce fuel consumption (CO_2) and NO_X. dDSF addresses these operating conditions at low loads to increase aftertreatment temperature quickly, thereby reducing NO_X precisely when and where it is most needed - in densely populated urban settings.

A 2020 ICCT study estimates cylinder deactivation technologies to cost $471 to meet the 2027 CARB low-NO_X regulations for 7L and 13L HD diesel engines. NREL's study has an average cost estimate for cylinder deactivation from $952 to $1,176. The latter includes extended warranty, full useful life and California-only volumes.

Truck Electrification

According to IHS Markit, diesel at 80% share of use, is currently the predominant commercial truck fuel. The share comes down to 66% by 2040 primarily due to growth in alternative fuels and electrification. Despite this, almost all line haul trucks (Class 8b) are projected to have diesel engines even in 2040.

Greater electrification depends heavily on the cost and power density of batteries and fuel cells. The purchase premium of a battery electric vehicle (BEV) truck for a line haul tractor-trailer is an additional $63,000 according to a 2019 report by S&P Global Platts Analytics. The smaller battery in a regional vehicle though, reduces the purchase premium of a regional truck to $22,500 from $63,000. So, regional and fleet vehicles such as delivery trucks and garbage trucks will be early candidates for full electrification. For line haul trucking, that $63,000 price premium on the cost of a BEV is too large for the fuel and maintenance cost savings to compensate in a meaningful timeframe and this sector is expected to be the last to move to full electrification.

BEVs also suffer from carrying the full weight of the battery, whether fully charged or nearly empty. A battery unit needed to service the average long-haul truck can weigh more than five tons. Weight of a vehicle is a significant contributor to a decline in efficiency.

For line haul trucks, diesel electric hybrid is an intermediate step to full electrification. The purchase premium of the diesel electric hybrid is around $15,000. One of the challenges of diesel electric hybrids is that the switching from electric to diesel during operation has high NO_X emissions impact due to the cooled down aftertreatment system when the truck is operating in EV mode. CDA and DSF help mitigate NO_X emissions by quickly bringing the emissions system to operating temperature during these switches. Electrically heated catalyst can also help supplement heating of the aftertreatment system but at the expense of excess energy for this purpose.

Conclusion

Heavy duty vehicle NO_X and CO_2 regulations are becoming more stringent around the world. Complete electrification of the truck fleet is still decades away. Truck and engine OEMs and Tier1s are innovating engine controls and aftertreatment technologies to reduce toxic emissions and reduce fuel consumption. Aftertreatment technologies to meet future regulations come at a significant cost, and CDA for diesel engines is an emerging technology that can simultaneously reduce NO_X and CO_2 emissions. Diesel dynamic CDA or dDSF is a meaningful evolution of CDA with greater efficiency and emissions benefits at little incremental cost.