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A comparison of nitrogen oxide (NO_x) emissions from heavy-duty diesel, natural gas, and electric vehicles

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California is close to finalizing an omnibus rule that will require a 90% reduction in nitrogen oxide (NO_x) emissions from heavy-duty vehicles in the 2024–2027 timeframe.[1] Other states, including New York, New Jersey, and Massachusetts, have indicated that they will adopt California's rule, as they are permitted to do under Section 177 of the Clean Air Act. Meanwhile, the United States Environmental Protection Agency (EPA) has been directed by the White House to propose by January 2022 a stringent national standard for NO_x emissions from heavy-duty vehicles (HDVs) that will apply nationwide starting around 2027.[2]

These proposals and plans continue a series of emissions regulations in the United States ratcheting down NO_x emissions limits from heavy-duty vehicles that began in 1985.[3] These standards have been, and the new ones will be, technology neutral, meaning that they do not specify what technologies, including powertrains, manufacturers must use to comply but only that they must comply. Diesel, natural gas, and electric heavy-duty vehicles can be designed and manufactured with the capability of complying with the ultra-low NO_x limits envisioned in the next set of California and federal HDV regulations. But that is not to say that the outcomes for each are equivalent.

1 California Air Resources Board, "Heavy-Duty Engine and Vehicle Omnibus Regulation and Associated Amendments," (2020), https://ww2.arb.ca.gov/rulemaking/2020/hdomnibuslownox
2 The White House, "Executive Order on Strengthening American Leadership in Clean Cars and Trucks," (2021), https://www.whitehouse.gov/briefing-room/presidential-actions/2021/08/05/executive-order-on-strengthening-american-leadership-in-clean-cars-and-trucks/
3 U.S. EPA, "*Heavy-Duty Highway Compression-Ignition Engines and Urban Buses: Exhaust Emission Standards,*" (2016), https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O9ZZ.pdf

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This briefing compares the capabilities of these three powertrain types in meeting an ultra-low NO_x standard across four key areas: feasibility, cost, health impacts, and climate impacts.

FEASIBILITY

The central questions concerning technology feasibility are (1) whether the technology will be available in the timeframe of the regulation and (2) whether the technology can be configured to produce ultra-low NO_x in line with the limits of the regulation.

Diesel. Diesel engines, fueled by ultra-low sulfur diesel fuel, predominate in heavy-duty vehicles in the state of California as well as nationwide. An extensive fueling infrastructure for these vehicles already exists. Diesel engines produce relatively high engine-out NO_x, but this can be reduced to ultra-low levels in line with the regulation through use of an emission control system based on selective catalytic reduction (SCR). While a commercialized ultra-low NO_x diesel emissions control system has yet to be produced, such a system has already been demonstrated by Southwest Research Institute.[4] The ultra-low NO_x SCR-based emissions control system is more complex than existing diesel emissions control systems as it requires additional catalysts, sensors, injectors, and thermal management.

Natural gas. Natural gas engines, fueled by either compressed (CNG) or liquified (LNG) natural gas, represented less than 1.5% of new HDV sales in the United States in 2020. Few public natural gas fueling stations are available in California or nationwide[5] and significant infrastructure investment would be required to support significant numbers of heavy-duty natural gas vehicles. There are two types of natural gas engines, spark ignited (SI) and compression ignition (CI). CI engines would have a similar emissions profile and require a similar aftertreatment system to diesel engines (discussed above), which also use compression ignition. SI engines also produce high engine-out NO_x, but the aftertreatment system is a three-way catalyst (TWC) that is capable of reducing NO_x to ultra-low levels in line with the regulation. TWCs have an advantage over SCR systems for reducing NO_x emissions to ultra-low levels in that they are less complex. Commercialized systems for ultra-low NO_x SI natural-gas engines have already been produced and are currently in use.

Electric. Electric vehicles, including battery electric (BEV) and fuel cell electric (FCEV) vehicles, currently represent approximately 0.08% of the HDV fleet in California and 0.02% of the fleet nationwide.[6] Few public charging stations and hydrogen fueling stations exist, and significant infrastructure investment would be required were the heavy-duty fleet to transition to electric vehicles. For example, ICCT estimates that by 2030 about 31,700 publicly accessible charging points and 220 hydrogen refueling stations will be necessary to support a fleet of 103,000 zero-emission tractor trailers, and that by 2050 about 530,000 publicly accessible charging points and 6,900 hydrogen refueling stations will be needed to support a fleet of 2.4 million.[7] Electric vehicles produce no tailpipe emissions, so NO_x control is not an issue. The

4 "SwRI engineers develop near-zero emissions engine technology," SwRI, accessed August 23, 2021, https://www.swri.org/press-release/near-zero-emissions-diesel-engine-technology

5 "Alternative Fueling Station Locator," Alternative Fuels Data Center, U.S. Department of Energy, accessed August 23, 2021, https://afdc.energy.gov/stations/#/find/nearest

6 Benjamin Sharpe, Claire Buysse, *Zero-emission bus and truck market in the United States and Canada: A 2020 update,* (ICCT: Washington, DC, 2021), https://theicct.org/publications/canada-race-to-zero-FS-may2021

7 Ray Minjares, Felipe Rodríguez, Arijit Sen, Caleb Braun, *Infrastructure to support a 100% zero-emission tractor-trailer fleet in the United States by 2040,* (ICCT: Washington, DC, forthcoming September 2021).

key question regarding the feasibility of electric vehicles is whether there will be commercially available models in all HDV segments within the time frame of the regulation. As of 2021, there are already commercially available HD electric vehicles in many segments, including buses, delivery trucks, drayage trucks, and short-haul tractors. Manufacturers have announced plans to commercialize additional models that will cover all HD segments through Class 8 over the next two to three years.[8] Manufacturers are incentivized to produce these additional EV models by the fact that they must also comply with the California Air Resources Board's (CARB) Advanced Clean Truck (ACT) rule, which also takes effect in 2024 and requires electric vehicle adoption in all HDV segments.

COST

The key questions concerning cost are the incremental cost of achieving regulatory compliance and the costs versus the benefits of a given technology.

Diesel. A significant amount of analysis has been done to estimate the incremental cost of adding the aftertreatment capabilities needed to achieve the 90% NO_x reduction mandated by CARB's ultra-low NO_x regulation. The median estimate is CARB's own, which projects that the regulation will add approximately $8,500 to the cost of a Class 8 diesel truck, or less than 5% of the vehicle cost.[9] CARB has also calculated that the benefits of the rule would outweigh the additional costs by a 7 to 1 ratio.

Natural gas. The cost of the added aftertreatment for spark-ignited natural gas vehicles to meet the ultra-low NO_x standard is nominal, approximately $400 per engine.[10] The upfront capital cost of CNG vehicles is typically around $10,000 higher than for a comparable diesel truck[11] (significantly more for LNG vehicles due to the cost of the cryogenic tanks).[12] No reliable comprehensive estimates have been made of infrastructure costs, but the total required for a significant shift to natural gas vehicles would certainly be in the billions of dollars.[13] In this case, it would be necessary to consider whether these investments would be advisable given the knowledge that the transportation fleet must transition almost fully away from fossil fuels within the next three decades in order to be in line with the Paris Agreement climate targets.

Electric. Electric vehicles incur no incremental cost for meeting the ultra-low NO_x standard. But the upfront capital cost of an electric HDV is significantly higher than either a heavy-duty diesel or natural gas vehicle being sold today, although EV costs are coming down rapidly. The majority of cost studies show that in the time

8 Benjamin Sharpe, Claire Buysse, Jason Mathers, Victor Poudelet, *Race to zero: How manufacturers are positioned for zero-emission commercial trucks and buses in North America*, (ICCT: Washington, DC, 2020), https://theicct.org/publications/canada-race-to-zero-oct2020

9 Rachel Muncrief, "What will it really cost to build the next generation of low-NO_x trucks?" ICCT staff blog, April 22, 2021, https://theicct.org/blog/staff/real-cost-low-nox-trucks-apr2021

10 California Air Resources Board, "Appendix C-3 Further Detail on Costs and Economic Analysis," Heavy-Duty Engine and Vehicle Omnibus Regulation and Associated Amendments (2020), https://ww2.arb.ca.gov/sites/default/files/classic/regact/2020/hdomnibuslownox/appc3.pdf

11 U.S. EPA, "Class 8 CNG / Diesel System Cost Analysis," (2015), https://nepis.epa.gov/Exe/ZyPDF.cgi/P100O584.PDF?Dockey=P100O584.PDF

12 Marissa Moultak, Nic Lutsey, Dale Hall, *Transitioning to zero-emission heavy-duty freight vehicles*, (ICCT: Washington, D.C., 2017), https://theicct.org/publications/transitioning-zero-emission-heavy-duty-freight-vehicles

13 U.S. Department of Energy, Alternative Fuels Data Center, "Natural Gas Fueling Infrastructure Development," https://afdc.energy.gov/fuels/natural_gas_infrastructure.html; Margaret Smith, John Gonzales, "Costs associated with compressed natural gas: Vehicle fueling infrastructure factors to consider in the implementation of fueling stations and equipment," (U.S. Department of Energy, September 2014), https://afdc.energy.gov/files/u/publication/cng_infrastructure_costs.pdf

frame of the rule the total cost of ownership (which includes the capital cost of the vehicle as well as the lifetime cost of fuel, maintenance, and other costs) for diesel, natural gas, and electric vehicles will be similar, and the total cost of ownership for electric vehicles will continue to decline over time, unlike the costs for diesel or natural gas vehicles.[14] The key factors that impact the total cost of ownership are vehicle segment and vehicle use profiles. The cumulative cost of publicly accessible infrastructure for tractor-trailers is about $6 billion to support a fleet of 103,000 by 2030 and $122 billion to support a fleet of 2.4 million by 2050.[15]

HEALTH IMPACTS

Overall health impacts can vary significantly from technology to technology, even when the ultra-low NO_x emissions standard is met.

Diesel. All new diesel vehicles come equipped with a diesel particulate filter which removes over 99% of particulate matter (PM) from the exhaust, so harmful direct PM emissions from diesel engines are typically very low. But health impacts from diesel vehicle exhaust can occur if NO_x emissions in actual use are significantly higher than certified emissions—that is, the amount of NO_x emitted during tests performed under controlled conditions in a test lab to certify that an engine type meets the emissions standard. Because no commercialized ultra-low diesel NO_x systems are available to test in use, we do not have direct evidence of what the gap between certification and real-world emissions may be. But numerous studies on the existing fleet of low-NO_x (i.e., certified to EPA 2010 standard) diesel engines have found that in many cases real-world emissions are much higher than the laboratory limits.[16] There are multiple causes of excessive real-world emissions. The most common are: (1) the existing regulation was not designed to ensure low NO_x during urban driving; (2) poor vehicle maintenance; (3) tampering with aftertreatment systems. CARB's new ultra-low NO_x regulation addresses the first issue but does little to address the second and third. It is still unclear what the real-world emissions of diesel vehicles certified under the new regulation will be.

Natural gas. Particulate matter is regulated on a gravimetric basis in the United States and not on a particle number basis, as in the European Union. It is possible to have vehicles that emit very high numbers of very small, yet very harmful, particles. These ultrafine particle emissions are detrimental to human health, delivering harmful toxins into the most sensitive regions of the lungs. Since these particles weigh very little, manufacturers may not need to use a particle filter to get the total weight of particulate emissions below the limits of U.S. regulation. In fact, this is the case with spark-ignited natural gas engines: none sold in the United States today are equipped with particulate filters. Yet studies have shown that SI natural gas engines can produce five to 50 times more ultrafine particles than diesel-fueled vehicles certified to the same emission

14 Dale Hall, Nic Lutsey, *Estimating the infrastructure needs and costs for the launch of zero-emission trucks,* (ICCT: Washington, D.C., 2019), https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf; Burnham, Andrew, et al., "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains," (Argonne National Lab, 2021), https://doi.org/10.2172/1780970

15 Ray Minjares, Felipe Rodríguez, Arijit Sen, Caleb Braun, *Infrastructure to support a 100% zero-emission tractor-trailer fleet in the United States by 2040*, (ICCT: Washington, D.C., forthcoming September 2021).

16 Badshah, Huzeifa, Francisco Posada, Rachel Muncrief, *Current state of NO_x emissions from in-use heavy-duty diesel vehicles in the United States*, (ICCT: Washington, D.C., 2019), https://theicct.org/publications/nox-emissions-us-hdv-diesel-vehicles

standards.[17] In addition, the three-way catalysts used to control NO_x from SI natural gas engines can produce very high levels of ammonia, a toxic precursor to PM 2.5 formation, under certain operating conditions—which happen to be the same operating conditions that allow for the greatest reduction of NO_x. CARB's standards leave ammonia emissions unregulated, which means the natural gas engine manufacturers have an incentive to calibrate their engines to allow for better NO_x reduction and uncontrolled ammonia emissions over the catalyst. Findings from tests carried out by the University of California Riverside[18] and West Virginia University[19] confirm very high ammonia emissions of natural gas HDVs, ranging up to 0.7 g/bhp-hr (note that the applicable NO_x limit is 0.2 g/bhp-hr, and that, compared to NO_x, less ammonia is needed to form the same amount of PM 2.5). In addition, a recent study of 15 natural gas trucks certified to the ultra-low NO_x limit found that 13 of them were emitting over the NO_x limit in real-world operation.[20] This indicates that the real-world emissions gap is likely an issue for natural gas vehicles as well as diesel-powered vehicles.

Electric. Electric vehicles produce no tailpipe emissions but do create additional emissions upstream where the electricity (or hydrogen in the case of FCEVs) is produced. Overall health impacts are thus determined by the electricity source and its proximity to population centers. The impacts would be balanced to some degree by the fact that each electric vehicle displaces the tailpipe emissions that would be emitted by a diesel or natural gas vehicle. Studies have shown that the overall health impact from the adoption of electric vehicles would be positive, even when considering the additional upstream emissions from electricity generation.[21]

CLIMATE IMPACTS

NO_x regulations are focused on reducing the health impacts from heavy-duty vehicles, but it is also important to consider the climate benefits of the different technology solutions.

Diesel. The majority of the climate impact from diesel vehicles comes from CO_2 produced in combustion. California and the U.S. EPA both have standards in place to reduce greenhouse gas (GHG) emissions from heavy-duty vehicles and engines through efficiency improvements. These standards will help to decrease the per-vehicle CO_2 emissions of new heavy-duty diesel vehicles by roughly 25% to 50% from 2010 to 2027. In California, the majority of diesel fuel is fossil-based. While some biofuel

17 Barouch Giechaskiel. "Solid Particle Number Emission Factors of Euro VI Heavy-Duty Vehicles on the Road and in the Laboratory." International Journal of Environmental Research and Public Health 15, no. 2 (2018): 304, https://doi.org/10.3390/ijerph15020304; Imad A. Khalek et al. "Solid Particle Number and Ash Emissions from Heavy-Duty Natural Gas and Diesel w/SCRF Engines." SAE (2018), https://doi.org/10.4271/2018-01-0362; Tianyang Wang et al. "Total Particle Number Emissions from Modern Diesel, Natural Gas, and Hybrid Heavy-Duty Vehicles During On-Road Operation." Environmental Science & Technology 51, no. 12 (2017): 6990–98, https://doi.org/10.1021/acs.est.6b06464

18 Hanwei Zhu et al. "Characterizing Emission Rates of Regulated and Unregulated Pollutants from Two Ultra-Low NOx CNG Heavy-Duty Vehicles." Fuel 277 (2020): 118192, https://doi.org/10.1016/j.fuel.2020.118192

19 Arvind Thiruvengadam et al. "Unregulated Greenhouse Gas and Ammonia Emissions from Current Technology Heavy-Duty Vehicles." Journal of the Air & Waste Management Association 66, no. 11 (2016): 1045–60, https://doi.org/10.1080/10962247.2016.1158751

20 California Air Resources Board, "In-Use Emission Performance of Heavy Duty Natural Gas Vehicles Lessons Learned from 200 Vehicle Project," (Fact Sheet, 2021), https://ww2.arb.ca.gov/sites/default/files/2021-04/Natural_Gas_HD_Engines_Fact_Sheet.pdf

21 Ernani F. Choma, John S. Evans, James K. Hammitt, José A. Gómez-Ibáñez, John D. Spengler. "Assessing the health impacts of electric vehicles through air pollution in the United States." Environment International, Volume 144, (2020), https://doi.org/10.1016/j.envint.2020.106015.

(biodiesel and renewable diesel) is blended into the diesel mix, the majority of this comes from feedstocks with limited supply.

Natural gas. The climate impacts of natural gas and natural gas vehicles come from two factors. The first is leakage, sometimes referred to as fugitive emissions. Natural gas is mostly composed of methane, which is a very powerful greenhouse gas, 82.5 times stronger than CO_2 on a 20-year basis and 30 times stronger on a 100-year basis.[22] There are numerous points in the natural gas supply chain where fugitive methane emissions can occur: at the well, from the pipeline, during vehicle fueling, etc. It takes only a small amount (less than 2%) of leakage to negate any climate benefit that natural gas vehicles have over diesel vehicles by virtue of their (10%–20%) lower tailpipe CO_2 emissions.[23] The majority of studies looking at fugitive emissions from the entire natural gas supply chain (well to wheel) indicate that natural gas vehicles are, on average, more harmful to the climate than diesel vehicles.

The second factor is the source of the natural gas. Fossil natural gas represents the bulk of the natural gas currently available in California as well as the rest of the United States. The majority of this is used in electric power plants. Renewable natural gas (RNG) represents approximately 1% of the total natural gas used in California and 0.2% of the total natural gas used in the rest of the United States.[24] Sources of RNG include landfills, manure, and wastewater treatment facilities. These sources of natural gas are much less carbon-intensive than fossil natural gas, but the amount of natural gas they could potentially produce is limited. The demand for RNG in the transportation sector competes directly with the power sector. There are fewer opportunities for fugitive methane emissions in the RNG supply chain if the biogas is burned on-site to make electricity instead of being transported by pipeline to a vehicle fueling station. Therefore, the most efficient and climate-friendly use for RNG in the transportation sector is to generate electrical power on-site and use that to power electric vehicles.

Electric. Electric vehicles are powered by either electricity from the power sector (BEVs) or hydrogen (FCEVs). For BEVs, the climate impacts will depend heavily on the carbon intensity of the grid. California's grid mix is currently 44% renewables, with an average carbon intensity of 75.9 gCO_2e/MJ. For comparison, the carbon intensity of diesel fuel is approximately 100 gCO_2e/MJ.[25] Given that a comparable electric motor is approximately three times more efficient than an HDV internal combustion engine (depending on the duty cycle), the carbon intensity of a diesel vehicle is approximately four times higher than a BEV. In addition, California is in the process of decarbonizing its grid and has committed to having a grid powered by fully renewables sources by 2045. Therefore, the climate impacts of BEVs will decrease over time. Currently, hydrogen in California is produced from natural gas as well as lower-carbon sources such as landfill gas and solar electricity. Heavy-duty FCEVs will deliver lower climate

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22 IPCC, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change," (Intergovernmental Panel on Climate Change, 2021), https://www.ipcc.ch/report/ar6/wg1/

23 Oscar Delgado, Rachel Muncrief, "Assessment of Heavy-Duty Natural Gas Vehicle Emissions: Implications and Policy Recommendations," (ICCT: Washington, DC, 2015), https://theicct.org/publications/assessment-heavy-duty-natural-gas-vehicle-emissions-implications-and-policy

24 Argonne National Laboratory, "Renewable Natural Gas Database," (2020), https://www.anl.gov/es/reference/renewable-natural-gas-database

25 California Air Resources Board, "LCFS Annual Updates to Lookup Table Pathways: 2021 Carbon Intensity Values for California Average Grid Electricity Used as a Transportation Fuel in California and Electricity Supplied Under the Smart Charging or Smart Electrolysis Provision," (2021), https://ww2.arb.ca.gov/sites/default/files/classic//fuels/lcfs/fuelpathways/comments/tier2/2021_elec_update.pdf

benefits compared to battery electric vehicles until there is a transition to hydrogen produced entirely from low-carbon sources such as renewable electricity.

CONCLUSION

Diesel, natural gas, and electric heavy-duty vehicles can all be designed to limit tailpipe NO_x emissions to ultra-low levels required by California's soon-to-be finalized omnibus rule. The costs to do so are similar on a total cost of ownership basis. Of the three technologies, electric vehicles have the lowest overall health and climate impacts, and it is crucial that regulations be put in place to support a transition to 100% electric HDVs as soon as possible. However, it is unlikely to be possible to transition to a 100% electric HDV fleet within the time frame of the regulation (2027). In this case, the next best short-term option for meeting ultra-low NO_x requirements is diesel. Diesel is a better alternative in the immediate term than natural gas for three main reasons: (1) adoption of natural gas vehicles would require significant investment in new infrastructure that could slow the transition away from fossil fuels; (2) the overall health impacts from natural gas due to high emissions of unregulated pollutants (ammonia and ultrafine PM) are significant; and (3) once fugitive methane emissions are factored in, natural gas heavy vehicles are on average more harmful to the climate than heavy-duty diesel vehicles.