TRANSPORTATION ENERGY INSTITUTE® MARKET REPORT

AUGUST 2026

Selective Catalytic Reduction and Diesel Exhaust Fluid

Executive Summary

- Nitrogen oxides (NOx) can contribute to the formation of ozone, which inflicts billions of dollars of damage to American industries and agriculture and can cause significant respiratory illnesses.
- In 2010, diesel engines in on and off highway vehicles accounted for 65% of U.S. NOx emissions.
- Installation of Selective Catalytic Reduction (SCR) systems and the use of Diesel Exhaust Fluid (DEF) on nearly all heavy-duty vehicles and nonroad equipment has contributed to 76% and 42% reductions in NOx emissions, respectively, accounting for 79% of total NOx reductions in the U.S. since 2010.
- More than two-thirds of commercial diesel trucks in operation are equipped with SCR systems, and DEF is available at more than 100,000 retail locations in North America.
- Shifting the burden of NOx emissions control from the engine to the aftertreatment system has allowed engines to be optimized for maximum fuel efficiency.
- Guidance issued by the U.S. Environmental Protection Agency in 2025 and 2026 provides more time for operators to make repairs to SCR/DEF systems before derating, addressing a primary user concern about these systems.
- SCR systems can experience significant and costly damage if operated without DEF.
- The continued supply and use of DEF are critical to ensure lasting air quality improvements as week as the durability, performance, and efficiency of diesel engines and equipment.

SCR and DEF 101

The regulatory landscape for heavy-duty diesel engines underwent a profound transformation beginning in the late 1980s and through the early 2000s, as the U.S. Environmental Protection Agency (EPA) established rigorous new standards requiring a 95% reduction in nitrogen oxides (NOx) by model year 2010.[1] These requirements triggered a shift from traditional in-cylinder emissions management to advanced aftertreatment solutions.

The EPA initially predicted that, to meet its standards, manufacturers would rely on lean NOx traps (NOx adsorbers) and Exhaust Gas Recirculation (EGR) to lower NOx by re-introducing exhaust gases into the combustion chamber; however, this approach often compromised engine performance and thermal efficiency. Most diesel engine manufacturers developed and adopted Selective Catalytic Reduction (SCR) systems using Diesel Exhaust Fluid (DEF) as the definitive compliance strategy. According to the National Research Council, "This was one of the few heavy-duty emission control technologies in history that simultaneously enabled increased efficiency and reduced emissions."[2]

SCR systems inject DEF, an aqueous urea solution, into the exhaust stream. DEF decomposes into ammonia, which reacts with NOx over a ceramic catalyst to yield harmless atmospheric nitrogen and water vapor. By shifting the burden of NOx reduction to the exhaust stream, SCR technology enabled engine manufacturers to tune for improved performance and greater fuel efficiency while meeting stringent environmental requirements.[3]

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[1] U.S. Environmental Protection Agency (EPA). (2016, March). *Heavy-duty highway compression-ignition engines and urban buses: Exhaust emission standards* (Publication No. EPA-420-B-16-018). Office of Transportation and Air Quality. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O9ZZ.pdf

[2] National Academies of Sciences, Engineering, and Medicine. (2014). *Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles Phase Two: First Report. (p. 26)*. The National Academies Press. https://doi.org/10.17226/18736

[3] Schaeffer, A. (2026, April 20). *Making Diesel Clean: What You Need to Know About SCR and DEF* [Webinar]. Engine Technology Forum. https://enginetechforum.org/webinars/

In 2022, the EPA finalized regulations for heavy-duty trucks that will cut NOx emissions by more than 80% beyond the 2010 standards to achieve near-zero emissions in model year 2027 heavy-duty diesel engines.[4] The standards require a NOx reduction from 0.2 g/hp/hr to 0.035 g/hp/hr, and the EPA expanded its testing methodology to require NOx reductions over a broader operating range. The EPA predicts new trucks will increase their DEF consumption as manufacturers deploy dual dosing points in the SCR system to meet the requirements.[5]

Since 2015, most nonroad equipment such as farm tractors and construction equipment have met EPA's Tier 4 emissions standards, which require a NOx limit of 0.4 g/kW-hr, equivalent to about 0.3g/hp-hr.[6] EPA standards do not require SCR systems for nonroad equipment below 75 horsepower, and some very large nonroad engines above 750 horsepower, such as generators and mining equipment may be equipped with SCR systems depending on the application.

Public Health and Environmental Implications of NOx Emissions

The EPA established NOx standards to address several health and environmental implications.[7] Nitrogen dioxide (NO_2) [8] is categorized as a criteria pollutant. It is a potent respiratory irritant and one of the primary contributors to ground-level ozone (smog) and secondary fine particulate matter.

According to the American Lung Association, ozone and particle pollution are linked to asthma attacks, respiratory illness, COPD exacerbations, metabolic disorders, heart attacks, strokes, lung cancer, nervous system issues, reproductive problems, and increased respiratory and cardiovascular related mortality.[9]

Long-term exposure is linked to permanent lung growth impairment and increased susceptibility to respiratory infections. These health burdens are disproportionately concentrated in "exposure hotspots" near high-traffic corridors, where approximately 72 million Americans live,[10] resulting in NO_2 concentrations that can be 30% to 100% higher than in surrounding areas.

In addition, ozone causes oxidative damage to vegetation, resulting in billions of dollars in annual crop losses for staples such as soy and wheat.[11] NOx also contributes to the formation of acid rain and nutrient pollution in coastal waters.[12]

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[4] U.S. EPA. (2023, January 24). Control of Air Pollution From New Motor Vehicles: Heavy-Duty Engine and Vehicles Standards Final Rule. *Federal Register*, 88(15), 4296–4718. https://www.govinfo.gov/content/pkg/FR-2023-01-24/pdf/2022-27957.pdf

[5] U.S. EPA. (2022, December). *Control of air pollution from new motor vehicles: Heavy-duty engine and vehicle standards regulatory impact analysis* (Report No. EPA-420-R-22-035). Office of Transportation and Air Quality. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016A9N.pdf

[6] U.S. EPA. (2004, June 29) Control of Emissions of Air Pollution From Nonroad Diesel Engines and Fuels*. Federal Register, 60 (124),* 38958-39273. https://www.govinfo.gov/content/pkg/FR-2004-06-29/pdf/04-11293.pdf

[7] U.S. EPA. (2023, July 8). *Basic Information about NO2.* https://www.epa.gov/no2-pollution/basic-information-about-no2#Effects

[8] NOx is the total category of nitrogen oxides, while NO2 is a specific, highly reactive gas within that category.

[9] American Lung Association. (2025, June 9). *Ozone*. https://www.lung.org/clean-air/outdoors/what-makes-air-unhealthy/ozone#how

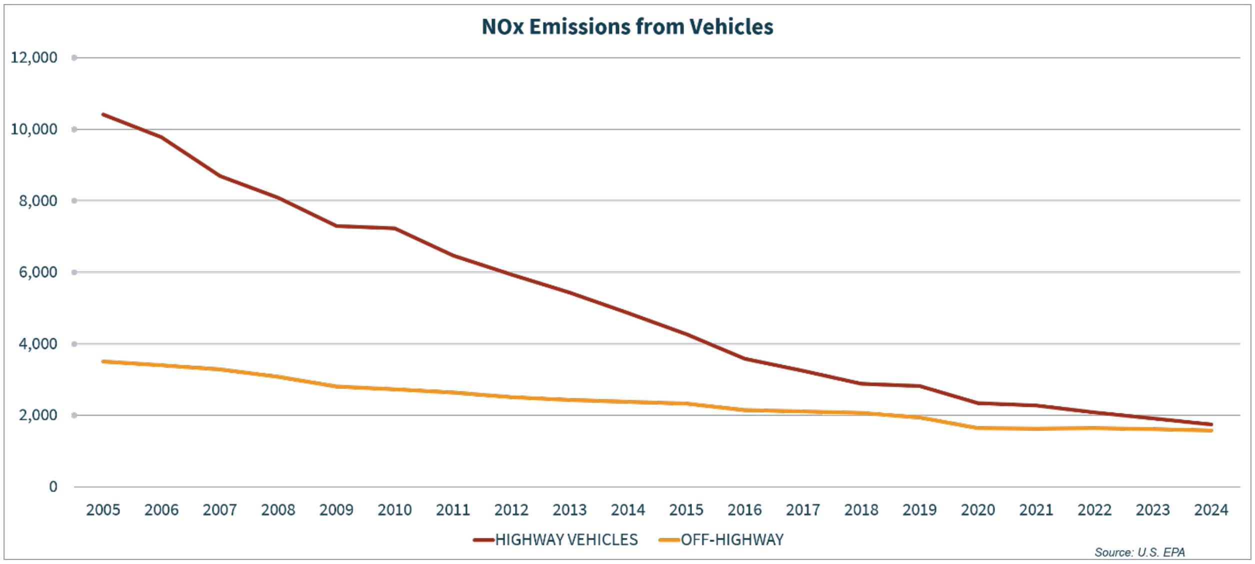
[10] American Lung Association. (March 2026). *Something in the Air: Heavy-Duty Traffic Pollution in Nearby Communities.* https://www.lung.org/getmedia/e2c6797d-b98c-4372-a352-928f54ca0fba/Traffic-Something-in-the-Air-Report-3.pdf

[11] McGrath, J. M. et al. (2015). *Proceedings of the National Academy of Sciences (PNAS), 112(46)*, 14390–14395. https://doi.org/10.1073/pnas.1509777112

[12] U.S. EPA. (2023, July 8). *Basic Information about NO2.* https://www.epa.gov/no2-pollution/basic-information-about-no2#Effects

Effect of SCR and DEF on NOx Emissions

The integration of SCR systems has become the primary means for the near elimination of NOx from heavy-duty diesel exhaust, which accounted for 65% of all NOx emission in the U.S. in 2010.[13] Modern SCR systems consistently achieve NOx conversion efficiencies of 95% to 99%.[14] Since the implementation of NOx standards that led to the adoption of SCR/DEF technology, national NOx emissions have dropped 76% from highway vehicles and 42% from off-highway vehicles. The combined NOx emissions reduction from these two sectors alone accounts for 79% of the total NOx emissions reduction in the U.S. since 2010.[15]



Selective Catalytic Reduction Systems in the Current Fleet

SCR technology has achieved a dominant market position across the North American diesel landscape. According to data from the Engine Technology Forum and S&P Global Mobility, as of December 2025 67% of all commercial diesel vehicles (Classes 3–8) in operation in the United States have been produced since 2010 and are equipped with SCR systems.[16] These vehicles, often referred to as the newest generation of advanced diesel trucks, represent an active population of approximately 7.95 million vehicles. The emissions reductions achieved in this sector will increase as the fleet continues to turnover to new models equipped with SCR technology.

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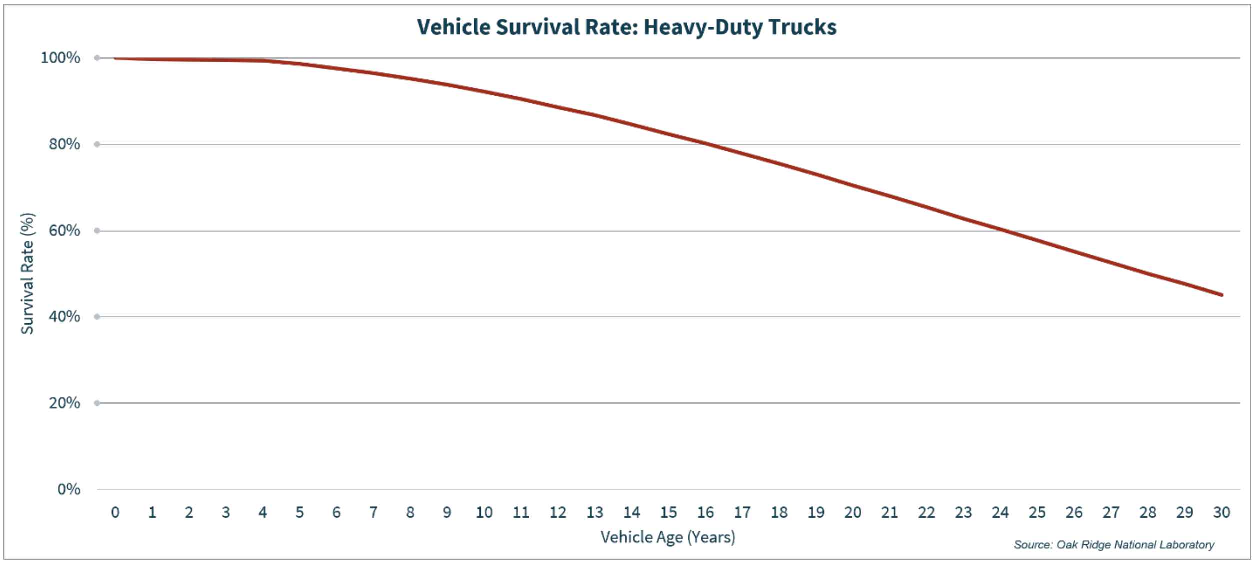
[13] U.S. EPA. (2025, February 3). *Air pollutant emissions trends data*. https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data

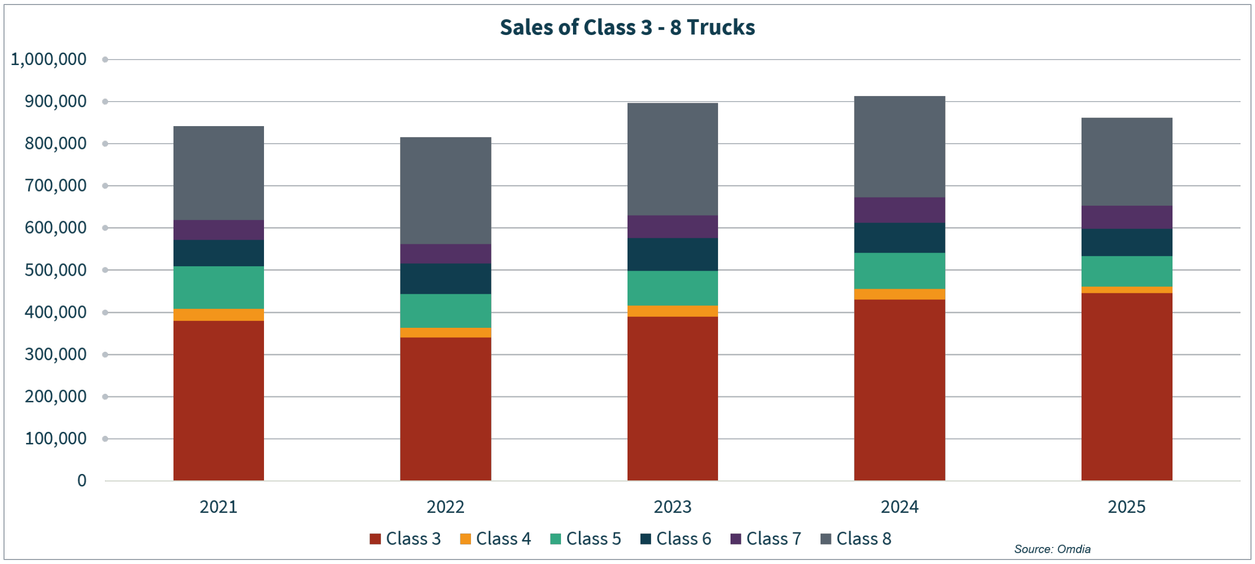
[14] Zhang, S., et al. (2024). *Experimental Study on NOx Reduction of Diesel Engine by EGR Coupled with SCR.* ACS Omega, 9(7), 8308-8319. https://doi.org/10.1021/acsomega.3c09052; Pillai, R., et al. (2022). Modeling and Predicting Heavy-Duty Vehicle Tailpipe Nitrogen Oxide (NOx) Emissions Using Deep Learning. *Frontiers in Mechanical Engineering, 8,* 840310. https://doi.org/10.3389/fmech.2022.840310

[15] U.S. EPA. (2025, February 3). *Air pollutant emissions trends data*. https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data

[16] Engine Technology Forum. (2026, May 6). *More of America's truck and bus fleets powered by advanced diesel engines than ever before* [Press release]. https://enginetechforum.org/press-releases/posts/more-of-americas-truck-and-bus-fleets-powered-by-advanced-diesel-engines-than-ever-before

The fleet of advanced diesel trucks is expected to dominate U.S. logistics for the foreseeable future. According to a study published by Oak Ridge National Laboratory, half of all heavy-duty trucks are expected to remain on the road for 27 years after their original sale, with some remaining in operation for much longer.[17] To put this into perspective, since 2021 U.S. fleets have purchased 4.3 million Class 3 – 8 trucks, of which 1.2 million were Class 8.[18] These modern vehicles are projected to remain in operation for at least the next two to three decades.





[17] Stacy C. Davis, et al. (2022). *Transportation Energy Data Book: Edition 40, ORNL/TM-2021/2372*. Oak Ridge National Laboratory. https://tedb.ornl.gov/wp-content/uploads/2022/03/TEDB_Ed_40.pdf.
[18] Omdia. (n.d.). *Vehicle sales – U.S. monthly*. https://omdia.tech.informa.com/collections/afcit031/vehicle-sales--us-monthly

Diesel Exhaust Fluid Availability in the U.S.

As SCR systems have been integrated into more vehicles and equipment, the DEF market has developed into a global industry essential to SCR's functionality in the newest generation of advanced diesel trucks and nonroad equipment. DEF uses synthetic urea, produced by reacting ammonia under high pressure and then purifying it to meet strict automotive-grade purity standards (ISO 22241-1).[19] The ISO standard mandates a precise chemical ratio of 32.5% high-purity synthetic urea and 67.5% deionized water, a concentration yielding the lowest freezing point of 12°F (-11°C), while setting strict limits on trace contaminants.[20]

Adherence to ISO 22241 purity standards is paramount because SCR aftertreatment hardware is extremely sensitive to contamination.[21] Using off-spec fluid such as agricultural urea introduces trace minerals and heavy metals that permanently poison the catalytic washcoat, while hydrocarbon ingress destroys internal dosing pump seals and injectors, incurring out-of-pocket repair costs. Using DEF which does not meet purity standards or diluting DEF with tap water can accelerate urea crystallization and catalyst face-plugging, elevating engine backpressure and triggering On-Board Diagnostic (OBD) fault codes.[22] As a result, major engine Original Equipment Manufacturers (OEMs) explicitly condition warranty coverage on ISO 22241 compliance, excluding all aftertreatment failures caused by contaminated or non-conforming fluid under standard warranty exclusions.

ISO 22241-3 specifies the process by which DEF is handled, transported and stored.[23] The ammonia feedstock is produced at nitrogen manufacturing plants by combining atmospheric nitrogen with natural gas via the Haber-Bosch process. These plants operate with dual-purpose capacity, giving them the flexibility to shift production streams to produce either agricultural-grade fertilizer or automotive-grade urea depending on market demand and profitability.

From there, DEF is distributed through three primary downstream channels: via dedicated bulk tanker trucks directly to high-volume retail outlets and truck stops; in intermediate bulk containers (275 or 330-gallon totes and drums) to commercial fleets, construction sites, and agricultural facilities; and in 2.5-gallon retail jugs with specialized spouts for light-duty diesel trucks and passenger applications.

With more than $12 billion of capital investment in deploying reliable retail infrastructure, DEF is now available at more than 100,000 retail facilities in North America, including more than 95% of North American truck stops.[24] In 2026, total North American DEF consumption was estimated to total 1.46 billion gallons, with 1.36 billion in the United States alone. The 2026 market value of the product was estimated at $2.7 billion, approximately $400 million of which came from off-highway applications.[25]

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[19] ISO standards are subject to mandatory, "Systemic Review" every five years. The ISO revision process is highly structured, rigorous, and consensus driven. Because ISO standards carry international legal and commercial weight, modifying a standard requires explicit agreement among global experts and national standards bodies. A typical revision process takes two to three years to complete from start to publication.

[20] International Organization for Standardization. (2019). *Diesel engines — NOx reduction agent AUS 32 — Part 1: Quality requirements (ISO Standard No. 22241-1:2019)*. ISO. https://www.iso.org/obp/ui/ru/#iso:std:iso:22241:-1:ed-2:v1:en

[21] Cummins Inc. (2023). *Service Bulletin: Diesel Exhaust Fluid (DEF) Quality Specifications and Warranty Requirements for Selective Catalytic Reduction Systems (Bulletin No. 4332711)*. Cummins Aftermarket Engineering. https://www.cummins.com/en-na/engines/def-purity-and-cleanliness

[22] Society of Automotive Engineers (SAE). (2018). *Characterization and Mitigation of Urea Deposit Formation in Selective Catalytic Reduction (SCR) Systems (SAE Technical Paper 2018-01-0329)*. SAE International. https://www.sae.org/papers/mitigating-urea-deposits-selective-catalytic-reduction-systems-software-control-improved-performance-low-duty-cycle-operations-2026-26-0424

[23] ISO. (2017). *Diesel engines — NOx reduction agent AUS 32 — Part 3: Handling, transportation, and storage*, *ISO Standard No. 22241-3:2017*. https://cdn.standards.iteh.ai/samples/66410/f94fcf0c46754aebb5e3056347110e3e/ISO-22241-3-2017.pdf.

[24] Smith, A. (2026, April 6). *Making Diesel Clean: What You Need to Know About SCR and DEF* [Webinar]. Engine Technology Forum. https://enginetechforum.org/webinars/

[25] Ibid.

Diesel Exhaust Fluid in Cold Climates

DEF has a freezing point of 12° F, making it susceptible to cold weather. When ambient temperatures drop below 12° F, the water that makes up two-thirds of DEF can freeze and expand, putting mechanical pressure on the internal components of the dosing systems. If the flow of DEF stops, residual fluid in the lines can evaporate quickly due to engine exhaust temperatures, which can result in the formation of urea crystals. Frozen DEF can also compromise Urea Quality Sensors (UQSs) and cause a fault code that could result in a derating event, a software-initiated power restriction triggered by sensor failures or empty DEF tanks.

The potential for cold weather issues, however, does not seem to have affected adoption of SCR technology. DEF is used throughout the world, including regions that endure cold climates. For example, SCR technology is universally prevalent in commercial trucks operating in northern regions like Canada[26] and Scandinavia, [27] with adoption reaching nearly 100% of active, new-generation fleets due to direct alignment with EPA 2010 and EU Euro VI emissions mandates. To prevent freezing when stationary, DEF systems are designed to purge the supply lines once the vehicle is turned off,[28] protecting against the formation of urea crystals. Tanks are also engineered with an integrated heating element, which safely liquifies the DEF once the engine is running.[29] Some integrate a 48-volt heater to accelerate the thawing cycle. Engine electronic control units delay active fault testing until after the system has had sufficient time to thaw.

Vehicle Performance and Economics

The integration of SCR has changed diesel engine management by shifting the emissions burden to the exhaust stream, enabling the engine to be tuned for maximum fuel economy and performance.

This shift has delivered a net positive in fuel economy. A 2020 National Academy of Sciences report found that 2010 engines equipped with SCR delivered a 5% reduction in fuel consumption compared to 2007 engines equipped with EGR.[30] In addition, because SCR reduces the burden of in-cylinder NOx control, less soot is produced, leading to less frequent Diesel Particulate Filter (DPF) regeneration cycles.

According to a study published by the National Renewable Energy Laboratory in 2020, the estimated incremental cost of equipping a model year 2023 heavy-duty diesel engine (12–13L class) with a full aftertreatment technology package would average $6,873, with a range between $3,488 and $10,485. The SCR and DEF components represented about 2%-4% of the average vehicle's cost at the time of this study.[31]

Recent EPA Guidance

The use of SCR systems requires operators to maintain an adequate level and quality of DEF on board the vehicle. Regulatory requirements mandate that OEMs develop suitable control systems that deter operators from diluting DEF or failing to maintain SCR system functionality. These requirements include driver notifications and eventually performance restrictions that can limit vehicle speed and torque or even prevent the engine from starting.

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[26] Environment and Climate Change Canada (ECCC). (2010/Amended 2021). *On-Road Vehicle and Engine Emission Regulations* (SOR/2003-2) under the *Canadian Environmental Protection Act, 1999 (CEPA)*. Government of Canada.

[27] European Commission. (2011). *Commission Regulation (EU) No 582/2011 of 25 May 2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy duty vehicles (Euro VI)*. Official Journal of the European Union, L 167, 1–168.

[28] ISO. (2019). *Diesel engines — NOx reduction agent AUS 32 — Part 4: Refilling interface*). (ISO 22241-4:2019).

[29] *Lahr, R. (2018, April 30).* High-flow coolant control valves: Keeping diesel exhaust fluid flowing in cold weather. *Fluid Power Journal*. https://fluidpowerjournal.com/high-flow-coolant-control-valves-keeping-diesel-exhaust-fluid-flowing-cold-weather/

[30] National Academies of Sciences, Engineering, and Medicine. (2020). Powertrain technologies. In *Reducing fuel consumption and greenhouse gas emissions of medium- and heavy-duty vehicles, phase two: Final report* (pp. 72–128). The National Academies Press. https://doi.org/10.17226/25542

[31] Lynch, L. A., et al. (2020). *On-road heavy-duty low-NOx technology cost study* (Report No. NREL/TP-5400-76571). National Renewable Energy Laboratory. https://doi.org/10.2172/1659977

Several operators of vehicles and equipment using SCR technology have reported problems with these systems. The greatest operational concerns are DEF inducements that result in a derate. In December 2022, the EPA relaxed DEF inducement requirements for new diesel engines produced in 2027 and beyond, and in August 2025 (with additional clarification in March 2026) took the additional step of relaxing DEF inducements for trucks, buses and nonroad equipment already on the road and in the field today.

These changes are meant to address operator concerns primarily through the implementation of a revised, graduated engine derate schedule. Prior to this adjustment, a "limp home mode" event could trigger a sudden and severe speed restriction to 5 mph, potentially stranding drivers on high-speed corridors and creating significant safety risks and operational disruptions. The 2025 guidance update replaces this with a 650-mile (or 10-hour) warning phase, followed by a 4,200-mile mild derate period for heavy-duty trucks.[32] The EPA similarly extended DEF inducement schedules for other diesel applications, such as buses and other vehicles and equipment, allowing operators to complete their immediate delivery or task and granting them sufficient time to correct any system errors before severe power restrictions apply. Diesel engine manufacturers are implementing the new guidance where feasible and integrating it into new products.[33]

In addition to reducing maintenance burdens on small businesses and farmers, in March 2026, the EPA clarified its requirements concerning UQS, allowing manufacturers to optionally use advanced NOx sensors instead to verify system efficacy. By eliminating a sensor often prone to failures the agency sought to reduce the upfront hardware cost and the frequency of false-positive error codes that historically plagued operators across the heavy-duty and agricultural sectors.

Operating SCR without DEF

Operating engines equipped with SCR without DEF will trigger a DEF inducement and might void manufacturers' warranties. Diesel engine manufacturers are required under the Clean Air Act to program engine and emissions management systems to trigger a DEF inducement when a DEF tank is empty, or the system detects an issue, such as poor-quality DEF, or the failure of a component in the SCR system. Absent a regulatory requirement, diesel engine and equipment manufacturers might continue to program DEF inducements for equipment protection purposes, just as they do for other system faults such as oil pressure too low or coolant temperature too high. In addition, while OEMs cannot mandate a specific brand of DEF, engine warranties often explicitly restrict coverage to systems operated with DEF that conforms strictly to ISO 22241-1 purity specifications. Failure to maintain fluid quality or operating the aftertreatment assembly dry can void the OEM base warranty.

If a DEF inducement was not triggered, continued engine operation can result in a significant increase in emissions and could result in long-term damage to the engine components with declining performance. Missing or altered SCR systems may be considered "tampering," which is a Clean Air Act violation and can have other negative outcomes including a potential loss of vehicle insurance, voided warranties, lower resale value, potential failure of vehicle emissions inspections, or unsafe vehicle operation.[34]

Without DEF, the SCR system loses its ability to reduce NOx emissions. As a result, tailpipe NOx emissions can increase by 10 to 50 times the regulated limits.[35] To compensate for the lack of aftertreatment, the engine control module may alter engine timing, which can result in cooler exhaust profiles or significantly higher engine-out

[32] Szabo, A. (2025, August 11). *Revised Guidance for Light Duty Vehicles, Heavy-Duty Diesel Engines and Nonroad Compression-Ignition (CI) Engines Using Selective Catalyst Reduction (SCR) Technologies* (IACD-2025-10) [Letter]. U.S. EPA. https://www.epa.gov/system/files/documents/2025-08/def-ltr-manufacturer-2025-0811.pdf

[33] Schaeffer, A. (2026, April 6). *Making Diesel Clean: What You Need to Know About SCR and DEF* [Webinar]. Engine Technology Forum. https://enginetechforum.org/webinars/

[34] Ibid.

[35] Zhang, H. et al. (2025, November 17). Research on the Impact of Typical SCR Faults on NOx Emission Deterioration of Heavy-Duty Vehicles. *Atmosphere, 16, 11*. https://www.mdpi.com/2073-4433/16/11/1299

soot. This can create an immediate burden on the DPF, leading to premature filter clogging and more frequent active regenerations, which would increase fuel consumption.

Operating an SCR system dry can permanently damage hardware. Residual urea in the dosing lines and injectors can dehydrate and form hard white crystals. These crystals can permanently clog the DEF injector and damage the dosing pump, which relies on the fluid for cooling and lubrication.

Without the active chemical reductions facilitated by DEF, the SCR catalyst brick could be subject to "face plugging," where particulate matter or unburned fuel accumulates on the catalyst surface, eventually poisoning the active precious metals and necessitating an expensive replacement.[36] This blockage of the catalyst can severely restrict exhaust gas flow and create systemic engine backpressure. Such pressure can force excessive thermal and mechanical stress backward into the engine exhaust manifold and turbocharger turbine wheels, resulting in lower fuel economy.[37]

Alternatives to Derating Events

In lieu of derating, other methods for reminding drivers to ensure that an adequate supply of DEF is provided to the SCR system can include visual and/or auditory signals. While these do not compel driver behavior, a significant amount of research has examined the form such notifications could take and what actions by the operator might result.

A Federal Highway Administration report found that operator performance can be improved by combining auditory and visual messages and that these should be used together to provide either redundant or complementary cues to the driver whenever possible.[38] The report also found that drivers process complex information more quickly through visual notifications, especially when presented as easily understood pictures. Auditory signals were found to create a nuisance and distraction when delivered continuously but perform better when delivered intermittently. In addition, automatic notifications that are not urgent are best delivered visually, while those that urgent should be delivered auditorily to capture the attention of the operator.

Another study found a relationship between driver’s comprehension of the notification and its associated implications and their likelihood of conducting preventive maintenance. An operator’s level of understanding of the severity (or lack thereof) of a notification will influence the urgency with which they conduct maintenance.[39] When drivers learn that a persistent indicator light (such as tire pressure or check engine) does not immediately impair vehicle drivability, they experience a loss of urgency. This results in extended compliance delays, where drivers defer routine servicing for weeks or months despite the continuous visual prompt.[40] Consequently, operator education about the notification and its importance is a significant factor in creating compliance.

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[36] McGrath, B. (2026, January 19). *DEF Crystallization Explained: Causes, SCR Damage, and How Fleets Can Prevent It.* Keller Heartt. https://info.kellerheartt.com/blogs/what-is-def-crystallization

[37] Yadav, P., & Kothmire, P. (2021). CFD analysis of exhaust pipe of a diesel engine. *AIP Conference Proceedings*, *2417*(1), 060002. https://doi.org/10.1063/5.0072779

[38] Campbell, J. L., Carney, C., & Kantowitz, B. H. (1998). *Human factors design guidelines for advanced traveler information systems (ATIS) and commercial vehicle operations (CVO)* (Report No. FHWA-RD-98-057). Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/safety/98057/ch03b.cfm

[39] Atombo, C., Akple, M. S., Dumenya, A., & Adzimahe, P. (2025). Comprehensibility and impact of vehicle dashboard indicator light symbols on drivers' preventive maintenance compliance. *PLOS ONE*, *20*(5), Article e0323386. https://doi.org/10.1371/journal.pone.0323386

[40] Parasuraman, R., & Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. *Human Factors*, *39*(2), 230–253. https://doi.org/10.1518/001872097778543886

Examples of Existing Audible and Visual Alerts

A common example of visual and auditory messages can be found with the introduction of the Distance-to-Empty (DTE) display related to fuel levels. While these successfully eliminated out-of-gas incidents caused by gauge misreading, data indicates that these signals have introduced a secondary operational challenge: behavioral adaptation and compliance delay. According to research by AAA, 74% of motorists rely on DTE readouts to schedule refueling. Despite this reliance, AAA also reports an estimated 24 million drivers regularly operate their vehicles with the low-fuel warning light actively illuminated. Rather than treating the low-fuel alert as an immediate trigger to seek service, drivers frequently consider the vehicle's reserve capacity to be usable operating range. Despite near-universal adoption of low-fuel indicators across modern light-duty fleets, fuel depletion remains a leading cause of roadside service dispatch, resulting in roughly 500,000 service calls annually in North America alone.[41]

The DTE display is not accompanied by a manufacturer induced vehicle impairment feature since the vehicle will become inoperable without fuel. However, other visible and audible signals that are designed to compel compliance with a regulation, such as those related to the use of seat restraints, do not include any vehicle impairment mechanisms. While these alerts have been successful with a large percentage of vehicle drivers and passengers, there is a segment that refuses to comply and has implemented strategies to circumvent the alerts.[42] For this reason, seat belt compliance is reinforced through local law enforcement and fiscal penalties.

Conclusion

The original EPA regulations to reduce NOx emissions were enacted based on environmental and public health concerns. The heavy-duty vehicle industry responded by investing in SCR technology and establishing a production, distribution and retail system to supply vehicles with the required DEF. The technology supported a dramatic decrease in NOx emissions and an increase in vehicle fuel efficiency and performance.

Despite these achievements, the technology created operational concerns about the impact of DEF inducements that result in derating events. These events could strand drivers for prolonged periods of time and take vehicles and equipment out of operation while drivers wait for repairs to be made. The revised EPA guidance to manufacturers that provides flexibility for drivers to reach their destinations and for operators to make necessary repairs was welcomed by the industry. However, the fact remains that operating an SCR system without DEF could present significant environmental and equipment risks that should be considered by operators.

Balancing the benefits of SCR/DEF technology with the operating requirements of vehicles and equipment is critical to ensure that the industries that depend on diesel technology, like trucking, farming and construction, can continue to serve the needs of the economy while reducing their impacts on public health and the environment.

[41] AAA Automotive Research Center. (2021). *In-dash fuel economy and range display accuracy evaluation*. American Automobile Association; AAA Public Affairs. (2018). *Driving on empty: American drivers take risks with low fuel*. American Automobile Association; Campbell, J. L., et al. (2004). *In-vehicle display icons and other information elements* (Report No. FHWA-RD-03-065). Federal Highway Administration.
[42] Kidd, D. G., et al. (2013, November 26). Attitudes toward seat belt use and in-vehicle technologies for encouraging belt use. *Traffic Injury Prevention*, 15. https://pubmed.ncbi.nlm.nih.gov/24279961/

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