

TIER 5 AND THE 19-56 kW OFF-HIGHWAY ENGINE: CURRENT ARCHITECTURES, TECHNOLOGY PATHWAYS, AND THE OPEN QUESTIONS

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Please note that this paper reflects CARB's Tier 5 draft proposal as of October 2026. Final limits and implementation dates may differ.

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1. Introduction

Modern diesel engines produce orders of magnitude lower oxides of nitrogen (NO_x) and particulate matter (PM) emissions than in past decades, largely thanks to the impact of selective catalytic reduction (SCR) and diesel particulate filter (DPF) implementation to satisfy emissions regulations. In the non-road space, the current Environmental Protection Agency (EPA) and California Air Resources Board (CARB) standard is Tier 4f. Nearly all engines with power output greater than 56 kW use SCR, and about half also carry a DPF. The regulations for engines in the 19 to 56 kW power category, however, have allowed original equipment manufacturers (OEMs) to produce engines that do not require SCR for NO_x control and sometimes do not require a DPF for particulate control. As of October 2026, just over half of model year (MY) 2020 and later Tier 4 certified 19–56 kW non-road compression ignition (NRCI) engine families have a DPF, and about 1% are equipped with an SCR system for NO_x control (Figure 1).

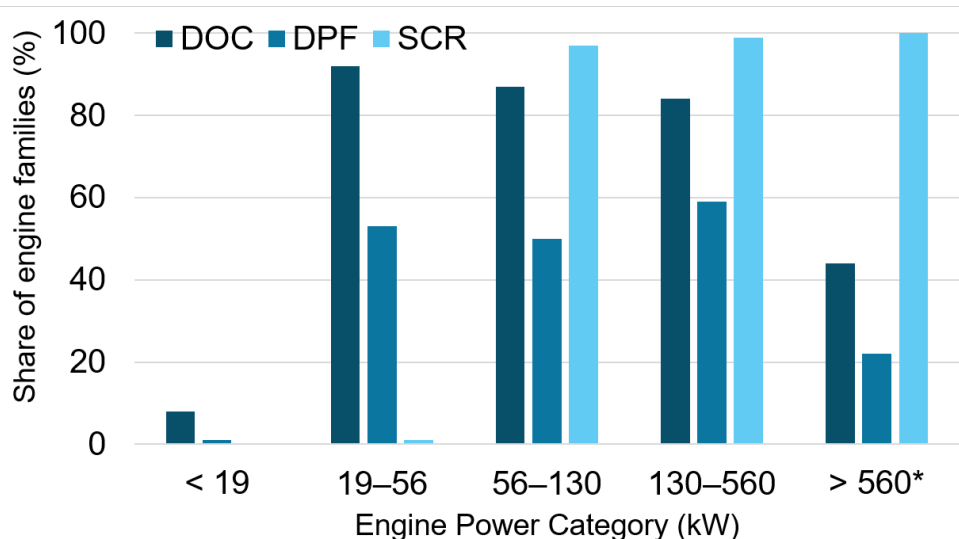


Figure 1: Share of aftertreatment technologies in MY2020+ Tier 4 certified NRCI engines [1]. Power categories in kW.
 * >560 kW = gensets only. DOC = Diesel oxidation catalyst

CARB has proposed the next step in emissions regulations for non-road engines, the Tier 5 regulation [2]. Under this proposal, nitrogen oxide (NO_x) reductions of up to 90% and particulate matter (PM) reductions of up to 75% will be required, depending on the engine power category [3]. Table 1 summarizes the proposed tailpipe out emission standards under the proposed Tier 5 emission standards for all power categories. The proposed standards affect every power category, and the technical response is likely to differ between them. This paper focuses on the 19–56 kW category. A cursory review of the proposed standards shows that there will likely be significant differences in the technical solutions for emissions control depending on the power

category, but all engines will be significantly impacted. For 19–56 kW engines, compliance will depend on how combustion system design, bore size, EGR, boost, aftertreatment, thermal management, controls and the application's duty cycle work together, and the right answer will differ by engine family and end use.

Table 1: Proposed Tier 5 emission standards per the February 2026 CARB regulation order [3]. Tier 4 emissions standards from [4, 5]. Tier 4f = Tier 4 final standard, Tier 5i = Tier 5 interim standard, Tier 5f = Tier 5 final standard, NMHC = non-methane hydrocarbon, CO = carbon monoxide

Power	Standard	Emissions (g/kWh)				
		NO _x	NMHC	NO _x + NMHC	PM	CO
< 8 kW	Tier 4f	-	-	7.5	0.4	8
	Tier 5f	-	-	5	0.2	8
8 ≤ kW < 19	Tier 4f	-	-	7.5	0.4	6.6
	Tier 5f	-	-	4	0.1	6.6
19 ≤ kW < 37	Tier 4f	-	-	4.7	0.03	5.5
37 ≤ kW < 56		-	-	4.7	0.03	5
19 ≤ kW < 56	Tier 5i	-	-	4.4	0.01	5
	Tier 5f	2.5	0.19	-	0.008	5
56 ≤ kW < 130	Tier 4f	0.4	0.19	-	0.02	5
	Tier 5i	0.35	0.19	-	0.01	5
	Tier 5f	0.04	0.08	-	0.005	5
130 ≤ kW ≤ 560	Tier 4f	0.4	0.19	-	0.02	3.5
	Tier 5i	0.35	0.19	-	0.01	3.5
	Tier 5f	0.04	0.08	-	0.005	3.5
> 560 kW Generator	Tier 4f	0.67	0.19	-	0.03	3.5
	Tier 5f	0.35	0.08	-	0.008	3.5
> 560 kW mobile machine	Tier 4f	3.5	0.19	-	0.04	3.5
	Tier 5f	3	0.19	-	0.04	3.5

Manufacturers in this category do not have to commit to a Tier 5 technology pathway before the final limits are known, but the testing that informs that choice takes years, and the time left for it shrinks once the rule is adopted. Published data at Tier 5 levels in this range is very limited with a narrow range of engine and aftertreatment systems [6]. None of them reports Tier 5-level emissions over the full useful life, and production-representative data across this range of engines and applications is not publicly available. This paper describes the segment as it stands,

summarizes what the Tier 5 proposal changes, outlines the technology options and sets out the questions that need answers before those choices can be made with confidence.

2. Sub-56 kW Sector Characterization Today

Shares in Figures 1 through 6 are calculated from CARB off-road compression-ignition executive orders for MY2020 and later (revised October 1, 2026) [7], counting each model-year certificate once, converting rated power from horsepower to kilowatts, and counting each certificate in every power band and application it covers. Valve counts, which CARB does not report, were taken from manufacturer and secondary sources or inferred from comparable engines of the same manufacturer.

2.1 Duty-cycle variations

The 19 to 56 kW range serves a wide variety of applications but broadly can be divided into two kinds of duty cycles. Applications like compressors, pumps and generators largely operate at a constant speed and sustained high loads. Mobile applications (skid steers, small excavators, tractors, and so on) have highly transient operating cycles and can also have significant idle time. Figure 2 shows the share of MY2020+ CARB Tier 4 certified engines depending on their application. Note that this plot also shows that the 19 to 56 kW power category is not a single monolithic bloc but can more accurately be subdivided into the four sub-categories called out in the figure legend. The Tier 4f regulation reflected this with separate regulated categories for 19 to 37 kW engines and for 37 to 56 kW engines. The current CARB proposal for Tier 5 does not make this separation, but the typical engine technologies used in these sub-categories suggest that emission compliance approaches for Tier 5 are likely to vary with the power output (and resulting technology mix) of the engine. For most applications, most certified ratings fall above 25 kW. The 19–25 kW band accounts for less than 10% of ratings in every application except TRUs and marine engines.

The engine application has further impact on the emissions aftertreatment technology beyond the engine power category and resulting technology mix. With more actively-controlled emission control devices on the engine, the duty cycle for the engine is more important than for Tier 4f and earlier standards. For instance, if exhaust gas recirculation (EGR) is employed for in-cylinder NO_x reduction then a DPF will experience faster loading than on an engine without EGR. This means that applications with extended low-load operation will require active thermal management to

initiate active regeneration of the DPF as required since the engine load cannot be guaranteed to be high enough to regenerate the DPF without intervention.

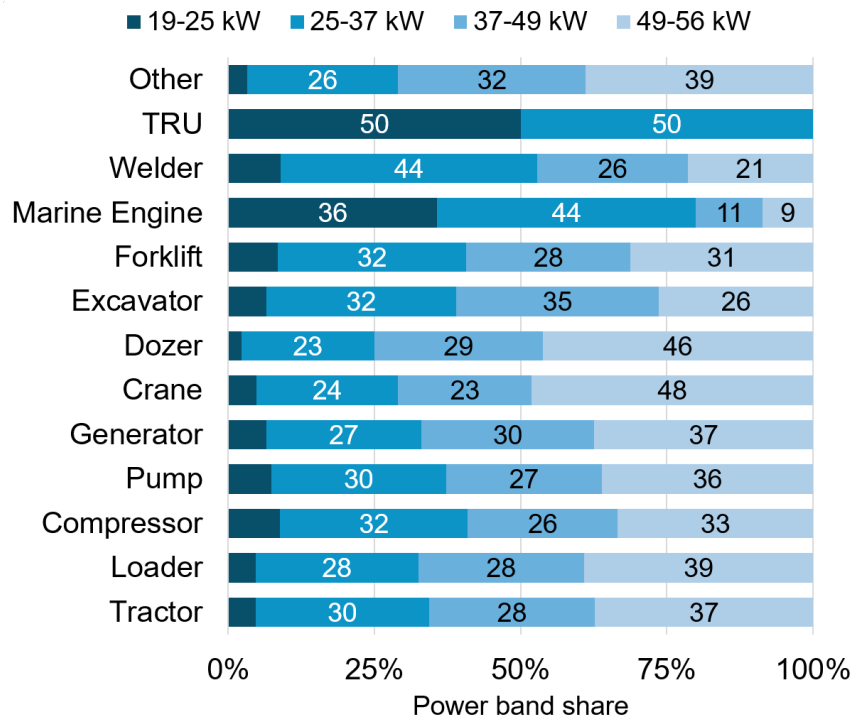


Figure 2: Application wise breakdown of < 56 kW MY2020+ Tier 4 certified engines [7]

TRU = Trailer refrigeration unit

If a NO_x reduction device such as a SCR system is employed this would again require increased active control of the engine relative to older regulatory Tiers. Higher-power engines have managed these controls since Tier 4f. How the duty cycles typical of smaller engines will interact with them is less well understood, and an early field report suggests that duty cycle already affects DPF regeneration in some smaller engines [8]. A CARB-funded study saw the same sensitivity in this power range. SCR NO_x reduction ranged from 26% to 91% depending on test cycle and exhaust temperature, with the lowest conversion on the cold-start NRTC [6].

2.2 EATS technologies

Aftertreatment technologies applied to Tier 4f engines in the sub-56 kW categories have been limited to DPF and diesel oxidation catalyst (DOC) devices. The NO_x limit for these engines is presently high enough that in-cylinder combustion controls have been sufficient to ensure

compliance, and only about 1% of 19–56 kW engine families use SCR (Figure 1). It is evident from Figure 1 that >90% of MY2020 and later 19–56 kW engine families use a DOC for hydrocarbon and carbon monoxide control and just over half use a DPF. Figure 3 shows that the DOC is close to universal above 25 kW and is still present on 78% of 19–25 kW engine families, while DPF use rises only modestly with power, from 48% at 19–25 kW to about 60% above 37 kW. In this segment, the DPF rather than the DOC is the aftertreatment device that Tier 5 will add to the most engines. The key question for OEMs as they consider a Tier 5 technology approach is whether the lower NO_x limit of CARB’s proposed Tier 5 regulation (and potentially an even lower limit should EPA decide to regulate more strongly) can be satisfied with in-cylinder combustion methods or if a catalytic solution is required. The CARB proposal for Tier 5 will require DPF and DOC devices for these engines regardless of the NO_x control strategy, so penetration of these technologies may be expected to reach 100% in this power category. If NO_x aftertreatment is determined to be needed by some OEMs, there is then the added system complexity of the various approaches that could be taken to implement those devices.

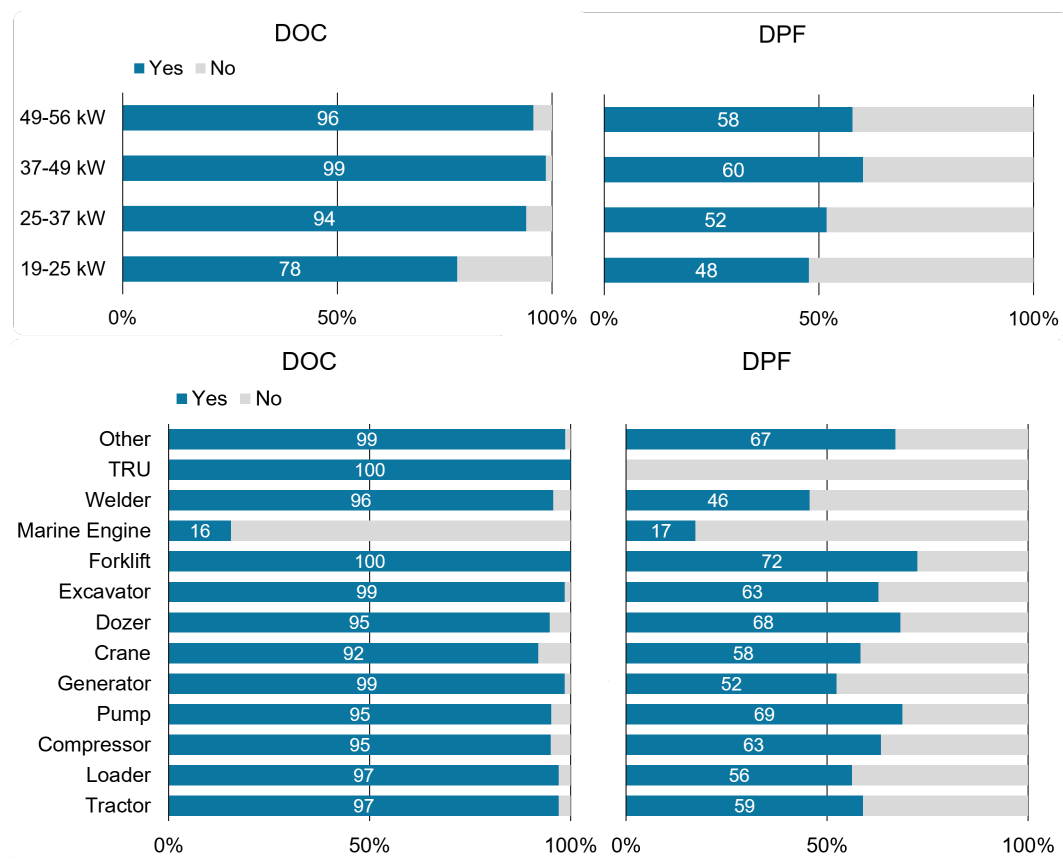


Figure 3: Penetration of DOC & DPF technologies in the sub-56 kW power segment [7]

2.3 Engine architecture

There are also significant differences in combustion system design across the 19 to 56 kW category. Figure 4 shows that 2-valve cylinder heads are the majority across every power band in the 19-56 kW range. 4-valve designs become more common with power, rising from 20% to 45%. This difference in valve arrangement will correspond to significant differences in combustion system performance with respect to emissions control (tolerance to EGR, for instance).

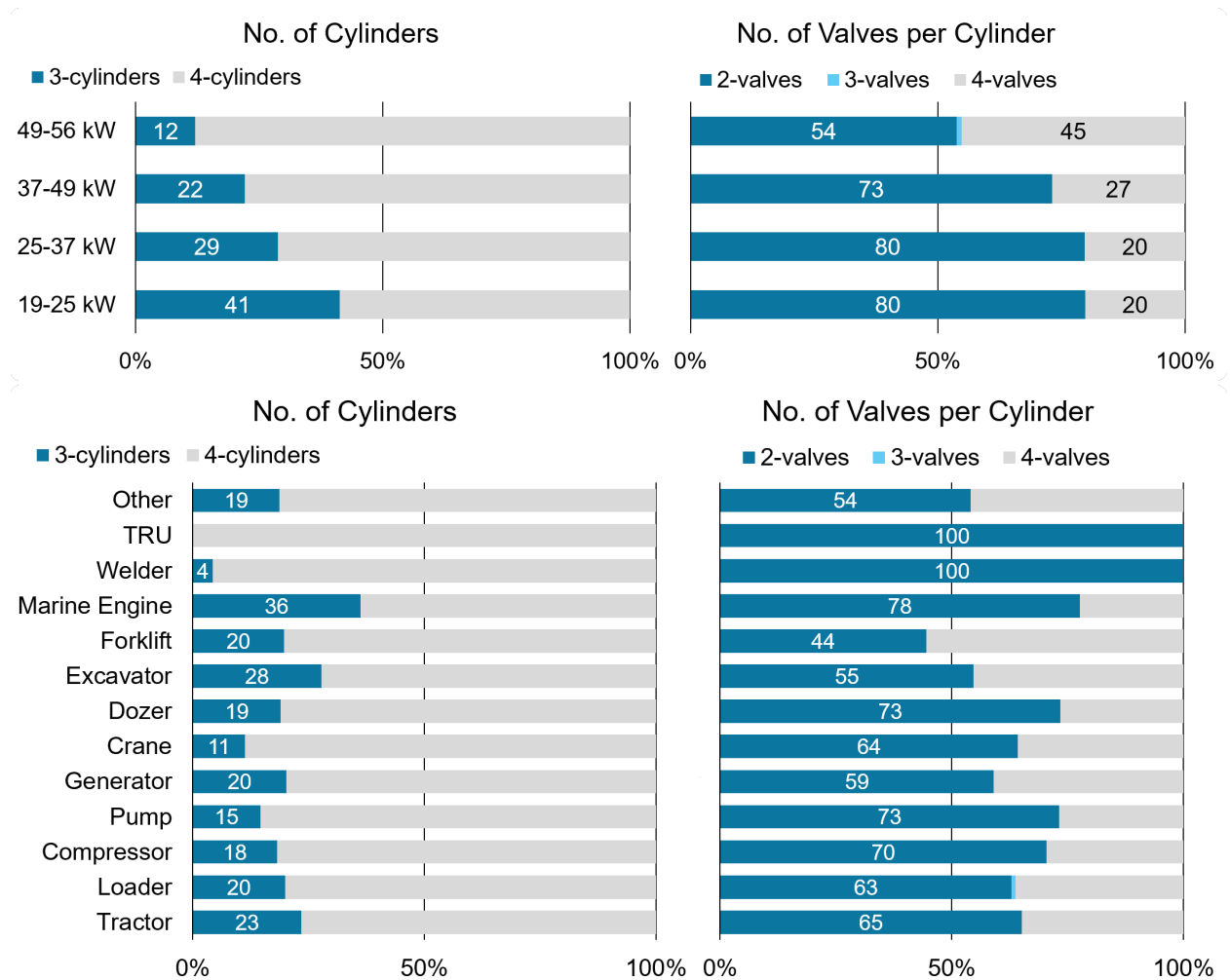


Figure 4: Differences in engine architecture within the 19 - 56 kW power band [7]

Figure 3 and Figure 5 in combination show how the air system architecture is closely linked to the aftertreatment technology for these engines. There is a strong correlation between the use of EGR for in-cylinder NO_x control and the use of a DOC, which is to be expected based on the expected impact of EGR on unburned HC and CO emissions. DPF use does not follow EGR the same way. Above 25 kW, EGR is used on 90% or more engine families while DPF use stays

between 52% and 60%, so at least a third of engine families in that range meet Tier 4f PM limits with EGR and no particulate filter. Boosting shifts sharply with power, from <50% turbocharged engines at 19–25 kW to about 96% at 49–56 kW. Charge air cooling also increases with power, but even at 49–56 kW, where 96% of engines are turbocharged, about 40% of engine families have no charge air cooling.

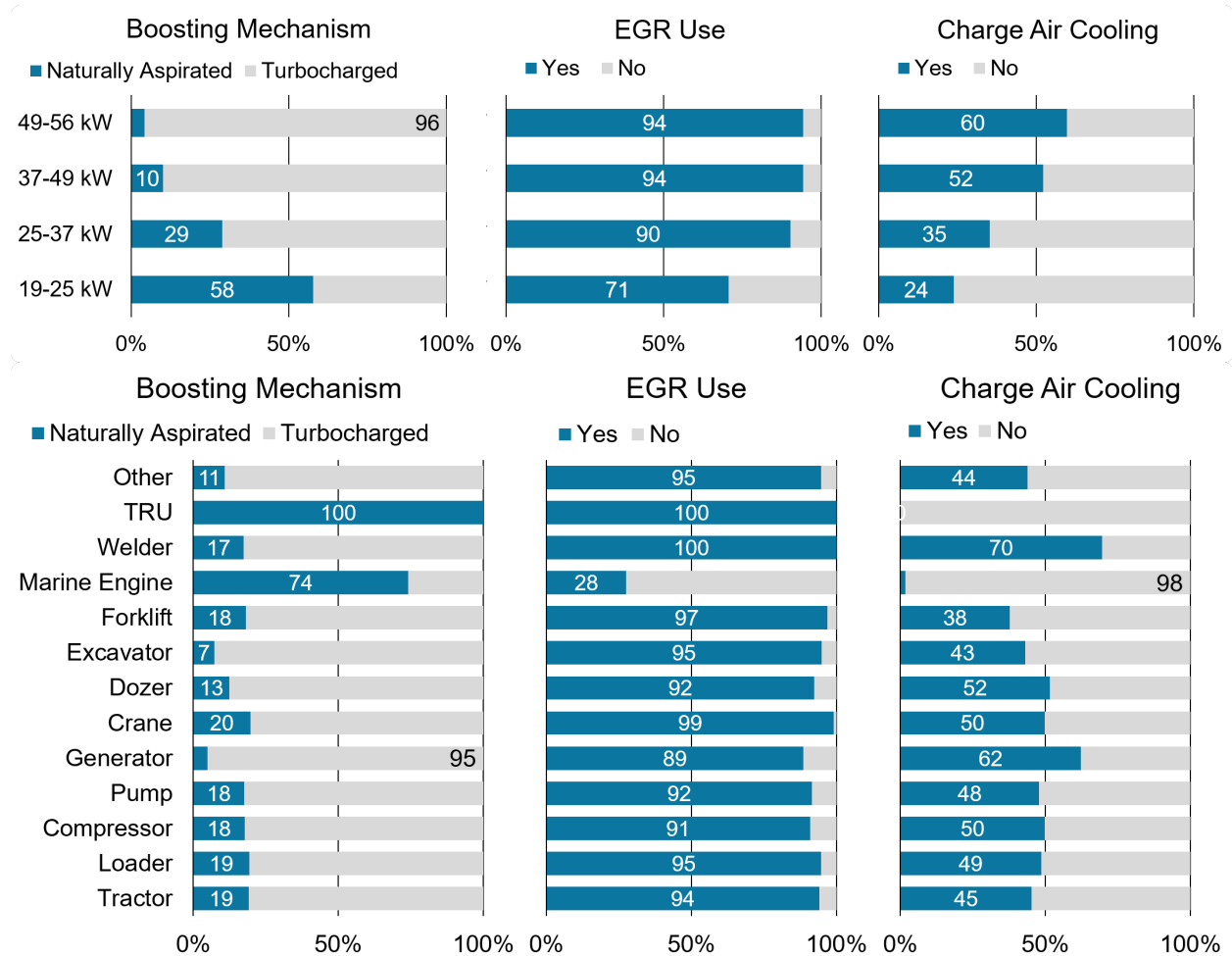


Figure 5: Differences in the air handling system within the 19 - 56 kW power band [7]

Figure 6 shows that the fuel system has largely converged on electronically controlled direct injection. Every sub-band above 25 kW is almost completely electronically controlled and direct-injected. Mechanical and indirect injection remain mainly at 19–25 kW, where almost a quarter of engine families are mechanically controlled and a similar share of the engines also indirect injection. For this remaining mechanical IDI group, the proposed Tier 5 regulation poses a

significant challenge, as it is uncertain whether these fuel systems can achieve the required emissions performance without conversion to electronic direct injection.

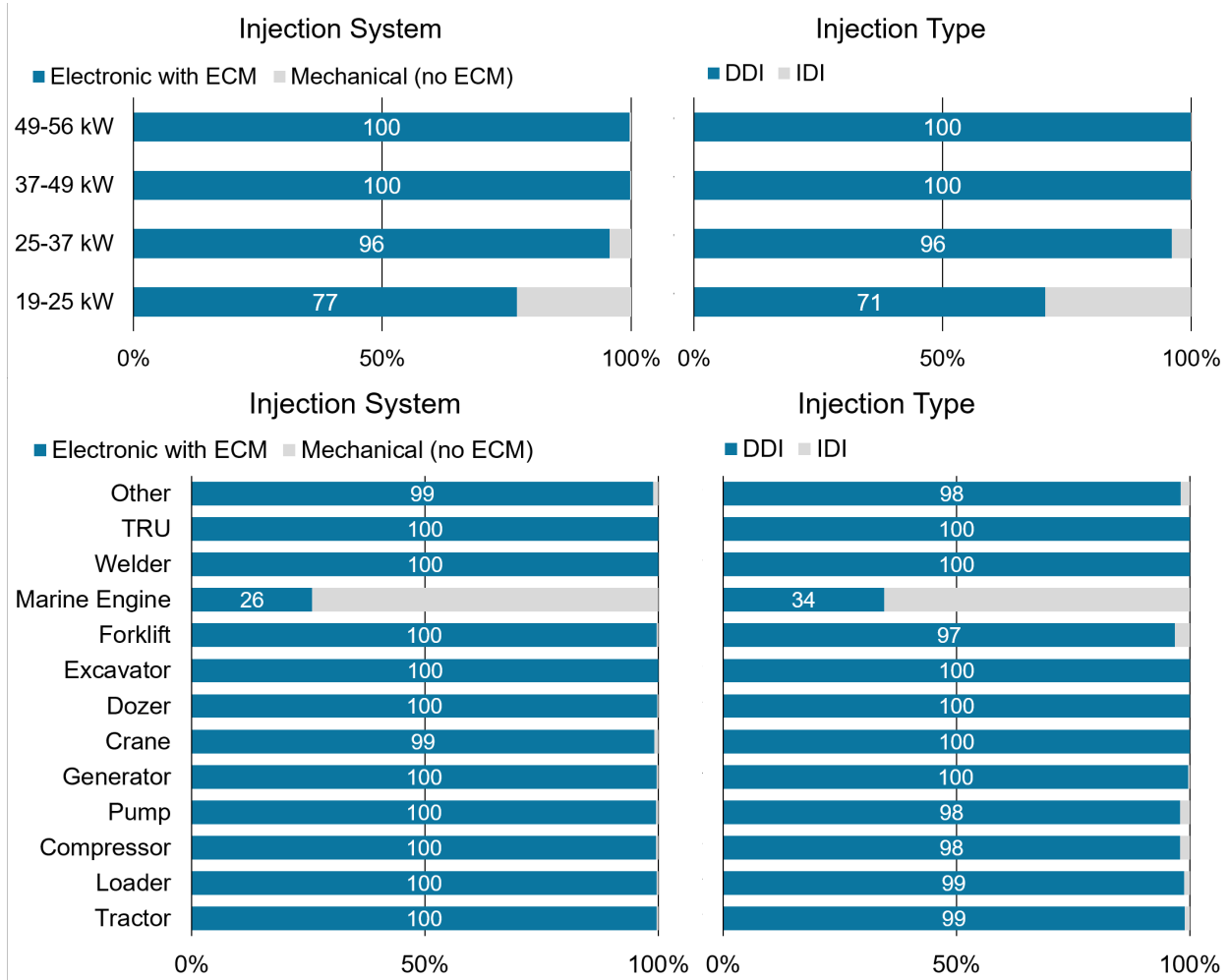


Figure 6: Differences in the fueling system within the 19 - 56 kW power band [7]

ECM = Electronic Control Module, DDI = Direct Diesel Injection, IDI = Indirect Diesel Injection

The result of this survey of the technology mix for engines in the 19 to 56 kW power category is that there is presently a significant amount of variation in the technologies implemented on the engine and aftertreatment systems for Tier 4f engines.

3. Tier 5 Compliance Requirements

3.1 Emission

Beginning with Tier 4, non-road engine certification requires both steady-state and transient tests. The steady-state cycle runs the engine through a fixed sequence of speed/load modes, each weighted to produce a cycle-average emission rate (Figure 7). Off-road CI engine certification in California is governed by Title 13 California Code of Regulations (CCR) Section 2423 [9], which contains altered or adapted sections of Title 40 Code of Federal Regulations (40 CFR) Parts 1039, 1065, and 1068. The duty cycles are federal requirements in 40 CFR Part 1039 and the test procedures are in Part 1065. Under these provisions, variable-speed non-road compression-ignition engines in the 19-56 kW power category are required to demonstrate compliance with applicable emission standards over both a steady-state duty cycle and a non-road transient cycle (NRTC) as seen in Figure 7. The NRTC is a composite duty cycle built from seven representative non-road equipment types, run once from a cold start and once from a hot start, with the cold start result weighted at 5% [9, 10]. CARB's Tier 5 proposal also proposes a non-road low-load cycle (LLC). The cycle has not been finalized, and under the current draft it would only apply to variable-speed engines in the 56 – 560 kW category and hence does not apply to sub-56 kW engines [11]. Tier 4 had also introduced a not-to-exceed (NTE) requirement: a zone under the engine's torque curve within which emissions at any sampled point cannot exceed the applicable standard by more than a fixed multiplier [10].

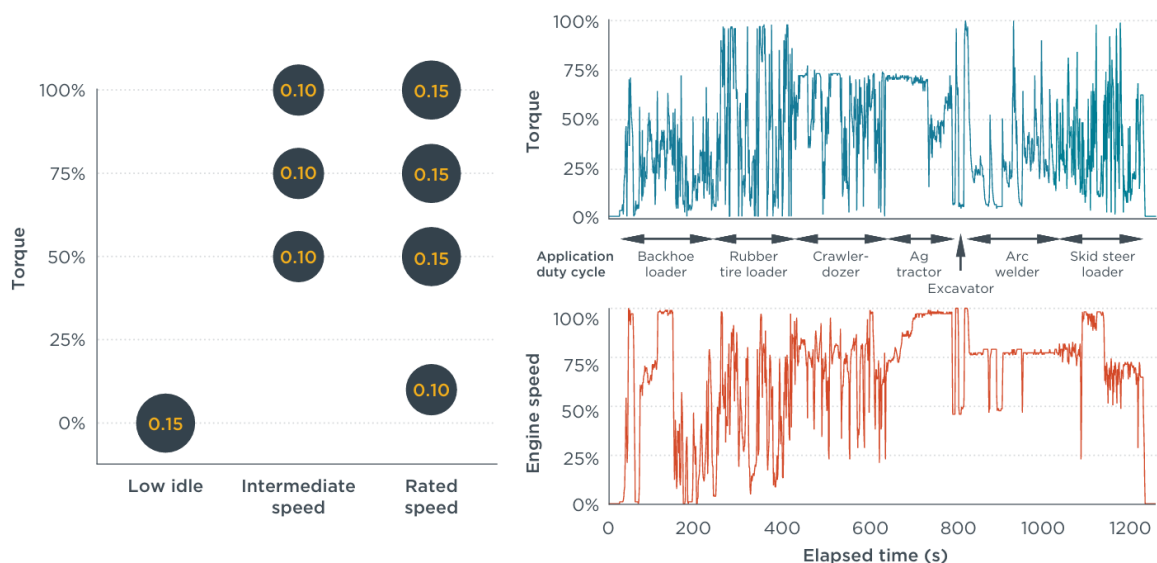


Figure 7: Operating modes for NRSC (left) and NRTC (right) engine test cycles [10]

3.2 Durability

CARB's Tier 5 rulemaking process has also proposed changes to useful life and warranty periods, independent of the emissions limits themselves. At an October 2023 workshop, CARB proposed keeping the current useful-life (UL) and warranty hour limits unchanged but extending the year limits by roughly 50% across all power categories [12]. For engines at or above 37 kW, useful life moves from 8,000 hours or 10 years to 8,000 hours or 15 years, and warranty from 3,000 hours or 5 years to 3,000 hours or 8 years [12]. Figure 8 summarizes the changes in full useful life and warranty requirements.

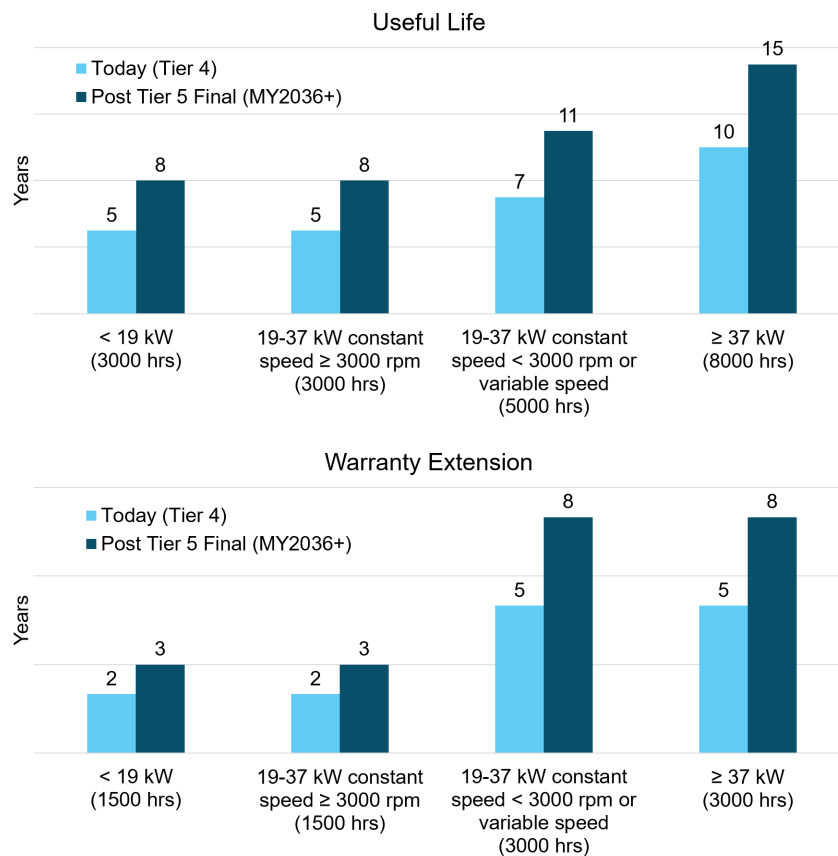


Figure 8: Proposed Tier 5 useful life & warranty extension [12]. Hours unchanged (shown in category labels)

CARB's own contractor-supplied data motivated the change. Average construction and agriculture equipment life runs closer to 10,000 hours over roughly 18 years, meaning most equipment reaches its year limit well before its hour limit under the current rule [12]. A contractor survey has also estimated that the incremental cost of the year-limit extension would be roughly \$401 per engine in the 56–130 kW class [12]. CARB has also proposed extending the minimum maintenance interval for EGR coolers from 1,500 hours to 3,000 hours for engines below 130 kW [12], based on data showing actual replacement frequency in off-road construction equipment

closer to 4,500 hours. A longer interval would reduce the scheduled maintenance burden for EGR-equipped engines. No public study has shown Tier 5-level emissions from an engine in this range at the end of its full useful life. The CARB-funded retrofit study aged its aftertreatment to the equivalent of 1,000 hours, through field operation or an accelerated dynamometer protocol, and saw no significant deterioration over that period [6]. Under Tier 5, useful life for these engines is 5,000 to 8,000 hours and up to 15 years (Figure 8). Whether engines and aftertreatment in this range hold Tier 5-level emissions over that period, and what deterioration factors they would carry at certification, are open questions.

3.3 Defect detection & handling

Beyond the useful life and warranty extensions discussed above, Tier 5 substantially restructures CARB's defect-detection framework which governs when a manufacturer must formally investigate a suspected emission-related component (ERC) defect, report it, and act on it. Two changes matter specifically for the sub-56 kW segment. From Table 2, the absolute-unit thresholds triggering each stage drop sharply and are unified across all power categories:

1. Investigation moves from 50 units (≤ 560 kW) or 25 units (> 560 kW) to a single 12-unit floor or 10% of California sales volume, whichever is greater.
2. Defect Reporting moves from 20 units to 12 or 4% of California sales volume, whichever is greater.
3. Corrective Action moves from 50 units to 12 or 4% of California sales volume, whichever is greater.

Note that the population these thresholds are measured against shifts from nationwide sales to CA-only sales.

This new defect-detection framework negatively affects the sub-56 kW power range since this new framework skews toward lower-volume, application-specific engine families rather than the high-volume platforms common in the on-highway-adjacent power classes. Under the current framework, several of these families could in practice avoid formal defect scrutiny purely through limited sales volume, independent of actual failure rate. But the Tier 5 proposal closes that gap directly by lowering the floor and switching to California-only sales. The Tier 5 proposal also codifies which failure types trigger a mandatory recall versus an extended-warranty remedy. Aftertreatment devices, on-board computers/systems, diesel exhaust fluid (DEF) dosers, and

hydrocarbon injectors are recall-eligible; other emission-related components get extended warranty to full useful life instead, with the CARB Executive Officer retaining discretion either way [12]. Note that the DEF dosers have been explicitly flagged. For the sub-56 kW power range it would thus mean that choosing an SCR-equipped approach would add an exposure to recalls in addition to the cost of extra equipment and DEF. Thus, the original equipment manufacturers in this segment need to plan for more stringent in-use compliance scrutiny under Tier 5 than the current framework provides, independent of any change to the emission standards themselves.

Table 2: Proposed updates to defect-detection framework under Tier 5 [12]

Stage	Current (Tier 4)		Tier 5 proposal
Power level	≤ 560 kW	> 560 kW	All
Investigation Unscreened defects	50 or 10% ^{a, b} Nationwide sales	25 or 10% ^{a, b} Nationwide sales	12 or 10% California sales
Defect reporting Screened defects	20 or 2% ^{c, d} Nationwide sales	10 if sales < 150 units, 15 if sales 150 – 750 units, 2% if sales > 750 units Nationwide sales	12 or 4% California sales
Corrective action Screened defects	50 or 4% ^e California sales	50 or 4% ^e California sales	12 or 4% California sales

Thresholds are a unit count or a share of sales volume, whichever is greater.

a: 5,000 if engine family sales > 50,000, b: 40 CFR 1068.501(e). c: 1,000 if engine family sales > 50,000, d: 40 CFR 1068.501(f), e: 13 CCR 2143

3.4 On-board diagnostics

CARB has also proposed that Tier 5 would introduce on-board diagnostics and on-board monitoring (OBD/OBM) requirements for off-road engines for the first time [12]. Non-road engines have never carried real-time fault-detection and malfunction-indicator systems that on-road engines have run for decades. The implication is that every Tier 5-compliant engine in this range is expected to need new sensors and control logic to monitor emissions-critical components, independent of which emission control architecture it uses. Thus, making a choice on preferred architecture in this already cost-sensitive power segment of sub-56 kW engines becomes more complicated since the burden is not evenly distributed across the approaches. For example, an SCR-equipped design needs to monitor NO_x conversion efficiency, reductant quality, and doser

function in addition to whatever an EGR-only design already monitors, which is one more reason SCR's added complexity in the 37–56 kW bin is not just a hardware and DEF cost question but an OBD and controls one as well. Because non-road vehicles are not inspected and registered in the same way that on-road vehicles are, OBD systems may require connectivity to the internet, creating potential data security issues.

4. Probable Technology Pathways for Tier 5

4.1 Emission control strategies and technologies available

Engine emissions can be dealt with inside the combustion cylinder itself or outside the cylinder by EATS. In-cylinder approaches encompass engine design changes that aim to limit pollutants formation during the fuel combustion process. For in-cylinder emission control approaches, there are trade-offs between the control of particulate matter and nitrogen oxides emissions. Because of fundamentally different formation mechanisms, PM control strategies may not be simultaneously effective in reducing NO_x emissions, and vice versa. The proposed Tier 5 regulation lowers emission standards to a point where in-cylinder strategies are not sufficient to control both NO_x and PM emissions. This would lead to the increased use of aftertreatment technologies. The key aftertreatment technologies applied in the non-road sector include DPF, DOC and SCR. Table 3 is a brief overview of important technologies and strategies that have been used for the control of emissions from non-road diesel engines.

4.2 Probable challenges

The bins in this range face a version of the same question: does EGR/SOI recalibration paired with DOC+DPF satisfy Tier 5's NO_x and PM requirements without SCR, and if so, at what point does SCR become worth adopting. The evidence available today answers that question differently in each bin.

1. <19 kW: Unlike the 19-56 kW range addressed in this paper, engines below 19 kW face a materially different regulatory trajectory. CARB's original November 2021 Tier 5 workshop proposed a zero-emission requirement for this power class [13]. This proposal was expected to remove the combustion pathway from consideration for this class entirely. CARB's technical assessment is that battery-electric alternatives are already viable substitutes at this power level [13]. Meeting Tier 5's tightened standards would require the same electronic control adoption as a prerequisite gateway and this segment is the

Table 3: Engine and EATS technologies that can be leveraged to reduce emissions [10]

Design strategy/technology	Description
Fuel injection system	
Electronic fuel injection	Advantages of variable start of injection (SOI) and high-pressure injection can be leveraged.
Fuel-injection pressure	Increased injection pressure promotes fuel atomization and better air and fuel mixing, resulting in improved combustion efficiency
Injection timing	Advanced or delayed fuel injections can be leveraged to deal with criteria pollutants within the cylinder itself.
Rate of fuel injection, multiple injections	Injection schedules like pilot & post can be adopted to deal with criteria pollutants within the cylinder itself.
Air-handling technology	
Turbocharging	Increased intake manifold air pressure allows better oxidation of fuel due to more available oxygen.
Charge air cooling	Lowers temperature of intake charge entering the combustion chamber to reduce peak combustion temperatures.
Exhaust gas recirculation (EGR)	Portion of exhaust gas mixed with intake air to serve as diluent and reduce peak combustion temperatures. Cooled EGR systems incorporate a cooler to increase system NO _x reduction efficiencies.
Aftertreatment devices	
Diesel oxidation catalyst (DOC)	A monolith honeycomb substrate coated with a platinum group metal catalyst.
Diesel particulate filter (DPF)	A filtration device which is regenerated using active and/or passive regeneration methods to oxidize and remove collected particulate. Sometimes catalyzed to serve a dual function of DOC and DPF.
Selective catalytic reduction (SCR) + ammonia slip catalyst (ASC)	SCR catalyst types include vanadium, iron-exchanged zeolite, and copper exchanged zeolite. These act as reducing agents to reduce nitrogen oxide. Ammonia is generated due to decomposition of urea solution and thus a separate ammonia oxidation catalyst is needed for ammonia control.
Engine construction	
4-valve heads	Improved volumetric efficiency and charge motion control for air-fuel mixing when compared to 2-valve heads.
Piston bowl	Some bowls are known to enhance turbulence in the combustion chamber allowing better overall soot oxidation.
Compression ratio	Reducing compression ratio reduces overall gas temperature, enabling nitrogen oxide reduction.

smallest, most cost-sensitive product category to absorb the expense. Combined with the packaging constraint inherent to the smallest engine class, there is proportionally less physical space to add an EGR cooler, DOC, and DPF stack relative to engine size than at any other power band in this paper's scope. Thus, the economics plausibly favor a battery-electric powertrain over a full combustion-and-aftertreatment retrofit for a meaningful share of this segment, independent of whether CARB ultimately mandates it. A CARB-funded study fitted DPFs to a 15.1 kW TRU engine and an 18.5 kW mini-excavator engine and cut PM by more than 98%, to 1–2.8 mg/kWh [6] but the same study recorded a DPF failure during field regeneration. Thus, whether a combustion engine with aftertreatment or an electric powertrain is the better answer for this class remains open. It should also be noted that many spark ignited (SI) options exist for the <19 kW category as well, and that the emission standards for the SI engines are not proposed to be as strict as Tier 5 for diesel. However, it should be noted that CARB's 2021 small off-road engine (SORE) amendments set zero-emission standards for most new spark-ignition engines at or below 19 kW from MY2024, and for generators and large pressure washers from MY2028 [14].

2. 19–37 kW: Published aftertreatment data in this bin is very limited. Many engines here have electronic fuel injection and EGR, the hardware the 55-kW demonstration used, but that does not mean they can follow the same path. Engines in this bin have smaller bores and lower power per cylinder, most use 2-valve cylinder heads unlike the 4-valve demonstration engine [15, 16], and most are not charge-air cooled. A minority at the bottom of the bin, roughly a quarter of 19–25 kW engine families, still uses mechanical, frequently indirect injection, and it is doubtful those engines can be calibrated below 2.5 g/kWh engine-out NO_x without moving to electronic common-rail DI first. For engines that make that transition, the remaining challenges are DPF regeneration under intermittent, low-load duty cycles within a 5,000-hour useful life, which leaves less operating time to recover the cost of added hardware. The CARB-funded retrofit study added SCR downstream of the OEM DOC and DPF on a 27.9 kW ride-mower engine [6] with the aftertreatment system aged for 1,000 hours against this bin's 5,000-hour useful life. Thus, whether a light SCR system becomes worthwhile in high-utilization applications such as agricultural or rental equipment remains open.
3. 37–56 kW: This bin's compliance question already has one demonstrated answer. A 2026 Southwest Research Institute (SwRI) internally funded demonstration ran a commercially

available 55 kW, four-cylinder diesel engine through EGR recalibration and supporting hardware changes to the EGR and turbocharging system and showed a potential compliance pathway to Tier 5 targets on both the RMC and NRTC cycles with sufficient margin, without using an SCR [15, 16]. However, the result came with a fuel-economy penalty relative to the Tier 4f calibration, and it does not establish that other engines in the bin can do the same. 4-valve heads are used by 38% of engine families in this bin and 2-valve heads by 68% across the segment (Figure 4). An SCR based system can buy back the efficiency that EGR-only calibration gives up while adding another fluid on board. Whether that trade-off is worth SCR's added packaging, thermal management, and urea-dosing complexity at this scale is the open question.

5. Recommendation

5.1 Technology readiness

Available data is limited to two single-engine studies on different routes: EGR recalibration with DOC and DPF on a 55-kW engine [15, 16], and retrofit SCR on a 27.9 kW and a 37 kW engine [6]. Whether these results transfer to other architectures in the 19–56 kW range, particularly mechanically injected, IDI engines and 2-valve cylinder heads, has not been shown. The starting point of each engine's architecture will decide how much each engine must change, and these will vary widely across the segment. Thus, what remains genuinely open is which approach makes sense for which application, and that answer depends on cost, durability, and duty-cycle data which the industry does not yet have in a generalizable form.

5.2 Policy and regulatory uncertainty

The final emissions limits are not yet known. CARB's Tier 5 rule is still in draft form, specific NO_x and PM limits by bin have moved between iterations, and the public comment process remains open. The United States EPA has not started consideration of their parallel nonroad rule, and California's authority over engines under 130 kW is limited by Clean Air Act §209(e)(1)(A) preemption [17] which mentions that states may not set standards for new engines below 175 hp (130 kW) used in farm or construction equipment. CARB's Tier 5 limits would therefore bind only the remaining applications in this range, such as generators, pumps, compressors, welders, forklifts, and TRUs. Farm and construction equipment would follow whatever EPA adopts. Under that kind of uncertainty, architectures that can be recalibrated to a range of possible final limits, EGR and injection-strategy-led approaches, carry less risk than committing early to a fixed

hardware solution like SCR, which is more expensive and complex. Hardware-only estimates used in CARB-funded work put SCR at about \$474 per engine for 2–2.5 L engines, against \$328 for a DOC and DPF [6]. What integration, OBD, DEF handling and warranty exposure add to those figures at this scale is an open question.

5.3 Answering the uncertainty through a consortium

The open questions in this paper go beyond which hardware to add. They include how close each engine family's combustion system can get to Tier 5 levels, how reliably a DPF can be regenerated in the duty cycles these engines see, and whether the result holds to full useful life. With roughly half of 19–56 kW engine families expected to add a DPF for the first time, the regeneration question applies to much of the segment rather than to a few products. Further questions include infrequent regeneration adjustment factors (IRAF), DPF loading under short-duration and low-load operation, and how much of the EGR fuel-economy penalty an SCR system can recover. The answers have to come from testing.

To help answer these and other questions, SwRI is forming the Technology Initiative for Emissions Reduction (TIER-5) consortium. The consortium enables a shared testing and characterization program spanning member-selected engine and aftertreatment configurations across the 19–56 kW range, covering multiple duty cycles and manufacturers rather than a single demonstration engine. The output is not a single recommended architecture but the operating-envelope dataset this review has argued the segment needs, real data on where each approach's NO_x, PM, and fuel-economy trade-offs land, across a wide variety of end-uses. Because the data comes from engines representative of the segment rather than a single demonstration, members can also use it in their discussions with CARB and EPA through the Engine Manufacturers Association (EMA) and other industry bodies. Manufacturers who need answers for a specific engine family, on their own schedule and kept confidential, can work with Southwest Research Institute directly. A dedicated program starts from the manufacturer's own engine and duty cycles and assesses engine-out capability, calibration, aftertreatment and durability for that product. SwRI's accelerated aging methodology and capability, which the CARB-funded study used to reach 1,000-hour equivalence [6], can extend aftertreatment aging to full-useful-life equivalence without years of field operation.

Suppliers, OEMs, and aftertreatment developers working in the 19–56 kW range who want direct visibility into that dataset are welcome to reach out about joining. For more information or to join the TIER-5 consortium, please visit tier5.swri.org or reach out to:

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6. References

- [1] “Annual Certification Data for Vehicles, Engines, and Equipment - Non-road compression ignition (NRCI) engines”. United States Environmental Protection Agency (US EPA). [Annual Certification Data for Vehicles, Engines, and Equipment | US EPA](#). Accessed July 2026.
- [2] Diesel Net, “CARB developing Tier-5 emission standards for off-road engines”, accessed March 2026.
- [3] California Air Resources Board, “Tier 5 Rulemaking Workshop – Draft Potential Off-Road Compression-Ignition New Engine Regulations”, https://ww2.arb.ca.gov/sites/default/files/2026-02/T5_workshop_2026_%231_v4.pdf, accessed April 2026.
- [4] California Air Resources Board, “Non-road diesel engine certification Tier chart”, <https://ww2.arb.ca.gov/resources/documents/non-road-diesel-engine-certification-tier-chart>, accessed March 2026.
- [5] Diesel Net, “USA: Nonroad Diesel Engines”, <https://dieselnet.com/standards/us/nonroad.php>, accessed March 2026.
- [6] McCaffery C., Yang J., Karavalakis G., Yoon S. et. al., “Evaluation of small off-road diesel engine emissions and aftertreatment systems”. Energy, Volume 251, 2022, 123903. ISSN 0360-5442. <https://doi.org/10.1016/j.energy.2022.123903>.
- [7] New Vehicle and Engine Certification: Executive Orders for Compression-Ignition and Heavy-Duty Engines and Vehicles. California Air Resources Board (CARB). [CIHD EO Summary.xlsx](#) Accessed October 2026.
- [8] Buckley J., “DiPerk reports duty cycles affecting regen in Stage 5 engines”. Power Progress. 17 July 2026. [DiPerk reports duty cycles affecting regen in Stage 5 engines - Power Progress](#)
- [9] California Air Resources Board, “Draft Potential – Regulation Order – New Regulations and Test Procedures for Off-Road and Marine Compression Ignition Engines, Amendments to the Regulation for Off-Road Hydrogen Spark-Ignition Engines, and Amendments to the In-Use Off-Road Diesel-Fueled Fleet Regulation”, <https://ww2.arb.ca.gov/sites/default/files/2026-02/Draft%20Potential%20Tier%205%20Reg%20Order%20-%2027-26%20Workshop.pdf>, accessed April 2026.
- [10] Dallmann T., Menon A., “Technology Pathways For Diesel Engines Used in Non-Road Vehicles and Equipment”. The International Council on Clean Transportation (ICCT). September 2016. [Non-Road-Tech-Pathways white- paper vF ICCT 20160915.pdf](#), accessed July 2026
- [11] Diesel Net, “CARB holds a public workgroup on Tier 5 emission standards for off-road engines”, <https://dieselnet.com/news/2022/08carb.php>, accessed March 2026.
- [12] California Air Resources Board, “Tier 5 Rulemaking Workshop II: Useful Life, Warranty, and Defects Reporting”. October 2023. [Useful Life, Warranty, and Defects Reporting](#), Accessed May 2026.
- [13] California Air Resources Board, “Tier 5 Rulemaking Workshop Potential Amendments to the Off - Road Diesel New Engine Regulations”. November 2021. [Tier 5 Rulemaking Workshop: Potential Amendments to the Off-Road Diesel New Engine Regulations](#)

- [14] California Air Resources Board, "ARB approves updated regulations requiring most new small off-road engines be zero emission by 2024". December 2021. <https://ww2.arb.ca.gov/news/carb-approves-updated-regulations-requiring-most-new-small-road-engines-be-zero-emission-2024?pubDate=20260531>, Accessed May 2026.
- [15] "SwRI demonstrates technologies that allow off-road vehicles to meet proposed emissions standards." Southwest Research Institute. June 2026. [SwRI demonstrates technologies that allow off-road vehicles to meet proposed emissions standards | Southwest Research Institute](#)
- [16] Patil, S., Michlberger, A., Bachu, P., Amaral Garcia, H., et al., "An Effective Pathway for Off-Road Tier 5 Emission Compliance," *SAE Int. J. Engines* 19(8), 2026, <https://doi.org/10.4271/03-19-08-0041>.
- [17] U.S. Environmental Protection Agency. "Preemption of state standards and procedures for waiver of federal preemption for nonroad engines and nonroad vehicles." Code of Federal Regulations, Title 40, Part 1074, accessed October 2026.