WORKING PAPER 2016-27

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Evaluation of emission-control scenarios for agricultural tractors and construction equipment in India

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Date: December 2016
Keywords: India, non-road engines, emission standards, engine technology

Background

NON-ROAD ENGINE AIR POLLUTANT EMISSIONS

Agricultural tractors and construction equipment are an integral part of the Indian economy and are cornerstones for the continued development of the agricultural and construction sectors in the country. This equipment is primarily powered by diesel engines, which provide performance advantages for the tasks required of such equipment. However, these diesel engines are also a significant source of air pollutant emissions and contribute to the severe air quality problems currently facing the country.

The markets for agricultural tractors and construction equipment in India are undergoing rapid growth. Between 2000 and 2012, sales of agricultural tractors grew by 139%. Similarly, sales of construction equipment grew by 136% between 2002 and 2014[1]. This growth is driven by a number of factors, including increased mechanization of the agricultural sector and the expansion of the Indian construction industry. As a consequence of this growth, air pollutant emissions from these equipment types are also increasingly rapidly.

Recently, a model was developed by the International Council on Clean Transportation (ICCT) to estimate emissions from Indian agricultural tractors and construction equipment[2]. Results from the application of this model show significant increases in two important pollutants of concern, particulate matter (PM) and nitrogen oxides (NO_x), between 2000 and 2015. During this time, emissions of PM and NO_x from agricultural tractors are estimated to have increased by 80% and 150%, respectively. For construction equipment, PM and NO_x emissions are estimated to have increased by 450% and 410% over the same period. More stringent emission-control requirements are necessary to mitigate the emissions impact of the continued growth projected for these sources.

In India, as is the case in other regions with mobile source emission-control programs, emissions from non-road sources are regulated differently than emissions from on-road sources, such as passenger cars and heavy-duty trucks. Emission standards for these source categories differ in, for example, allowable emission limits, certification test requirements, and implementation schedules. In India, much progress has been made in the regulation of on-road sources of air pollution, with Bharat Stage (BS) IV standards scheduled for nationwide implementation in 2017 and BS VI standards to take effect in 2020. The BS VI standards will essentially bring the Indian regulatory program for on-road vehicles into alignment with current European Union (EU) regulations, and will greatly reduce emissions from new vehicles sold in the country. BS IV and VI emission standards are accompanied by fuel quality standards, which will ensure that low sulfur fuels (50 ppm) are available countrywide from April 2017, and ultra low sulfur fuels (10 ppm) are available from April 2020 onward. For diesel engines, low sulfur fuels are required for best-available emission-control technologies, such as diesel particulate filters (DPF) and selective catalytic reduction systems (SCR).

In comparison to the established regulatory program for on-road vehicles in India, emission-control requirements for non-road vehicles and equipment lag significantly behind. Current emission standards for agricultural tractors and construction equipment were introduced more than 5 years ago and are considerably less stringent than standards in force in

1 Zhenying Shao, *An emissions inventory for agricultural tractors and construction equipment in India* (ICCT: Washington DC, 2016). http://www.theicct.org/non-road-emissions-inventory-india

2 Zhenying Shao, *Non-road emission inventory model methodology* (ICCT: Washington DC, 2016). http://www.theicct.org/non-road-emission-inventory-model-methodology

the United States (U.S.) and EU. Without further regulatory action, PM and NO_x emissions from these non-road sources are expected to surpass those from on-road vehicles in the next 10–15 years. Figure 1 shows projected emissions from on- and non-road vehicles and equipment in India, assuming no changes to current and proposed regulatory programs and full compliance. In the case of on-road vehicles, regulatory efforts are already reducing PM emissions and proposed standards are expected to result in significant NO_x reductions beginning around 2020. In contrast, current standards for agricultural tractors and construction equipment are not stringent enough to offset the expected growth in each of these sectors, and emissions are projected to increase substantially by 2035.

To curb transportation-related air quality impacts in India, stringent regulatory programs for on-road vehicles should be matched by equivalent steps toward controlling emissions from non-road equipment. The purpose of this paper is to explore different emission-control scenarios for agricultural tractors and construction equipment, considering potential air pollution emission reductions resulting from alternative regulatory pathways. The programs considered are based on similar regulations in place in the U.S. and EU, as well as forward-looking improvements to these regulations. Results presented here will help to inform the establishment of a roadmap toward world-class emission standards for non-road vehicles and equipment in India.

INTERNATIONAL NON-ROAD ENGINE EMISSION-CONTROL PROGRAMS

Emissions from non-road vehicles and equipment have been regulated in the U.S. and EU since the mid 1990s. Emission regulations in these regions have progressed through a series of more stringent Tiers (U.S.) or Stages (EU). The stringency of these programs has been increased through both the tightening of pollutant mass emission limits, as well as the introduction of more challenging certification test requirements. While emission regulations in the U.S. and EU have been largely harmonized, differences exist in regulated engine sizes, implementation dates, and in some cases, emission limits. Currently, non-road engines are regulated through the Tier 4f program in the U.S. and the Stage IV program in the EU. Stage V emission standards have recently been adopted in the EU and will take effect beginning in 2018[3]. In both regions, emission standards and implementation dates are set by engine size. The progression of PM and NO_x emission limits (130 kW engine) are shown in Figure 2.

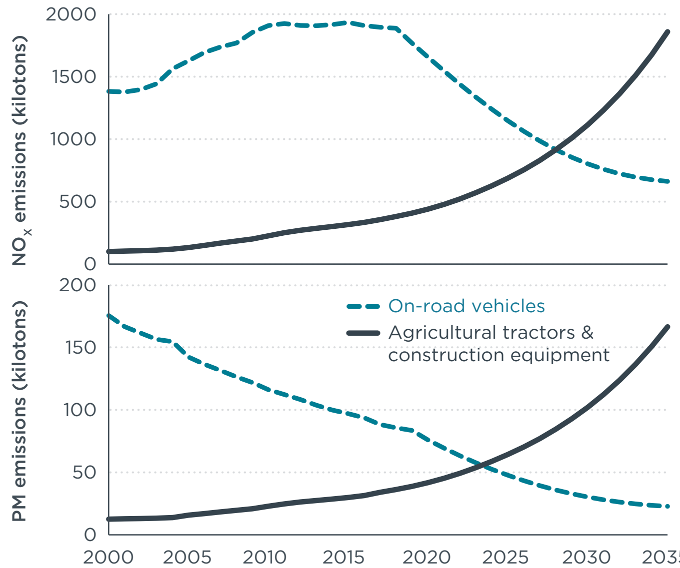

Figure 1. Historical trends and projections for emissions of NO_x and $PM_{2.5}$ from on-road vehicles and non-road equipment in India, 2000-2035.[4]

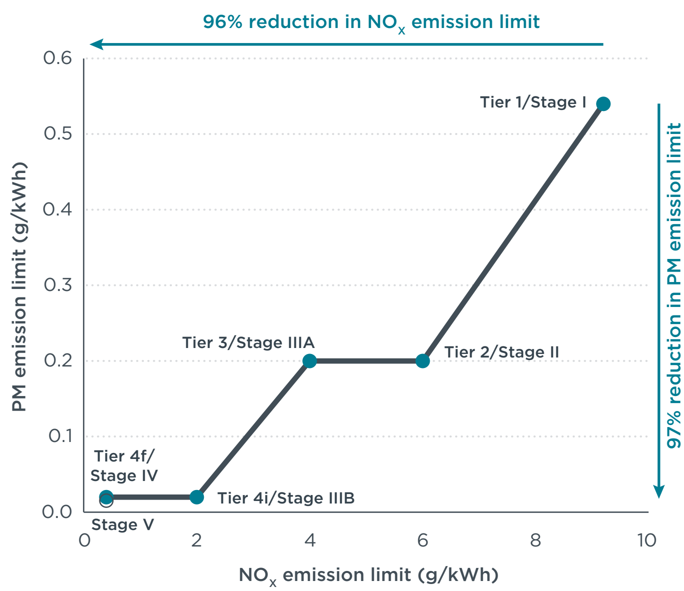

Figure 2. Progression of PM and NO_x emission limits in U.S. and EU non-road engine emission-control programs (130 kW engine).

3 International Council on Clean Transportation, “European Stage V non-road emission standards” (November, 2016). http://www.theicct.org/EU-stage-V-policy-update

4 Zhenying Shao, *An emissions inventory for agricultural tractors and construction equipment in India* (ICCT: Washington DC, 2016). http://www.theicct.org/non-road-emissions-inventory-india

As shown in Figure 2, current PM and NO_x emission limits are 96–97% lower than those when standards were introduced in Tier 1/Stage I regulations. The increasingly stringent regulatory programs in the U.S. and EU have led to advances in engine design strategies and technologies applied to control emissions from non-road engines. Through initial Tiers/Stages, engine manufacturers were able to meet emission requirements with in-cylinder emission controls. Beginning with Tier 4i/Stage IIIB standards, these strategies were no longer sufficient to meet regulatory requirements for most engine sizes and aftertreatment control technologies were incorporated into non-road engine designs.

To meet current standards in the U.S. and EU, NO_x emissions are generally controlled using SCR in engines larger than 56 kW and with exhaust gas recirculation (EGR) or other in-cylinder controls for smaller engines. Diesel oxidation catalysts (DOC) are generally sufficient to meet Tier 4f/Stage IV PM standards, though some engine designs also include a DPF[5]. The lack of DPFs in a large number of Tier 4f/Stage IV certified engines has contributed to the decision by the EU to promulgate Stage V emission standards. These standards set more stringent PM mass emission limits and introduce a particle number emission limit for engines between 19 and 560 kW. These changes are expected to compel the use of DPFs to control PM emissions from engines in this size range.

In India, agricultural tractors and construction equipment are regulated through separate standards. Bharat Tractor Emission (Trem) standards apply to agricultural tractors and Bharat Construction Equipment Vehicle (CEV) standards apply to construction equipment. Current emission standards, Trem Stage IIIA and CEV Stage III, were fully implemented in 2011. For engines with rated power between 19 and 560 kW, Trem IIIA and CEV III standards are equivalent and adopt EU Stage IIIA/U.S. Tier 3 pollutant emission limits. Engines smaller than 19 kW are not included in the European regulatory program and thus, U.S. Tier 2 emission limits were adopted in the CEV III standard. Trem IIIA standards for engines in this size range differ slightly from Tier 2, with a more stringent carbon monoxide (CO) limit and less stringent hydrocarbon (HC) + NO_x limit. Aftertreatment technologies are not necessary to meet Trem IIIA and CEV III emission standards.

The progression of non-road engine emission standards in the U.S. and EU provides a preliminary roadmap for the continued regulatory control of agricultural tractors and construction equipment in India. In the following sections, we report results from the modeling of various emission-control scenarios based on this progression and identify opportunities for Indian regulators to accelerate emissions reductions from non-road engines.

5 Tim Dallmann, Aparna Menon, *Technology pathways for diesel engines used in non-road vehicles and equipment* (ICCT: Washington DC, 2016). http://www.theicct.org/technology-pathways-for-non-road-diesel-engines

Emission-control scenarios

The purpose of this paper is to compare different regulatory control pathways for Indian agricultural tractors and construction equipment on the basis of air pollutant emissions. Three separate regulatory scenarios are compared against a baseline scenario, which assumes no change in current regulatory requirements for non-road engines. Descriptions of modeling methods and regulatory scenarios are included in the following sections.

MODELING METHODS

For this study, an internal model developed to quantify emissions from Indian agricultural tractors and construction equipment is used to estimate emissions for each modeled scenario. The methodology of the Indian non-road emission inventory model is based on the U.S. Environmental Protection Agency (EPA) NONROAD model, and has been modified to incorporate information and data specific to the Indian context. Full documentation of the model and results from initial applications can be found in companion publications.[6,7]

Air pollutant emissions (NO_x, PM[8], CO, HC) are estimated by engine power class for each sector. For construction equipment, emissions are quantified directly for predominant equipment types: backhoe loaders, crawler excavators, mobile cranes, compactors, and wheeled loaders, which together make up greater than 90% of the market. Other construction equipment is aggregated into a single category. The focus of this analysis is placed on PM and NO_x emissions, the pollutants of greatest concern from diesel engines.

SCENARIO DESCRIPTIONS

Regulatory requirements for each modeled emission-control scenario are primarily based on current and proposed emission regulations in the U.S. and EU. These programs

6 Zhenying Shao, *An emissions inventory for agricultural tractors and construction equipment in India* (ICCT: Washington DC, 2016). http://www.theicct.org/non-road-emissions-inventory-india

7 Zhenying Shao, *Non-road emission inventory model methodology* (ICCT: Washington DC, 2016). http://www.theicct.org/non-road-emission-inventory-model-methodology

8 Following EPA NONROAD model methodology, all PM emissions are assumed to be smaller than 10 microns (PM_{10}), and 97% of the PM is assumed to be smaller than 2.5 microns ($PM_{2.5}$).

are largely similar, with differences relevant to this analysis outlined in the following sections. The scenarios considered would align emission requirements for agricultural tractors and construction equipment in terms of both emission limits and implementation dates. The implementation schedule and emission standards for each modeled scenario are shown in Figure 3 and Table 1, respectively.

Trem/CEV IV (Tier 4f equivalent)

In the Trem/CEV IV scenario, it is assumed India transitions directly from current Stage IIIA standards to U.S. Tier 4f equivalent standards in 2019, thereby leapfrogging the Stage IIIB/Tier 4i emission level. While largely equivalent, U.S. Tier 4f standards were selected for this stage rather than EU Stage IV standards due to the inclusion of engines smaller than 19 kW and more stringent standards for engines between 19 and 37 kW. Highlights of Trem/CEV stage IV standards include large reductions in the PM emission limit for engines between 19 and 560 kW (> 90%) and the NO_x emission limit for engines between 56 and 560 kW (90%).

Trem/CEV V (Stage V equivalent)

The Trem/CEV V scenario adds, as a further stage to the Trem/CEV IV scenario, the implementation of EU Stage V equivalent emission standards in 2023. This stage focuses on controlling PM emissions from agricultural tractors and construction equipment through the reduction of PM emission limits by 40–50% and the introduction of a particle number limit of 1e12 #/kWh for engines between 19 and 560 kW. This stage is expected to lead to near universal use of DPFs in engines of this size range. Emission limits for NO_x remain unchanged in the stage and no significant changes are made to emission requirements for engines below 19 kW.

Trem/CEV VI (Low-NO_x pathway)

The Trem/CEV VI scenario adopts emission limits that are more stringent than current or proposed in U.S. and EU regulatory programs, and it aims specifically at limiting NO_x emissions from smaller engines. In this case, U.S. Tier 4f equivalent standards are implemented in 2019 and forward looking emission standards based on Euro VI standards for on-road heavy-duty vehicles are implemented in 2024. Relative to Stage V standards, Trem/CEV VI standards adopt more stringent NO_x emission limits for engines smaller than 56 kW. The proposed Trem/CEV VI NO_x standards for engines in this size are 90% lower than Stage IV/V levels and would bring NO_x emission limits in line with requirements for larger engines. Also, more stringent PM and PN emission limits are adopted for engines between 19 and 560 kW in the Trem/CEV VI stage relative to the Trem/CEV V stage.

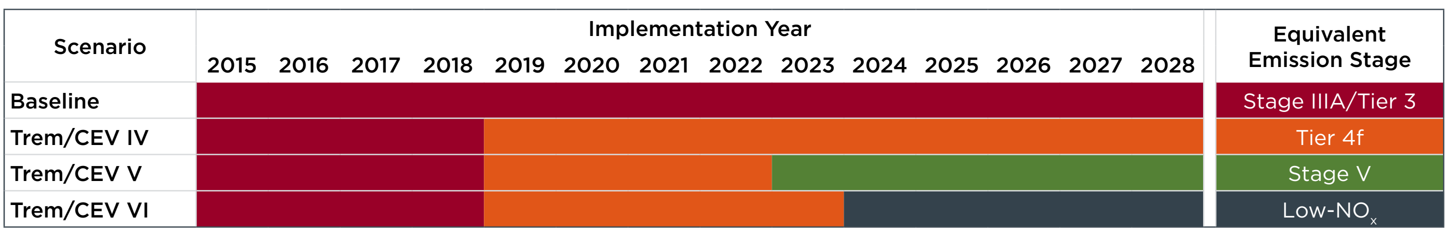

Figure 3. Implementation timelines for modeled emission-control scenarios for Indian non-road diesel equipment.

Table 1. Pollutant exhaust emission limits for non-road diesel engine emission-control stages.

Engine rating (kW)	Engine rating (hp)	Baseline		Trem/CEV IV	Trem/CEV V	Trem/CEV VI
		TREM IIIA	CEV III			
P < 8	P < 11	5.5 / (8.5) / 0.8	8.0 / (7.5) / 0.8	8.0 / (7.5) / 0.4	8.0 / (7.5) / 0.4	3.5 / 0.19 / 0.4 / 0.4
8 ≤ P < 19	11 ≤ P < 25	5.5 / (8.5) / 0.8	6.6 / (7.5) / 0.8	6.6 / (7.5) / 0.4	6.6 / (7.5) / 0.4	3.5 / 0.19 / 0.4 / 0.4
19 ≤ P < 37	25 ≤ P < 50	5.5 / (7.5) / 0.6	5.5 / (7.5) / 0.6	5.5 / (4.7) / 0.030	5.0 / (4.7) / 0.015[a]	3.5 / 0.19 / 0.4 / 0.010[b]
37 ≤ P < 56	50 ≤ P < 75	5.0 / (4.7) / 0.4	5.0 / (4.7) / 0.4	5.0 / (4.7) / 0.030	5.0 / (4.7) / 0.015[a]	3.5 / 0.19 / 0.4 / 0.010[a]
56 ≤ P < 75	75 ≤ P < 100	5.0 / (4.7) / 0.4	5.0 / (4.7) / 0.4	5.0 / 0.19 / 0.40 / 0.020	5.0 / 0.19 / 0.4 / 0.015[a]	3.5 / 0.19 / 0.4 / 0.010[b]
75 ≤ P < 130	100 ≤ P < 175	5.0 / (4.0) / 0.3	5.0 / (4.0) / 0.2	5.0 / 0.19 / 0.40 / 0.020	5.0 / 0.19 / 0.4 / 0.015[a]	3.5 / 0.19 / 0.4 / 0.010[b]
130 ≤ P < 560	175 ≤ P < 750	3.5 / (4.0) / 0.2	3.5 / (4.0) / 0.2	3.5 / 0.19 / 0.40 / 0.020	5.0 / 0.19 / 0.4 / 0.015[a]	3.5 / 0.19 / 0.4 / 0.010[b]

Pollutant key: CO / (HC+NO_x) / PM or CO / HC / NO_x / PM
[a] Particle number emission limit of $1{\times}10^{12}$ #/kWh applies.
[b] Particle number emission limit of $8{\times}10^{11}$ #/kWh applies.

Modeling results

The following sections present detailed results of air pollutant emissions modeling for each of the considered non-road regulatory control scenarios. Results are presented separately for agricultural tractors and construction equipment.

AGRICULTURAL TRACTORS

Agricultural tractors in India are predominately powered by engines with sizes between 23 and 37 kW. As shown in Figure 4, equipment using engines in this size range accounted for greater than 70% of the agricultural tractor population in 2014[9]. This point is important when considering emissions impacts of alternative non-road regulatory pathways, as the current framework for setting emission standards is based on engine size; different engine power classes are subject to different emission standards at each regulatory step. As will be shown below, the predominant regulatory changes impacting emissions from agricultural tractors in India are those that apply to the 19–37 kW power class.

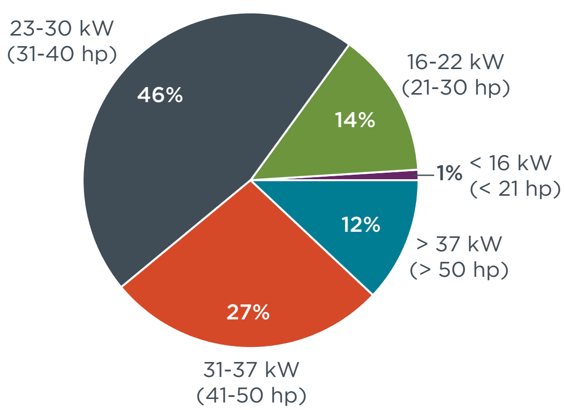

Figure 4. Estimated engine power distribution for agricultural tractors in India, 2014.

Modeled annual emissions of PM and NO_x from agricultural tractors for each of the scenarios considered in this analysis are shown in Figure 5. Results are presented for the years 2015–2040, allowing for the impact of more stringent regulatory stages to be seen. These results clearly show that current emission standards in India are not stringent enough to control emissions from the rapidly growing agricultural tractor fleet. In the baseline scenario, which assumes no change in current standards, emissions

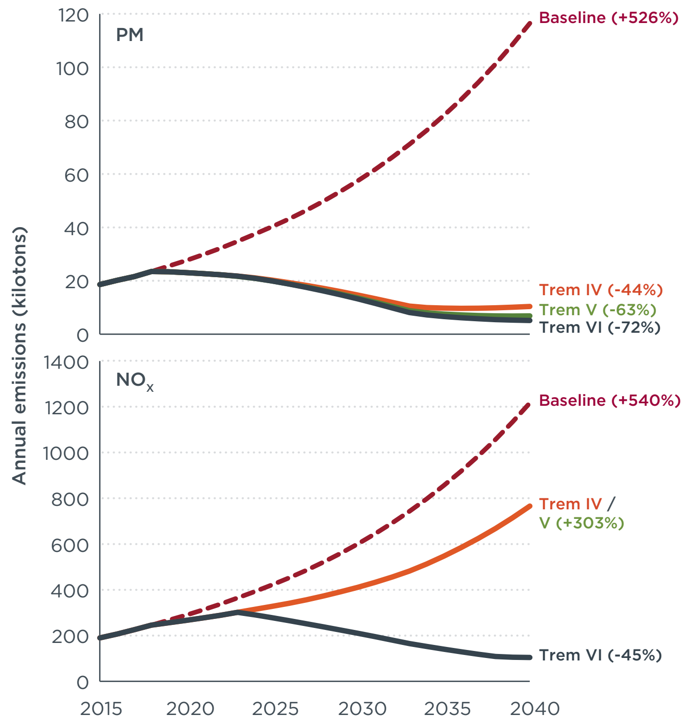

Figure 5. Projected annual PM and NO_x emissions for modeled agricultural tractor emission-control scenarios. Values on the right side of the plots show the percentage change in emissions between 2015 and 2040 for each scenario.

of PM and NO_x increase by greater than 500% between 2015 and 2040.

For PM, strong emissions benefits are accrued from implementing Trem IV standards. In each of the modeled control scenarios, Trem IV level standards are implemented in 2019. In all cases, this introduction results in a halt of the growth in PM emissions from agricultural tractors seen in the baseline scenario, and initiates an overall decrease in sector-wide PM emissions. The primary reason for these substantial emissions reductions is the 0.030 g/kWh PM emission limit for engines between 19 and 37 kW introduced at the Trem IV stage, which represents a 95% reduction from the corresponding Trem IIIA level. For the Trem IV scenario, annual PM emissions are reduced by 44% relative to 2015 levels in 2040, despite a 535% increase in the size of the agricultural tractor fleet. Relative to the Trem IV scenario, additional PM benefits are realized from the adoption of filter forcing Trem V or VI emission standards.

With respect to NO_x, Trem IV and V level standards are not as effective in reducing emissions for agricultural tractors as they are for PM. For these scenarios, NO_x emissions increase by ~300% between 2015 and 2040. The primary

9 Zhenying Shao, *An emissions inventory for agricultural tractors and construction equipment in India* (ICCT: Washington DC, 2016). http://www.theicct.org/non-road-emissions-inventory-india

reason for this increase is that **NO_x emission limits for the most commonly used engine power class for agricultural tractors, 19–37 kW, remain more than 10 times higher than those for larger engine size ranges. Additional reductions in the NO_x emission limits for small engines are required to offset the growth in the Indian agricultural tractor market.** Such is the case for Trem VI scenario, which achieves long-term NO_x emissions reductions through the adoption of more stringent standards for engines smaller than 56 kW. As a result, this pathway yields NO_x emissions reductions of 45% between 2015 and 2040. Cumulatively, 5,100 kilotons of NO_x emissions are avoided during this timeframe through the Trem VI pathway relative to the Trem V pathway.

It is important to reiterate that modeled Trem VI stage NO_x emission limits are more stringent than existing or proposed standards in U.S. and EU. The need for modified emission standards in India reflects a fundamental difference in the engine markets of the various regions. Larger engine sizes that are more typical of the U.S. and EU markets are subject to more stringent Tier 4f/Stage IV and Stage V NO_x emission standards than smaller engines commonly used in Indian agricultural tractors. Thus, relaxed NO_x standards for small engines are less consequential from an emissions standpoint in these regions. Engines less than 56 kW make up only about 20–30% of the agricultural equipment market in the U.S. and EU. **Simply adopting standards developed in other regions will not be sufficient to address the unique challenges imposed by the nature of the Indian agricultural tractor market.**

Emissions of HC and CO for each scenario are presented in Figure 6. In all emission-control scenarios, benefits are accrued from the implementation of Trem IV emission standards, but no further emissions reductions are seen with the implementation of more stringent control stages.

The importance of emissions control for engines between 19 and 37 kW cannot be overstated in the case of the Indian agricultural sector. Figure 7 shows the relative contributions of individual engine power classes to emissions reductions in the Trem VI scenario relative to the baseline scenario. Due to their large market share, engines between 23 and 37 kW are responsible for most of the emissions reductions projected for the Trem VI scenario. This size range accounts for 85% and 77% of projected PM and NO_x emissions reductions, respectively, between 2020 and 2040. From a regulatory perspective, it is important to note that these engines are all included in a single regulated power class of engines between 19 to 37 kW (25 to 50 hp). Thus, the regulatory trajectory for this power class is of primary importance for the control of air pollutant emissions from agricultural tractors.

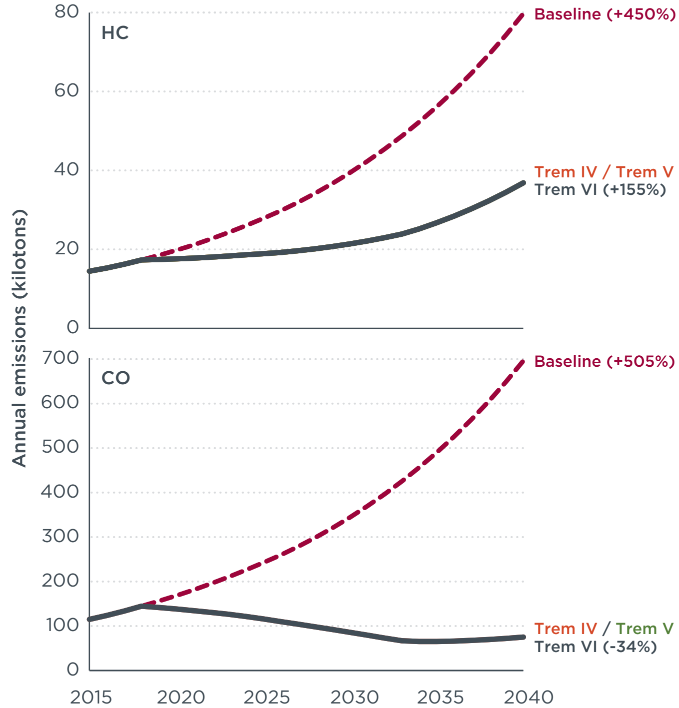

Figure 6. Projected annual HC and CO emissions for modeled agricultural tractor emission-control scenarios. Values on the right side of the plots show the percentage change in emissions between 2015 and 2040 for each scenario.

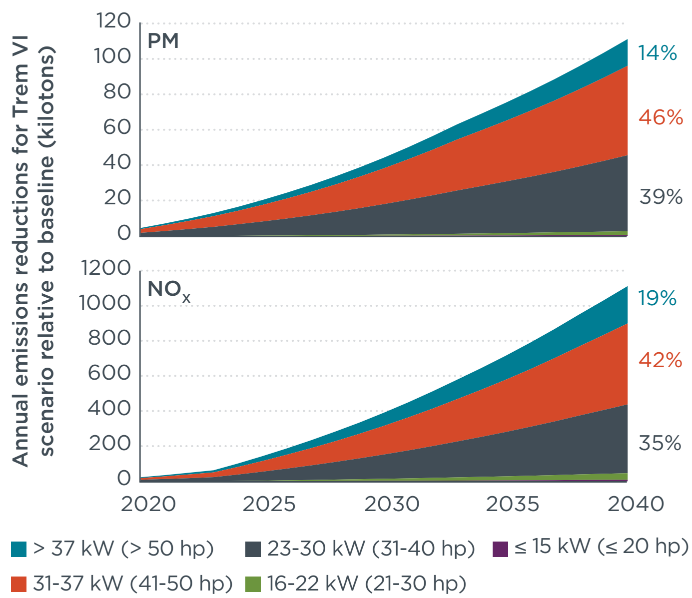

Figure 7. Annual PM and NOx emission reductions for agricultural tractors in Trem VI scenario relative to baseline, disaggregated by engine power class. Percentages show relative share of cumulative emission reductions between 2020 and 2040 for select power classes.

Due to the predominance of engine sizes between 19 and 37 kW in the Indian agricultural sector, it is worthwhile to further investigate current and projected engine emission-control technologies. Figure 8 shows model PM and NO_x emission rates for each regulatory emission-control level, along with engine technologies that enable transitions to more stringent emission-control stages. Baseline technology for Indian agricultural tractor engines consists of naturally aspirated, mechanically controlled direct injection engines. This engine design is robust, simple, and well suited to the current market. However, significant engine design changes will be required to meet progressively more stringent emission standards. Indian manufacturers have already considered a transition to U.S. Tier 4f equivalent emission standards and found that emission limits can be met through a transition to common rail fuel injection, cooled EGR for NO_x control, and a diesel oxidation catalyst for PM control[10]. Further PM reductions required in the Trem V and VI stages would likely require a diesel particulate filter, as evidenced by technology pathways in the U.S. and EU[11]. Modeled NO_x emission rates for Trem VI go beyond the most stringent requirements of current or proposed EU or U.S programs. Thus, technical development would be required of non-road engine manufacturers to bring emissions from this power class down to a level matching what is currently required of larger engines. Ways to achieve this may consist of applying control technologies developed for larger engine sizes, such as selective catalytic reduction and lean NO_x traps (LNT), or new strategies more targeted to this specific engine size.

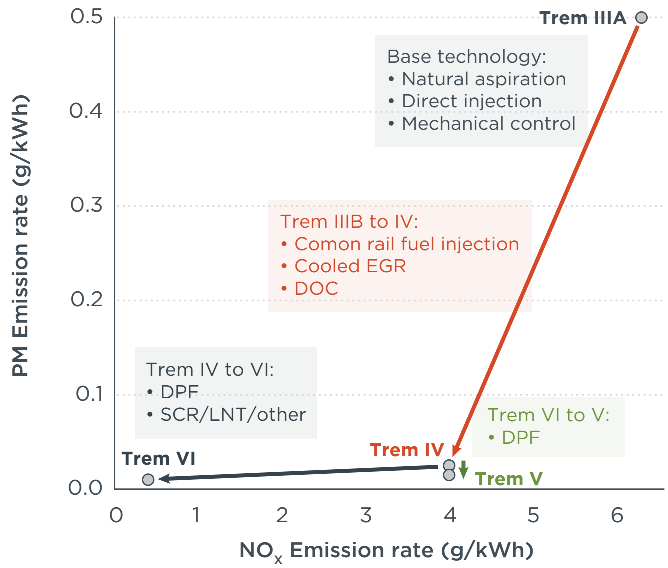

Figure 8. Projected technology pathway for agricultural tractor engines between 19 and 37 kW (25 and 50 hp).

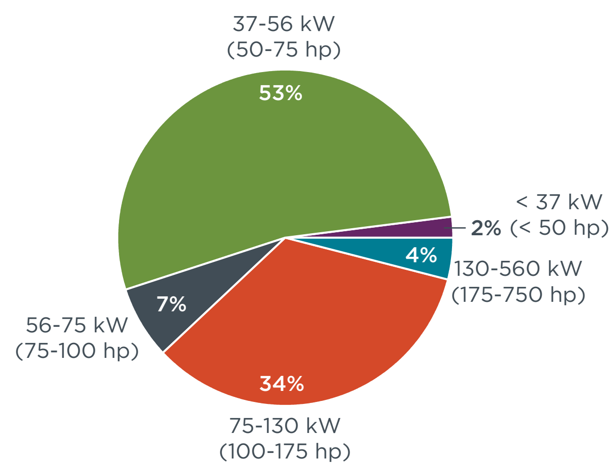

Figure 9. Estimated engine power distribution for construction equipment in India, 2014.[13]

CONSTRUCTION EQUIPMENT

Engines used in Indian construction equipment tend to be larger than engines used in agricultural tractors. Figure 9 shows estimates of the engine size distribution for construction equipment in the year 2014. While agricultural tractors primarily use engines less than 37 kW, only 2% of construction equipment engines are in this size range. The predominant power classes for construction equipment engines are 37–56 kW and 75–130 kW, which together make up greater than 80% of the total engine population in 2014. Based on the study of Indian Construction Equipment Manufacturers' Association, construction equipment is expected to reach a growth rate over 10% in the coming decades[12]. Among all the equipment types, the study projected that wheeled loaders would achieve the highest growth rate, which is 16.6%. In the regulatory scenarios discussed below, changes to emission requirements for these engine power classes have the greatest influence on sector-wide emission projections.

10 Sadanand Bhosale et al., "Cost efficient Bharat (Trem) Stage IV solutions for tractor engines," SAE Technical Paper 2015-26-0092, 2015, doi:10.4271/2015-26-0092

11 Tim Dallmann, Aparna Menon, *Technology pathways for diesel engines used in non-road vehicles and equipment* (ICCT: Washington DC, 2016). http://www.theicct.org/technology-pathways-for-non-road-diesel-engines

12 Indian Construction Equipment Manufacturer's Association, "Rebooting Indian infrastructure – Indian construction equipment industry, vision 2020," 2015, New Delhi, India.

13 Zhenying Shao, *An emissions inventory for agricultural tractors and construction equipment in India* (ICCT: Washington DC, 2016). http://www.theicct.org/non-road-emissions-inventory-india

Annual emissions of PM and NO_x from construction equipment for the years 2015–2040 are shown in Figure 10 for each modeled scenario. As was the case with agricultural tractors, emissions of PM and NO_x are projected to increase significantly during this timeframe without further regulatory control. Results for the baseline scenario show PM and NO_x emissions increase by factors of 10 and 15, respectively, between 2015 and 2040.

PM emission trends with the implementation of more stringent standards for construction equipment largely mirror those observed for agricultural tractors. Results show strong PM emissions benefits from the adoption of CEV IV standards in 2019. These emission reductions are attributable to the greater than 90% reduction in the PM emission limit for predominant Indian construction equipment engine sizes. Between 2015 and 2040, CEV IV standards lead to a 40% reduction in PM emissions from Indian construction equipment and cumulatively prevent 700 kilotons of PM emissions relative to the baseline scenario. The implementation of filter forcing CEV V or VI emission-control stages results in additional PM emissions reductions. For these scenarios, 2040 PM emissions are 63–75% lower than 2015 levels.

For the CEV IV and V scenarios, PM emission benefits are not matched by comparable control of NO_x emissions, largely due to only modest (if any, depending on engine size) reductions in NO_x emission limits for engines less than 56 kW relative to CEV III levels. For these scenarios, NO_x emissions are estimated to increase by a factor of about 3 between 2015 and 2040. NO_x emissions from larger engines are effectively controlled, but the lack of stringent NO_x emission limits for engines less than 56 kW leads to the overall NO_x emissions increase during this time period. As was the case with agricultural tractors, the largest NO_x emission reductions relative to baseline levels are not realized until the implementation of CEV VI level emission standards.

Results for emissions of HC and CO from construction equipment, shown in Figure 11, follow similar trends as those for agricultural tractors. Large emissions reductions relative to the baseline scenario result from the implementation of CEV IV standards, and no further emissions benefits are accrued from more stringent regulatory stages.

As part of this analysis, emissions from individual construction equipment types were estimated separately. Figure 12 shows annual reductions in annual PM and NO_x emissions for the CEV VI scenario relative to the baseline scenario, disaggregated by equipment type. Crawler excavators are the main source of emissions from construction equipment,

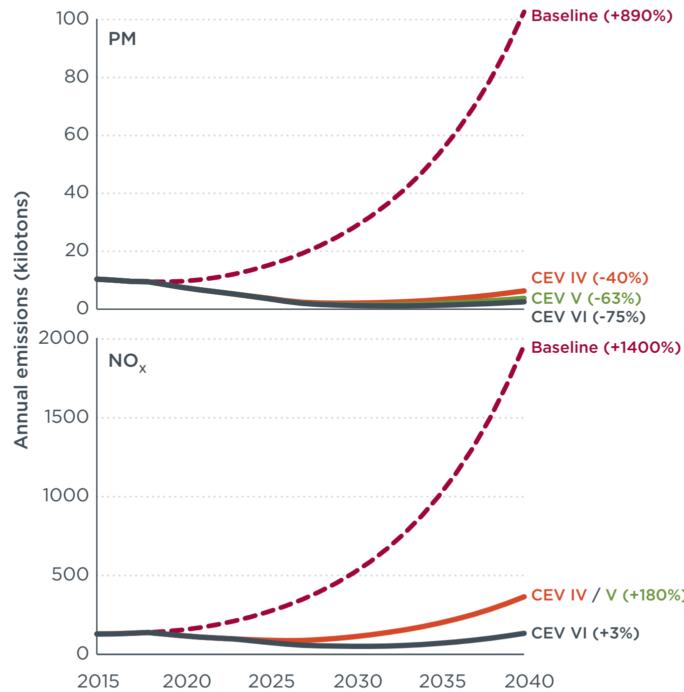

Figure 10. Projected annual PM and NO_x emissions for modeled construction equipment emission-control scenarios. Values on the right side of the plots show the percentage change in emissions between 2015 and 2040 for each scenario.

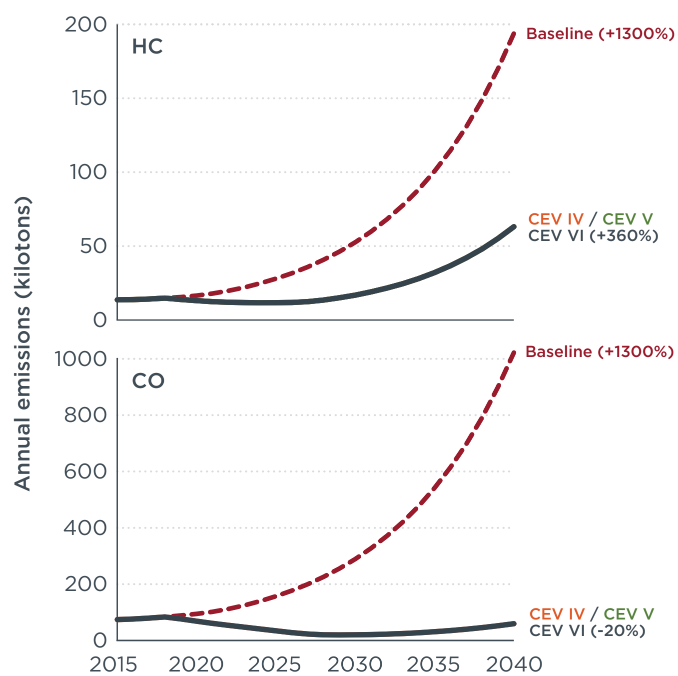

Figure 11. Projected annual HC and CO emissions for modeled construction equipment emission-control scenarios. Values on the right side of the plots show the percentage change in emissions between 2015 and 2040 for each scenario.

and greater than half of the emissions reductions in the CEV VI scenario come from control of this equipment type. Backhoe and wheeled loaders account for most of the remaining NO_x and PM emissions reductions in the CEV VI scenario, with other equipment contributing less than 10% to total reductions.

A similar disaggregation is presented in Figure 13, which shows PM and NO_x emissions reductions in the CEV VI scenario relative to the baseline scenario separated by engine power class. The greatest emissions reductions come from the control of the most common engine power classes, 37–56 kW and 75–130 kW. Together, these classes respectively account for 83% and 76% of PM and NO_x reductions estimated for the leapfrog scenario. Approximately 50% of these emissions reductions come from 75–130 kW class, which despite accounting for a smaller market share then 37–56 kW engines, tend to have a higher sector-wide power output.

Potential technology pathways for engines between 75 and 130 kW are shown in Figure 14. Current engine technologies vary somewhat. Natural aspirated and turbocharged engines are both found in this size range and electronic fuel injection systems are common. Charge air cooling is used in some engines. To achieve PM reductions required in the transition to CEV IV standards, engine manufacturers will likely have to incorporate turbocharging, a diesel oxidation catalyst and cooled exhaust gas recirculation into engine designs, though these standards may be able to be met with alternative technology packages (e.g., DPF). Based on current Tier 4f/Stage IV engine designs for the U.S. and EU markets, SCR will likely provide sufficient NO_x control for CEV IV emission requirements. Further reductions of the PM emission limit and the introduction of a particle number limit in CEV V and VI programs will likely force the use of a DPF for PM control from engines between 75 and 130 kW.

Summary

The market for agricultural tractors and construction equipment in India is growing rapidly. Without further regulatory action to control emissions from these sources, they are expected to surpass on-road vehicles as the predominant transportation-related source of PM and NO_x emissions in the next 10–15 years. While a stringent regulatory schedule has been proposed for on-road vehicles in India, no such similar program exists for non-road vehicles. This study used an emission inventory model to evaluate alternative regulatory control scenarios for non-road equipment in India on the basis of air pollutant emissions. Regulatory

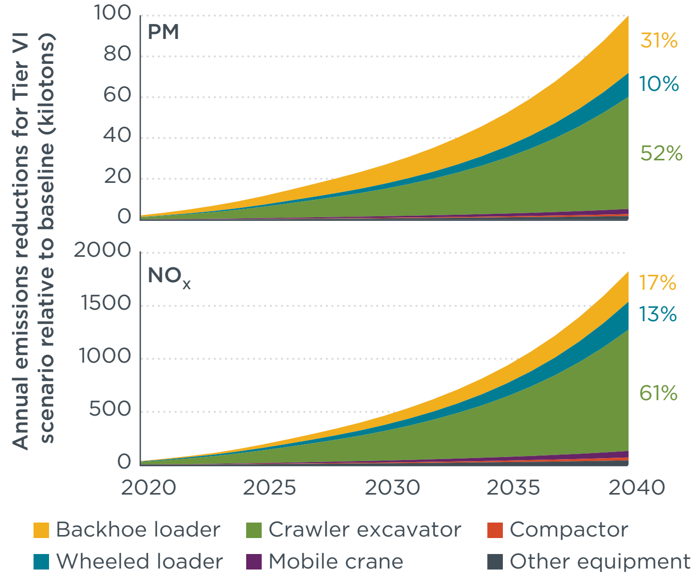

Figure 12. Annual PM and NO_x emission reductions for construction equipment in the CEV VI scenario relative to baseline, disaggregated by equipment type. Percentages show relative share of cumulative emission reductions between 2020 and 2040 for select equipment types.

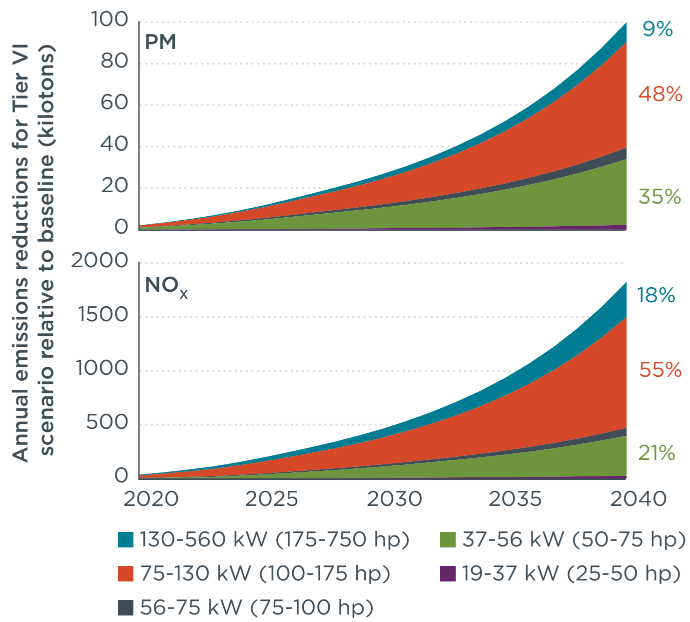

Figure 13. Annual PM and NOx emission reductions for construction equipment in the CEV VI scenario relative to baseline, disaggregated by engine power class. Percentages show relative share of cumulative emission reductions between 2020 and 2040 for select power classes.

pathways are based on similar programs implemented or proposed in the EU and the U.S., as well as forward-looking improvements to these programs.

Results indicate that a Trem/CEV VI regulatory scenario provides the largest emissions reductions between 2015 and 2040 relative to the baseline scenario in which no changes are made to current regulatory requirements. In this scenario, U.S. Tier 4f equivalent emission standards are adopted in 2019, and forward-looking standards based on Euro VI on-road heavy-duty vehicle standards are adopted in 2024. Trem/CEV VI standards are primarily characterized by more stringent NO_x control requirements for engines less than 56 kW. Relative to baseline projections, this pathway results in PM and NO_x reductions of 1,000 and 9,500 for agricultural tractors and 740 and 13,000 kilotons for construction equipment, respectively, between 2015 and 2040.

Emissions reductions in other scenarios are largely dependent on the emission limits set for engine power classes most representative of current and projected agricultural tractor and construction equipment markets. For agricultural tractors, which are predominately powered by engines between 19 and 37 kW, large PM emission reductions are realized with the adoption of Trem IV emission standards, with additional PM emission control with the implementation of filter forcing Trem V or VI level standards. Trem IV and V standards are not as effective at controlling NO_x emissions from agricultural tractors due to relatively lax emission standards for engines below 56 kW. Next generation, low-NO_x Trem VI level emission standards are required to achieve significant reductions in NO_x emissions from this sector.

For construction equipment, which tends to use somewhat larger engines than agricultural tractors, long-term PM reductions are achieved through the adoption of CEV IV standards, which include stringent PM limits for predominant engine sizes. Additional PM emission benefits are accrued through the adoption of filter forcing CEV V or VI standards. Due to the relatively larger engine sizes used in construction equipment, CEV IV standards are more effective at controlling NO_x emissions than comparable Trem IV standards for agricultural tractors. However, CEV VI level standards are required to reduce NO_x emissions from engines smaller than 56 kW and thereby fully offset emissions increases projected for the baseline scenario between 2015 and 2040.

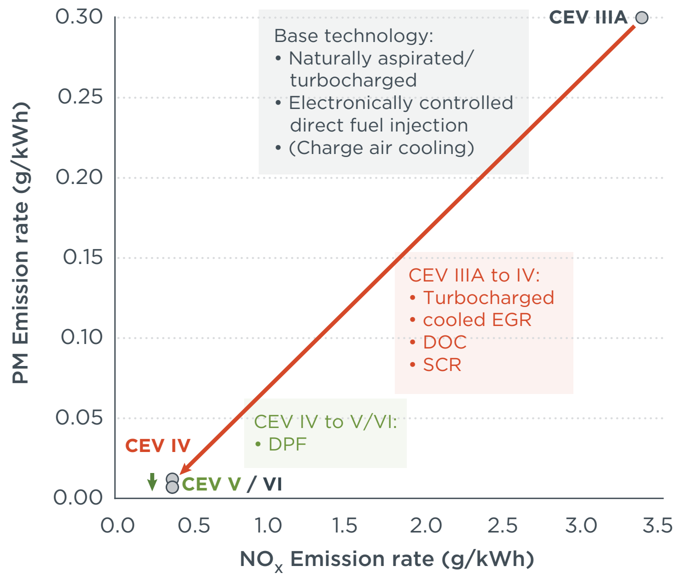

Figure 14. Projected technology pathway for diesel engines used in construction equipment between 75 and 130 kW (100 and 175 hp).

Emission-control technologies needed to meet the proposed regulatory pathways presented here are largely available to engine manufacturers now. In the mid- to long-term, engine manufacturers will likely have to apply best available after-treatment technologies to control emissions from non-road diesel engines, including SCR systems and particulate filters. For most engine sizes, the use of these technologies in agricultural and construction engine applications has been established by manufacturers selling in the U.S. and European markets. The challenge for engine manufacturers will be adapting these designs for the Indian market while maintaining engine affordability and durability.

The Trem/CEV VI scenario modeled here represents a more stringent step beyond current world-class global emission standards for non-road engines. To meet these standards, engine manufacturers will need to adapt emission-control strategies and technologies that have proven successful in larger engines to smaller engine sizes. This will be challenging, but the implementation schedule proposed here would give manufacturers close to 10 years to develop the emission-control solutions required to minimize the long-term air quality impacts of agricultural tractors and construction equipment in India.