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Non-road emission inventory model methodology

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Introduction

Effectively controlling air pollutant emissions depends (among other things) on a thorough understanding of non-road mobile sources, such as construction and agricultural equipment, generators and other industrial equipment, and consumer products like lawnmowers and leaf blowers. Increasing activity, especially in the agriculture and construction sectors, has led to an increase in non-road mobile-source emissions, but the diversity of engine categories, sizes and applications complicates the process of analyzing the non-road market. This diversity, along with the limited attention that has been devoted to non-road engines and equipment outside the U.S. and European Union (EU), has resulted in a lack of reliable data. And non-road emission control regulations, particularly concerning compliance and enforcement, are relatively weak compared to those governing on-road sectors.

Modeling is essential to identifying and assessing sources, forecasting future activity and emissions, and evaluating the impacts of potential policies. A non-road emission inventory model is a tool to portray the non-road engine and equipment market, historical and future emissions, and the estimated impact of policies.

This document outlines the methodology adopted for the non-road emission inventory model developed by the International Council on Clean Transportation (ICCT).

The ICCT's non-road emission inventory model estimates current and future emission inventories by region and equipment type for different scenarios, each characterized by a set of policies and technologies. It simulates emissions of both carbon dioxide (CO_2) and local air pollutants based on technology improvements and various policy efforts, including new emission standards, fuel quality improvements, alternative fuels, etc. This model is designed to:

- Determine sets of policies to achieve a given emission reduction target
- Evaluate the effects of different sets of policies on non-road emissions
- Evaluate and compare emission trends from different regions (or globally)

The objectives of this paper are to:

- Describe the model structure, processes, and data flows for the non-road emissions model, based on the review of international best practices
- Evaluate data collection needs for critical inputs and parameters

This study is limited to land-based, non-road mobile sources and excludes water-based and stationary engines and equipment, as well as locomotives. Refer to ICCT's previous publications for more information on locomotives (ICCT, 2012).

METHODOLOGY

This section summarizes the methodology ICCT has adopted for the non-road emission inventory model based on a review of three modeling tools from the U.S. and EU: the California OFFROAD model, the U.S. NONROAD model, and the European model. This section introduces the main equation for estimating emissions, addresses the preliminary category setting, and discusses each key parameter in the main equation.

EMISSION CALCULATION

Based on models and technical reports from the U.S. Environmental Protection Agency (EPA), California Air Resources Board (ARB), and European Environment Agency (EEA), a methodology for calculating non-road emissions is summarized in Equation 1, below. Consistent with all models reviewed, non-road exhaust emissions is estimated as the product of five key parameters—average horsepower (AHP), emission factor (EF), activity (ACT), load factor (LF), and population (POP).

EQUATION 1

$$\text{EXHAUST EMISSION}_{REG,TIM,EQP,POL,SCE} = \sum_{FUL,SIZ,STA} (AHP_{REG,TIM,EQP,FUL,SIZ,SCE} \text{ x } EF_{REG,EQP,FUL,SIZ,STA,POL,SCE} \text{ x } ACT_{REG,TIM,EQP,FUL,SIZ,STA,SCE} \text{ x } LF_{REG,TIM,EQP,FUL,SIZ,SCE} \text{ x } POP_{REG,TIM,EQP,FUL,SIZ,STA,SCE})$$

where:

AHP= Average maximum rated horsepower (hp or kW)
EF = Emission factor (g/hp-hr or g/kWh)
ACT = Annual activity (hours/year)
LF = Load factor (unitless)
POP= Population

Note: the final exhaust emissions will be calculated as grams per year.

The subscripts are defined as:

REG : Modeled region
TIM : Each calendar year
EQP : Non-road equipment type
FUL : Fuel type
SIZ : Engine size
STA : Emission standard
POL : Pollutant
SCE : Scenario

The formula quantifies exhaust emissions of selected pollutants (POL) for targeted equipment type(s) (EQP), which include all relevant fuel types (FUL), engine sizes (SIZ), and emission standards (STA) in modeled regions (REG) and calendar year (TIM) for different policy scenarios (SCE).

This methodology can be adopted to calculate exhaust emissions from non-road engines and equipment that use diesel, gasoline (for both 2-stroke and 4-stroke engines), LPG/CNG fuel, or electricity, which covers most of the

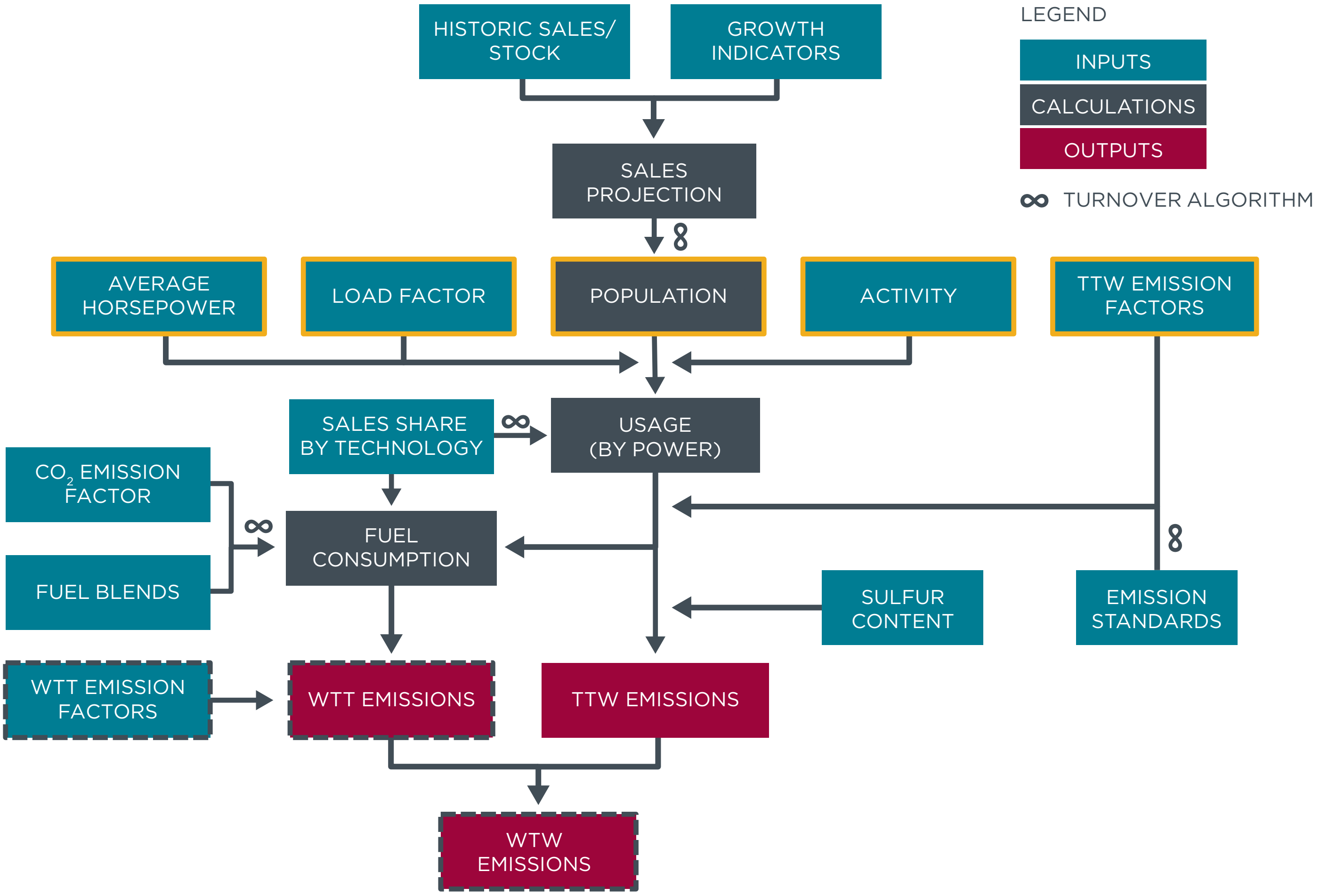

Figure 1: Flow chart for non-road modeling

non-road engines and equipment used in the agriculture, forestry, construction, industrial, and residential sectors.[1] The pollutants included in our model are hydrocarbon (HC), carbon monoxide (CO), particulate matter (PM), methane (CH_4), nitrous oxide (N_2O), nitrogen oxide (NO_X), sulfur dioxide (SO_2) and carbon dioxide (CO_2). This methodology applies to a broad spectrum of non-road machinery across all regions, though there exists a challenge in consistent categorization, especially with regard to the ranges used for engine size.

A flow chart of the non-road modeling process is shown above in Figure 1. In this chart, the blue boxes represent key inputs and the red boxes represent key outputs. The boxes with a yellow perimeter represent inputs in Equation 1, which will be discussed in the following sections. Other inputs are also important in the estimation of emissions, but they can be obtained directly from statistical data and/or certain assumptions. For instance, the input of sales share by technology is generally obtained from annual sales statistical data in the targeted region. But for the calendar years where such information is missing or incomplete, historic numbers can be adopted under the assumption of consistent local market. The intermediate calculations are shown in dark grey, but some of them (e.g. fuel consumption) can also be used as outputs. For each region and calendar year, tank-to-wheel (TTW) emissions can be generated based on this flow chart. Although well-to-tank (WTT) emissions (represented by a black-dashed perimeter) are shown in the flow chart, they are not discussed in this paper. The WTT emissions will be addressed in the future.

CATEGORIES

Non-road vehicle and equipment classification, even within the U.S., is not consistent. This is partly due to the large diversity that exists in both engine sizes and applications within the non-road sector. For example, "industrial" and "construction" are listed together under "diesel in-use off-road equipment" in ARB's OFFROAD model, but listed as independent categories in EPA's NONROAD model. Although these differences may have a minor effect on emission estimates, they can lead to some variation when collecting relevant data and evaluating regulations.

Table 1 shows the differences in non-road engine and equipment categories among the models reviewed.

Table 1: Non-road engine and equipment categories in the EU, U.S., and California.

Europe EEA (Winther et al., 2013)	U.S. NONROAD (EPA, 2005a)	California OFFROAD (ARB, 2013)
Mobile combustion in manufacturing industries and construction land-based mobile machinery; Commercial and institutional land-based mobile machinery; Mobile combustion used in residential areas: household and gardening land-based mobile machinery; Off-road vehicles and other machinery used in agriculture/forestry land-based mobile machinery (excluding fishing).	Agriculture equipment; Airport Support equipment; Commercial equipment; Construction equipment; Industrial equipment; Lawn/ Garden equipment; Logging equipment; Oil Field equipment; Underground Mining equipment.	Diesel in-Use Off-Road Equipment (Construction, Industrial, Ground Support and Oil Drilling); Diesel cargo Handling Equipment; In-Use Mobile Agricultural Equipment; Diesel transport Refrigeration Unit (TRU); Gasoline Recreational Vehicles; Gasoline lawn and Garden.

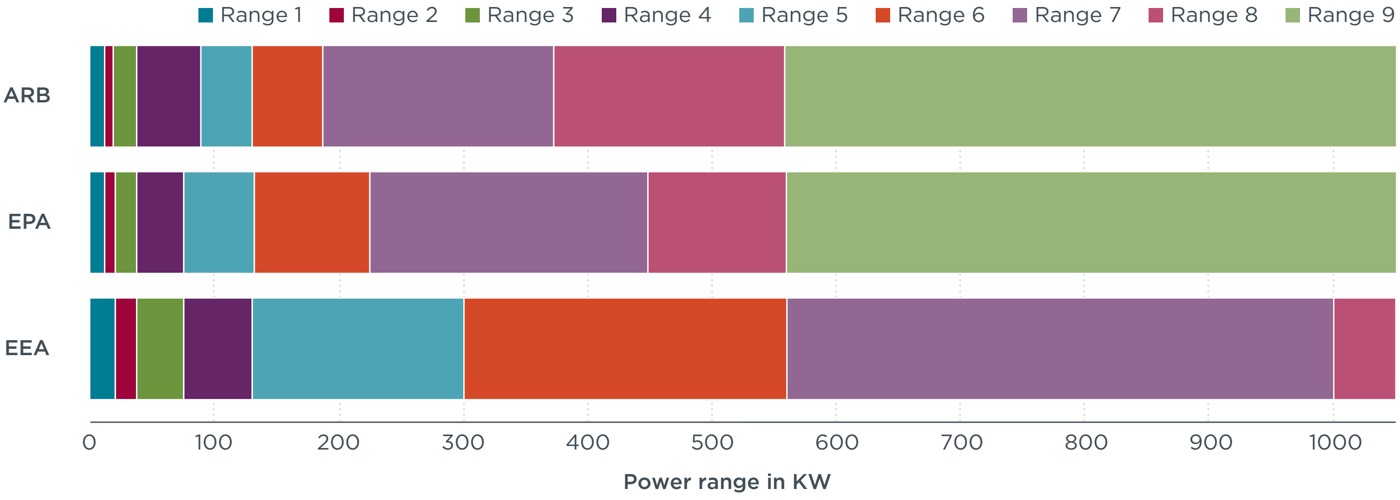

Figure 2: Non-road diesel engine size range categorization used in ARB, EPA, and EEA models

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[1] The exception is recreational vehicles, such as all-terrain vehicles and off-road motorcycles.

In addition to equipment classification, engine size category is another area where inconsistency exists. Figure 2 sheds some light on the differences among EPA's, ARB's, and EEA's definition of non-road diesel engine size ranges. Each color in the chart above represents one engine size range defined in the reviewed models. Both ARB and EPA have nine engine size categories, however, there is a slight variation between the models in categorizing engines less than 560 kW (751 hp). EEA groups engines into eight types, and consequently each engine range is wider compared to ARB's and EPA's, especially for those under 560 kW (751 hp).

Due to the inconsistency in category definition, we define the categories for non-road engines and equipment by the following four tiers: 1) equipment type (EQP), 2) fuel type (FUL), 3) engine size (SIZ), and 4) type of emission control technology (STA) for the designated region.

1. The equipment type (EQP) determines the function of the engine. Depending on how non-road equipment is used, operation cycles and emission rates (for both CO_2 and conventional pollutants) can vary. In addition, equipment population can indicate the level of use and the importance of each equipment type.
2. The fuel type (FUL) that the equipment is designed for—diesel, gasoline (2-stroke or 4-stroke), LPG/CNG or electricity—is normally consistent with the required loads. For example, construction non-road equipment tends to be powered by diesel due to their heavy loads. Some equipment types may also be designed to run on other fuel types.
3. The engine size (SIZ) is another key element of performance, which is measured by the rated horsepower (maximum power defined). Similar operational patterns, emission level, and most importantly, regulation requirements (e.g. emission limits, durability, etc.) are fundamental to define the ranges of engine size in the model. Further discussion on this topic follows in the next paragraph.
4. The type of emission control technology (STA) used for engines and equipment are based on their emission standards. This is mostly because technology requirements and emission rates are driven by the relevant regulatory standards.

Considering the inconsistency of the non-road equipment category definitions, reliable data on the local non-road engines and equipment market are key to modeling non-road emissions. Categorization of non-road equipment will be defined and/or adjusted based on the targeted region. Table 2 provides an example of category definitions proposed by the ICCT using the 4-tier approach introduced above. We begin with the mode and then show several sample equipment types in the second column. Considering the equipment varies based on the modeled region, our model offers the flexibility to update the equipment type accordingly based on the ones used in the targeted region. For simplicity, we adopted the engine size categories

Table 2: Non-road category samples

Mode	Equipment (EQP) (Sample)	Fuel Type (FUL)	Engine Size (SIZ)	Technology Assessment (STA)
Agriculture Forestry Construction Industry	Tractor Harvester Drill Others	Gasoline Diesel Biodiesel Electricity LPG/CNG	0-7kW/ 0-9HP 8-18kW/ 10-24HP 19-36kW/ 25-48HP 37-55kW/ 49-74HP 56-129kW/ 75-173HP 130-560kW/ 174-751HP > 560 kW/ >751 HP	Stage I/ Tier 1 Stage II/ Tier 2 Stage IIIA/ Tier 3 Stage IIIB/ Tier 4 Interim Stage IV/ Tier 4 Final Stage V
Resident/ Small Gasoline	Chain Saw Trimmer Mower Others	Gasoline 2-stroke Gasoline 4-stroke Electricity LPG/CNG	TBD	TBD, With only CO and HC+NOx limits
Others	Others	Gasoline Diesel Biodiesel Electicity LPG/CNG	0-7kW/ 0-9HP 8-18kW/ 10-24HP 19-36kW/ 25-48HP 37-55kW/ 49-74HP 56-129kW/ 75-173HP 130-560kW/ 174-751HP > 560 kW/ >751 HP	Stage I/ Tier 1 Stage II/ Tier 2 Stage IIIA/ Tier 3 Stage IIIB/ Tier 4 Interim Stage IV/ Tier 4 Final Stage V

from the latest proposed regulation—European Stage V Standards (Stage V)[2]— due to differences in defining engine size category between the models and also because Stage V covers a wider range of engine sizes. These categories are preliminary and will be adjusted based on the modeled equipment market and available data. Both the European Stage standards and the U.S. Tier standards can be adopted in the model for technology assessment due to their broad global application. The equivalence of each step in the two types of standards is determined by the emission limits.

AVERAGE HORSEPOWER (AHP)

The horsepower used in the calculation is the average rated (maximum) power level in each engine size category (as shown in Table 2), and this value is based on the engine size range defined for each modeled region (see Figure 2 and Table 2 as examples). Additionally, EPA recommends using local sales data to generate a weighted average horsepower value for each engine size category (EPA, 2005c). However, for regions with limited local data, ARB and EPA have provided suggested average horsepower values, separately (ARB, 2007a; EPA 2005c). A thorough review of those numbers, as well as adjustments, is required before adopting them for other regions. In our model, EPA's suggested values are used as placeholders, but regional information and/or adjustments are required based on the category of the equipment.

For each region (REG), the average horsepower is determined by the calendar year (TIM), equipment type (EQP), fuel type (FUL), and engine size (SIZ). The value could also change with the assumptions in each scenario (SCE).

EMISSION FACTOR (EF)

Emission factor represents the unit emissions of a pollutant emitted when the equipment is turned on (running and idling). The values used in the model are expected to reflect real-world emission rates and not emission limits.

New non-road engines are tested by the ISO 8178 test cycle to measure exhaust emission rates for emission certification and/or type approval testing in many regions, including the U.S., EU, and Japan. The ISO 8178 test cycle—or its 8-mode schedule C1 in particular—is also referred to as the Non-Road Steady Cycle (NRSC). In order to better represent emissions in real-world operating conditions, EPA, in cooperation with the authorities in the EU, developed the Non-Road Transient Cycle (NRTC). NRTC includes both cold- and hot-start, and is now required by EU Stage III/IV/V regulations, the US EPA Tier 4 interim and final rule, and Japanese 2011/13 regulations.

The tested exhaust emission factors of each pollutant (POL) are equipment-specific (EQP), and vary by fuel type (FUL), engine size (SIZ), and emission standard (STA). Although one type of engine can serve different types of equipment, their duty cycles are still unique because of the designed function/usage. In some cases, the region (REG) and the scenario (SCE) can affect the emission rates as well. Adjustments on the emission rates generated directly from tested cycles (NRSC and NRTC) are required for appropriate emission factors for each equipment category. These emission factors, with the appropriate adjustments, serve as zero-hour emission rates (ZH) in the formula.

HC, CO, $PM_{2.5}$, CH_4, N_2O and NO_X

For HC, CO, $PM_{2.5}$, CH_4, N_2O and NO_X emission factors,

EQUATION 2

$$EF_{REG,EQP,FUL,SIZ,STA,POL,SCE}$$
$$= (ZH_{REG,EQP,FUL,SIZ,STA,POL,SCE}$$
$$+ DR_{REG,EQP,FUL,SIZ,STA,POL,SCE}$$
$$\times CHrs_{REG,EQP,FUL,SIZ,STA,POL,SCE})$$
$$\times TAF_{REG,EQP,FUL,SIZ,STA,POL,SCE}$$

where:

EF = Emission factor (g/bhp-hr or g/kWh)

ZH = Zero-hour emission rate or when the equipment is new (g/bhp-hr or g/kWh)

Dr = Deterioration rate or the increase in ZH emission as the equipment is used (g/bhp-hr^2 or g/KWh-hr)

CHrs = Cumulative hours per year, total number of hours accumulated on the equipment in one year

TAF = Transient Adjustment Factor (unitless)

Conversion : (g/kWh) x 0.7457 = (g/hp-hr)

Source: Proposal by ICCT after reviewing the methods in ARB (2007b), EPA (2010b), and Winther et al. (2013)

The emission factors are assumed to be equal to zero-hour emission rates for new engines and equipment (used for 0 hours or 0 years). The rates will increase with usage (hours or years used) through the application of deterioration rates (Dr). Emission factors can be set to increase throughout an engine or equipment's lifetime (Winther et al., 2013) or be capped at either 12,000 hours (ARB, 2007b) or the average or median life (EPA, 2010b; EPA, 2010c), based on data availability and local fleet usage.

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[2] The European Stage V emission standard for the non-road sector is still a proposal at this stage, and is not implemented yet.

Emission factors will be further adjusted by the transient adjustment factor (TAF), which represents the ratio between the transient emission factor and steady-state factor. For equipment tested with NRTC, the TAF is set to one. For the equipment tested with NRSC, the TAF is set so that the emission factors can be more representative of real-world operations (EPA, 2010b).

EPA's suggested values are adopted for zero-hour emission rate (ZH), Dr and TAF in our model.

Sulfur effects

For PM emissions, it is recommended that sulfur effects be considered to account for the effects of different diesel sulfur levels. Sulfate can be a major component of PM emissions from diesel engines, and emissions of sulfates are positively correlated with the sulfur content of diesel fuel. Because the sulfur content in the diesel fuel varies considerably from that in the testing fuel, it is important to adjust the PM emissions accordingly in the model. The EPA compared real-world PM emission from nine engines running on both default and tested sulfur diesel fuel, and proposed a method (as shown in Equation 3) to capture the sulfur adjustment for PM (EPA, 2010b).[3] This method is used in our model as well.

EQUATION 3

$$PM_{sulfur\ REG,FUL,SIZ,STA,SCE} = BSFC_{REG,FUL,SIZ,STA,SCE} \times 7.0 \times soxcnv_{REG,FUL,STA,SCE} \times 0.01 \times (soxdsl_{REG,FUL,SCE} - soxbas_{REG,FUL,SCE})$$

where:

PM_{sulfur} = *PM sulfur adjustment (gram/hp-hr)*

BSFC = *In-use adjusted brake-specific fuel consumption rate (gram fuel/hp-hr) (x 453.6 if it is in units of lb fuel/hp-hr)*

7.0 = *grams PM sulfate/grams PM sulfur*

soxcnv = *grams PM sulfur/grams fuel sulfur consumed*

$$\begin{cases} 0.30, \text{ if the PM limit below } 0.1g/hp-hr \\ 0.02247, \text{ others} \end{cases}$$

0.01 = *Conversion from percent to fraction*

soxdsl = *Episodic fuel sulfur weight percent*

soxbas = *Default certification fuel sulfur weight percent*

Note: The calculation here is in units of g/hp-hr. If the unit of g/kWh is required, use the equation [(g/kWh) x 0.7457 = (g/hp-hr)] for conversion.
Source: EPA (2010b)

The sulfur effects are calculated based on the fuel used (in-use adjusted brake-specific fuel consumption rate (BSFC)), the PM relationship with fuel sulfur consumed (soxcnv), and the difference in sulfur content between used fuel (soxdsl) and testing/default fuel (soxbas). The soxcnv value is provided based on EPA's tests, as discussed above. The soxbas in EPA's model is 0.33%, and the soxdsl is an input based on the diesel sulfur level in the modeled region.

The BSFC value for non-road equipment and engines, shown in Table 3, is not affected by the emission control technology assessment (EPA, 2010b; Winther et al., 2013).[4] Additionally, the BSFC of uncontrolled engines can be applied for all equipment types. Suggested BSFC values from the EPA are shown in Table 3.

Table 3: BSFC value suggested by EPA

Engine size (hp)	BSFC (g/hp-hr)	BSFC (lb/hp-hr)
0-100	185	0.408
>100	166	0.367

Note: The calculation here is in units of g/hp-hr. If the unit of g/kWh is required, use the equation [(g/kWh) × 0.7457 = (g/hp-hr)] for conversion.
Source: EPA (2010b)

The final PM emission rate is the sum of the basic PM emission rate and PM sulfur adjustment (PM_{sulfur}). This method applies only to engines not equipped with advanced oxidation catalyst technologies (those manufactured before U.S. Tier 4 interim equivalent or EU Stage IIIB equivalent) (EPA, 2010b).

PM_{10} and Black Carbon (BC)

The PM_{10} emission factor is calculated using the $PM_{2.5}$ emission factor and applying an adjustment factor ranging from 1.03 to 1.09. The BC emission factor can be estimated with its emission rate generated by test cycles or real-world testing, but can also be calculated based on $PM_{2.5}$ by adopting an adjustment factor from EEA's emission inventory guidebook, if reliable local sources are lacking (Winther et al., 2013).

CO_2 and SO_2

The calculation of CO_2 and SO_2 emission factors is different from that of the other pollutants, as they are typically calculated based on brake-specific fuel consumption (BSFC) and the emission rate of HC. The calculation methods for CO_2 and SO_2 emissions are summarized below in Equation 4 and Equation 5, respectively:

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[3] The default sulfur level assumed in the EPA NONROAD model is 0.33 weight percent, and the level in the tested fuel is 0.28 weight percent. Though the equation is generated through real-world testing, the EPA finds it is applicable for general use.

[4] This conclusion is summarized based on the existing emission control technology. In the model, we recommend that standards (STA) be added as an extra level of detail for BSFC to capture the fuel consumption improvement in the future or in potential scenarios.

EQUATION 4

$$CO_{2\ REG,EQP,FUL,SIZ,STA,SCE} = (BSFC_{REG,FUL,SIZ,STA,SCE} - HC_{REG,EQP,FUL,SIZ,STA,SCE}) \times 0.87 \times (\frac{44}{12})$$

where:

CO_2 = CO_2 emission factor (g/hp-hr)

BSFC = In-use adjusted fuel consumption (g/hp-hr) (x 453.6 if it is in units of lb/hp-hr)

HC = In-use adjusted hydrocarbon emission factor (g/hp-hr)

0.87 = Carbon mass fraction of diesel

44/12 = Ratio of CO_2 mass to carbon mass

Note: The calculation here is in units of g/hp-hr. If the unit of g/kWh is required, use the equation [(g/kWh)×0.7457 = (g/hp-hr)] for conversion.
Source: EPA (2010b)

EQUATION 5

$$\begin{aligned} SO_{2\ REG,EQP,FUL,SIZ,STA,SCE} &= (BSFC_{REG,FUL,SIZ,STA,SCE} \times (1 - soxcnv_{REG,FUL,STA,SCE}) \\ &- HC_{REG,EQP,FUL,SIZ,STA,SCE}) \times 0.01 \\ &\times soxdsl_{REG,FUEL,STA,SCE} \times 2 \end{aligned}$$

where:

SO_2 = SO_2 emission factor (g/hp-hr)

BSFC = In-use adjusted fuel consumption (g/hp-hr) (x 453.6 if it is in units of lb/hp-hr)

soxcnv = gram PM sulfur/gram fuel sulfur consumed

$$\begin{cases} 0.30, \text{ if gasoline, CNG/LPG engines,} \\ 0.30, \text{ if PM limit below 0.1g/hp-hr} \\ 0.02247, \text{ others} \end{cases}$$

0.01 = Conversion from percent to fraction

soxdsl = Episodic fuel sulfur weight percent (specified by user) (default value for gasoline is 0.0339) (default value for CNG and LPG is 0.008)

2 = grams of SO2 formed from a gram of sulfur

Note: The calculation here is in units of g/hp-hr. If the unit of g/kWh is required, use the equation [(g/kWh)×0.7457 = (g/hp-hr)] for conversion.
Source: EPA (2010b)

Both CO_2 and SO_2 are estimated based on the BSFC, and the emission rate of HC. The BSFC value recommended by EPA can be found in Table 3, above. Although the formulas indicate that both CO_2 and SO_2 emissions will be affected by the emission rates of HC, the impact is very minor (EPA, 2010b). Similar to sulfur effects, SO_2 requires further adjustments based on the sulfur content in the fuel consumed (soxdsl). The default value for the calculation in our model is obtained from EPA's NONROAD model.

The CO_2 emission inventory can be estimated and/or validated directly from fuel consumption data since limited improvement in fuel efficiency is found from technology improvements required by the stringent emission control standards (EPA, 2010b; Winther et al., 2013). The CO_2 emission rates for fuel consumed are shown in Table 4.

Table 4: CO_2 emission rates by fuel type

Fuel type	Emission rate (gram/metric ton fuel)
Diesel	3160
Gasoline	3197
LPG/CNG	2990

Source: Winther et al. (2013)

Evaporative emission

For evaporative emissions of volatile organic components (VOC) from gasoline engines and equipment, the following formula can be applied but with only diurnal losses taken into account.[5] The population (POP), and activity (ACT) are identical to those used in the calculation of exhaust emissions (Equation 1). The suggested evaporative emission factors (Evap) are available in EEA's emission inventory guidebook (Winther et al., 2013)

EQUATION 6

$$\begin{aligned} Evaporative\ Emission_{REG,EQP,SCE} &= \sum_{FUL,SIZ,STA} (POP_{REG,EQP,FUL,SIZ,STA,SCE} \\ &\times ACT_{REG,EQP,FUL,SIZ,STA,SCE} \\ &\times Evap_{REG,EQP,FUL,SIZ,STA,SCE}) \end{aligned}$$

where:

POP = Gasoline non-road equipment population

ACT = Annual activity (hours/year)

Evap = Evaporative emission factor (gram/hour)

NOTE: Evaporative emissions are calculated only for gasoline engines. The subscript FUL represents the fuel type for gasoline 2-stroke and gasoline 4-stroke only.
Source: Winther et al. (2013)

The ICCT adopts the emission rates suggested by EPA as default. If reliable data are available, regional specified emission factors are preferred.

ACTIVITY (ACT)

Activity data are used to estimate the annual usage (in units of hours per year) for targeted equipment. They depend on the region (REG), calendar year (TIM), equipment type (EQP), fuel type (FUL), engine size (SIZ), and scenario (SCE).

The data normally comes from relevant studies or surveys in the designated regions. U.S. models provide suggested

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[5] More information on non-road engines and equipment evaporative emissions is required. Evaporative emission from hot-soak, resting and running losses are not included in this study. (Winther et al., 2013)

values, which cover a wide range of non-road equipment (ARB, 2007a; EPA, 2010a). For regions without local data, we set values consistent with the ones in the EPA's NONROAD, and then apply adjustments based on local market conditions.

It is widely recognized that activity declines with increasing age (ARB, 2007a; EPA, 2010a). Oftentimes, old equipment is kept as a backup in case new equipment breaks down. However, precise information may not be available for any single type of non-road engine and equipment. From an existing study on construction and mining equipment in California, usage rate declines up until the equipment's median useful life, and then stays constant (MacKay, 2003). More information is necessary to determine the patterns of activity change. Due to lack of reliable data, no activity degradation is considered in our model currently.

LOAD FACTOR (LF)

Load factor is defined as the ratio between average power usage and the rated (maximum) value. Non-road engines are rated at their maximum power level when running at designed speed and load. But in reality, engines are operated at various speeds and loads, and are rarely used at designed conditions. Thus, load factors are applied to reflect normal in-use operation status including idle, partial load conditions, and transient operation (EPA, 2010a).

Load factor data can be collected through surveys by equipment users or estimated from data on hours of usage per year, fuel consumption per year, and fuel consumption rate at rated power for each type of engine (EPA, 2010a). Suggested values can be found in ARB's and EPA's technical reports (ARB, 2007a; EPA, 2010a). Similarly, adjustments should be tailored to local markets when applying those default values from the U.S. models. Similar to the previous parameters, we use EPA's recommendation as default. But regional data are always preferred since they are more representative.

POPULATION (POP)

Sales & stock

Generally, local statistical data on non-road sales and stock are essential to estimate the emission inventory. Historical sales and stock sorted by detailed equipment types are critical to understanding the market components and development. These data can be obtained through various sources including industry associations, government agencies as well as sample and survey studies. Sales are adopted by ICCT as an input to estimate stock with growth rates and scrappage for each category. Both U.S. and EU models take stock as a direct input. However, in most regions (especially in developing countries), the quality of stock data is relatively poor when compared to sales data because of inconsistent registration requirements for non-road equipment, especially older ones.[6] However, governmental agencies or industry associations normally keep good records of production and sales volume from manufacturers, ensuring better data quality and availability. Thus, sales are the suggested input to predict stock in ICCT's non-road model.[7]

Growth rate

For the sales growth rate, recommendations from local studies, interviews, and/or surveys are suggested for use in the model. However, for regions lacking this information, market (stock) growth rate can be used to estimate the sales growth rate.

We adopt socioeconomic indicators combined with historical trends, and in-sector measurement (e.g. construction sites) in the model to estimate market shifts. Historical data on employment, dollars spent, sales and fuel expenditures, and other economic indicators can provide information on non-road engines and equipment population growth or decline rate (Puri & Kleinhenz, 1994). However, there is a drawback to using the economic indicators alone: they fail to correlate well with some sectors (e.g. agricultural growth is not necessarily affected by the employment rate), as well as trends within each sector (e.g. the share of fuel type (gasoline, diesel, CNG/LPG, and electricity) for a single equipment type) (EPA, 2004). Given that capital costs are high, owners also have a strong incentive to get the most activity out of the equipment and will not purchase new equipment unnecessarily. Thus, historical trends of non-road equipment and engines, and/or key in-sector measurement are required to adjust the growth rate projected by the socioeconomic indicators.

The relationship between sales growth rate and stock growth rate can be expressed in the formula below. This also ensures consistency between sales and stock projected in the model.

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[6] Owners usually keep old equipment as spares and use these very occasionally when new equipment breaks down (EPA, 2010a).

[7] Base year stock is still required in the model for better market projection. Certain market research and/or literature review is needed to obtain this number.

$$SalesGrw_{REG,TIM,EQP,FUL,SIZ,SCE} = PopGrw_{REG,TIM,EQP,FUL,SIZ,SCE} / [(-1.4306 \times PopGrw_{REG,TIM,EQP,FUL,SIZ,SCE}) \times Median\ (Average)\ lifetime_{REG,TIM,EQP,FUL,SIZ,SCE}] + (-0.24 \times PopGrw_{REG,TIM,EQP,FUL,SIZ,SCE})+1) \quad \textbf{EQUATION 7}$$

where:

SalesGrw = Growth in engine sales as a percent of the initial year sales. Thus, the sale value (percent and absolute number) is applied each year.

PopGrw = Growth in fleet population, as a percent of the base year population

Median (Average) lifetime = Median or average lifetime (years)

Source: EPA (2005b)

Median (average) lifetime

The median (average) lifetime (in years) represents the expected lifetime of the equipment used at average load and activity. Median (average) life (in hours, at full load) is one of the key parameters to determine median or average lifetime as shown below.

$$Median\ (Average)\ Lifetime_{REG,TIM,EQP,FUL,SIZ,SCE} = (Median\ (Average)\ Life_{REG,TIM,EQP,FUL,SIZ,SCE}) / (ACT_{REG,TIM,EQP,FUL,SIZ,SCE} \times LF_{REG,TIM,EQP,FUL,SIZ,SCE}) \quad \textbf{EQUATION 8}$$

where:

Median (average) lifetime = Median or average lifetime (years)

Median (average) life = Median or average life (in hours at full load)

ACT = Annual activity (hours/year)

LF = Load factor

Source: EPA (2010a)

The median (average) lifetime varies based on engine category and size. In general, the lifetime of larger engines is longer than that of smaller ones, and the lifetime of diesel engines is longer than that of gasoline ones. Table 5 summarizes suggested values for median/average life of compression-ignition (CI) engines (mostly diesel) by size from EPA and ARB. Though there is some degree of variability between ARB and EPA estimates in each engine size, there is a major difference for small engines (0-16hp). Note that Table 5 is a very high level summary and the default values for median (average) life vary for each type of engine and equipment (ARB, 2007a). EEA also provides suggested values derived from Danish inventory results for median (average) lifetime, which are not listed here (Winther, 2012; Winther et al., 2013). The median (average) lifetime in the EEA model ranges between 3 and 31 years across different types of machineries, which is slightly lower than that of ARB, which is 10 to 38 years (ARB, 2007a). This is probably driven by the difference in the usage and maintenance in the modeled regions. This indicates the great diversity in market components and usage of non-road engines and equipment, so adjustments on these suggested values are recommended based on local conditions and equipment in the modeled region.

For consistency, ICCT adopts EPA's default value in the model, but certain adjustments are recommended when reliable regional data are available.

Table 5: Compression-ignition (CI) engine median life

Engine Size (Horsepower)	Median (average) life (hrs)	
	ARB OFFROAD	EPA NONROAD
0-16	1,250	2,500
16-25	2,500	2,500
25-50	2,500	2,500
50-300	4,000	4,667
300+	6,000	7,000

Source: EPA (2010a)

Scrappage/survival curve

Equipment turnover is determined by the average vehicle age of the fleet and the survival/retirement rate, which is described by the scrappage/survival curve. The scrappage/survival curve is generated from a statistical function, which indicates the relationship between time and scrapped/surviving population. The curve answers the question: on average, what proportion of the fleet will survive after reaching a certain age? In this study, the curve recommended by EPA represents an average proportion of retirements under the assumption that half of the equipment will be replaced when it reaches the average lifetime (EPA, 2005b).

Ideally, the scrappage curve should be generated using the age-distributed stock data for each equipment category. However, due to lack of data, the scrappage curve is simplified by considering only historic sales and stock under the assumption that the retirement rate will not change over time (calendar years).

The default scrappage curve (shown below in Figure 3) is based on EPA's recommended scrappage/survival curve and can be applied to all non-road equipment. When the equipment reaches the median life (1 on the x axis), half of the fleet is retired. By the time twice the median life is reached (Age/Median Life = 2), all of the equipment is scrapped. The retirement rate is slow for old equipment because old equipment is normally kept as a spare, but rarely used. The curve indicates that the retirement rate is the highest (the slope is steepest) when equipment reaches the median lifetime.

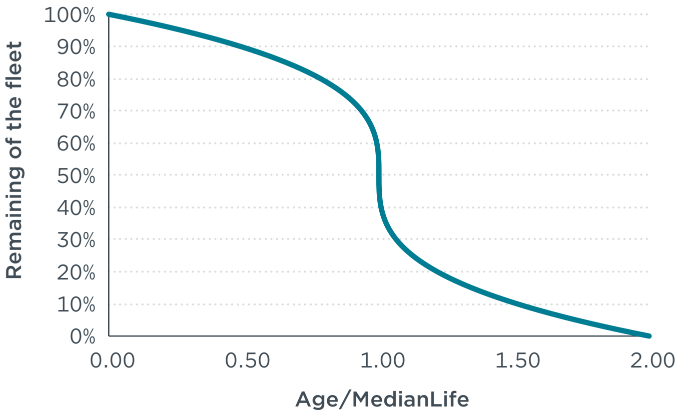

Figure 3: Default scrappage curve (Source: EPA (2005b))

The default scrappage curve is based on a normal distribution of cumulative retirements versus age (EPA, 2005b). Other distributions can be adopted in the model if they illustrate better representations for a designated region.

AGE DISTRIBUTION (IN THE BASE YEAR)

To determine the equipment population distribution by age in the model base year, historical sales and stock data are ideally required. In cases that such data are not available, fleet age distribution in the base year can be estimated as a function of average lifetime and a default scrappage curve assumed from international data (EPA, 2005b). By creating a simulated fleet for each equipment category (EQP), fuel type (FUL), and engine size (SIZ) from an arbitrary starting sales value (1,000 units/year) and projecting sales until twice the median life of the equipment with the scrappage assumption, a projection of relative sales could be generated (EPA, 2005b).

An example is shown in Figure 4 for the age distribution in the base year, using data from EPA's NONROAD model for 75-100 hp diesel agricultural tractors with a 3.0% sales growth rate (EPA, 2005b). The ICCT follows EPA's recommendation in the model unless detailed regional data are available.

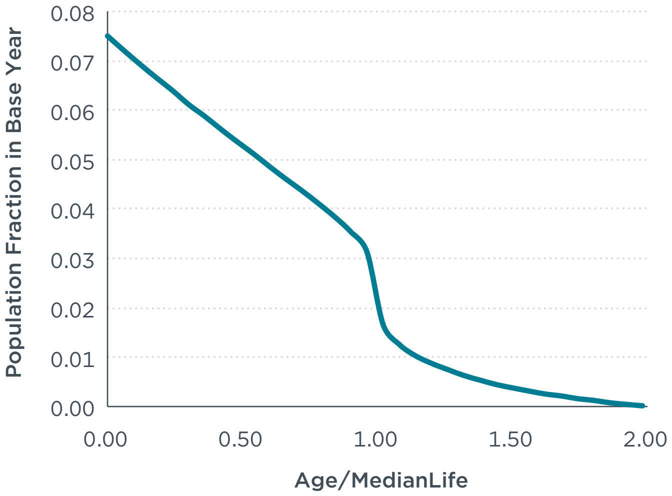

Figure 4: Age distribution example (with growth)

CALCULATION APPROACH

Our model calculates emissions using an age-based approach (i.e., disaggregate calculation of emissions by equipment age). The decision to calculate based on equipment age was mostly determined by the model platform, data quality, and scope of the project. In general, an age-based approach requires higher performance of the model platform as well as higher data quality, while an average approach places lower requirements for the model platform and data quality. Thus, the age-based approach can provide more detailed results.

The age-based approach calculates emissions at each equipment age. Thus, age-specific inputs are required for all key parameters. Average horsepower (AHP), load factor (LF), and activity (ACT) can be set constant with age, but emission factors (EF) and population (POP) should vary with age.

CONSISTENCY

The methodology presented in this study is based on a review of three models from ARB, EPA, and EEA. Although the methods in each model are roughly consistent, variation exists between all three models and our non-road model. Table 6 compares the methodology adopted in ICCT non-road model with the ones we reviewed to illustrate variations across models.

The main equation (Equation 1) is widely adopted in all the models, and can be regarded as the standard approach to estimate non-road emission inventory. Three inputs—AHP, LF, and ACT—are key direct inputs for all the models with suggested values available in both ARB's and EPA's models. EEA provides suggestions on relevant data collection, but no suggested values. The ICCT adopts the suggested value from EPA for

Table 6: Methodology consistency for methods and key inputs

Method/key inputs		ARB	EPA	EEA	Notes/ICCT non-road model
Main equation		🟩	🟩	🟩	Consistent method
Average horsepower (AHP)		🟩	🟩	N/A	EPA's suggested value with adjustment when no regional data available
Load factor (LF)		🟩	🟩	N/A	EPA's suggested value with adjustment when no regional data available
Activity (ACT)		🟩	🟩	🟨	EPA's suggested value with adjustment when no regional data available
Emission factor (EF)	**Emission factor**	🟨	🟩	🟨	EPA's method and suggested value
	Sulfur effects	N/A	🟩	N/A	EPA's method and suggested value
Population (POP)	**Stock**	🟥	🟥	🟥	This is a calculated parameter in our conceptual model, while other models consider stock as a direct input
	Sales	N/A	🟨	N/A	Relationship between sales growth rate and stock growth rate is adopted from EPA's model. Relevant socio-economic growth factors can be adopted as stock growth rates.
	Survival curve	N/A	🟩	N/A	EPA's method and suggested value
	Median lifetime	🟩	🟩	🟩	EPA's suggested value with adjustment when no regional data available
🟩	Very consistent approach;				
🟨	Similar approach, with adjustments applied;				
🟥	Not consistent approach.				

these three inputs as default inputs, but adjustments are applied accordingly when those data are applied to regions outside U.S.

The method and value for estimating EFs proposed in ICCT's model is consistent with the method in EPA's NONROAD, as we uses EPA's approach and values as defaults. The methods used in ARB's and EEA's models are very similar, but fail to reveal the adjustments for EFs tested by NRSC—that is, there is no indication of TAF used to adjust EFs for better real-world representation. All three models have indicated the deterioration in EF with usage, but without an agreement on the cap for EF deterioration.[8]

In this calculation, the major difference comes from POP data, which are treated as direct inputs in all other models except ours. Considering the poor stock data availability in most of the regions, we decide to use sales data as the direct input to estimate the stock. This provides our model higher flexibility to estimate the market of non-road equipment globally.

DATA COLLECTION NEEDS

Data quality is one of the key elements to determine model accuracy. Many regions still remain at the initial stage of non-road engines and equipment data collection, due to low availability of reliable data. As a result, proxy values from the U.S. EPA's NONROAD model are necessary for modeling efforts at this stage.

Table 7 summarizes the data needs for key parameters. Suggested values can be found in the EPA's reports. The ICCT has reviewed available data and evaluated the adequacy of using them in other regions through a qualitative star system. More stars represent the data being more interchangeable. Five stars (★★★★★) indicate that using suggested values from EPA works as long as the assumptions match. One star (★) suggests that local statistics or survey data are required.

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[8] ARB suggests to cap the EF deterioration rate by 12,000 hours (ARB, 2007b); EPA suggests to cap it when reaching the average/median lifetime (EPA, 2010b; EPA, 2010c); and EEA does not set a cap for EF deterioration (Winther et al., 2013).

Table 7: Data collection needs

Parameters	Inputs	Data adequacy
Average horsepower (AHP)	Average Horsepower	★★★★
Emission Factor (EF)	Zero-hour emission rate (ZH)	★★★★★
	Deterioration rate (Dr)	★★★★★
	Cumulative hours used (CHrs)	★★★
	Transient adjustment factor (TAF)	★★★★★
	In-use adjusted fuel consumption (BSFC)	★★★★
	Ratio between PM sulfur and fuel sulfur (soxcnv)	★★★★★
	Default fuel sulfur weight percent (soxbas)	★★★★★
	Episodic fuel sulfur weight percent (soxdsl)	★
	Evaporative emission factor (Evap)	★★★★★
Activity (ACT)	Activity	★★★
Load factor (LF)	Load factor	★★★
Population (POP)	Sales	★
	Stock	★
	Growth rate	★★
	Median/average lifetime	★★
	Survival/retiring curve	★★★★
	Age distribution	★★★★
Others	Sales share by technology	★
	Emission standard	★
	Fuel blends	★

Note:

★★★★★	Data could be directly adopted as long as assumptions match.
★★★★	Data could be used with adjustments.
★★★	Local information is preferred, but data can be used with adjustments.
★★	Local information is recommended; data can be used only with significant adjustments.
★	Local information is required.

Although five stars (★★★★★) are given to some of the parameters in Table 7 above (e.g. EF), local data are preferred in our model. Applying the experienced data from other regions would still potentially under- or over-estimate emissions because the usage and pattern of modeled equipment vary across regions.

Using consistent local data for the model inputs is always preferred for the following reasons. First, data collected in the designated area serve better to describe fleet characteristics as long as they are properly processed and validated. Second, adopting local data wherever applicable encourages more data collection to happen and allows for better understanding of the targeted fleet for the long-term. Finally, local data can best reflect the different compliance and enforcement practices in the modeled region.

In our model, EPA's EF and survival curve data as well as age-based method are adopted with no adjustment. For AHP, ACT and LF, EPA's value is set the default. Adjustment is recommended for regions outside U.S., but is not required. We obtain the sales, (base year) stock, and growth rate from local statistical data, academic research, industry associations, as well as reliable consultants for the targeted regions.

Due to the fact that EPA's suggested value is significantly adopted in the model for regions without local data, the uncertainty of the results can be high even with adjustment. Thus, it is essential for us to validate the model results to ensure the assumptions and estimates are representative. We could validate the model by comparing fuel consumption—an intermediate calculation result—with available regional fuel sales studies or statistics. This comparison would help us gain a better understanding about whether the assumptions we make in the model represent appropriate usage, as well as any under- or over-estimates we make in the market in the modeled region.

PLATFORM

At this stage, the ICCT non-road model uses Microsoft Excel to generate the emissions by equipment type. Excel offers sufficient flexibility for an age-based

Table 8: Model platform summary

Model name	Platform	Approach	Notes
NONROAD, EPA	A graphical user interface written in Visual Basic, the core model written in Fortran, and a reporting utility written in Microsoft ACCESS.	Age-based	NONROAD2008, the latest version, is included in the latest Motor Vehicle Emission Simulator (MOVES2014).
OFFROAD, ARB	Access 2003 (database file) with Visual Basic Editor	Age-based	The OFFROAD model is replaced by category specific models. OFFROAD 2007 is the latest version for the updated model.
Guidebook 2013, EEA	N/A	Average	The results and methodology are released in the EEA emission inventory guidebook.

approach, and easily allows for adjustments to be made (as needed). The equipment type and engine size can be adjusted based on the availability of input data (sales). EPA's suggested values, including those for activity, emission factors, and average usage, are adopted as default values unless specific data are provided.

Table 8 summarizes the platforms used by ARB, EPA, and EEA models, which can be insightful for our future improvement.

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