METHODOLOGICAL GUIDE

Programa Clima y Aire limpio en Ciudades de América Latina

METHODOLOGICAL GUIDE FOR ESTIMATING EMISSIONS FROM NON-ROAD MOBILE MACHINERY

(Inventory emissions calculation)

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Methodological guide for estimating emissions from non-road mobile machinery (Inventory emissions calculation)

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TECSUP headquarters in Lima, Peru; AVESCO Langenthal Switzerland (below); Skid-steer loader on public roads in Lima, Peru (above)

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The Climate and Clean Air project in Latin American Cities Plus (CALAC+) pursues a vision of healthier cities that seek to reduce their emissions of pollutants and greenhouse gases (GHGs) by encouraging a shift to soot-free, low-carbon city buses and non-road mobile machinery.

This guide is part of a series of 7 technical documents developed by CALAC+ to promote knowledge and environmental management of machinery emissions reduction in Latin America. The topics covered include the generation of inventories, estimation of pollutants, emission control systems, regulatory standards policies and monitoring of measures adopted.

The *Methodological guide for estimating emissions from non-road mobile machinery* completes the first guide and provides the background and rationale for estimating emissions from this fleet.

Content

1. INTRODUCTION

This methodology aims at developing an inventory of emissions from Non-Road Mobile Machinery (NRMM) in the countries of the Climate and Clean Air project in Latin American Cities Plus (CALAC+).[1] It has been developed based on the experience of Santiago de Chile in the preparation of its non-road mobile machinery (NRMM) inventory for 2013. This guide complements the ***METHODOLOGICAL GUIDE FOR DEVELOPING THE NON-ROAD MOBILE MACHINERY INVENTORY*** which provides an estimation of the population of this type of source. The objective now is to show the background and rationale for estimating emissions from this fleet.

The scope of this guide covers the following air pollutants:

- Particulate matter (PM and $PM_{2.5}$),
- Carbon monoxide (CO),
- Hydrocarbons (HC)
- Nitrogen oxides (NOx)

In addition, the following are included:

- Carbon dioxide (CO_2)
- Black carbon (BC)
- Fuel consumption.

With regard to the machinery considered, the scope covers those with diesel engines with rated powers between 19 and 560 kW, in accordance with the scope of the previous guide.

For the preparation of this guide, the following methodologies were reviewed for reference: MOVES[2] of the United States Environmental Agency (EPA), defined in their various technical reports; CORINAIR of the European Union (EU), defined in the document "EMEP/EEA emission inventory guidebook 2016" [CORINAIR 2016] and the "Non-road energy consumption and pollutant emissions" of the Swiss Environmental Office (FOEN).

In the case of the MOVES model, the technical reports considered in this methodology correspond to the documents indicated in the Table 1.

[1] The cities of Bogota, Mexico City, Lima and Santiago de Chile are currently participating in this initiative.

[2] Moves is the emissions model for the EPA's on-road and off-road component. The Non-Road part corresponds to the adoption of the previous NONROAD model.

Table 1: EPA Reference Documents for NRMM Emissions Estimates

Technical Report	**See in References**
Exhaust and Crankcase Emission Factors for Nonroad Compression-Ignition Engines	[EPA2014b]
Median Life, Annual Activity and Load Factor Values for Nonroad Engine Emissions Modeling	[EPA2008]
User's Guide for the Final NONROAD2005 Model	[EPA2005]
Calculation of Age Distributions in the Nonroad Model: Growth and Scrappage	[EPA2005-A]
Geographic Allocation of Nonroad Engine Population Data to the State and County Level	[EPA2005-B]
Nonroad Engine Growth Estimates	[EPA2005-C]

2. METHODOLOGY FOR CALCULATING EMISSIONS

The proposed methodology for estimating the emissions inventory consists of calculating the fleet's emissions based on the activity in terms of annual hours of use and its emission rate. This requires stratifying or segmenting the machinery population according to the technical attributes that determine both the activity and the pollutant emission rate. The attributes defined by the reference methodologies as relevant for this characterization are those indicated below:

Table 2: Technical attributes for the characterisation of fleet emissions

Attribute	Description	Acronym
Power Range	Power range of the machinery according to its rated engine power in [kW]. The fleet is defined in standardized power ranges according to [EPA2008].	*PwR*
Engine type	Defined by the type of ignition: spark (Otto) or compression (Diesel). It is also defined by the type of fuel (gasoline, CNG/LPG, diesel). Spark-ignition engines are subclassified into two or four strokes. Only diesel engines are considered for the scope of the study. This classification defines the applicable emission standard as well as the emission rate or emission factor per pollutant.	*Entyp*
Equipment type	The equipment type corresponds to the standardized typologies included in the EPA methodology that are described in CALAC+´s METHODOLOGICAL GUIDE FOR DEVELOPING THE NON-ROAD MOBILE MACHINERY INVENTORY which is consistent with [EPA2005]. For example, bulldozer, front loader, excavator, etc.	*Etyp*
Emission level	The emission level is how we characterize the emission control technology which in turn determines the emission rates of the pollutant, based on compliance with any (or no) emission regulation or standard. European-origin equipment meets the standards defined in [CORINAIR 2016] and US-origin equipment meets the standards defined in [EPA2014b]. In order to harmonize this attribute under the same calculation methodology, Table 5 provides equivalences between both. This is required for fleets that import machinery from different origins, as is the case with CALAC+ member countries.	*Elev*
Age	The age of the machinery is determined from the distribution of the fleet by year of manufacture and is related to aspects such as the deterioration or wear factor.	*Age*

Based on the table above, emissions need to be calculated for each sub-segment (*sub*), which groups together machines with identical technical attributes and which are therefore equivalent in terms of their emission performance and activity. In order to carry out such a calculation in all reference methodologies, very similar forms of algebraic expression can be found. An extended form of the basic equation for calculating emissions is as follows:

$$\boldsymbol{E}_{\boldsymbol{i}} = \sum_{\boldsymbol{sub}}[\boldsymbol{N}_{\boldsymbol{sub}} \cdot \boldsymbol{A}_{\boldsymbol{sub}} \cdot \boldsymbol{Pw}_{\boldsymbol{sub}} \cdot \boldsymbol{LF}_{\boldsymbol{sub}} \cdot (\boldsymbol{EF}_{\boldsymbol{sub,i}} \cdot \boldsymbol{TAF}_{\boldsymbol{sub,i}} \cdot \boldsymbol{DF}_{\boldsymbol{sub,i}} - \boldsymbol{SPM}_{\boldsymbol{sub,i}})]$$

Equation 1

Where:

Sub : Index indicating the fleet sub-segment with the same technical attributes: power range, engine type, equipment type, emission level and age.

Ei : Emissions for the sub-segment ***sub*** of the fleet, for pollutant *i* during the period of the inventory calculation (typically one year), in [g].

N_{sub} : Population or fleet in equipment units of the sub-segment *sub* of the fleet.

A_{sub} : Activity per machine in hours of use per year [hr], for equipment in the subsegment *sub* of the fleet.

Pw_{sub} : Average rated power in [kW] for the population in the power range of the sub-segment *sub*.

LF_{sub} : Load factor representative of the operating conditions of the sub-segment *sub* of the fleet. It represents the fraction of the rated engine power, at which the machinery typically operates (non-dimensional).

EF_{subi} : Emission factor of pollutant *i* of the new equipment (zero hour), for any unit of the sub-segment *sub*, operating in steady state. It represents the emission rate in grams per unit of work [g/kW-hr].

TAF_{subi} : Transient adjustment factor of the steady-state emission factor EF_{subi} of equipment from sub-segment *sub*, to adjust the engine emissions from the steady-state operation to the transient operation[3] (non-dimensional)

DF_{subi} : Deterioration factor representing the emission factor adjustment of pollutant *i*, due to ageing or deterioration of the engine and the emission control systems of the equipment in the sub-segment *sub* (non-dimensional).

$SPM_{sub,i}$: Adjustment or discounting of PM mass concentration due to variations of the sulphur content in the fuel with respect to the sulphur values of the certification fuel used for measuring EF_{subj}. For pollutants other than PM, $S_{PM} = 0$. It is expressed in [g/kW-hr].

[3] Transient engine operation is here understood as that resulting from the constant change of speed and load, as in actual operation. It has the opposite sense of steady-state operation, under constant speed and load conditions, as seen during the emissions certification cycle.

The next chapters of this document will elaborate on the development of each of these variables and factors, considering mainly the recommendations and values proposed by the APS for each one of them. However, in all cases, the recommendation is to seek locally representative values for these variables and factors, or at least to have a discussion with local experts from the Non-Road Mobile Machinery sector, for validation purposes.

EXAMPLE 1: STEP 1

The following is an example of a fleet of construction machinery with diesel engines, grouped into sub-segments according to their technical attributes for characterising the fleet emissions indicated in Table 2. The example considers the estimated emissions for 2015.

sub	*Sector*	*Etyp*	*PwR [kW]*	*Year*	*Age [years]*	N_{sub}	Pw_{sub} *[kW]*	*Elev*
1	Construction	Excavator	130 ≤ kW < 225	2012	4	47	136,4	Tier 3
2	Construction	Excavator	130 ≤ kW < 225	2009	7	25	145,3	Tier 2
3	Construction	Excavator	75 ≤ kW < 130	2009	7	12	122,7	Tier 2
4	Construction	Motor grader	130 ≤ kW < 225	2012	4	50	184,3	Tier 3
5	Construction	Motor grader	75 ≤ kW < 130	2012	4	38	89,5	Tier 3

The table above shows that each sub-segment differs from the others in some of the technical attributes relevant to the characterization of emissions. In order to make the calculation of E_i emissions possible, according to Equation 1, the value of A, LF, EF, TAF, DF, SPM must be determined. These will be calculated in the next steps of this example.

3. STEADY-STATE EMISSION FACTOR FOR NEW EQUIPMENT

The emission rate expressed in **Equation 1**, as New Equipment Emission Factor for pollutant i ($EF_{sub,i}$), represents the emission condition of the engine at the time of emission certification with zero hours of use. This means that all engines certified to some emission standard, according to $Elev$, have had to demonstrate it with measurements of their exhaust emissions and fuel consumption, under a steady-state operation cycle, i.e. in a set of steady-state torque and engine speed operating points. The cycles for such certification are regulated under the ISO DP 8178 standard, and the particular cycle used depends on the type of engine application. For example, for **NRMM**, the C1 and C2 cycles are used as shown in **Table 3**.

At the same time, the emission standards that must be met by the machinery in the emission certification, and that define the technological levels according to $Elev$, have been established in accordance with the engine power range[4]. Therefore, the emission factors are dependent on the $Elev$ and PwR attributes. To represent this $EF_{sub,i}$ value, the reference models use the directly measured certification value (EPA), grouped according to the $Elev$ and PwR sub-segments, or the corresponding emission standard (COPERT), and may also define an intermediate value. The values presented in **Table4** correspond to those defined by the EPA model, which considers the certification values, with the exception of technologies prior to the implementation of emission standards, for which it considers values available from other measurements made. Other EF values by emission level and power range can be found in [CORINAIR 2016].

Table 3: Steady-state operating points - ISO DP 8178 cycle

Torque, %	100	75	50	25	10	100	75	50	25	10	0
RPM	Rated Speed					Intermediate speed					Idle
Non-Road Vehicles (weighting factor of each operating point in the final emissions result)											
Type C1	0.15	0.15	0.15	-	0.10	0.10	0.10	0.10	-	-	0.15
Type C2	-	-	-	0.06	-	0.02	0.05	0.32	0.30	0.10	0.15

HC Crankcase Emission Factors

Crankcase emissions are those emissions that escape from the combustion chamber past the piston rings, into the crankcase. For diesel engines with vented crankcases, the HC emission factor is equal to 2.0% of the exhaust HC emission factor including deterioration. This applies to all Tier 3 and earlier engines. For Tier 4 engines, crankcase emissions are assumed to be zero.

Fraction of $PM_{2.5}$ and Black Carbon (BC)

The emission factors given in **Table4** were used to calculate the PM of 10 microns or less in diameter. [EPA2014b] considers an adjustment of 0.97 that applies to all PM values, to convert to $PM_{2.5}$ emissions (less than 2.5 microns). This means that only a small fraction of 0.03 of the PM is greater than 2.5 microns. To transform the PM to BC emission factors, since the

[4] The emission standards are also dependent on the year of manufacture from and to which a certain emission standard applies. This consideration of which emission standard the engines meet should be part of the NRMM fleet characteristics according to the "Methodological Guide for Developing the NRMM Inventory".

[MOVES2014] methodology does not indicate the BC fraction in the PM, the fractions reported in [CORINAIR 2016] listed in **Table 6** can be used.

Table4 Emission factor for new equipment and fuel consumption

Engine Power [kW]	Emission Standard	BSFC [g/kW- hr]	Emission Factor [g/kW-hr]			
			HC	CO	NOx	PM
>18 A 37	Tier 0	246	2.4138	6.7051	9.2531	1.0728
	Tier 1		0.3740	2.0548	6.3402	0.4545
	Tier 2		0.3740	2.0548	6.3402	0.4545
	Tier 4IA		0.5632	1.8412	5.2367	0.2159
	Tier 4FA		0.1824	0.5471	3.7039	0.0362
	Tier 4FC		0.0241	0.0630	2.9288	0.0013
>37 A 56	Tier 0	246	1.3276	4.6802	9.2531	0.9682
	Tier 1		0.6987	3.1729	7.5084	0.6343
	Tier 2		0.4922	3.1729	6.3028	0.3218
	Tier 4IA		0.2374	1.3115	4.0633	0.1998
	Tier 4FA		0.0992	0.3581	3.7374	0.0322
	Tier 4FC		0.0241	0.0738	2.9744	0.0013
>56 A 75	Tier 0	246	1.3276	4.6802	9.2531	0.9682
	Tier 1		0.6987	3.1729	7.5084	0.6343
	Tier 2		0.4922	3.1729	6.3028	0.3218
	Tier 3B		0.2467	3.1729	4.0231	0.2682
	Tier 4IA		0.1167	0.5257	3.3807	0.1542
	Tier 4IC		0.0094	0.0362	2.6217	0.0094
	Tier 4FA		0.1006	1.7997	4.3905	0.2494
	Tier 4FB		0.0161	0.1354	0.1824	0.0201
	Tier 4FC		0.0000	0.0000	2.7679	0.0094
	Tier 4FD		0.0107	0.0000	0.1220	0.0000
>75 A 130	Tier 0	221	0.9119	3.6208	11.2378	0.5391
	Tier 1		0.4533	1.1627	7.5795	0.3755
	Tier 2		0.4533	1.1627	5.4982	0.2414
	Tier 3		0.2467	1.1627	3.3526	0.2950
	Tier 4IA		0.0469	0.2682	2.6499	0.0443
	Tier 4IB		0.0228	0.3513	2.7209	0.0148
	Tier 4IC		0.0040	0.0121	2.5318	0.0054
	Tier 4ID		0.0094	0.1006	0.3004	0.0000
	Tier 4FB		0.0094	0.0697	0.1931	0.0148
	Tier 4FC		0.0040	0.0054	2.4514	0.0027
	Tier 4FD		0.0134	0.0308	0.1287	0.0013
>130 A 225	Tier 0	221	0.9119	3.6208	11.2378	0.5391
	Tier 1		0.4144	1.0031	7.4789	0.3379
	Tier 2		0.4144	1.0031	5.3641	0.1770
	Tier 3		0.2467	1.0031	3.3526	0.2012
	Tier 4IA		0.1529	2.2020	3.3083	0.1448
	Tier 4IB		0.0107	0.3312	1.4751	0.0148
	Tier 4IC		0.0148	0.0697	1.4966	0.0013
	Tier 4ID		0.0375	0.0000	0.1475	0.0094
	Tier 4FB		0.0107	0.0268	0.1985	0.0121
	Tier 4FC		0.0148	0.2870	1.5462	0.0000
	Tier 4FD		0.0134	0.0201	0.1059	0.0027
>225 to 450	Tier 0	221	0.9119	3.6208	11.2378	0.5391
	Tier 1		0.2722	1.7514	8.0662	0.2695
	Tier 2		0.2240	1.1305	5.8133	0.1770
	Tier 3		0.2240	1.1305	3.3526	0.2012
	Tier 4IA		0.1529	2.2020	3.3083	0.1448

Engine Power [kW]	Emission Standard	BSFC [g/kW- hr]	Emission Factor [g/kW-hr]			
			HC	CO	NOx	PM
	Tier 4IB		0.0107	0.3312	1.4751	0.0148
	Tier 4IC		0.0161	0.0711	1.4952	0.0013
	Tier 4ID		0.0375	0.0000	0.1475	0.0094
	Tier 4FB		0.0107	0.0268	0.1985	0.0121
	Tier 4FC		0.0148	0.2870	1.5462	0.0000
	Tier 4FD		0.0134	0.0201	0.1059	0.0027
>450 a 560	Tier 0	221	0.9119	3.6208	11.2378	0.5391
	Tier 1		0.1971	1.7795	7.8074	0.2950
	Tier 2		0.2240	1.7795	5.4982	0.1770
	Tier 3		0.2240	1.7795	3.3526	0.2012
	Tier 4IA		0.1529	2.2020	3.3083	0.1448
	Tier 4IB		0.0107	0.3312	1.4751	0.0148
	Tier 4IC		0.0161	0.0711	1.4952	0.0013
	Tier 4ID		0.0375	0.0000	0.1475	0.0094
	Tier 4FB		0.0107	0.0268	0.1985	0.0121
	Tier 4FC		0.0148	0.2870	1.5462	0.0000
	Tier 4FD		0.0134	0.0201	0.1059	0.0027

Notes: The original values in HP were transformed by their equivalent in kW (1HP=0.745kW).
Tier 4I = Interim Tier 4; Tier 4F = Final Tier 4; Tier 4/Tier 3 technology types:

Index	DPF	SCR
A	No	No
B	No	Yes
C	Yes	No
D	Yes	Yes

Source: Prepared by the authors, based on [MOVES2014b].

In the case of fleets with imported machinery of different origins, as may be the case of the CALAC+ member countries, the fleet will be made up of at least Tier or Stage technologies. Therefore, an equivalence must be defined between the technological levels of both types of regulation, which in general fortunately exists.

Table 5 shows the equivalencies used in Chile's inventory.

Table 5: Equivalences between EPA Emission Standards and Stage[5]

EPA	Stage
Tier 0	Pre Stage I
Tier 1	Stage I
Tier 2	Stage II
Tier 3	Stage IIIA
Interim Tier 4	Stage IIIB
Tier 4 Final	Stage IV
Tier 4FD	Stage V

Source: From [GEASUR 2014].

Table 6: Black Carbon Fraction in Non-Road Engine PM

Technology	Diesel < 130 kW		Diesel ≥ 130 kW	
	f-BC	+/- (%)	f-BC	+/- (%)
<1981	0.55	10	0.50	20
1981-1990	0.55	10	0.50	20
1991-Stage I	0.55	10	0.50	20
Stage I	0.80	10	0.70	20
Stage II	0.80	10	0.70	20
Stage IIIA	0.80	10	0.70	20
Stage IIIB, not DPF	0.80	50	0.70	20
Stage IIIB, DPF	0.15	50	0.15	20
Stage IV, not DPF	0.80	50	0.70	30
Stage IV, DPF	0.15	50	0.15	30
Stage V	0.15	50	0.15	30

Source: Prepared by the authors, based on [CORINAIR 2016].

CO_2 Emission Factor

The CO_2 emission factor is usually calculated based on the brake specific fuel consumption (BSFC). The equation for calculating this emission factor is presented below:

$$EF_{CO2} = (BSFC - EF_{HC}) \cdot 0.87 \cdot (44/12)$$

Equation 2

Where:

EF_{CO2} CO2 emission factor in [g/kW-hr].

$BSFC$ Fuel consumption per unit of work delivered by the engine to the axle (Brake Specific Fuel Consumption), in [g/kW-hr], calculated during the certification cycle

EF_{HC} HC emission factor in [g/kW-hr] (see Table4 for values).

[5] In the case of Stage V, in force in Europe since 2018, there is no equivalence with Tier, since it included the particle number limit not considered by the EPA. However, for the purposes of preparing the emissions inventory, the emission factors corresponding to Tier 4FD must be considered.

0.87 Mass fraction of carbon in diesel.

44/12 Ratio of the mass of CO_2 and its mass of carbon.

In any case to obtain the aggregate emission values expressed in **Equation** 1, such as E_{CO2} and E_{SO2}, the transient adjustment and deterioration factors must be applied to $BSFC$ and EF_{HC} previously and where appropriate.

EXAMPLE 1: STEP 2

Continuing with our example, we can now incorporate, from the values given in Table4, the emission factor of each sub-segment, according to PwR and $Elev$, as follows:

sub	*Sector*	*Etyp*	*PwR [kW]*	*Year*	*Age [years]*	*N_{sub}*	*Pw_{sub}*	*Elev*	*$EF_{sub, pm}$ [g/kW-hr]*
1	Construction	Excavator	130 ≤ kW < 225	2012	4	47	136,4	Tier 3	0,2012
2	Construction	Excavator	130 ≤ kW < 225	2009	7	25	145,3	Tier 2	0,1770
3	Construction	Excavator	75 ≤ kW < 130	2009	7	12	122,7	Tier 2	0.2414
4	Construction	Motor grader	130 ≤ kW < 225	2012	4	50	184,3	Tier 3	0,2012
5	Construction	Motor grader	75 ≤ kW < 130	2012	4	38	89,5	Tier 3	0,2950

Particularly, the Particulate Material EF has been incorporated. For the two power ranges in the example, the emission factor for PM is increased from Tier 2 to Tier 3. This is because, on the one hand, these standards do not reduce the limit for this pollutant, and on the other, the emission factors used correspond to emission certification values. Therefore, they are generally lower than the limit and have room to increase, without exceeding the limit. In practice it is likely that, if we consider the overlap between NOx and PM, a reduction in the NOx limit for the Tier 3 standard was partly resolved by increasing PM emissions.

4. ACTIVITY

The activity of the non-road machinery fleet is an important parameter in the calculation of emissions and generally corresponds to local conditions of machinery use. However, in the absence of local statistics on this parameter, the activities reported in [EPA2008] can be considered. As shown in **Table 7**, the activity is considered to be a function of the equipment type.

Table 7 Activity by equipment type.

Equipment type	A [hrs/year]
Agricultural and forestry tractors	475
Asphalt paver	821
Backhoe	1135
Bulldozer	899
Drill	466
Dumper	566
Excavators	1092
Fork crane	1700
Front loader	761
Harvester	110
Log forwarder	1276
Mini-excavators	818
Motor graders	962
Non-agricultural tractors	1135
Off road trucks	1641
Other agricultural equipment	381
Other construction equipment	606
Other underground mining equipment	1533
Rollers	760
Rough terrain forklift	662
Skid-steer loaders	818
Snowplough	40
Sweepers	1220
Telescopic boom lift	384
Telescopic crane	990
Telescopic handler	878
Trenchers	593

Source: Prepared by the authors based on [EPA2008].

There is a history that indicates that the Activity may be decreasing with the age of the equipment. In this regard, [FOEN2015] proposes, for the specific case of Switzerland, a correction by age of the fleet. However, since there is no local information on this matter, this guide adopts the EPA's criterion of not making age corrections.

EXAMPLE 1: STEP 3

Next, we will incorporate the Activity provided in Table 7 to each sub-segment of the example (according to *Etyp*) as follows:

sub	*Etyp*	*PwR [kW]*	*Year*	*Age [years]*	N_{sub}	Pw_{sub}	*Elev*	$EF_{sub,pm}$ *[g/kW-hr]*	*A [hr/year]*
1	Excavator	130 ≤ kW < 225	2012	4	47	136,4	Tier 3	0,2012	1092
2	Excavator	130 ≤ kW < 225	2009	7	25	145,3	Tier 2	0,1770	1092
3	Excavator	75 ≤ kW < 130	2009	7	12	122,7	Tier 2	0.2414	1092
4	Motor grader	130 ≤ kW < 225	2012	4	50	184,3	Tier 3	0,2012	962
5	Motor grader	75 ≤ kW < 130	2012	4	38	89,5	Tier 3	0,2950	962

5. LOAD FACTOR

The Load Factor (LF) represents the fraction of the rated engine power at which the machinery typically operates. This means that the engine is seldom forced to work up to its maximum power (rated power) and is usually operating at a fraction of that power. The total energy consumption of the fleet expressed in [kW-h] is considered to be equal to the total population (N) multiplied by the average power of use ($Pw \cdot LF$), which is in turn multiplied by the hours of use of each unit or activity (A). The load factor is the fraction of the energy consumed by the machinery population in relation to its use under full load, as indicated in the following expression,

$$\boldsymbol{W = \sum_{sub} N_{sub} \cdot A_{sub} \cdot Pw_{sub} \cdot LF_{sub}}$$

Equation 3

where the sub-index *sub* designates the fleet belonging to the sub-segment sub, which has identical values for activity, power range and load factor.

The load factor is a highly variable parameter as it depends on the actual operating cycle of the machinery, which in turn depends on the operator and the type of work to be carried out. The EPA provides values for LF according to the equipment type, for the conditions of use in the United States. **Table 8** shows these values for the equipment types considered in this Guide.

Table 8 Load factor.

Equipment type	Load factor
Agricultural and forestry tractors	0.59
Asphalt paver	0.59
Backhoe	0.21
Bulldozer	0.59
Drill	0.43
Dumper	0.21
Excavators	0.59
Fork crane	0.59
Front loader	0.59
Harvester	0.59
Log forwarder	0.59
Mini-excavators	0.21
Motor graders	0.59
Non-agricultural tractors	0.21
Off road trucks	0.59
Other agricultural equipment	0.59
Other construction equipment	0.59
Other underground mining equipment	0.21
Rollers	0.59
Rough terrain forklift	0.59
Skid-steer loaders	0.21
Snowplough	0.34
Sweepers	0.43
Telescopic boom lift	0.21
Telescopic crane	0.43
Telescopic handler	0.43
Trenchers	0.59

Source: Prepared by the authors based on [EPA2008].

EXAMPLE 1: STEP 4

The Load Factor is incorporated into each sub-segment according toTable 8, and in accordance with the equipment type ($Etyp$). Similarly, both equipment types have the same value for LF:

sub	Etyp	PwR [kW]	Year	Age [years]	N_{sub}	Pw_{sub}	Elev	$EF_{sub,pm}$ [g/kW-hr]	A [hr/year]	LF_{sub}
1	Excavator	130 ≤ kW < 225	2012	4	47	136,4	Tier 3	0,2012	1092	0,59
2	Excavator	130 ≤ kW < 225	2009	7	25	145,3	Tier 2	0,1770	1092	0,59
3	Excavator	75 ≤ kW < 130	2009	7	12	122,7	Tier 2	0.2414	1092	0,59
4	Motor grader	130 ≤ kW < 225	2012	4	50	184,3	Tier 3	0,2012	962	0,59
5	Motor grader	75 ≤ kW < 130	2012	4	38	89,5	Tier 3	0,2950	962	0,59

6. DETERIORATION FACTOR

Deterioration is the increase in engine emissions that occurs with use and is represented by a factor ($DF_{sub,i}$), which corrects the zero-hour emission factor ($EF_{sub,i}$) of the engine, for the sub-segment sub and pollutant i.

For this emission model, the deterioration factor is represented as follows, according to [MOVES2014b]:

$$DF_{sub,i} = 1 + A_{sub,i} \cdot (Age\ Factor_{sub})^{b};\ \ If\ Age\ Factor_{sub} \leq 1$$

Equation 4

$$DF_{sub,i} = 1 + A_{sub,i}\ ;\ If\ Age\ Factor_{sub} > 1$$

Equation 5

Where:

$A_{sub,i}$ — For each pollutant, ***i*** is a constant defined for all equipment belonging to the sub-segment with the same emission standard ***Elev.*** In percentage terms (A*100), this constant represents the maximum percentage increase in emissions due to deterioration, at the end of the median life of the engine.

b — Constant, for diesel vehicles it is considered to be linear deterioration in time of use, so $b=1$.

$Age\ Factor_{sub}$ — The fraction of the median life in which all the units belonging to the same sub-segment are found. It is calculated as the quotient between the accumulated hours of engine operation under full load (rated power) and the median life[6] of the engine.

$$Age\ Factor_{sub} = \frac{(Age \cdot A_{sub} \cdot LF_{sub})}{Median\ Life_{sub}}$$

Equation 6

The Age Factor is the fraction of hours of use equivalent to full load, accumulated by the subsegment of equipment with the same age, annual activity and load factor, divided by the corresponding median life.

The EPA has values for the A and $Median\ Life$ factors, which depend on pollutant i and the $Elev$ emission standard, for the former, and the PwR engine power range, for the latter. The values of these factors are presented in

Table9 and **Table10 Median** *life*.

Table9 Values of coefficient A

Pollutant	Tier 0	Tier 1	Tier 2	Tier 3+
HC	0.047	0.036	0.034	0.027
CO	0.185	0.101	0.101	0.151
NOx	0.024	0.024	0.009	0.008
MP	0.473	0.473	0.473	0.473

Source: [MOVES2014b]

Table10 *Median life* according to diesel engine power

Power (kW)	Median Life (Hrs)
>19 - 37	2.500
>37 - 75	4.667
>75 - 130	4.667
>130 - 225	4.667
>225 - 450	7.000
>450 - 560	7.000
> 560	7.000

Source: EPA2008]

[6] Median life is defined as the period of time in hours of use under full engine load (load factor=1 or 100%), for which 50% of the machinery is scrapped. For more information see "METHODOLOGICAL GUIDE FOR DEVELOPING THE NON-ROAD MOBILE MACHINERY INVENTORY".

EXAMPLE 1: STEP 5

To calculate the Deterioration Factor (DF), according to Equation 4, we must previously calculate the A factor (Table9) and the $Age\ Factor$ (Equation 6). In turn, to calculate the $Age\ Factor$, we must assign the $Median\ Life$ value according to Table10 $Median\ life$, as follows:

sub	PwR [kW]	Age [years]	N_{sub}	Pw_{sub}	Elev	$EF_{sub,pm}$ [g/kW-hr]	A [hr/year]	LF_{sub}	$A_{sub,pm}$	Median Life [hr]	Age Factor	$DF_{sub,pm}$
1	130 ≤ kW < 225	4	47	136,4	Tier 3	0,2012	1092	0,59	0,473	4.667	0,552	1,261
2	130 ≤ kW < 225	7	25	145,3	Tier 2	0,1770	1092	0,59	0,473	4.667	0,966	1,457
3	75 ≤ kW < 130	7	12	122,7	Tier 2	0.2414	1092	0,59	0,473	4.667	0,966	1,457
4	130 ≤ kW < 225	4	50	184,3	Tier 3	0,2012	962	0,59	0,473	4.667	0,486	1,230
5	75 ≤ kW < 130	4	38	89,5	Tier 3	0,2950	962	0,59	0,473	4.667	0,486	1,230

Whereas for all cases the $Age\ Factor$ < 1, Equation 4 was considered for the calculation of $DF_{sub.}$

7. TRANSIENT ADJUSTMENT FACTOR

As stated above the emission factors and specific fuel consumption (BSFC) for non-road machinery engines are obtained from steady-state testing during the emissions certification process. However, steady-state operation is not always representative of actual machinery operating conditions. The differences are due to engine load, speed and transient demands. The EPA applies "transient adjustment factors" ($TAFs$) to the steady-state emission factors described above (EF_i). The TAF applies to emission factors for *Tier 0*, *Tier 1*, *Tier 2* and *Tier 3* emission standards. For *Tier 4*, the certification emission factors already include measurement under a Non Road Transient Cycle (NRTC), so a TAF of 1 applies in this case.

Since the TAF depends on the engine operating condition and the engine technology, the EPA provides values for this factor by equipment type ($Etyp$), emission standard ($Elev$) and pollutant i as can be seen in **Table 11 Transient Adjustment Factor by Type**.

Table 11 Transient Adjustment Factor by Type

	HC	CO	NOx		PM		BSFC
Typology	T0-T3	T0-T3	T0-T2	T3	T0-T2	T3	T0-T3
Agricultural tractors	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Asphalt paver	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Backhoe (10)	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Bulldozer (1)	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Drilling machine / Drill	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dumper	2.29	2.57	1.10	1.21	1.97	2.37	1.18
Excavators	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Forklift truck	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Front loader (3)	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Harvester (4)	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Log forwarder (2)	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Mini-excavator (7)	2.29	2.57	1.1	1.21	1.97	2.37	1.18
Motor graders	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Non-agricultural tractor (10)	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Off road trucks	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Other agricultural equipment	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Other construction equipment	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Other underground mining equipment	2.29	2.57	1.10	1.21	1.97	2.37	1.18
Rollers	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Rough terrain forklift (5)	1.05	1.53	0.95	1.04	1.23	1.47	1.01
Skid-steer loaders (7)	2.29	2.57	1.1	1.21	1.97	2.37	1.18
Snowplough (9)	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sweepers / Scrubbers	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Telescopic boom lift (8)	2.29	2.57	1.10	1.21	1.97	2.37	1.18
Telescopic cranes	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Telescopic handler (6)	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Trencher (11)	1.05	1.53	0.95	1.04	1.23	1.47	1.01

Notes: T0=No Standard; T0-T3=Tier0 to Tier3; T0-T2: No Standard to Tier2, etc. (1) Certified with the term "Rubber Tire Dozers". (2) Certified with the term "Logging Equip Fell/Bunch/Skidders". (3) Certified as "Rubber Tire Loaders". (4) Certified as "Swather". (5) Certified as "Rough Terrain Forklifts". (6) Certified as "Other General Industrial Equipment". (7) Certified as 'Skid Steer Loaders'. (8) Certified as 'Aerial Lifts'. (9) Certified as 'Snowmobiles'. (10) Certified as 'Tractors/Loaders/Backhoes'. (11) Certified as 'Trenchers'.

Source: Prepared by the authors based on [MOVES2014b].

EXAMPLE 1: STEP 6

To calculate the Transient Adjustment Factor (TAF) for Particulate Matter (PM), we must consider the values in **Table 11 Transient Adjustment Factor by Type**, according to $Etyp$ and $Elev$, as shown below:

sub	*Etyp*	N_{sub}	Pw_{sub}	*Elev*	$EF_{sub,pm}$ [g/kW-hr]	*A* [hr/year]	LF_{sub}	$DF_{sub,pm}$	$TAF_{sub,pm}$
1	Excavator	47	136,4	Tier 3	0,2012	1092	0,59	1,261	1,47
2	Excavator	25	145,3	Tier 2	0,1770	1092	0,59	1,457	1,23
3	Excavator	12	122,7	Tier 2	0.2414	1092	0,59	1,457	1,23
4	Motor grader	50	184,3	Tier 3	0,2012	962	0,59	1,230	1,47
5	Motor grader	38	89,5	Tier 3	0,2950	962	0,59	1,230	1,47

8. SULPHUR ADJUSTMENT IN FUEL

This additive factor adjusts the EF_i value for the PM pollutant by varying the sulphur content of the commercial fuel that the equipment uses during its field operation from the sulphur content of the certification fuel that is used to obtain the EF_i values of the new equipment. Sulphur contributes to the measurement of PM mass concentration since a fraction (soxcnv) of the sulphur consumed as part of the fuel in the engine is transformed into PM, in the form of sulphates, which weigh the same as the sulphur[7]. Thus, the sulphur content adjustment (SPM) is expressed as follows:

$$SPM = BSFC \cdot TAF \cdot 7.0 \cdot soxcnv \cdot 0.01 \cdot (soxbas - soxdsl)$$

Equation 7

Where:

$BSFC$: Brake Fuel Consumption, [g/kW-hr]

TAF : Transient adjustment factor for BSFC specific consumption

7.0 : Grams of PM sulphate / grams of sulphur in PM

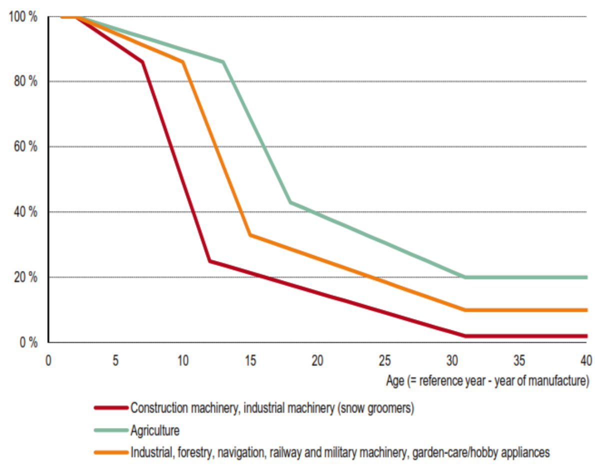
Soxcnv[8] : Grams of sulphur in PM / grams of sulphur in consumed fuel

0.01 : Conversion from percentage to fraction

Soxbas[9] : Sulphur content used in certification fuel [%].

Soxdsl[10] : Sulphur content of the fuel [%].

Figure 1 Annual reduction in machine operating hours according to age.



Source: FOEN 2015

[7] [MOVES 2014B], Chapter 8: Sulfur Adjustment for PM Emissions.
[8] Soxcnv = 0.02247 (Tier 0 to Tier 4A); Soxcnv = 0.3 (Tier 4) MOVES2014b]
[9] Soxbas =0.33 % (Tier 0 a Tier 1); Soxbas = 0.2% (Tier 2 a Tier 3); Soxbas = 0.05 (Tier 4Interim); Soxbas = 0.0015 (Tier 4). [MOVES2014b] 4.1 Default Certification Sulfur Level.
[10] Example, for Chile Soxdsl = 0.0015 (Metropolitan Region); Soxdsl = 0.005 (other regions)

EXAMPLE 1: STEP 7

In this example, the certification fuel is considered to have a sulphur content of 2000 ppm (Soxbas=0.2%), for Tier 2 and Tier 3 certifications. Whereas for commercial diesel used in the operation of the fleet, the sulphur content is 15 ppm (Soxdsl=0.0015%). In turn, for Tier 2 and Tier 3 technologies, such as those in the example, the *Soxcnv* value is 0.02247 (see note 8). Considering the *BSFC* values of Table4, according to the power range (*PwR*), the emission standard (*Elev)* and the transient adjustment factor of Table 11 **Transient Adjustment Factor by Type** (by *Etyp* and *Elev of* each subsegment), it is possible to calculate *SPM* from Equation 7, as follows:

sub	Etyp	N_{sub}	PwR [kW]	Elev	BSFC [g/kW]	TAF_{BSFC}	$SPM_{sub,pm}$
1	Excavator	47	130 ≤ kW < 225	Tier 3	221	1,01	0,070
2	Excavator	25	130 ≤ kW < 225	Tier 2	221	1,01	0,070
3	Excavator	12	75 ≤ kW < 130	Tier 2	221	1,01	0,070
4	Motor grader	50	130 ≤ kW < 225	Tier 3	221	1,01	0,070
5	Motor grader	38	75 ≤ kW < 130	Tier 3	221	1,01	0,070

EXAMPLE 1: STEP 8

With the calculation of *SPM* in STEP 7 of the example, we have completed the determination of all the variables of Equation 1, which allows the calculation of the emissions for each sub-segment from *sub=1* to 5. In the following table we will complete this calculation by combining all the results of the previous steps of the example for each sub-segment, calculating $E_{sub,pm}$ and the sum for *sub*=1 to 5:

sub	N_{sub}	Pw_{sub}	$EF_{sub,pm}$ [g/kW-hr]	A [hr/year]	LF_{sub}	$DF_{sub,pm}$	$TAF_{sub,pm}$	$SPM_{sub,pm}$	$E_{sub,pm}$ [g/year]	$E_{sub,pm}$ [g/year]
1	47	136,4	0,2012	1092	0,59	1,261	1,47	0,070	1.252.605	1,253
2	25	145,3	0,1770	1092	0,59	1,457	1,23	0,070	579.308	0,579
3	12	122,7	0.2414	1092	0,59	1,457	1,23	0,070	344.308	0,344
4	50	184,3	0,2012	962	0,59	1,230	1,47	0,070	1.538.639	1,539
5	38	89,5	0,2950	962	0,59	1,230	1,47	0,070	895.177	0,895
									TOTAL	4,610

The expression of emissions in tons is the product of an arrangement of units by multiplying the grams by 10^{-6}.

9. PROJECTION OF NON-ROAD MACHINERY POPULATION

According to the methodology presented so far, in order to project the inventory of future emissions from non-road machinery, the activity and the corresponding emission factors must be projected in accordance with Equation 1. As for the projection of future emission factors, these will depend on the future emission standards defined by the legislation in each country. Therefore, this component of the projection corresponds to governments. Given the above, the projection of the activity is still pending, for which the growth of the machinery population is used as a direct indicator, assuming that the activities by equipment type, as defined in Table 7, are constant over time.

For population growth projections, the EPA[11] methodology has chosen market trends based on historical population growth for Non-Road Equipment.

EXAMPLE 2

For this example, we have historical data on imports and we use the projected imports as an indicator of the activity growth (considering that all imported machinery is sold in that year, given the costs of maintaining stock). As an example, Table 12 shows the amount of machinery imported per year from 2002 to 2013, according to the destination.

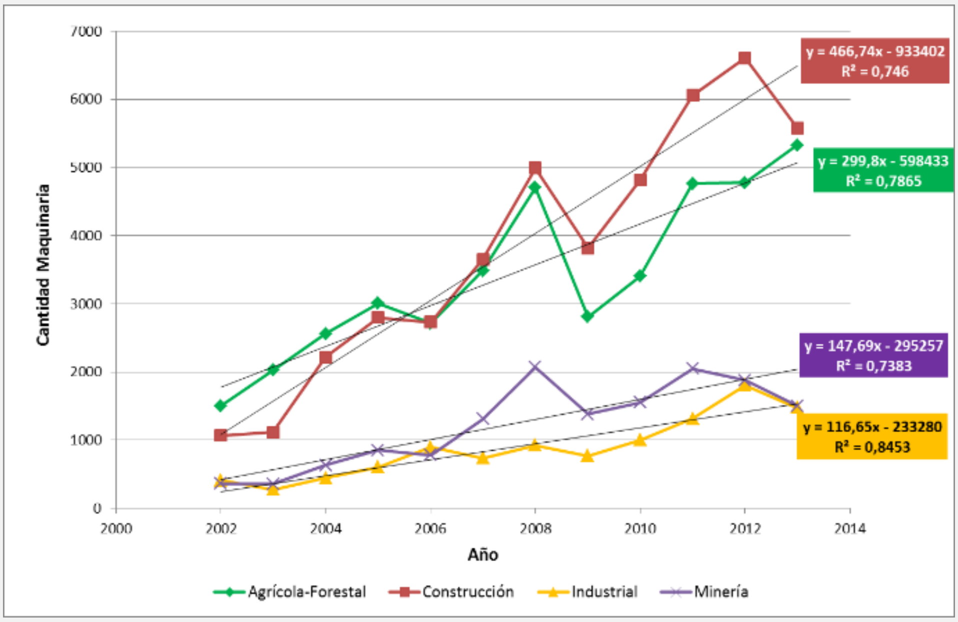
Table 12 Quantity of machinery imported by year and sector

Year of import	Agricultural-Forestry	Construction	Industrial	Mining
2002	1.501	1.070	414	362
2003	2.026	1.118	275	356
2004	2.559	2.217	448	633
2005	3.008	2.799	603	854
2006	2.715	2.732	895	784
2007	3.488	3.650	735	1.312
2008	4.706	4.987	923	2.071
2009	2.825	3.863	1.412	515
2010	3.406	4.812	1001	1.553
2011	4.762	6.057	1.316	2.050
2012	4.776	6.602	1.808	1.880
2013	5.327	5.580	1.476	1.504

According to the [EPA 2002] methodology, a linear regression is used to project the future population from historical data. To get an overview and see if there is a trend in growth, they are shown in the data with linear regression, to see the adjustment of the data.

Figure 2 Quantity of machinery according to sector and year of import With linear regression.

[11] Non-Road Growth Engine Estimations, Report No. NR-008, 2002. [EPA 2002]



Based on the adjusted linear regressions obtained, the projection of the machinery for the different sectors is made over a 10-year horizon; i.e. an increase in the fleet from 2014 to 2025 (see results in **Table 13**).

Table 13 Projected sales of non-road machinery, by sector.

Year of import	Agricultural-Forestry	Construction	Industrial	Mining
2014	5.364	6.612	1.653	2.191
2015	5.664	7.079	1.770	2.338
2016	5.964	7.546	1.886	2.486
2017	6.264	8.013	2.003	2.634
2018	6.563	8.479	2.120	2.781
2019	6.863	8.946	2.236	2.929
2020	7.163	9.413	2.353	3.077
2021	7.463	9.880	2.470	3.224
2022	7.763	10.346	2.586	3.372
2023	8.062	10.813	2.703	3.520
2024	8.362	11.280	2.820	3.668
2025	8.662	11.747	2.936	3.815

The forecasts presented in the table above are distributed according to their power range, sector and type. The share of each equipment in the final amount obtained in the baseline is calculated and will be distributed according to its weight in the fleet. The following distribution tables will be used particularly for the construction sector:

Power range	Bulldozer	Front loader	Excavator	Skid-steer loader	Backhoe	Roller	Grand total
19 ≤ kW < 37	0,02%	0,15%	0,10%	2,52%	0,05%	0,72%	3,56%
37 ≤ kW < 56	0,01%	0,40%	0,32%	12,67%	3,31%	4,23%	20,95%
56 ≤ kW < 75	0,06%	0,58%	2,16%	4,26%	30,07%	0,37%	37,49%
75 ≤ kW < 130	0,51%	4,74%	10,47%	0,02%	1,57%	4,07%	21,38%
130 ≤ kW < 225	0,51%	6,45%	3,51%	0,01%	0,06%	0,17%	10,71%
225 ≤ kW < 450	2,71%	2,44%	0,31%	0,00%	0,00%	0,01%	5,46%

450 ≤ kW < 560	0,42%	0,00%	0,00%	0,00%	0,00%	0,03%	0,45%
Totals	4,24%	14,76%	16,87%	19,47%	35,06%	9,61%	100,00%

Considering the fleet projected in the construction sector for 2020, for 9,413 machines imported in this area, we have the following fleet distribution, in quantities:

Power range	Bulldozer	Front loader	Excavator	Skid-steer loader	Backhoe	Roller	Grand total
19 ≤ kW < 37	2	14	10	237	4	68	335
37 ≤ kW < 56	1	38	30	1.193	312	398	1.972
56 ≤ kW < 75	6	54	203	401	2.830	35	3.529
75 ≤ kW < 130	48	446	985	2	148	383	2.012
130 ≤ kW < 225	48	607	330	1	6	16	1.008
225 ≤ kW < 450	255	229	29	-	-	1	514
450 ≤ kW < 560	39	-	-	-	-	3	43
Totals	399	1.389	1.588	1.833	3.300	904	9.413

10. REFERENCES

[MOVES2014b] “Exhaust and Crankcase Emission Factors for Nonroad Compression-Ignition Engines in MOVES2014b”, EPA420-R-18-009, July 2018.

[EPA2008] “Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling”, EPA-420-R-10-016 NR-005d July 2010.

[EPA 2005-A] “User’s Guide for the Final NONROAD2005 Model”, EPA420-R-05-013 December 2005.

[EPA 2005-B] “Calculation of Age Distributions in the Nonroad Model: Growth and Scrappage”, EPA420-R-05-018 December 2005 NR-007c.

[EPA 2005-C] “Geographic Allocation of Nonroad Engine Population Data to the State and County Level”, EPA420-R-05-021 December 2005 NR-014d

[CORINAIR 2016] “Non-road mobile sources and machinery”, Guidebook 2016.

[GEASUR 2014] " Análisis técnico-económico de la aplicación de una nueva norma de emisión para motores de maquinaria fuera de ruta a nivel país", study carried out by Geasur in 2014.

[Winter and Nielse 2006] “Fuel use and emissions from non-road machinery in Denmark from 1985–2004 – and projections from 2005-2030”, Environmental Project No. 1092 2006 Miljøprojekt.

[FOEN 2015] “Non-road energy consumption and pollutant emissions”, Bern 2015

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