

Calculating emissions for Dutch NRMM fleet

EMMA – MEPHISTO model

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1 Introduction

This report aims to provide a comprehensive documentation of the EMMA – MEPHISTO¹ model, developed by TNO to calculate emissions of non-road mobile machinery (NRMM) in the Netherlands. The EMMA model was initially developed in 2009 by TNO to calculate historic NRMM emissions for the Dutch national emission inventory (Hulskotte & Verbeek, 2009). The MEPHISTO model is a later extension of the EMMA model that allows making projections of future NRMM emissions given certain scenarios. The MEPHISTO model is primarily used by the Netherlands Environmental Assessment Agency (PBL) as the basis for NRMM emission projections in the Dutch Climate and Energy Outlook (KEV). In this report these models will be treated as one combined model.

The EMMA – MEPHISTO model performs a simulation of the complete NRMM fleet in the Netherlands, including machinery such as tractors, excavators, chainsaws, lawnmowers, forklift trucks, etc. For every year in the period 1990 – 2050, the model derives a complete fleet including the number of machines by type, engine type and power, construction year, and emission classification. Based on the annual fleet, the fuel consumption and emissions are calculated using data driven assumptions on the annual active hours, the engine load profiles, and representative fuel- and emission factors by engine type. While for the historic years, the fleet is derived from a combination of collected machinery sales data, vehicle registrations and machine survival rates, for the future years, the fleet composition follows from a straightforward extrapolation. The user should provide assumptions on the relative growth or decline in the NRMM activity in a number of subsectors (construction, agriculture, residential, commercial/institutional, industry, ground support equipment, container handling) to scale the model output.

The EMMA – MEPHISTO model is optimized to be able to use actual monitoring data from engine telematics and continuous emission measurements of machine tailpipes. While emission measurements of NRMM are relatively scarce compared to, e.g., passenger cars, TNO has completed numerous measurement campaigns in real-world circumstances over the past decade on various machinery models to arrive at realistic emission factors that often deviate from the legal emission limit values.

As the share of battery- and cable-electric NRMM is increasing, the model also performs an extrapolation of the shares of electric NRMM by machine type. This calculation is expected to be improved further in the future.

Considerable uncertainty in the results remain, due to limited availability of public data on machinery sales, fleet composition and usage, real-world emission factors and more. Therefore, the model is under constant development, with regular improvements being implemented in input data and model parameters. Furthermore, opportunities to perform model validation are continuously explored to improve completeness, accuracy and consistency.

The report provides a brief history of the model in chapter 2. The methodology is described in detail in chapter 3. Chapter 4 highlights some model outputs. Finally, chapter 5 discusses the model uncertainties, options for validation and ideas for future model improvements.

¹ EMMA: Emissiemodel Mobiele Machines gebaseerd op machineverkoop in combinatie met brandstof Afzet
MEPHISTO: Machinery Emissions Prognosis Helped by Information on Sales of Technology and Oils

2 Model history

The EMMA model was first developed in 2009, in cooperation with several branch organizations representing sectors in which mobile machinery is used, sold or hired-out (see Hulskotte & Verbeek, 2009). Since then, there have been many updates, improvements and extensions to the model. Over time, missing machinery types and sectors have been added to the model, such as those used in container handling (see Dellaert, 2016). Furthermore, emission factors have been improved and the calculation method for fuel use and emissions has been made more sophisticated. Finally, the EMMA model was merged with the MEPHISTO model to allow generating emission projections.

These improvements have been described annually in the national reporting of greenhouse gases (National Inventory Report, NIR) and air pollutants (Informative Inventory Report, IIR). Furthermore, an overview of the then current methodology has been published each year in the methodological report (latest version is Geilenkirchen et al., 2023) of the Taskforce Transportation of the Dutch PRTR (Pollutant Release and Transfer Register). Recently, a user manual for the MEPHISTO model has been published, describing the steps to run the model, together with some background information on the model and calculations (Dellaert, 2022).

Figure 1 below shows a comparison between the original EMMA model from 2009 and the current version in terms of modelled NRMM diesel consumption and NOx emission totals. As the figure shows, the model updates have led to modelling significantly higher fuel consumption and emissions. In section 5.2.1, the diesel consumption totals from the current model are compared to historic fuel sales statistics.

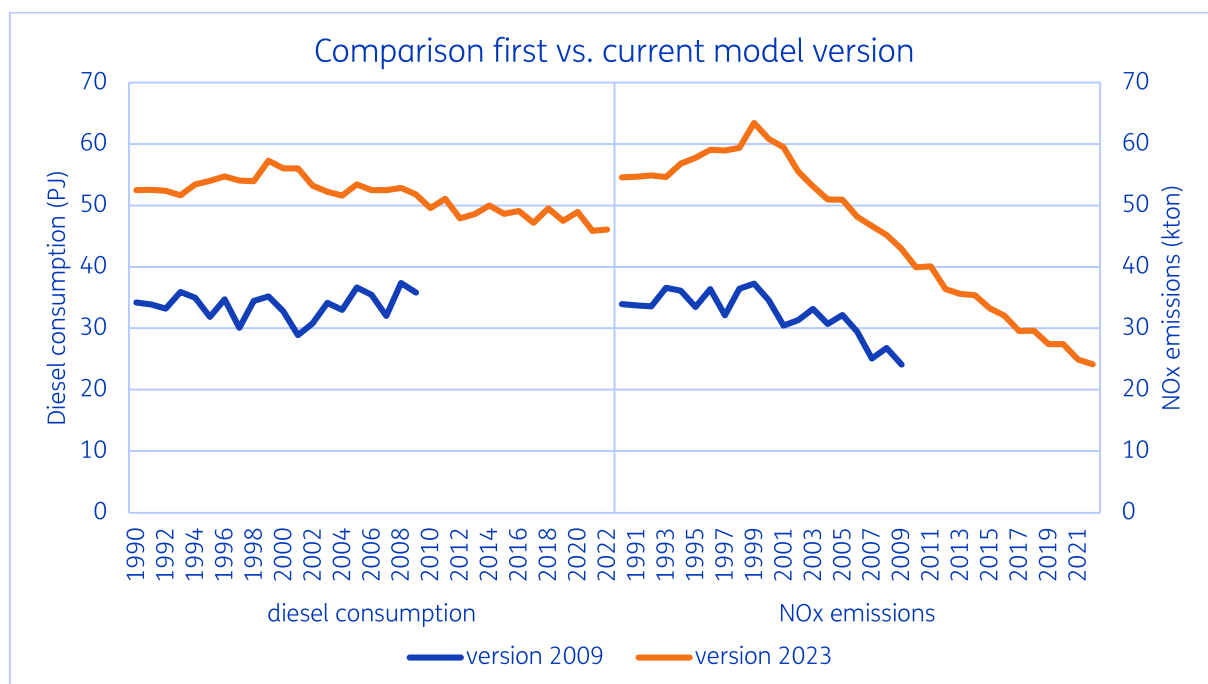


Figure 1: Comparison first vs. current model version: NRMM diesel consumption (left) and NOx emissions (right)

3 Methodology

3.1 Overview

The purpose of the EMMA-MEPHISTO model is twofold:

- › To calculate NRMM emissions by sector for the period of 1990 up to the previous calendar year, using a consistent, comprehensive and accurate methodology.
- › To project NRMM emissions by sector from the current year up to 2050, based on user-defined scenarios of activity levels by sector.

Figure 2 on the next page outlines the data and processing flow of the EMMA-MEPHISTO model. For practical purposes, the model is split into two parts:

- › In part 1, data from a number of sources are combined to compile an inventory of annual introduction of new machinery into the Dutch fleet. These could be newly manufactured machines sold in the Netherlands, or used machinery imported to the Netherlands.
- › In part 2, the annual introduction of machinery is used to model the active machinery fleet for every reporting year. From the modelled active fleet, the fuel consumption and exhaust emissions are calculated. There are various steps of correcting/scaling the initial results. The final step is to apply the user-defined projection factors to generate a projection of fuel consumption and emissions from the Dutch NRMM fleet up to 2050.

In the figure, the orange boxes represent model parameters, discussed in section 3.2. The yellow boxes represent input data, discussed in section 3.3. The blue boxes represent calculation/processing steps, described in section 3.4. The red box represents the projections described in section 3.5. The green rounded boxes represent intermediate and final model outputs, some examples of which are visualized in chapter 4.

Input data that underly some of the model parameters, such as engine telematics data and emissions measurements, are not shown in the overview. More information on how these model parameters were derived is included in section 3.2.

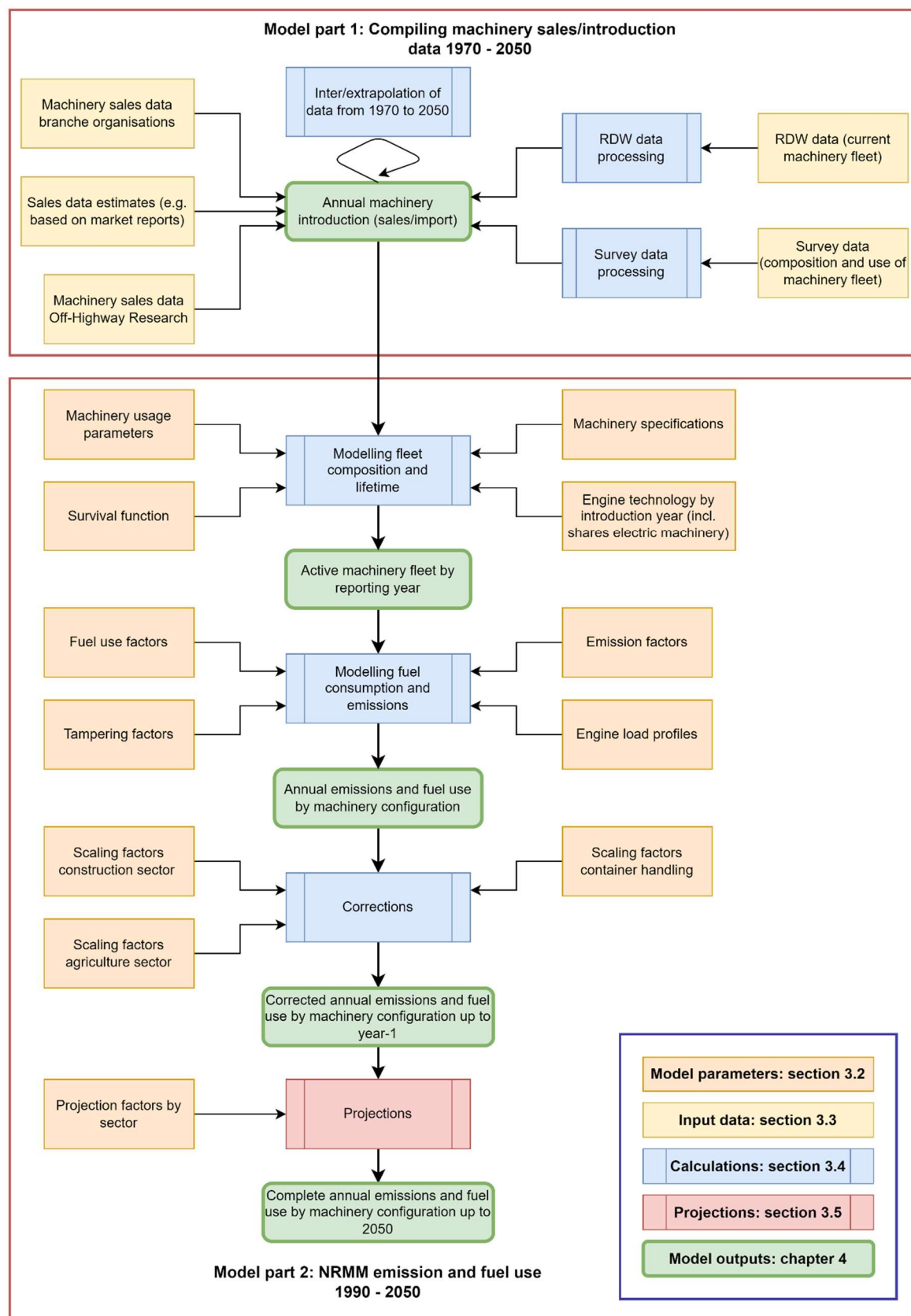


Figure 2: EMMA-MEPHISTO model overview

3.2 Model parameters

3.2.1 Machinery specifications

The model currently distinguishes 65 machinery types, with a total of 405 unique configurations. A unique configuration exists of a specific machinery type, engine type, typical engine power rating and engine technology level (emission class). The engine type prescribes the fuel type. For each unique configuration, representative values for the usage statistics have been defined (see section 3.2.2).

3.2.1.1 Engine type

The model includes 6 engine types as shown in Table 1 below.

Table 1: Engine types

Engine type	Fuel type
Petrol - 2-stroke	Petrol
Petrol - 4-stroke	Petrol
Diesel	Diesel
LPG	LPG
Cable electric	n/a
Battery electric	n/a

3.2.1.2 Engine power

The rated engine power is expressed in kilowatts (kW). For each engine type, the relevant power ranges as they are referred to in EU (emission) regulation are shown in Table 2 below. For petrol engines, the engine displacement is considered instead of the engine power.

Table 2: Engine power categories

Category	EU group*	Model group
Diesel engines	< 19 kW	< 19 kW
	19-37 kW	19 ≤ kW < 37
	37-56 kW	37 ≤ kW < 56
	56-75 kW	56 ≤ kW < 75
	75-130 kW	75 ≤ kW < 130
	130-560 kW	130 ≤ kW < 300
	130-560 kW	300 ≤ kW < 560
	560-1000 kW ²	560 ≤ kW < 1000 kW
Petrol handheld 2-stroke and 4-stroke	≥ 1000 kW	1000 ≤ kW
	SH1	< 20 cc
	SH2	20 ≤ cc < 50
Petrol non-handheld 2-stroke and 4-stroke	SH3	50 ≤ cc
	SN1	< 66 cc
	SN2	66 ≤ cc < 100
	SN3	100 ≤ cc < 225
	SN4	225 ≤ cc

² The model distinguishes between 560-1000 kW and > 1000 kW diesel engines, although this distinction does not exist in the legislation

LPG	SN4	LPG < 56 kW
	SN4	LPG 56 ≤ kW < 130
	SN4	LPG 130 ≤ kW < 560
	SN4	LPG 560 ≤ kW

* categories as referred to in EU emission legislation

For each machinery type, the machine fleet is distributed over these power categories based on sales and registration data. For each machine type/power category combination, a representative engine power value has been derived to be used as default. This typically represents the rated power of a common machine brand/model in the specific category.

3.2.1.3 Engine technology level

Engine technology level refers here to the environmental performance of the NRMM engines. The environmental performance is governed by EU regulation, specifically Directive 97/68/EC³ including its five amendments, and Regulation 2016/1628⁴, superseding the previous regulation. These regulations have introduced increasingly stringent emission standards named STAGE I – STAGE V. Regulated pollutants include NO_x, HC (hydrocarbons), CO, PM (particulate matter) and, from STAGE V onwards, PN (particle number). The standards have been typically defined by engine power category and engine type, and are expressed as emission limit values in grams of pollutant per kWh generated by the engine. The implementation dates differ between engine power categories. An up-to-date overview of the emission limit values can be found on the website of Dieselnets (2023).

While the legislation specifies the minimum emission performance under defined test conditions, the actual real-world emissions may be higher or lower than the emission limit values. The actual emission factors used by the model are described in section 3.2.3.

The model distinguishes 11 technology levels, with 3 of the levels representing engines built before the STAGE standards were in place, and one electric level which generates no exhaust emissions. The technology levels and implementation⁵ years are shown in Table 3 below.

Table 3: Technology levels and implementation years

Technology level	Implementation year
≤ 1980	
1981-1990	
1991-STAGE I	
STAGE I	1999
STAGE II	2001 – 2004
STAGE IIIA	2006 – 2008
STAGE IIIB	2011 – 2013
STAGE IV	2014
STAGE V	2019 – 2020
STAGE V NRG	2019
Electric	

³ <http://data.europa.eu/eli/dir/1997/68/2016-10-06>

⁴ <http://data.europa.eu/eli/reg/2016/1628/2022-07-17>

⁵ In some cases there are transitional provisions, which may cause a delay in implementation

3.2.1.4 Sector allocations

To align with emission reporting requirements and improve policy relevance, the modelled Dutch NRMM fleet is allocated to a number of sectors.

The sectors included are:

- › Agriculture
- › Construction
- › Commercial/institutional
- › Industry
- › Container handling
- › Residential

The allocation is based fully on the machinery type, with each machinery type linked to one or more sectors. For example, the fleet of tractors is split 70% / 30% to the agricultural and construction sectors respectively. This split is held constant over the time span of the model. The machinery specifications and usage are kept identical between applications in different sectors. The sector split is also relevant when applying sector specific scaling factors for projecting emissions, as is explained in sections 3.2.4 and 3.5.

3.2.1.5 Electrification parameters

Electrification of the NRMM fleet is modelled by estimating the share of electric machinery in the annual introduction of new machinery for each unique machinery configuration. The model distinguishes battery- and cable electric machinery. The share of electric machinery by configuration is determined by four machinery specification parameters: 1) current availability of electric models, 2) potential for using a cable electric model, 3) required battery capacity for a working session, and 4) the typical number of days of job assignment on location.

These parameters have been determined for each machinery configuration and are static except for the availability of electric models, which can be projected into the future by the user. For each configuration, the electric machinery version has the same machinery specifications (except the engine type) and usage parameters as the combustion engine version.

The four machinery-specific parameters that influence electrification are described below. The formulas that use these parameters to determine the introduction of electric machinery are described in section 3.4.3.

1. Current availability of electric models (E , %):

What share of current models could be replaced by an equivalent electric model.

Typically the following holds:

- a. Common machinery types are more often available as an electric model, compared to more specialist machinery types.
- b. Smaller machinery types with lower engine power ratings are more often available as an electric model, compared to very large and heavy machinery.

2. Potential for using cable electric models (C , yes/no):

For machinery with limited mobility requirements, e.g., pumps, lifts and lights, using a cable electric model may be feasible. This will typically make the switch to using electric machinery more easy.

3. Required battery capacity for a typical working session (BC , kWh):

This value is calculated by dividing the annual active hours over 200 working days and calculating the battery capacity needed for a working day, based on a typical engine

load of 30%. A battery with this capacity would then only need to be charged once per day.

4. **Typical number of days assigned on a job (D , days):**

The longer the period that a machine is used at a specific location, the more feasible it is to arrange for either battery charging facilities and/or power outlets for cable electric machinery.

3.2.2 Machinery usage

For each unique machine configuration in the model, representative values for the usage parameters have been defined. These determine the average annual active hours, median lifetime, and typical engine load profile.

3.2.2.1 Annual active hours

The annual hours are mostly derived from technical reports (e.g. Van Kempen, 2022; US EPA, 2010), talks with branch organizations, and a survey held among machinery users (Dellaert et al., 2021). They represent the typical average active hours, including machine idling (when the engine is running, but engine load is minimal). Dellaert et al. (2021) identified for several machinery types that the active hours for brand new machines were higher than the typical average active hours for these machines but declined as the machine age increased. This effect is incorporated in the model by a function (see figure 3) that is applied to all machinery types.

In Figure 3 below, the static average is shown as 100%, the model then applies a correction depending on the age of the machine. For example, at 3 times the nominal median lifetime, annual active hours are just 5% relative to the average active hours. At the same time, with increasing age, a larger percentage of machines that were originally introduced into the fleet have been scrapped (see section 3.2.2.2). Together, these effects yield the same effective annual active hours as in the static case, but with a larger share of the activity being performed using newer machinery.

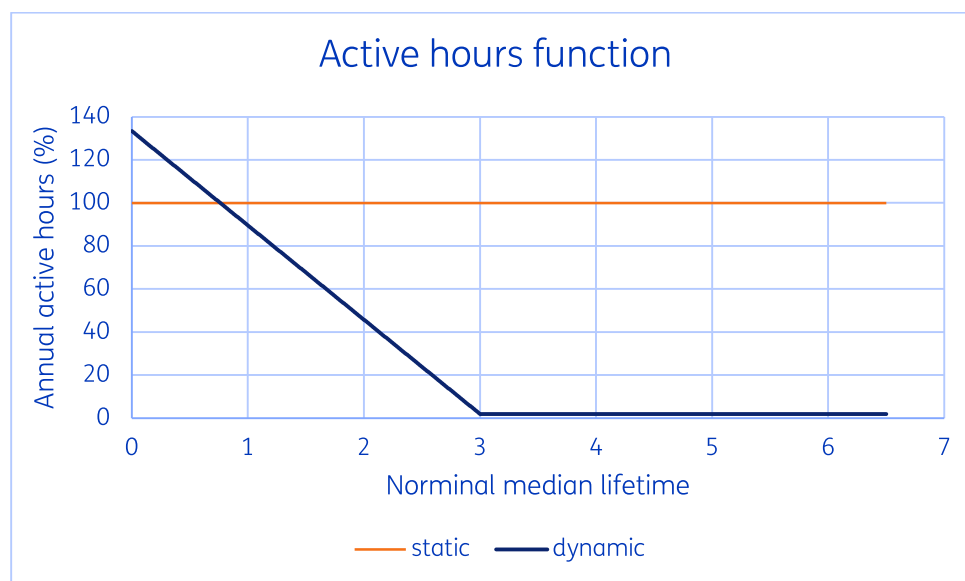


Figure 3: Active hours function - the annual active hours in the model, relative to the average annual hours, as a function of age (relative to the normalised nominal median lifetime).

3.2.2.2 Median lifetime and survival function

The median lifetime represents the cumulative active hours at which 50% of the machines with a specific configuration, that were introduced into the fleet in a given year, are lost from the fleet. The derivative of the survival function can therefore be interpreted as the loss or scrapping rate. There can be various reasons for a machine leaving the active fleet, such as malfunction, disuse, scrapping or export.

While, by definition, 50% of machines have been lost from the fleet after 1 median lifetime, the scrapping rate is not linear. In the beginning, the loss rate is minimal for new machines. Later, the rate of loss increases and then decreases again, leading to a long ‘tail’ of a small share of old machines still being actively used from time to time (see Figure 4).

The survival function used in the model is based on data on the survival of heavy duty vehicles in the Netherlands used by PBL Netherlands Environmental Assessment Agency for their annual projections on climate and energy (PBL, 2021). Although the function is scaled through the median lifetime defined for each unique machine configuration, the shape of the function is currently identical for all machinery types. For some machinery types, the actual survival function is likely not well represented by the current function. As an increasingly longer time stretch of RDW machine registration data becomes available, these data could potentially be used to track machine loss from the fleet and derive machinery type specific survival functions for the model. This data could also help improve the current typical median lifetime specified by machinery type.

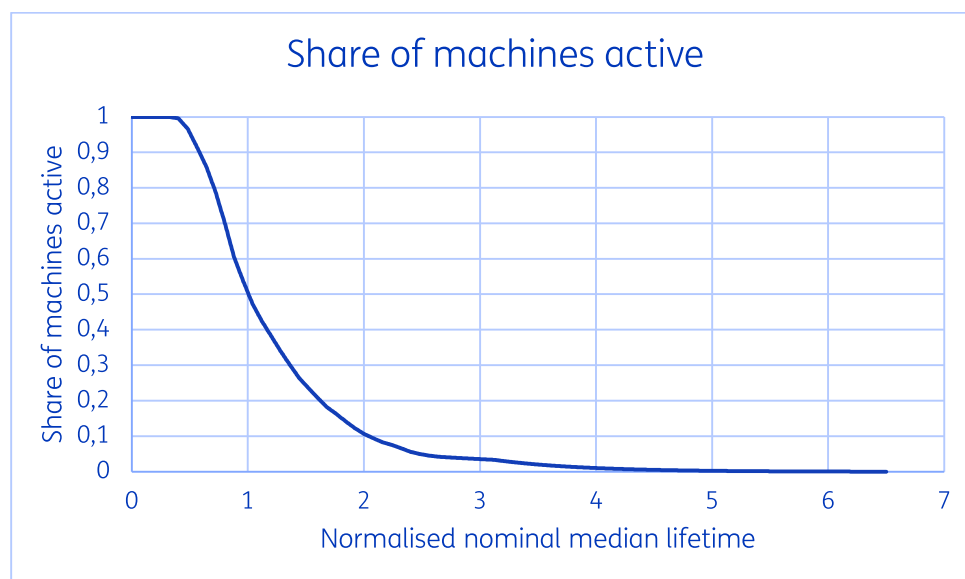


Figure 4: Survival function - Share of machines still active in the fleet as a function of age (relative to the normalised nominal median lifetime).

3.2.2.3 Engine load profiles

For each unique machine configuration, a nominal engine power has been defined. In typical usage situations, the actual engine power applied may vary depending on the work requirements. Based on engine data collected from a range of machines in real-world conditions, a number of default engine load profiles have been derived (Ligterink et al., 2018; Vermeulen et al., 2021; Van Mensch et al., 2023). Each unique machine configuration in the

model has been assigned an engine load profile that seems to best fit the machine characteristics and typical usage. The default profiles as seen for various types of machines are listed in Table 4 below.

Table 4: Default driveline and engine load profiles

Engine load profile	Description
dhc	Hydraulic, Continuous
dhi	Hydraulic, Intermittent
dtc	Transmission, Continuous
dti	Transmission, Intermittent
fa	Fixed axle, Continuous
fpc	Fixed speed, Continuous
fpi	Fixed speed, Intermittent

An engine load profile specifies the share of the total active time that is typically spent around a certain engine load setting. The share of time between 0% to 10% engine load can be considered the idling time. Figure 5 below shows the default load profiles in the model.

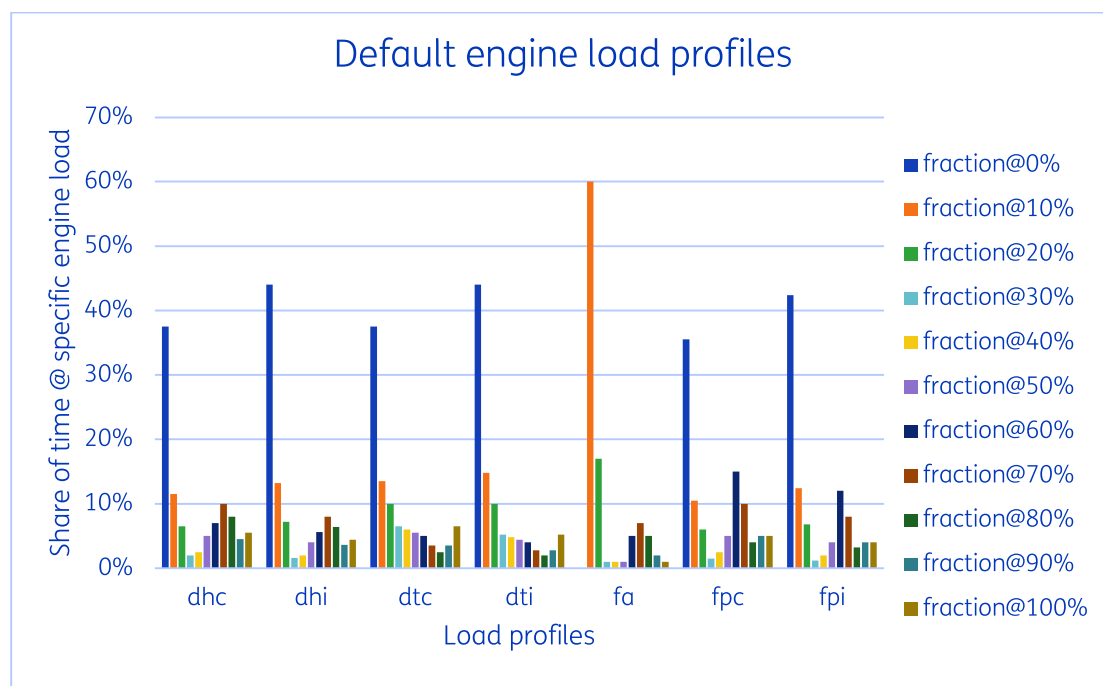


Figure 5: Default engine load profiles: fraction of time at engine load (relative to nominal power)

3.2.3 Emission and fuel factors

The model calculates the NRM emissions for 62 pollutants. The full list is shown in table 12 in the Appendix.

3.2.3.1 Fuel consumption

Fuel consumption is calculated using a Willans line approach (Verbeek et al., 2008; Ligterink et al., 2021) that has been applied to experimentally collected data on the relation between engine size, engine load, engine age, fuel type, active hours, and the resulting fuel consumption. The fuel consumption factor is calculated with the following formula:

$$\text{Fuel factor} = \frac{(c_1 \times (1 + \eta_{\text{year}}) \times \frac{(c_2 + c_3 \times P_{\text{rated}})}{c_4} + \eta_{\text{year}} \times \left(1 + e^{\frac{-P_{\text{rated}}}{c_5}}\right) \times P_{\text{rated}} \times L_{\text{avg}})}{P_{\text{rated}} \times L_{\text{avg}} \times c_6} \times c_7$$

In which:

- › Fuel factor = consumption of fuel per unit of engine power delivered (MJ/MJ);
- › $\eta[\text{year}]$ = engine efficiency factor relative to machine construction year 2010 (.);
- › P_{rated} = the typical rated engine power for this type of machinery (kW);
- › L_{avg} = typical average engine load based on the applicable engine load profile (%);
- › c_1 = Reduced improvement stationary losses (0.5);
- › c_2 = Constant stationary losses (0.4 grams/second);
- › c_3 = Power dependent stationary and internal losses (0.0025 g/s*kW);
- › c_4 = CO₂ factor (0.2 g/s*kW);
- › c_5 = Reduced efficiency small engines (5 kW);
- › c_6 = Base year optimal engine efficiency (37%);
- › c_7 = Correction factor to translate from average fuel economy of diesel engines to petrol or LPG engines. Value is 1.23 for petrol and 1.28 for LPG (.).

The engine efficiency is assumed to improve with 1% each (machine construction) year, yielding a $\eta[\text{year}]$ value of 1.49 in 1970, 1 in 2010, and 0.90 in 2020.

Table 5 shows the resulting fuel use per unit of work produced for different engine sizes from different construction years, assuming an average engine load of 35%. Newer engines are typically more efficient, as are engines of larger sizes. Note that the current implementation results in very high engine efficiencies in future years after 2040. The function may be adjusted in future model versions to account for physical efficiency limits.

Table 5: Fuel consumption rates for diesel engine of different sizes and construction years, per unit of work delivered (MJ / MJ)

	Rated engine power (kW) →	5	10	20	30	50	75	100	150	200	250	300	400
Year	Engine efficiency factor (η) ↓	MJ heating value/MJ work at rated engine power											
1960	1.49	9.47	6.61	5.18	4.79	4.53	4.40	4.34	4.27	4.24	4.22	4.21	4.19
1965	1.49	9.47	6.61	5.18	4.79	4.53	4.40	4.34	4.27	4.24	4.22	4.21	4.19
1970	1.49	9.47	6.61	5.18	4.79	4.53	4.40	4.34	4.27	4.24	4.22	4.21	4.19
1975	1.42	9.09	6.33	4.95	4.58	4.32	4.19	4.13	4.07	4.04	4.02	4.01	3.99
1980	1.35	8.72	6.06	4.73	4.37	4.12	4.00	3.94	3.88	3.85	3.83	3.82	3.80
1985	1.28	8.38	5.81	4.52	4.17	3.93	3.81	3.75	3.69	3.66	3.65	3.63	3.62
1990	1.22	8.05	5.57	4.32	3.98	3.75	3.63	3.58	3.52	3.49	3.47	3.46	3.45
1995	1.16	7.73	5.34	4.13	3.81	3.58	3.46	3.41	3.35	3.33	3.31	3.30	3.28

2000	1.10	7.44	5.12	3.95	3.64	3.41	3.30	3.25	3.20	3.17	3.15	3.14	3.13
2005	1.05	7.15	4.91	3.78	3.47	3.26	3.15	3.10	3.05	3.02	3.00	2.99	2.98
2010	1.00	6.88	4.71	3.62	3.32	3.11	3.01	2.95	2.90	2.88	2.86	2.85	2.84
2015	0.95	6.62	4.52	3.46	3.17	2.97	2.87	2.82	2.76	2.74	2.72	2.71	2.70
2020	0.90	6.38	4.34	3.32	3.03	2.83	2.73	2.68	2.63	2.61	2.60	2.59	2.57
2025	0.86	6.14	4.17	3.17	2.90	2.70	2.61	2.56	2.51	2.49	2.47	2.46	2.45
2030	0.82	5.92	4.00	3.04	2.77	2.58	2.49	2.44	2.39	2.37	2.35	2.35	2.33
2035	0.78	5.71	3.85	2.91	2.65	2.46	2.37	2.33	2.28	2.26	2.24	2.23	2.22
2040	0.74	5.51	3.70	2.79	2.54	2.35	2.26	2.22	2.17	2.15	2.14	2.13	2.12
2045	0.70	5.31	3.56	2.68	2.43	2.25	2.16	2.11	2.07	2.05	2.04	2.03	2.02
2050	0.67	5.13	3.42	2.57	2.32	2.15	2.06	2.02	1.97	1.95	1.94	1.93	1.92

3.2.3.2 Engine derived emissions

For several pollutants such as CO, NO_x, PM, NH₃ and HC, engine emissions are influenced substantially by the engine technology and engine load. The emission factors of CO, NO_x, PM and HC used in the model are originally derived from the German TREMOD model (Lambrecht et al., 2004; Helms et al., 2010) and partly correspond to the legal limit values. PM emission factors include the bulk of the condensable PM. Later updates have been implemented based on EEA (2019) and Ligterink et al., (2018). These updates are validated with recent studies, like Van Mensch et al. (2023). An overview of all engine derived emission factors will be reported in Geilenkirchen et al. (2024).

As historically the emissions increase mostly linearly with the fuel consumption and therefore with engine power output (above 10% engine load), the emission limit values in EU regulations are defined in the unit of grams of pollutant per kWh of engine power generated. However, with modern engines this linear relationship falls apart in some cases. Especially for NO_x emissions from modern engines, the effectiveness of the emission reduction technology (typically SCR, selective catalytic reduction) is limited at low engine loads, leading to a substantial share of emissions occurring during machine idling, when engine generated power is actually minimal and fuel consumption is low (Ligterink et al., 2018).

For this reason, the model has moved from using emission factors expressed in grams/kWh to using emission factors defined for each engine load bin, in terms of grams/second/kW (rated). For NO_x from modern engines, the emission factors have been derived from Ligterink et al. (2018). The other emission factors have been directly converted from the available g/kWh factor to grams/second/kW (rated), assuming a classic linear increase with engine power output. In combination with representative engine load profiles, this method can more accurately reproduce the emission behaviour of modern engines. Furthermore, the required emission factors can be derived in a straightforward manner from typical real-world emission measurements (when available).

3.2.3.3 Fuel derived emissions

For pollutants such as CO₂, SO₂, N₂O and fuel contained metals, emissions are mostly determined by the fuel type and total fuel consumption. For this reason, these emissions are calculated by multiplying fuel-specific emission factors with the fuel consumption. As fuel composition has changed over time, due to fuel regulation and biofuel mixing, some emission factors are defined relative to the reporting year. The model distinguishes between diesel complying with the European EN-590 norm (introduced in 1993), and non-

standardised diesel. The non-standardised diesel (also known as “red diesel” in the Netherlands) did not meet the same standards for sulphur content (see Table 7) and was allowed for non-road use until 2013.

The annual CO₂ emission factors in grams per MJ are updated each year and presented in the methodological report of the Taskforce Transportation (Geilenkirchen et al., 2023, table 2.7). The N₂O emission factors are shown in Table 6. The default factors are based on the IPCC Revised guidelines 1996 (IPCC, 1996). For diesel, a higher factor is used for modern engines using SCR, which is derived from the 2023 Guidebook (EEA, 2023). The year-specific SO₂ emission factors are shown in Table 7 and are calculated from the fuel sulphur content. The heavy metal emission factors are shown in Table 8 and are derived from Pulles et al. (2012).

Table 6: N₂O emission factors by fuel type

Fuel type	Emission factor default (g/MJ)	Emission factor SCR (g/MJ)
Diesel (EN-590)	0.0006	0.00319
Diesel	0.0006	0.00319
Petrol	0.0006	0.0006
LPG	-	-

Table 7: SO₂ emission factors by fuel type and year

Fuel type	Year from	Year until	Emission factor (g/MJ)	Sulphur content (ppm)
Diesel (EN-590)	1995	2004	0.0023	50
	2005	2009	0.0012	25
	2010	2050	0.0005	10
Diesel	1990	1990	0.0834	1,780
	1991	1993	0.0843	1,800
	1994	1994	0.0820	1,750
	1995	2007	0.0796	1,700
	2008	2008	0.0468	1,000
	2009	2009	0.0234	500
	2010	2010	0.0117	250
	2011	2050	0.0005	10
Petrol	1990	1990	0.0109	240
	1991	1991	0.0095	210
	1992	1992	0.0086	190
	1993	1993	0.0073	160
	1994	1994	0.0059	130
	1995	1995	0.0045	100
	1996	2000	0.0032	70
	2001	2001	0.0023	50
	2002	2002	0.0027	60
	2003	2004	0.0014	30
	2005	2007	0.0009	20
	2008	2050	0.0005	10
LPG	1989	2050	-	-

Table 8: Emission factors for heavy metals from fuels

Fuel type	Emission factor ($\mu\text{g}/\text{MJ}$)
Diesel (EN-590)	0.95843
Diesel	0.95843
Petrol	1.31864
LPG	0.0

3.2.3.4 Speciation of organic gases

Emissions of organic gases from NRMM consist of a large variety of chemical compounds, some of which are of special concern due to their substantial detrimental health effects. The Dutch National Institute for Public Health and the Environment (RIVM) maintains a list of pollutants of high concern, whose release should be especially reduced (RIVM, 2023). To derive an estimate of the release of the various chemical compounds that are part of the organic gases emissions, speciation profiles are used that define the fraction of each compound with the total organic gases.

The speciation profiles for VOC, PAHs and dioxin compounds are derived from the US EPA MOVES 3 model (US EPA, 2022). Most of these profiles are expressed relative to the mass of total organic gases (TOG). However, emission limit values and emission factors for organic gases are expressed in terms of mass of total hydrocarbons (THC). As most measurement equipment has reduced sensitivity for oxygenated organic compounds, most importantly acetone, it will therefore underestimate the mass of total organic gases. For this reason, all speciation profiles have been converted to fractions relative to mass of THC for use in the model, using the correction factors suggested by the US EPA (2022).

The latest speciation profiles for VOC compounds, PAHs and dioxins can be found in the methodology report of the Taskforce Transportation (Geilenkirchen et al., 2023, table 9.11).

3.2.3.5 Speciation of heavy metals

Using the fuel-specific heavy metal speciation profile, the total heavy metal emission is split into individual components. The current profiles have been derived from Pulles et al. (2012). The latest heavy metal speciation profile can be found in the methodology report of the Taskforce Transportation (Geilenkirchen et al., 2023, table 9.11).

3.2.4 Tampering factors

Based on findings on tampering incidence in trucks (motivated by reduced maintenance and repair costs), incidence in tampering with emission control technology such as SCR catalysts and particulate filters was estimated also for NRMM. For NO_x , tampering of SCR catalysts is assumed to happen in 10% of STAGE IV and V machines (56–560 kW range). For PM, tampering with particulate filters is assumed to happen in 5% of STAGE V machines with particle filter (19–560 kW range). Adjusted emission factors that represent emission rates in absence of active emission control technology are applied in these cases. An overview of all engine derived emission factors will be reported in Geilenkirchen et al. (2024).

3.2.5 Scaling factors

Various scaling factors are used to compensate for known model limitations and improve the raw model results. These scaling factors are explained in more detail below.

3.2.5.1 Agriculture

Every year, Wageningen University Economic Research (WEcR) estimates the annual diesel consumption of agricultural companies by extrapolating the diesel consumption derived from the financial administration of a sample of agricultural companies (WEcR, 2023). CUMELA, the branch organisation for contractors in the construction and agricultural sector, uses a similar approach to estimate the diesel consumption of contractor companies in the agricultural and construction sectors respectively (CUMELA, 2022). The combined diesel consumption of agricultural companies and agricultural contractors is compared with the uncorrected model output for the agricultural sector to derive an annual scaling factor. The scaling factor is then used to scale the fuel consumption and emissions for the agricultural sector. As the model value would ideally correspond well with the sector value, the sector data can also be used for model validation, as is further explained in section 5.2.2.

3.2.5.2 Construction sector

The construction sector is quite susceptible to changes in economic situation and outlook. This means that year-to-year changes in economic climate may lead to increases or decreases in activity, which are not well captured by changes in machinery sales and resulting changes in the active fleet. For this reason, the model applies a scaling factor, based on the year-to-year change in economic production volume by various construction subsectors as reported by Statistics Netherlands (CBS, 2023).

The model scales the active hours, fuel consumption and emissions for all machinery in the construction sector in a specific year, using the change in economic production volume between the previous and the current year. This approach does not keep the model output tightly linked to economic output, but is only intended to compensate for short term variations in activity, as longer term developments are assumed to be reflected in the machinery sales data.

3.2.5.3 Container handling

As there are detailed annual statistics on the number of container handlings in the Netherlands, the fuel consumption and emissions for this sector are scaled directly based on these statistics. As is explained in Dellaert (2016), an average energy requirement of 13.4 kWh / TEU (twenty-feet equivalent unit) container is assumed. This is the work output for handling a full container. To move an empty container, the energy requirement is assumed to be one third of a full container. As the container handling machinery fleet is renewed, the fuel consumption to deliver this work is reduced through improved engine efficiency and electrification.

The annual data on container handlings is collected from the Port of Rotterdam (2023a; 2023b) and from Eurostat (2023).

3.3 Input data

3.3.1 Overview

Table 9 below shows which primary data sources have been used (in green) to compile the machinery introduction data needed to derive the active fleet. The individual data sources are discussed in the next section (3.3.2).

Table 9: Data sources used for NRMM fleet by sector

Data source	Residential	Container handling	Commercial / institutional	Industry	Agriculture	Construction
BMWT data						
Fedecom data						
Off-Highway Research data						
RDW registration data						
Estimate based on Fedagrim economic dossiers 2006-2020						
Estimate based on Hoenderken, 2004						
Estimate based on DCMR / Dellaert, 2016						
Estimate based on TNO survey 2021						
Other estimates						

As the primary data sources typically only cover a limited number of years, additional estimates and extrapolation are used to complete the machinery introduction data. Table 10 below shows the data source for sales data for the different NRMM types in the model by introduction year. The sources described above have been categorised into three groups:

- › M for 'Monitoring': BMWT, Off-highway research, Fedecom and RDW data;
- › S for 'Estimate': TNO survey, DCMR, Hoenderken, and introduction estimates derived from other sources;
- › E stands for 'Extrapolation': Extrapolation of monitoring or estimated data into historic or future years.

Table 10: Data source NRMM fleet introduction data

Sector	Machinery name	1980	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2030	2040
Construction sector	asphalt pavers	E	E	E	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E
	surfing equipment	E	E	E	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
	truck-mounted cranes	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	bandsaws/grinders	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	cement and mortar mixers	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	dozers	E	E	E	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E
	carriers	E	E	E	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E
	bitumen sprayers	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	portable generators, construction	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E	E	E	E	E	E	E
	asphalt heaters	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	backhoes	E	E	E	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E
	excavators	E	E	E	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E
	graders	E	E	E	E	E	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E
	pile hammers	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	pillers	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	aerial lifts	E	E	E	E	E	E	E	E	E	E	E	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E	E
	hydraulic power packs	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	wheeled loaders	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	M	M	M	M	E	E
	crawler loaders	E	E	E	M	M	M	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
	agricultural tractors	S	S	S	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E
	welding generators	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	light towers	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	bore/drill rigs	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	mobile compressors	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	mobile cranes	E	E	E	E	E	E	E	M	E	E	M	E	E	E	M	E	E	E	M	E	E	E	E	E	E	E	E	E
	portable pumps	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	mobile sieves/crushers	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	excavators	E	E	E	E	E	E	E	E	E	E	E	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E	E
	crawler cranes	E	E	E	E	E	E	E	M	E	E	M	E	E	E	M	E	E	E	M	E	E	E	E	E	E	E	E	E
	rough terrain forklifts	E	E	E	M	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E	E
	skid steer loaders	E	E	E	M	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E	E
	mobile tower cranes	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	S	E	E	E	E
	tampers/rammers	E	E	E	M	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E	E
	fork lifts	E	E	E	M	M	M	M	M	M	M	M	M	M	M	M	M	M	E	E	E	E	E	E	E	E	E	E	E

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3.3.2 Data sources

Below, the data sources are described that are used to compile an annual inventory of machinery introductions into the Dutch fleet.

BMWT

The annual fleet introduction of construction machinery is compiled using various data sources. For the years 1997 – 2014, annual sales data for a significant subset of construction machinery types was shared annually by BMWT, the branch organization for construction and transport machinery importers (BMWT, 2015). These data covered the sales of e.g. excavators, loaders and fork lifts. As these data could no longer be shared after 2014, commercial sales data for construction machinery was acquired from other sources.

Off-Highway Research

Commercial sales data for various types of construction machinery was acquired from Off-Highway Research (2022) for the years 2002 to 2026 (the data includes extrapolations to the near future). These sales data were mapped to the model machinery types.

Fedecom

The annual fleet introduction of tractors is compiled using data provided by Fedecom, the branch organization for producers, importers and dealers of machinery for the agricultural, horticultural, industrial and transport sectors (Fedecom, 2022). The available data covers the years 1999 – 2021.

RDW database

As of 2022, all machinery that accesses the public road network with speeds exceeding 6 km/h, should be registered with the Netherlands Vehicle Authority (RDW) and carry a license plate. The registration data is available in a public database and contains information on the type of vehicle/machine, the brand and model, the fuel type, the date of first admittance, and in some cases the rated engine power. This registration data thus represents the active machine fleet, with exception of some machinery types such as hand-held machinery and other machinery that does not access public roads, such as lawnmowers, generators, pumps, compressors and machinery on tracks (e.g. crawler excavators), or machines which do not leave a specific industrial estate or port area. Since the RDW registry of NRMM becoming available, these data have been assessed and applied for two purposes:

- › To validate the modelled machinery fleet;
- › To improve the composition of the modelled machinery fleet through improved estimates of annual introduction of new machinery.

As the amount of data in the RDW registry is considerable, validation and improvements are implemented step by step and will continue in the future (see section 5.3).

To estimate historic machinery introduction rates from the current active fleet, the data are grouped by machinery type, engine power range, and the year of first admittance (which is used as a proxy for the machine construction year). Then the current active number of machines is used to estimate the original introduction in a specific year, by inverting the survival function, thus modelling the original introduction needed to arrive at the current fleet by estimating the number of machines that are scrapped between the introduction year and the current fleet.

The advantage of this approach is that the model will accurately reproduce the current active fleet. However, it should be noted that the historic introduction rates have a high

uncertainty because they are strongly influenced by various assumptions such as the expected median lifetime and survival function. Furthermore, import of used machinery may lead to errors in the estimation of the historic fleet. This leads to substantial uncertainty in the active machinery fleets for historic years that are based on this approach. It is therefore preferred to combine this approach with other available statistics on machinery sales.

TNO survey of machinery users and dealers

In 2020/2021, a survey was distributed through a number of branch organizations to owners, users and dealers of NRMM in the Netherlands. The respondents were asked to give a detailed overview of their machinery fleet in terms of numbers, specifications and usage. The design and results of this survey are described in Dellaert (2021). Based on the survey, several NRMM types were identified that were not yet included in the model. The missing machinery types were prioritized on the basis of numbers in the survey. A selection of types was then added to the model through estimation of historic sales data. In most cases, historic sales/introduction are kept constant as little is known about the age distribution.

Fedagrim economic reports

Fedagrim is the Belgian federation for agriculture and horticulture mechanisation. They publish an annual report of machinery sales to the Belgian market (Fedagrim, 2020). As such data does not currently exist for the Dutch market of horticulture machinery, the data from Fedagrim is used as a proxy for sales in the Netherlands for machinery such as lawnmowers, leaf blowers and chainsaws.

Hoenderken, 2004

An article by Hoenderken (2004) in the magazine 'Landbouwmechanisatie' provides an overview of historic tractor sales for the years 1950 – 1999. These have been processed to match the model input format.

DCMR, 2010 / Dellaert, 2016

Information on the fleet of container handling equipment has been based on a study by DCMR (2010) on container terminals in the Rijnmond area, which was further analysed and extrapolated to the national level in Dellaert (2016).

3.4 Calculations

3.4.1 Sales data extrapolation

The estimation of machinery sales/introduction data for missing or future years follows a simple extrapolation. For missing data in historic years, for each unique machinery configuration, the 3 earliest available years for which annual sales data is available, are averaged and extrapolated back to 1970. For missing future years, the 3 latest available years for which annual sales data is available, are averaged and extrapolated to future years until 2050.

3.4.2 Machinery scrappage and active fleet

The machinery survival function has been explained in section 3.2.2.2. The derivative of the survival function is the loss or scrapping rate. Using the fleet introduction data and the survival function, the active fleet is modelled for each reporting year. The following approach is taken:

1. For each reporting year, the fleet introduction of machinery before that reporting year is considered (e.g. for reporting year 2000, all historic excavator sales are considered from 1999 and before).
2. For each introduction year, the nominal age of the machinery introduced in that year is calculated using:

$$Age_{nominal} = \frac{Year_{reporting} - Year_{introduction}}{median\ lifetime}$$

3. For each introduction year, the share of machinery that is still active in the reporting year is calculated using the survival function:

$$share_{active} = F_{survival}(Age_{nominal})$$

4. The share of active machines is multiplied with the original fleet introduction number to determine the number of machinery still active in the reporting year, by introduction year:

$$Machines_{active} = Machines_{introduced} \times share_{active}$$

5. Engine technology level is then assigned based on the introduction year.

3.4.3 Electric machinery

The introduction of electric machinery is projected into the future using 6 projection parameters that influence the share of annual machinery introduction that is cable electric (CE) or battery electric (BE). The first five factors have been defined as follows:

1. **Break-even value for days on assignment (X).** Power supply is essential for the application of electric machinery, both for cable and battery electric machinery. The value of X is the typical number of days above which the arranging of adequate power supply is financially feasible.
2. **The break-even value for battery capacity (Y, kWh per day),** is the maximum battery capacity for which it is still financially feasible to replace a combustion engine machine. This is related to the substantial increase in battery cost at higher capacities.
3. **The fraction of electric machinery that is battery electric (Z, %),** compared to the fraction that is cable electric (1 - Z).

4. The maximum battery capacity (L , kWh) which can be transported to the working location. With a large battery and limited use, the battery does not need to be charged on location, which offers the alternative of “charging at home”. When this is possible, the barrier for electrification is lowered.
5. The growth in availability of electric machinery models (B , % improvement from current estimate to 100%). This parameter increases the electric availability (see section 3.2.1.5) from the initial value to 100% availability over time.

Together, parameters 1 to 5 determine the potential share of machinery that can be replaced by electric machinery in a technically and financially feasible manner, assuming the electric model is accepted as being equivalent to the non-electric model, with regards to characteristics such as reliability, lifetime and power output. Then there is a final sixth parameter that influences the actual share of electric machinery by configuration and introduction year:

6. Acceptance (A , %) is the fraction of buyers/renters who, when a financially feasible electric alternative is available, also chooses this electric alternative.

It is expected that these parameters will develop autonomously over time. However, it is also possible for policy makers to influence these parameters through targeted policy measures to speed up the uptake of electric machinery into the NRMM fleet in the Netherlands. For each of the six parameters, the user can specify the annual value from 1990 to 2050. Together with the machinery specifications explained in section 3.2.1.5 (Current availability of electric models: E ; Potential for using cable electric models: C ; Required battery capacity for a typical working session: BC ; Typical number of days assigned on a job: D), these determine the annual introduction of electric machinery.

The introduction is made up of three separately calculated parts: battery electric machinery that can be charged locally at the work site (BEL), battery electric machinery that can be charged “at home” (BEB) and cable electric machinery (CE), through the following formulas:

$$Introduction\ BEL_{model, year} = (E_m + (1 - E_m) \times B_y) \times \left(\frac{D_m}{D_m + X_y} \right) \times if(C_m; Z_y; 1) \times \left(\frac{Y_y}{Y_y + BC_m} \right) \times A_y$$

$$Introduction\ BEB_{model, year} = (E_m + (1 - E_m) \times B_y) \times if(C_m; Z_y; 1) \times \left(\frac{L_y}{L_y + D_m \times BC_m} \right) \times A_y$$

$$Introduction\ CE_{model, year} = (E_m + (1 - E_m) \times B_y) \times \left(\frac{D_m}{D_m + X_y} \right) \times (1 - if(C_m; Z_y; 1)) \times A_y$$

With the term: $if(C_m; Z_y; 1)$ to mean that if a machinery type can be electrified using a cable ($C_m = True$), then fraction Z_y is used, else 1.

It should be noted that the current implementation of the projections of electrification of machinery is based on limited research. More research is needed in order to improve the parameter values and overall approach.

Current and future expected values for parameters X and L could be requested from contractors. Parameter Y could be derived from comparing cost curves of battery electric systems with combustion engine systems. All factors, but especially X , B and A can be influenced by policy measures stimulating the uptake of electric machinery and provide adequate power supply on work locations. (Historic) introduction rates of electric machinery can also be derived from the RDW registration, which will be explored in the future (see chapter 5.3).

3.4.4 Fuel use and emissions

The formulas below describe the calculations of NRMM fuel and electricity consumption and emissions.

3.4.4.1 Fuel consumption

The fuel consumption of NRMM is calculated using the following formulas:

$$Work\ delivered = N \times T \times P_{rated} \times L_{avg}$$

With:

- › Work delivered = amount of total useful work delivered by the NRMM engine (kWh);
- › N = Number of machines of a specific configuration and construction year (.);
- › T = the average annual active hours for this type of machinery (hours);
- › P_{rated} = the typical rated engine power for this type of machinery (kW);
- › L_{avg} = typical average engine load based on the applicable engine load profile (%).

Together with the fuel factors described in section 3.2.3.1, the total fuel consumption is calculated using:

$$Fuel\ consumption = Work\ delivered \times c \times FF$$

With:

- › Fuel consumption = annual fuel consumption (MJ);
- › Work delivered = amount of total useful work delivered by the NRMM engine (kWh);
- › c = kWh to MJ conversion factor (3.6 MJ/kWh);
- › FF = Fuel factor (MJ/MJ).

3.4.4.2 Electricity consumption

The grid electricity consumption of electric machinery is calculated as follows:

$$Electricity\ consumption = Work\ delivered \times \eta$$

With:

- › Electricity consumption = Consumption of grid electricity (kWh);
- › Work delivered = amount of total useful work delivered by the NRMM engine (kWh);
- › η = efficiency factor electric driveline, assuming 20% losses for battery electric machinery and no losses for cable electric machinery.

3.4.4.3 Engine derived emissions

As discussed in section 0, for some pollutants the emissions are strongly dependent on the specific engine characteristics. The emissions of CO, NO_x, PM, NH₃ and HC are calculated using the following formula:

$$Emission = \sum_{load} N \times P_{rated} \times T \times S_{load} \times EF_{load, technology}$$

In which:

- › Emission = Emission (grams);

- › N = the number of machines of a specific configuration and construction year, with emission factors applicable to the machine's year of construction (.);
- › P_{rated} = the typical rated engine power for this type of machinery (kW);
- › T = the average annual active hours for this type of machinery (seconds);
- › S[load] = the average fraction of time that the machine engine is in a specific load range (%);
- › EF[load, technology] = Specific load dependent emission factors, per kW of rated engine power for different technology levels related to the year of construction and the emission standards (grams/(second*kW (rated))).

3.4.4.4 Fuel derived emissions

For the pollutants discussed in section 3.2.3.3, the emissions are determined primarily by the amount and type of fuel combusted. The emissions of CO₂, N₂O, SO₂ and heavy metals are calculated using the following formula:

$$Emission = F \times EF_{fuel, year}$$

In which:

- › Emission = Emission (grams);
- › F = Amount of fuel combusted of specific type and composition (MJ);
- › EF[fuel, year] = Fuel type and composition specific emission factor (g/MJ).

3.4.4.5 Sulphur content PM correction

Due to regulation, diesel sulphur content has decreased over time, from around 1800 ppm in 1990 to around 10 ppm for current diesel fuels. For petrol, the sulphur content has decreased from around 240 ppm to 22 ppm (see Table 7). As sulphur content decreases, both SO₂ emissions and PM emissions decrease. To adjust the PM emissions for this effect, a correction factor is applied, which was derived from EPA (2004). The correction factor for PM emissions in a specific year is calculated as follows:

$$Correction_{year} = \frac{S_{REF} - S_{year}}{1000} \times 0.157$$

With the reference sulphur contents of 1700 ppm for “red” diesel (non-standardised), 50 ppm for diesel (EN-590), and 100 ppm for petrol (see section 3.2.3.3).

3.4.4.6 Heating value correction

The heating value of market fuels is not constant over time and depends on factors such as carbon content and biofuel mixing. RIVM and TNO have performed testing of market fuels to derive a representative lower heating value (LHV, in MJ/kg) for each fuel type and year (CBS, 2017). The updated data is presented each year in the methodological report of the Taskforce Transportation (latest version is Geilenkirchen et al., 2023).

For equal power output, the amount of fuel combusted in terms of weight and volume is higher when the LHV is lower, most likely leading to higher emission rates per unit of output. For this reason, the emission values are corrected when the year-specific LHV deviates from the default LHV value, which is the value thought to be most representative for the fuel LHV during testing. The following formula is used:

$$Emission = Emission \times \frac{LHV}{LHV}$$

3.5 Projections

To generate a projection of future NRMN emissions and fuel consumption, the model makes various assumptions and allows the user to specify expected growth/decline rates. These assumptions are explained below.

3.5.1 Machinery fleet

To project the composition of the future machinery fleet, an extrapolation of machinery introduction rates is performed by the model. For each unique machinery configuration, the 3 latest years for which annual sales data is available, are averaged and extrapolated to future years until 2050. As the technology level is determined by the introduction year, the fleet composition shifts to higher shares of newer technology in future years, with typically lower emission factors. Machinery usage parameters such as median lifetime and annual active hours are kept constant over the full time range.

As emission limit values are more lenient for lower engine powers for the latest STAGE V emission standard, it is expected that manufacturers will choose to stay below 56 kW or even below 19 kW when possible. This will likely impact the future fleet. However, this effect is not currently included in the model.

3.5.2 Container handling

To project the use of NRMN in container handling, the user can specify the rate of change in total containers handled in the Netherlands, the share of container handling operations that are performed using electric machinery, and the share of containers handled that are empty (requiring less energy to move). Together, these parameters are used to scale the uncorrected model output for container handling machinery for future years.

3.5.3 Ground support equipment

The historic emission data for ground support equipment (GSE) at Dutch airports is taken from the TNO CLEO model for aviation emissions (Dellaert & Hulskotte, 2017). To project the GSE emissions and fuel consumption, the user can specify for each airport the expected rate of change in the total maximum take-off weight (MTOW) of the airplanes and the amount of fuel used per MTOW serviced. Together, these parameters are used to extrapolate the model output for GSE machinery to future years.

3.5.4 Other sectors

Users can define year-to-year developments in the (machinery-related) activity within a sector, expressed as the total MWh of energy generated by the machinery in a specific year. Here, MWh generated is used as a proxy of productivity in the sector. The user defined activity is used to scale the uncorrected model output based on the extrapolated machinery fleet for these sectors for future years. As the power output is used as scaling factor, improved engine efficiency and increasing electrification will lead to lower fuel consumption and emissions per unit of output over time.

3.5.5 Projection of other model parameters

Emission factors

Emission factors related to a specific technology level are fixed in the model. However, the technology composition of the fleet will change due to the introduction of new machinery and machinery scrappage.

Scaling factors

The scaling factor for the agricultural sector from the latest available year is used for all future years. For the construction sector, no scaling is applied in projected emissions.

Electrification

The share of newly introduced machinery that is electric is determined by the function explained in section 3.4.3.

Engine efficiency

Engine efficiency follows a continuous improvement based on the machine construction year, as explained in section 3.2.3.1.

4 Model output

In this chapter, a brief summary of the output of the current model version is presented. Note that due to model updates and improvements, these results may not represent the latest insights.

4.1 Introduction of machinery to active fleet

Figure 6 to Figure 11 show a sample of the current modelled annual introduction of NRMM into the Dutch fleet for the period 1990 – 2030. Unique machinery configurations have been aggregated to the machinery type. Some machinery types are not included in the overview. In some graphs, double Y-axes have been used, with the dashed curves corresponding with the right (secondary) Y-axis.

For most machinery types, introduction estimates are available only for years in the period 2000 – 2021, with estimates for earlier and later years being based on extrapolations (see section 3.4.1). For some machinery (such as generators), due to a lack of data, a single value has been extrapolated to all years, leading to a constant introduction rate. To model a realistic fleet age composition, the fleet introduction is extrapolated back to 1970 and onwards to 2050.

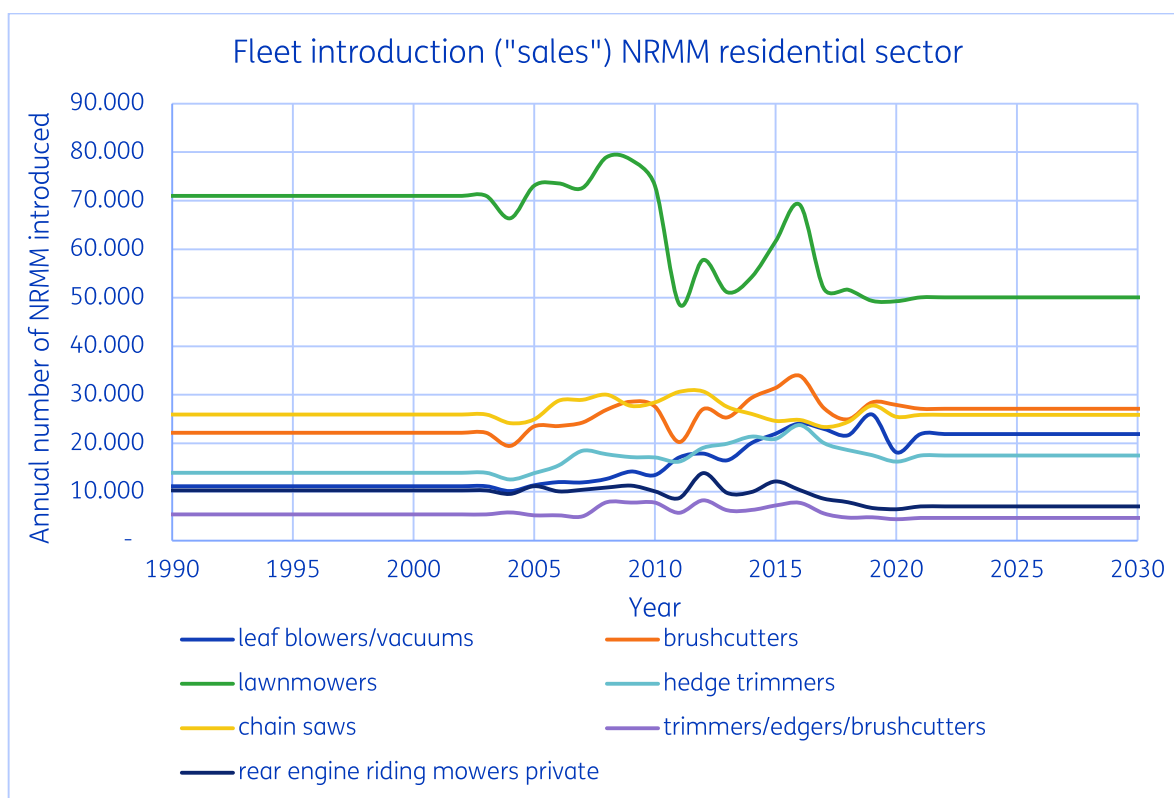


Figure 6: Fleet introduction of NRMM residential sector

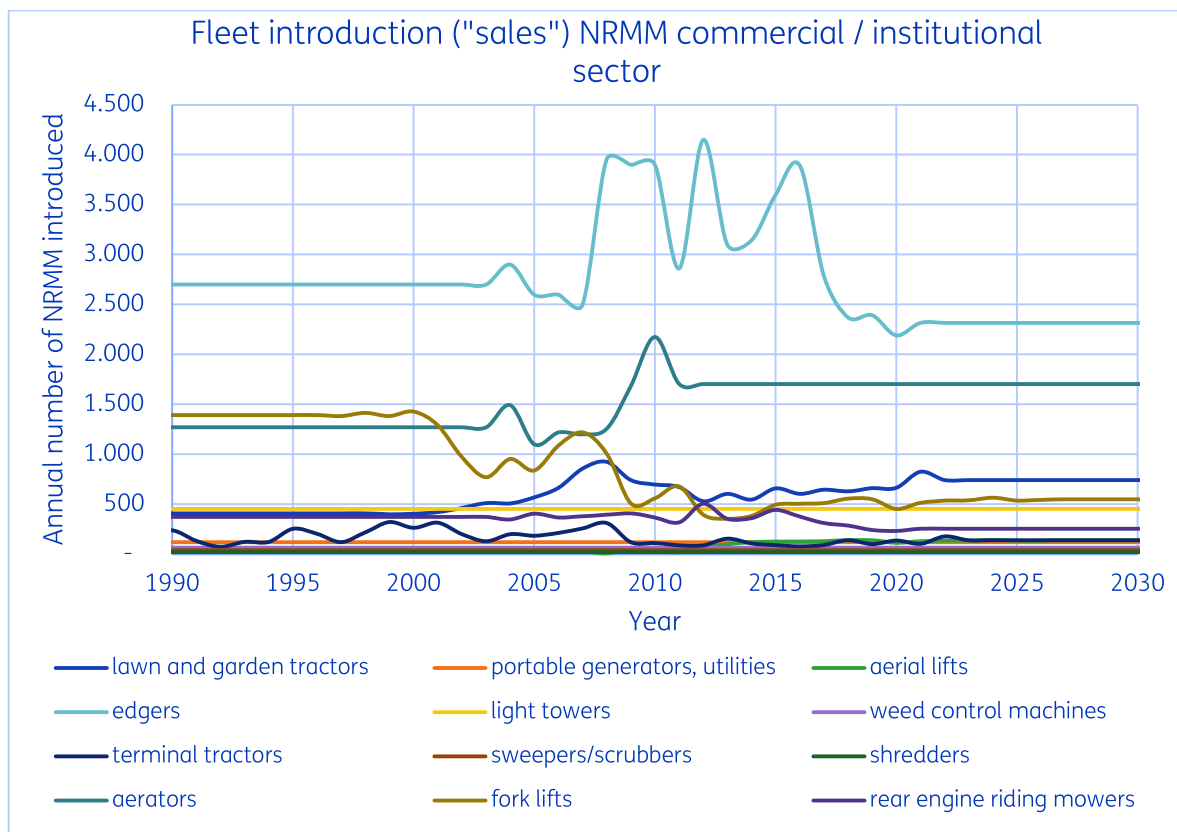


Figure 7: Fleet introduction NRMM commercial / institutional sector

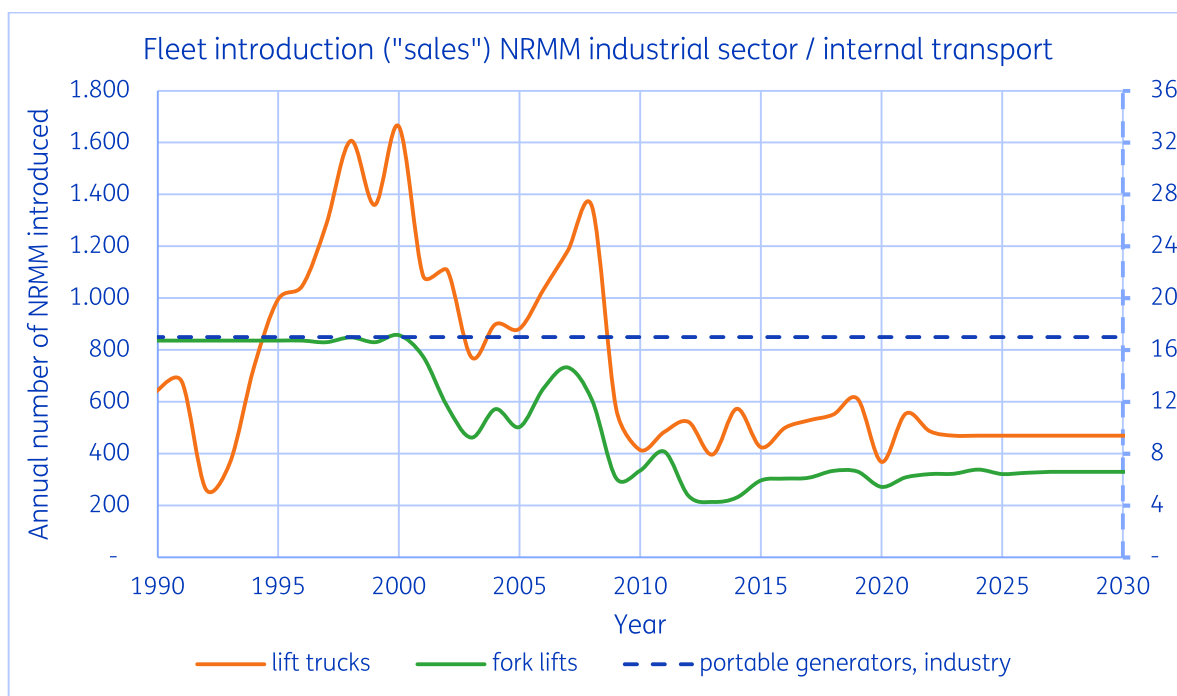


Figure 8: Fleet introduction NRMM industry sector, generators on right Y-axis

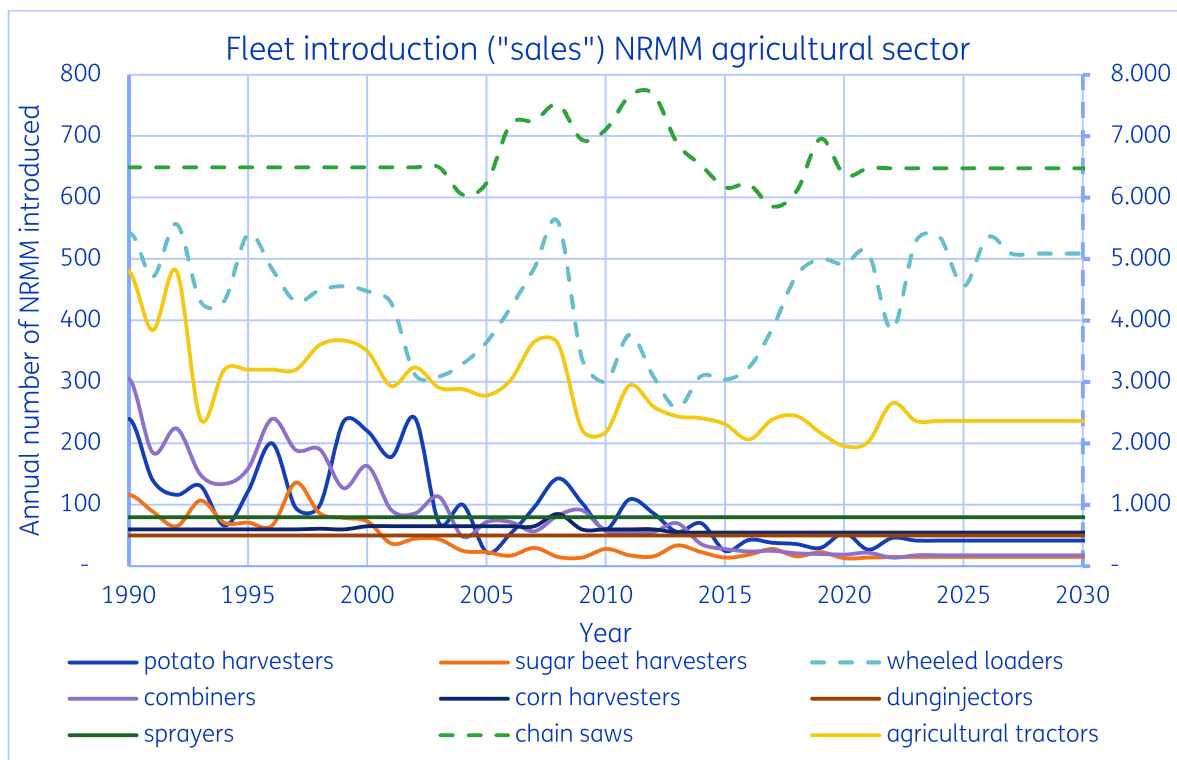


Figure 9: Fleet introduction NRMM agricultural sector, loaders and chain saws on right Y-axis

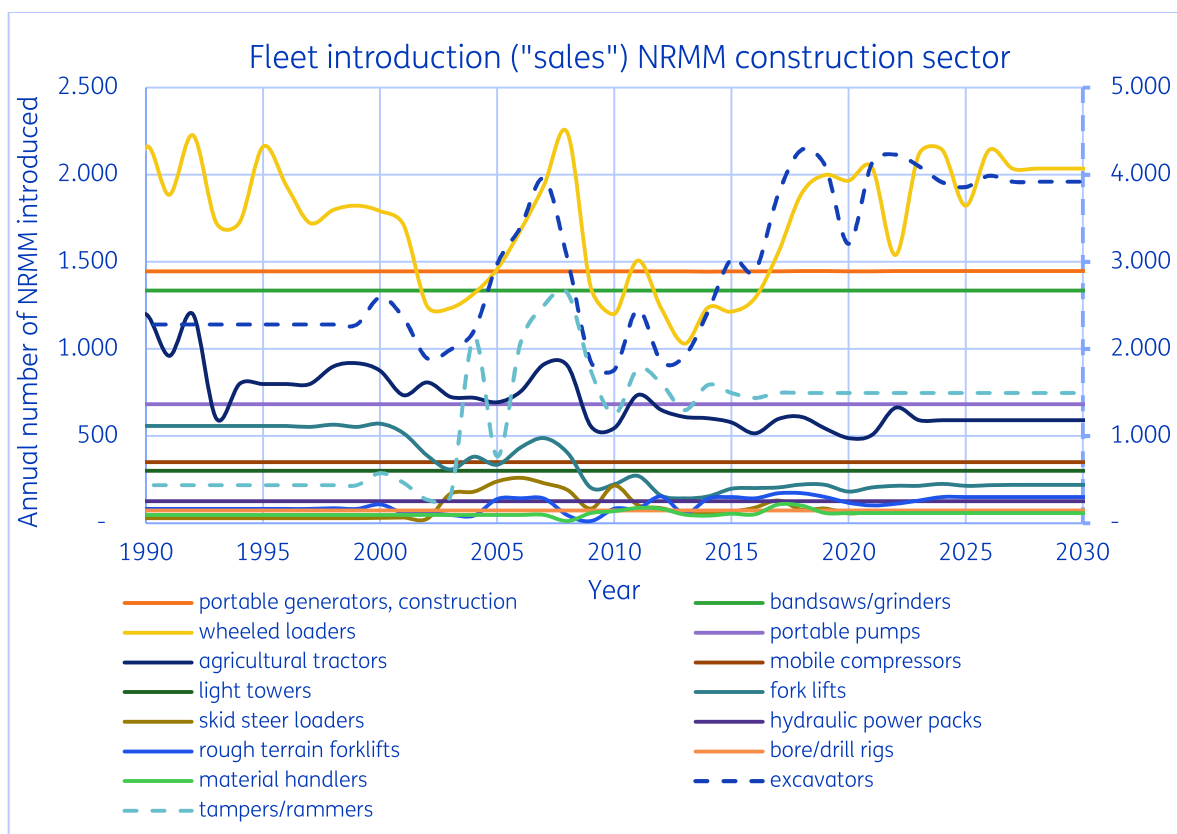


Figure 10: Fleet introduction NRMM construction sector, excavators and tampers/rammers on right Y-axis

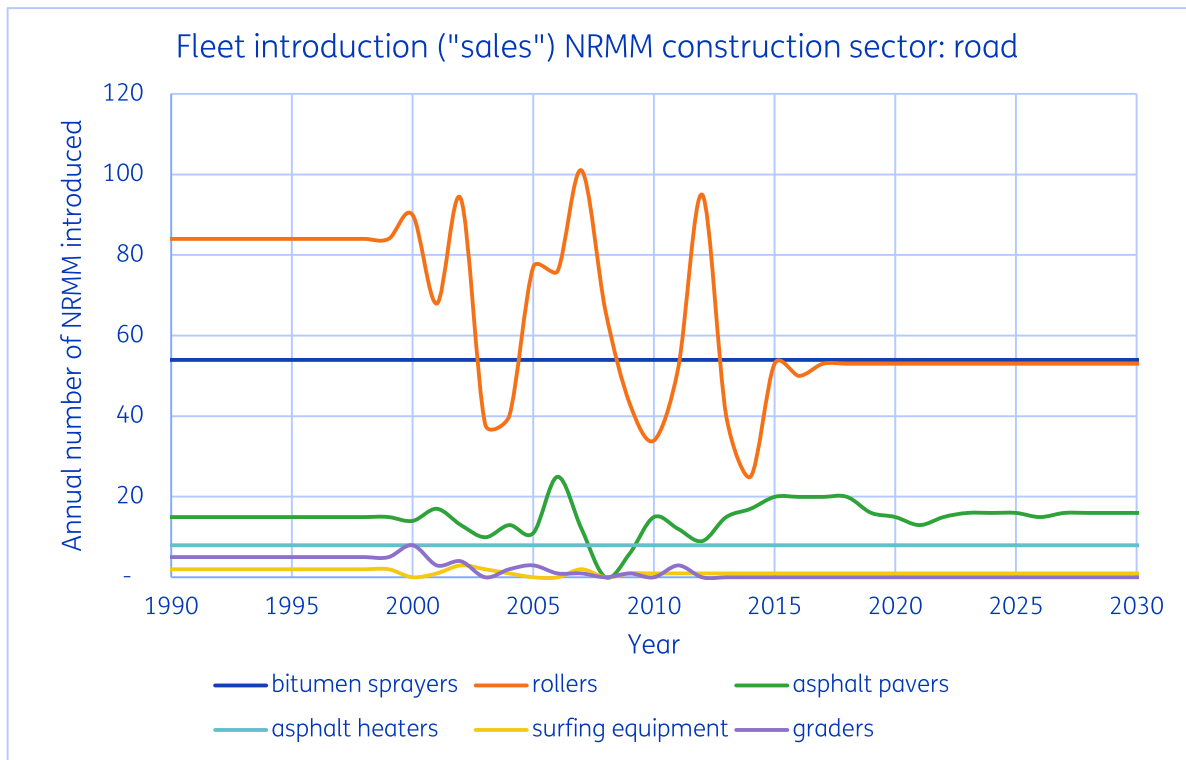


Figure 11: Fleet introduction NRMM road construction

4.2 Technology splits

Figure 12 to Figure 15 present the modelled technology splits in terms of machinery numbers for machinery in the two most dominant sectors: agriculture and construction, and for two of the most dominant NRMM types: tractors and excavators.

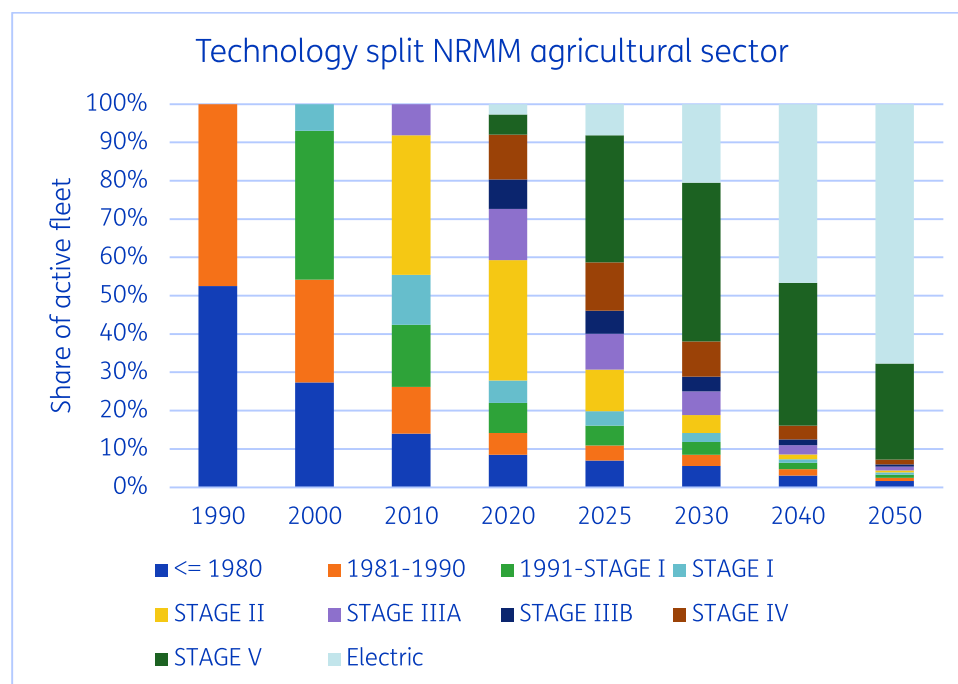


Figure 12: Modelled technology split by reporting year for NRMM in agriculture sector

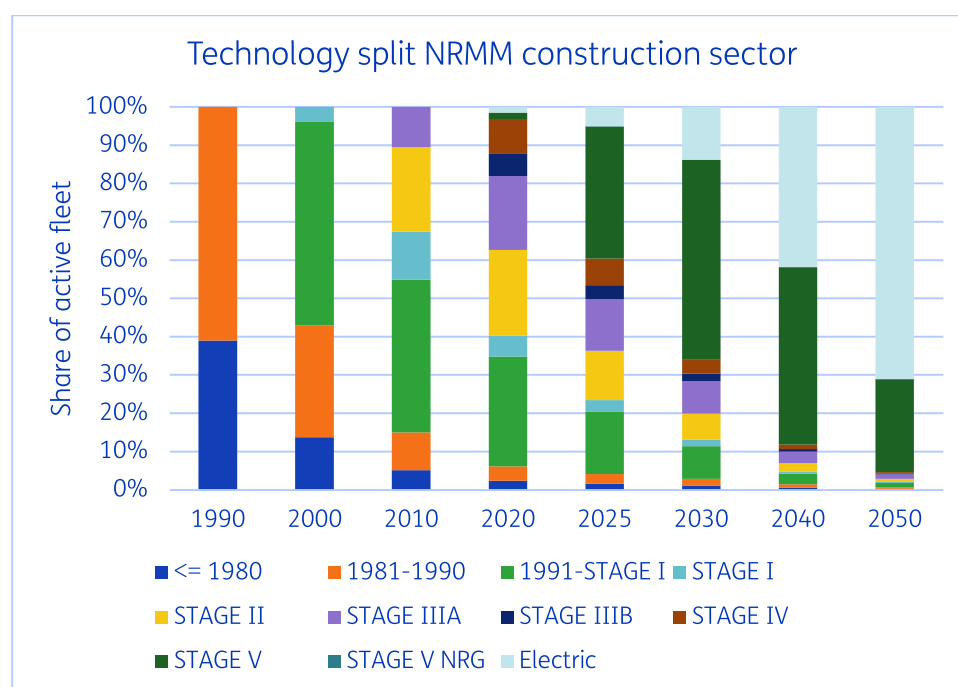


Figure 13: Modelled technology split by reporting year for NRMM in construction sector

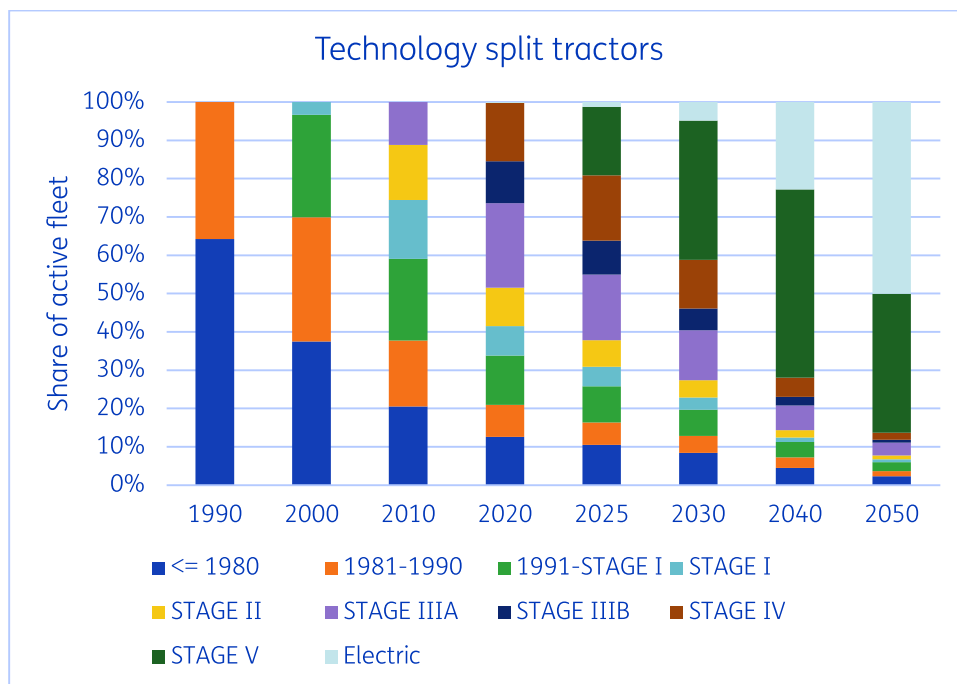


Figure 14: Modelled technology split by reporting year for tractors

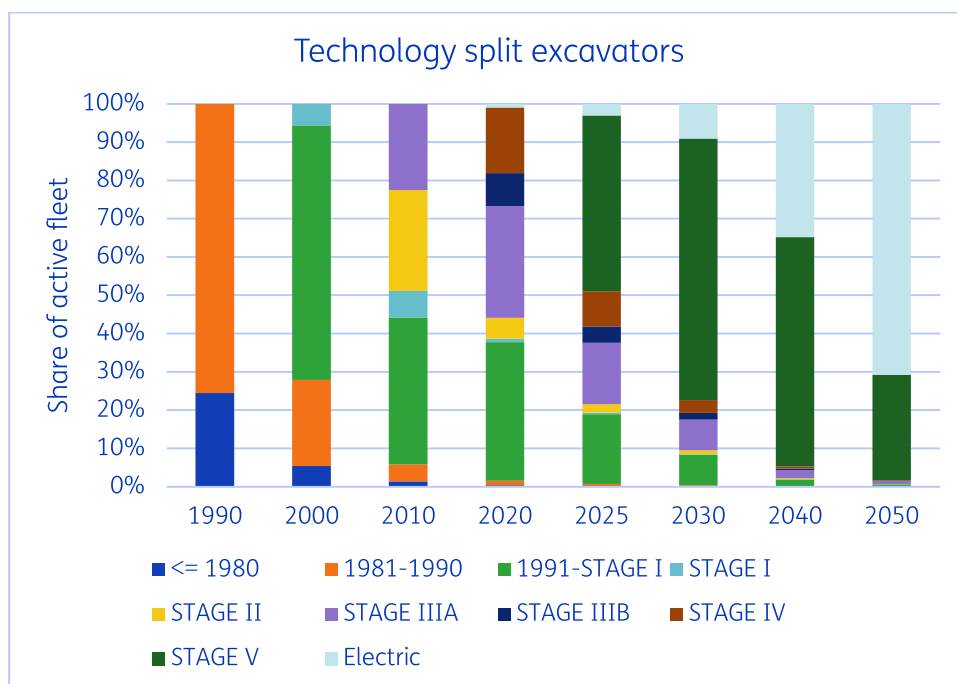


Figure 15: Modelled technology split by year for excavators

4.3 Fuel consumption

The model calculates the fuel consumption and emissions for each reporting year and unique machinery configuration. As such, the model output can be analysed and presented in a large number of ways.

4.3.1 Historic

Figure 16 below shows the model output for fuel consumption in 2022 by NRMM type. Figure 17 shows the modelled fuel consumption by fuel type for historic years.

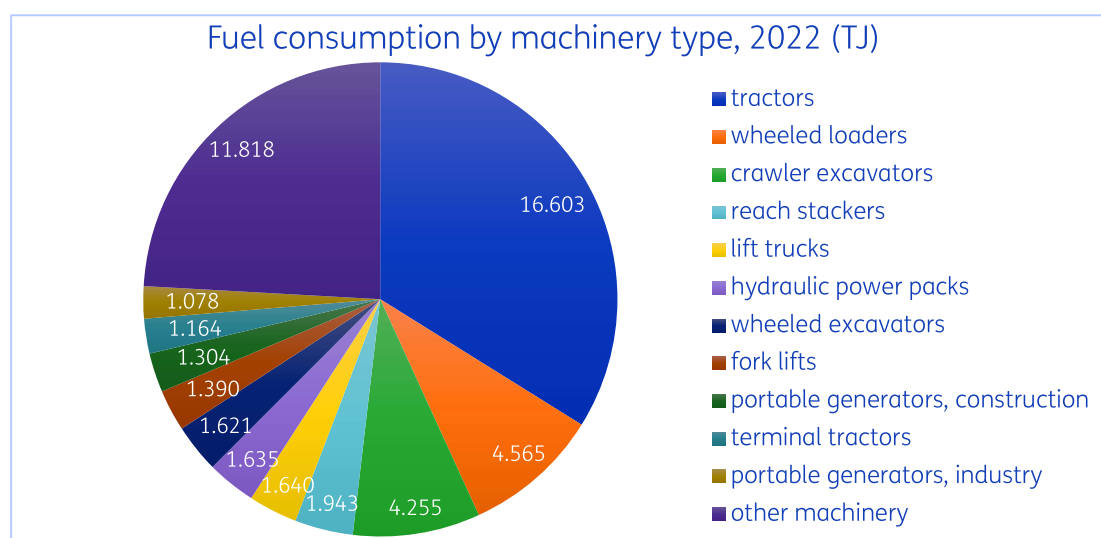


Figure 16: Overview fuel consumption by machinery type, for 2022

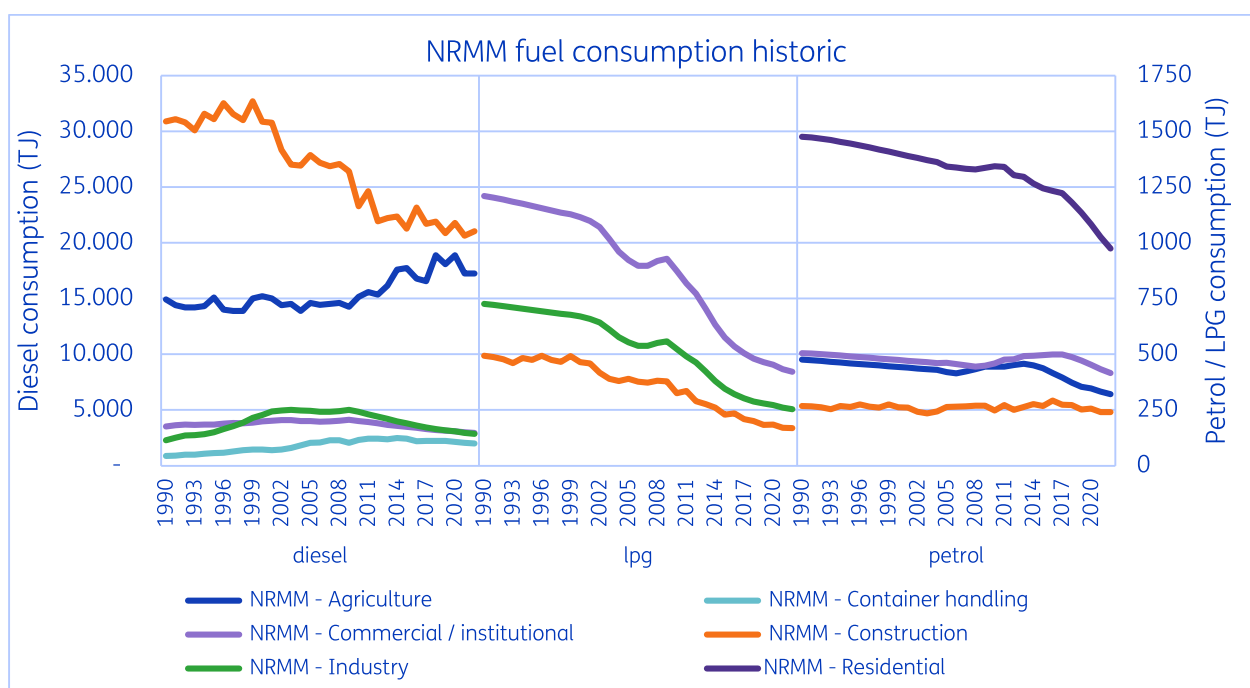


Figure 17: NRMM historic fuel consumption

4.3.2 Projections

Figure 18 shows the fuel consumption by sector, based on model projections up to 2050. Note that these projections are based on the models' default projection parameters, which are not linked to actual policy or economic projections. The results are shown only for illustration purposes. Actual projections using the EMMA-MEPHISTO model are published periodically by PBL in their Dutch Climate and Energy Outlook (KEV) (PBL, 2021).

In general, the fuel consumption is reduced over time due to increased engine efficiency and a shift to electric machinery, while being also dependent on expected activity in the sectors. Electricity consumption will increase due to a shift to electric machinery (see Figure 19). In the current implementation, the electricity consumption of container handling and GSE are not yet modelled.

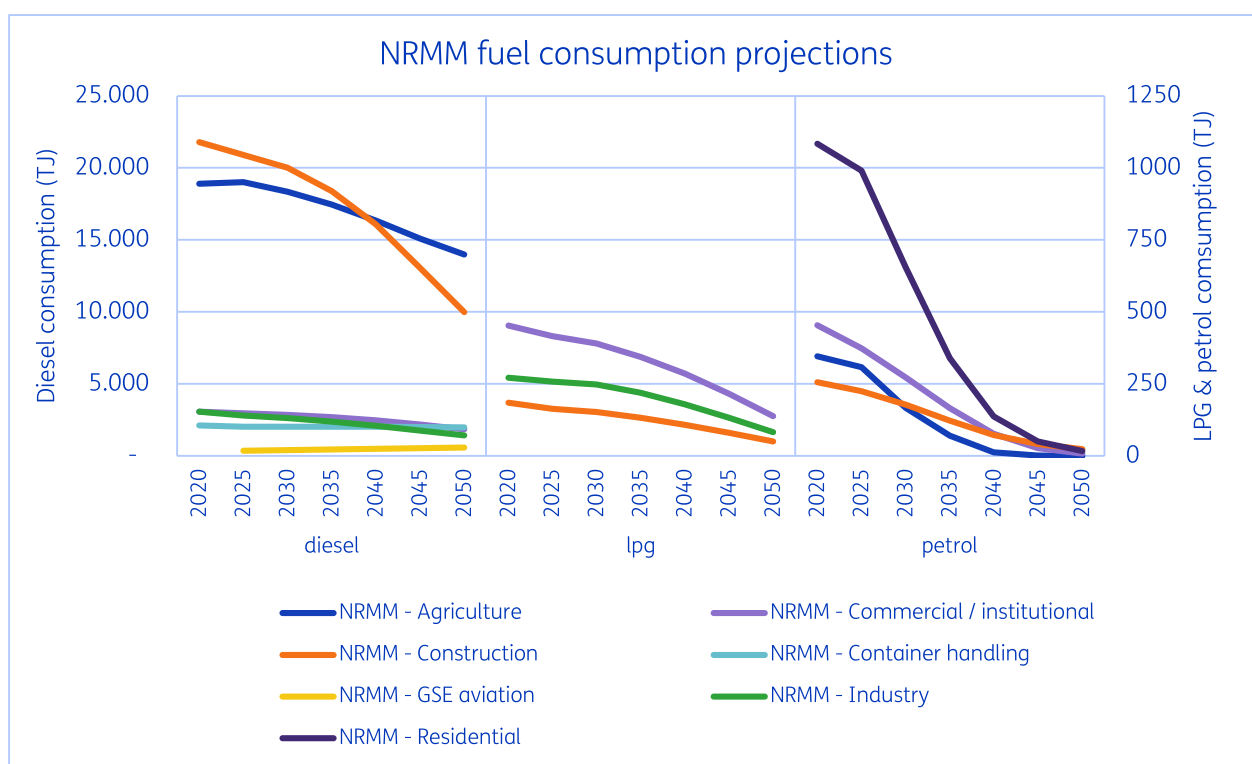


Figure 18: NRMM - Fuel consumption projections “default”, for illustration purposes

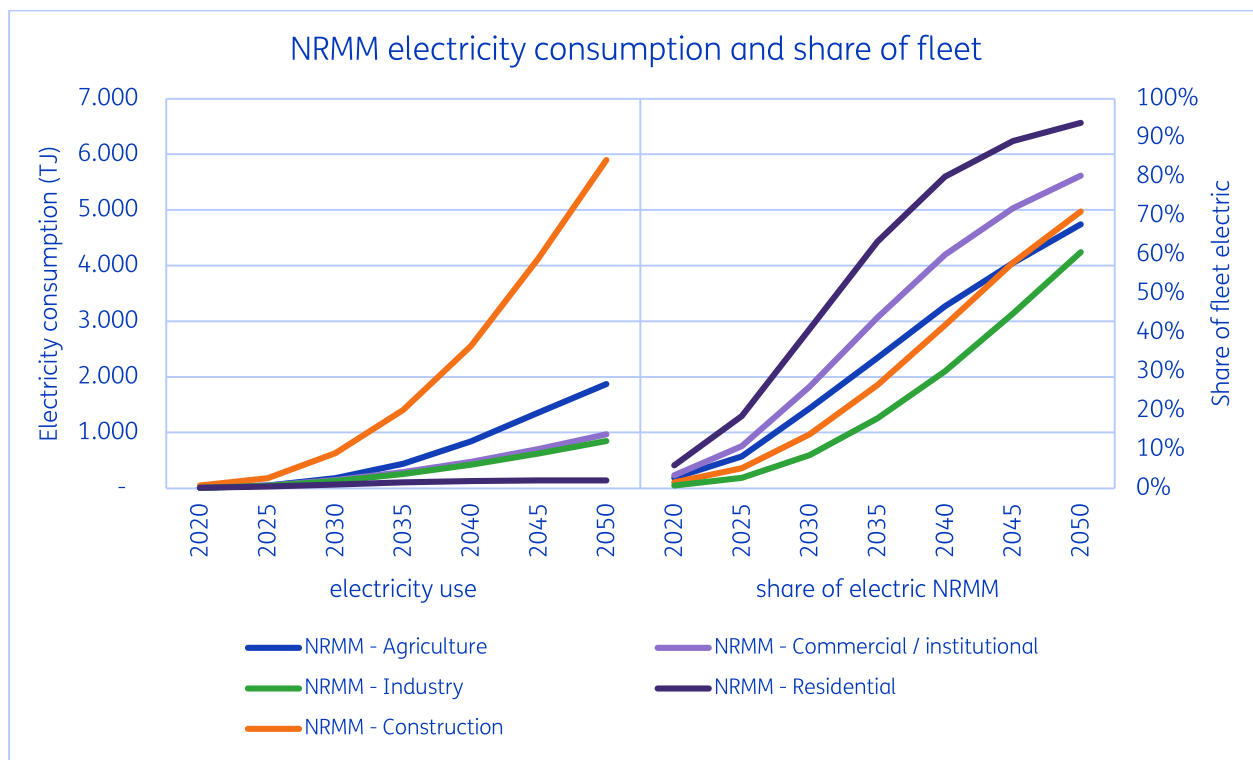


Figure 19: NRMM - Electricity consumption and electric machinery fleet projections “default”, for illustration purposes

4.4 Emissions

4.4.1 Historic

Figure 20 and Figure 21 show the NRMM emissions by sector for historic years. NH₃ emissions show a steep increase since the introduction of SCR catalysts (Stage IV and V), as the abatement of NO_x emissions comes at the cost of increased NH₃ and N₂O emissions.

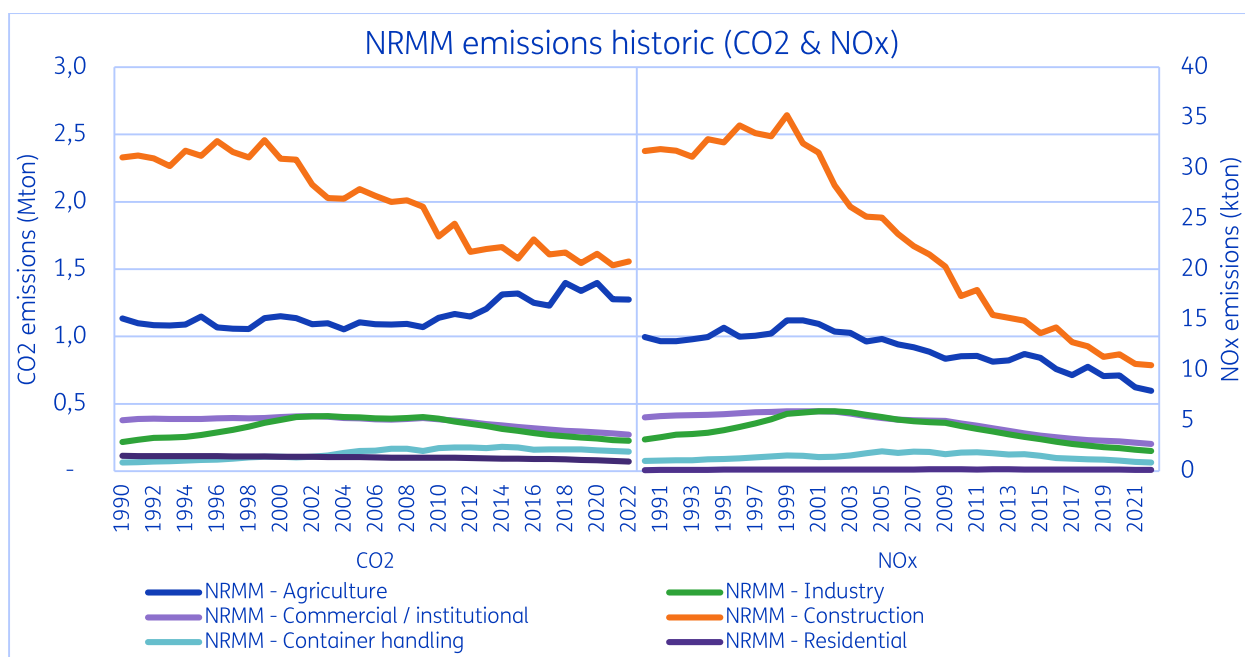


Figure 20: NRMM - CO2 and NOx emissions historic

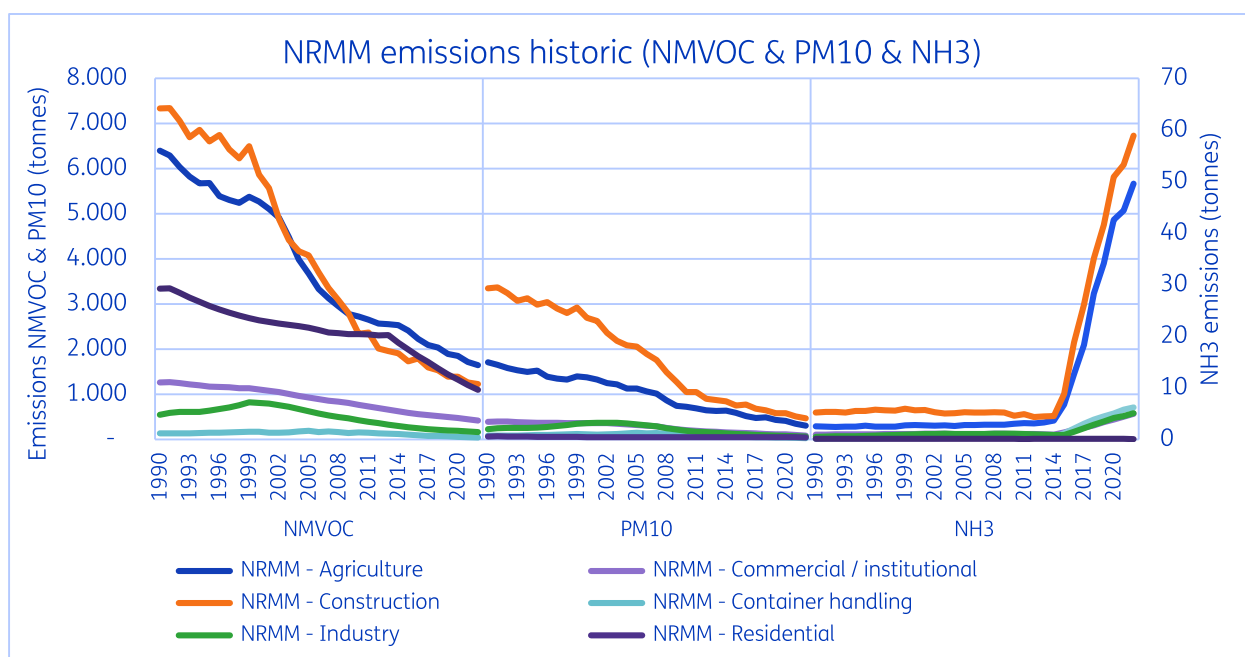


Figure 21: NRMM – NMVOC, PM10 and NH3 emissions historic

4.4.2 Projections

Figure 22 and Figure 23 show the emissions by sector, based on the model projections up to 2050. Note that these projections are based on the models' default projection parameters, which are not linked to actual policy or economic projections. The results are shown only for illustration purposes. Actual projections using the EMMA-MEPHISTO model are published periodically by PBL in their Dutch Climate and Energy Outlook (KEV) (PBL, 2021).

In general, total emissions are expected to decline due to improved engine efficiency and emission control technologies, and a shift to electric machinery, while being also dependent on expected activity in the sectors.

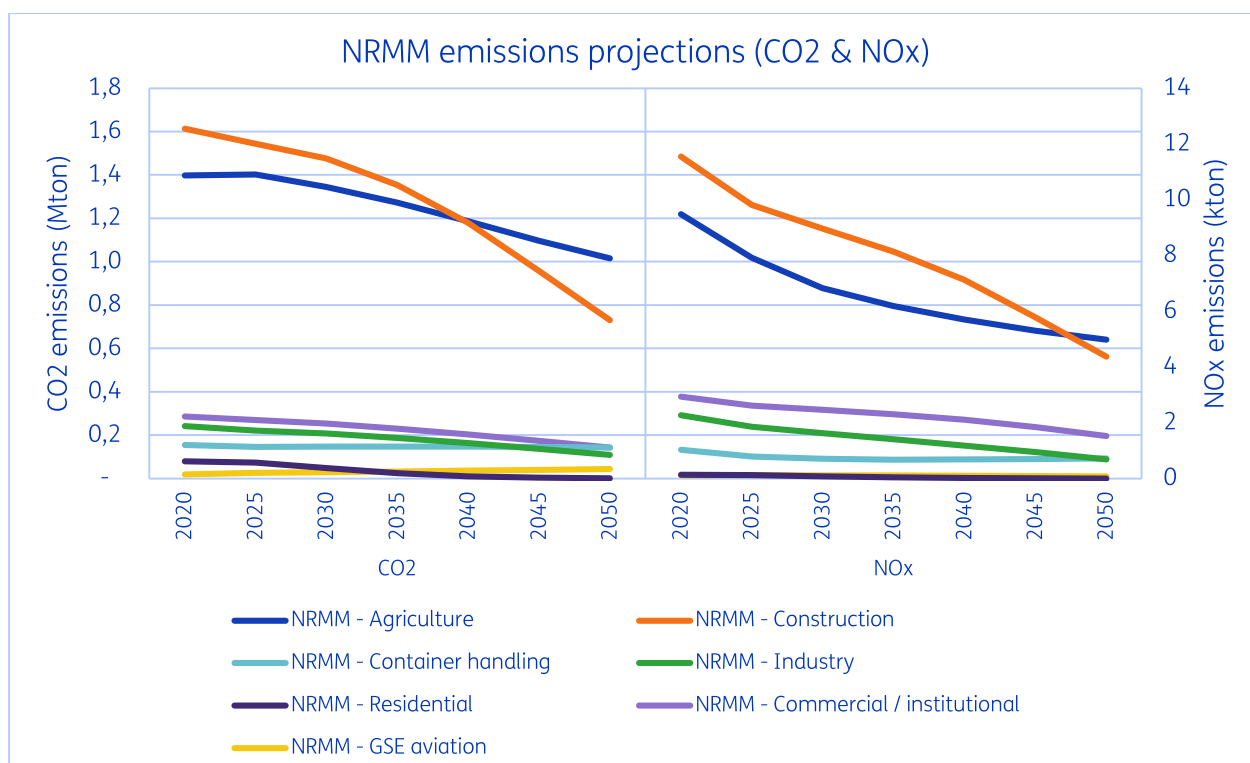


Figure 22: NRMM - CO2 & NOx emission projections “default”, for illustration purposes

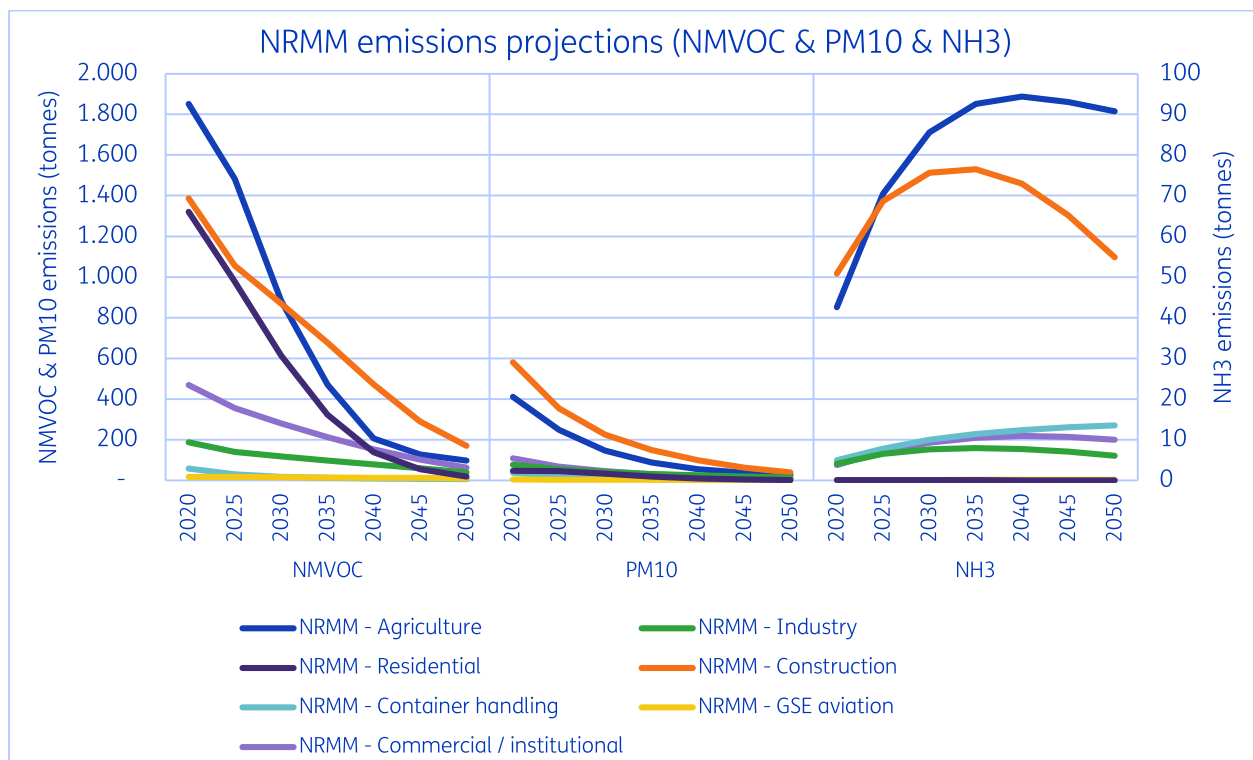


Figure 23: NRMM – NMVOC, PM10 and NH3 emission projections “default”, for illustration purposes

5 Discussion

This chapter reflects on the uncertainties, validation and suggestions for future improvement of the model.

5.1 Uncertainties

NRMM represents a broad range of machinery across many types of sectors, applications, users, and configurations. There is only a partial registration of the current NRMM fleet and limited data on the historic fleet. Moreover, in most cases there is no registration of actual active hours, fuel use, maintenance, engine load and most other factors that influence real-world emissions. For this reason, emission calculations are dependent on limited data and various assumptions to arrive at a good approximation of the emissions.

In 2016, an expert workshop was organized with the members of the Taskforce Transportation of the Dutch PRTR. In this workshop, the uncertainties in the activity data and emission factors used for the emission calculations for the transport sector were discussed and estimated. These estimates were based on the confidence in and known limitations of current data and insights. Uncertainties were estimated at the level of the source categories. The setup and outcomes of the workshop are described in Dellaert & Dröge (2017).

With every significant model update, the uncertainties are re-evaluated and updated when appropriate. The currently estimated uncertainties are shown in Table 11 below. The most up-to-date uncertainty values can be found in the methodological report of the Taskforce Transportation (latest version is Geilenkirchen et al., 2023).

Uncertainty in activity data is deemed highest for petrol-fuelled machinery due to limited insight in the major machinery types. Uncertainty in emission factors is lowest for NO_x and SO₂ and large for PM, EC, NH₃ and NMVOC due to a lack of emission measurements across a range of machinery types.

Table 11: Uncertainty estimates for NRMM activity data and emission factors

Sector	Fuel type	Uncertainty activity data	Uncertainty implied emission factors					
			NO _x	SO _x	NH ₃	PM ₁₀ /PM _{2.5}	EC	NMVOC
Construction	Petrol	100%	50%	20%	200%	100%	100%	100%
	Diesel	50%	50%	20%	200%	100%	100%	100%
Industry	Diesel	50%	50%	20%	200%	100%	100%	100%
	LPG	50%	50%	20%	200%	100%	100%	100%
Commercial / institutional	Petrol	100%	50%	20%	200%	100%	100%	100%
	Diesel	50%	50%	20%	200%	100%	100%	100%
Container handling	Diesel	50%	50%	20%	200%	100%	100%	100%
Residential	Petrol	100%	100%	20%	200%	200%	200%	200%
Agriculture	Petrol	200%	100%	20%	200%	200%	200%	200%
	Diesel	35%	50%	20%	200%	100%	100%	100%

5.2 Validation

Validation of the model results is important to increase confidence in the results and find the most urgent areas where further model improvement is needed. For NRMM, validation of the results has proved challenging for several reasons:

- › There exists no separate registration of fuel sales for use in NRMM. Statistics Netherlands (CBS) cannot distinguish the fuel sales of diesel, petrol and LPG between NRMM and road transport;
- › Most branch organizations have limited information on the machine fleet and fuel consumption of their members;
- › There is no public data available on annual hours or mileage from periodic technical inspections of machinery (as is available for most road vehicles);
- › There is very limited public data on machine sales in the Netherlands;
- › There is only partial registration of the current machine fleet and a lack of historic fleet data.

There are currently a few routes for validation:

1. **Historic sales data of ‘red’ diesel, from 1990 – 2012.** During this period, there existed a separate tax regime for fuel used for NRMM. Therefore, the diesel consumption could be roughly separated between NRMM and road transport. This is explained further in section 5.2.1 below.
2. **Comparison and scaling of diesel consumption in the agricultural sector with fuel sales statistics derived from companies’ financial administration.** This is explained further in section 5.2.2 below.
3. **Continued involvement of branch organizations when implementing large model changes.** As done before in the development of the original model and in implementing changes following the machine user survey (Hulskotte & Verbeek, 2009; Dellaert et al., 2021).

5.2.1 ‘Red’ diesel

Figure 24 shows the comparison between the historical ‘red’ diesel, i.e., non-road or No. 2 diesel with lower fuel excise taxes until 1-1-2013, sales statistics for 1990 – 2012 and the EMMA modelled NRMM diesel consumption. It should be noted that the red diesel statistics are also subject to various uncertainties (e.g. due to its lower tax regime, red diesel may have been used in other vehicles besides NRMM). Furthermore, there is no distinction between NRMM sectors or machinery types. The current model version appears to recreate the fuel sales statistics more accurately than the original model version. Still, there appears to be an underestimation of fleet usage, size and fuel consumption in the period 1990 – 1998. Also, the model appears to underestimate the effects of the financial crisis on the NRMM sector in the period 2008 – 2011.

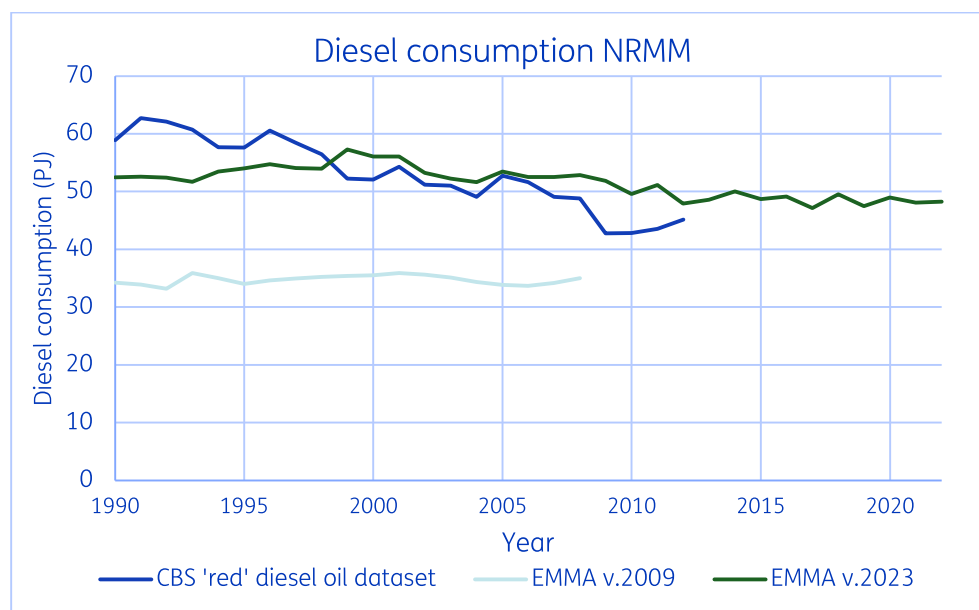


Figure 24: Validation diesel consumption NRMM

5.2.2 Agricultural NRMM diesel consumption

Figure 25 shows the comparison between the uncorrected model results on agricultural NRMM diesel consumption and the data collected by WEcR and CUMELA, on the basis of the financial administration of a sample of agricultural companies (WEcR, 2023; CUMELA, 2022). As discussed in section 3.2.5.1, the uncorrected model results are scaled to match the branch data. However, if the fleet composition and usage in the model are accurate, the model should yield similar results to the diesel consumption estimate from the branch. The figure shows that the current model fails to reproduce an ongoing growth in diesel consumption since 2010.

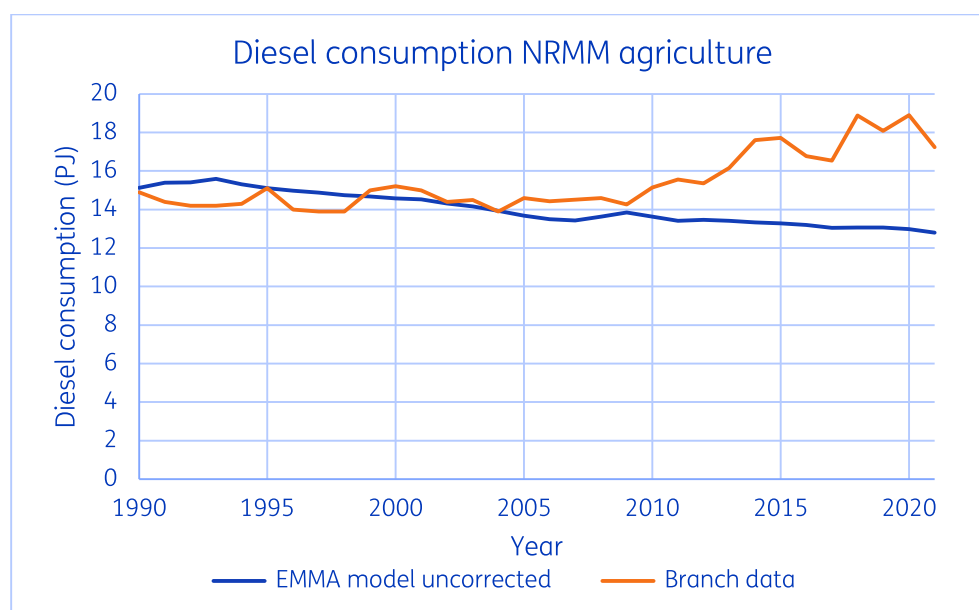


Figure 25: Validation diesel consumption NRMM agriculture

5.3 Future improvements

The EMMA-MEPHISTO model has been under continuous development since its creation and every year potential improvements are considered, discussed, and implemented. Below, the most important points of improvement are listed that can improve the completeness, consistency, accuracy and reliability of the model in the future:

- › Further implement the use of RDW registration data to:
 - Improve the machine fleet composition;
 - Derive introduction rates for zero-emission machinery, such as electric and hydrogen fuel cell powered machinery;
 - Improve survival function and typical lifetime by machine type;
 - Get insight into import and export of machinery.
- › Improve insight in the actual usage of machinery, including annual hours and the effects of various parameters on the machinery usage:
 - Machine age;
 - Machine rental, lease or direct ownership;
 - Economic or policy developments in the relevant sectors (e.g. better recreating the effect of the economic crisis between 2008 and 2011, see section 5.2.1).
- › Improve engine load profiles based on real-world engine telemetry data;
- › Improve fuel- and emission factors based on real-world emission measurements, including quantification of the effects of machine aging, wear, tampering and maintenance;
- › Improve fleet composition and usage data on hand-held and consumer machinery, for which current estimates are highly uncertain;
- › Improve sophistication of fleet and emission projections, e.g.:
 - Model effects of expected shift to lower engine power due to less restrictive emission limit values in the emission legislation;
 - Electricity-producing machinery such as generators should be dropped from the model when they are replaced by cabled electricity supply.
 - Adjust fuel consumption function to better account for physical efficiency limits (see section 3.2.3.1).
- › Further validation of model outcomes through comparison with fuel statistics and/or data collected by branch organisations.

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Signature

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Appendix A

List of pollutants

Table 12: List of pollutants calculated by the EMMA - MEPHISTO model

Pollutant	Calculation method
CO	Engine derived
HC	Engine derived
NH ₃	Engine derived
NO _x	Engine derived
PM	Engine derived
CO ₂	Fuel derived
Dioxins (PCDD/PCDF, I-TEQ)	Fuel derived
Heavy metals total	Fuel derived
N ₂ O	Fuel derived
SO ₂	Fuel derived
Arsenic & compounds (as As)	HM profile
Cadmium & compounds (as Cd)	HM profile
Chromium & compounds (as Cr)	HM profile
Copper & compounds (as Cu)	HM profile
Lead & compounds (as Pb)	HM profile
Mercury & compounds (as Hg)	HM profile
Nickel & compounds (as Ni)	HM profile
Selenium & compounds (as Se)	HM profile
Zinc & compounds (as Zn)	HM profile
Acenaphthene	PAH profile
Acenaphthylene	PAH profile
Anthracene	PAH profile
Benz(a)anthracene	PAH profile
Benzo(a)pyrene	PAH profile
Benzo(b)fluoranthene	PAH profile
Benzo(g,h,i)perylene	PAH profile
Benzo(k)fluoranthene	PAH profile
Chrysene	PAH profile
Dibenzo(a,h)anthracene	PAH profile
Fluoranthene	PAH profile
Fluorene	PAH profile
Indeno(1,2,3,c,d)pyrene	PAH profile
Naphthalene	PAH profile
Phenanthrene	PAH profile

Pyrene	PAH profile
1,3-Butadiene	THC profile
1-Methylnaphthalene	THC profile
2,2,4-Trimethylpentane	THC profile
2-methylnaphthalene	THC profile
Acetaldehyde	THC profile
Acetylene	THC profile
Acrolein	THC profile
Benzene	THC profile
Crotonaldehyde	THC profile
Ethane	THC profile
Ethanol	THC profile
Ethene	THC profile
Ethyl Benzene	THC profile
Formaldehyde	THC profile
Hexane	THC profile
Isobutane	THC profile
Isoprene	THC profile
Isopropyl Benzene	THC profile
Methane	THC profile
N-butane	THC profile
Other NMVOC	THC profile
Propane	THC profile
Propionaldehyde	THC profile
Propylene	THC profile
Styrene	THC profile
Toluene	THC profile
Xylenes	THC profile

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