QUANTIFICATION OF PAVING EQUIPMENT EMISSIONS ON ASPHALT CONSTRUCTION SITES

19-08-2020

Rebecca Bock
BSc Thesis Civil Engineering
Faculty of Engineering Technology
University of Twente
In Cooperation with Dura Vermeer

Internal Supervisors:
Dr. Seirgei Miller
Afshin Jamshidi

External Supervisors:
Dr. Stephen Mookhoek
Marleen Versteegen

Contributors

Student	Rebecca Bock	
Student Number	s2028670	
Email	r.bock@student.utwente.nl	
External Organization	Dura Vermeer Infra BV	
Address	Taurusavenue 100	
Postal Code	2132 LS, Hoofddorp	
Country	Netherlands	
External Supervisors	Dr. Steven Mookhoek	Marleen Versteegen
Position	Manager Asfaltproces	Adviseur Duurzaamheid
Email	s.mookhoek@duravermeer.nl	m.versteegen@duravermeer.nl
University	University of Twente	
Address	Drienerlolaan 5	
Postal Code	7522 NB, Enschede	
Country	Netherlands	
Faculty	Engineering Technology	
Program	Bachelor of Civil Engineering	
Internal Supervisors	Dr. Seirgei Miller	Afshin Jamshidi
Email	s.miller@utwente.nl	a.jamshidi@utwente.nl

Preface

This thesis was written as part of the bachelor program in Civil Engineering at the University of Twente. It was developed in cooperation with Dura Vermeer and the help of the ASPARi research group.

I want to thank Seirgei Miller and Afshin Jamshidi, for their supervision during this process. For taking their time to read through drafts and revisions of texts and give feedback and ideas to improve them. For helping me develop this research from the idea to the final report. For helping me reframe the research time and time again when the research approach was turned upside down several times due to a lack of available data. For reaching out to their contacts to help me collect data. For giving me ideas of what to focus the research on when I needed the help.

I also want to thank Marleen Versteegen and Steven Mookhoek, for their time and dedication to this research. For spending their time looking for data to support the project, answering my many questions on the documentation and procedures in the company, and sitting through meetings of trying to find different ways to help out further.

I also want to thank the companies, who so freely provided me with data that was crucial to my research.

Finally, I want to thank my family and friends for supporting me during this research period and helping me get through the difficulties.

Rebecca Bock

Enschede, 19-08-2020

Summary

The research focuses on the use of a model to predict emissions from paving equipment on a project-scale. With the growing importance of emission reduction and emission reporting, companies try to keep their impact on the environment as low as possible. For a long time, emissions of non-road machinery were dismissed as being of little significance, but in recent years predictions have shown that they have a large impact on air quality especially in urban areas. Previous studies of current models have shown large uncertainties on a smaller scale and emission factors that poorly reflect in-use emissions. Despite the increased attention to non-road machinery, a large data gap surrounds paving equipment emissions.

This study investigates the question: "***How can emissions modeling help Dura Vermeer estimate the impact of measures to reduce nonroad emissions on asphalt construction sites and what parameters could be adjusted to improve the accuracy of the model?***" In this research, two different emission reduction measures are considered, on the one hand replacing older machines with newer ones that have higher emission standards, and on the other hand switching the fuel used from regular diesel to HVO fuels or blends of the two.

Much of this study was based on a literature review, further data sources were Dura Vermeer and four companies from the ASPARi group. The provided data included vehicle specifications, fuel consumption data, and load factors from in-use vehicles. The focus of the literature review was the current emission models and their calculation procedures. Also, the uncertainty of the models and studies evaluating the assumptions made in the model were considered. Based on the literature review an emissions model was then chosen and restructured to better fit the intended purpose. The data collected was used to adjust the model, provide the input data, and provide comparative values for the results.

The expectation was that a model would show the effect of different emission reduction measures on the amount of the pollutant emitted and the environmental cost indicator (ECI) connected to the emissions. This proved only partly true, as the NOx and PM emissions were significantly reduced by both considered measures, but the ECI of the emissions was largely unaffected. This connects to the measures lacking influence on the CO2 emissions, which contribute to 99% of the ECI. The model further shows that each pollutant requires a different strategy to reduce the pollutant emissions and that the effectiveness of each strategy depends on the intent and initial emissions of the vehicle.

Further findings showed that the idling rate was more influential on the emissions than expected. The results indicate a correlation between high idling rates and lower emissions. Another finding was a confirmation of the large uncertainty and lack of measurements when connecting the parameters to emission values, that was already expected from the literature review. The research highlights the need for company internal emission measurements and the necessity to add further parameters to the model.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

In a society more and more adept to the impacts it has on its environment, air quality and emissions have long been talked about. Especially in the past three decades, the research on air pollution and its effects on climate change were put into focus. Air pollution is a worldwide problem and all nations are responsible to reduce the pollution created. A large factor in air pollution and climate change are emissions from internal combustion engines as they contain many harmful substances. Vehicle emissions include greenhouse gases (GHGs) like carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), as well as harmful gases and airborne particles such as carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), hydrocarbons (NMHC or NMVOC) and particulate matter (PM_{10} & $PM_{2.5}$) (Litman, 2009).

All of these pollutants have their own harmful effects on the environment and human health. The GHGs from transport are some of the biggest contributors to climate change, while the other pollutants negatively affect human health. (Litman, 2009) They are related to respiratory and cardiovascular diseases, affect the pulmonary functions, and can cause irritation of the airways. Further, air pollution is connected to cancer and asthma. (Sule, 2013) The WHO (2020) estimates that around 7 million people die every year from health problems caused by air pollution $PM_{2.5}$ has the biggest impact on mortality and is responsible for over 50% of these deaths, but other pollutants are just as toxic. (WHO, 2020a) This toxicity is caused by the substance's reactive potential. Especially SO_2 and NO_2 are highly reactive and some of the biggest contributors to the formation of secondary pollutants like ground-level ozone, as well as smog and acid rain.

The construction industry is one of the biggest contributing industries for emissions. It is responsible for almost a fourth of global air pollution (Snook, 2017). The emission sources in the industry depend on the construction phases, and most pollution comes from the material production and the in-use phase of the construction process. In the past, most of the research towards making the industry more sustainable had been focused on these two areas. Very little focus is given to direct emissions during the actual construction process of a building (Junila, Horvath, & Guggemos, 2006), which makes up only 1% of the total construction emissions (Department for Business, Innovation and Skills, 2010). However, these emissions can be very harmful to workers on the construction sites and affect the local environment, i.e. the air quality (Fan, 2017). Especially in cities already struggling with emissions and air quality improvement, these emissions contribute to the severity of the problems.

During the construction process, most of the emissions are emitted by the construction equipment. Construction equipment is comprised of on-road vehicles such as trucks and NRMMs such as excavators, dumpers, or generators. The primary source of emissions is the fuel combustion process, but also tire wear, road surface wear, and resuspension contribute to the total emissions (Boulter, McCrae, & Barlow, 2007). Due to the fossil nature of the pollutants, the highest emission factor is related to CO_2, which makes up about 12% of all exhaust gases (Reşitoğlu, Altinişik, & Keskin, 2015) Because of the impacts these pollutants can have, their emissions should be regulated and monitored. Especially in the Netherlands, there have been many problems with NO_x in the recent past, with the Netherlands emitting four times the EU average per capita (Meijer, 2019). Other reasons for reducing emissions are reduced costs due to fuel-saving and compliance with government regulations (Lewis, Rasdorf, Frey, Pang, & Kim, 2009).

To reduce emissions, it is necessary to first quantify and analyze the emissions. This report proposes a model to help Dura Vermeer monitor and improve its emissions. First, it explores the current problems with emissions quantification and introduces the steps taken to implement such a model. Further, it will explore the model and its parameters. Then it will look into the uncertainties of the model and finally propose ways for Dura Vermeer to reduce this uncertainty.

1.1 Problem Context

The main source for on-site emissions is the construction equipment (Fan, 2017), but for a long time, these emissions were not looked at closely, due to a perceived lack of significance. With developments to decrease the emissions in other parts of the construction process, the focus has now shifted to making a construction site itself more sustainable and also consider the impact of the direct emissions at the construction site. However, researchers claim the "lack of comprehensive data and generic methodology has restricted" (Sandanayake, Zhang, & Setunge, 2018) the progress in this field.

Researchers see the role of construction equipment emissions in relation to the total emissions very differently. In a study by Sandanayake, Zhang, and Setunge (2018), the emissions of equipment usage made up 7% of the whole construction process. In a different research by Liu, Wand, and Li (2017), the results showed an impact of the equipment usage of 11-45% depending on the type of road constructed. The UK Department for Business, Innovation, and Skills (2006) released a report saying the emissions from equipment are responsible for about 6% of the total construction process emissions.

Independent of the total emissions of a project, NRMMs are responsible for a large part of internal combustion engine emissions. 90% of the fuel used for NRMM is diesel (Helms, Lambrecht, & Knörr, 2010), which has higher values of PM and NO_x than other fuels (Reşitoğlu, Altinişik, & Keskin, 2015). Figure 1 shows the average composition of diesel emissions. The dominant pollutant is CO_2 related to fossil fuel combustion, with about 12% of the exhaust gases. Just in the Netherlands, it is estimated that 9% of the CO_2 emissions relate to NRMM usage (Ligterink, Louman, Verbeek, & Buskermolen, 2018). But other toxic substances like CO, NMVOC, NO_x, SO_2, and PM are also emitted during the combustion process (Fan, 2017).

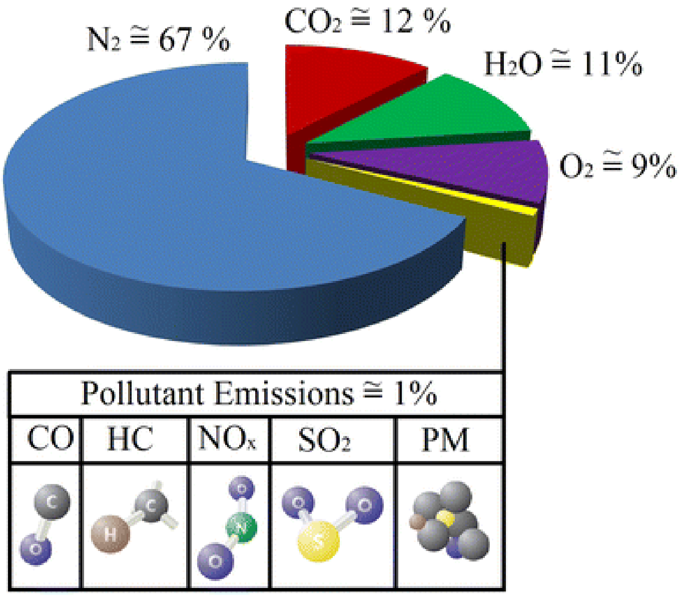


Figure 1: Composition of Diesel Exhaust Gas (Reşitoğlu, Altinişik, & Keskin, 2015)

The construction industry is one of the biggest polluters through NRMM. It is the second-largest consumer of fuel for NRMM after agriculture, the largest emitter of CO, and the second largest for PM and NO_x. (Helms, Lambrecht, & Knörr, 2010)

As shown in Figure 2, the construction industry emits 6% of the total NO_x and 10% of the total PM emissions from mobile sources in Germany. This agrees with data from the Greater London Authority (2016), which estimates that at least 7% of NO_x emissions, 8% of PM_{10} emissions, and 14.5% of $PM_{2.5}$

emissions come from construction equipment. The PM emissions of only one bulldozer are as high as those of 500 cars (Clean Air Act Advisory Committee, 2006).

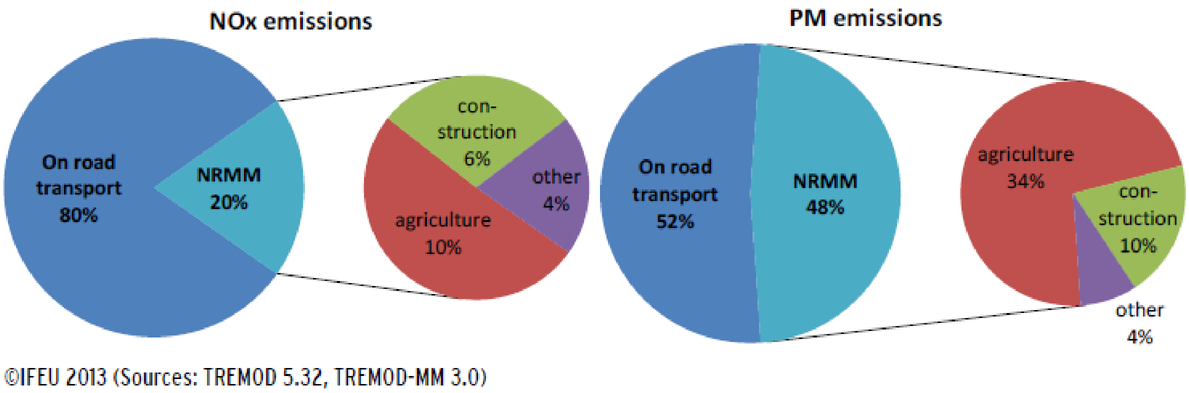


Figure 2: Comparison of NO_x and PM Emissions from the On-road Sector and the NRMM Sector (Helms & Heidt, 2014)

While there are different ways to calculate emissions, there are uncertainties on the methodology of quantifying emissions from construction equipment and what parameters are important for their calculation. Some researchers claim only the fuel consumption is important for the calculation of the emissions and use the average hourly fuel consumption of a vehicle to calculate emissions (Liu, Wand, & Li, 2017; Sandanayake, Zhang, & Setunge, 2018), but other researchers claim that especially on a project-based level these are difficult to quantify due a complex assortment of parameters affecting the fuel consumption (Barati & Shen, 2016).

Barati and Shen (2016) conducted a study to determine the parameters affecting the emission rates of construction equipment and showed that there is a strong linear relationship between the engine load and emissions with a correlation of >90%. They also determined the most influential parameters on the engine load as acceleration, slope, and speed. Some of the other parameters for the emissions in their study were the payload, the engine size, and the fuel type. A different study by Heidari and Marr (2015) also claims site altitude, humidity, and temperature as influential. They further investigated the differences between emission rates during different operational modes and found that especially idling and hauling had significantly different emission rates compared to other activities.

Several models have been developed to estimate emissions. Models using the aggregated approach are very simple and calculate emissions based on the general specifications of a vehicle. Parametric models use driving patterns for more accurate results. Modal models further consider the effect of engine size and power and different operational modes of vehicles. Simulation-based models include detailed parameters such as emission rates, fuel consumption, and fuel type and make use of driving patterns and engine specifications. (Barati & Shen, 2016)

There have been different attempts to assess the model validity. Barati and Shen (2016) used Portable Emissions Measurement System (PEMS) devices for measuring emissions and measuring equipment for different model input parameters. They compare their results to a model using parameters similar to OFFROAD and determines that the model has a 90% accuracy, which is acceptable but could be improved. Heidari and Marr (2015) provide another comparison between models and measured data also using the PEMS system for field measurements. They compare the observed data to NONROAD, one of the most prolific models, and MLR (modular linear regression). At the same time, they assessed the variability in emissions during different activities. The results show that the measured CO_2 emissions are 60-95% lower than the NONROAD predictions and 70% higher to 70% lower than the MLR predictions. Similar discrepancies were found for other pollutants. Their studies also show that the results are worse for vehicles with integrated emission control methods. The authors conclude that these discrepancies likely result from a lower fuel consumption than predicted by the models and emission rates should be tested under real-life conditions and recommend more frequent updates of vehicle databases. (Heidari & Marr, 2015)

In conclusion, there seems to be a consensus on the complexity of emission calculation, especially on a project level due to the varied activities executed by construction vehicles and the multitude of construction vehicles with different specifications. Further, the large influence of environmental factors that have to be measured individually, provides another level of complexity. None of the current methods of theoretical calculation seem to yield robust results on a project level. Because of their complexity, emission rates are often generalized. To consider more emission parameters and use more factors, they have to be determined specifically for the purpose and region they are used in.

1.2 Research Aim & Questions

The company Dura Vermeer is currently calculating its on-site emissions taking into account the work time and averaged emission values. The goal of this research is to find a better methodology to calculate the crucial emissions of construction sites and give advice on further research to comply with future government regulations. This research will be structured through research questions. The next two sections will focus on the original research approach and the revised research approach after further review of the available data.

1.2.1 Original Research Approach

What are the main uncertainty factors in a model predicting CO_2 and NO_x emissions from non-road mobile machinery on a construction site and what is the effect of different emission parameter measurements on those factors?

To answer the research question, the following four sub-questions are investigated:

(1) What is the framework for the model?

One of the main findings in the literature review was the lacking consensus on what is included in their research on emissions of construction projects. Thus, the first sub-question will find the boundary conditions of the method and define the pollutants to be included for the calculations and the sources of the pollutants that should be considered in the method. This section also includes deciding on which parameters will be considered when quantifying the emissions and the data and measurements that are available for the process.

(2) How does the model quantify the emissions?

The second question determines the method to be used for the theoretical calculation of emissions during the construction process. First, it looks into what equations can be used and for which methods the data is available. Then the question will decide on the emission factors and parameter definitions used for the equation. It recommends the standards or values to be used and how to calculate or find them for other vehicles. This part also considers how the results are displayed to be useful for the analysis and interpretation of the data.

(3) How reliable is the method?

The third sub-question aims to make an uncertainty analysis of the created model. This analysis shows what factors and parameters have the greatest uncertainty and thus are the weakest points. This analysis will be the basis for the parameters investigated to improve reliability.

(4) What are future recommendations for the company?

The last point aims to give the company a recommendation on what measures and research they could implement to get more accurate results and improve the model further. This section also looks at the possibilities of validating the calculated data in the future.

Once all the sub-questions are answered, the main question will be answered by summarizing and concluding a piece of advice to the company based on the results of the research.

1.2.2 Revised Research Approach

Some of the assumptions made at the planning stage of this research changed after further literature review. The lack of data got more evident over time and led to other ideas to improve the model being looked into. Due to these changes, the research procedure was changed to cover the following topics:

How can emissions modeling help Dura Vermeer estimate the impact of measures to reduce nonroad emissions on asphalt construction sites and what parameters could be adjusted to improve the accuracy of the model?

To answer the main research question, the following sub-questions are answered:

(1) What is the framework for the model?

Before creating a model, the purpose of the model needs to be formulated. This question will explore the requirements for the model and what the expectations for the further process are. Then it will also define the boundaries of the model and the modeling process and the expectations for the output of the model.

(2) What are the current emission models used for NRMM?

As mentioned in the problem context, there are several existing models currently in use to calculate NRMM emissions. This question looks at different models currently used in the USA or Europe to calculate NRMM emissions to create a basis for the structure of the model to be developed. Further, this question will look at why the models are so disputed and where the sources for the uncertainty lay.

(3) How can the model be adapted to fit its purpose?

The different models considered in the previous question were made to calculate national emissions on a yearly basis. To use them on a more frequent and small-scale basis, changes have to be made to the structure and parameters. This chapter will show the concept of the model and explain the calculation procedure of the goal variables. Further, it will analyze the results of the calculations and explore its uses for policy decisions.

(4) How does the model compare to measured values?

The validation of the model without measured emissions data is difficult, however, there are different measured values the model can be compared to. The chapter will draw conclusions by comparing the modeled values from the previous chapter to the fleet averages of different companies. Further, it will compare modeled NOx values to measured NOx emissions for certain vehicles.

(5) How could the model be further improved with measurements?

While the model was revised in the third question, the structure and parameters are largely based on existing models which are considered to be uncertain. This question will propose ideas to improve model accuracy and make suggestions for further research on the topic.

1.3 Available Data

The data used in this project was provided by Dura Vermeer and different companies in the ASPARi research group. Dura Vermeer provided data on their asphalt paving equipment and weekly working hours of different employees. The vehicle data includes the following information:

- Machine Type
- Manufacturer & Model
- Emission standard
- Engine size [kW]
- Fuel type
- Year of Production

This data will be used as the main input for the model and to derive its parameters. Missing data will be supplemented from manufacturers' data or derived from other literature sources. The working hours are given in weekly totals per employee on an asphalt construction team. This data is used to derive the average weekly working hours of the machinery as model input.

Company 4 provided raw data from engine measurements including the following data:

- Machine Type
- Measured Time [s]
- Usage Time [s]
- Work Mode
- Average fuel consumption [l/h]
- Average load factor [%]

This data will be used to derive average load factors for each vehicle type to improve the parameters in the model. Further, the average fuel consumption of each machine type is used as a comparison to the model values. Further, the idling rate is derived for each vehicle type and used in the interpretation of the data.

Different other companies also provided data on the average fuel consumption of their machinery, which will also be used as comparative values for the model.

1.4 Project Scope

This project is about emissions calculation and reduction on construction sites. The focus is on the adjustment of an emissions model for daily use in the company. The study encompasses the research on the base structure of the model, the definition of the main parameters, and their calculation procedure as well as a discussion of the results of the model in different contexts. The model is intended to be used by the company as a tool for their projects and to communicate information to their clients.

1.5 Methodology

This chapter introduces the methodology used to conduct the research project. The project is divided into five large sections guided by the five sub-questions mentioned in Chapter 1.2.2. A diagram of the process is shown in Appendix A, Figure 19.

First, the framework for the model is laid out by studying research on different ways to model emissions and what parameters to consider. Further, consultations with Dura Vermeer are conducted to gain insight into their needs and expectations towards the model. Their opinion was also considered to decide which emissions to consider in the model. The research should result in the requirements and boundaries of the project.

The second section focuses on the basis the model will be built on. The time is too short to create a completely new model, thus literature on the different models currently in use is used to decide on a basis for the model. Further, uncertainty analyses have been conducted about the accuracy of said models. This research is looked at and helps with identifying weak points in the current models and find areas where it could be improved.

In the third section, the information gained in the previous section is used to create a model structure and define the calculation procedure for the model. Further, the parameters of different models are studied to find which ones are most suitable for the model. In addition, the load factor values from the engine measurement data are used to create average load factors for the different vehicle types to use in the model, and research on HVO fuels is used to create fuel-based emission reduction factors. Based on the devised calculation procedure, the emissions of the vehicles mentioned in the vehicle data are calculated using the working hour information provided by Dura Vermeer. These results are then analyzed to give conclusions on possible ways to reduce the emissions of the vehicle fleet. Then, different policies, like adding a new vehicle to the fleet or switching the type of fuel used are implemented to see their impact on the emissions of the vehicle.

The fourth section uses the fuel consumption averages provided by different companies to compare to the model values. A second comparison is made to NO_x and fuel consumption values measured in a study on paving equipment, by calculating the modeled emissions for the vehicles mentioned and comparing them to the measured data. The results should give an indication of the accuracy and reliability of the model.

The fifth section of the report focuses on recommendations for the model. The results from the uncertainty analysis and the comparison are used to consider what could be improved about the model. The total results of the research are then summarized in the conclusion and discussion at the end.

2 Literature Review

2.1 Non-road Mobile Machinery (NRMM)

Non-road mobile machinery is a vehicle category that includes all transportable equipment mobile machines that possess an internal combustion engine but are not intended for the transport of goods or people on the road (Mayor of London, 2020; Greater London Authority, 2017). This includes gardening or handheld equipment (i.e. chainsaw, mower, etc.), agricultural and farming equipment (tractor, seeder, sprayer, etc.) or transport machinery (railcars, locomotives, etc.) as well as construction equipment (European Commission, n.d.). This report is focused on the construction equipment defined as NRMMs, these include excavators, bulldozers, mobile cranes, dumpers, compressors, etc.

2.2 NRMM Emission Regulations

Emission standards have been set for most machines nowadays. However, NRMM regulations were much slower to be implemented than those for cars or trucks, and they continue to be higher (Ligterink, Louman, Verbeek, & Buskermolen, 2018). In 1997 the EU has implemented directive 97/68/EC that places gradually more strict pollutant emission limits on nonroad machinery, then in 2018 the old directive was replaced by EU Regulation 2016/1628. The regulations encompass air pollutants caused through direct emission and apply to all engines sold to or in an EU country. The EU has stated multiple reasons for restricting emissions. These include health and environmental considerations, the need to improve air quality, and a basis for fairness on the international market. In favor of the international cooperation on emissions reduction, the EU has equalized Stages III and IV with the EPAs Tier 3 and 4 regulations. (VCA, 2020; European Commission, n.d.) Because the reduction in emissions is largely related to a higher technological standard and the year the engine was produced or admitted in, the emissions regulation is also referred to as technology level or emission standard of a vehicle. This is also the formulation used in the main part of the report.

The limits are dependent on the pollutant considered, the fuel type, and the engine size. The limits are leveled into Stages. Stage I and II are set in the 1997 directive and were implemented between 1999 and 2004. Stage III was split into IIIA and IIIB, both Stages were implemented between 2006 and 2013 and then followed by Stage 4 in 2014. Stage V was proposed in 2014 and then implemented between 2019 and 2020. Stages I-IV are only regulating engines of 19-560 kW power output, Stage V introduced further regulations on machines below 19 kW and above 560 kW. The emissions regulations are usually given in the maximum mass of each pollutant that is allowed to be emitted per power output of the machine. The following tables show the emission limits for NO_x and PM in grams of pollutant per kWh. (DieselNet, 2020)

Table 1: NO_x Emission Limits in g/kWh

Power [kW]	Stage I	Stage II	Stage IIIA	Stage IIIB	Stage IV	Stage V
P < 19	-	-	-	-	-	7.5[2]
19 ≤ P < 37	-	8[1]	7.5[2]	-	-	4.7[2]
37 ≤ P < 56	9.2	7	4.7[2]	-	-	4.7[2]
56 ≤ P < 75	9.2	7	4.7[2]	3.3	0.4	0.4
75 ≤ P < 130	9.2	6	4.0[2]	3.3	0.4	0.4
130 ≤ P < 560	9.2	6	4.0[2]	2.0	0.4	0.4
P > 560	-	-	-	-	-	3.5

[1] the power range is defined from 18 kW to 37 kW

[2] emission limits defined for HC + NO_x

Table 2: PM Emission Limits in g/kWh

Power [kW]	Stage I	Stage II	Stage IIIA	Stage IIIB	Stage IV	Stage V
P < 8	-	-	-	-	-	0.4
8 ≤ P < 19	-	-	-	-	-	0.4
19 ≤ P < 37	-	0.8	0.6	0.025	-	0.015
37 ≤ P < 75	0.85	0.4	0.4	0.025	-	0.015
75 ≤ P < 130	0.7	0.3	0.3	0.025	-	0.015
130 ≤ P < 560	0.54	0.2	0.2	0.025	-	0.015
P > 560	-	-	-	-	-	0.045

2.3 NRMM Emission Estimation

There are many different models in use to quantify emissions from passenger vehicles. The number of models for the quantification of NRMM emissions is significantly smaller and most require detailed engine measurements. Two main approaches were identified, the first of which uses the manifold absolute pressure (MAP) in the engine, another is based on the power output of the vehicle and emission factors. The most prolific models for emissions from NRMM are the NONROAD model created by the EPA, the TREMOD-MM model in Germany, and the national atmospheric emissions inventory (NAEI) developed by the UK government. All of them are based on the power output and activity data, and all of them are similar to the model first proposed by the EPA in 1994. This report will focus on the implementation of a model using basic vehicle specifications since the MAP model requires detailed data from the motor to calculate the emissions, the focus will be on the models using the power output.

2.3.1 Emission Parameters

Emission parameters are the parameters that influence the emission factor of an engine during a certain measurement period. The emission parameters for nonroad machinery have not yet been fully explored and different studies define a multitude of parameters in different categories. Barati & Shen (2016) have composed a framework of the parameters they thought would influence the emission rate of NRMM that can be seen in Figure 3.

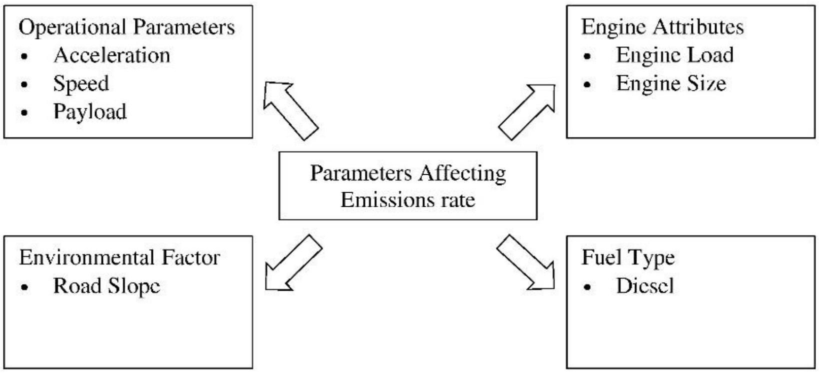


Figure 3: Parameters Affecting Emission Factors (Barati & Shen, 2016)

They divide the parameters into four main categories. First, the operational parameters of the vehicle, like the speed it moves at, whether and how much the machine accelerates and the payload on the vehicle that might influence the power necessary to move the vehicle. The second factor is the engine attributes, unchangeable engine specific data that determines the general emission factor of an engine. The engine load is often adjusted in the calculations with a load factor. The third category focuses on the environmental conditions that affect emissions, like the slope of the terrain driven on.

The last category considers the fuel type, very similar to the previously named parameters. According to Barati & Shen (2016), it is this multitude of parameters that makes it hard to quantify emissions at a project level, where these factors would have a larger impact than on a larger scale. Of these parameters, they would also like to highlight the engine load, as it was important to define the relationships between different emission factors. Further, they conclude that based on their study, acceleration, slope, and speed have the highest impact on the actual emissions.

Fan (2017) proposes yet another framework (Figure 4) very similar to that of Barati & Shen. He augments the framework and adds new categories with a focus on the maintenance of the vehicle and the operations of the vehicle. His first category focuses on the equipment used and takes into account the engine specifications and fuel specifications. He also considers the age and model of the vehicle and its overall condition. The second category focuses on equipment maintenance. There he looks at the routine maintenance and tire conditions and any repairs or replacements that were made.

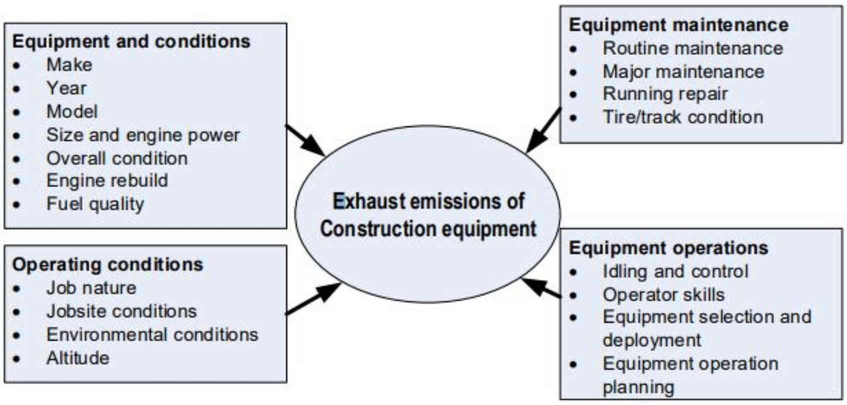


Figure 4: Parameters Affecting Emission Factors (Fan, 2017)

In the third category, he looks at the operating conditions, which also includes the environmental conditions mentioned by Barati & Shen (2016), but also the altitude and the conditions on the job site. Lastly, he defines the equipment operations as a category, looking at the management of the operations and operator skills. He also considers the idle time and suitability of the chosen equipment for the site.

Other parameters suggested by researchers is the ambient temperature of the construction site (Boulter, McCrae, & Barlow, 2007; Heidari & Marr, 2015), the humidity (Heidari & Marr, 2015), the technology level, mileage and gear selection (Boulter, McCrae, & Barlow, 2007).

2.3.2 Emission Factors

Emission factors represent the amount of a pollutant emitted per unit. There are different units to define the emission factor. The emission factor can be given in:

- ➔ g/kg-fuel (grams of pollutant emitted per kg of fuel used)
- ➔ g/kilowatt-hour (grams of pollutant emitted per kilowatt-hour of energy produced)
- ➔ g/hour (grams of pollutant emitted per hour of vehicle usage)

These fuel emission factors are usually chosen depending on purpose and data availability. For example, if comparing a hybrid vehicle to a diesel vehicle, measuring emissions in g/kg-fuel would not be fitting as a hybrid would be more productive with less fuel. The goal is comparing the emissions for the same operational capacity thus measuring the emissions in g/kWh is the best fit. (Johnson, et al., 2016) Further studies found that fuel-based emission factors are largely independent of engine size and load and work best for CO_2 emissions, while time-based factors show better results for non-carbon emissions (Frey, Rasdorf, & Lewis, 2010). Among the studies on emission factors, fuel-based emission factors are more commonly used than time-based emission factors (Zhang, Sandanayake, Setunge, Li, & Fang, 2017). They assume that this is due to the higher flexibility in emission parameters for fuel-based emission rates or the availability of data for fuel consumption compared to that of the power output of a vehicle. Other sources claim that fuel-based emission factors are less variable than power output related ones (Li, Zhang, Pang, & Di, 2016).

One of the most widely used emission calculation models NONROAD (EPA, 2018a) uses EPA emission standards to calculate emissions, but has been criticized in several studies for not representing the real-world duty cycles (Lewis, Rasdorf, Frey, Pang, & Kim, 2009) and overestimating emissions (Heidari & Marr, 2015). Many other governments in developed countries have since developed their own models based on that developed by the EPA (IFEU, 2004; Winther & Nielsen, 2006; Notter & Schmied, 2015). Another study shows that none of the currently used emission models are very reliable or accurate. The current CO_2 emission factors from the US EPA, EEA, AUS NGA, and IPCC Tier 1 were compared to PEMS measurements and showed great variability compared to the measured emissions. They conclude that it is best to use local factors if available and that time-based emission factors were more accurate. The same study also looked at NO_x and PM emission factors and found that while none of the emission factors predicted the real emissions, the US EPA standards gave the best approximation for the measured values. (Zhang, Sandanayake, Setunge, Li, & Fang, 2017)

The core problem for the inaccuracy is stated as the lack of data regarding NRMM and lack of transient emissions measurement. The lack of data is especially influential for emission factors of newer machinery, which are often derived from the limit values given in the regulations, and expert opinions. (Helms, Lambrecht, & Knörr, 2010; Winther & Dore, 2019)

2.3.3 Engine Load and Load Factor

The engine load is the resistance the engine has to work against to keep the vehicle moving. Every engine has a maximum power production capacity, the rated power, or the nominal power of an engine. If the engine is producing the maximum power, the engine load is at its maximum too. (Helms & Heidt, 2014)But most engines rarely work at full engine load, since the engine is designed to have more power than necessary for the machine's daily activities. The fraction of the maximum power that the engine is using at any given moment in time is the load factor. It is usually given in % of the maximum load. (Barati & Shen, 2016)

Engine load is one of the most important factors for emissions calculation. According to Barati & Shen (2016) the modeling of operational emissions and found the engine load to be a "crucial parameter in modeling the relationship between operational factors on emissions". Thus, instead of relating different operational factors like speed, slope, and acceleration to changes in emission rates, they related these factors to the engine load, which then relates to the emission rates. They suggest, that knowing these operational parameters will greatly increase the accuracy of emissions models.

But the engine load is not only correlated to the vehicle emissions in total, different studies also suggest that lower engine load factors cause proportionally higher emissions per power output unit. This effect influences especially NO_x emissions (Johnson, et al., 2016) and is more noticeable in vehicles with newer emission standards (Ligterink, Louman, Verbeek, & Buskermolen, 2018).

In most emission models the engine load is given as an average factor. Lewis (2009) questions this custom and insists that engine loads are continuous and thus not well represented in average factors. Johnson et al. (2016) also suggest that the differences in engine load during different machine operations are the main factor leading to variability in emissions.

2.4 Environmental Cost Indicator (ECI)

The environmental cost indicator (ECI) is used as a tool for comparing the environmental impacts of a product or project by summarizing them in a single score indicator that is given in Euro. The ECI is often called shadow costs because it is the hidden cost of the project associated with the environmental damage caused. (Hillege, 2020)

Environmental impacts are related to pollutants created in all stages of the project's life cycle. Because there are multiple pollutants involved and their impacts on the environment are varied, they are divided into impact categories that concern different aspects of the environment. Those different categories are difficult to compare and are thus each translated into a cost per unit of a pollutant that gives a final score of the impact of all pollutants. Especially in the Netherlands, the environmental cost of projects is increasingly considered. The ECI is often a deciding factor in tenders. Often tenders include a maximum ECI for a project to be considered and lower ECIs are encouraged. Many have adopted a discount system, where a project gets a percentual discount on its price when having a lower ECI than asked for. This way projects can win a tender even if they cost more by reducing their environmental impacts. (Hillege, 2020)

The ECI is calculated in four steps (Hillege, 2020):

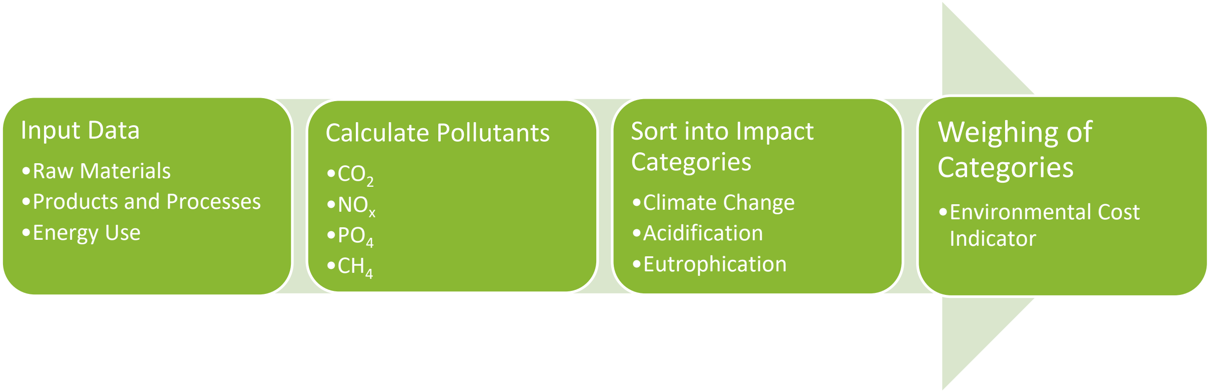


Figure 5: ECI Calculation Procedure

The third and fourth step require impact categories and their cost indicator units. Table 3 shows an overview of different indicators and their cost indicators as denoted by Dura Vermeer. The table should not be seen as complete. There are different categories that can be included in this analysis and it depends on the creator which ones are chosen.

Table 3: ECI Impact Categories

Impact Category	Unit	Cost Indicator [€/unit]
Global Warming Potential (GWP 100)	kg CO2 eq.	0.05
Ozone Layer Depletion	kg CFC-11 eq.	30
Human Toxicity	kg 1,4-DB eq.	0.09
Freshwater Toxicity	kg 1,4-DB eq.	0.03
Freshwater Ground Toxicity	kg 1,4-DB eq.	0.02
Marine Water Toxicity	kg 1,4-DB eq.	0.0001
Marine Ground Toxicity	kg 1,4-DB eq.	0.0003
Terrestrial Toxicity	kg 1,4-DB eq.	0.06
Photochemical Oxidation	kg C2H4 eq.	2
Acidification	kg SO2 eq.	4
Eutrophication	kg PO4 eq.	9
Abiotic Exhaust	kg Sb eq.	0.16
Energy Exhaust	kg Sb eq.	0.16

The main factor for Dura Vermeer is the global warming potential in CO_2 equivalent. This considers all GHG emissions from the vehicles, the main ones consist of CO_2, CH_4, and N_2O. Each of the pollutants has its own GWP determining how impactful it is in regard to climate change. Table 4 shows the CO_2 eq. for the different pollutants (Climate Change Connection, 2020).

Table 4: GWP of Different GHG Pollutants

GHG	GWP [kg CO2 eq./kg pollutant]
CO2	1
CH4	25
N2O	298

2.5 HVO Fuels

Hydrotreated vegetable oil (HVO) fuels are a type of renewable biodiesel that can be used to reduce emissions in vehicles compared to regular diesel. The EU has directive 2009/28/EC that mandates at least 10% of the energy used in transport to be from renewable sources and a 6% reduction in emissions. (Neste Corporation, 2016)

HVO fuels are produced through hydroprocessing of fats and oils. These can be either animal fats or vegetable oils like rapeseed, palm or sunflower oil. Compared to diesel fuels, HVO fuels have very high cetane numbers. (Neste Corporation, 2016) The cetane number indicates the percentage of cetane in diesel fuel. High cetane numbers reduce the temperature required for the ignition of the fuel, which causes the fuel to burn up more completely. This reduces tailpipe emissions and makes the engine work more efficiently. (Stenhouse, Hanania, Afework, & Donev, 2018)

HVO fuels can be blended with diesel or used in their pure form. In a blend, they preserve the qualities of diesel and improve them, but HVO fuel can cause up to a 3% increase in fuel consumption. The cetane numbers also increase nearly linearly with the HVO content. Theoretically, all HVO blends are possible, especially with ASTM D975 diesel (US standard), but the HVO fuels have a lower density than EN590 diesel (EU standard) and might cause motor problems when the blend falls below the minimum fuel density for the motor. This problem sometimes limits the blend ratio to up to 35% HVO.

Pure HVO fuels can be classified as EN15940 (‘paraffinic diesel from hydrotreatment’) in emission standards. (Neste Corporation, 2016) Diesel that falls under the EN15940 standard has an ash number and sulfur content of 0. All European vehicles have to be approved for EN590 standards, but the EN15940 standard is not yet tested for many vehicles. Only newer vehicles from some manufacturers include the standard. (Den Hertog BV, 2018)

The reduction in emissions is in most cases more effective when the blend ratio is higher, but also 30% blends have noticeable emissions reductions. According to Neste, PM emissions have an exponential decrease in emissions for higher blends. The reduction of tailpipe emissions especially benefits vehicles with high emissions, like busses and trucks or older vehicles. Especially the NO_x emissions are reduced for trucks, which is likely to be similar for NRMM. Newer Euro VI vehicles are already so low in emissions that the change of fuels barely has an effect. (Neste Corporation, 2016) Next to tapetail emission reduction, depending on the type of fat or oil used for the production, HVO fuels also have lower production chain emissions for the creation of HVO fuels (Verbeek, 2018).

3 Model Context

The first step to modeling the emissions is to clearly define the model's purpose. The following chapter explores the requirements and boundaries for the model and modeling process. Further, it describes the intended output of the model.

Model Purpose

The model is created to calculate the emissions of chosen pollutants from mobile machinery on asphalt construction sites. It can serve as a tool for a company to estimate their emissions at a project or vehicle level and thus evaluate their emissions for clients and government reports. This includes the use of the model to compare the effects of measures to reduce the fleet emissions.

Actor Analysis

The actors regarding the model are the company, Dura Vermeer, themselves, their clients, and the government. The clients have the smallest influence on the model, as most of them are only interested in the results of the model and the predictions as far as they concern their own projects or use it to consider the increase in emissions of high pollution areas like urban or highway sections, during the construction phase. The government on the other hand has a great influence on the modeling strategy used since the model should comply with any national, European, or international standards of emission reporting.

Dura Vermeer has the highest interest and power regarding the model. They can use the model for internal and external purposes. On the internal side, the model can be used to evaluate different policies for emission reduction, like new vehicles with lower emissions or changes to fuel and operating times. Further, the estimates are helpful to see to the health of their workers and civilians around the construction sites. Externally, Dura Vermeer is required to report their emissions to the government and make sure their emissions are conforming with national and EU standards regarding air pollution. Additionally, the environmental cost indicator (ECI) plays a big role in project tenders, giving them better chances to win a tender with a lower ECI.

Requirements

This report intends to introduce an adjusted model, that is more specific to the company and the equipment used than the previously employed model. For this purpose, an existing model is chosen and adjusted, because developing a completely new modeling approach is not possible in the short timeframe. Also, the chosen model should include some parameters not included in the current approach, mainly the age of the vehicle and the related deterioration factor, as well as a fuel adjustment for HVO fuels. It should be based on the data available and give estimates in line with the European standards for emissions calculation for NRMM.

The model should use a widely accepted calculation approach and be previously validated since there is no possibility to validate the model with emission measurements. Further, due to the timeframe, the parameters should be clearly outlined and adjustable through the available data. Because the intended assessment procedures require intermediate outputs, the model should have a white box structure.

The focus of the model is on calculating five different pollutants emitted in tailpipe emissions. The primary objective are the NOx, CO2 and PM emissions, but to calculate the GWP and ECI of the emissions, CH4 and N2O were also included. The process of determining the parameters and calculating the different factors for the equations using the vehicle specifications as input should be clearly outlined. The intention is to use the model for future projects of Dura Vermeer, thus it should be understandable without intense study of the topic and require no specific software or technological equipment to use. The results should be available quickly and easily comparable to be able to observe differences. Additionally, the model should have inherent flexibility and be adjustable to new vehicles and projects at any time.

Boundaries

The model is focused on the direct emissions of asphalt pavers and rollers on the construction site, also bitumen spray trucks, and asphalt trucks are considered as supporting vehicles. All emissions caused by other vehicles or machinery will not be included. Neither are indirect emissions from e.g. tire wear, road abrasion or resuspension, or other factors that might influence air quality around the construction site. The research is only focused on the five pollutants mentioned above, any other primary or secondary pollutants that might be emitted from or caused by the equipment is not considered in this research. Neither are supply chain emissions or life cycle emissions of the considered machines. The calculated ECI is solely based on the GWP, any other environmental indicators are not considered.

The timeframe for this project is relatively small and set at a total of 10 weeks (prolonged to 16 weeks during the course of the research due to problems with data availability), thus limiting the depth this research can go into. Further, the data available for this project is very limited and includes only external data from different sources, which may lead to higher uncertainties or misinterpretations. The lack of direct emissions data also prevents the direct validation of the model. Parts of the model will be , but the conclusions drawn from the validation should be regarded with caution. The company hopes to reach accuracy values for the model of 80-85%.

Output Variables

The output of the model will be given in the mass of NOx, PM, CO2, CH2, and N2O emitted per vehicle per defined timeframe. The time in the model can be adjusted to cover different periods of time given in hours. The mass of CO2, CH4, and N2O is then transformed into the CO2 eq. that is used to calculate the ECI.

4 Current Emission Models

The emissions from non-road mobile machinery are currently calculated through standards set on national and international levels. On the international level, the IPCC gives guidelines for the reporting of emissions from transportation, which includes NRMM. On the national level, the USA was the first state to develop a nationwide model for NRMM emissions called NONROAD. The model was then also adopted by European states. The EU has its own guideline for calculating emissions, the European Emissions Inventory, the nonroad section of which is largely based on the NONROAD model as well as the German TREMOD-MM model.

4.1.1 NONROAD/MOVES Model

The Motor Vehicle Emission Simulator (MOVES) is the US EPA model for the calculation of all motor vehicle-related emissions in the United States. The original NONROAD model for nonroad emission sources was integrated into MOVES, but the calculation procedure of the model is the same. (EPA, 2018a) Equation 1 is used by the NONROAD model to quantify the emissions (Lindhjem & Beardsley, 1997).

$$Emissions = (Pop)(Power)(LF)(A)(EF) \qquad \text{Eq. 1}$$

Where

Pop = engine population
Power = average power [hp]
LF = load factor (fraction of available power)
A = activity [hrs/year]
EF = emission factor [g/hp-hr]

The engine population is taken from data provided by the model that is based on the year, application, fuel type, and power level of the vehicle. The average power and also the power-based emission factor are based on the horsepower, due to the US origin of the model. The activity of the model is given by showing the hours of work time per year, and the engine load is adjusted by a load factor. The load factor is the ratio between the maximum and the average horsepower output of the engine during the observed period. The emission factor in the equation is an adjusted emission factor calculated with equations 2 and 3 (EPA, 2018b):

$$EF_{adj(HC,CO,NO_x)} = EF_{SS} \times TAF \times DF \qquad \text{Eq. 2}$$

Where:

$EF_{adj(HC, CO, NOx)}$ = Emission factor after adjustment [g/hp-hr] for HC,CO and NO_x
EF_{SS} = zero-state steady-state emission factor [g/hp-hr]
TAF = transient adjustment factor
DF = deterioration factor

And

$$EF_{adj(PM)} = EF_{SS} \times TAF \times DF \times S_{PMadj} \qquad \text{Eq. 3}$$

Where:

$EF_{adj(PM)}$ = Emission factor after adjustment [g/hp-hr] for PM
S_{PMadj} = PM adjustment factor for variations in fuel Sulphur content

Both of these formulas use the zero-state steady-state emission factor that is related to the technology level and the horsepower class the vehicle fits into. The emissions are then adjusted to reflect the age and the usage cycles of the vehicles. The PM emission factor is also adjusted to the Sulphur content in the fuel.

The emission factors for many vehicles, especially older ones, are tested in steady-state cycles. Because the NRMMs are rarely used stationarily, a transient adjustment factor is used for vehicles that are not stationary and have varying power outputs in one usage cycle. (EPA, 2018b; Winther & Nielsen, 2006; Helms, Lambrecht, & Knörr, 2010) When the power output is not continuous, then neither are the emissions of the machine, which can cause large differences in the emissions characteristics of a machine. Because there is often no data on the exact power output at any time during the usage cycle, the transient factor is an average for the different usage cycles. The transient adjustment factor is the ratio between the transient emission factor and the steady-state emission factor (EPA, 2018b):

$$TAF = \frac{EF_{trans}}{EF_{SS}} \qquad \textit{Eq. 4}$$

The transient emission factor is determined by measuring the emissions of different engines in different operational cycles. The obtained results were then averaged to get the transient emission factor. The emission factors are divided into different categories based on the work cycle and load factor during the testing. (EPA, 2018b)

Further, an engine's emissions can change throughout its lifetime. This is also called deterioration of the motor and is compensated for through the deterioration factor. The deterioration occurs naturally through the usage, but can also be caused through a lack of maintenance, changes made to the motor, or other forms of misuse. To determine the grade of deterioration, the usage time of the vehicle is compared to the median lifespan. (Lindhjem, Janssen, Sklar, & Wilcox, 1998) The deterioration factor is calculated as

$$DF = 1 + A * (Age\ Factor)^b \qquad \text{for Age Factor} \leq 1 \qquad \textit{Eq. 5}$$

$$DF = 1 + A \qquad \text{for Age Factor} > 1 \qquad \textit{Eq. 6}$$

Where:

Age Factor = fraction of median life expended = $\frac{(cumulative\ hours * load\ factor)}{median\ life\ at\ full\ load\ [hrs]}$

A, b = constants for given pollutant/technology level; b ≤ 1

Deterioration is capped at the end of the median lifetime because if emissions increase through further deterioration, the necessary maintenance is expected to reduce the emissions in equal measure. In general, the expectation is that the engine size and fuel type are the decisive factors, with large diesel engines having the longest expected lifetime (EPA, 2004). The constants for the equation were derived from highway engines due to a lack of data for nonroad engines. (EPA, 2018b)

4.1.2 European Emissions Inventory Guideline (EMEP/EEA)

The EMEP first introduced a guideline for the reporting of air pollution to the UNECE in 1996. The guidebook was then updated to also report to the EU National Ceilings Directive in 2009. The guidelines define the emissions calculations for natural and anthropogenic sources in Europe. The following model is described in Chapter B.1.A.4 by Winther and Dore (2019).

The method for calculating the emissions of NRMM is split into three tiers dependent on the information available on the equipment. The EEA provides the following flowchart to help decide which method is appropriate:

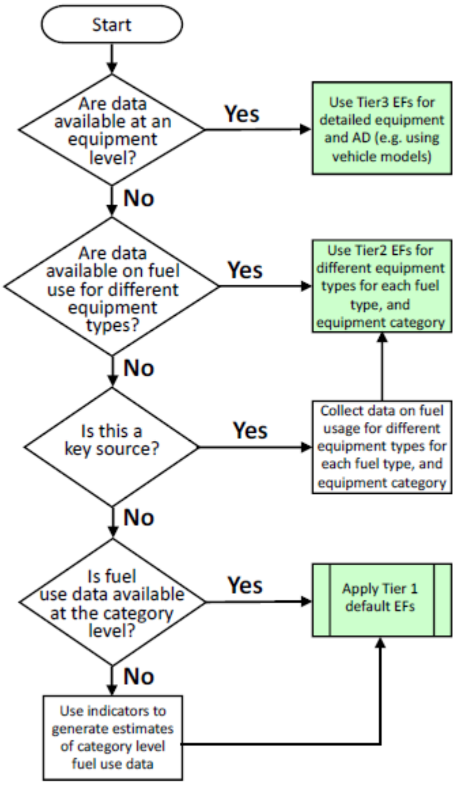


Figure 6: EEA Method to Find Emissions Formula (Winther & Dore, 2019)

The first tier depends on the fuel consumption and a generic emission factor for each pollutant that depends on the fuel type and the sector the machine is used in (e.g. forestry/agriculture, construction, etc.). The second tier takes the same factors into account as the first tier but also considers the technological level of the equipment for the emission factor. This technological level is defined by the construction year of the equipment or its emission standard. The third tier is the most detailed in the calculations and depends on vehicle-specific data.

For this report, the focus is on the third tier. The equation from Winther and Dore (2019) is very similar to the equations found in the EPA model. The total amount of pollutants emitted during the calculation period is determined by

$$E_i = N \times HRS \times P \times (1 + DFA) \times LFA \times EF_{Base} \qquad \text{Eq. 7}$$

Where:

E_i = mass of emissions of pollutant i during the inventory period
N = number of engines (units)
HRS = annual hours of use
P = engine size [kW]
DFA = deterioration factor adjustment
LFA = load factor adjustment
EF_{Base} = base emission factor [g/kWh]

The equation is very similar to a combination of equations 1 and 2/3 in the EPA model. Instead of adjusting the emission factor separately, the adjustments are added to the final equation. The load factor, engine size, and hours of use determine the estimated activity output of the vehicle in kWh. To be able to use this formula, it is necessary to split the vehicles into different categories and have data of the vehicles that include the technology level, the power range, and the engine load. (Winther &

Dore, 2019) The base emission factors and fuel consumption are given for each power category. The data used in this model is mainly derived from the German TREMOD-MM model.

An engine's emission may change throughout its lifetime. This change is accounted for in the model through a deterioration factor that depends on the emission level and the average engine lifetime of the vehicle. The deterioration factor for the EEA model is calculated through the formula:

$$DF_{D,2ST} = \frac{K}{LT} * DF_{y,z} \qquad \text{Eq. 8}$$

Where:

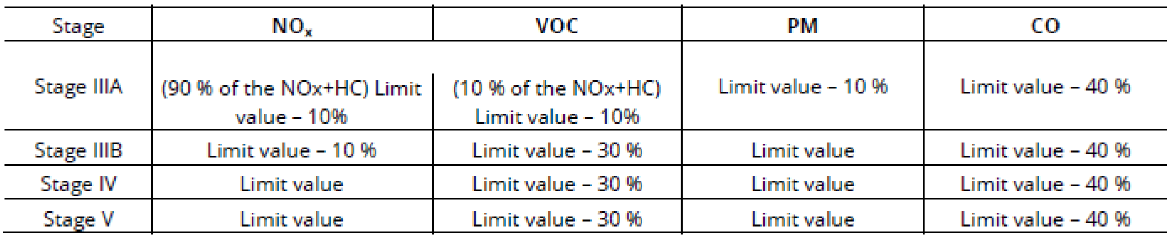
$DF_{D,2ST}$ = deterioration factor adjustment for diesel machinery and 2-stroke gasoline machinery
K = engine age (between 0 and average lifetime)
LT = average lifetime
y = engine size class
z = technology level

The formula gives a linear interpolation of the maximum deterioration factor related to the age of the vehicle and the average lifespan. The maximum deterioration factor is taken from the German TREMOD-MM model from 2004 (IFEU, 2004), which in turn has similar values to the NONROAD model.

The load factor adjustment replaces the transient adjustment factor from the EPA model. The adjustment factor is dependent on the load factor, which is the difference between the maximum power output and the actual power output of the engine. The load factor is often averaged for a vehicle category. The load factor adjustment for this model is taken from the IFEU values (Helms, Lambrecht, & Knörr, 2010). Only vehicles of the technology level Stage IIIA and lower are given a transient adjustment factor, all newer classes are given the value 1 because the emission factors for newer vehicles are measured based on a transient cycle already.

The base emission factor is the estimated emission factor before the age or usage pattern of the engine are considered. For the older engines, there are validated measurements available, but for the newer vehicles, the emission factor is derived from the limit values set by the emission regulations as described in Table 5. The emission factors for each engine size class and technology level are given in the guideline. (Winther & Nielsen, 2006)

Table 5: Derivation of Emission Factors from Limit Values (Winther & Dore, 2019)



Stage	NO_x	VOC	PM	CO
Stage IIIA	(90 % of the NOx+HC) Limit value – 10%	(10 % of the NOx+HC) Limit value – 10%	Limit value – 10 %	Limit value – 40 %
Stage IIIB	Limit value – 10 %	Limit value – 30 %	Limit value	Limit value – 40 %
Stage IV	Limit value	Limit value – 30 %	Limit value	Limit value – 40 %
Stage V	Limit value	Limit value – 30 %	Limit value	Limit value – 40 %

4.1.3 EMMA

The EMMA model is the national model for NRMM emissions and fuel consumption is based on the EPA NONROAD model and mainly uses the Tier 3 methodology of the European Emissions Inventory for calculating emissions. Only NH3 emissions are calculated from a Tier 1 methodology. The model also uses the inventory's emission factors but has adjusted them for their own use. Especially the NOx emission factor was increased to better reflect in-use emissions of the vehicles based on emission measurements conducted in 2018. The emission factors are based on fuel consumption and the production year of the vehicle. (Geilenkirchen, et al., 2020)

The methodology uses annual sales data and survival rates to estimate the vehicle fleet composition and uses estimates for the average working hours and power output per vehicle. Because the average working hours are subject to fluctuations, they are adjusted based on economic indicators. (Geilenkirchen, et al., 2020)

4.1.4 Uncertainty in Current Models

The uncertainty of the current emissions models is very high and has not been sufficiently calculated. Because the emissions of different vehicles vary greatly depending on their usage cycle and age, there is a lot of uncertainty in the activity rates. Also, the emission factors often have high levels of uncertainty, mainly because they have been determined through expert opinions based on the emission regulations. This review of the uncertainty of different emission models will focus on the parts of the model relevant to this report, so mainly the fuel consumption, NOx and PM emissions, and load factors, or any other information deemed relevant for this context.

The uncertainty of the European Emissions Inventory was evaluated on a qualitative basis in the report by Winther & Dore (2016), evaluating the data quality of the input of the model. The factors for fuel consumption, NOx, and PM emissions are considered to be of good quality. They are based on different tests and represent a large part of the considered population. The load factors on the other hand are considered to be of mediocre quality. They approximate the value considered and are sufficiently representative of the population. Further, the report recommends further data collection for activity data of the vehicles and fuel consumption values to increase the accuracy of the model. Additionally, they suggest further inclusion of transient cycles in the estimation of emission factors and identify the lack thereof as one of the weakest points of the model. In-use emission rates should be taken into consideration and the model revised accordingly. (Winther & Dore, 2019)

The report on the revision of the TREMOD-MM model by Helms, Lambrecht, & Knörr (2010) also estimated the uncertainty of the emission factors suggested for the model based on emission measurements by the BAFU. The measurements were only of relevance for the machinery of Stage II or earlier, for the Stages III-IV, not enough measurements were available for comparisons. The evaluation concluded that up to Stage II the emission factors assumed in the model were sufficiently accurate with most differences between model predictions and measurements between 5-50%. The emission factors for Stage III and IV were evaluated and adjusted through expert judgment. Another report on the uncertainty of the German model suggests that uncertainty especially in the construction sector is high, especially in regards to activity data (Knörr, Heldstab, Kasser , & Keller , 2010).

The uncertainty of the EMMA model is given through expert judgment from a conference paper on the uncertainty of emissions from transport by Dellaert & Dröge (2017). The uncertainty of the activity data of the model is set at 35%. The emissions of NOx were estimated at 50% and PM emissions at 100% uncertainty. The model values are further compared to other European uncertainty estimates. The Finnish and French estimates are very similar to the Dutch ones, while Swedish estimates tend to be lower. Within the report of the panel, no mention is made of the judgement process and it is unclear how the values were found. Research by Ligterink, Louman, Verbeek, & Buskermolen (2018) suggests that the NOx emission factors are higher than the limits and the model values should be revised.

The reviewed uncertainty estimates of the emissions are mostly based on quantitative bases and mostly lack any verification through measurement data. This allows for the conclusion that a large data gap exists in the form of measurement-based data for modeling. The emission measurements could be used to adjust emission factors for different vehicles based on the in-use emission rates. Or look into the influence of load factors on emission rates. Much of the judgment is connected to literature revision and expert judgment leaving room for high uncertainties. Uncertainty rates of up to 50% or more are very common in the estimates.

The estimates suggest that load factors and emission factors are in need of revisions. The data gathered allows for an adjustment of the load factors based on vehicle data that can be averaged per vehicle type considered in the model. Further, the emission factor of NOx can be slightly adjusted based on measurements in a study for rollers and pavers.

5 Adapting the Model

The models reviewed in the previous chapter all have a similar way of calculating emissions based on activity data and emission factors per unit of activity. The models outlined above are very helpful when calculating the yearly emissions of a whole sector or nation but might be less suited for regular use and specific vehicles. The following section will outline the model as imagined most helpful to a company trying to calculate the emissions of every project. First, the concept of the model is explained and then the calculation procedure is described. The basic equations remain similar to the equations in the EU model and the input of the EU model will be the default input. Further, the load factor is adjusted to fit measurement data.

5.1 Conceptual Model

The conceptual model for the emissions calculations is shown in Figure 7.

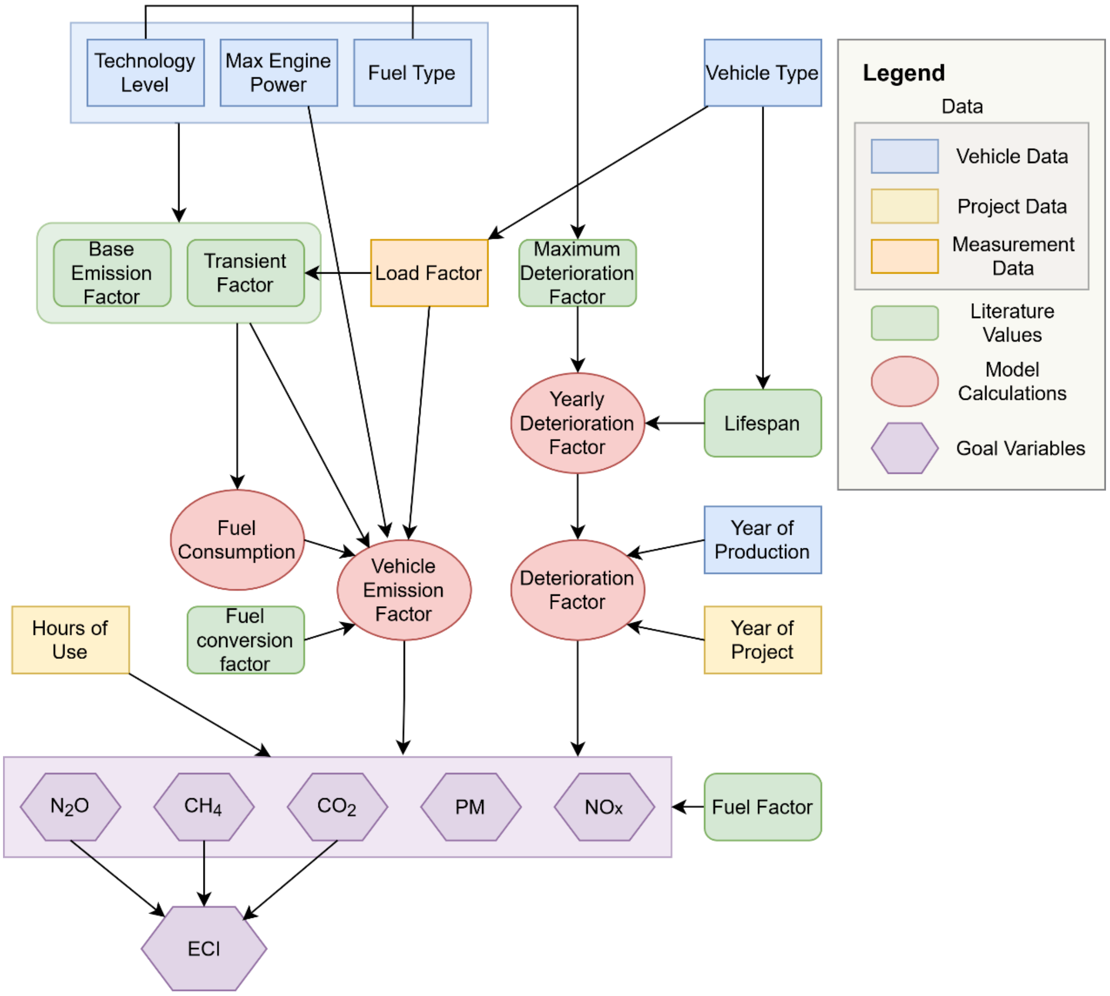


Figure 7: Conceptual Diagram of the Emissions Model

The model has six goal variables, the emissions of each of the five pollutants and the ECI as a combined factor for the CO2, CH4 and N2O emissions. The emissions of each vehicle are calculated by using a vehicle emission factor that is specific to the vehicle and independent of the age of the equipment. The deterioration factor is an extra variable calculated next to the vehicle emission factor. This allows the data to be spread into two parts, the vehicle related input and the project related input. The project related input includes the year of the project and the hours of use during that project. The rest of the model can be calculated and stored in a vehicle database. This way the calculation of different parameters for the vehicle has to be conducted only once.

The vehicle emission factor is calculated for each pollutant through parameters derived from the vehicle data. Further, a yearly deterioration factor is calculated for each vehicle. This deterioration factor is then multiplied with the age of the vehicle once the project data is used.

5.2 Calculation Procedure

The emissions inventory focuses on energy output and emission factors. This works well for the data available, which is mainly taken from energy statistics and extrapolation from sales data. For Dura Vermeer, it would be more practical to have their emissions based on different subcategories to improve the functionality for the company. For this purpose, the equations will use all the same factors used in the EEA model, but combine them at different points during the calculation process. The emission factors and adjustment factors are largely chosen from the European emissions inventory. The load factor is derived from vehicle measurement data from different types of rollers and pavers. This chapter will explain how to calculate the parameters based on the available data and combine them for the emission results. Because all the vehicles in consideration are diesel engines, the calculations and literature values will need to be revised for gasoline engines. It was decided to calculate the CO2 emissions of the vehicles from the fuel consumption of each vehicle, while the other pollutant emissions are calculated using power output related emission factors. The N2O emissions do not have separate adjustment factors, but it is assumed that the NOx adjustment factors are applicable, because N2O is part of the NOx value.

The calculations will be separated into two parts, the vehicle-based part, and the project-based part. First, the emission factor is calculated for each vehicle in a database. The emission factors and project data are then used to calculate the total emissions. This increases the ease of use and makes the calculations easier and faster than reiterating the emissions factors for each vehicle in each project.

The final emissions of each pollutant will be calculated using the following formulas:

$$E_i = VEF_i * (1 + (DF_i)) * T \qquad \text{Eq. 9}$$

$$E_{CO2} = VEF_{CO2} * T \qquad \text{Eq. 10}$$

Where

E_i = total emissions of pollutant i by one vehicle [g]
VEF_i = vehicle emission factor of pollutant i [g/h]
DF_i = deterioration factor of pollutant I [-]
T = hour of use [h]

The emissions are calculated using a vehicle emission factor that gives the amount of pollutant emitted per hour. Each vehicle has a VEF for each pollutant, which is then multiplied with the amount of time the vehicle was used in hours and the deterioration factor of each pollutant.

The CO_2 emissions are not dependent on a deterioration factor. CO_2 depends on fuel consumption, which is not expected to increase during the lifetime of the vehicle (Winther & Dore, 2019). The total emissions are given in grams per vehicle. To calculate the final emissions of each pollutant for the whole project, the sum of the emissions per vehicle is taken.

5.2.1 Vehicle Emission Factor

The vehicle emission factor for NOx, Pm, CH4, and N2O is calculated using equation 11:

$$VEF_i = P_{nom} * LF * TAF_i * EF_{Base,i} \qquad \text{Eq. 11}$$

Where:

VEF_i = vehicle emission factor of pollutant i [g/h]
P_{nom} = average engine power output [kW]
LF = load factor for vehicle type [-]
TAF_i = transient adjustment factor for pollutant i [-]
$EF_{Base,i}$ = base emission factor of pollutant i [g/kWh]

The vehicle emission factor for CO_2 is determined based on the fuel consumption of the vehicle:

$$VEF_{CO2} = P_{nom} * LF * TAF_{FC} * EF_{Base,FC} * CF \qquad \text{Eq. 12}$$

Where:

VEF_{CO2} = vehicle emission factor for CO_2 [g/h]
TAF_{FC} = transient adjustment factor for fuel consumption [-]
$EF_{Base,FC}$ = base factor for fuel consumption [g/kWh]
CF = fuel conversion factor [g CO_2/ g fuel]

The vehicle emission factor is based on the fuel consumption of the vehicle, which can be calculated like the emission factors for NO_x and PM. The amount of fuel consumed is then multiplied with a conversion factor that gives the amount of CO_2 emitted for the amount of fuel consumed.

The conversion of diesel fuel is dependent on fuel quality and composition. For this report a diesel fuel conversion factor of $CF = 3.15\ g\ CO_2/g\ fuel$ is used. The factor was averaged based on estimates from different reports as shown in Appendix C.

5.2.2 Load Factor

The concept of load factors is explained in Chapter 2.3.3. The load factors for different vehicles based on literature research are compared in Table 6. There are large differences between the different sources, however, a trend towards lower load factors in more recent reports can be seen.

Table 6: Comparison of Load Factor in Literature

Source	Asphalt Paver	Roller Compactor
AEAT (McGinlay, 2004)	0.35	0.4
EPA (2004)	0.59	0.59
IFEU (2004)	0.5	0.5
IFEU 2009 (Helms, Lambrecht, & Knörr, 2010)	0.2	0.2
IFEU 2014 (Helms & Heidt, 2014)	0.3	0.3
BAFU (Notter & Schmied, 2015)	0.2	0.2

From the data in Appendix D, the average load factors for the relevant vehicles were derived as shown in Table 7. The load factors are very similar to the load factor as determined by Helms & Heidt (2014). It is apparent that they are also much higher than those estimated by Notter & Schmied (2015) or Helms, Lambrecht & Knörr (2010), and lower than those estimated by the EPA. This difference may lay in the duty cycles or testing locations. Because the exact method used to determine the load factors is unknown, it is assumed that data derived from vehicles on construction sites similar to the ones considered in this model are more accurate than literature values. Further, the derived factors allow for a distinction between different roller types.

Table 7: Derived Load Factors

Machine Type	**Load Factor**
Asphalt Paver	0.32
Tandem Roller	0.28
Static Three-Wheel Roller	0.35
Pneumatic Roller	0.39

5.2.3 Transient Adjustment Factors

For any machine that has a technology level of Stage IIIA or earlier, a transient adjustment factor is needed to compensate for a machine's transient use cycle, later emission standards are assumed to consider this during testing. Both rollers and pavers are transient use machines that require a TAF. The adjustment factors depend on the technology level and load factor. In Table 8, the transient adjustment factors used in the European Emissions Inventory are listed, they are taken from Winther & Dore (2019).

Table 8: Transient Adjustment Factors for Diesel Engines

Technology Level	Load	Load Factor	NO_x	CH_4[1]	PM	FC
Stage II and prior	High	> 0.45	0.95	1.05	1.23	1.01
Stage IIIA	High	> 0.45	1.04	1.05	1.47	1.01
Stage IIIB - V	High	> 0.45	1	1	1	1
Stage II and prior	Medium	0.25 ≤ LF ≤ 0.45	1.025	1.67	1.6	1.095
Stage IIIA	Medium	0.25 ≤ LF ≤ 0.45	1.125	1.67	1.92	1.095
Stage IIIB - V	Medium	0.25 ≤ LF ≤ 0.45	1	1	1	1
Stage II and prior	Low	< 0.25	1.1	2.29	1.97	1.18
Stage IIIA	Low	< 0.25	1.21	2.29	2.37	1.18
Stage IIIB - V	Low	< 0.25	1	1	1	1

[1] the values for CH4 are taken from the VOC values in the report

5.2.4 Base Emission Factor

The base emission factors for the vehicles are taken from the EEAs emissions inventory guideline (Winther & Dore, 2019), because it is the most recent publication and complete for all relevant technology levels. The base emission factor depends on the fuel type, the rated engine power, and technology level and is given for each pollutant as well as fuel consumption. The complete list for vehicles up to Stage V and every power class can be found in Appendix E. The relevant emission factors for this research are summarized in Table 9.

Table 9: Base Emission Factors for NO_x, PM and FC [g/kWh] for Diesel Engines

Engine Power [kW]	Technology Level	NO_x	PM	CH_4[1]	N_2O	FC
8 ≤ P < 19	Stage II	11.20	1.600	0.060	0.035	270
	Stage IIIA	11.20	1.600	0.060	0.035	270
	Stage IIIB	11.20	1.600	0.060	0.035	270
	Stage IV	11.20	1.600	0.060	0.035	270
	Stage V	6.08	0.400	0.016	0.035	270
19 ≤ P < 37	Stage II	6.50	0.400	0.014	0.035	262
	Stage IIIA	6.08	0.400	0.014	0.035	262
	Stage IIIB	6.08	0.400	0.014	0.035	262
	Stage IV	6.08	0.400	0.014	0.035	262
	Stage V	3.81	0.015	0.010	0.035	262
37 ≤ P < 56	Stage II	5.5	0.200	0.010	0.035	260
	Stage IIIA	3.81	0.200	0.010	0.035	260

	Stage IIIB	3.81	0.025	0.007	0.035	260
	Stage IV	3.81	0.025	0.007	0.035	260
	Stage V	3.81	0.015	0.007	0.035	260
56 ≤ P < 75	Stage II	5.50	0.200	0.010	0.035	260
	Stage IIIA	3.81	0.200	0.010	0.035	260
	Stage IIIB	2.97	0.025	0.007	0.035	260
	Stage IV	0.40	0.025	0.007	0.035	260
	Stage V	0.40	0.015	0.003	0.035	260
75 ≤ P < 130	Stage II	5.20	0.200	0.007	0.035	255
	Stage IIIA	3.24	0.200	0.007	0.035	255
	Stage IIIB	2.97	0.025	0.003	0.035	255
	Stage IV	0.40	0.025	0.003	0.035	255
	Stage V	0.40	0.015	0.003	0.035	255
130 ≤ P < 560	Stage II	5.20	0.100	0.007	0.035	250
	Stage IIIA	3.24	0.100	0.007	0.035	250
	Stage IIIB	1.80	0.025	0.003	0.035	250
	Stage IV	0.40	0.025	0.003	0.035	250
	Stage V	0.40	0.015	0.003	0.035	250

[1] the CH4 emission factor is calculated as 2.4% of the VOC emission factors, for other adjustment factors the VOC factors are used

5.2.5 Deterioration Factor Adjustment and Median Lifespan

The equation the emissions inventory uses is split into two parts for the model. The deterioration factor is determined through:

$$DF_i = DF_{a,i} * Age\ of\ vehicle \qquad \text{Eq. 13}$$

Where

$DF_{a,i}$ = yearly deterioration factor of pollutant i

This equation is used in the final emissions equation and is based on the yearly deterioration factor, that shows the change in emissions per year the vehicle is used. This split in the calculation improves the flexibility of the calculations and allows the company to calculate the emissions of a project from any year without needing to constantly update the vehicle database.

The yearly deterioration factor is dependent on the average lifespan of the vehicle in comparison to the maximum deterioration factor. This factor is determined per vehicle and included in the database.

$$DF_a = \frac{DF_{max,i}}{average\ lifespan} \qquad \text{Eq. 14}$$

Where

$DF_{max,i}$ = maximum deterioration factor of pollutant i

The maximum deterioration factors are taken from Winther & Dore (2019) which have in turn expanded the numbers previously found in the TREMOD-MM and EPA models. The values have been sorted depending on the technology level. The fuel consumption is not expected to change through the deterioration of the motor, so there will be no deterioration factor applied to CO_2 emissions.

Table 10: Maximum Deterioration Factors for Diesel Engines

Technology Level	NO_x	CH4	PM
Before Stage I	0.024	0.047	0.473
Stage I	0.024	0.036	0.473
Stage II	0.009	0.034	0.473

Stage IIIA - V	0.008	0.027	0.473

The average lifetime of NRMM can vary with usage levels and maintenance. Most of the studies mainly consider the average work hours per year compared to the total work hours expected from the machinery as the measure for the average lifespan. The EPA has given different lifespans for nonroad machinery ranging from 2500 total work hours to 7000 total work hours depending on machine size. It suggests that nonroad machinery with higher engine power has a longer lifespan. Table 11 compares different values from literature sources in emissions models. It was decided to use the average vehicle age presented in the emissions inventory, for it is the most recent data and most reflective of the actual vehicle ages when replaced as perceived in the data from Dura Vermeer.

Table 11: Comparison of Literature Values for the Average Lifespan

	Paver		Roller	
EEA (Winther & Dore, 2019)		10		14
EMMA (Hulskotte & Verbeek, 2009)	50 kW	12.1	15/28 kW	15
	100 kW	19.4	50/90 kW	20
AEAT (McGinlay, 2004)		3.9		8.8

5.3 Supporting Vehicles

The vehicles used on the construction site are mainly NRMM, but in road construction, several supporting vehicles are needed next to the specific equipment. The most notable of these are bitumen sprayers and dump trucks. The bitumen sprayer is needed to spray bitumen on the surface before the asphalt is applied to make the asphalt stick to the layer beneath. The dump truck is needed to transport the asphalt mix to the construction site and load it onto the paver.

Both the bitumen sprayers and asphalt dumper are truck-mounted trailers, being operated from a truck chassis. Thus, the emissions are part of heavy-duty vehicle emissions. The emissions from HDVs are typically calculated using distance-related emission factors. The EU emissions inventory for road transport (Ntziachristos & Samaras, 2019) suggests the following fuel consumption factors for HDVs.

Table 12: Distance-based Fuel Consumption of Diesel HDVs

Vehicle Weight	FC in g/km
16 – 32t	210
> 32t	251

However, the measure seems inaccurate in this instance because the vehicles on the construction site do not follow the usage pattern expected for those factors. Compared to transport use vehicles, trucks on construction sites spend more time idling and driving at low speeds. A study by Grigoratos, Fontaras, Giechaskiel, & Zacharof (2019) shows that for most vehicles distance and power output related emission rates increase at lower speeds. Especially NOx emission rates were often several times as high as during lower speeds. Considering that the driving behavior or distance driven by the vehicles is unknown, it is best to use a time-based fuel consumption factor. This factor can be combined with fuel-based emission factors for the Netherlands given by the emissions inventory (Ntziachristos & Samaras, 2019) shown in Table 13. Company 2 has provided fuel use estimations on a time basis, suggesting that an asphalt transport truck uses around 8 l/h of fuel. Using the conversion factor for the volume of fuel into mass given in Appendix C, the mass of fuel consumed per hour is given in Equation 15. Because both the asphalt dumpers and the bitumen sprayers are operated from a truck chassis, it is assumed that both have the same fuel consumption and emissions.

$$FC_{dump\ truck} = 8\,l/h * 0.85\ kg/l = 6.8\ kg/h \qquad \text{Eq. 15}$$

Table 13: Fuel-based Emission Factors for Diesel HDVs

Pollutant	EF [g/kg fuel]
CO2*	5470
NOx	31.6
PM	0.8
CH4	0.18

**CO2 is a combined value for the CO2 emissions from fuel and the CO2 emissions from lubricants*

This gives a set VEF for each pollutant for supporting vehicles. The emission factors are given in Equations 16-19.

$$VEF_{CO2} = 6.8\, kg/h * 5470\, g/kg\ fuel = 37{,}196\, g/h \quad \text{Eq. 16}$$

$$VEF_{NOx} = 6.8\, kg/h * 31.6\ \ g/kg\ fuel = 214.88\, g/h \quad \text{Eq. 17}$$

$$VEF_{PM} = 6.8\, kg/h * 0.8\ \ g/kg\ fuel = 5.44\, g/h \quad \text{Eq. 18}$$

$$VEF_{CH4} = 6.8\, kg/h * 0.18\ \ g/kg\ fuel = 1.224\, g/h \quad \text{Eq. 19}$$

While the factors are from 2005 and not adjusted to newer emissions regulations, they are the most fitting estimates found for this model. A study on dump trucks by Frey & Kim (2006) calculates time-based emission factors for dump trucks of EPA Tier 1 and 2. The study is from the US and will not provide more accurate emission factors, but can be used to check the order of magnitude of the calculations.

5.4 HVO Fuel Emission Factors

The inclusion of HVO fuels will be an added factor that can be applied to the vehicle emission factor to calculate the vehicle emissions using different diesel and HVO blends. The factor can also be used to compare the emissions from different vehicles when using HVO fuels compared to regular diesel for policy decisions. The reduction factor is derived from two different sources, which focus on different vehicles and blends each. Tables 14 and 15 list the reduction factors from both sources for comparison.

Table 14: Reduction in Emissions of Different HVO Blends Compared to Regular Diesel in % (Neste Corporation, 2016)

Blend [% HVO fuel]	PM	NOx	HC[1]	CO2
30%	2	3	44	-
50%	5	5	48	-
100%	28	10	48	4
[1]will be assumed to represent CH4 reduction				

Table 15: Reduction in Emissions of Different HVO Blends Compared to Regular Diesel in % (Verbeek, 2018)

Blend [% HVO fuel]	PM	NOx	CO2
30%	4	3	27
100%	15	10	91

The values from the Neste Corporation (2016) were derived from the reduction measured in Euro IV trucks, while the percentages in Verbeek (2018) were derived from measurements on ‘special vehicles’ in Amsterdam, this is assumed to include any machinery used by the city in Amsterdam. Both sources have the same estimate for NOx reduction. The Neste report states that the NOx emission reduction is mainly linear. This agrees with the data from both reports, suggesting the maximum reduction of NOx emissions is 10%. For all other blends, it can be assumed that the reduction rate is 0.1% per percent of HVO. The PM rates are very different for both sources, with the Verbeek (2018) having lower values for the total reduction, but higher values for the reduction of a 30% blend. Because both reports give conflicting values, a third report calculating the reduction in emissions was considered. Erkkilä, et al. (2011) give similar values to the Neste report in PM emissions, even though they would assume a more linear reduction with increasing blends. As a result, the PM reduction is assumed to be linear and reduces by 0.3% per percent of HVO with a maximum reduction of 30% at pure HVO fuel. The Verbeek (2018) report does not give any indication on the reduction of hydrocarbons, thus the reduction shown in the Neste report will be used for comparisons. The CO2 emission reduction in the reports is very different. Verbeek (2018) considers the total reduction in CO2 emissions including those during the production chain, while Neste (2016) only considers the tailpipe emissions for their report. The boundary for this model is set at the calculation of on-site construction equipment emissions, thus the reduction of emissions in the production chain will not be considered. Based on the results in Erkkilä, et al. (2011), it will be assumed that the reduction in blends is linear depending on the blend ratio at 0.04% reduction per percent of HVO, with a maximum reduction of 4%.

Considering the conclusions drawn, the reduction factors for HVO fuels on the total emissions of a vehicle are shown in Table 16.

Table 16: Reduction Factors for HVO Fuels

Blend [% HVO fuel]	PM	NOx	CH4	CO2
30	0.91	0.97	0.56	0.988
50	0.85	0.95	0.52	0.980
100	0.70	0.90	0.52	0.960

When an HVO blend is used, the factor can be added to equations 9 and 10 for the corresponding pollutants. With N2O being part of the NOx emissions, the N2O reduction is expected to be equal to the relative NOx reduction, therefore the NOx factor will also be applied to N2O emissions.

5.5 ECI Calculation

The ECI is calculated for the GWP considering the total CO2, CH4, and N2O emissions from the machinery. The final ECI in Euro will be calculated using Equations 20 and 21. The equations use the factors mentioned in Chapter 2.4.

$$ECI = GWP * 0.05€ \quad \text{Eq. 20}$$

$$GWP = E_{CO2} + E_{CH4} * 25 + E_{N2O} * 298 \quad \text{Eq. 21}$$

5.6 Results

The goal was to calculate the emissions of the vehicles used during the construction process of different projects to then see how the emissions can be best reduced. Following the model structure decided on, the first step was to create a vehicle database. The vehicle database uses the vehicle specifications of different construction equipment shown in Table 17, Appendix B as the main input. This input is then used to determine the different model parameters, the results of which are shown in Table 31, Appendix G. Based on the parameters the vehicle emission factor and yearly deterioration factors for the different pollutants were calculated and summarized in Table 32, Appendix G.

To better compare the differences in emissions between different vehicles, a larger timeframe would be beneficial to increase the small differences in emission factors to visible differences. For this, the weekly emissions of a vehicle are used. In lack of vehicle hours for a project, data of the working hours of employees on the construction site was used. The data was given for several months at the end of 2019 and the beginning of 2020. The data used was divided into the hours worked per worker per week. Since these are very different for each worker and no division could be made for the different vehicles, the average working time of all workers per week was calculated and used as the average weekly working time of the machines. The weekly average per worker was 37.7h.

The vehicles at Dura Vermeer are grouped into sets. The corresponding set for each vehicle is listed in the vehicle specifications in Appendix B. The pneumatic rollers do not belong to any of the mentioned sets specifically but were included in the calculations to use for the comparison of the fuel consumption in the next chapter. They will not be included in the analysis of the results of this chapter. The sets each consist of a paver and three rollers. Most sets have one static three-wheel roller, but AS-07 has three tandem rollers in its set. Each set is also equipped with two supporting vehicles, one bitumen sprayer, and asphalt truck, the VEFs of which are listed separately. The sets were combined to calculate the weekly emissions per set and compare the different sets to each other. The results of the calculations can be found in Tables 33-38 in Appendix H.

In general, it was found that for most emission values the supporting vehicles made up the largest singular parts of the emissions. This is surprising as the expectation was for trucks to have lower emissions than the NRMM. Due to the outdated emission factors that are not specific to the vehicles directly, this could be a miscalculation that needs revision. Due to this large impact of the trucks on the total emissions, it was decided to leave the trucks out of the further analyses and include only the NRMM to better see the differences between the asphalt sets and the individual vehicles.

The figures are designed to compare the emissions of different asphalt sets during an average week in 2020 with each other, while also seeing the contribution of the different vehicles to the total emissions to better analyze the main contributors to emissions.

5.6.1 NOx Emissions

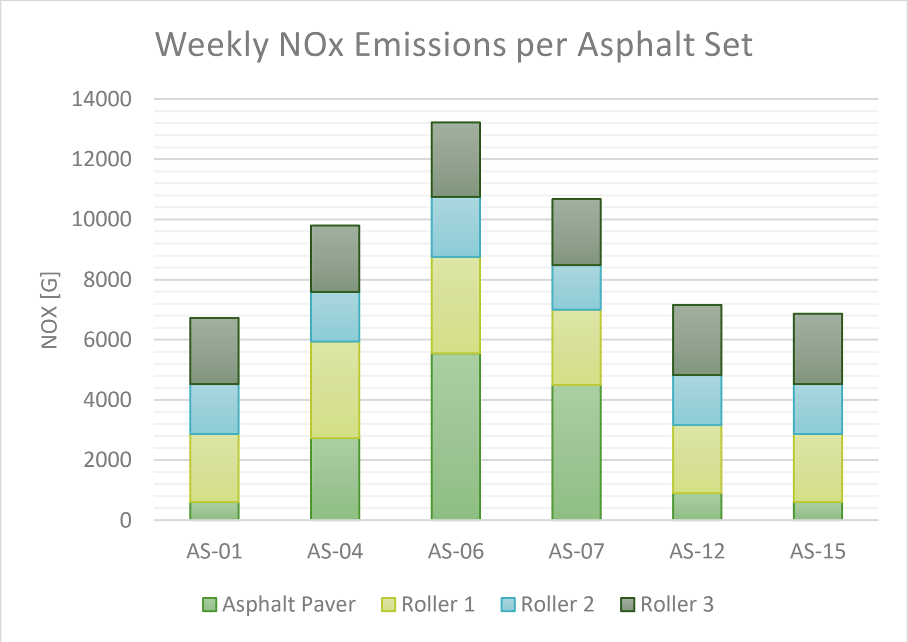


Figure 8: Weekly NOx Emissions per Asphalt Set

Figure 8 shows the NOx emissions of the different asphalt sets separated into the respective emissions of the paver and the different rollers. For the asphalt sets with a static three-wheel roller, this value is given in Roller 1, the other rollers represent tandem rollers. The tandem rollers are shown in Roller 2 and 3, whereby Roller 2 is usually the one with a smaller engine.

The NOx emissions vary much between the sets. The sets with the lower emissions only emit about half as much NOx as AS-06. The vehicle division shows that most rollers of one category have very similar emissions and that the main difference between the asphalt sets is caused by the pavers. The highest NOx emissions are caused by AP-3 in AS-06, which also makes it the set with the highest NOx emissions. In general, Asphalt Sets 01, 12 & 15 have very similar emissions. These sets also have the oldest pavers of the sets. It is reasonable to assume that the replacement of older pavers with newer ones will decrease the NOx emissions significantly. Further, among the rollers, the static rollers used in sets 04 & 06 have the highest NOx emissions among the rollers, while also being the oldest static rollers in the fleet. This leads to the conclusion that the age of the vehicle fleet has a great impact on the NOx emissions and that the replacement of a vehicle will cause a large reduction in NOx values.

5.6.2 PM Emissions

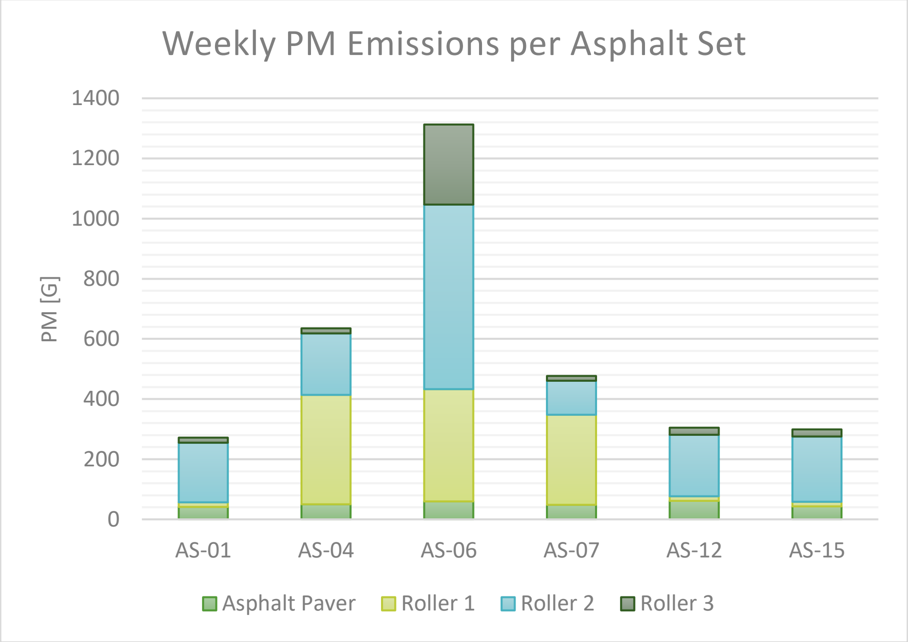


Figure 9: Weekly PM Emissions per Asphalt Set

Figure 9 shows the PM emissions per asphalt set divided into the contributions of each vehicle in the set. The division of vehicles is the same as that in Figure 8. The variation between the different asphalt sets is very large. AS-06 has more than four times the PM emissions of AS-01, 12, or 15. In this case, it is remarkable that despite having the largest engines, the pavers only have very low PM emissions and that the Roller 2 category, with the smallest rollers, has the biggest impact on the emissions. Further, the static rollers in AS-04, 06 & 07 also have a large impact on the respective total. In this case, the high PM emissions result from a combination of older vehicles and small engine sizes. The PM emissions would also be reduced through replacing vehicles, seeing as in Stage IIIB the emission standards became more stringent, especially smaller engines like small rollers.

5.6.3 GHG Emissions

Figure 10 shows the CO2 emissions of each asphalt set divided into different vehicle contributions. The CO2 emissions have a relatively smaller difference. The main influence on CO2 emissions is the paver. They make up around 50% of the emissions per asphalt set. AS-04 has the highest CO2 emissions among the sets. The discrepancy between the spread of the CO2 emissions and that of PM or NOx emissions shows that the age of the machine has little influence in the model. The CO2 emissions would not be reduced through newer equipment. To reduce CO2 emissions, there have to be changes made to the fuel or fuel consumption. This might be reached through the replacement of diesel fuel with biodiesel or HVO fuel that reduces tailpipe CO2 emissions. Further, this could be reached through changes in driving behavior or reduced idling time.

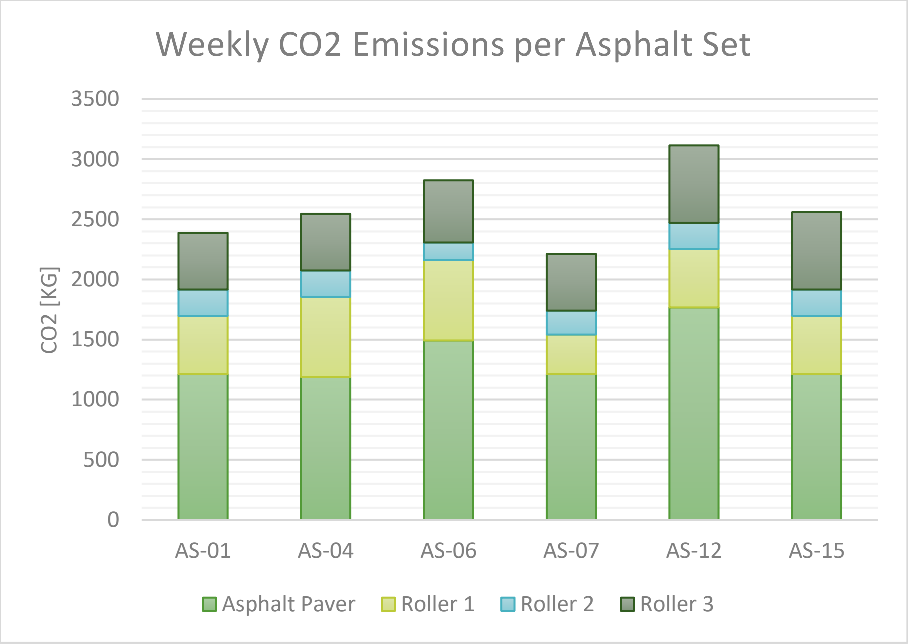


Figure 10: Weekly CO2 Emissions per Asphalt Set

The CH4 emissions are shown in Figure 11. The emissions are similarly spread out to the NOx and PM emissions with AS-06 showing the largest modeled emissions. Once again, a combination of the age of the machine and its power seems to be the determining factor in reducing CH4 emissions. AS-06 has two of the oldest rollers in the fleet and it is very noticeably the highest emitter in most pollutants so far.

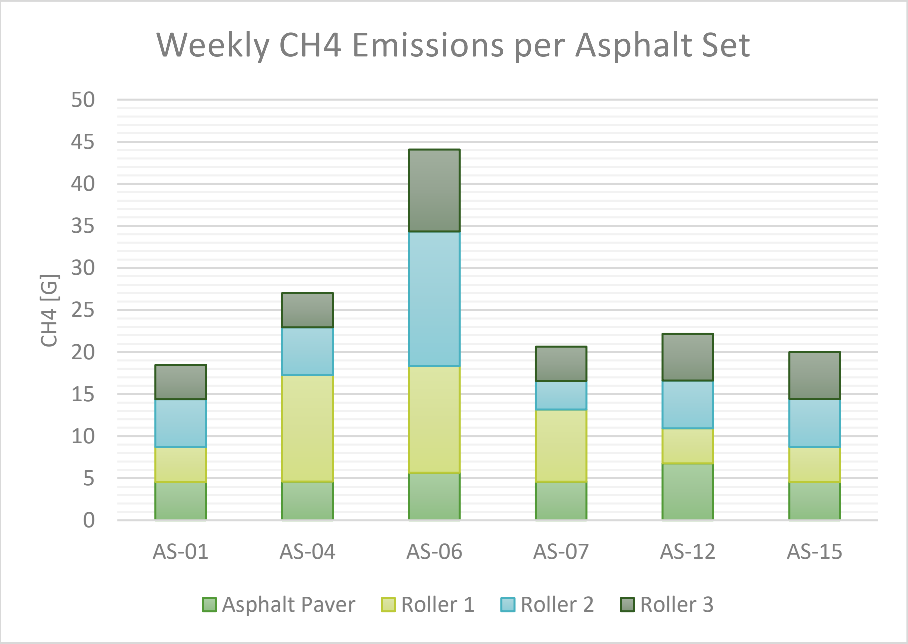


Figure 11: Weekly CH4 Emissions per Asphalt Set

The N2O emissions in the model are a reflection of the power output of the machines because there is no differentiation for the NOx factor depending on the vehicle’s engine size or emission standards. The spread of the values is very similar to the CO2 emissions spread and it is likely also to be reduced through similar measures.

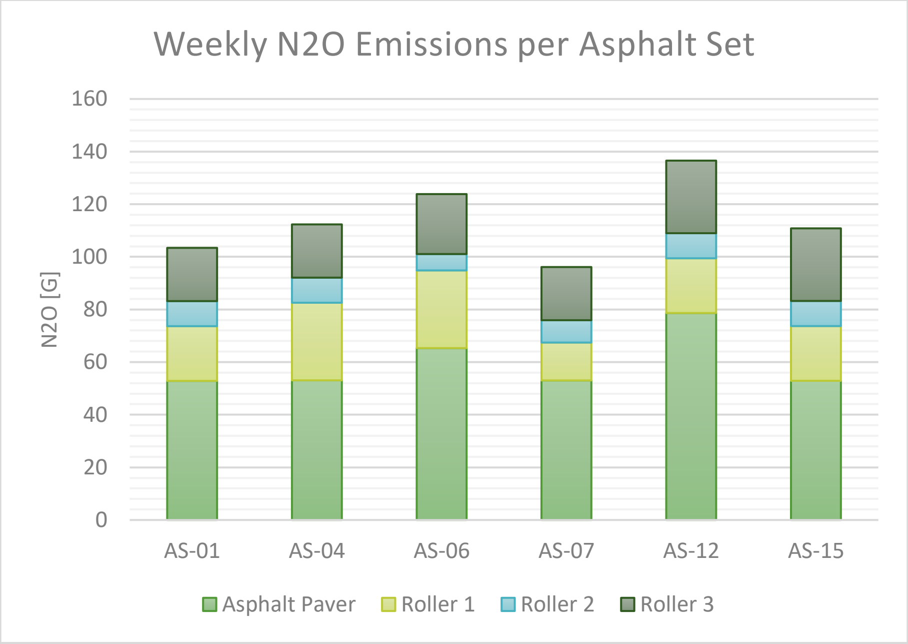


Figure 12:Weekly N2O Emissions per Asphalt Set

The GHG emissions are not only shown in the total mass of pollutant emitted but are also translated into the ECI, that indicates the GWP100 for the emissions. The ECI is mainly composed of direct CO2 emissions, with around 99% of the GWP being from the carbon emissions. The CH4 and N2O emissions, despite being more impactful on the environment per mass unit, are so small compared to the CO2 emissions that they only amount to 1% of the related cost. Seeing that the ECI is mostly influenced by the CO2, the ECI is also not expected to decrease using newer machinery. The ECI would decrease when using different fuels or optimizing fuel efficiency.

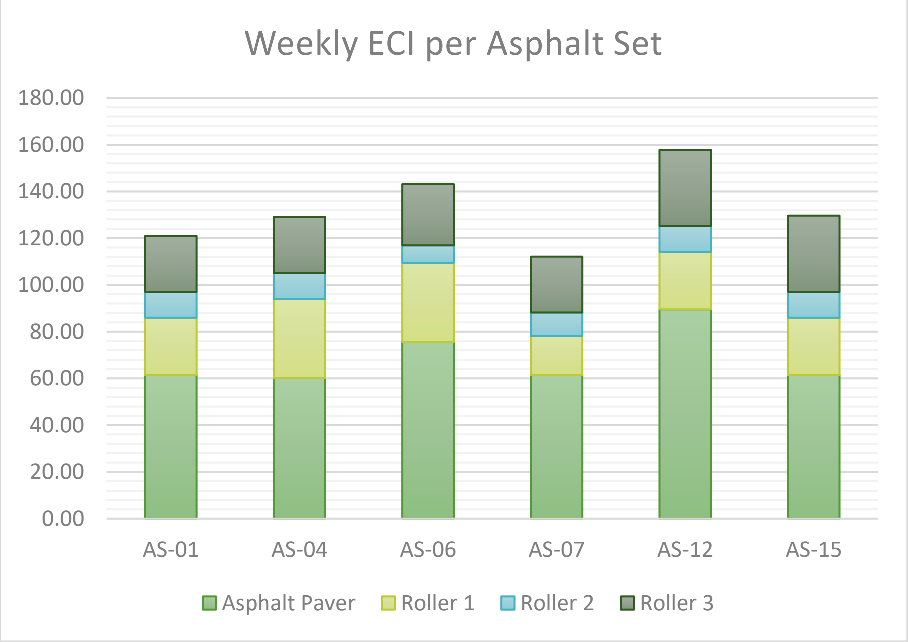


Figure 13: Weekly ECI per Asphalt Set in €

5.7 Usage for Policy Decisions

Next to predicting emissions for the current or future construction projects, the model is intended to help with policy decisions like buying new machinery or switching different fuels. The model can be adapted to fit the policy changes and compare the changes. This chapter will explore the changes to two asphalt sets when using a new paver, and the changes to the emissions of all asphalt set when using different blends of HVO fuels.

5.7.1 Replacement of Pavers

For a company to get a new machine is expensive and the new vehicle should bring some benefits to the company for it to be bought. This year Dura Vermeer is planning to replace two of its oldest pavers in the fleet, AP-2 and AP-4 in AS-04 and AS-07 respectively. The exact replacement for the machines is not known, but it is assumed that the machine would have approximately the same engine size. The emission standards of the new vehicles would be Stage V. The vehicle specifications, emission factors, and calculation results are listed in Appendix I.

In the previous chapter, the assumption was made that the replacement of older vehicles with newer ones would mainly influence the NOx, PM, and CH4 emissions. Figure 14 shows the percentual reduction in emissions and the ECI when the respective vehicles would be replaced by a new Stage V paver.

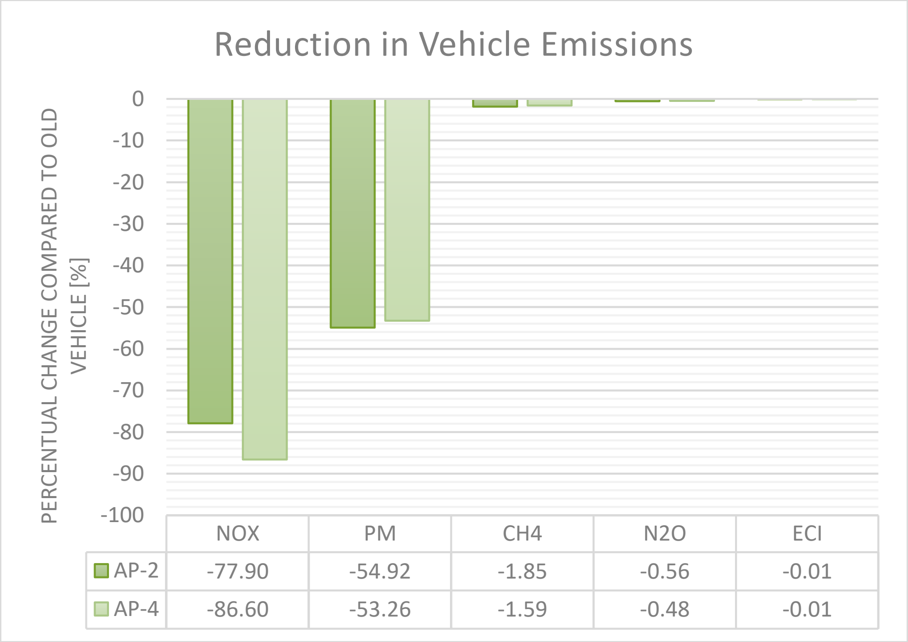


Figure 14: Reduction of Vehicle Emissions Between Old and New Pavers

The figure highlights the major reduction in NOx and PM emissions, that reach up to 86% and 54% respectively. The CH4 emission reduction, in this case, is rather small, but the expectation was to lower the emissions for smaller machinery, while the pavers have rather large engine sizes compared to rollers. The only category that did not experience any change and is therefore excluded from the graph is the CO2 emission. The CO2 emissions are not partial to the age of the machinery and therefore the ECI also had only marginal changes. The reduction in N2O and CH4 have little to no impact on these numbers either.

The benefit of buying new pavers is a clear reduction in NOx and PM emissions. Regarding Dutch policies for the reduction of NOx levels throughout the country, the new pavers provide a large improvement to the vehicle fleet. They also have a large influence on the whole fleet, as the NOx values for AS-04 and AS-07 are expected to be reduced by 8.2% and 14.5% respectively. Also, the PM emissions are expected to reduce fleet emissions, which are expected to sink by about 3% per set. This reduction seen on a whole year would bring clear advantages to the environmental impact of construction projects, especially of the local environment and air quality. The steep reduction in NOx values is especially beneficial to construction sites in urban settings.

5.7.2 HVO Fuel Blends

Next to the replacement of equipment, Dura Vermeer is thinking about reducing emissions by introducing HVO fuel blends to their fleet. Because the HVO fuels are more expensive than regular diesel, the question for the company is whether it is worth investing in the fuels when they are more expensive. To compare the different blends of HVO fuel, the ECI for every vehicle per hour was calculated for each blend of fuel. The resulting cost was then divided by the hourly fuel consumption of the vehicle. Figure 15 shows the difference in the ECI per liter of fuel consumed.

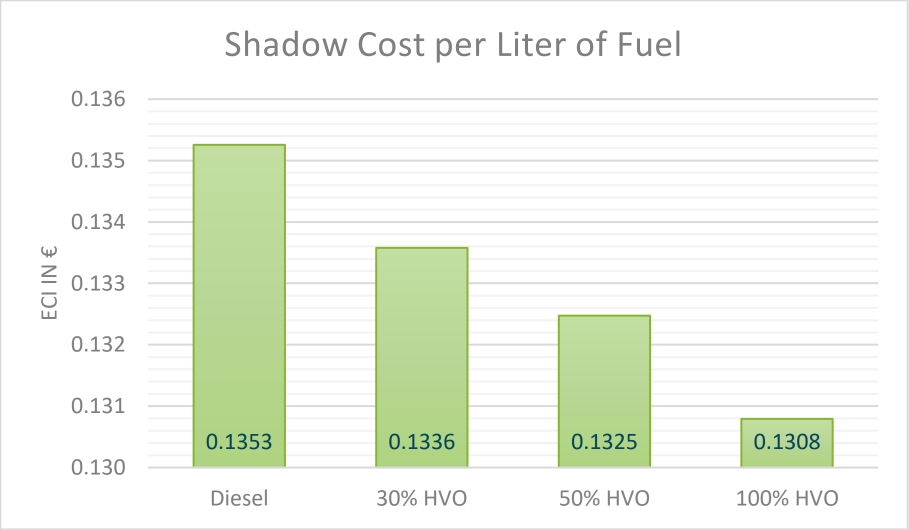


Figure 15: ECI per Liter of Fuel for Diesel and HVO Blends

The average ECI saving per liter fuel is 0.48 cents for pure HVO. When this amount is related to the large fuel consumption of NRMM and trucks, this will make a large difference to a projects ECI. But if compared to the average cost increase due to the higher cost of the HVO fuel, it will not make up for that. The average liter of HVO fuel costs about 0.15€ more than a liter of diesel (OrangeGas BV, 2020). The decision for HVO fuel, in the end, would not be on a financial stance, but on the benefits, the fuel brings that are not monetized in this study, like the reduction of NOx and PM emissions. Further, due to the reduction being a percentage of the total amount emitted with regular diesel, the measure is most effective on vehicles with high emission factors for the considered pollutants.

6 Comparison to Measured Values

A model should be validated before using it in any setting. The circumstances of this research prevent direct validation through emission measurements, but different proxy values can be used to estimate the accuracy of the model in different circumstances.

6.1 Fuel Consumption

The fuel consumption of each vehicle is definitive of the CO2 emissions of the vehicle. While no exact fuel measurements for each vehicle are available, many companies have averages for their vehicle fleets available. Three different companies have provided average values for the fuel consumption of their vehicle fleet per vehicle type. To make the data more comparable, the model values are also averaged for the fleet. Further, the vehicle system measurements provided also included average fuel consumption values, the statistical analyses are shown in Appendix D. Another source was values from Li, Zhang, Pang & Di (2016) who did a study on fuel-based emissions factors which also included average fuel consumption values for different rollers and a paver. Figure 16 shows the different data sources compared to the averages per vehicle category in the model. The exact values are given in Appendix F.

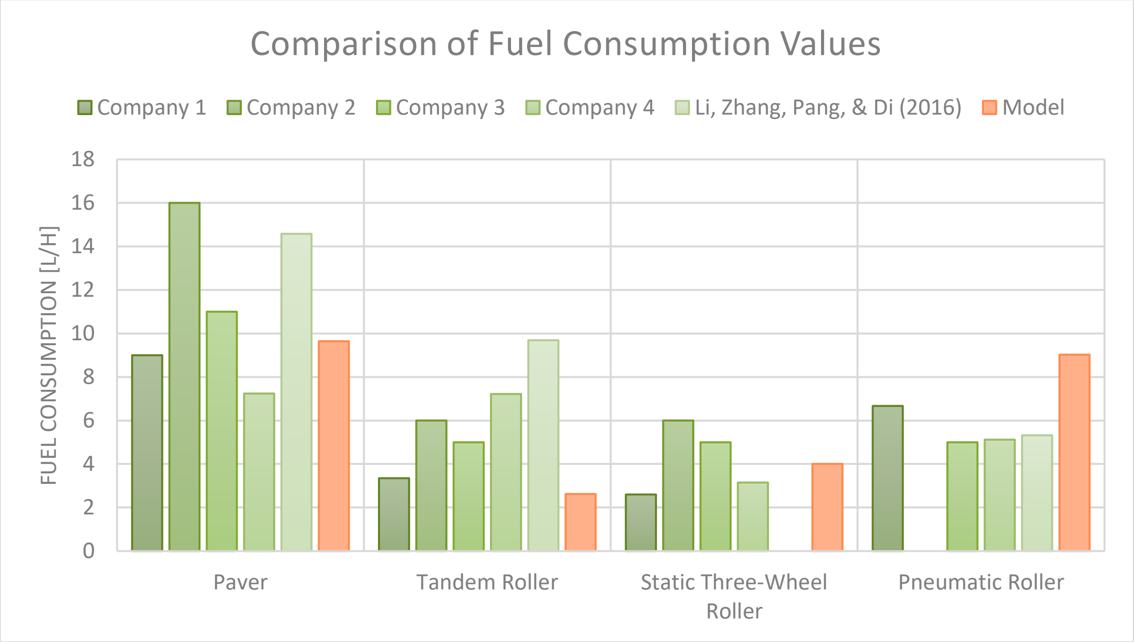


Figure 16: Comparison of the Model to Different Fuel Consumption Values

Two of the model values stand out when compared to the data. The tandem rollers in the model are estimated to have a much lower average fuel consumption than the data points. Meanwhile, the pneumatic rollers have a much higher average value compared to the data. Both the paver and the static roller fall in the middle of the averaged values.

The difference between the values for tandem rollers could have multiple reasons. The values for tandem rollers have a high range. The highest data point is more than double that of the lowest, suggesting that even within different tandem rollers there are great differences in fuel consumption. This could also be connected to the engine size of the vehicle, seeing as the tandem rollers can have highly varying engine sizes amongst them depending on their size. The model values and the values found in a Chinese study have the highest difference between them. Remarkable is the difference in engine size because while the modeled engine average at 40.9 kW, the study considers a 132 kW engine. This difference is likely crucial to the difference in emissions.

The pneumatic rollers present a different problem, as there are too few measurements to draw lasting conclusions. There are only two pneumatic rollers considered in the model, both with rather large engines that may not be representative of the population.

6.2 Comparison to NOx Measurements

The emission factors used in emission models have been often questioned. Especially NOx values are often seen as uncertain and not researched enough, especially in connection with low load factors (Ligterink, Louman, Verbeek, & Buskermolen, 2018). The research gap is especially evident in the paving equipment sector. While many articles are written about excavators, loaders, and bulldozers, it is hard to find research about pavers or rollers. Li, Zhang, Pang, & Di (2016) were one of the few pieces of research on pavers and rollers including comparable emission measurements. Further explanations of their research and the calculation behind this comparison are given in Appendix J.

The differences between the measured values and the calculated values are shown in Figure 17.

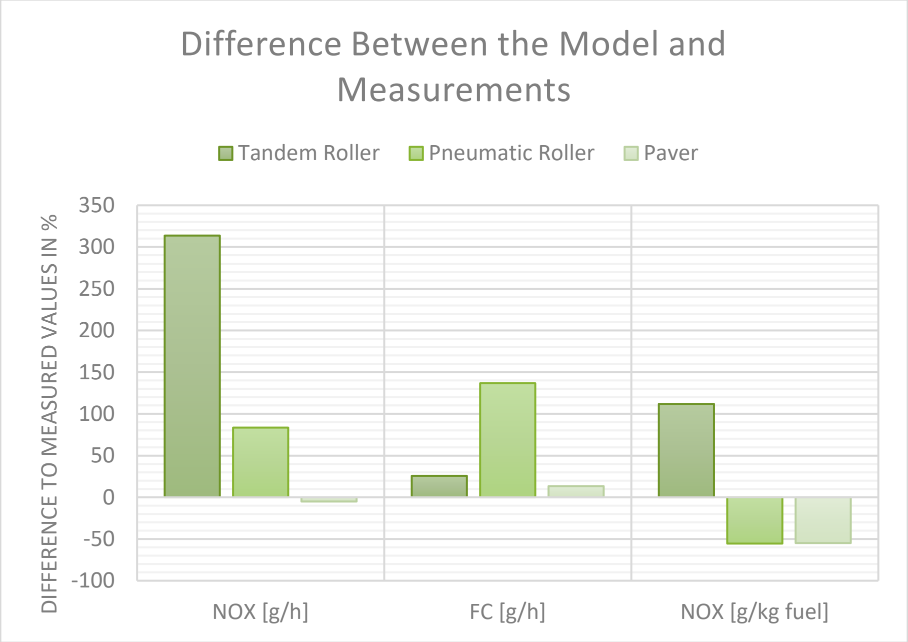


Figure 17: Difference Between the Modeled and Measured Emissions

The figure shows clear deviations of the model to the measured values. The differences in this example range from +314% to -5% of the measured model. The most noticeable difference is the NOx calculation for the tandem roller. The calculated value is more than three times higher than the measured one. On the other hand, the estimated fuel consumption is relatively close to the measured values. The closest the model came to the measured values is for the paver. Both of the measured values are very close to the model values. The tandem roller showed the highest difference in the fuel consumption. In general, the fuel consumption values are more accurate than the NOx values. The fuel-based emission rate is based on the previous two estimations and will thus reflect the differences of the other two model values, but it is interesting that none of the values are close to the measured values.

It is hard to determine one single reason for this because there are many variables that cannot be isolated on the basis of a singular measurement per vehicle type. However, some conclusions can be drawn, and assumptions are made. One possible cause for the high differences may be that the research was conducted in China, while the emission factors used for the model were specific to Europe. There might be differences based on national regulations for the machines or differences in the types of fuel used. Based on the comparison, the emission factors should be reviewed to better represent the in-use emissions and reduce the overestimation, especially for the tandem roller. However, another variable influencing the emission rate is the amount of time a vehicle spends idling. Figure 18 shows a comparison between the time spent in each work mode during the experiment in China and the expected idling rate derived from vehicle internal measurements in the Netherlands depicted by the line. The data for this chart can be found in Appendix J.

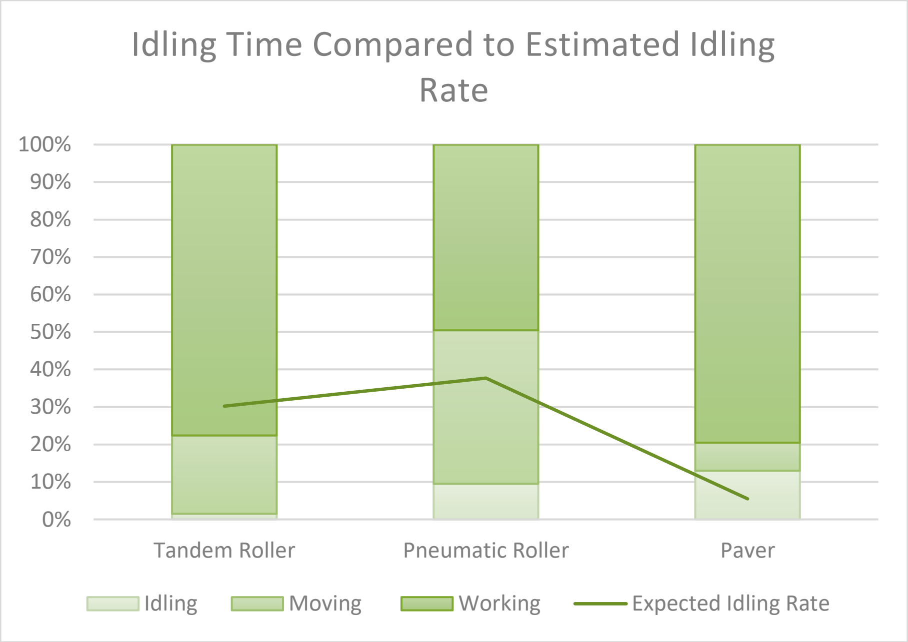


Figure 18: Comparison of the Measured Idling Time and the Expected Idling Rate

The idling times from the Chinese project show immense differences to the idling rate, especially assuming that vehicle measurements would classify both moving and working as usage. This difference may originate from the organization of the work, the standards in the country, or differences in the type of road constructed. The Chinese research was conducted on a highway construction site, where the vehicles might have worked long stretches of time without having to reset the machines, while the projects monitored in the data might include a variety of smaller and larger projects. Regardless of the source of the difference, it could be a cause for the difference between modeled and measured emissions. Ligterink, Louman, Verbeek, & Buskermolen (2018) stated that emission factors, especially for NOx, were higher for lower engine loads. The vehicle data in Appendix D shows the average load factor for every vehicle for the use mode and the idling mode. The load factor is always significantly lower during high periods if idling. Assuming that the idling rate determined in the vehicle data is close to the European average reflected in the emission factors, it can also be assumed that increased periods of idling cause higher emissions when using an average emission factor based on an average idling rate. Should the vehicle have more idling time, the emissions are underestimated by the model, and is the idling time decreased the estimation of emissions is too high.

This reflects the values shown in Figures 17 and 18. Looking at the tandem roller, the idling time is twenty times lower than the expected idling rate, and the emissions are largely overestimated. Similarly, the idling time of the pneumatic roller is only a quarter of the expected idling rate and the NOx emissions are overestimated. On the other hand, the idling time of the paver is more than double the expected value and the emissions are slightly underestimated. While the exact effect of different idling rates cannot be determined in one measurement, there seems to be a connection that should be investigated further.

While there are many possible explanations for the difference between measured and modeled values, the data shows that especially on the level of individual vehicles for one specific time frame, the model can be very inaccurate. These inaccuracies for NOx emissions need to be kept in mind when using the model, especially regarding shorter calculation periods. It can be assumed that larger time periods and the averaging of several vehicles will increase the accuracy of the emissions calculation as is shown in the fuel consumption compared with the fleet averages. This comparison also needs to be analyzed with caution, considering the values were based on measurements of a singular vehicle during a random duty cycle. A similar comparison following measurements of a different vehicle in a different duty cycle may show very different results.

7 Recommendations

The emission model considers a variety of parameters influencing emissions, but there are many lacking. Most of the lacking parameters are also hard to measure and estimations are very uncertain, but in this chapter, some ideas for additional parameters will be explored. Further, some of the input data and parameters used in the model might be partial to high uncertainty, so some realistic ways to reduce the uncertainty for these factors are mentioned.

(1) Validation and uncertainty analysis of the model based on emission measurements

The emission results of this model were compared to different data points for individual vehicles and fleet averages, and while the results did allow some assumptions, the data sets were very few and no definite conclusions could be drawn. To validate the values the model provides, it should be compared to emission measurements of the vehicles modeled. Further, the uncertainty of the model should be determined to know how reliable the model values are and how exact the emissions can be determined.

(2) Monitor fuel consumption and working hours for vehicles

The fuel consumption of the vehicle is the main indicator for CO2 consumption. When the fuel consumption per day or hour is known, the CO2 emissions can be calculated very exactly. Further, the monitored values could be used to adjust the fuel consumption calculations in the model to better reflect the real values.

The working hours of a vehicle are the deciding input for the model. The calculations shown are only based on the average working hours of the workers on the construction site. This time is only an average and does not reflect the time machines might spend idling during breaks, the time taken before turning them on or the time after the machine is turned off. While helping to make assumptions on the emissions, a daily usage time of each vehicle would improve the model accuracy greatly. Simple notations like the time a vehicle was turned on and the time it was turned off would be helpful.

(3) Collect data on the usage of supporting vehicles and refine the emission calculation

The supporting vehicles were added to the asphalt sets because they are very important to the construction process and should be considered as part of the machinery. However, they are trucks, not NRMM, thus they do not fit in the model well. Models for truck emissions are usually aimed at trucks driving average road speeds and using the highways, not at construction vehicles. However, vehicles on the construction site move much slower and have more idling or waiting time in their driving cycle. Grigoratos, Fontaras, Giechaskiel, & Zacharof (2019) showed that vehicle emissions peak at low speeds, so using the standard emission model that uses distance based emission factors would largely underestimate the emissions.

The estimates used were based on very uncertain data and are likely to be much too large, considering they were based on emission factors from 2005. But because there is little consideration for trucks on construction sites, and little research was done on the topic, not much is known about the emissions from the vehicles. Further, the usage patterns of the vehicles are just as important as those of the nonroad machinery and should be looked at closer. Considering that about half of the emissions calculated for each asphalt set were caused by estimates for the supporting vehicles, it would be helpful to look into it further and try to find more accurate values.

(4) Revise the unit of the emission factors

Several studies throughout the research for this project pointed out that fuel-based emission factors would be more accurate than power output based ones. Because there was no fuel consumption data available, it was decided to use a power output based model, because it fits the available data better. However, the fuel consumption of vehicles is much easier to track than the power output and would be much easier to calculate. More research towards the accuracy of fuel-based emission factors and their uses should be conducted to see if they could be more useful for the model than power output based factors.

(5) Revise the emission factors

The emission factors were stated as the main source of uncertainty in the model due to the lack of measurement data backing up the expert opinions on the factors. Further, the factors are mainly classified into engine size classes, without much other consideration. Through emission measurements of each new vehicle, emission factors could be documented more accurately and have more meaning to the model. Additionally, when the factors are determined during the construction work of the vehicle, they would not need transient adjustment anymore, which was another point of uncertainty in the model.

(6) Consider seasonal differences to emissions

Vehicle emissions now are generalized over the year, but seasonal differences in temperatures have an influence on the energy and fuel needed by the vehicle because some energy is needed to warm the motor and some pavers even have heating to keep the asphalt mixtures warm. Further, there is a difference between winter and summer fuels (Notter & Schmied, 2015), which causes them to emit more CO2 during colder periods. It might help to keep in mind that winter emissions are likely to be higher and consider implementing a factor to account for it in the model.

(7) Consider vehicle driving patterns and modal emissions

The model developed is very basic and works with the minimum of data. Further insight into ways to reduce emissions could be gained from the analysis of driving patterns and the optimization of the vehicle usage time. Further, the driving pattern could give insight about the speed and acceleration of the vehicle which can then be related to emissions.

The model could even be adapted into a modal model, where each mode is assigned its own emission factors and the driving patterns are used to define the amount of time spent in each of the driving patterns.

8 Conclusion

An emissions model can be of great help for efficient emissions reduction by using it to determine where different measures have the greatest effect. This can prevent spending money on inefficient measures and show whether a measure will reach the desired effect.

There are three major findings in this research. First, that every pollutant is influenced differently by the different parameters. Where the age of the vehicle has a great effect on the NOx emissions, it does not much affect the CO2 emissions. CO2 emissions on the other hand heavily depend on the size of the engine. Due to these differences, different measures to reduce each pollutant are necessary. Depending on the intent when applying a measure, the model can help identify which measure is most effective to reduce the intended pollutant.

Secondly, the ECI of the tailpipe emissions of a vehicle is mainly dependent on CO2 emissions. This also means that the two options to reduce emissions explored in this research have little to no effect on the ECI. With more importance being placed on low ECIs for project tenders, the most effective measures to reduce the CO2 emissions are reducing the fuel consumption of a vehicle or switching the fuel for one with lower carbon emissions.

Lastly, the idling rate of a vehicle is of great importance to the emissions. The data derived from company 4 shows that the load factors as well as the fuel consumption for measurements with high idling rates are much lower than those of measurements with low idling rates. With the load factor being a major parameter for emissions and the fuel consumption being the determinant for CO2 emissions, the numbers indicate that during usage cycles with high idling rates the emissions would be much lower than when the idling rate is low. Idling rates should be integrated into a model when trying to make the predictions more accurate.

This research builds a basis for emissions quantification from paving equipment, but to use the model to its best efficiency, the emissions quantification should be refined by the addition of further parameters and supported by on-site measurements. As mentioned previously, the idling rate seems to be a previously underestimated parameter in the model, that will be very influential, especially on the emissions of an individual vehicle. However, in many cases idling rates are not considered at all, or idling times not counted towards machine use times. This leads to gross misestimations of the actual emissions of vehicles. Further research in this field should put more focus on the idling rate and emissions caused by switching between the two modes.

Also, during this research, the lack of measurement-based parameters hindered the development of a more refined model. Further research should try and base the different adjustments to the model in measurement values that reduce the uncertainty in the model. In other words, only on-site measurements of vehicle emissions will increase the reliability of the model predictions. Every company needs to conduct its own measurements to get reliable values on their own machinery. This could not only make the ECI predictions more dependable but also give an advantage for a future with ever more strict emissions monitoring regulations.

9 Discussion

This research was heavily impacted by the data gap in the calculation of NRMM emissions. While the research clearly shows that the impact of NRMM emissions is not neglectable, there is little research done on the topic. Because this research was aimed at a very niche area of NRMM, the paving equipment, finding reliable data sources was made even harder. The majority of research on emissions considers loaders, excavators or bulldozers, all of which work very differently from paving equipment.

When the research was planned at first, the idea was to collect data in the field. Due to COVID-19 no such data collection was possible leading, which led to a restructuring of the research. Instead of working in the data gap, it now had to work around it. This led to a continuous restructuring of the methodology and goals of the model depending on the availability of data.

With a lack of validation measurements, data collection from several sources acquired enough data to make some comparisons, but they seem very inconclusive and do not have the intended effect of proving the effectiveness of the model. Many of the data sets might be based on industry averages or manufacturer’s sheets rather than measured data, making it even more difficult to judge their accuracy. Especially the emissions for singular vehicles were further off than expected. Due to the lack of validation, the model should be used only for loose estimates until more research is conducted.

Much of the data was based on uncertain values, but one modeling decision stands out for me. Using a singular average value to estimate the emissions of the vehicles is questionable and was done in an attempt to include the vehicles as they are part of the ‘Asphalt Sets’, despite a severe lack of information on the vehicles. Also, as explained in other chapters, the research on truck-based construction equipment is practically nonexistent. The attempt to still include the vehicles was less successful than hoped. Not only did the truck emissions overshadow the NRMM emissions, but they also weren’t useful to analyze in terms of emission reduction, because their values were all the same.

Moreover, many of the expectations at the start of the research were not met. For instance, CH4 and N2O emissions were added to the research in the expectation that their high GWP would increase the ECI significantly. Contrary to this assumption, it was found that these pollutants only make up about 1% of the ECI in the model. Their influence is much lower than initially thought. Another assumption was that HVO fuels would significantly decrease tailpipe CO2 emissions. Instead, further research shows that the main reduction in CO2 emissions happens during the production chain of the fuel, not in the combustion process. While this is still a large environmental benefit, it affects the emissions model only minimally.

Overall, much of the initial literature for this research was confirmed in the following weeks. Many sources had voiced their discontent on the lack of emissions data and the data gap in this field, which was also felt through the entirety of this research. Further, the high uncertainty in emission models and the large differences to measured emissions has been echoed in this research.

While this research brought a lot of hindrances, it has allowed an insight into the problems in the modeling of emissions and the progress that still has to be made on the topic. The insight gained and concluded into the recommendations will hopefully help to improve the current model and help towards getting more research done in the future.

10 References

AV Calc LLC. (2020). *Density of diesel (material)*. Retrieved July 26, 2020, from Aqua-Calc.com: https://www.aqua-calc.com/page/density-table/substance/diesel

Barati, K., & Shen, X. (2016). Operational level emissions modeling of on-road construction equipment through field data analysis. *Automation in Construction*(72), pp. 338-346. doi:10.1016/j.autcon.2016.08.010

Boulter, P. G., McCrae, I. S., & Barlow, T. J. (2007). *A Review of Instantaneous Emission Models for Road Vehicles.* Transport Research Laboratory.

Clean Air Act Advisory Committee. (2006). *Recommendations for Reducing Emissions from the Legacy Diesel Fleet.* US EPA.

Climate Change Connection. (2020, July 23). *CO2 Equivalents*. Retrieved from Climate Change Connection: https://climatechangeconnection.org/emissions/co2-equivalents/

Dellaert, S., & Dröge, R. (2017). *Uncertainty of the NOx, SOx, NH3, PM10, PM2.5, EC2.5 and NMVOC emissions from transport.* Utrecht: TNO.

Den Hertog BV. (2018). *Quality*. Retrieved July 31, 2020, from CO2 Saving Diesel: https://www.co2savingdiesel.nl/kwaliteit-co2-saving-diesel/

Department for Business, Innovation and Skills. (2010). *Estimating the amount of CO2 emissions that the construction industry can influence.* London.

DieselNet. (2019, July). *China: Nonroad Engines*. Retrieved August 03, 2020, from DieselNEt: https://dieselnet.com/standards/cn/nonroad.php

DieselNet. (2020). *EU: Nonroad Engines*. Retrieved from DieselNet: https://dieselnet.com/standards/eu/nonroad.php

EPA. (2004). *Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling.* US EPA.

EPA. (2018a, December 03). *MOVES and Related Models: Nonroad Technical Reports*. Retrieved June 2020, from United States Environmental Protection Agency: https://www.epa.gov/moves/nonroad-technical-reports#2014b

EPA. (2018b). *Exhaust and Crankcase Emission Factors for Nonroad Compression-Ignition Engines in MOVES2014b.* Office of Transportation and Air Quality, Assessment and Standards Division. USA: US EPA.

Erkkilä, K., Nylund, N.-O., Hulkkonen, T., Tilli, A., Mikkonen, S., Saikonnen, P., . . . Amberla, A. (2011). *Emission performance of paraffinic HVO diesel fuel in heavy duty vehicles.* Society of Automotive Engineers of Japan.

European Commission. (n.d.). *Environmental aspects of the automotive industry: Non-Road mobile machinery emissions*. Retrieved April 15, 2020, from European Commission: https://ec.europa.eu/growth/sectors/automotive/environment-protection/non-road-mobile-machinery_en

Fan, H. (2017). A Critical Review and Analysis of Construction equipment emission factors. *Procedia Engineering*(196), pp. 351-358. doi:10.1016/j.proeng.2017.07.210

Frey, C. H., Rasdorf, W., & Lewis, P. (2010, January 1). Comprehensive field study of fuel use and emissions of nonroad diesel construction equipment. *Transportation Research Record: Journal of the Transportation Research Board, 2158*(1), pp. 69-76. doi:10.3141/2158-09

Frey, C., & Kim, K. (2006, January 01). Comparison of Real-World Fuel Use and Emissions for Dump Trucks Fueled with B20 Biodiesel Versus Petroleum Diesel. *Journal of the Transportation Research Board, 187*, 110-117.

Geilenkirchen, G., Roth, K., Sijstermans, M., Hulskotte, J., Ligterink, N., Dellaert, S., & 't Hoen, M. (2020). *Methods for calculating emissions of transport in the Netherlands.* The Hague: PBL.

Greater London Authority. (2016). *London Datastore.* Retrieved from Datasets: London Atmospheric Emissions (LAEI) 2016: https://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory--laei--2016

Grigoratos, T., Fontaras, G., Giechaskiel, B., & Zacharof, N. (2019, March 15). Real world emissions performance of heavy-duty Euro VI diesel vehicles. *Atmospheric Environment, 201*, 348-359. doi:10.1016/j.atmosenv.2018.12.042

Heidari, B., & Marr, L. C. (2015). Real-time emissions from construction equipment compared with model predictions. *Journal of the Air & Waste Management Association*(65), pp. 115-125. doi:10.1080/10962247.2014.978485

Helms, H., & Heidt, C. (2014). *Erarbeitung eines Konzepts zur Minderung der Umweltbelastung aus NRMM (non road mobile machinery) unter Berücksichtigung aktueller Emissionsfaktoren und Emissionsverminderungsoptionen für den Bestand.* IFEU. Dessau-Roßlau: Umweltbundesamt. Retrieved from https://www.umweltbundesamt.de/publikationen/erarbeitung-eines-konzepts-zurminderung-

Helms, H., Lambrecht, U., & Knörr, W. (2010). *Aktualisierung des Modells TREMOD - Mobile Machinery (TREMOD-MM).* IFEU. Dessau-Roßlau: Umweltbundesamt. Retrieved from http://www.umweltbundesamt.de/uba-infomedien/

Hillege, L. (2020). *Environmental Cost Indicator (ECI) - Overview*. Retrieved from Ecochain: https://ecochain.com/knowledge/environmental-cost-indicator-eci/

Hulskotte, J., & Verbeek, R. (2009). *Emissiemodel Mobiele Machines gebasserd op machineverkopen in combinatie met brandstof Afzet (EMMA).* Utrecht: TNO.

IFEU. (2004). *Entwicklung eines Modells zur Berechnung der Luftschadstoffemissionen und des Kraftstoffverbrauchs von Verbrennungsmotoren in mobilen Geräten und Maschinen.* Heidelberg.

Johnson, K. C., Maldonado, H., Scora, G., Cocker, D. R., Russell, R. L., Durbin, T. D., & Cao, T. (2016). Evaluations of in-use emission factors from off-road construction equipment. *Atmospheric Environment*(147), pp. 234-245. doi:10.1016./j.atmosenv.2016.09.042

Jörß, W., Emele, L., Scheffler, M., Cook, V., Handke, V., Theloke, J., . . . Appelhans, J. (2014). *Luftqualität 2020/2030: Weiterentwicklung von Prognosen für Luftschadstoffe unter Berücksichtigung von Klimastrategien.* Dessau-Roßlau: Umweltbundesamt. Retrieved from https://www.umweltbundesamt.de/publikationen/luftqualitaet-20202030-weiterentwicklung-von/

Juhrich, K. (2016). *CO2 Emission Factors for Fossil Fuels.* Dessau-Roßlau: Umweltbundesamt .

Junila, S., Horvath, A., & Guggemos, A. (2006). Life-cycle assessment of office buildings in Europe and the United States. *Journal of Infrastructure Systems, 12*(1), pp. 10-17.

Knörr, W., Heldstab, J., Kasser , F., & Keller , M. (2010). *Ermittlung der Unsicherheiten der mit den Modellen TREMOD und TREMOD-MM berechneten Luftschadstoffemissionen des landgebundenen Verkehrs in Deutschland.* Dessau-Roßlau: Umweltbundesamt.

LECTURA GmbH Verlag. (2020a). *Rubber-wheeled Rollers Hamm: Hamm HD 150 TT Specifications & Technical Data (2002 - 2004)*. Retrieved June 23, 2020, from Lectura Specs: https://www.lectura-specs.com/en/model/construction-machinery/rubber-wheeled-rollers-hamm/hd-150-tt-1005920

LECTURA GmbH Verlag. (2020b). *Rubber-wheeled Rollers Hamm: Hamm GRW 280-16 Specifications & Technical Data (2010 - 2020)*. Retrieved June 23, 2020, from Lectura Specs: https://www.lectura-specs.com/en/model/construction-machinery/rubber-wheeled-rollers-hamm/grw-280-16-1140425

Lewis, P. (2009). *Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles.* PhD Thesis, North Carolina State University, Raleigh.

Lewis, P., Rasdorf, W., Frey, C., Pang, S. H., & Kim, K. (2009, May). Requirements and incentives for reducing construction vehicle emissions and comparison of nonroad diesel engine emissions data sources. *Journal of Construction Engineering Management, 135*(5), pp. 341-351.

Li, Z., Zhang, K., Pang, K., & Di, B. (2016). A fuel-based approach for emission factor development for highway paving construction equipment in China. *Journal of the Air & Waste Management Association, 66*(12), 1214-1223. doi:10.1080/10962247.2016.1209256

Ligterink, N., Louman, R., Verbeek, R., & Buskermolen, E. (2018). *De inzet van bouwmachines en de bijbehorende NOx- en CO2-emissies.* Den Haag: TNO.

Lindhjem, C. E., & Beardsley, M. (1997). *Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling.* Washington D.C.: US EPA, Office of Mobile Sources.

Lindhjem, C., Janssen, G., Sklar, M., & Wilcox, R. (1998). *Emission Deterioration Factors For the NONROAD Emissions Model.* EPA, Nonroad Engine Emission Modeling Team. EPA.

Litman, T. A. (2009). Air Pollution. In T. A. Litman, *Transportation Cost and Benefit Analysis Techniques, Estimates and Implications.* Victoria , British Columbia, Canada: Victoria Transport Policy Institute.

Liu, Y., Wand, Y., & Li, D. (2017). Estimation and uncertainty analysis on carbon dioxide emissions from construction phase of real highway projects in China. *Journal of Cleaner Production*(144), pp. 337-346.

McGinlay, J. (2004). *Non-Road Mobile Machinery Usage, Life and Correction Factors.* AEAT.

Meijer, B. (2019, October 31). Dutch construction boom set to end as nitrogen rules bite. *Reuters*. Retrieved March 25, 2020, from https://www.reuters.com/article/us-netherlands-construction/dutch-construction-boom-set-to-end-as-eu-nitrogen-rules-bite-idUSKBN1XA1GI?smbl=esg

Neste Corporation. (2016). *Neste Renewable Diesel Handbook.* Espoo: Neste Corporation.

Notter, B., & Schmied, M. (2015). *Energieverbrauch und Schadstoffemissionen des Non-road-Sektors. Studie für die Jahre 1980-2050.* Bern: Bundesamt für Umwelt.

Ntziachristos, L., & Samaras, Z. (2019). Passenger cars, light commercial trucks, heavy-duty vehicles including busses and motor cycles. In EEA, *EMEP/EEA air pollution emission inventory guidebook 2019.* Luxembourg: Publications Office of the Euopean Union.

OrangeGas BV. (2020). *HVO 100: Frequently asked questions*. Retrieved from orangegas.nl: https://orangegas.nl/en/our-fuels/hvo-100

Reşitoğlu, İ. A., Altinişik, K., & Keskin, A. (2015). The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. *Clean Technologies and Environmental Policy*(17), pp. 15-27. doi:10.1007/s10098-014-0793-9

Sandanayake, M., Zhang, G., & Setunge, S. (2018). A comparative method of air emission impact assessment for building construction activities. *Environmental Impact Assessment Review*(68), pp. 1-9. doi:10.1016/j.eiar.2017.09.003

Snook, J. (2017, June 21). *Blog: How Does Construction Impact The Environment*. Retrieved from GoContractor: https://gocontractor.com/blog/how-does-construction-impact-the-environment/

Stenhouse, K., Hanania, J., Afework, B., & Donev, J. (2018, Juli 21). *Cetane Number*. Retrieved July 28, 2020, from Energy Education University of Calgary: https://energyeducation.ca/encyclopedia/Cetane_number#:~:text=Figure%201.,the%20engine%20of%20a%20vehicle.

Sule, T. (2013, August). The Influence of Primary Air Pollutants on Human Health Related Risk. *Journal of Environment and Earth Science, 3*(8), pp. 147-156.

VCA. (2020, June 18). *Outline of Non-Road Mobile Machinery (NRMM) Emissions Regulations*. Retrieved from Vehicle Certification Agency: https://www.vehicle-certification-agency.gov.uk/other/non-road-mobile-mach.asp

Verbeek, M. (2018). *Ondersteuning voor het afwegen van gunningscriteria bij de aanbestedingvan brandstof te gebruiken in speciale dieselvoertuigen in Amsterdam.* Den Haag: TNO.

WHO. (2020a). *Factsheets: Ambient (outdoor) air pollution*. Retrieved from World Health Organization: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

Winther, M., & Dore, C. (2019). Non-road mobile sources and machinery. In EEA, *EMEP/EEA air pollutant emission inventory guidebook 2019.* Luxembourg: Publications Office of the European Union. doi:10.2800/293657

Winther, M., & Nielsen, O. (2006). *Fuel use and emissions from non-road machinery in Denmark from 1985-2004 - and projections from 2005-2030.* National Environmental Research Institute. Retrieved from https://www2.mst.dk/Udgiv/publications/2006/87-7052-085-2/pdf/87-7052-086-0.pdf

WIRTGEN GROUP. (2020). *Tandem Rollers: HD 12 VV*. Retrieved June 23, 2020, from WIRTGEN GROUP Web site: https://www.wirtgen-group.com/ocs/en-st/hamm/hd-12-vv-1830-p/#

Zhang, G., Sandanayake, M., Setunge, S., Li, C., & Fang, J. (2017). Selection of emission factor standards for estimating emissions from diesel construction equipment in building construction in the Australian context. *Journal of Environmental Management*(187), pp. 527-536. doi:10.1016/j.jenvman.2016.10.068

11 Appendix

11.1 Appendix A: Methodology

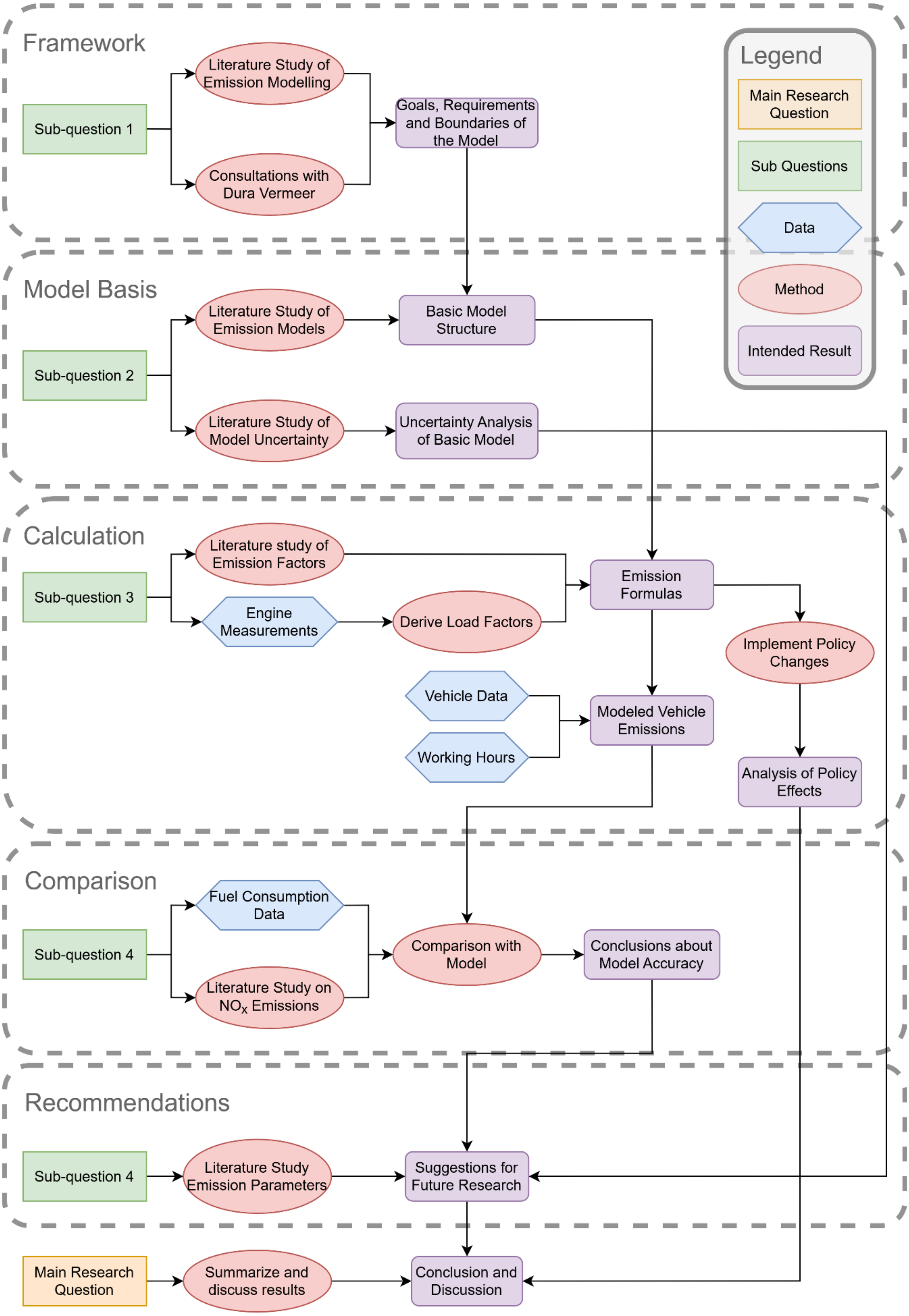


Figure 19: Methodology Flowchart

11.2 Appendix B: NRMM Vehicle Data

Table 17: Vehicle Specifications

Code	Set	Machine Type	Emission Class	Engine Size	Production Year
AP-1	1	Asphalt Paver	Stage IV	125	2018
AP-2	4	Asphalt Paver	Stage IIIB	125	2013
AP-3	6	Asphalt Paver	Stage IIIB	154	2014
AP-4	7	Asphalt Paver	Stage IIIB	125	2014
AP-5	12	Asphalt Paver	Stage IV	186	2018
AP-6	15	Asphalt Paver	Stage IV	125	2017
PR-1	Other	Pneumatic Roller	Stage II	95[1]	n.d.
PR-2	Other	Pneumatic Roller	Stage IIIA	100[2]	n.d.
SR-1	1	Static Three-wheel Roller	Stage IIIB	45	2019
SR-2	4	Static Three-wheel Roller	Stage IIIA	56.5	2012
SR-3	6	Static Three-wheel Roller	Stage IIIA	56.5	2011
SR-4	12	Static Three-wheel Roller	Stage IIIB	45	2019
SR-5	15	Static Three-wheel Roller	Stage IIIB	45	2019
TR-1	1	Tandem Roller	Stage IIIA	22.9	2018
TR-2	1	Tandem Roller	Stage IIIB	54.6	2015
TR-3	4	Tandem Roller	Stage IIIA	22.9	2017
TR-4	4	Tandem Roller	Stage IIIB	54.6	2015
TR-5	6	Tandem Roller	Stage IIIA	14.9	2012
TR-6	6	Tandem Roller	Stage IIIA	54.6	2014
TR-7	7	Tandem Roller	Stage IIIA	34.6	2018
TR-8	7	Tandem Roller	Stage IIIB	22.9	2015
TR-9	7	Tandem Roller	Stage IIIB	54.6	2017
TR-10	12	Tandem Roller	Stage IIIA	22.9	2017
TR-11	12	Tandem Roller	Stage IIIB	74.4	2014
TR-12	15	Tandem Roller	Stage IIIA	22.9	2015
TR-13	15	Tandem Roller	Stage IIIB	74.4	2014

[1] **(LECTURA GmbH Verlag, 2020a)**

[2] **(LECTURA GmbH Verlag, 2020b)**

11.3 Appendix C: Fuel Conversion Factors

Table 18: Fuel Conversion Factors in Literature

Source	kg CO2/kg fuel
Geilenkirchen, et al. (2020)	3.121
Notter & Schmied (2015)	3.150
Juhrich (2016)	3.165
Ntziachristos & Samaras (2019)	3.169
Average	3.15

For any transformation of the unit of fuel, the following conversion factors from mass to volume and back were used (AV Calc LLC, 2020).

$$Density\ of\ Diesel = 0.85\ kg/l = 1.18\ l/kg$$

11.4 Appendix D: Vehicle Measurement Data Summary

The following statistics were crated from internal vehicle measurement data form rollers and pavers during their usage cycles. This data can be helpful in creating average values over the use cycles of the machines used in asphalt construction. The data was taken from different machines for each machinery type during the months of May and April.

The data includes many machine measurements, a list of the ones used for this analysis is given in Table 19. The other measurements were either considered inconsequential for this research or left out for confidentiality purposes.

Table 19: Explanation of Vehicle Measurement Data

Measurement	**Unit**	**Description**
Machine Type	Asphalt Paver, Tandem Roller, Static Roller, Pneumatic Roller	The type of machine being measured, the data from each machine type includes different vehicles
Usage Mode	Use, Idle, Off, Contact on	The data set categorizes four types of work modes; Usage, Idle: The two categories are defined as the machine being used or idle, the exact determinant for classifying this measurement is unclear Off, Contact on: The categories are very inconsistent in their data (often no measurements in the regarded categories or zero values) and would likely have skewed the usage data, thus they were excluded
Time Measured	Seconds	The amount of time that the measurement encompasses given in seconds, most measurements are around 300s long, some differ for unknown reasons
Time Used	Seconds	The amount of time the machine was used during the timespan measured, use is not clearly defined, it is assumed that this includes any form of movement
Average Fuel Consumption	l/h	The average fuel consumption of the machine during the measured timespan
Average Load Factor	%	The average engine load factor during the measured timespan

Additional to the given measurements, some related values were concluded:

- ➔ Idle Rate [%]: The idle rate expresses the percentage of the measured time that the vehicle spent idling. It was considered for two reasons, one to allow the analysis of usage patterns of the vehicle and two to see the relation between the vehicle determined work modes in terms of idling. To determine the idle rate, the following formula was used:

$$Idle\ Rate = \frac{(Time\ Measured - Time\ Used)}{Time\ Measured} \qquad \text{Eq. 22}$$

- ➔ Corrected Idle Rate [%]: The measurements have errors at times with the used time being longer than the measured time, which creates a negative idle rate. Since that is impossible, and to prevent any influence of the negative values on the average, any value that was below zero was set to 0.
- ➔ Work Mode Re-evaluation [1,0]: As previously explained, the work mode as defined by the datasheet did not always seem plausible and could not be correlated to any of the direct

measurements. Because there were large inconsistencies with the usage time during the use mode (sometimes zero) and the other way around for the idle mode, it was decided to create new work and idle modes based on the idle rate. This helps to differentiate between the load factors and fuel consumption of idling versus in-use.

$$If \begin{cases} Idle\ Rate \leq 0.5 \rightarrow Work\ Mode = 0 \\ Idle\ Rate > 0.5 \rightarrow Work\ Mode = 1 \end{cases}$$

The average load factors and fuel consumption rates are determined for each vehicle type and then analysed through their statistical data. The statistical data was determined as follows:

Sample Mean
$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \qquad \text{Eq. 23}$$

Sample Variance
$$\sigma^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \qquad \text{Eq. 24}$$

Standard Deviation
$$\sigma = \sqrt{\sigma^2} \qquad \text{Eq. 25}$$

Standard Error
$$SE = \frac{\sigma}{\sqrt{n}} \qquad \text{Eq. 26}$$

11.4.1 Load Factor [%]

Table 20: Load Factor Analysis Paver

Paver	Average	Use	Idle
Count	4350	4131	219
Mean	31.67	32.11	23.27
Standard Error	0.131	0.134	0.304
Median	32	33	22
Standard Deviation	8.662	8.603	4.497
Sample Variance	75.027	74.006	20.227
Range	62	51	38
Minimum	2	13	2
Maximum	64	64	40

Table 21: Load Factor Analysis Tandem Roller

Tandem Roller	Average	Use	Idle
Count	4896	3716	1180
Mean	28.37	31.20	19.45
Standard Error	0.095	0.073	0.119
Median	29	31	19
Standard Deviation	6.671	4.473	4.101
Sample Variance	44.505	20.010	16.819
Range	46	31	46
Minimum	0	15	0
Maximum	46	46	46

Table 22: Load Factor Analysis Static Three-Wheel Roller

Static Three-Wheel Roller	Average	Use	Idle
Count	3230	2396	834
Mean	35.09	37.78	27.38
Standard Error	0.116	0.091	0.196
Median	36	38	25
Standard Deviation	6.617	4.466	5.661
Sample Variance	43.783	19.943	32.048
Range	54	36	43
Minimum	5	23	5
Maximum	59	59	48

Table 23: Load Factor Analysis Pneumatic Roller

Pneumatic Roller	Average	Use	Idle
Count	3448	2375	1073
Mean	38.68	43.32	28.41
Standard Error	0.159	0.115	0.235
Median	40	43	27
Standard Deviation	9.364	5.612	7.682
Sample Variance	87.686	31.496	59.017
Range	77	49	56
Minimum	0	28	0
Maximum	77	77	56

11.4.2 Fuel Consumption [l/h]

Table 24: Fuel Consumption Analysis Paver

Paver	Average	Use	Idle
Count	4350	4131	219
Mean	7.24	7.48	2.65
Standard Error	0.041	0.040	0.058
Median	6.5	6.8	2.3
Standard Deviation	2.712	2.556	0.862
Sample Variance	7.357	6.532	0.744
Range	20.6	18	6
Minimum	0.3	2.9	0.3
Maximum	20.9	20.9	6.3

Table 25: Fuel Consumption Analysis Tandem Roller

Tandem Roller	Average	Use	Idle
Count	4896	3716	1180
Mean	7.22	8.61	2.83
Standard Error	0.049	0.043	0.041

Median	7	8.7	2.3
Standard Deviation	3.428	2.607	1.396
Sample Variance	11.750	6.797	1.947
Range	15.2	13	10.5
Minimum	0.1	2.3	0.1
Maximum	15.3	15.3	10.6

Table 26: Fuel Consumption Analysis Static Three-Wheel Roller

Static Three-Wheel Roller	**Average**	**Use**	**Idle**
Count	3230	2396	834
Mean	3.51	4.03	2.00
Standard Error	0.022	0.018	0.028
Median	3.7	3.9	1.7
Standard Deviation	1.234	0.871	0.805
Sample Variance	1.522	0.759	0.648
Range	7.9	6.5	3.8
Minimum	0.3	1.7	0.3
Maximum	8.2	8.2	4.1

Table 27: Fuel Consumption Analysis Pneumatic Roller

Pneumatic Roller	**Average**	**Use**	**Idle**
Count	3448	2375	1073
Mean	5.12	6.20	2.72
Standard Error	0.037	0.033	0.038
Median	5.1	5.9	2.5
Standard Deviation	2.189	1.585	1.232
Sample Variance	4.793	2.512	1.518
Range	14.2	11.3	6.5
Minimum	0.1	3	0.1
Maximum	14.3	14.3	6.6

11.4.3 Idling Rate

Table 28: Idling Rate Analysis for Average Vehicle Usage

	Paver	**Tandem Roller**	**Static Three-Wheel Roller**	**Pneumatic Roller**
Count	4350	4896	3230	3448
Mean	0.055	0.302	0.262	0.377
Standard Error	0.0029	0.0050	0.0072	0.0059
Median	0.003	0.077	0.003	0.223
Standard Deviation	0.1937	0.367764	0.407079	0.349
Sample Variance	0.037506	0.13525	0.165713	0.122

11.5 Appendix E: Baseline Emission Factors and Fuel Consumption

Table 29: Baseline Emission Factors and Fuel Consumption for Diesel NRMM [g/kWh] (Winther & Dore, 2019)

Engine Power (kW)	Technology Level	NO_x	VOC	CH_4	CO	N_2O	NH_3	PM	PM_{10}	$PM_{2.5}$	BC	FC
P<8	<1981	12.00	5.00	0.120	7.00	0.035	0.002	2.800	2.800	2.800	1.540	300
P<8	1981-1990	11.50	3.80	0.091	6.00	0.035	0.002	2.300	2.300	2.300	1.265	285
P<8	1991-Stage I	11.20	2.50	0.060	5.00	0.035	0.002	1.600	1.600	1.600	0.880	270
P<8	Stage V	6.08	0.68	0.016	4.80	0.035	0.002	0.400	0.400	0.400	0.320	270
8<=P<19	<1981	12.00	5.00	0.120	7.00	0.035	0.002	2.800	2.800	2.800	1.540	300
8<=P<19	1981-1990	11.50	3.80	0.091	6.00	0.035	0.002	2.300	2.300	2.300	1.265	285
8<=P<19	1991-Stage I	11.20	2.50	0.060	5.00	0.035	0.002	1.600	1.600	1.600	0.880	270
8<=P<19	Stage V	6.08	0.68	0.016	3.96	0.035	0.002	0.400	0.400	0.400	0.320	270
19<=P<37	<1981	18.00	2.50	0.060	6.50	0.035	0.002	2.000	2.000	2.000	1.100	300
19<=P<37	1981-1990	18.00	2.20	0.053	5.50	0.035	0.002	1.400	1.400	1.400	0.770	281
19<=P<37	1991-Stage I	9.80	1.80	0.043	4.50	0.035	0.002	1.400	1.400	1.400	0.770	262
19<=P<37	Stage II	6.50	0.60	0.014	2.20	0.035	0.002	0.400	0.400	0.400	0.320	262
19<=P<37	Stage IIIA	6.08	0.60	0.014	2.20	0.035	0.002	0.400	0.400	0.400	0.320	262
19<=P<37	Stage V	3.81	0.42	0.010	2.20	0.035	0.002	0.015	0.015	0.015	0.002	262
37<=P<56	<1981	7.70	2.40	0.058	6.00	0.035	0.002	1.800	1.800	1.800	0.990	290
37<=P<56	1981-1990	8.60	2.00	0.048	5.30	0.035	0.002	1.200	1.200	1.200	0.660	275
37<=P<56	1991-Stage I	11.50	1.50	0.036	4.50	0.035	0.002	0.800	0.800	0.800	0.440	260
37<=P<56	Stage I	7.70	0.60	0.014	2.20	0.035	0.002	0.400	0.400	0.400	0.320	260
37<=P<56	Stage II	5.50	0.40	0.010	2.20	0.035	0.002	0.200	0.200	0.200	0.160	260
37<=P<56	Stage IIIA	3.81	0.40	0.010	2.20	0.035	0.002	0.200	0.200	0.200	0.160	260
37<=P<56	Stage IIIB	3.81	0.28	0.007	2.20	0.035	0.002	0.025	0.025	0.025	0.020	260
37<=P<56	Stage V	3.81	0.28	0.007	2.20	0.035	0.002	0.015	0.015	0.015	0.002	260
56<=P<75	<1981	7.70	2.40	0.058	6.00	0.035	0.002	1.800	1.800	1.800	0.990	290
56<=P<75	1981-1990	8.60	2.00	0.048	5.30	0.035	0.002	1.200	1.200	1.200	0.660	275
56<=P<75	1991-Stage I	11.50	1.50	0.036	4.50	0.035	0.002	0.800	0.800	0.800	0.440	260
56<=P<75	Stage I	7.70	0.60	0.014	2.20	0.035	0.002	0.400	0.400	0.400	0.320	260
56<=P<75	Stage II	5.50	0.40	0.010	2.20	0.035	0.002	0.200	0.200	0.200	0.160	260
56<=P<75	Stage IIIA	3.81	0.40	0.010	2.20	0.035	0.002	0.200	0.200	0.200	0.160	260
56<=P<75	Stage IIIB	2.97	0.28	0.007	2.20	0.035	0.002	0.025	0.025	0.025	0.020	260
56<=P<75	Stage IV	0.40	0.28	0.007	2.20	0.035	0.002	0.025	0.025	0.025	0.020	260
56<=P<75	Stage V	0.40	0.13	0.003	2.20	0.035	0.002	0.015	0.015	0.015	0.002	260
75<=P<130	<1981	10.50	2.00	0.048	5.00	0.035	0.002	1.400	1.400	1.400	0.770	280
75<=P<130	1981-1990	11.80	1.60	0.038	4.30	0.035	0.002	1.000	1.000	1.000	0.550	268
75<=P<130	1991-Stage I	13.30	1.20	0.029	3.50	0.035	0.002	0.400	0.400	0.400	0.220	255
75<=P<130	Stage I	8.10	0.40	0.010	1.50	0.035	0.002	0.200	0.200	0.200	0.160	255
75<=P<130	Stage II	5.20	0.30	0.007	1.50	0.035	0.002	0.200	0.200	0.200	0.160	255
75<=P<130	Stage IIIA	3.24	0.30	0.007	1.50	0.035	0.002	0.200	0.200	0.200	0.160	255
75<=P<130	Stage IIIB	2.97	0.13	0.003	1.50	0.035	0.002	0.025	0.025	0.025	0.020	255
75<=P<130	Stage IV	0.40	0.13	0.003	1.50	0.035	0.002	0.025	0.025	0.025	0.020	255
75<=P<130	Stage V	0.40	0.13	0.003	1.50	0.035	0.002	0.015	0.015	0.015	0.002	255
130<=P<560	<1981	17.80	1.50	0.036	2.50	0.035	0.002	0.900	0.900	0.900	0.450	270
130<=P<560	1981-1990	12.40	1.00	0.024	2.50	0.035	0.002	0.800	0.800	0.800	0.400	260
130<=P<560	1991-Stage I	11.20	0.50	0.012	2.50	0.035	0.002	0.400	0.400	0.400	0.200	250
130<=P<560	Stage I	7.60	0.30	0.007	1.50	0.035	0.002	0.200	0.200	0.200	0.140	250
130<=P<560	Stage II	5.20	0.30	0.007	1.50	0.035	0.002	0.100	0.100	0.100	0.070	250
130<=P<560	Stage IIIA	3.24	0.30	0.007	1.50	0.035	0.002	0.100	0.100	0.100	0.070	250
130<=P<560	Stage IIIB	1.80	0.13	0.003	1.50	0.035	0.002	0.025	0.025	0.025	0.018	250
130<=P<560	Stage IV	0.40	0.13	0.003	1.50	0.035	0.002	0.025	0.025	0.025	0.018	250
130<=P<560	Stage V	0.40	0.13	0.003	1.50	0.035	0.002	0.015	0.015	0.015	0.002	250
P>560	Stage V	3.50	0.13	0.003	1.50	0.035	0.002	0.045	0.045	0.045	0.002	250

11.6 Appendix F: Fuel Consumption Data

Table 30: Fuel Consumption Data

Vehicle	Company 1	Company 2	Company 3	Company 4	Research[1]	Model
Paver	9	16	11	7.24	14.58	9.64
Tandem Roller	3.35	6	5	7.22	9.69	2.63
Static Three-Wheel Roller	2.6	6	5	3.15	-	4.00
Pneumatic Roller	6.67	-	5	5.12	5.32	9.02
Bitumen Sprayer Truck	0.04 l/km	-	-	-	-	-
Dumping Truck	0.0345 l/km	8	0.33 l/km	-	-	-

[1] ***(Li, Zhang, Pang, & Di, 2016)***

11.7 Appendix G: Modelling Results

11.7.1 Vehicle Parameters

Table 31: Vehicle Parameters

Code	LF	TAF NOX	TAF PM	TAF VOC	TAF FC	EF NOX	EF PM	EF CH4	EF N2O	EF FC	Lifespan	DF MAX NOX	DF MAX VOC	DF MAX PM
						[g/kWh]	[g/kWh]	[g/kWh]		[g/kWh]	years			
AP-1	0.32	1	1	1	1	0.4	0.025	0.003	0.035	255	10	0.008	0.027	0.473
AP-2	0.32	1	1	1	1	1.8	0.025	0.003	0.035	250	10	0.008	0.027	0.473
AP-3	0.32	1	1	1	1	2.97	0.025	0.003	0.035	255	10	0.008	0.027	0.473
AP-4	0.32	1	1	1	1	2.97	0.025	0.003	0.035	255	10	0.008	0.027	0.473
AP-5	0.32	1	1	1	1	0.4	0.025	0.003	0.035	250	10	0.008	0.027	0.473
AP-6	0.32	1	1	1	1	0.4	0.025	0.003	0.035	255	10	0.008	0.027	0.473
PR-1	0.39	1.025	1.6	1.67	1.095	5.2	0.2	0.007	0.035	255	14	0.008	0.034	0.473
PR-2	0.39	1.125	1.92	1.67	1.095	3.24	0.2	0.007	0.035	255	14	0.008	0.027	0.473
SR-1	0.35	1	1	1	1	3.81	0.025	0.007	0.035	260	14	0.008	0.027	0.473
SR-2	0.35	1.125	1.92	1.67	1.095	3.81	0.2	0.01	0.035	260	14	0.008	0.027	0.473
SR-3	0.35	1.125	1.92	1.67	1.095	3.81	0.2	0.01	0.035	260	14	0.008	0.027	0.473
SR-4	0.35	1	1	1	1	3.81	0.025	0.007	0.035	260	14	0.008	0.027	0.473
SR-5	0.35	1	1	1	1	3.81	0.025	0.007	0.035	260	14	0.008	0.027	0.473
TR-1	0.28	1.125	1.92	1.67	1.095	6.08	0.4	0.014	0.035	262	14	0.008	0.027	0.473
TR-2	0.28	1	1	1	1	3.81	0.025	0.007	0.035	260	14	0.008	0.027	0.473
TR-3	0.28	1.125	1.92	1.67	1.095	6.08	0.4	0.014	0.035	262	14	0.008	0.027	0.473
TR-4	0.28	1	1	1	1	3.81	0.025	0.007	0.035	260	14	0.008	0.027	0.473
TR-5	0.28	1.125	1.92	1.67	1.095	11.2	1.6	0.06	0.035	270	14	0.008	0.027	0.473
TR-6	0.28	1.125	1.92	1.67	1.095	3.81	0.2	0.01	0.035	260	14	0.008	0.027	0.473
TR-7	0.28	1.125	1.92	1.67	1.095	6.08	0.4	0.014	0.035	262	14	0.008	0.027	0.473
TR-8	0.28	1	1	1	1	6.08	0.4	0.014	0.035	262	14	0.008	0.027	0.473
TR-9	0.28	1	1	1	1	3.81	0.025	0.007	0.035	260	14	0.008	0.027	0.473
TR-10	0.28	1.125	1.92	1.67	1.095	6.08	0.4	0.014	0.035	262	14	0.008	0.027	0.473

TR-11	0.28	1	1	1	1	2.97	0.025	0.007	0.035	260	14	0.008	0.027	0.473
TR-12	0.28	1.125	1.92	1.67	1.095	6.08	0.4	0.014	0.035	262	14	0.008	0.027	0.473
TR-13	0.28	1	1	1	1	2.97	0.025	0.007	0.035	260	14	0.008	0.027	0.473

11.7.2 Vehicle Emission Factors and Annual Deterioration Factors

Table 32: Vehicle Emission Factors and Deterioration Factors

Code	FC	VEF NOX	VEF PM	VEF CH4	VEF N2O	VEF CO2	DF A NOX	DF A PM	DF A VOC
	[g/h]	[g/h]	[g/h]	[g/h]	[g/h]	[g/h]			
AP-1	10200	16.00	1.000	0.1200	1.4000	32130	0.00080	0.04730	0.00270
AP-2	10000	72.00	1.000	0.1200	1.4000	31500	0.00080	0.04730	0.00270
AP-3	12566	146.36	1.232	0.1478	1.7248	39584	0.00080	0.04730	0.00270
AP-4	10200	118.80	1.000	0.1200	1.4000	32130	0.00080	0.04730	0.00270
AP-5	14880	23.81	1.488	0.1786	2.0832	46872	0.00080	0.04730	0.00270
AP-6	10200	16.00	1.000	0.1200	1.4000	32130	0.00080	0.04730	0.00270
PR-1	10345	197.48	11.856	0.4331	1.2968	32588	0.00080	0.03379	0.00243
PR-2	10890	142.16	14.976	0.4559	1.3650	34303	0.00057	0.03379	0.00193
SR-1	4095	60.01	0.394	0.1103	0.5513	12899	0.00057	0.03379	0.00193
SR-2	5630	84.76	7.594	0.3302	0.6921	17734	0.00057	0.03379	0.00193
SR-3	5630	84.76	7.594	0.3302	0.6921	17734	0.00057	0.03379	0.00193
SR-4	4095	60.01	0.394	0.1103	0.5513	12899	0.00057	0.03379	0.00193
SR-5	4095	60.01	0.394	0.1103	0.5513	12899	0.00057	0.03379	0.00193
TR-1	1840	43.86	4.924	0.1499	0.2244	5795	0.00057	0.03379	0.00193
TR-2	3975	58.25	0.382	0.1070	0.5351	12521	0.00057	0.03379	0.00193
TR-3	1840	43.86	4.924	0.1499	0.2244	5795	0.00057	0.03379	0.00193
TR-4	3975	58.25	0.382	0.1070	0.5351	12521	0.00057	0.03379	0.00193
TR-5	1233	52.57	12.816	0.4180	0.1460	3885	0.00057	0.03379	0.00193
TR-6	4352	65.53	5.871	0.2553	0.5351	13710	0.00057	0.03379	0.00193
TR-7	2779	66.27	7.440	0.2265	0.3391	8755	0.00057	0.03379	0.00193
TR-8	1680	38.98	2.565	0.0898	0.2244	5292	0.00057	0.03379	0.00193

TR-9	3975	58.25	0.382	0.1070	0.5351	12521	0.00057	0.03379	0.00193
TR-10	1840	43.86	4.924	0.1499	0.2244	5795	0.00057	0.03379	0.00193
TR-11	5416	61.87	0.521	0.1458	0.7291	17061	0.00057	0.03379	0.00193
TR-12	1840	43.86	4.924	0.1499	0.2244	5795	0.00057	0.03379	0.00193
TR-13	5416	61.87	0.521	0.1458	0.7291	17061	0.00057	0.03379	0.00193

11.8 Appendix H: Results

Table 33: Emissions of AS-01 per Average Working Week

AS-01	**Age**	**T**	**FC**	**NO$_X$**	**PM**	**CH$_4$**	**N$_2$O**	**CO$_2$**	**GWP**	**ECI**
	[years]	[hrs]	[kg]	[g]	[g]	[g]	[g]	[kg]	[kg CO2 eq.]	[€]
AP-1	2	37.7	384.5	604	41.3	4.55	52.8	1211.3	1227.1	61.36
SR-1	1	37.7	154.4	2264	15.3	4.16	20.8	486.3	492.6	24.63
TR-1	2	37.7	69.4	1655	198.2	5.67	8.5	218.5	221.1	11.06
TR-2	5	37.7	149.9	2202	16.8	4.07	20.2	472.0	478.2	23.91
SV-1	-	37.7	256.4	8101	205.1	46.14	0.0	1402.3	1403.4	70.17
SV-2	-	37.7	256.4	8101	205.1	46.14	0.0	1402.3	1403.4	70.17
Total	**-**	**-**	**1270.8**	**22927**	**682**	**111**	**102**	**5192.7**	**5226**	**261**

Table 34: Emissions of AS-04 per Average Working Week

AS-04	**Age**	**T**	**FC**	**NO$_X$**	**PM**	**CH$_4$**	**N$_2$O**	**CO$_2$**	**GWP**	**ECI**
	[years]	[hrs]	[kg]	[g]	[g]	[g]	[g]	[kg]	[kg CO2 eq.]	[€]
AP-2	7	37.7	384540	2730	50.2	4.61	52.8	1211301	1203.4	60.17
SR-2	8	37.7	212249	3210	363.7	12.64	26.1	668584	676.7	33.83
TR-3	3	37.7	69351	1656	204.5	5.68	8.5	218454	221.1	11.06
TR-4	5	37.7	149853	2202	16.8	4.07	20.2	472037	478.2	23.91
SV-1	-	37.7	256360	8101	205.1	46.14	0.0	1402289	1403.4	70.17
SV-2	-	37.7	256360	8101	205.1	46.14	0.0	1402289	1403.4	70.17
Total	**-**	**-**	**1321172**	**26000**	**1045**	**119**	**108**	**5351204**	**5386**	**269**

Table 35: Emissions of AS-06 per Average Working Week

AS-06	**Age**	**T**	**FC**	**NO$_X$**	**PM**	**CH$_4$**	**N$_2$O**	**CO$_2$**	**GWP**	**ECI**
	[years]	[hrs]	[kg]	[g]	[g]	[g]	[g]	[kg]	[kg CO2 eq.]	[€]
AP-3	6	37.7	473753	5544	59.6	5.66	65.0	1492323	1511.8	75.59
SR-3	9	37.7	212249	3212	373.3	12.67	26.1	668584	676.7	33.83
TR-5	8	37.7	46501	1991	613.8	16.00	5.5	146479	148.5	7.43
TR-6	6	37.7	164089	2479	266.2	9.74	20.2	516880	523.1	26.16
SV-1		37.7	256360	8101	205.1	46.14	0.0	1402289	1403.4	70.17
SV-2		37.7	256360	8101	205.1	46.14	0.0	1402289	1403.4	70.17
Total			**1409312**	**29428**	**1723**	**136**	**117**	**5628844**	**5667**	**283**

Table 36: Emissions of AS-07 per Average Working Week

AS-07	**Age**	**T**	**FC**	**NO$_X$**	**PM**	**CH$_4$**	**N$_2$O**	**CO$_2$**	**GWP**	**ECI**
	[years]	[hrs]	[kg]	[g]	[g]	[g]	[g]	[kg]	[kg CO2 eq.]	[€]
AP-4	6	37.7	384540	4500	48.4	4.60	52.8	1211301	1227.1	61.36
TR-7	2	37.7	104783	2501	299.5	8.57	12.8	330066	334.1	16.70
TR-8	5	37.7	63334	1474	113.0	3.42	8.5	199502	202.1	10.11
TR-9	3	37.7	149853	2200	15.9	4.06	20.2	472037	478.1	23.91
SV-1		37.7	256360	8101	205.1	46.14	0.0	1402289	1403.4	70.17
SV-2		37.7	256360	8101	205.1	46.14	0.0	1402289	1403.4	70.17
Total			**1215230**	**26877**	**887**	**113**	**94**	**5017485**	**5048**	**252**

Table 37: Emissions of AS-12 per Average Working Week

AS-12	**Age**	**T**	**FC**	**NO_X**	**PM**	**CH_4**	**N_2O**	**CO_2**	**GWP**	**ECI**
	[years]	[hrs]	[kg]	[g]	[g]	[g]	[g]	[kg]	[kg CO2 eq.]	[€]
AP-5	2	37.7	560976	899	61.4	6.77	78.5	1767074	1790.6	89.53
SR-4	1	37.7	154382	2264	15.3	4.16	20.8	486302	492.6	24.63
TR-10	3	37.7	69351	1656	204.5	5.68	8.5	218454	221.1	11.06
TR-11	6	37.7	204195	2341	23.6	5.56	27.5	643215	651.5	32.58
SV-1		37.7	256360	8101	205.1	46.14	0.0	1402289	1403.4	70.17
SV-2		37.7	256360	8101	205.1	46.14	0.0	1402289	1403.4	70.17
Total			**1501623**	**23361**	**715**	**114**	**135**	**5919624**	**5963**	**298**

Table 38: Emissions of AS-15 per Average Working Week

AS-15	**Age**	**T**	**FC**	**NO_X**	**PM**	**CH_4**	**N_2O**	**CO_2**	**GWP**	**ECI**
	[years]	[hrs]	[kg]	[g]	[g]	[g]	[g]	[kg]	[kg CO2 eq.]	[€]
AP-6	3	37.7	384540	605	43.0	4.56	52.8	1211301	1227.1	61.36
SR-5	1	37.7	154382	2264	15.3	4.16	20.8	486302	492.6	24.63
TR-12	5	37.7	69351	1658	217.0	5.71	8.5	218454	221.1	11.06
TR-13	6	37.7	204195	2341	23.6	5.56	27.5	643215	651.5	32.58
SV-1		37.7	256360	8101	205.1	46.14	0.0	1402289	1403.4	70.17
SV-2		37.7	256360	8101	205.1	46.14	0.0	1402289	1403.4	70.17
Total			**1325187**	**23069**	**709**	**112**	**110**	**5363851**	**5399**	**270**

11.9 Appendix I: Vehicle Replacement

Table 39: Vehicle Parameters of a New Paver

Machine Type	Emission Class	Engine Size	Production Year	LF	TAF NOX	TAF PM	TAF VOC	TAF FC	EF NOX	EF PM	EF CH4	EF N2O	EF FC
Asphalt Paver	Stage V	125	2020	0.32	1	1	1	1	0.4	0.015	0.003	0.035	255

Table 40: Vehicle Emission Factors and Weekly Emissions of New Paver

FC	VEF NOX	VEF PM	VEF CH4	VEF N2O	T	NOX	PM	CH4	N2O	CO2	ECI	VEF CO2
10200	16.00	0.6	0.12	1.40	37.7	603.2	22.62	4.52	52.78	1211301	61.36	32130

Table 41: Comparison of New Paver and Old Pavers

	NOX	PM	CH4	N2O	CO2	ECI
New Paver	603.2	22.62	4.52	52.78	1211301	61.36
AP-2	2729.6	50.18	4.61	53.08	1211301	61.36
AP-4	4500.3	48.40	4.60	53.03	1211301	61.36

11.10 Appendix J: NOx Measurement Comparison

Li, Zhang, Pang, & Di (2016) conducted research on fuel-based emission factors for highway paving equipment in Chengdu, China. They measured the emissions of rollers and a paver during their duty cycle and divided their usage time into three different modes. They defined them as idling, moving, and working. The study measures the NOx emission rate as well as the fuel consumption and then derives a fuel-based emission factor. All three values will be compared to the model to see where it agrees with or derives from the measurements. Each measurement is given for each mode, but using the ratio between the working modes and average values was calculated. The study was conducted in China, and the vehicles were classified as Stage III in the Chinese emission standards. To enable the comparison with the model, the European equivalent was found through a comparison of the standards for NOx (DieselNet, 2019). The research concludes that fuel-based factors are less variable than time-based ones. Table 42 shows the vehicle specifications used for the model and Table 43 the consequential model parameters. Tables 44-46 show the comparison between the model and the measured values sorted by the vehicle.

Table 42: Vehicle Specifications of Research Vehicles

Machine Type	Power [kW]	Stage [CHN]	Stage [EU]	Age [yrs]
Tandem Roller	132	III	IIIA	3
Pneumatic Roller	98	III	IIIA	3
Paver	160	III	IIIA	3

Table 43: Parameters and Emissions of Research Vehicles

Machine Type	LF	TAF NOX	TAF FC	EF NOX	EF FC	DFA NOX	NOX	FC	NOX
				[g/kWh]	[g/kWh]		[g/h]	[g/h]	[g/kg fuel]
Tandem Roller	0.28	1.125	1.095	3.24	255	0.00571	137.03	10320	13.28
Pneumatic Roller	0.39	1.125	1.095	3.24	255	0.00571	141.70	10672	13.28
Paver	0.32	1.125	1.095	3.24	250	0.008	191.10	14016	13.63

Table 44: Comparison Between Modeled and Measured Values for the Tandem Roller

Tandem Roller	Model	Measured	Difference [%]
NOX [g/h]	137.03	33.12	**313.77**
FC [g/h]	10320	8207	**25.74**
NOX [g/kg fuel]	13.28	6.26	**111.96**

Table 45: Comparison Between Modeled and Measured Values for the Pneumatic Roller

Pneumatic Roller	Model	Measured	Difference [%]
NOX [g/h]	141.70	77.20	**83.55**
FC [g/h]	10672	4509	**136.71**
NOX [g/kg fuel]	13.28	29.83	**-55.49**

Table 46: Comparison Between Modeled and Measured Values for the Paver

Paver	**Model**	**Measured**	**Difference [%]**
NOX [g/h]	191.10	201.33	**-5.08**
FC [g/h]	14016	12364	**13.36**
NOX [g/kg fuel]	13.63	30.20	**-54.86**

Table 47: Comparison Between Measured and Expected Idling Rate

	Idling	**Moving**	**Working**	**Expected Idling Rate**
Tandem Roller	0.015	0.209	0.776	0.302
Pneumatic Roller	0.095	0.41	0.496	0.377
Paver	0.13	0.075	0.796	0.055