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Developing a New Emission Model for Freight Transport

Improving the Environmental Performance of the Freight Transport Industry

Thesis for the degree of Philosophiae Doctor

Trondheim, July 2012

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Preface and acknowledgements

Sometimes one bites off more than one can chew, as was the case of my first Ph.D. project proposal; autonomous vehicles for passenger transport. After spending nearly a year trying to implement the project proposal, I realized that it was unattainable. In line with mountain code number 8, turn back in time – it is no disgrace, I decided to change the Ph.D. topic and start over. But before abandoning the autonomous vehicles project one paper was published: "Implementing new transport solutions in existing transport models." The last two sentences of that paper mark the beginning of this Ph.D. project:

"Attention should also be paid to indicators such as emissions. Do the models or their post processing tools give sensible results for these indicators?" (Levin, 2008).

From then on, the Ph.D. topic was to be emission modeling. My Ph.D. project was to be linked to the Green Freight Transport project funded by the Research Council of Norway. In addition to this monograph, four papers were published from the new Ph.D. project. My role in the Green Freight Transport project was to develop the calculation routines needed.

Completing a Ph.D. may be a "small" step for some, but it is a huge step for the dyslexic kid who wasn't too happy with the start of middle school. This thank you goes to my homeroom teacher Liv Tetlie: I still live by a few words that you said one day when I was fed up with the "special education class" that Norwegian education system tried to force on me: "Tomas, if the system doesn't fit you, then find your own solution and make us believe that your solution is the right one for you." I never took a "special education class" again, but rather focused on finding my own solutions and enjoying the learning process.

First of all I would like to extend my sincere gratitude to the Norwegian Public Roads Administration for funding my Ph.D. study. Financial support from the Norwegian Research Council to the Green Freight Transport project is also gratefully acknowledged.

I would like to thank my former boss Eirik Skjetne for his role in making this Ph.D. study possible and his ability to "create" the Green Freight Transport project. Beginning on a Ph.D. study also meant leaving my colleagues at Rambøll after four years. Ola, Tor and Jens: I sincerely believe that the skills I acquired while working together with you helped me pull through, and that the experience from working as a consultant has been positive for my Ph.D. work and the Green Freight Transport project.

I have had a great time working at SINTEF, both past and present colleagues have contributed to making my days there fun. Torgeir: thank you for opening up your academic network to me. Trude: thank you for all the great discussions we have had.

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There may not be any disgrace in turning back, but you have to set out on the trip once more and you have to make up for the lost time. This book would have been nothing more than a Ph.D. project description if it had not been for my better half, Silje. Silje, you are my rock. Without your effort and ability to take care of the kids, the house, and me there would be no Ph.D. thesis. You made it possible for me to make up for the lost year. I would also like to thank you for the two wonderful children, Thea and Elise. The three of you bring me joy and happiness every day. Blood is thicker than water; thank you Morten for much needed guidance and advice!

Trondheim, 2012

Tomas Levin

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Key terminology used in this thesis

Key terms in relations to emission modeling are presented here along with a description of how they are used in this thesis.

Emission standard is a legal standard that defines the maximum amount of pollutants that can be emitted from a vehicle under a specific test condition. The emission standard is used for type approval, and emission standards are different for different judicial areas. Norway uses the European emission standard also known as the Euro standard.

Driving cycle is a specific test condition used when testing engines against regulatory emission requirements. A driving cycle is a speed against time profile that is used to describe driving behavior. Legislative driving cycles are used for emission testing, but the legislative driving cycles may not accurately represent real world driving conditions.

Real world driving condition is driving behavior that can be observed and measured for vehicles on the road. A real world driving cycle is a driving cycle based on statistical analysis of real world driving conditions.

Emission factor is constant value of emissions that is connected to some activity. For passenger cars it is common to use grams pollutant emitted per kilometer as an emission factor. For a heavy-duty truck it is more common to use grams pollutant emitted per kilowatt-hours as a measure.

Emission function is a set of emission factors combined to create a mathematical function that has extra variables used to describe a phenomenon that has an impact on emissions. A typical example is an average speed emission function, where the average vehicle speed is an extra input variable and the function has been built from driving cycles that have different average speeds.

Emission measurement is normally carried out under laboratory conditions on a dynamometer to simulate the effect of gradient and load. The values obtained are for a specific vehicle under a specific driving condition. There exist portable emission measurements systems that can be hooked up to trucks that will allow for measuring emission under real world conditions.

Calculated / Estimated emissions are terms that are used interchangeably in literature regarding finding the amount of pollutants emitted from transport. But it is the author's point of view that these should be defined separately as to give users a better understanding of the uncertainty of calculations. Such a differentiation will give user the ability to understand if the key input to the emission functions was measured or assumed data. There will be gray areas when some input to the emission function is assumed and some are observed values. If the majority of input data is assumed then the formulation estimated emission should be used about the end value.

Calculated emissions: when key values used in the emission functions are measured for the specific vehicle on the specific trip.

Estimated emissions: when average values for key indicators are used in the emission model.

Tool is in the context of this thesis is an implementation of the emission model as a software application that has access to required input data and is able to produce an emission estimate for a specified activity. An activity is in this context the movement of an amount of goods as recorded in a freight transport service providers production system.

Model is used to describe a set of mathematical functions, computational routines and parameters that are needed to calculate or estimate emissions. A model takes input data and uses the computational routines and parameters to generate a result.

Framework relates to the internal design of the model. A key issue with emission models is that emission functions will change over time, new emission standards will come and more accurate emission functions will be developed. New vehicles will be used for transports and thus have to be included. The infrastructure will change as new roads are built and changes to the logistic networks are made. Thus designing the model with an internal framework allows for the replacement of calculation routines, and data will extend the lifespan of the model. The internal framework design of the model allows for using only parts of the model to study problems that the model was not originally designed for.

Module is a piece of software code that has an internal logic, and can do something meaningful by itself. Modules are placed into the framework, and communication between the modules and program flow is controlled by the framework. Thus separate modules could be updated or replaced without inducing a need to modify the whole model.

Vehicle is a general term for equipment used for moving goods. Typical examples of vehicles are trucks, trains, ships and planes.

Top-down emission model is a model that focuses on the total energy used and the emissions associated with specific energy carriers and combustion technology. Emissions are then linked to an activity, for example kilometers driven and load moved.

Bottom-up emission model is a model that focuses on the single vehicle and emissions relating to vehicle operating conditions. An operating condition could be a combination of vehicle speed, gradient and load.

g/km gram pollutant emitted or energy used per kilometer.

g/tkm gram pollutant emitted or energy used per tonne-kilometer, where tonne is defined as 1000 kilograms.

1 INTRODUCTION

We do not inherit the earth from our ancestors, we borrow it from our children, is a Native American proverb. Our children and grandchildren will be faced with the consequences of our actions that impact the climate and environment on earth. Global warming is a key challenge that our children will face. In 1998 the intergovernmental panel on climate change was set up to understand more of the science behind climate change. In 1994 The United Nations Framework Convention on Climate Change (UNFCCC) entered into force. The UNFCCC is the result of the earth summit in Rio in 1992. The goal of the UNFCCC is to reduce the global temperature via cooperation. The Kyoto protocol is a result of the UNFCCC that sets emission reduction targets for developed countries. Emissions regulated by the Kyoto protocol are those that are believed to have a global warming potential, CO_2 is the best known emission. The measures resulting from the UNFCCC are national reporting and compliance with politically negotiated emission reduction targets. The nations will try to agree on emission reduction targets and then each nation will try to find solutions to achieve agreed upon reduction. Klimaforliket from 2008 (The climate compromise) serves as a political platform for how Norway is to reduce our emissions. A challenge with Klimaforliket is that the measures are very high level, for example more funds to research on renewable energy and increased fuel taxes. But it will take time before we see emission reductions as results of these actions. An interesting question would be: are there complementary ways to reduce emissions that cause global warming? In the perspective of transportation it is worrying to see that transport of persons and freight are responsible for 30% of Norway's CO_2 equivalent emissions in 2004 (Lavutslippsutvalget, 2006).

In addition to the climate challenge that transport poses there are issues with local pollution caused by transportation. Locally and regionally polluting emissions are a result of transport. Emissions from road vehicles have been a concern for a long time. In 1970 the EEC adopted regulation to reduce air emissions, directive 70/220/EEC. This was followed by the Euro emission standards for motor vehicles. CO_2 is not regulated by the Euro emission standard as it focuses mainly on locally and regionally polluting emissions. To preserve the planet and local environment for future generations both climate change and local environmental consequences must be kept in mind.

One way to complement the national efforts in reducing emissions is to enable actors at the operational level to participate in reducing emissions. In order to motivate actors to reduce their emissions there is a need for knowledge and tools to accurately depict emissions associated with different transport related activities. The actors must be able to calculate or assess the effect of different measures that they may make and see the resulting change in emissions. In this context a good emission model would be sensitive to measures that are relevant for the different actors in the transport sector.

Looking at freight transport's environmental performance will not stop the human-induced changes, but it can complement the traditional political measures with better and more detailed knowledge about the potential for reductions in emissions. Having more readily available emission information will hopefully lead to more involvement in reducing the negative climate and environmental aspects of freight transport, thus giving back a "less damaged Earth" to our children.

1.1 A BRIEF INTRODUCTION TO EMISSIONS

To improve environmental performance it is important to understand the basics of transport related emission. When combusting fossil fuels several different pollutants will be released into the air. Watkins (1991 p. 6) lists the following compounds expected to be present in exhaust gasses from vehicles:

- Water vapor (H_20)
- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Oxides of nitrogen (NO_x)
- Lead compounds (Pb)
- Hydro carbons (HC)
- Sulfur dioxide (SO_x)
- Carbon particles (smoke) (PM)

Water vapor is not regarded to be a pollutant. Lead is an additive to petrol fuel to reduce the risk of auto ignition which can cause engine failure. In most countries lead has been replaced as an additive due to health implications of lead exposure. Sulfur is a pollutant that is present in the fuel and is not "created" during the combustion process. Thus burning of fossil fuels will release the sulfur present in the fuel to the air. Cleaning the fuel is a way to reduce sulfur dioxide emissions. CO_2 is formed from the complete combustion of hydrocarbons while CO is a product of incomplete combustion. CO_2 is linearly dependent on the amount of fuel used, for example, to get CO_2 emission from diesel-powered vehicles it is sufficient to multiply the amount of diesel per liter times 2.66 to get the kilograms of CO_2 emitted. Oxides of nitrogen (NO_x) are formed when fuel and air is combusted, the higher temperature the more NO_x. Hydro-carbons are unburned fuel from incomplete combustion or evaporation. PM is particulate matter that is suspended in the air from the combustion, and can consist of a variety of solid particles. PM could be produced by other vehicle parts than the engine; breaks, tires and studded tires are sources that can produce particulate matter. The final pollutant CO_2 is not directly harmful to humans, but is believed to be one of the main causes of global warming. CO_2 is used as a reference for the pollutant's ability to "heat the globe." An index for heating ability of gasses has been created and is known as the Global Warming Potential (GWP) index; from this index one can for example see that one gram of N_20 has 310 times the warming effect of 1 gram of CO_2. Carbon dioxide equivalents are usually written as CO_2e. The official GWP index developed by the Intergovernmental Panel on Climate Change (IPCC) is listed in Solomon et al. (2007 p. 212-213).

Thus transport that uses fossil fuels will emit pollutants that affect the local and regional environment (PM, NO_x, HC SO_x, and CO) and CO_2 that affects the climate. There is a need to understand how emissions are affected by infrastructure and vehicle operating conditions to improve the environmental performance of freight transport.

1.2 Purpose of this Ph.D. project

Knowing that there are emissions and knowing the scale of the emissions related to freight transport could be sufficient for the national efforts to reduce CO_2 emissions. Macro approaches to understanding and documenting emissions could be used to create and monitor governmental policy. But what can be done at the operational level in the freight transport industry to improve its environmental performance? To answer this question there is a need for knowledge on how emissions are affected by everyday actions and ways to document changes in emission levels resulting from everyday actions. The existing emission models for freight transport are top-down models based around average emission factors that camouflage the effects of operational changes. Operational changes may be altering vehicle routing, using different vehicles or deciding when to use intermodal transports. The purpose of this Ph.D. project was to develop a new emission model for freight transport that takes a bottom-up approach to calculating emissions in order to make it sensitive to measures under the control of single firms. Thus freight transport service providers using the new model will see that changes in everyday operations are reflected in the emission inventory. If vehicles are changed or capacity is better utilized then the results of these actions will be documented in the emission inventory.

As mentioned the result of this Ph.D. project is a bottom-up emission model which also can be integrated into existing production systems in freight transport companies. Integration into existing production systems is important as it automates the process of calculating emissions based on data found in the production systems without the need for human intervention.

The secondary purpose of the Ph.D. project is to create an open model. An open model, using open data allows for peer review of assumptions and implemented algorithms. The term open is used to indicate that the data and source code for the model are publicly accessible. The final product and resulting databases are available as open source[1]. The openness around the model and the model data should help in making it a transparent and credible model.

[1] http://www.opensource.org/docs/osd

The model design as a framework of modules also allows for using only part of the model to study emission impacts. The paper "Do Details Matter?" (Levin and Norvik, 2010) uses only parts of the model to study the differences associated with different levels of details in the digital infrastructure descriptions.

Building an emission model for freight transport links together vehicle emission factors, geographic data and shipment data. The weakest link will determine the quality of the end result. In order to build a credible model it is important to show the data used and how the data is used. When creating an emission model some assumptions have to be made because there is a lack of data. Assumptions that can greatly affect the results are checked. Both assumptions about emissions factors and geographic data can greatly influence the results and are thus checked.

The main purpose of this Ph.D. project was to build a credible model for freight transport emission that focuses on measures that are under the control of the actors in the freight transport industry, from the driver / locomotive engineer / captain and up to the freight transport service provider. The model is open and accessible for third-parties to use and develop further. The new model uses state of the art emission functions and digital infrastructure descriptions.

1.3 STATE OF THE ART IN FREIGHT TRANSPORT EMISSION MODELING

The focus on global warming has led to an increased interest in calculating CO_2 emissions. But in addition to CO_2 there are several other pollutants emitted from vehicles, vessels and trains. There exist several tools to calculate emissions from freight transport. A review done by SINTEF (Knudsen, 2007) showed that the resulting emissions calculated varied considerably between the different tools. Non-documented assumptions were believed to be the cause of the differences. To increase transparency freight transport emission calculations could be split into four parts:

- Allocating emissions to freight
- Single vehicle emissions
- Infrastructure descriptions
- Data on shipments

Emissions from freight transport do not originate from the freight moved but from the vehicle used to move the freight. Part of the freight transport industry operates in a public transit manner. Loads are consolidated and split and thus emissions have to be allocated from the vehicle to the freight. In order to allocate, emissions have to be calculated at the vehicle level and the variables that affect emissions have to be taken into account. Emissions are not only dependent on the vehicle but on the infrastructure that the vehicle utilizes.

1.3.1 ALLOCATING EMISSIONS TO FREIGHT

The challenge with freight transport emissions is that emissions are to be allocated to the freight and not only to the vehicle. None of the tools reviewed in Knudsen (2007) were suspected of using faulty emission factors. But it was believed that the issues with different results were related to how emissions were allocated to the freight. Two important factors when allocating emissions to freight has been: load factor and empty running rate. The load factor is the percentage utilized of a vehicle's cargo capacity weight. An empty run is a movement of a vehicle when there is no freight present in the vehicle. The percentage of the driving distance that the vehicle is running empty is the empty running rate. The load factor is not necessarily defined in a consistent manner; sometimes empty runs are included in the load factor (Sturm and Hausberger, 2006). Different definitions of the load factor will have a profound impact on the emissions reported for shipment. The EcoTransIT[2] (Knörr, 2008, Knörr et al., 2010) and NTMCalc[3] (Bäckström, 2007) tools have included both the load factor and empty running factors as parameters in their calculators. The parameters could be changed by the user if the user has data available to calculate a new factor. For real world freight operations the vehicle load factor will change, either because a vehicle is picking up or dropping off freight. Or there is a variation in the day to day flow of freight. There may be a strong imbalance in freight volume on specific freight corridors. By using average load factor and empty running, users will get results with little input data, but the average values give little insight into how every day freight operations should be changed to reduce emissions.

There is ongoing standardization work in the field of emission accounting, and the most notable is the draft CEN standard: Methodology for calculation and declaration on energy consumption and GHG (Green House Gas) emissions in transport services (goods and passenger transport) (European committee for standardization, 2011). A key message from the standard is that all emissions from the vehicle should be allocated to the freight. A challenge with the standard is that it focuses on GHG emissions and does not take into account the locally polluting emissions. The standard promotes the use of as detailed emission calculations as possible, first measured values and lastly average default values. But the standard does not go into any detail about how detailed emission calculations should be done, but only states that the methodology should be transparent. The network behind the NTMCalc software is involved in the work with the prEN 16258 standard. There is cooperation between NTMCalc and EcoTransIT, as NTMCalc uses rail factors from EcoTransIT and EcoTransIT uses ferry emission allocation rules set by NTMCalc. Allocating emissions to freight is an especially challenging task if modes of transport are shared between passenger and freight transport. The discussion in Foss et al. (2007 p. 38) exemplifies this.

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[2] www.ecotransit.org

[3] www.ntmcalc.org

The emissions that are to be allocated stem from emission factors that are used to calculate emissions. Emission factors are connected to the vehicle type and an activity. The next section will focus on vehicle level emission factors.

1.3.2 Single vehicle emissions factors

The ARTEMIS project (Assessment and Reliability of Transport Emission Models and Inventory Systems) was a large research project that was to look into methodologies to calculate emissions for passenger and freight modes. The project was funded by the EU 5th Framework research programme. The ARTEMIS project builds on a long line of European research projects in the field of transport related emissions. COST 319 action "Estimation of pollutant emissions from transport" (Joumard, 1999) and COST 346 "Emissions and Fuel Consumption from Heavy-duty Vehicles" (Sturm and Hausberger, 2006) and the MEET project (Hickman et al., 1999) are key research initiatives. These initiatives have created methods for establishing emission factors and published key emission factors. The heavy-duty vehicle emission factors have been developed using the model PHEM (Passenger car and Heavy-duty Emission Model) (Hausberger et al., 2003). A country specific rail model has been developed, but the Norwegian rail system was not included in this model (Cordeiro et al., 2005). Emission factors for ships have been developed using the Lloyd's Register-Fairplay database (Sjöbris et al., 2005) as part of the ARTEMIS project.

For ships there is interesting work going on at the NCA (Norwegian Coastal Administration), developing ship specific emission factors based on databases that hold information about the ships and ship activity (Mjelde et al., 2008). The methodology described in this technical report is very detailed and requires position data on the ships. But the methodology could be used to estimate emission factors for single ships without having the need for AIS (Automatic Identification System) data. AIS data allows for following in ships along the Norwegian coastline. Single ship data based on actual engine certificates and possible exhaust after treatment technology will be an improvement over the average emission factors available through ARTEMIS.

For trains there exists an energy settlement system that reports actual energy consumption for running trains with appropriate measurement devices[4]. Norway, Sweden, Denmark and Belgium have this system in place. Data availability depends on freight train locomotives having energy meters that are linked to the system installed. There exists section specific rail electric energy usage factors for locomotives that do not have energy meters installed (Jernbaneverket, 2006).

State of the art emission factors are only part of the puzzle as the emission factors need to be multiplied by an activity. Simple emission factors usually take the form of gram per tonne kilometer. Thus one only needs to know the vehicle type, weight of what is to

[4] www.eress.eu

be moved and the distance the freight is to be moved. The ARTEMIS project has taken forward road emission factors that are dependent on vehicle speed, road gradient and vehicle loading. Thus there is a need to get access to these attributes.

1.3.3 The effect of infrastructure

To calculate emissions from single vehicles there is a need to know the route that the vehicle has taken. Distance traveled has an important effect on emissions, but there are also other factors that can effect emissions. For heavy-duty vehicle emissions, topography has a profound effect (Hassel and Weber, 1997). To use the most detailed emission functions there is a need to have equally detailed infrastructure descriptions. In addition to having the data available there is a need to have tools to analyze the data and do the calculations.

Norway has digital infrastructure descriptions for road, rail and sea. The infrastructure descriptions are managed by national authorities. There is little technical information about the infrastructure descriptions available to the general public. Both the National Public Roads Administration (NPRA) and the Norwegian National Rail Administration (NNRA) have developed their databases for specific internal operations. Thus documentation on usage of the data is limited, especially for the purpose of building networks for vehicle routing. For road data commercial providers could serve as a potential data source that is being used for routing. Both the infrastructure descriptions hosted by national agencies and commercial providers are stored in proprietary formats. Thus usage of data in general routing tools will involve data transformations.

General routing tools exist in geographic information systems that will allow for calculation of routes and route parameters. Several network analysis tools exist; from full GIS implementations like ESRI's Network Analyst[5] to more general network analysis tools like NetworkX[6] form Los Alamos National Laboratory.

1.3.4 Data on shipments

In order to have systems to track freight there is a need to have computer systems to record the movement of the freight. Data from the tracking systems combined with other data could be used to reverse engineer the path that the freight took and which pieces of freight traveled together. These systems may be developed internally especially in large companies or by using off the shelf products that integrate with other transport company software. Thus there is a potential to harvest data from the company IT systems, but the availability of data is dependent on the specific freight transport service provider. Some freight transport service providers may have a high integration of their business related software so that they form an Enterprise Resource Planning

[5] www.esri.com/software/arcgis/extensions/networkanalyst/index.html
[6] networkx.lanl.gov/index.html

(ERP) tool. There is a large potential to harvest data in the ERP systems to recreate a digital description of the physical transports.

The existing tools for calculating emissions from freight transport do not have a high enough level of detail to help users identify potential areas for emission reductions. But on the other hand there exist rules for allocation of emissions to freight, single vehicle emission factors, digital infrastructure descriptions and data on shipments. Putting all these elements together in a new model could be a way forward in enabling the freight industry to improve its own environmental performance. This is done in the thesis at hand.

1.3.5 Existing emission calculation tools

The existing emission calculation tools base their calculation on emission factors. Emission factors are simple formulae that express the amount of a pollutant emitted in relation to a measure of activity. The most commonly used emission factors for freight transport are expressed as grams per tonne kilometer. Many of the emission calculators use a top-down approach where emission calculation and allocation of emission are merged into the same factor. A problem with this approach is the utilization factor used. Most of the tools use a utilization factor for calculation and allocates emissions according to weight. The problem with utilization factors is that they are usually an average value. A bottom-up approach will allow for using the specific weight in the calculation instead of an average value.

As mentioned earlier there are several tools available for estimating freight transport emissions, of which EcoTransIT (Knörr, 2008) and NTMCalc (Bäckström, 2007) are the most prominent. EcoTransIT is used by DB Schenker who is one of the main freight transport service providers in Norway. Tollpost Globe (TPG) is using an internally developed system based on emission factors found in Thune-Larsen et al. (1997). One problem with these tools is that they gave different results for the same transport (Knudsen, 2007). Possible reasons for these differences could be different emission factors, quality of digital infrastructure descriptions or other assumptions. Tools like EcoTransIT have the possibility of automatically finding a route between origin and destination. This allows for the automatic calculation of distances for each mode. But this can lead to serious errors if the infrastructure description is not complete. Discovering routing errors is challenging especially if the routes are not presented graphically on a map. An example of a faulty infrastructure description was found when the EcoTransIT tool was tested as part of the Green Freight Transport project. Appendix B shows the erroneous route that was created by the routing feature in EcoTransIT (Toftegaard and Knudsen, 2009 p. 12). The requested route was for a freight transport by boat from Trondheim to Oslo. EcoTransIT did not return a direct ship route from Trondheim to Oslo. But multimodal route, where the first leg was with truck from Trondheim to Bergen and the next leg was with ship from Bergen to Oslo. The reason for showing the error is not to say that EcoTransIT is a faulty tool, but it serves as an illustration of the challenges involved in routing with respect to infrastructure description quality. Other tools like NTMCalc do not offer routing and thus the user has to enter the distance traveled by each mode.

The main problem with the existing calculation tools is that they rely on general emission factors. The general emission factors represent averages for large geographic areas. Both NTMCalc and EcoTransIT use or modify existing emission factors in addition to building their own emission factors. NTMCalc has a disclaimer on their web page that states this clearly: *"Data and methods are prepared by NTM after due and careful enquiry, based on information provided by NTM members and other information on which NTM relied and did not independently verify. The data and methods states a number of assumptions made during the analysis."* For road emission both EcoTransIT and NTMCalc states the same source as a starting point, the INFRAS Handbook of emission factors[7]. But even if the tools refer to the same source the calculations give different results for the same shipment (Knudsen, 2007 p. 26). These differences are probably due to assumptions made when modifying the emission factors. For rail the NTMCalc tool uses the rail factors developed by EcoTransIT.

The tool previously used by TPG today was very general. It did not differentiate between Euro standard classes for trucks, and only two types of trucks existed: long-haul and delivery.

EcoTransIT has some extra factors that influence emissions; load factor is a measure of how much of the vehicle's weight capacity is utilized. Empty factor is the share of distance the vehicle will run empty for the transport (Knörr, 2008). Changing the values of these factors has a great impact on the results. The NTMCalc tool has the ability to differentiate between rural and urban driving for the road mode.

The key weaknesses with the tools are their inability to take trip specific topography and driving speed into account when calculating emissions. The impact of gradients is left out or included in a simplified manner. In EcoTransIT mountainous countries like Switzerland and Austria are given a 5% increase in energy consumption. Flat countries like Denmark, Sweden and the Netherlands are given a reduction of 5% in energy consumption (Knörr, 2008). Gradients are believed to have a great impact on fuel consumption, the belief that what is lost uphill can be gained going downhill is shattered in Hassel and Weber (1997). The report abstract states: "*Even in the case of large-scale considerations, however, it cannot be assumed that – for example – the extra emission when traveling uphill is compensated by correspondingly reduced emissions when traveling downhill.*" And continues: *"Because of the higher vehicle mass the gradient influence is even more important for heavy-duty vehicles."*

[7] www.hbefa.net/e/index.html

Road vehicle emissions are usually measured in a laboratory where the vehicle is driven according to a predefined sequence of speeds. The predefined sequence of speeds is called a driving cycle. Legislative driving cycles are the driving cycles used for testing Euro standard compliance. The work done by Hassel and Weber used legislative driving cycles and not real world driving cycles; this could be a weak point of the Hassel and Weber (1997) report. But on the other hand the legislative driving cycles were modified for gradients greater than ±2% on the basis of surveys.

Driving speed is important for the amount of emissions. An average speed emission function gives the amount of pollutants emitted at an average vehicle speed. The average speed is calculated as an average speed of a driving cycle and several driving cycles are used to build an average speed emission function. Appendix C shows a typical average speed NO_x curve developed within the ARTEMIS project for a heavy-duty vehicle. Low average driving speeds result in high emissions per kilometer while driving at medium speed (40-80 km/h) gives lower emissions. The increase in emissions at higher speeds is relatively small compared to that seen at lower speeds. A lower speed indicates congestion, while higher speeds indicate free flow highway operation.

For annual total emission accounting, existing emission tools like EcoTransIT, NTMCalc and the TPG tool could be sufficient. Using averages developed for the whole of Norway, like those described in Thune-Larsen et al.(1997), will probably give good emission figures at a high level of aggregation, since they are created using national fuel totals. But for a single truck driver a tool like EcoTransIT does not offer much assistance on route choice as vehicle speeds and road topography are not used. In practice there are only four possible options for the truck driver: drive shorter, move less freight, increase vehicle utilization, or change vehicle type. The following questions cannot be answered by the existing calculation tools: Should the driver go around the mountain pass or over it? Should the driver go through or around urban areas? What is the effect of congestion on fuel consumption? Thus to improve the environmental performance of the driver a more detailed tool is needed.

In both NTMCalc and EcoTransIT rail energy consumption and resulting emissions are country specific. Thus it is not possible to evaluate domestic variations in rail energy usage and resulting emissions. Most of the freight moved in Norway is moved on single track infrastructure. Thus freight trains have to stop for passing trains, starting and stopping freight trains consume considerable amounts of energy. Having a possibility of investigating differences between different rail routes and the effect of train prioritization would be valuable.

At present the Norwegian National Rail Administration differentiates energy consumption between the different railway lines. The difference in energy consumption per tkm is due to infrastructure quality, topography and state of the electrical supply. One of the more extreme differences observed today is for Ofotbanen. The energy consumption is thirty-two times larger in the west- east direction compared to the east-west direction (Jernbaneverket, 2006 appendix 1, p. 2). This is due to the topography and that Ofotbanen crosses into Sweden close to its highest point. From Kiruna (530 meters above sea level) it is downhill to Narvik (six meters above sea level) and the rail wagons are filled with Swedish iron ore, which is shipped out from Narvik. There are other differences that are interesting. For example, there is 17% difference in energy consumption between trains going from Oslo to Bergen and Trondheim. These macro numbers show that there is a difference, but it does not help identifying reasons for the differences.

From an emission perspective it is often argued that there is not a need to look into electrified rail in Norway because electricity is regarded as clean. Norwegian electric energy is argued to be clean because it is produced with renewable resources. There are arguments for monitoring energy efficiency of transport modes that use electricity. The first is the fact that Norway is a part of the European electrical grid. This means that Norway imports electrical energy when consumption is greater than production from renewable sources within Norway. And when there is a surplus in Norway electric energy is exported to Europe. The exported energy from Norway could be used to substitute energy produced from fossil fuels in Europe. Thus reducing electrical energy consumption in Norway could reduce CO_2 emissions in mainland Europe.

Another reason to look closer at modes using electric energy is that the future electric energy production in Norway may not be solely based on renewable sources. Appendix D shows a graph over historical development and predicted future development for GHG emissions by activity for Norway. After year 2005, both Statistics Norway and Lavutslippsutvalget predict that our renewable resources will not be sufficient to meet our demand for electric energy. Thus nationally produced electricity could no longer be considered CO_2 free.

Existing tools do not focus on detailed terminal emissions. The terminal makes multimodal transports possible. But little is known about emissions from Norwegian domestic terminal activities. It would be interesting to include the terminals in emission estimates, and to look at possible differences between terminals. In the 2010 edition of EcoTransIT terminal handling has been included. One average factor for all terminals is used, and the factor is differentiated between different types of goods; container, liquid cargo, bulk cargo and other cargo. This use of terminal emission factors could be useful when trying to account for total emissions. But a general emission factor offers little help to companies that want to reduce emissions from their terminals.

1.3.6 State of the art summary

To summarize one could argue that the existing tools can give an annual grand total of emissions. But for actors aiming to improve their environmental performance there is little help in the existing tools. The tools are too coarse to show effects of measures that freight transport companies are able to implement without a considerable investment. There exist more detailed emission factors and emissions functions that could be utilized to improve the calculation routines to make them sensitive to actions that single freight companies can take to improve their environmental performance. There exist digital infrastructure descriptions that are not utilized by existing tools. There are commonly accepted ways of allocating emissions from single vehicles to freight in the shape of a proposed CEN standard. Transport service providers also have systems that track individual shipments and pieces of freight. What is lacking is a unified model that utilizes the available sources and a model that could be implemented as a tool in companies in the freight industry.

1.4 RESEARCH QUESTION

The existing tools for calculating emissions from freight transport do not have a high enough level of detail to help users identify potential areas for emission reductions. But on the other hand there exist rules for allocation of emissions to freight, single vehicle emission factors, digital infrastructure descriptions and data on shipments. Putting all these elements together in a new model could be a way forward in enabling the freight industry to improve its environmental performance. Thus the research question is:

How to develop a detailed emission model to be used in everyday freight transport operations?

The important message in this question is: "to make a part of everyday freight operations." This implies that emission estimates should be used differently from the way they are used today – not only to use emission estimates to report emissions, but as a tool to improve the freight transport service provider's environmental performance. Even if CO_2 emissions are a global problem there are reasons to act at the local level. Principle 10 of the Rio declaration on environment and development states that: "Environmental issues are best handled with the participation of all concerned citizens, at the relevant level." (United Nations, 1992) The introduction of a new detailed bottom-up emission model for freight transport is believed to be a way to involve actors at the lowest level in the freight industry in the global challenge of reducing CO_2 emissions. A goal for the new model is to show the actors at the lowest level that their actions have real impact on the CO_2 emitted from freight transport. Air emissions from freight transport are intrinsically linked to usage of fossil fuels. Thus there is an economic gain from reducing emissions via reducing energy produced by combusting fossil fuels.

The new freight transport emission model will be a supplement to the existing reporting schemes that are used to shape the Norwegian National Transport Plan (NTP). The NTP calls for a shift from road-based transport to rail and sea as they are assumed to be more climate-friendly. The new model is able to show the effects of such shifts and to see the true potential for such shifts. The model will then be used to find the potential that the freight transport industry has to improve its environmental performance without major infrastructure developments. The role of the new model is to provide answers to detailed questions like: what is the break even distance for CO_2 emissions for a direct truck shipment and an intermodal shipment? How are locally/regionally polluting emissions changed when a shipment is changed from direct truck to intermodal rail or sea transport? What is the running phase emission difference between a ferry and a deep sea tunnel? What is the emission effect of congestion on delivery trucks? What is the difference in fuel usage for a fully loaded truck compared to a partially loaded truck on a specific route? Can truck based freight routes be optimized for fuel usage as opposed to the traditional time / distance routing?

The challenge is to create a tool that is usable for the actors in the freight transport industry. Cost is a crucial element in succeeding in getting the tool into everyday use. Thus the input to the new model has to be simple (like existing tools) or the input data has to be provided for the user. Simple inputs are not a viable option as the result will not have the required level of detail. Automatic collection of needed input data has to be explored in order to make the new model a useful tool for companies in the freight transport industry.

A way to answer the research question is to create a new model for calculating emissions from freight transport and to see if this could be implemented in a firm in the freight transport industry. The task of building a new emission model could be split into several sub questions that need to be answered.

1. Is it possible to find emission functions and factors that could be used to calculate emissions from a single vehicle that are sensitive to measures under the control of single firms?
2. Is needed input data for the emission functions available and how to structure emission calculations?
3. How can the new model be integrated into a freight transport service provider's production system to become a useful tool?
4. Is it possible to check transferability of emission function by collecting vehicle data to compare with data used to create the emission functions?

By answering these questions and developing a model one should be able to reduce one of the main barriers for freight transport service providers to use emission data as input to everyday decisions. The Green Freight Transport project user-needs assessment identified the lack of a tool to measure emissions as a key barrier for them in relation to environmental performance (Lervåg, 2009). Thus the model will not force the actors in the freight transport industry to use the tool to become more environmentally friendly, but it has removed the argument that there does not a tool to assist them.

Thus the focus of this Ph.D. project will be to create a new model to calculate emissions from freight transport. Key tasks will be: finding suitable emission functions, testing input data, exploring assumptions, finding a suitable model design and comparing results from the new model.

1.5 Scope of the new freight transport emission model

Developing a bottom-up emission model for all freight transport is a tremendous task. The main reason is that emission models are context sensitive. Thus there is a need to narrow the scope of the model to be developed. This section presents arguments for narrowing the scope to make model development possible within the time and financial confines of a Ph.D. project while still maintaining high quality results and being useful for companies in the Norwegian freight transport industry.

The first major scope reduction is choosing Norwegian domestic freight transport as the model context. The problem of global warming is challenging, and has received a considerable amount of attention. Countries have created CO_2 emission inventories and come together to try to agree on reductions, but are struggling to make the necessary cuts. The transport sector is responsible for approximately one-third of Norway's total CO_2-equivalent emissions according to Statistics Norway[8]. Forty-two percent of the transport sector's emissions are associated with freight transport. Thus the freight transport industry is responsible for a big part of the Norwegian CO_2 emissions. And thus the scale of freight transport emissions warrants a closer look at how and if emissions could be reduced. From a logistical perspective, CO_2 emissions from transport may be small when compared to the other parts of the value chain. The production of goods may produce significantly more CO_2 than the transport of the goods. But that is not a valid argument to waste energy and produce more CO_2 emissions in the transport part of the value chain. The new model seeks to give freight transporters a tool to understand the emission impact of their actions and improve on it. Even if their emissions are a small part of the value chain their emissions are still a large part of the Norwegian domestic CO_2 emissions. A political challenge for Norway is deciding on how much of our committed reductions we are to take on a domestic level as opposed to financing cuts in other parts of the world. The new model will assist in finding the potential that the Norwegian domestic freight industry has without altering the volumes of freight moved. Thus a Norwegian domestic emission model for freight transport would fill a political need.

For practical purposes the new model will be limited to Norway and domestic freight in Norway. From a logistical perspective this may seem very limiting, but then again the data requirements for having a detailed bottom-up model of freight transport emissions are considerable. If the model works for Norway, separate models could be built for

[8] http://www.ssb.no/klimagassn/

other countries and interlinked. There are two main reasons for linking country and context specific models rather than having one large model: The first is that models have to be specific for different countries, emission models are context sensitive. There may be significant differences in driving behavior between countries that could warrant the creation of a different model. There exist different vehicle emission regulations for different countries and regions. The second reason is usability in terms of computational time. In 2012 the open street network database (the file planet.osm) was about 250 GB large, while a compressed binary version was 14 GB[9]. Routing operations in such a database will be time consuming and probably impractical. Thus splitting the data into smaller blocks that can be connected later will be a better solution. Thus for this Ph.D. project the Norwegian infrastructure will be used as a case to see if it is possible to develop such a model and gain some experience with the amount of data and computational time involved. In contrast, the Norwegian road model set used for the National Transport Plan calculations splits Norway into five regions (Tørset et al., 2008). Managing routing in a network for the whole of Norway is believed to be challenging.

The aim is to create a model that will focus on measures under the control of single firms and their daily activities, which means that a life cycle perspective is too broad. The emission calculations will be limited to core activities, and not include upstream or downstream activities. Emissions from building the infrastructure and the vehicles are examples of upstream processes, while dismantling of infrastructure and vehicles are examples of downstream processes. The focus will be on the emissions related to usage of the freight infrastructure and vehicles.

There are many types of negative impacts of freight transportation. This Ph.D. project will focus on emissions to air for a subset of emissions: the air emissions, which are regulated by the European emission standard; and CO_2, which has gained a lot of focus because of its effect on global warming. Thus the following emissions are to be included in the model: CO, NO_x, HC, PM, CO_2 and SO_x. In addition energy usage is included, this is because it can enable users to check the plausibility of calculations. It is believed that truck drivers have a better sense of liters of fuel used on a trip than the amount of NO_x emitted. Thus if the fuel/energy calculation for a trip is unrealistic then the emission calculations are probably unrealistic. Including energy consumption allows for comparing energy efficiency between different modes of transport.

When freight is split or consolidated this usually happens at terminals, because terminals have specialized equipment to process and move goods between vehicles. Some terminal equipment runs on fossil fuels and others on electricity, thus there could be emissions related to the terminals. There could be emissions associated with terminal handling, but the scale of emissions was unclear and the literature did not provide any

[9] http://wiki.openstreetmap.org/wiki/Planet.osm

trustworthy emission factors for terminals. The model design would cater to inclusion of terminal emissions, but only if relevant terminal emission factors could be found.

Rail, road and sea modes were to be included in the model. Air freight was left out because it was assumed that the volume of domestic air freight was low. Air freight was assumed to consist mostly of high value and time critical freight. Thus the possibility for moving air freight to other modes was believed to be limited. Air freight was therefore not included in the model.

Within the time and financial constraints of the Ph.D. project, choices had to be made on which modes to focus on when doing more detailed studies. The road mode was chosen because it was assumed that it would be easier to collect data from trucks that could be used for comparison with existing emission research. An exploration of low-cost GPS equipment and hardware to access the vehicle's internal communication network would be undertaken to see if emission related data could be measured from the road vehicles. The recorded data could be used to check emission estimates against detailed emission models and to document the effect of driver behavior on emissions.

The model was to be developed as open source so that it would be used by all who wish to use it free of charge. No fees will be associated with the model, neither will there be any restrictions on including the software in any other software system.

A measure of success is if the tool will be adopted by freight transport service providers to calculate and implement measures to reduce emissions in addition to reporting them. This would show a real effort in reducing emission from freight transport rather than a quest to be perceived as a green company. McKinnon (2010 p. 17) provides some interesting evidence indicating that a company's image is more important than protecting the environment. It is interesting to see that in all the three studies cited in McKinnon (2010), cost of energy or transportation is ranked as one of the top six drivers for greening logistics.

1.6 Relation to the Green Freight Transport project

Norwegian freight transport companies are experiencing a growing demand for emission figures by their clients, both for CO_2 and other pollutants. It is believed that customers are seeking emission numbers to enter into their environmental statements, and thus there is a momentum in the freight transport industry to provide customers with data. In response to this a research project was created: The Green Freight Transport project. This Ph.D. dissertation was tightly integrated in the project and the Ph.D. candidate was given academic lead on work packages 6, 7 and 9 as shown in Figure 1. Appendix A holds a statement of the Ph.D. candidate's role in the Green Freight Transport project and the contributions to the project.

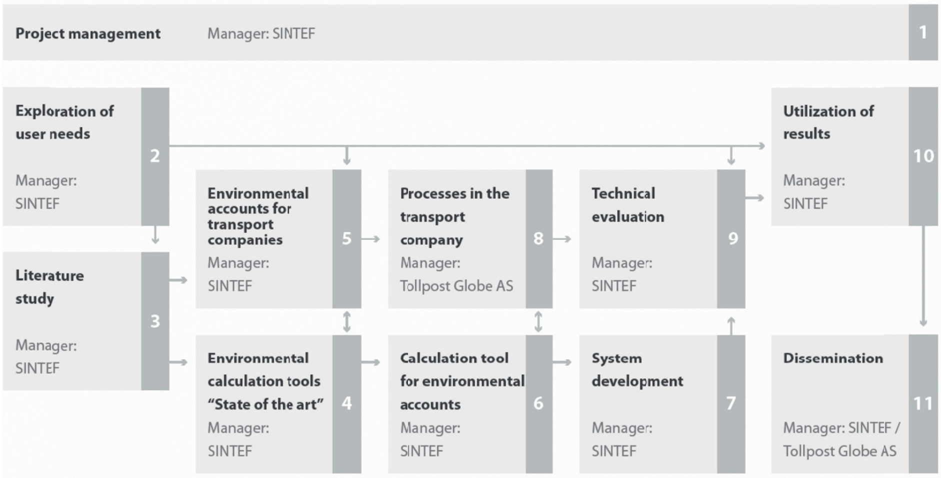


FIGURE 1 ORGANIZATION AND WORKPACKAGES OF THE GREEN FREIGHT TRANSPORT PROJECT (SOURCE: WWW.GRONNGODSTRANSPORT.NO)

1.7 STRUCTURE OF RESEARCH

To enable actors in the freight transport industry to include detailed emission calculations in their everyday operations will require a computational model. The research in this Ph.D. thesis focuses on developing a new model that can be used by freight transport companies to enhance their environmental performance.

The model core concept can be broken down into four parts:

- Accurate representation of direct emissions related to freight transport
- Ability to test measures under the control of single firms
- Low user entry level
- Transparency of calculations

The core concepts function like a prioritized wish list where the wishes have to be balanced against each other. For example a near perfect model is unusable if the user is not able to supply the model with the needed input data. A successful criterion of the model can be implemented and used by freight transport service providers. Emission research is an applied science and the model must be seen in the context of the users and the available data. A challenge in the field of freight transport emissions is that there exists little detailed documentation on existing tools that will allow external users to create and test the models that the tools utilize. Peer review of the computational models is not a common practice in the field of freight transport emission studies. Thus the computational model has to be built from scratch. The core concept of the model envisioned breaks with the design concept of existing models like EcoTransIT and NTMCalc, as the new model will be more detailed and require more detailed data in order to test measures under the control of single firms.

In order to build a model within the time and economic frame of a Ph.D. project, there is a need to focus on efforts that are believed to be critical in order to create a model that fits with the core concepts. To help with the focusing process, three questions are posed in relation to model design and one question is related to model testing. The questions match the sub questions of the research questions very closely.

Model development questions:

1. Is it possible to find single vehicle emission functions which can calculate emissions from freight transports that are sensitive to measures under the control of single firms?
2. Is the input data needed for the emission functions available and how can emissions be calculated?
3. How can the results from the envisioned model be integrated with a freight transport service provider's production system?

Testing question:

1. Is it possible to collect engine parameters from trucks under real world conditions, and can the collected data be used to calculate emissions that could be compared to the envisioned model results?

To answer the first modeling question a literature review was conducted with the aim of finding credible sources of emission factors that could be used for single vehicle emissions from freight vehicles. The second question is harder to answer via a literature review as little documentation is publically available. To find possible sources of input data, partners of the Green Freight Transport project were asked to look into sources that they had available. The input data would then be subject to an exploratory study to assess the quality of the data. The third question was answered through discussions with a major freight transport company. The goal was to understand how the existing production systems function and to find a strategy for how the new model could be implemented in the production system.

The challenge with testing a freight transport emission model is that it is very costly to do measurements that can be compared to model results. Thus a typical way to assess the quality of different emission models is to compare the results to other models and see if differences exist and if these differences could be explained. A weakness of this approach is that different errors can mask each other thus creating plausible results. In this thesis these limitations have been recognized and additional tests were conducted. Checking underlying assumptions is a useful extension to only testing final results. In addition to comparing the result to results from other existing tools, a check of the transferability of the road emission functions was conducted within the Ph.D. project. Emission factors and functions are context dependent.

One assumption that was checked was if driving behavior used to generate the emission factors differed from observed driving behavior. This check was conducted as an experimental study to test if it was possible to capture data from the truck and use this data to calculate emissions. The idea was to use consumer grade technology to plug into the vehicle for the data collection and use another state of the art emission model to calculate emission result. The test setup and results are presented in chapter 5.

1.8 Ideas for developing a new model

One central idea of this Ph.D. project was formed after a talk given by Professor Alan McKinnon at "Transport og Logistikk 2008." In his talk he briefly commented on Tesco's wish to mark every product with a CO_2 tag. The CO_2 tag would state the amount of CO_2 emitted when the product was produced and transported. His comment was regarding the point of the CO_2 marking. Will putting a number on supermarket products save the climate? This sparked off some thinking about the importance of how one ends up with a CO_2 figure contrary to the value of the CO_2 figure. In other words, is the value important or is it important to understand how emissions come about? The requirement from the Green Freight Transport project was to have a number that could be passed on to clients for them to mark their products or put in their environmental inventories. Could the process of establishing emission figures be used to reduce the emissions in addition to reporting them?

In essence the idea became to develop a model that could be used to look at environmental effects at the company level. The transport service providers should be able to look at the environmental impacts of transports conducted in their specific logistic network. Mode, route, time of day, weight and volume of freight all influence emissions, thus these factors should be included in a model to calculate emissions. The challenge in building such a model is the level of detail needed. First there is a need for detailed descriptions of the logistic network. Then there is a need for detailed information on the flow of freight. Finally there is a need for emission functions that can utilize the detailed logistic network and flow of freight to produce emission figures. This way of estimating emissions would be interesting because the input data was not built on historical averages, but on the actual routes, vehicles and freight moved. It is here the freight transport service provider's internal production systems are crucial. The production systems are used for tracking freight through the logistic network and billing. As a simplification, this could be seen as a digital mirror image of real transport. The Green Freight Transport project owner, TPG, has a production system where every terminal handling is recorded. Thus it is possible to follow a single package through the system and find the real world route of the package. The production system knows which vehicles were used to move the freight. And last but not least it knows which other packages traveled together with the specified package. Knowing which packages are on the same vehicle is important when it comes to establishing the total weight on the vehicle. The emissions from the specific vehicle can then be allocated to the individual packages that were on the vehicle.

To investigate if it was possible to use the production system as an integral part of calculating emissions, access to the design of the TPG production system was required. It was assumed that the other large freight transport service providers have the same kind of production systems with more or less the same capabilities. The production system could be used to calculate the emissions and to report the emissions to the customers. This could justify using detailed, data intensive calculations as the process can be fully automated.

The emission tool was not only to report estimated emission from conducted transport, but predict changes in emissions due to alterations in the logistic network. A fully automated emission calculation system allows for some interesting emission analysis. For example, if a freight transport service provider was to introduce a ship between Oslo and Bergen the emission impact of this could be estimated using last year's activity data on the specific relation. The ship could be entered into the logistic network and the logistic route to Bergen could be set to include the ship. Then the emission tool could be run again to find the total emissions using this logistic network configuration.

Another key issue for the Green Freight Transport project board was dissemination, the results from the project were to be used not only by TPG. The final product was to be available for as many freight transport service providers as possible. This has an impact on the design of the final product, it cannot be a specific application tailored for TPG and their logistical network. But there must be some core routines that can be used with their production systems. This has some practical consequences when it comes to software design and development. Especially, types of applications needed and last but not least the cost of the applications needed to be able to calculate freight transport emissions. Software that is costly and has a high entry level could be an obstacle to successful implementations.

Traditional emission research in Norway has been carried out from a top-down perspective. Usually total fuel consumed has been measured and then linked to different activities. Tonnes moved, cars transported or containers moved are examples of measures of activity. This is a way to estimate an average fuel consumption factor with the denomination g/tkm. Fuel usage is then converted into emissions based on fuel specific emission factors. Engine operating conditions are not considered. Both Thune-Larsen et al. (1997) and Foss et al. (2007) are examples of the top-down approach. One could be tempted to use the emission factor for ferries that was calculated in Foss et al. (2007) for other ferry links. But there are reasons for being cautious if doing so. The emission factor was based on average fuel consumption per engine-hour. Even if the vessels are the same they could have different fuel consumption per engine-hour due to differences in engine operating modes. A basic ferry trip could be split into three parts: hoteling, maneuvering and cruising. Ship hoteling is when the vessel is docked in port and using auxiliary engines to supply the ship with energy. If there is a significant difference between cruising, hoteling and maneuvering time, then there could be a significant difference in emissions. During cruising the engine operates at a relatively steady state, while one would expect transient operating conditions when maneuvering. Transient operating conditions lead to increased emissions. Thus it is important to know the origin of the emission factors in order to make an assessment of transferability. The bottom-up approach is susceptible to the same kind of problems. Vehicles are usually tested in a dynamometer and tailpipe emissions are measured. The test vehicle is driven according to a predefined set of speeds that constitute the driving cycle. If the real world driving behavior is different from the driving cycle then the emission factor could be wrong. In order to use emission factors to get credible results, it is important to understand the underlying assumptions and to check them if possible.

Norway does not have a car manufacturing industry like Sweden that warrants vehicle emission research. Thus it is highly likely that sources outside of Norway have to be found to find vehicle specific emission functions. This belief is strengthened when looking at the sources used for the national emission inventory. There is only one reference to Norwegian emission research/testing and that is to measurements performed by the National Institute of Technology in Norway from 1993. The same reference is stated in both the 2000 and 2007 versions of the national emission inventory documentation (Flugsrud et al., 2000, Aasestad, 2007). The measurements conducted included only light vehicles.

Care should be taken when developing a software tool to ensure that design choices maximize the software's life time. This is particularly challenging when dealing with a subject of such a nature that the input data and calculation routines are expected to change over time. New emission standards, new engines types and alternative propulsion systems are expected to enter the market in coming years. Thus an internal framework design of the new model would be beneficial to adapt to the expected changes, where modules in the model's framework could be updated, replaced or expanded without changing the behavior of the tool. The model developed within this Ph.D. project will have such a structure.

1.9 Structure of Thesis

Chapter 2 Documents the search for emission factors and functions from freight transport. The aim was to find sources of emission factors and functions and to understand how they could be used for calculating emissions from freight vehicles on the Norwegian infrastructure.

Chapter 3	Documents model design considerations and assesses the quality and availability of digital infrastructure descriptions. The goal was to find a suitable model design and understand how digital infrastructure descriptions should be used to match the emission factors and functions found in the previous chapter.
Chapter 4	Documents the unified Python software module used to calculate link-based emissions that will be used to calculate emissions for specific routes with specific vehicles. For rail two sub models are presented; one using the rail energy consumption model from the ARTEMIS project and one developed using rail line specific energy consumption factors. The computational routines presented in this chapter are generic and can be applied to any network as long as the required input data to the functions exists.
Chapter 5	Documents how underlying assumptions for the road model is tested. This includes an explorative study to capture data from the vehicles. Setup of a large scale data collection scheme and development of methods to analyze data.
Chapter 6	Documents the work done to make the detailed model from chapter 4 could be extended with a final phase to make it more usable to freight transport companies. In this chapter the model is finalized with a last stage called result management and a database for public use is created. The last part of the chapter gives some pointers on practical use for freight transport service providers.
Chapter 7	Documents testing of the complete model and the emission database produced. Estimated emissions for specific trips are compared with other existing and accepted tools.
Chapter 8	Presents concluding remarks on model design, digital infrastructure descriptions, emissions functions, routing and analysis and result management. Fulfillment of the research question and the need for further research is addressed.

2 EMISSION FACTORS AND FUNCTIONS FOR FREIGHT TRANSPORT

Atmospheric emissions have been a concern for local governments for a long time. High school textbooks mention events like the Great Smog of '52 in London. The "1956 Clean Air Act" was a direct response to the Great smog of '52[10]. The main problem for the cities at the time was emissions from fuel burnt to heat homes. On the other side of the Atlantic, California started facing problems with smog early on. Similar to London, emission regulation started to appear, but focus in California quickly turned to the automobile. Unburned fuel was the first pollutant to be studied and regulated in California. At the end of the 1960's initial tail pipe emissions regulation started to come out. Catalytic converters were required for cars produced after 1975. This set the trend for technology forcing regulation, where legislative governments set emission standards that producers had to adhere to, thus forcing the vehicle producers to develop technology to reach the emission levels stated (South Coast Air Quality Management District, 1997). The European Union set its own standards, the Euro standards. These standards limit the amount of specific pollutants in the exhaust. If a vehicle is to be sold in Europe it is to adhere to the appropriate standard. Thus Europe forces vehicle producers to develop cleaner technologies. Both in the U.S. and in Europe focus has historically been on locally polluting components. In the Euro 5 standard, as defined in regulation (EC) No 715/2007, for light vehicles the following components are regulated:

TABLE 1 REGULATED COMPONENTS OF THE EURO 5 STANDARD

Diesel vehicles	Petrol, natural gas or LPG vehicles
Carbon monoxide	carbon monoxide
Particulates	non-methane hydrocarbons
Nitrogen oxides	total hydrocarbons
Combined hydrocarbons and nitrogen oxides	nitrogen oxides

As climate awareness has grown the focus has shifted and there has been a move to include CO_2 emissions in regulatory form. EC Directive 1999/94/EC was created to give the consumers information on fuel economy and CO_2 emission when buying new cars. A study into directive 1999/94/EC concluded that the directive did not have the desired effectiveness (Gärtner, 2005). Thus there was a move forward when the Regulation EC No 443/2009 stated that the fleet average for registered cars in the EU should be 130 CO_2 g/km. The long-term target for 2020 is 95 CO_2 g/km. The regulation is designed so that manufacturers can have vehicles with higher emissions as long as their fleet average is under the limit.

[10] http://www.metoffice.gov.uk/education/teens/case-studies/great-smog

Figure 2 shows the evolution of European emission standards for heavy-duty diesel engines commonly used in freight trucks. The improvements are quite dramatic for NO_x and PM. From 1992 to 2013 the engine producers were expected to have reduced NO_x emissions by 95% and PM by 97%. These improvements were made possible by technological developments. According to SCANIA Norge's director of communications there has not been a significant reduction in CO_2 emissions measured from their engines between 1993 and now. This can be seen by the dark blue line in Figure 3.

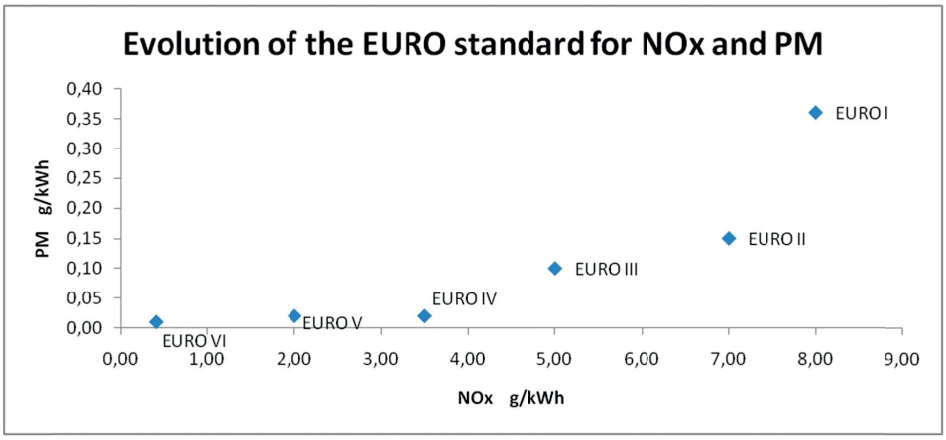


FIGURE 2 EVOLUTION OF THE EURO STANDARD FOR HEVY DUTY DIESEL ENGINES

Figure 3 shows the reductions for different pollutants as a function of the Euro emission standards. The unregulated CO_2, the blue line does not show a decrease since introduction of the European emission standards. CO_2 is directly dependent on fuel consumption, thus engine fuel consumption has been stable.

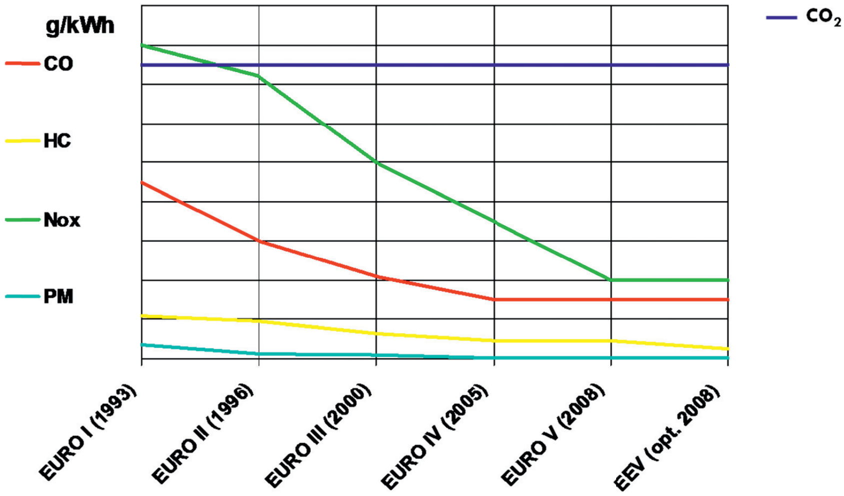


FIGURE 3 EMISSIONS FROM SCANIA HEAVY-DUTY ENGINES, SOURCE: SCANIA NORGE

From the truck manufacturers point of view there is a challenge if NO_x and CO_2 are to be reduced at the same time. They are keen to point out that engine-wise this reduction is quite challenging, because there is a tradeoff between NO_x and CO_2 emissions. From an engine control perspective it is simple to reduce NO_x emissions if one allows for a fuel consumption increase. But even if the engine's fuel efficiency has not increased there has been an increase in the truck's total fuel efficiency. From 1970 to 2000 SCANIA claims to have reduced fuel consumed per tonne kilometer by 50%. Four reasons are given for this reduction: improvements to the engine, rolling resistance, aerodynamic drag and increased payload capacity. The Euro emission standards may have helped to solve the problem of locally polluting emissions, but the emission of CO_2 from road vehicles have not been reduced to the same degree.

The Euro emission non-road standards regulate diesel train emissions; while ship and aircraft emissions are exempt from the regulations. The international Maritime Organization, an agency of the United Nations, has laid down ship pollution rules in the "International Convention on the Prevention of Pollution from Ships" known as MARPOL 73/78. This document is available from IMO's website[11] under the heading "Marine Environment." The ship air emission regulation is contained in "The protocol of 1997 adoption of Annex VI." The rules here limit the SO_x and NO_x in ship exhaust emissions. The International Civil Aviation Organization has certification standards aircraft engines. These standards are contained in "Annex 16 – Environmental Protection, Volume II – Aircraft Engine Emissions to the Convention on International

[11] http://www.imo.org

Civil Aviation". More information on aircraft emissions can be found on the Air Transport Bureau (ATB) web page[12].

The effects of some pollutants are not only local, but regional. From high school textbooks one can remember the connection between SO_x and NO_x in the acidification of Norwegian lakes. Emissions from Britain were believed to be the cause of much of the acidification of lakes. In 1993 the Norwegian environmental minister Torbjørn Berntsen was so fed up with the lack of response from Britain to the problems observed in Norway, that he insulted the British environmental minister and called him the biggest "drittsekk" (shitbag) he had ever met. Still today a Google search for the words "shitbag Norwegian minister" gives about 14,000 hits as of July, 2010. Norway would have little or no way of knowing that Britain was the culprit unless they had access to SO_x and NO_x emission figures for Britain. Like many other countries Norway reports emission data to international bodies. The climate and pollution agency (KLIF) and Statistics Norway (SSB) have been given the responsibility for reporting emissions to United Nations Framework Convention on Climate Change (UNFCCC) and Economic Commission for Europe (ECE). The latter is the 1979 Geneva Convention on Long-Range Trans boundary Air Pollution (CLRTAP). Thus emissions at the national level are monitored by our own and foreign governments.

The sections above indicate that there has been a focus on emissions for quite some time. There exist regulations and emission standards that producers of transportation equipment have to follow. It would be useful if one could use these regulations and standards to calculate emissions. But sadly that is not the case, because there are many factors that influence the amount of pollutants emitted. Mainly how the equipment is used and where it is used. To measure emission performance there is a need to link the emissions with a measure of activity. For freight, emission performance is usually expressed as grams of pollutant emitted per tonne kilometer (g/tkm). If a truck is run with high engine speed, the emissions measured in g/tkm will be higher than if the appropriate gear was chosen. The same is true for ships; if the speed is pushed beyond the hull speed the emissions will be higher in g/tkm then if run at hull speed. Hull speed is an approximate measure for maximum efficient speed. Thus operation of equipment will impact emission. The same is true for where the equipment is used. Driving in mountainous areas is associated with higher energy usage and thus higher emissions. If the sailing route for a ship is against the trade winds then energy usage will be greater. If one uses the emission regulation to calculate emissions then one will be calculating the worst case. Engine producers are free to develop engines that have lower emissions that the standards require. At the national level SSB and KLIF cooperate to establish emission factors and create calculation routines to generate an emission inventory for Norway.

[12] http://www.icao.int/icao/en/env/Standards.htm

2.1 TRACING THE SOURCES OF THE EMISSION FACTORS USED BY TPG

The existing calculation routines in TPG are based around an emission factor model presented in Thune-Larsen et al. (1997). The emission factors are given as grams per tonne kilometer (g/tkm). The emission factors used by TPG are listed in Thune-Larsen et al. (1997). The road emission factors are calculated by the tool used in the national emission inventory and documented in Bang et al. (1993).

TABLE 2 EMISSION FACTORS USED BY TPG IN THE 2003 EMISSION INVENTORY

Type	CO_2 (g/tkm)	SO_2 (g/tkm)	NO_x (g/tkm)	CO (g/tkm)
Pickup and delivery	158,96	0,02	1,49	0,63
Long-haul road	52,71	0,01	0,47	0,17
Long-haul diesel rail	69,30	0,06	0,87	0,23
Long-haul electric rail	0,00	0,00	0,00	0,00
Long-haul sea	91,00	0,24	2,15	0,06

This model is quite basic as it differentiates between delivery/collection and long-haul stretches. The long-haul stretches are split by mode. To use the model only volume moved and distance is needed as input. The input data is extracted from the TPG production system.

Using this kind of environmental accounting makes it hard to test future schemes. A reasonable question could be: what is the impact of only using Euro IV vehicles? The problem is that there is no explicit notation of the Euro emission standard in the factors used by TGP, thus this cannot be done without creating a new emission factor.

Initial pressure from the Green Freight Transport project group was to come up with new grams per tonne kilometer factors that could be used. The new factors were to be more trustworthy than the factors in use in Norway at the time. But from a scientific point of view this was not satisfactory. It would not allow companies to look at their operations in more detail than distance driven, tonnes moved and mode of transport. The emission impact of vehicle utilization, route choice and time of day could not be studied. To be able to study changes in emission at company level more detailed data was needed. The production system was believed to be a source of information that could make more detailed emission calculations possible.

The first place to search for new emission routines was to check the sources of the emission factors that TPG was using. Thune-Larsen et al. (1997) is a collection and summary of data gathered from other sources. The emission factors used by TPG have the same origin as those in the national emission inventory.

As earlier mentioned transport related emissions are calculated and reported in the Norwegian emission inventory. Documentation of the methodology and data used is presented in Aasestad (2007). This document is the latest in a chain that was started in 1993, and updated in 1995, 2000, 2005 and 2006. Appendix B of Aasestad (2007) presents emission factors in the form of kilo grams emitted per tonne fuel used. The document is not a primary source of emission factors. Emission factors are collected from different sources and different sources are combined to create a set of emission factors for a type of activity. The document is brief and does not state the reasons for why emission factors from different sources are used. An example of this mix of sources is found in the rail section 3.2.4.3 on page 36. A problem with the emission factors stated in the national inventory is that they are very general. The impact of gradients and vehicle utilization are not explicit variables in the national inventory emission functions. Thus companies will have little help from these emission functions in assessing route choices and vehicle utilization. The emission factors can be used to test (or study) emissions for the company based on the company's fuel accounts. The positive side of using these factors is that they are updated by a government agency as part of the Convention on Long-range Trans boundary Air Pollution. Another benefit is that emission factors relevant to all modes of freight transport are presented there.

For road transport a separate model is used, this model was developed in 1993 (Bang et al., 1993), and revised in 1999 (Bang et al., 1999). These reports document how emission factors for road are created. Resulting average emission factors are used in building the national emission inventory. The basic layout of the model is described in the outset of the report. In the second paragraph we get a heads up that this is not the model we are looking for. The model formulation explicitly states that the model does not take topography into account. As mentioned earlier, the assumption that the losses uphill can be turned to gains going downhill is not valid (Hassel and Weber, 1997). The authors have commented on their assumption and that may not always be valid. But on the other hand they have a model formulation that divides vehicles into groups of fuel, type, weight and technology (age). The grouping of vehicles according to type is listed in Table 3.

TABLE 3 TABLE OF VEHICLE TYPES IN THE ROAD SUB MODEL OF THE NATIONAL EMISSION INVENTORY SOURCE: (BANG ET AL., 1999 P. 21)

Fuel	Group code	Type description	Total weight (tonne)
Petrol	BM1	Car	-
Petrol	BN1	Minivan / minibus	< 3.5
Petrol	BHL	Commercial	> 3.5
Petrol	BHB	Bus	> 3.5
Diesel	DM1	Car	-
Diesel	DN1	Minivan / minibus	< 3.5
Diesel	DHLL	Light commercial	3.5 – 7.5
Diesel	DHLM	Medium commercial	7.5 - 16
Diesel	DHLH	Heavy commercial	> 16
Diesel	DHB	Bus	> 3.5

The grouping is useful at the company level because it allows for differentiation between vehicles that might be used for freight transport. It is possible to see the difference between a small truck and a large truck. But on the other hand the emissions are independent of vehicle loading. Thus a truck loaded to its maximum weight capacity will emit the same amount as a truck running without a load. The model takes five driving modes as input parameters.

- Urban driving with speed limit up to 30
- Urban driving with speed limit between 30 and 50
- Rural or byway with speed limit 60 -70
- Trunk road with speed limit 80
- Motorway with speed limit 90

The five modes could be useful to make our emission model sensitive to route choice. The real strength of the model is that it is based on fuel accounting. One begins with the total of fuel used and then splits it by activity. The use of total fuel consumption will ensure that the scale of the total emissions is correct, at least for emissions that are relatively unaffected by engine operating conditions. CO_2 and SO_x are examples of emissions. A strong point of the emission model is that particulate matter originating from studded tires is included. The major objection to using this model is that vehicle loading and gradients are not explicit variables. And thus user of such a model would not be able to study the impact of vehicle loading, gradients or the combination of gradients and load.

The emission factors created in the aforementioned model are based on several sources that have been combined to create one emission factor (Bang et al., 1993 p. 52-53). This is further complicated in the 1999 update (Bang et al., 1999) where some of the old emission functions for rural driving (landeveiskjøring) from the 1993 report by Bang et al. have been updated using correction factors created from the COPERT II speed curves, but not using the empirical speed curves. This was because some of the old factors were believed to be better than the COPERT II functions (Bang et al., 1999 p. 50). To update these factors based on new research could become quite tedious because some emission factors are a result several of other sources.

This leads to the conclusion that other sources should be found in order to create an emission model that is sensitive to measures under the control of single firms. This is in line with the view that simple emission factor models are best suited for reporting at the national level.

2.2 Sources for other existing tools

Both EcoTransIT and NTMCalc provide emission calculation tools that specifically relate to air emissions from freight transport. According to the EcoTransIT documentation there has been a discussion on methodology and data harmonization between EcoTransIT and NTM. Rail data included in NTMCalc is mostly taken from EcoTransIT and EcoTransIT use data and methodology for ferry transport from NTMCalc. A major difference between the two tools is treatment of routing. EcoTransIT has the ability to calculate routes based on origin and destination choices, while NTMCalc does not. As mentioned in the introduction, routing can be challenging due to data quality. The source of the network used in EcoTransIT is not mentioned in Knörr (2008). In Knörr et al. (2010) which is an update of Knörr (2008), the following information is given for the network: "*Therefore EcoTransIT World uses in the background a huge geo-information database including world wide networks for streets, railways, aviation, sea and inland waterways*" (Knörr et al., 2010 p. 28). This is not a good reference to the network dataset used, neither is the network available as a download for user inspection.

Both EcoTransIT and NTMCalc try to reduce the burden on the user by giving default values for several input variables. Thus emissions could be calculated with little input data. This generalization has positive and negative sides. When generalization is applied the user needs to input less data. A detailed NTM road calculation is based on six stages (Bäckström, 2007):

1. Selection of relevant vehicle type
2. Set fuel type and fuel consumption (FC)
3. Calculate vehicle environmental performance data (energy use and emissions to air) for the operation of the vehicle
4. Compensate for the effect of applicable exhaust gas abatement techniques
5. Vehicle operation distance
6. Allocation to investigated cargo

First the user needs to select the road vehicle that is to be used. Then the fuel consumption is to be set. Fuel consumption is set as a factor g/km where default values are given. NTM uses fuel based emission factors expressed as grams of emission per liter fuel used. In stage 3 the appropriate fuel emission factors are chosen on the basis of vehicle type. Stage 4 reduces emissions if any after treatment technologies are used. Particle filters and catalysts are examples of such after treatment equipment. The distance the vehicle has traveled is needed to compute the total emissions from the vehicle trip. The last step is allocation of emissions. This way of calculating emissions is interesting because it is focused on the vehicle and has a final allocation step. This allows for the separation of vehicle emission calculation and allocation of emissions to the freight moved.

The NTM documentation is critical to its previous estimation routine that relied on vehicle manufacturers emission figures. NTM has opted to use factors from the Handbook Emission Factors for Road Transport (HBEFA) until ARTEMIS data becomes available. The extraction of data from HBEFA is documented in appendix 2 of Bäckström (2007). EcoTransIT also uses emission factors derived from HBEFA. The EcoTransIT documentation (Knörr, 2008) does not contain a description of how emission factors are extracted from the HBEFA.

Both in the NTMCalc (Bäckström, 2007 p. 12) and EcoTransIT (Knörr, 2008 p. 20) documentation there were references to the ARTEMIS project. The ARTEMIS website[13] contains a large amount of documentation. ARTEMIS is an acronym for Assessment and Reliability of Transport Emission Models and Inventory Systems. The ARTEMIS project started in 2000 and the final report was published in October 2007. The documentation along with emission factors, rail and road models can be downloaded from the website.

2.3 The ARTEMIS project

Figure 4 shows the ARTEMIS work packages and partners involved in the project. The first thing to note is that all freight transport modes are covered by ARTEMIS. In a guest editorial in the journal Atmospheric Environment, Robert Joumard gives a short, but concise explanation to why ARTEMIS came about. "Comparisons between the results from different emission models and different national inventories have highlighted substantial differences" (Joumard, 2009). The ARTEMIS project had two goals (Boulter and McCrae, 2007 p. 10):

1. *To gain, through a program of basic research, a better understanding of the causes of the differences in model prediction, and thus to address the uncertainties in emission modeling.*
2. *Develop a harmonized methodology for estimation emissions from all modes at the national and international levels.*

For calculating emissions from freight transport the project is important because it looks at road, rail, sea, inland sea and air-transport. An inclusion of all modes does not necessarily indicate that the modes are treated with the same level of detail. The level of detail can be attributed to the less extensive research efforts in general for rail, shipping and air transport (Boulter and McCrae, 2007 p. 10).

13 http://www.inrets.fr/ur/lte/publi-autresactions/fichesresultats/ficheartemis/artemis.html

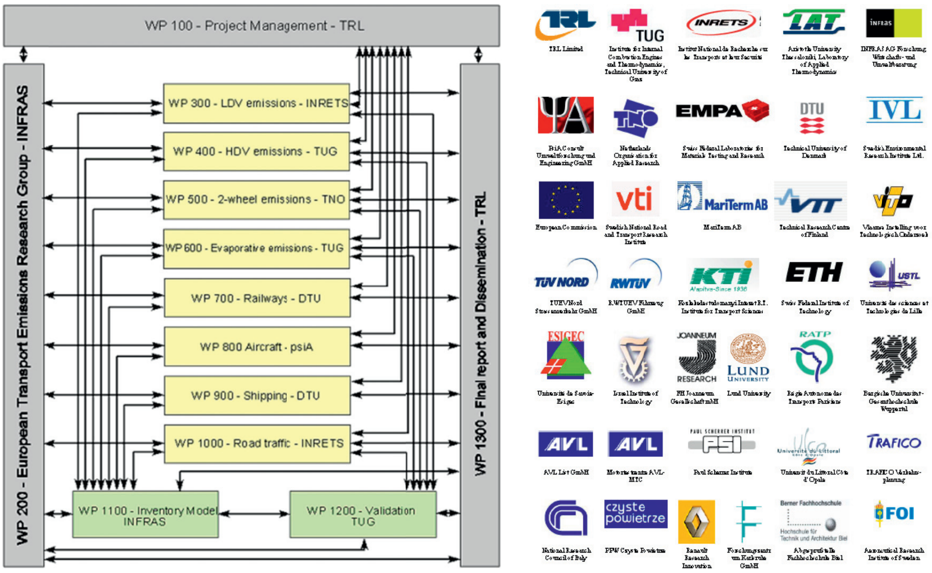


FIGURE 4 ARTEMIS WORKPACAGES AND PARTNERS

The ARTEMIS project builds on several earlier research projects. In 1993 a European Co-operation in the Field of Scientific Research (COST) set up a program to look into estimation of pollutant emissions from transport. This program is known as COST 319. Estimation of pollutant emissions from transport and documentation from this project is available on an INRETS website[14]. The COST 319 objective was to coordinate emission research in Europe with regards to regulated and unregulated emissions, fuel consumption and energy usage. Four transport modes were included in COST 319 air, rail, road and sea. The COST 319 project ran from 1993 to 1998. The main deliverable from COST 319 is Joumard (1999) which is a state of the art description for the four main transport modes. There was little financial support for the COST 319 and some of the partners in the project participated in a project called Methodologies for Estimating Air Pollutant Emissions from Transport (MEET) that would partially cover the work needed to be done in COST 319. MEET was funded by the European Commission.

It is interesting to note the number of pages used to describe the state of the art of each mode. Figure 5 shows how many pages were dedicated to each mode in the final report as a percentage. It is quite clear that the authors had more to say about road based transport as compared to the other modes in the COST 319 project. The same trend is evident in the ARTEMIS final report, the major shift is for sea. In the ARTEMIS report sea is split into two different categories, inland shipping and maritime shipping. Inland shipping is for boats running on the inland waterways such as canals, rivers and lakes.

[14] http://www.inrets.fr/ur/lte/cost319/index.html

The huge difference in pages spent on each mode is probably indicative of the level of detail and data available from the different modes.

There is another project that has been essential for ARTEMIS and that is “COST 346 Emissions and Fuel Consumption from Heavy Duty Vehicles.” The final report from COST 346 (Sturm and Hausberger, 2006) is available from the COST website[15]. The COST 346 project ran from 1999 to 2005. The work done on heavy-duty vehicle emissions stems from cooperation between COST 346 and HBEFA.

The ARTEMIS project is attractive because it incorporates calculation routines from previous research projects and makes them available. The ARTEMIS final report contains brief summaries of more detailed reports for each mode. For the emission model the heavy-duty vehicle (HDV), light duty vehicle (LDV), rail and marine shipping chapters are most interesting along with the detailed reports on the same topics.

[15] http://www.cost.esf.org/domains_actions/tud/Actions/Energy-and-Fuel-Consumption

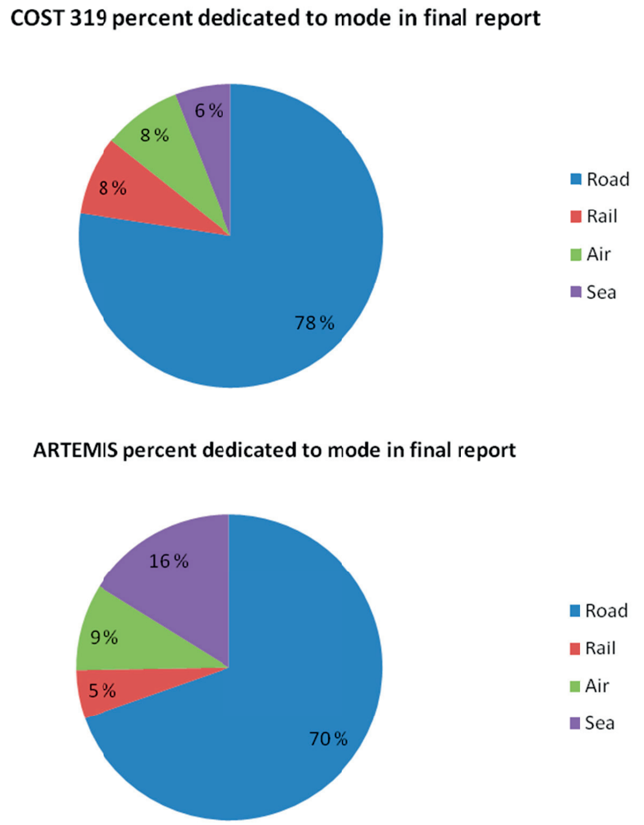


FIGURE 5 PERCENT OF FINAL REPORT DEDICATED TO MODE BY PAGES

2.3.1 ARTEMIS Heavy Duty Vehicle (HDV)

As mentioned earlier the heavy-duty vehicle work done in ARTEMIS is done in cooperation with COST 346 and HBEFA. Direct measurements of emissions are expensive, (Esteves-Booth et al. (2002) site an author claiming costs of £10,000 for a single vehicle emission test. The interacting between gradient and loading for heavy-duty vehicles will mean testing many combinations. Thus it would be very expensive to test all these combinations. In the ARTEMIS project this was solved by the use of a model to estimate emissions from engines. The Passenger car and Heavy-duty Emission Model (PHEM) was developed as a response to the aging of heavy-duty vehicle emission measurements. The PHEM model was developed as part of three projects, ARTEMIS, COST 346 and HBEFA. The model was validated against road tunnel measurements in the Plabutschtunnel in Austria (Hausberger et al., 2003). Hausberger et al. (2003) conclude that emissions from heavy-duty vehicles have been underestimated in the past. Modern engine control allows the engine developers to optimize fuel consumption in off-cycle points and emission in on-cycle points. In this context the point is a combination of load on the engine and engine speed. Figure 8 shows a plot of on-cycle points, the ESC and thirteen mode points are used for type approval (on-cycle points). Combinations of load on the engine and engine speed that are not on these points are said to be off-cycle points.

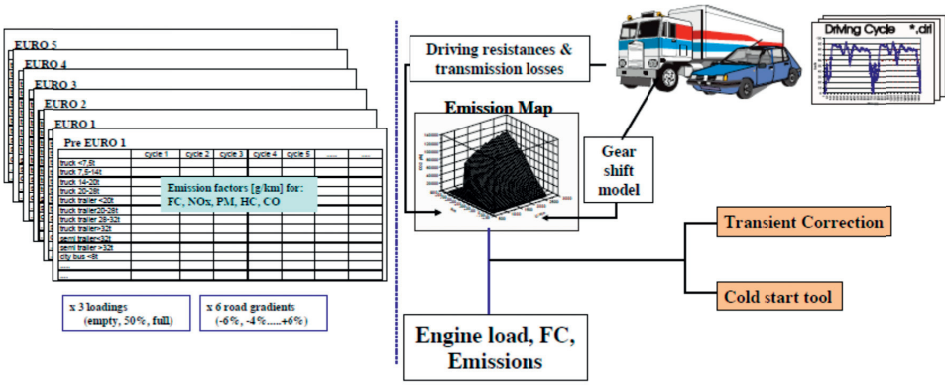


FIGURE 6 EMISSION FACTORS AND THE PHEM MODEL, SOURCE: (REXEIS ET AL., 2005 P. 7)

Figure 6 shows the emission factors derived from the PHEM model along with a schematic of the PHEM model. The foundation for the PHEM model is the input driving cycle. A driving cycle is a set of points of driving speeds against time; see Figure 7 for a graphical representation. The driving cycle is then used to calculate the amount of energy required from the engine to move the vehicle including transmission losses. There is a gear shift model that is used to calculate the engine speed. Then emissions are interpolated from a steady state emission map on the basis of calculated power and engine speed. Transient corrections and cold start corrections are applied if required. The combination of pollutant, vehicle category, Euro class, driving cycle, vehicle load and road gradient gives one emission factor when used as input to PHEM. This means that close to 170,000 runs of PHEM were required to generate the ARTEMIS heavy-duty vehicle emission factors.

Prof. Stefan Hausberger, the author of PHEM, was contacted via E-mail in an attempt to acquire the PHEM model for testing with observed data from truck operating in Norway. The cost of acquiring the model and the cost of necessary training was too great for the Ph.D. project. It was hoped that emission factors could be established from GPS positional data and engine load and engine speed collected from the vehicle. The response apart from the costs was that it was possible to use GPS speed data, but probably not gradients from GPS observations to calculate emissions from a specific trip.

Thus the emission factors created in the ARTEMIS project would be the most detailed emission factors publicly available for Europe. There is emission research done in the US. The US EPA has developed MOVES (Koupal et al., 2003). MOVES is a tool to estimate emissions at three levels, macro, meso and micro. The micro level is at the project level to calculate effects of infrastructure changes. MOVES will attempt to use the same emission factor for all levels to ensure agreement between emissions at all the three levels. One reason not to use MOVES is transferability between Norway and the US could be challenging due to different emission regulations. Vehicles and infrastructure can give systematic differences between the US and Europe.

The ARTEMIS heavy-duty emission factors are a part of the ARTEMIS road model computer program (Keller et al., 2007). The ARTEMIS road model is an MS Access database that can inventory emissions from road based transport. The database holds both calculation routines and input data. One set of input data that is of great concern when doing road emission studies is the driving cycles used when creating the emission factors. The driving cycle is directly related to the driving behavior. And if driving behavior on Norwegian roads differ radically from the driving behavior that make up the driving cycles used in ARTEMIS then there could be a potential problem. It is possible to extract the driving cycles used from the ARTEMIS road model. Thus these cycles could be compared to observed driving behavior in Norway for heavy-duty vehicles. Gathering data on driving behavior of a subset of trucks could be used as a comparison.

2.3.2 THE DRIVING CYCLE

To fully understand emissions from road based vehicles an understanding of driving cycles is needed. In order to test for compliance with emission standards a testing procedure has been developed. Common for emission testing procedures is that they use a driving cycle. A driving cycle is a series of speed/time points. Figure 7 shows a speed by time plot of the New European Driving Cycle (NEDC). The NEDC is used to measure tailpipe emissions for certification of road vehicles in Europe.

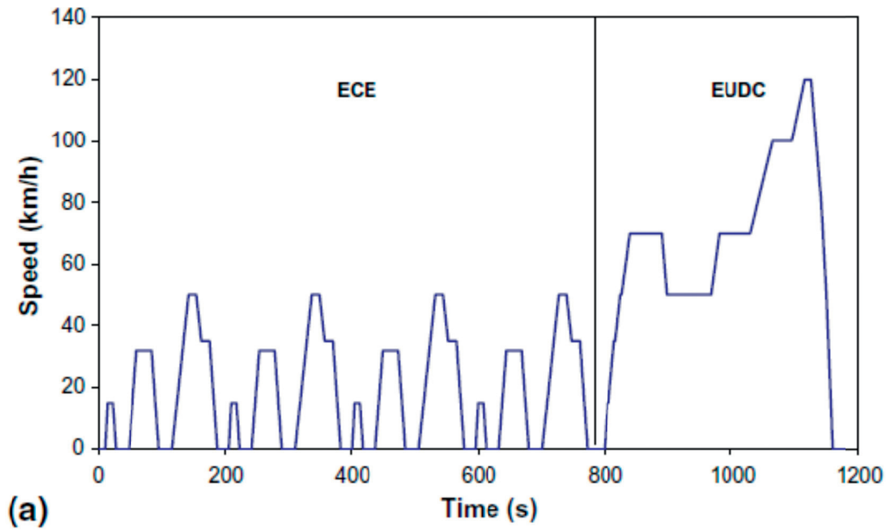


FIGURE 7 NEW EUROPEAN DRIVING CYCLE NEDC (ECE + EUDC) , SOURCE: (PELKMANS AND DEBAL, 2006)

It is important to realize that the Euro emission standards are legislative standards. The driving cycle used for testing Euro emission standard compliance might not represent real world driving conditions. The New European Driving Cycle suffers from the one-size-fits-all problems. The cycle might be representative for some types of driving in specific areas while unsuited in others. Tzirakis (2006) developed a real world driving cycle for Athens Greece and compared it to the European driving cycles. There were quite large differences between the Athens driving cycle and the European driving cycles. The difference resulted in fuel consumption ranges from 9% to 79% depending on the vehicle tested. So it is safe to say that real world driving gives different emissions than the legislative driving cycles. This is confirmed by Pelkmans and Debal (2006) who report that a Euro 4 vehicle could generate ten times higher emissions then in real-world traffic.

To make matters worse there exists a phenomenon known as "cycle beating." The point of cycle beating is to optimize emission for the specific driving cycle. Thus for operating conditions outside the driving cycle emissions could be higher (Kågeson, 1998). As indicated in (Kågeson, 1998) several heavy-duty diesel engine manufacturers were accused of cycle beating by the U.S. Environmental Protection Agency (EPA). The issue was settled with a $83.4 million civil penalty and the introduction of not-to-exceed (NTE) regulation (Osenga, 1998). The idea behind NTE testing is to deter heavy-duty diesel engine producers from using advanced engine control technology to beat the legislative emission driving cycles. A NTE test is a measurement of thirty seconds at any normal operating condition. The measured tailpipe emission has to be under the NTE limit.

Cycle beating can be seen in the in the PHEM engine emission maps in Figure 9. The technologically oldest engine (Euro I) has a relatively "flat" emission surface. The surface in the figure resembles a plane that rises toward higher emissions with a higher engine load and engine speed, while for the Euro II engine the 3D emission map has got a valley in the middle. In the most advanced engine of the three the surface has clear peaks and valleys. The bottoms of the valleys are at about 40% and 85% of full engine speed. Looking at Figure 8 the bottoms of the valleys coincide with the engine speed used for type approval.

The legislative cycle used for engines up to and including Euro II is the 13-mode. This cycle is known as ECE R49. The ECE R49 was replaced by the ECE for Euro III. More details on emission test cycles are available from DieselNet[16]. Looking at the Euro II engine in Figure 9 and looking at 13-mode points in Figure 8 shows that there are "valleys" where the measurement points are. For the Euro III engine there are "valleys" where the measurements are taken, and the hills outside the measurement area are higher.

The effect of cycle beating is that the advanced engine control technology is used to keep the engine operating within Euro emission standards at the measurements points, while outside the measurement points the emissions might be higher.

For NO_x the Euro standard has the following values:

- Euro I 8 g/kWh
- Euro II 7 g/kWh
- Euro III 5 g/kWh

However, it is unlikely that the real world emission reduction is of the same size because of the ability to tune the engines to reduce emissions in the ranges measured by the legislative driving cycles.

To get better real-world emission ARTEMIS added more measurement points. These points are placed between and around the existing measurement points, thus they will give a better view of the emissions for the full specter of power utilization and engine speed. The new ARTEMIS points are shown in Figure 8. According to the ARTEMIS HDV project the reason for cycle beating is fuel saving. The key is the trade-off between fuel efficiency and NO_x emissions. This causes an interesting dilemma between local pollutants and emissions responsible for global warming. Increasing fuel consumption and CO_2 emissions can lead to less NO_x emissions and vice versa.

[16] http://www.dieselnet.com/standards/cycles/

One weakness of the ARTEMIS database is that emissions from newer engines, Euro IV and Euro V have not been measured as no vehicles were available during the measurement campaign. To be able to model Euro IV and V a set of assumptions on after treatment and engine emission maps have been developed. These are presented in chapter 5 of Rexeis et al. (2005). Thus even if Euro IV and Euro 5 vehicles were not available for emissions testing, emission factors for these vehicles has been developed. The HDV report recommends that emission factors be updated when Euro IV and Euro V become available for testing.

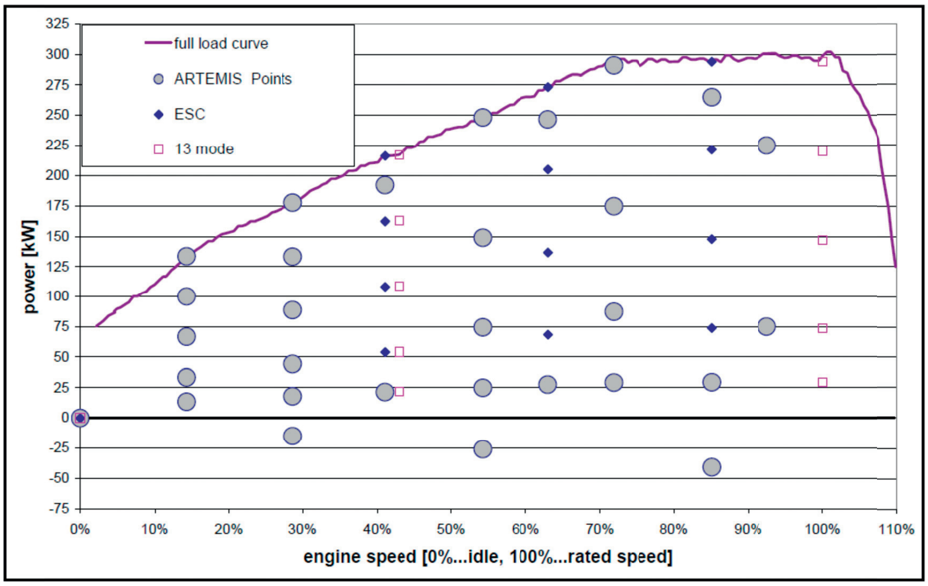


FIGURE 8 MEASUREMENT POINTS FOR EMISSIONS, SOURCE: (BOULTER AND MCCRAE, 2007 P. 122)

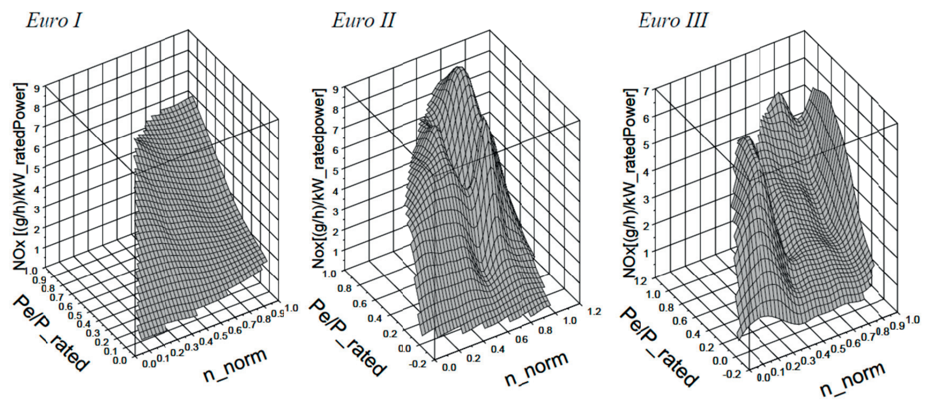


FIGURE 9 STEADY STATE NO_X EMISSION MAP, SOURCE: (BOULTER AND MCCRAE, 2007 P. 123)

The driving cycle has a clear impact on the emissions generated from a vehicle. Thus one way of checking transferability of emission functions to Norwegian conditions is to develop real world driving cycles for Norwegian conditions. Developing Norwegian driving cycles is outside the bounds of this Ph.D. project, but a comparison between observed driving behavior and the driving cycles found in the ARTEMIS road model could still be possible. There have been a few studies that have developed real-world driving cycles: Hung et al. (2007), Kamble et al. (2009), Wang et al. (2008) and E.Tzirakis et al. (2006). These studies give an insight into the development of real-world driving cycles. The development of the ARTEMIS driving cycles are described in André (2004). Ericsson (2001) studied the parameters that effect fuel usage and emissions and found that relative positive accelerations (RPA) was the most important parameter. RPA is a measure of strong positive accelerations in relation to the duration of the trip. Figure 10 shows RPA, fuel and NO_x emission taken from Pelkmans and Debal (2006). When plotting RPA values against fuel consumption (FC) and NO_x emissions the picture is quite unclear. But it looks like there is a bit better match between fuel consumption and RPA then between RPA and NO_x emissions. But the R-squared values are low both for fuel consumption and NO_x emissions in relation to RPA.

If single firms in the freight transport sector are to compare driver behavior in relation to environmental performance it would be of interest to create a performance index based on observed driving behavior. A simple parameter to compute after a trip has ended is RPA. Thus using RPA will show the presence hard positive accelerations which could indicate unwanted driving behavior.

Driving cycles and the observation of driving patterns are of key concern when creating emission factors. If the observed driving behavior is very different from the behavior used for emission factor creation then the emission factor is likely to be inaccurate.

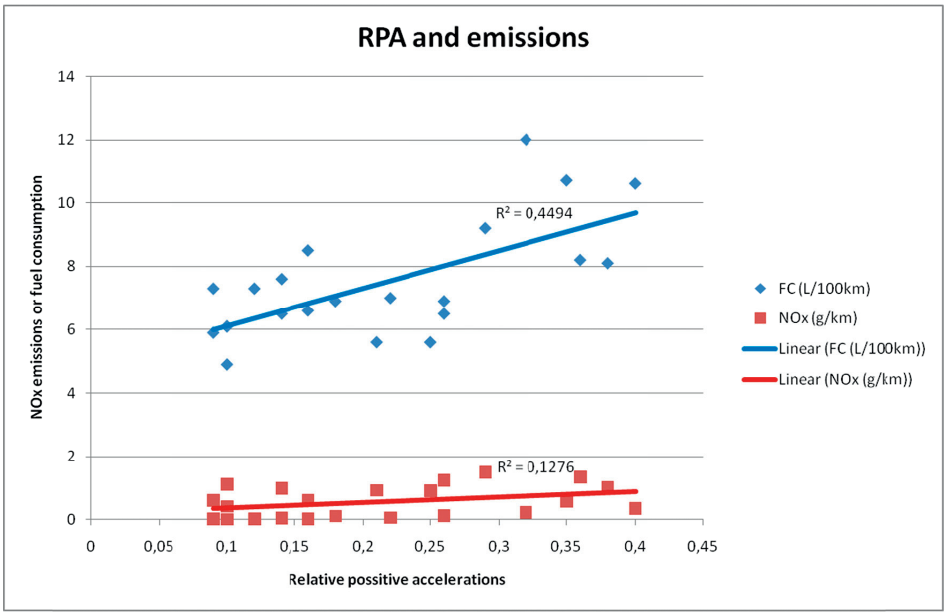


FIGURE 10 RPA AND EMISSIONS, DATA POINTS TAKEN FROM TABLE 3,4,5 & 6 IN (PELKMANS AND DEBAL, 2006)

2.4 AVERAGE SPEED FUNCTIONS

One of the most promising deliverables from the ARTEMIS project in relation to building a new model for freight transport emissions are the average speed functions. Average speed functions are equations that describe emissions as a function of vehicle speed. A total of 11,970 average speed functions have been developed within the ARTEMIS project. There are 114 vehicle types, five pollutants, seven gradients and three vehicle loadings. The average speed functions are documented in Boulter and Barlow (2005). The emission database was used for curve fitting and one of sixteen different functions was automatically chosen. The shape of the emission functions resembles each other quite closely. A typical average speed emission curve can be seen in Appendix C. All the average speed functions for HDV vehicles are reported in excel sheets that are available to the general public. The excel sheet can be downloaded from the INRETS website[17]. The average speed emission functions are given for seven gradients between -6% and +6%, the vehicle loadings 0%, 50% and 100% of maximum total weight. It should be noted that the PHEM model adjusts the driving cycles to match the given engine performance. Thus the driving cycle used in the creation of the average speed emission factor can be adjusted especially for heavy loads on steep gradients.

Appendix A in Boulter and Barlow (2005) holds some examples of average speed emission factors in the format they are available in the excel sheets. One should especially note the valid speed range. If the emission functions are used outside this region strange emissions can occur. The functions are found on page 8 in Boulter and Barlow (2005).

[17] http://www.inrets.fr/ur/lte/publi-autresactions/fichesresultats/ficheartemis/road3/modelling33/ARTEMIS_HDV_Functions_and_Report.zip

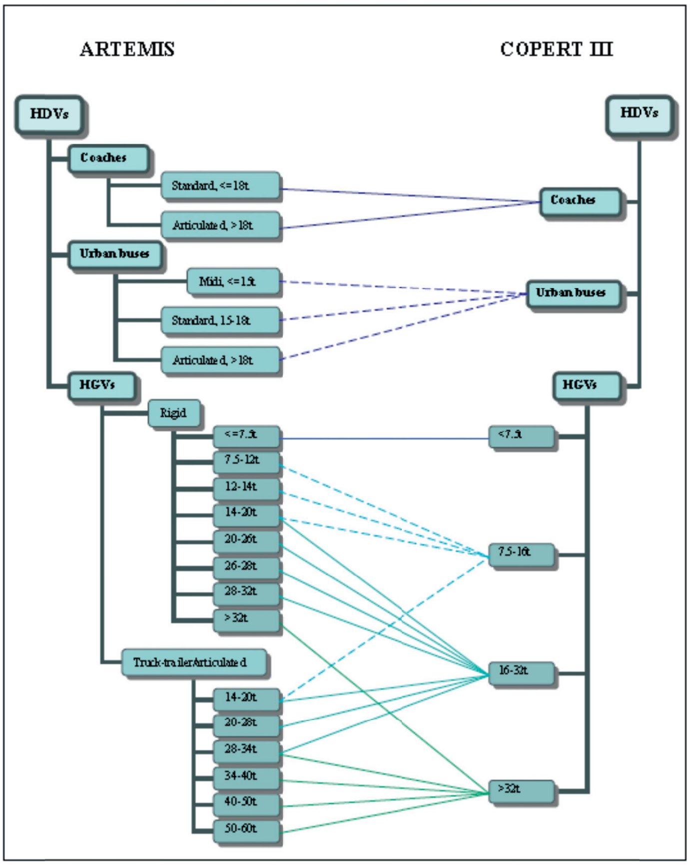


FIGURE 11 HEAVY-DUTY VEHICLE CLASSIFICATION IN ARTEMIS AND COPERT III, SOURCE: (BOULTER AND BARLOW, 2005 P. 16)

The ARTEMIS heavy-duty vehicle classification scheme is more detailed than the one found in COPERT III. Figure 11 shows the classification in ARTEMIS and COPERT III. One of the main differences is that ARTEMIS divide truck into two categories, rigid and truck-trailer. ARTEMIS has emission functions for fourteen truck categories while COOPERT III has four categories. A detailed vehicle classification allows for detailed studies and could possibly be used by companies to test the emission consequences of using different vehicle sizes.

Verification of the ARTEMIS road model was done through verification of the underlying PHEM model and by road tunnel measurements for real world traffic operation. Figure 12 shows validation results taken from the ARTEMIS final report. Fuel consumption is consistently reported within 2 percent. For NO_x the maximum deviation was 4%.

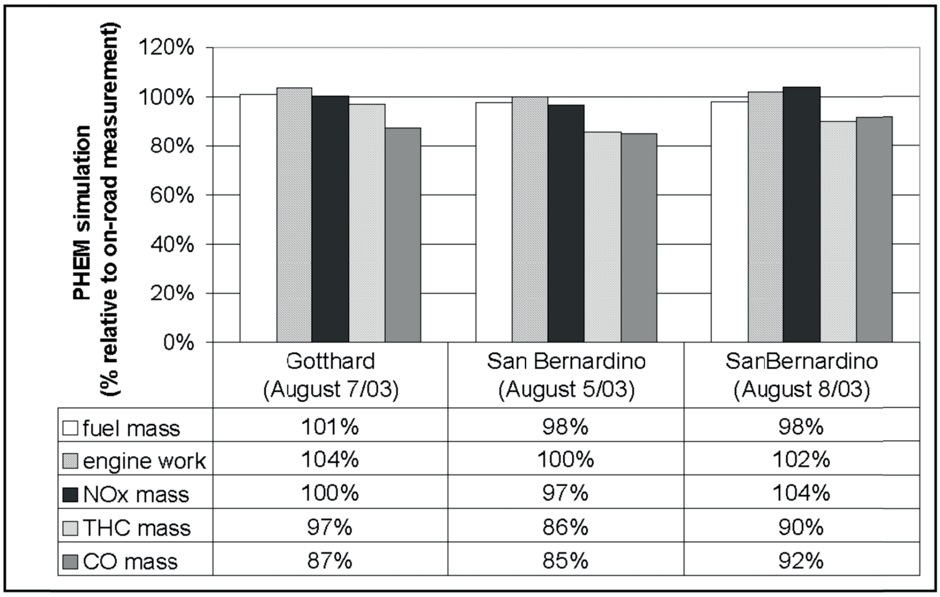


FIGURE 12 VALIDATION RESULTS FOR PHEM, SORUCE: (BOULTER AND MCCRAE, 2007 P. 140 FIGURE B5-8)

The results for THC and CO were within 15% of the measurements.

Real world studies of emissions can be conducted using road tunnel studies. Hausberger et al. (2003) presents a comparison of measurements and calculations where PHEM used an observed driving cycle. The PHEM model gave realistic results. The calculation and measurement of NO_x is within 1.5% for uphill direction (+1% grade) and within 1.7% in downhill direction (-1% grade).

A comparison between on-road emissions measured by remote optical sensing and HBEFA 2.1, ARTEMIS 0.4d and COPERT 4 showed an underestimation of NO_x emissions for Euro III and Euro IV HDV's (Sjödin and Jerksjö, 2008). No Euro IV HDV vehicles were available when the ARTEMIS HDV emission factor data base was built thus emission control technologies for Euro IV and Euro V had to be assumed. This could be one reason for the emission underestimation. Another could be the measurement technique. It would be interesting to see the equipment tested against vehicles in dynamometer and on fixed driving cycles and ordinary measurement techniques.

2.5 RAIL EMISSIONS

The ARTEMIS project has developed a rail model for calculating emissions from rail transport. The model is built within a Microsoft Excel sheet. The rail model is capable of calculating emissions from freight and passenger trains. The ARTEMIS final report gives an overview of the rail calculation methods. Calculation details are documented in Lindgreen and Sorenson (2005b), Lindgreen and Sorenson (2005a). The model developed in ARTEMIS was to use simple input data. The "simple" input is an operating matrix. An operating matrix is a table of speeds and accelerations. This matrix is then in turn turned into a spatial or temporal distribution. The temporal or spatial distribution is then multiplied by the driving resistance to get energy consumption. Driving resistance is the sum of rolling resistance and air resistance, hence the energy needed to keep the train moving. Then emissions are calculated from the energy usage.

This type of model will limit the usage to looking at measures that affect the operating matrix. Thus there is a need for a model to calculate the effects of measures on the operating matrix. For reporting emissions at the national level a model based on an operating matrix is ok, but it is not detailed enough for the company level. A typical question at the company level could be: What happens if the number of stops on a rail stretch was reduced from five to three? What is the environmental consequence of switching freight trains off the main line in order to give priority to passenger trains? The ARTEMIS rail model does not have the required operating matrix for Norway.

A more detailed model is needed to answer these questions. Lindgreen and Sorenson (2005b) contains detailed calculation routines for energy usage based on energy equations. The calculation routines are based around three main types of resistances that trains need to overcome; aerodynamic resistance, rolling resistance and gradient resistance. Train weight is an input to the rolling and gradient resistance functions, thus train loading will have an effect on the amount of energy needed to move the train. Curve resistance is left out because of the very detailed input requirements needed to calculate this resistance. Based on the documentation in Lindgreen and Sorenson (2005b) and Lindgreen and Sorenson (2005a) it is possible to develop a simplified rail energy consumption model that takes average gradients, speed and accelerations into account. This type of model assumes that there are no energy losses due to breaking on steep slopes. Thus energy usage will be systematically underestimated especially if there are steep slopes.

2.5.1 Information on train energy usage in Norway

According to Lukaszewicz (2001) there exists quite a few computer programs that calculate running time and energy usage. The programs are developed by traffic operators and train suppliers and availability of documentation is limited. There exists software for running time calculations in Norway. One such program is TogKjør. This program uses energy equations as a means of calculating running time. According to a master thesis Monsen (2006), TogKjør has the ability to use railroad horizontal and vertical curvature, tunnel data, speed limits, locomotive type, brake percentage and train type. Driving resistance is the sum of gradient-, curve-, rolling- and air-resistance. Technical staff in CargoNet, a Green Freight Transport project partner, knew of the software and had used results from it for energy estimates on the railroad stretch from Trondheim to Bodø for diesel trains. At present staff in the Norwegian national rail administration is able to run the software.

By law, the Norwegian National Rail Administration is obliged to charge the train operators for their energy usage and sell energy to the train operators at cost price. The principles for energy accounting are presented in Jernbaneverket (2006). What is interesting about this document is the amount of information that can be collected. The energy meters use GPS for positioning, and for the most detailed energy meters five minute intervals with energy usage are available. The energy recorded by the meter is from the pantograph; this is where the energy leaves the catenary (overhead electric wire) and enters the locomotive. If regenerative braking systems are utilized energy is returned to the catenary and the energy is subtracted from the energy used. There are three ways to record energy usage for running trains:

- Traction units with energy meter with time and position fix.
- Traction units with energy meter without time resolution.
- Traction units without energy meters.

In the beginning of 2010 CargoNet had installed energy meters on several of their locomotives. The energy meters installed in the CargoNet locomotives have time and positional data recording for trains. Reporting is done electronically and historical data is available from a division in the Norwegian National Rail Administration called Bane Energi. Bane Energi has access to train data and can provide information on the train and weight of freight on the train.

For traction units with no energy meter installed simulations have been done to calculate average train energy usage. A software tool called SIMPOW TRACFEED was used for the simulations. In addition several internal sources in Norwegian National Rail Administration were used to create the energy consumption factors (Jernbaneverket, 2006). The factors take the form of kWh/GTKm.

The energy consumed by the locomotive is not the same type as the energy available from the public power grid. In Norway and Sweden trains run on a 16 2/3Hz 15kV electrical system. Thus energy has to be taken from the public power grid and converted into the type used by the trains. For the southern part of Norway the loss is said to be 16.5% for the long distance cables and converter stations. In addition there are losses in the catenary lines of about 5.3% according to Jernbaneverket (2006). The train operators are billed for the energy losses between the public power grid and the locomotive. Thus train energy usage should include all losses after the energy leaves the public energy grid. Chapter 2.2 in Andersson and Lukaszewicz (2006) gives a good introduction to the power supply and losses for electric trains in Norway and Sweden. Figure 13 shows an overview of the Swedish power supply to the railroad network. The Swedish rail energy system is much like the Norwegian system, thus this figure can illustrate the Norwegian system.

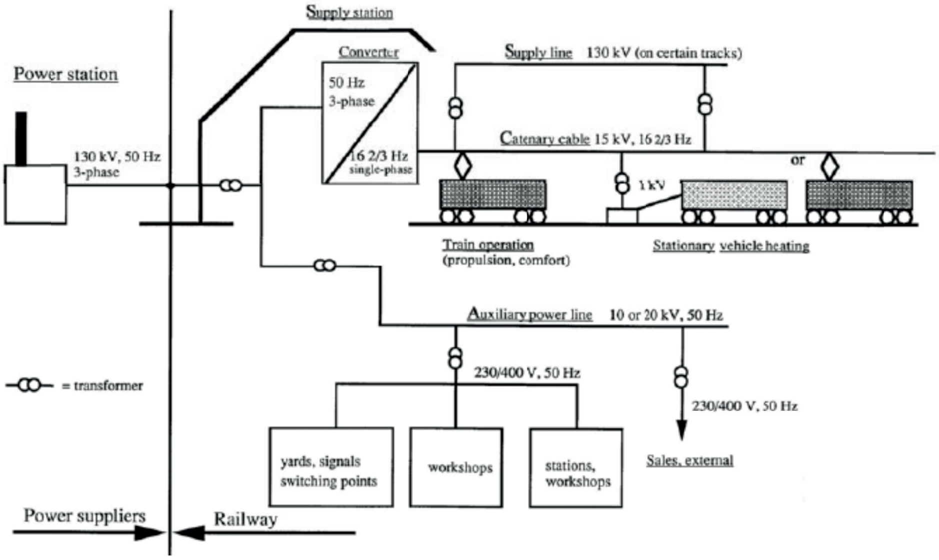


FIGURE 13 OVERVIEW OT THE SWEDISH RAILWAY POWERSUPPLY SOURCE: (ANDERSSON AND LUKASZEWICZ, 2006)

The rail model in ARTEMIS is a bit coarse for use at company level. But the rail sector, at least in Norway, is heavily regulated and has electronic reporting routines for trains including gross train weight. Both the Norwegian National Rail Administration and the train operator CargoNet has access to data on energy used and gross weight of trains. CargoNet runs mostly system trains with a stable wagon configuration on the Norwegian rail network. This should enable them to build their own emission factors for future use, and it should enable them to calculate energy usage factors for conducted transports. It should be possible to estimate separate factors for each train in their schedule. This could bring about data on the true cost of assigning priority between passenger and freight trains.

Energy consumption in the ARTEMIS model was calculated within 15% of measured values for passenger trains and somewhat higher for freight trains (Boulter and McCrae, 2007).

2.5.2 CONVERTING ENERGY USAGE INTO EMISSIONS

Using energy-based calculation routines returns energy used and not pollutants emitted. Thus the amount of energy has to be multiplied by a fuel specific emission factor. In the ARTEMIS rail model the emission factors are documented in the sheet "Emission_factors." There are two traction types, electric and diesel. For diesel the factors are the same for all countries. For CO_2 and SO_x that are only dependent on fuel attributes this makes sense as long as the fuel is the same. But it assumes that diesel train operations have the same characteristics in all the countries, since the emission factors for NO_x, PM and HC are the same for all countries. Table 4 presents the emission factors for train diesel engines developed as part of the MEET project.

TABLE 4 FUEL SPECIFIC EMISSION FACTORS FOR DIESEL TRAINS IN EUROPE, SOURCE: (JØRGENSEN AND SORENSON, 1997 CH. 10, LINDGREEN AND SORENSON, 2005B P. 16, EUROPEAN ENVIRONMENT AGENCY, 2009, FLUGSRUD ET AL., 2000 P. 23)

Pollutant	Emission factor (g/GJ)	Emission factor (g/kWh)	Emission factor (g/kg)	Range (g/kg)	EEA 2009 (g/kg)	SSB 2001/1 (g/kg)
CO_2	74440	640	3180	3180	3140	3170
CO	250	3.9	22	5 – 40	10.7	11
NO_x	1320	10.7	53	30 – 70	52.4	47
SO_x	90	0.80	4	1 – 10		0.8
HC	70	2.0	11	3 – 25		
PM	80	0.6	3	1 – 6	1.44/1.37 (PM_{10}/$PM_{2.5}$)	3.8

Jørgensen and Sorenson (1997) is the source of diesel fuel emission factors used in ARTEMIS. Chapter 10 in Jørgensen and Sorenson (1997) looks at Danish, Austrian, French, British and American emission factors. The reason for the variance in SO_x factors is different sulfur content in the fuels used. The range of the emission factors indicates that there could be considerable uncertainties in the emission factors. The last column in Table 4 presents the emission factors found in the EMEP/EEA air pollutant emission inventory guidebook 2009 edition (European Environment Agency, 2009). The factors in the EMEP/EEA guidebook is in turn based on a rail diesel study (Halder and Löchter, 2005) commissioned by the International Union of Railways (UIC) which is used as a source in EcoTransIT. What is interesting in the 2009 guidebook is that they present general diesel emission factors and that they also differentiate between locomotives. Emission factors for three groups are presented: line-haul locomotives, shunting locomotive and rail cars. This differentiation allows for more detailed studies and for more accurate emission studies to be conducted around terminals where there is a high degree of shunting activities.

"Cycle beating" could be a problem when generating emission factors for train diesel engines, as it is for cars and trucks. But the age of existing locomotives indicate that they are pre electronic fuel injection. CargoNet is leasing a new locomotive (CD 312) the Vossloh Euro 4000 which features electronic fuel injection and hence cycle beating could occur.

TABLE 5 FUEL SPECIFIC EMISSION FACTORS FOR DIESEL TRAINS, SOURCE: (KNÖRR ET AL., 2010)

Fleet	NO_x (g/kg)	NMHC (g/kg)	PM (g/kg)
Different European Railway Companies, 2001	40 - 70	1.8 – 5.7	0.6 – 5.0
UIC Rail Diesel, main locomotives (2005)	64.7		1.15
DB 2008	48.3	4.63 (HC)	1.35
Canada 2003	63.9	2.8 (HC)	1.4
Default Eco-Transit World 2010	48.3	4.63	1.3

A collection of emission factors are found in the EcoTransIT documentation. The emission factors are presented in Table 5. For PM and HC the EcoTransIT emission factors are in the lower region of the range found in Jørgensen and Sorenson (1997) and thus quite a bit lower than the ARTEMIS emission factors. While for NO_x the emission factor used in ARTEMIS and EcoTransIT are quite comparable.

By measurement it is possible to figure out which emission factors are correct for diesel locomotives. While for electric locomotives measuring emissions is not possible. Electric locomotives have no direct emissions to measure. The emission will occur where the electricity is produced. The power that the Norwegian national rail administration buys and sells to the train operators come from the public power grid. The Norwegian power grid is connected to neighboring countries like Sweden and Denmark. And in 2008 a new transfer plant and accompanying subsea cable was opened in Kvinesdal that links the Norwegian power grid to the grid in the Netherlands. Even if almost all energy production in Norway comes from hydroelectric power it cannot be categorically concluded that power used from the Norwegian grid is emission-free. In (Andersson and Lukaszewicz, 2006) three different views are presented on electrical emission factors: Nordic market, Green electricity and marginal. It is unclear which emission factors are the correct ones to use, and within the scope of this Ph.D. project the goal was to focus on measures that companies have control over. So for estimation purposes it is sufficient to select one set of emission figures and document which factors were used. It is likely that the emission figures will change in future for Norway. Appendix D shows CO_2 emissions for the different sectors in Norway. The figure shows a clear increase in the amount of CO_2 emitted from the production of electricity beyond the year 2005. If the CO_2 increase comes from combustion of fossil fuels then one should see an increase in the other emissions.

TABLE 6 EMISSION FACTORS FOR ELECTRIC TRAIL, SOURCE: (ANDERSSON AND LUKASZEWICZ, 2006, KNÖRR ET AL., 2010)

Source	CO_2 (g/kWh)	NO_x (g/kWh)	CO (g/kWh)	HC (g/kWh)	SO_2 (g/kWh)	NMVOC (g/kWh)	PM_{10} (g/kWh)
EcoTransIT	0.006	0.018			0.008	0.003	0.013
Nordic market	96	0.208	0.014	0.001			
Green Electricity	0.07	0.00027	0.0019	0.00026			
Marginal	0	0	0	0			

In a report by Statistics Norway a table of CO_2 emissions related to different assumptions was presented in Toutain et al. (2008 p. 17 table 2.2). The data from this table is reproduced in Table 7 along with a translation of the production assumption.

TABLE 7 CO_2 EMISSIONS FROM THE PRODUCTION OF ELECTRICITY, SOURCE: (TOUTAIN ET AL., 2008 P. 17 TABLE 2.2)

Production assumption Norwegian description	English description	Emission factor CO_2 (g/kWh)
Vannkraft	Hydropower	0
Norske elektrisitetsmiks (2004)	Norwegian mix (2004)	7
Nordisk elektrisitetsmiks(Nord Pool 2006)	Nordic mix (Nord Pool 2006)	200
Europeisk elektrisitetsmiks, gjenomsnitt OECD-Europa (2004)	European average mix (OECD-Europe 2004)	357
Gasskraft på marginen	Gas power plant on the margin	400
Kullkraft på marginen	Coal power plant on the margin	1000

In ARTEMIS the emission factors for electric power are different for every nation. Norway is not included in the ARTEMIS rail model and thus it is not possible to use electrical factors from ARTEMIS. Factors from EcoTransIT and the EMEP/EEA guidebook are a more likely source of emission factors for Norway.

The ARTEMIS model for trains was able to calculate NO_x with the same uncertainty as energy consumption, about 15%. While CO, HC and PM were estimated within 25-30% using the average factors (Boulter and McCrae, 2007).

2.6 Sea emission

Like the rail emission model the sea emission model has received less focus than the road models. It is not to say that little has been done in terms of reducing emissions from ships, but the methodology for emission calculation offered is coarser than for road. According to the detailed report on maritime transport only 2% of the EU funds spent on environmental research are spent on the sea transport sector. And heavy-duty road vehicles get 80% of all the research funds (Sjöbris et al., 2005). The conclusion of chapter E in the ARTEMIS report (Boulter and McCrae, 2007) begins with: "The quantification of emissions from maritime shipping can still be regarded as being in its initial stages." The estimation routines presented in ARTEMIS build on five previous works: the MariTerm studies, the MEET Model, the TRENDS model, the SMED study and the ENTEC study. A central source of information about sea or maritime emissions is the Lloyd's Register – Fairplay that have begun to include environmental data in their register[18].

The model developed is based on data from the Lloyd's Register – Fairplay. Data from 45,000 ships were used in building the model. Within the ARTEMIS project two models were built, one simple and one more elaborate. The first part of the ARTEMIS maritime project was to re-evaluate shipping categories. Table 8 is taken from the ARTEMIS final report and lists the ship types along with a short description. For Norwegian domestic freight transport many of the ship types can be found, except for type 12 and 8.

The simple model for maritime emissions is a table of the twelve ship types with ship size as a sub category. The emission factors take the form of gram pollutants per DWT per day or gram pollutants per GT per day. Dead Weight Tonnage (DWT) is a measure of how much weight a ship can carry safely. While Gross Tonnage (GT) is a constructed number related to the enclosed volume of a ship. The more detailed method uses tables to look up parameters based on GT or DWT. The model has four steps and two extra steps. The last two steps are the same for both the simple and the more elaborate model. The detailed model is as follows:

1. Determination of average speed
2. Determination of main engine power output
3. Identification of engine type
4. Estimation of fuel consumption and emissions
5. Emissions associated with auxiliary engines
6. Effects of emission abatement technologies

An alternative source to the ARTEMIS project could be emissions presented in Bjørn Foss et al. (2007). Fuel consumption for general cargo ships is found in this report. The problem is that in the report are based on tonnes of fuel used per day and is thus very general. The fuel per day number includes loading/unloading operations and fuel used when lying in port. Thus the model is coarser than the detailed ARTEMIS model.

Another source of emission factors could be found in Toutain et al. (2008 p. 30 table 2.30) where a table of average emission factors for ferries, high speed passenger boats and the coastal express for 1993, 1998 and 2004 using marine gas oil (MGO) is presented. These factors could be used for checking the ARTEMIS model results.

[18] http://www.sea-web.com/about.html

The problem with the ARTEMIS maritime model is that it is not very sensitive to factors under the control of single firms. The emissions are insensitive to the weight of freight carried and time in maneuvering phases. If one has detailed fuel consumption figures for a specific ship it could be preferable to use these. The database is built up of average emission factors. On the other hand the main engines might have been retrofitted after installment and hence original emission factors are not the correct to use. One example of retrofitting technology is direct water injection (DWI) which reduces combustion temperature and reduces NO_x emissions by injecting water into the cylinders.

TABLE 8 ARTEMIS DESCRIPTION OF SHIP TYPES, SOURCE: (BOULTER AND MCCRAE, 2007 P. 250 TABLE E-2)

	Ship type (alternative name)	General description
1	Bulk ship (bulker)	Free-flowing dry bulk of all types and of low value.
2	Dry cargo (general cargo)	All types of unitised cargo (non rolling), free-flowing bulk, project cargo, *etc*. Average ship size about 3,500 DWT, handling smaller quantities - in many cases directly to industries.
3	Container	Traditionally high-value cargo. Containerisation results in a widening of the range of products handled. Mainly palletised and unitised cargo, but can be everything from digital cameras to bags of fertilizer.
4	Ro-Ro	Road vehicles and rolling terminal vehicles carrying unitised cargo or cargo units. Medium-to-high value cargo.
5	Reefer	Refrigerated or temperature-controlled cargo on pallets/hanging or unitised. Mainly food. To a large extent, losing market to container ships.
6	Cargo ferry	Normally a Ro-Ro ship having passenger capacity, usually operating between two ports only.
7	Passenger ferry (non-cargo ferry)	Smaller ship (*e.g.* for servicing islands or crossing rivers) having passenger carrying capacity. Takes various forms, depending on the market. Service speed less than 30 knots.
8	High-speed ferry (fast ferry)	Cargo and passenger ferries with a stated service speed greater than or equal to 30 knots.
9	Tanker	Oil tankers carry crude oil. Product tankers carry various types of refined oil products, and have smaller tanks to carry different products at the same time. Chemical Tankers are built to carry oxidising and hazardous products in smaller, specially coated tanks, and are often found competing in the product tanker market.
10	Gas tanker	LPG and LNG tankers, carrying liquified gas under pressure.
11	Cruise vessel	A ship that carries only passengers.
12	Vehicle carrier	A Ro-Ro ship specially designed for the shipping of new cars. Some larger vessels can handle large, rolling cargoes on a number of decks.

The ARTEMIS methodology is state of the art at the time of writing, but there are some other interesting developments. Currently the Norwegian Coastal Administration (NCA) is developing an emission accounting system that uses Automatic Identification System (AIS) data as measure of activity. The AIS is a system for tracking ships introduced by the International Maritime Organization (IMO). The AIS system transmits data packets that other ships in the vicinity can receive. The data packet contains information on vessel speed, bearing, position, ship identification, ship category, dimensions, destination and estimated time of arrival (ETA). Some of the information is taken directly from onboard systems, such as speed, while bearing and position are usually taken from the GPS. Other information like destination is entered manually into the system. A technical description of the system is available in International Telecommunication Union (2010), while a brief introduction in English is available on the U.S. Coast Guard's Navigation Center pages[19]. A brief Norwegian introduction is available on the Norwegian Coastal Administration's (NCA) website[20]. Figure 14 shows input data to the calculation of emissions to air and other emissions from ships in Norwegian waters.

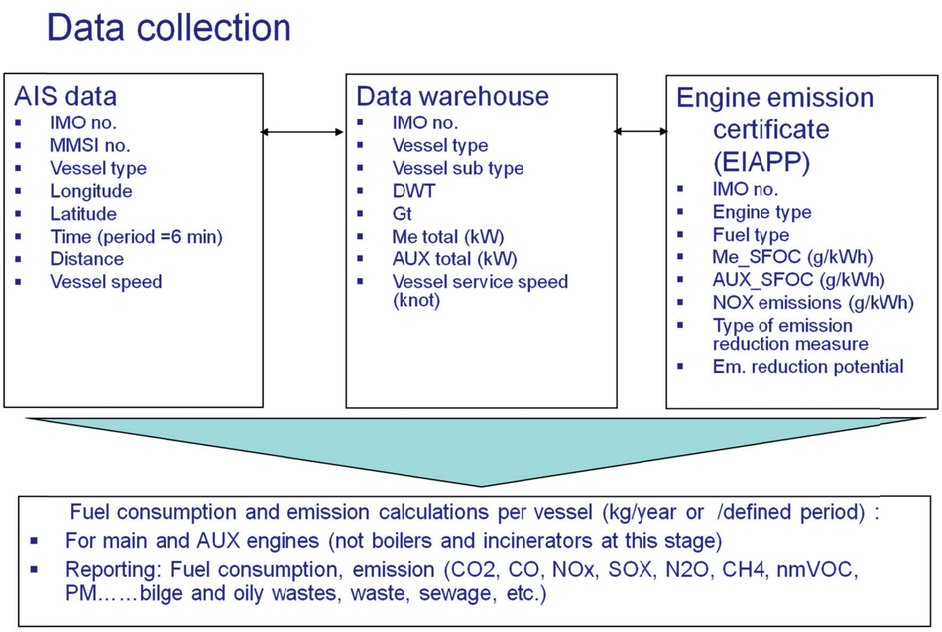


FIGURE 14 DESCRIPTION OF DATA USED IN THE AIS BASED EMISSION CALCULATIONS, SOURCE: KYSTVERKET – JON-ARVE RØYSET

AIS is normally used for ship to ship communication, but land-based listening stations are set up to collect data on ship movements. In total there are thirty-nine listening stations along the Norwegian coast. The listening stations give quite good coverage, but there are some black spots where no data from the ships can be received. The calculation tool uses the data collected from the listening stations and combines this with other data sources that the NCA has access to. Thus data on ship movements, ship type and engine emission certificate can be extracted. The linking of databases is

[19] http://www.navcen.uscg.gov/?pageName=AIS
[20] http://www.kystverket.no/?aid=9030961

possible through the IMO number. The IMO number is a unique number that follows the vessels hull, and is mandatory for vessels over 300 GT. Using this system it should be possible to calculate emission factors for a fleet of ships. The strong point of this calculation method is that it will have up-to-date information on the ships and their activity.

According to Jon-Arve Røyset at the NCA, fleet level calculations were available, but permissions from the ship-owners were needed if single ship data was to be used. We attempted to get permission to monitor a ship chartered by TPG, but this effort was unsuccessful.

Ship emissions in Norway can be calculated with the ARTEMIS method, but due to the diversity to the ship fleet detailed data on the ship has to be collected for each ship. The three most important pieces of data to collect are: engine type; fuel type; and emission abatement equipment. If cruising speed is available then this should be collected.

No measure of uncertainty is given for ship emissions. There is a note on the methodology and that relates to the use of average populations. If a ship is close to the center of the population then calculations for that ship will tend to be more accurate (Boulter and McCrae, 2007 p. 263). The emission factors relating to fuel consumption are collected from the engine manufacturers, but only data for vessels delivered on or after 1980 were used (Sjöbris et al., 2005 p. 42). Thus for ships pre-1980, caution should be used as engine emission factors might not be included.

There are NO_x emission standards for ships as defined in MARPOL 73/78 Annex VI. The standards came into force in 2000. The emission standards are knows as Tier I, Tier II and Tier III. Tier I is retroactive for some engines with rated output over 5000 kWh and single cylinder volume over 90 liters built after 1990 (DieselNet, 2010).

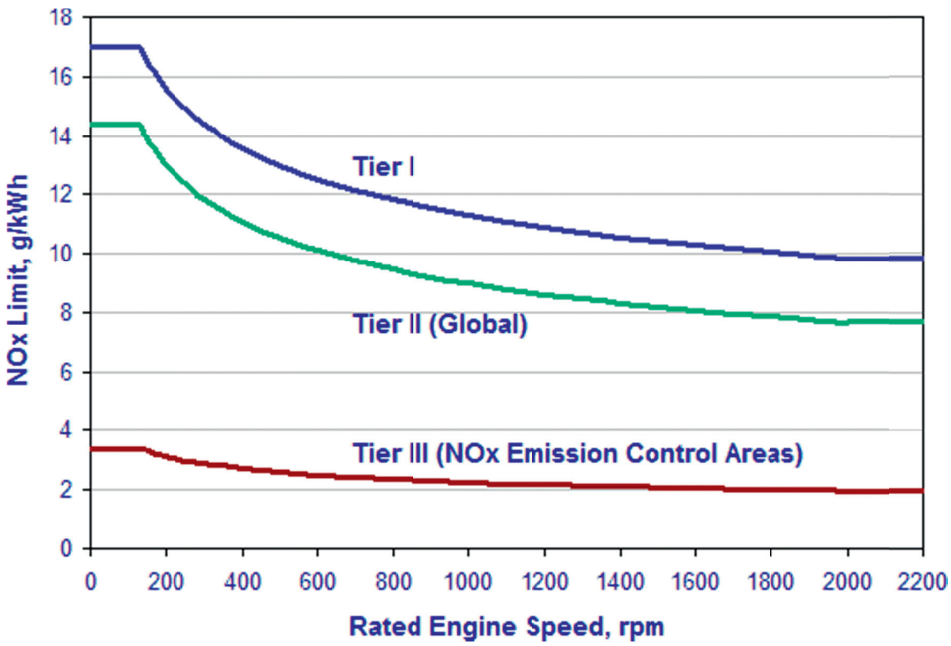


FIGURE 15 IMO NO_X EMISSION STANDARDS, SOURCE: (DIESELNET, 2010)

The Tier II regulation is for rapid running engines (1700-2200 rpm) and is at the same level as Euro I emission regulation for road vehicles that entered into force in 1992. Tier III was expected to be put in force for new engines in 2011.

2.7 SUMMARY

Emission factors for freight transport exist. Weight and distance dependent emission factors are the most common for freight transport. This is probably due to the ease of use with these emission factors. Only three pieces of information are needed to generate an emission figure: weight of goods; distance; and technology used for the transport. These factors are able to generate large scale emission figures for use in national inventories. But these emission factors are not well suited for applicable measures at the company level. For example, if one wants to look at routing of freight trucks then the only parameter that will influence routing is distance. Thus one must assume that distance traveled in urban areas and in rural areas will result in the same amount of emissions. For the road transport this has been proven to be incorrect. Emissions from road vehicles are highly dependent on vehicle speed and traffic conditions as well as road gradients.

For road vehicles there is much information available especially for passenger cars. But there has also been a focus on heavy-duty vehicles. A major breakthrough in heavy-duty vehicle emissions is the use of emission modeling based on engine emission and fuel consumption maps. Within the ARTEMIS project 11,970 average speed emission curves were developed based on close to 170,000 emission factors. For heavy-duty vehicles it is possible to calculate emissions based on vehicle technology (Euro class), vehicle loading, average speed and gradient. If ARTEMIS heavy-duty emission functions are to be used in Norway then one must assume that driving behavior is the same in Norway and Europe.

Emissions from rail transport are coarser than for road transport. Emissions are based on energy calculations and distributions of speed and accelerations. The final model developed in ARTEMIS is available as a spreadsheet. Rail data for Norway is not included in the ARTEMIS model. Emission data from rail diesel engines are available from several sources. Emission factors from electrified rail are available according to different perspectives on the production sources involved in powering the Norwegian national grid.

For sea transport the emission factors are built from statistical averages and emissions collected from engine manufacturer when available. This has some implications for ships that are off the average, as results will tend to get distorted. The ARTEMIS project presents two models, one based on a single table lookup and the other based on a more elaborate set of table lookups. There is work on alternative model in Norway that uses ship data from international registers for vessel and engine, and combines this data with AIS data. The system developed by the Norwegian Coastal Administration could be used to generate single ship emission factors.

The search for emission factors revealed there are detailed emission factors available. The search has mainly focused on European sources of emission factors due to legal requirements for engines set in the Euro standards. For ships' emission, the module is based on the world fleet. For ships the emission regulation is valid for the whole world, at least for the countries that have ratified MARPOL 73/78 and its relevant annexes.

The challenge with using emission factors that are dependent on more than weight and distance is the availability of input data. There will be a trade-off between available input data and detail level of emission function. The challenge of getting high quality input data will be explored in the next chapter.

3 MODEL DESIGN AND INFRASTRUCTURE DESCRIPTIONS.

This chapter focuses on key issues of model design in conjunction with an assessment of available infrastructure descriptions. The previous chapter provided knowledge of emission factors and function that could be used in the model. The next step is to decide on a model structure and then choose suitable input data to utilize the emission factors and functions found in the previous chapter. Thus the existing geographic data will be explored to learn about the quality of the data and possible issues in using the data. Having geographic data for only one country may seem limiting, but from a computational perspective this is quite an achievement. The state of the art transportation model for Norway is divided into five regions to make runtimes acceptable. Thus building a national model will be challenging. If this model is to be a success then it could be expanded to other countries that have digital infrastructure descriptions. And the national models could be linked together similarly to how regional transport models are linked together.

In the process of designing a model it is important to think of the end user. A goal of this Ph.D. project is to give freight transport companies a tool to calculate the environmental impact of their operations. Thus the users will most probably not be part of the scientific community, and may put too much trust in models developed by the scientific community. Thus if model results are uncertain then it is important to communicate this uncertainty to the users. And it is at this point that nomenclature gets challenging, a common way to express that calculations are uncertain is to say that the calculations provide an estimate. The Oxford Advanced American dictionary defines to estimate as: “to form an idea of the cost, size, value, etc. of something, but without calculating it exactly.” Thus the results of the model should be viewed as emission estimates. The choice to describe the model results as estimates does not imply that the quality of the model results is more inaccurate than other tools. The terms calculate and estimate emissions are used interchangeably in emission literature, but this is an attempt to separate the two and to give the user a notion if important input values are measured or assumed. In this sense both EcoTransIT and NTMCalc provide the users with estimates of emissions.

From the ARTEMIS final report one can see that emissions functions are quite uncertain, for ships no uncertainty was given, for rail 15% uncertainty was given for energy calculations and for the most detailed road model fuel consumption was within 2%, but for THC and CO only 15% accuracy was achieved (Boulter and McCrae, 2007).

A user-needs assessment was carried out in the Green Freight Transport project to get a better understanding of freight transport companies’ environmental agenda. Every company answered that environmental issues are important for the company’s operations. The companies expected that environmental issues were to become more important in the future. Most of the companies did have some sort of environmental management system, but they wanted to improve this (Lervåg, 2009). The user needs assessment had some pointers on the development of a new tool for estimating emissions. From a company perspective the use of Life Cycle Assessment (LCA) was not important, half of the interviewed thought that LCA was a bit important while the rest said that LCA should/could be left out. This is to be expected since close to 60% wanted to be able to calculate the effect of different environmental measures that the company could implement. The user needs assessment showed that there was a wish to differentiate between global warming emissions and other pollutants.

The project partners expressed their wishes for the tool in several workshops during the first years of the project. There were few absolute requirements except for that only air emissions were to be covered and three modes were to be included; rail, road and sea. A point that the project group expressed was fairness; the tool should give a fair representation of the different modes.

From a scientific perspective building yet another environmental calculator was not the most satisfying. One worrying view that was uncovered in the user-needs assessment was why the environment was so important. The top reason for having an environmental management system for a freight transport company was that focus on the environment could serve as a competitive advantage. From a cynical perspective this could indicate that they were looking to satisfy customer request rather than looking at how they can improve their environmental performance. The user-needs assessment was used as a guide when developing the calculation.

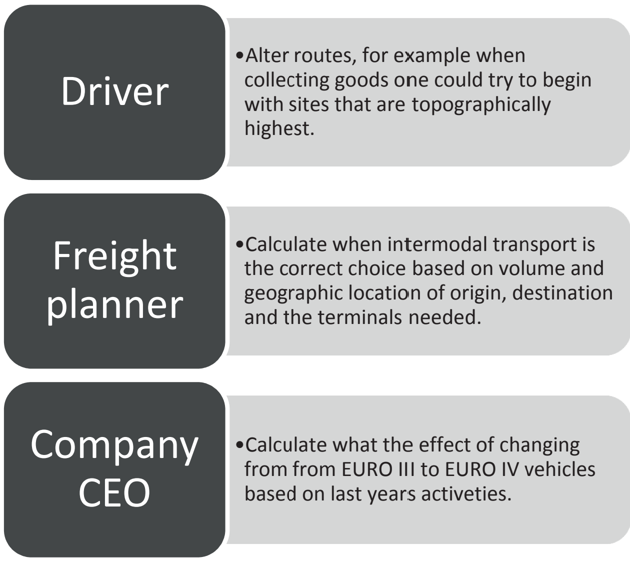


FIGURE 16 EXAMPLES OF MEASURES AT DIFFERENT LEVELS WITHIN A FIRM

It would be more gratifying from a personal and scientific perspective if one was to create a new emission model that would encourage a genuine interest in reducing emissions. A genuine interest in this context would be that every worker could check measures she/he experimented with and see if it made a difference. This is a tall order because it means that usage of the calculation routines will have to fit every level in the firm. Figure 16 shows some examples of measures that could be evaluated for workers at different levels within the firm. To be able to answer these questions one needs quite detailed calculation routines, but one needs ways to aggregate the detailed calculations.

Traditional top-down methodologies that are applied in the national inventories could be applied. But this would require companies to build their own energy usage factors at a very detailed level. If fuel accounting was used, then fuel usage has to be linked to the different activities. The level of detail in the activities would in the end determine the quality of the emission factors. The more detailed the emission factors are the more versatile the emission factors would be. Activities for road need to differentiate between driving collection/distribution routes and long-haul routes and for different loadings. To estimate the impact of the first measure in Figure 16, gradients have to be included in the activities and be used for estimation of emission factors. A very detailed list of activities would create many emission factors because real-world driving would consist of combinations of activities. Estimation of emission factors has to be done for each company unless general factors are to be used. The benefit of such an approach is that one gets control over the totals, at least for the pollutants that are not dependent on engine operating conditions. CO_2 and SO_x are such emissions. A big negative side of this approach is that the user has to have experience with the technology to be able to calculate the consequences. For example if hybrid vehicle was planned for a distribution route then there would be a need to try the vehicles out to get emission factors or get emission factors from other companies that already use the technology on a similar route.

The alternative approach is to use a bottom-up methodology. This means to find the most detailed emission factors and functions available at vehicle level, and use these for calculations. And finally to aggregate results up to the desired level. This methodology will depend on detailed registrations from the companies in order to utilize the full potential. For example to utilize gradient dependent emission functions there is a need to know where the vehicles were driven and in what direction. If this information is not known then the alternative is to use assumptions to create general emission factors for specific areas. The larger companies in the freight transport sector have tracking systems that enable them to follow shipments with a large degree of detail. The challenge with a bottom-up approach is that the total will be wrong if all activities are not recorded. A typical omission would be emission due to repositioning at terminals or short trips that are taken without being recorded in the company databases. Another omission could be vehicle relocation without freight. But NO_X and PM estimates will probably be better in bottom-up models since it is capable of predicting engine operations better. The other benefit is that all users of the model will be using the same foundation for their calculations, but possibly at different levels of aggregation.

3.1 The model as a framework of modules

To create a durable tool to estimate emissions is challenging. New transport technologies will be coming and new emission standards will be put into effect. Thus much of the model contents, algorithms and input data are expected to change. Building a static tool will mean rebuilding the tool when changes occur. The alternative is to build the tool as a set of building blocks that are connected in a systematic way. One way to accomplish this is to build a framework which consists of code modules that can be modified or completely replaced when changes occur without affecting the tool as a whole. Thus the model could be broken down into smaller sub models where the interactions between the sub-models are controlled by the framework. Each of the sub-models should be created as computer executable code. A computer executable sub-model that includes the necessary parameters to perform calculations is referred to as a module.

The core of the envisioned model was to be a module capable of routing between origin and destination and analysis of the resulting route.

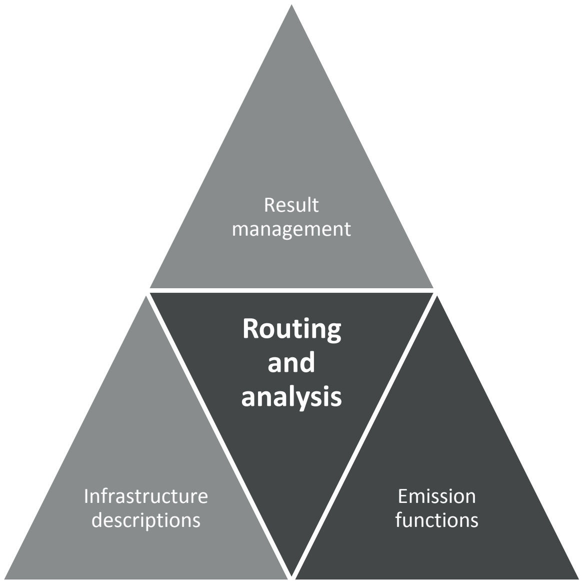


FIGURE 17 LAYOUT OF THE MODEL AS A FRAMEWORK OF MODULES

Figure 17 shows a schematic layout of the model framework, the core of the framework is the center triangle, routing and analysis. This part is built on top of two other triangles that provide input data, infrastructure descriptions and the emission functions. To make emission studies part of everyday operations, then results from calculations have to be adapted to the existing production system in the firms. Thus there is a section for result management in the top the triangle. The strength of this design is that all but the center triangle are able to perform useful actions. Infrastructure descriptions could be useful for other purposes such as illustrating the logistical networks. The emission functions could be used for generic calculations for example to calculate the difference in fuel consumption and emissions for a specific truck on different grades. Before the routing and analysis has been run then the results management module does not make much sense. But after a run, emission data for a specific network can be stored and used without the need for running the core routing analysis routines again. The lighter colored triangles represent triangles that are company specific, the darker colored triangles are generic. The infrastructure descriptions are based on public infrastructure and company logistical networks. Roads, rail and sea networks should be common for all users, but location of terminals and which parts of the networks that are utilized are specific to each company.

3.2 Software development

From the outset of this Ph.D. project it became clear that some software development would be needed. The search for emission functions did not turn up general software that could be used for the level of detail desired and specifically for freight transport. A mix and match of several computer applications could be an alternative, but this would not create a single unified model. Such an approach would lock the user into design decisions made by the original programmers. An alternative approach was to build software needed around an existing platform that could be heavily customized. Routing and analysis of routes is the core of the envisioned framework design of the model. These operations are commonly used in Geographic Information Systems (GIS). There are several providers of GIS applications, both commercial and open source. The ArcGIS platform was chosen for 2 reasons. The first reason was the existence of a routing extension that has a user friendly interface. The second reason was that the ArcGIS platform supports Python[21] as a means of extending platform functionality. Python is a high level programming language with an extensive amount of routines available in the standard library. This allows for efficient programming and for scientists to focus on the problem to solve and not the code needed to solve the problem.

The design decision was to develop a model based around the ArcGIS and Network Analyst platform from Environmental Systems Research Institute, Inc. (ESRI). The extensions needed would be programmed in Python where possible. A benefit of using Python is that it is an interpreted language and thus the source code will be available to the user. Releasing the source code as the application will allow expert users to modify the routines and to use the routines for other purposes. Open source makes it easier for outsiders to find bugs and logical errors in the code.

3.3 Input data – infrastructure

In chapter 2 a search for emission functions was conducted. Sources of potential emission function were identified. The most detailed and publically available functions were from the ARTEMIS project. To use detailed emission functions there is a need to have detailed input. To use the average speed functions for road emissions there is a need for infrastructure description that includes average vehicle speed, length and road gradient data. In this section we will look at developing an infrastructure description and adapting it to the logistic network used by TPG. Appendix B shows how GIS tools can be used to visualize and find errors in transportation networks. A GIS approach has been used before in Norway when building transport models for the whole country. The national and regional transport models for Norway use a GIS approach to coding transport networks to be used in highly specialized computer applications (Ness, 2006, Tørset et al., 2008).

In this Ph.D. project networks for road, rail and sea had to be built along with terminals. The terminals have an important role in freight transport networks because they are where mode changes, consolidation and splitting of freight can occur. A schematic of

[21] `http://www.python.org/`

the three networks is presented in Figure 18; the left figure shows a simplified representation of the networks. The figure on the right shows how terminals can be linked in. Some terminals are not located together and thus transport between the terminals is needed. Most often the public road network is used. But there are exceptions, especially when the terminals are located close to each other. At Alnabru, Norway's biggest rail terminal, two operators have the possibility to move freight from the road terminal to the rail terminal on a private road network. To cater for this terminal transfer, links have been created in addition to links to connect the terminals to the networks. This can be seen on the right side of Figure 18.

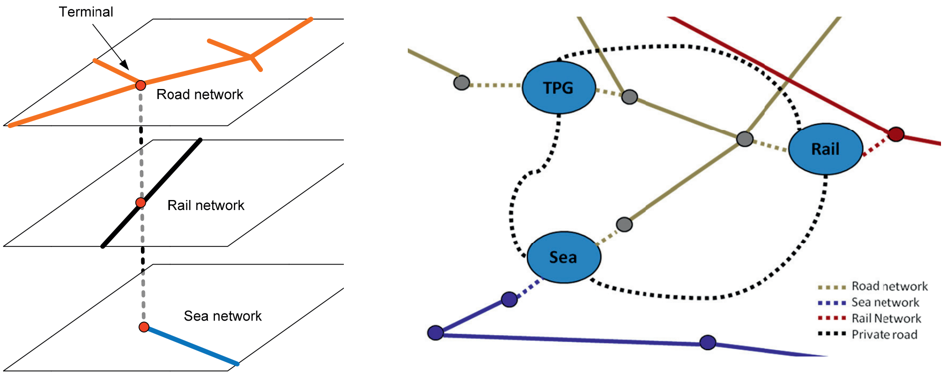


FIGURE 18 SCHEMATIC OF SIMPLE NETWORK AND NETWORK WITH TERMINAL CONNECTORS

3.4 NETWORKS

GIS tools can be used to transform the real world into computational models. An understanding of network theory is helpful for understanding freight transport emissions network analysis. The combination of roads, railways and fairways at sea constitute a network that can be used by different vehicles to move freight. One of the prime causes of air emissions from freight transport is distance, the longer freight is shipped the more emissions are associated with the shipment. Distance tables are one way of keeping track of distances between places. A distance table consists of origin and destination pairs and a measured distance between them. This is a quick way to find distances between two places. The problem is that the number of pairs grows at n^2-n. Thus a distance table between 430 municipalities in Norway would be 184,470 lines long. An alternative to distance tables is to use concepts from graph theory. A graph is a set of vertices connected via edges. From Figure 19 one can see the close resemblance between the graph and a map of the real world.

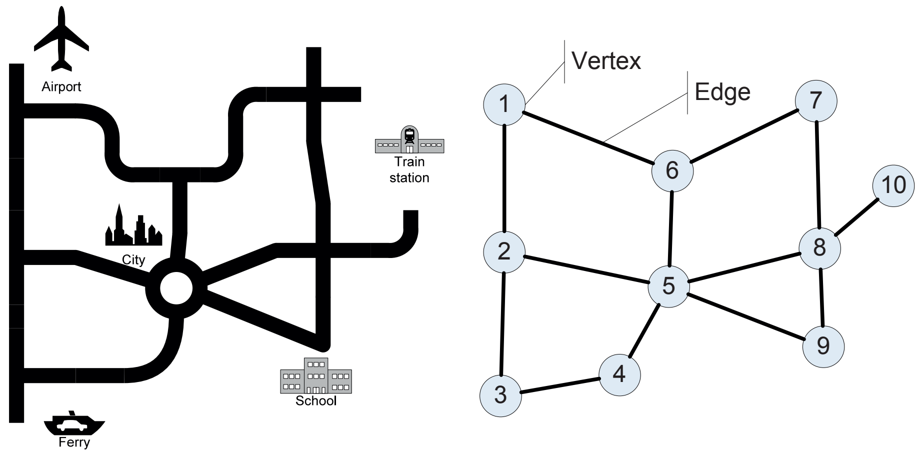


FIGURE 19 MAP OF ROAD NETWORK AND GRAPH OF THE SAME NETWORK

Edges in graphs can have weights; a weight could for example be the distance between two intersections in the map. In GIS nomenclature a vertex is usually called a node and the edge is called a link, while a GIS vertex is a point on a line where there is a change in the line geometry. The term network is used instead of graph. Links and nodes usually have more information connected to them; this additional data is often referred to as attributes. To measure the distance between the airport and the train station one could follow the road and measure the length via measurement tools available in the GIS application. But if the road network was converted to a graph then Dijkstra's algorithm could be used to find the distance between two vertices. Dijkstra's algorithm is the standard algorithm for finding the shortest path from start to finish in a network.

In the rest of this chapter, we will look at building networks from available georeferenced data. When building a network, links and nodes that share a common coordinate par are connected and a graph data model is built. The ArcGIS Network analyst is a tool for building networks from geographic features and for doing network analysis. ArcGIS network analyst has five types of analyses:

- Finding the best route
- Finding the closest facility
- Finding service areas
- Creating an origin-destination matrix
- Solving vehicle routing problems

Finding the best route is the most important, as this will find the shortest path from origin to destination based on link attributes. Finding the closest facility could be used to find the closest terminal from any point in the network. If one wants to build a distance table the "create an origin-destination matrix" is the tool to use. This tool will calculate the shortest path between all given points. The "Solving vehicle routing problems" is an optimization tool that utilizes information in the network to find optimal routes and sequence of stops. Network analyst allows for the integration of different networks by setting connectivity rules. And thus automatic intermodal routing is available to the users of the model if input data is available.

Building a network is not a one-time affair. Changes to the infrastructure will require networks to be updated with the changes. Lessons learned from usage of the national transport models indicate that delegated user updating of networks could be challenging. The tool that is developed within this Ph.D. project does not have a defined user group that could be given the responsibility of updating the network. An alternative choice is to look for sources that are updated frequently and create automated ways of building networks from these sources. Thus the update issue could be solved, and when updated infrastructure descriptions become available new networks could be built automatically.

3.4.1 THE RAIL NETWORK

The source of the rail network is the national rail databank. The Norwegian national rail administration has a database that describes the rail network. The data in the databank is mainly used for in-house computer applications developed specifically for the Norwegian national rail administration. Thus the problem was not if data existed, but if it could be exported to formats that could be read by off-the-shelf GIS applications. There were several attempts at getting a digital description of the rail network that included the elevation of the rail lines. But the export routines did not manage to export the elevation data that would be used to calculate railroad gradients. In the end a simplified rail network had to be built manually. The data exists in the databank, but the databank has a proprietary data format that links poorly with off-the-shelf software. Internal computer applications used in the Norwegian national rail administration use very detailed data, but it is believed that the program extracts data via a proprietary application programming interface (API).

The solution was to use the received track and split this into strategic sections between stations and to average grades to these sections. All rail lines in Norway are included in the module, but each line was assigned an attribute to indicate if the railway was used for freight transport. Lines that are not a part of the logistic network are not included when calculating routes. Figure 20 left shows the total rail network in Norway; the green lines indicate the railway lines are part of the CargoNet's system train logistic network. The map on the right in Figure 20 shows which lines are electrified.

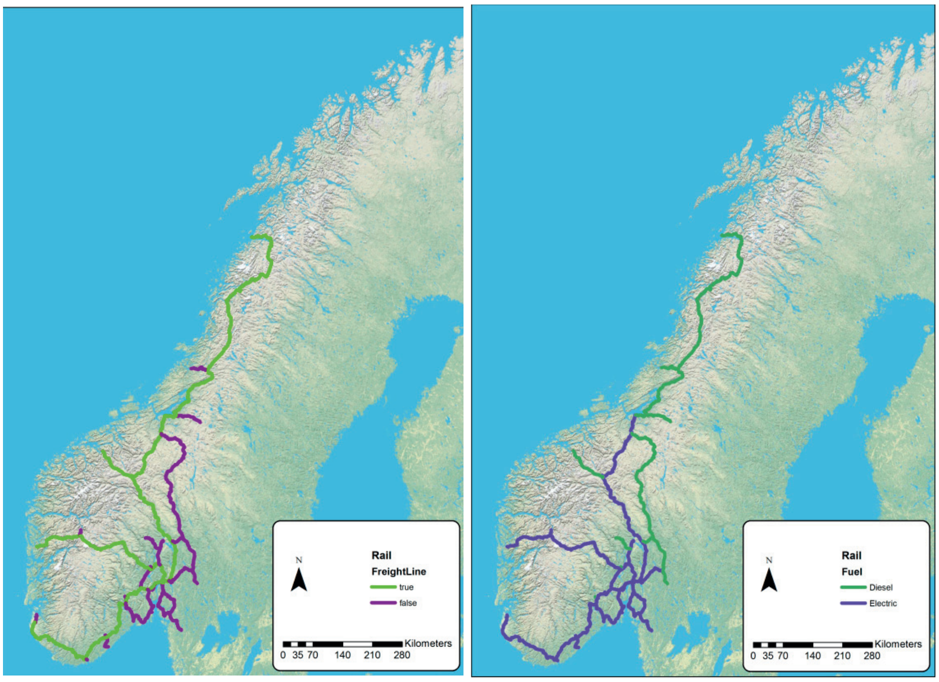


FIGURE 20 NORWEGIAN RAIL NETWORK, FREIGHT LINES AND ELECTRIFICATION

Diesel locomotives can run on electrical and non-electrical lines. Electric locomotives can only run on electrical lines. For the relation Alnabru – Åndalsnes, which has both electrified and non-electrified rail lines, it is important to check if a diesel locomotive has been used on the electrified sections.

One thing that can influence rail freight emissions is the number of stops due to passing trains. Most of the Norwegian rail network is single track and thus trains have to stop to pass. Table 9 shows train times and number of stops for some trains from Trondheim to Alnabru. There is quite a big difference in the number of stops for different departures, from 6 to 11 stops for the same route.

TABLE 9 FREIGHT TRAIN TIME TABLE

Train number	Departure time	Arrival time	Stops	Time stopped	Total Time	Avg. speed
5708	22:00	05:49	6	0:17	7:49	75.6
5730	23:25	07:49	7	0:50	8:24	69.4
5704	10:52	20:49	11	1:38	9:52	67.3

For trains the schedule was used as a basis for calculating average speed between key stations. As mentioned earlier the stations were chosen as to give fairly stable average gradients between the stations. Due to export problems from the national rail databank the coding and splitting job had to be done manually.

The time tables for freight trains were developed from “Grafiske togruter” (graphic train schedules) which are time distance diagrams for trains on the same line. “Grafiske togruter” are available from the Norwegian national rail administrations web page[22], but only from the Norwegian pages.

The way that the rail network is built has some consequences for uncertainties. The first challenge relates to topography, due to export issues from the national rail databank average grades had to be used. Careful splitting of the network at strategic stations was done to minimize the problem. The manual splitting of the railway into sections and calculating average time based on the schedule violates the wish for automatic updating. Due to time and financial constraints it was not possible to pursue the issue further. It would be recommendable that the Norwegian National Rail Administration developed export routines to open standards so that rail line and train speed could be extracted for use by external computer applications.

The other issue is the schedule, and how this is used to calculate average driving speed. After talking to a locomotive engineer on a freight train from Trondheim to Alnabru it became clear that the schedule serves as guidance for freight trains. For passenger trains the schedule has to be followed for passenger comfort; it is beneficial for passenger to know when the train arrives and when it departs, but the schedule is not important for safety reasons. Safety and signaling are controlled by the presence of trains and not time. This allows for energy aware locomotive engineers to use the topography to minimize energy consumption. While not so energy aware locomotive engineers could spend more time waiting at signals. The use of average speed between the strategic stations could be influenced by driver behavior.

It was possible to create a rail network that could use the rail emission functions based on those found in the ARTEMIS project. But there is a concern over the assumption that there is no energy loss due to braking. From the train trip from Trondheim – Alnabru it became clear that breaking was needed to keep the train speed under the speed limit. The topography in the Norwegian rail network is quite challenging according to the locomotive engineer. Breaking a freight train without regenerative breaks is turning kinetic energy into heat through the brakes. Thus energy consumption based on calculations from the ARTEMIS project will tend to be underestimated. Another challenge with Norwegian rail is that it is mostly single track, thus there are several stops to wait for passing trains.

[22] http://www.jernbaneverket.no/no/Marked/Informasjon-for-togselskapa/

The available rail network used by the Green Freight Transport project does not have an optimal quality. The missing elevation data meant that it was not possible to use a rail energy model based on the detailed equations found in Lindgreen and Sorenson (2005b) and in Lindgreen and Sorenson (2005a). An alternative rail energy and emission model had to be developed.

3.4.2 The road network

Unlike the rail network the road network is denser. There are more intersections and alternative routes. Figure 21 shows the road hierarchy in Norway. (E)uropaveg is at the highest level, and then there is the (R)iksveg, (F)ylkesveg and (K)ommunalveg. The differentiation into E, R, F and K roads is an administrative classification.

A transport model network for Norway exists, but it lacks gradient attributes that influence emissions. The gradient has a major influence on heavy-duty vehicle emissions (Hassel and Weber, 1997). From a design perspective it is better use data directly from the source rather than to use data from a derivate of the source. On the other hand using the transport model network would make it easy to include emission calculations in regional transport models. There is an issue with the level of detail; according to the manual for coding the RTM road network, the following road categories should be included (NTP Transportanalyser, 2007 p. 100):

- All (E)uropaveger (Primary trunk roads)
- All (R)iksveger (Secondary trunk roads)
- All (F)ylkesveger (Regional roads)
- Some (K)ommuneveger (Municipal roads)
- (P)rivateveger, private roads are coded if needed

The problem with the municipal roads (K) was that only some roads are coded. It was up to the user to decide if a road was important enough to be coded. There is a chance that the networks will have different levels of detail based on the knowledge of the person doing the coding. The national level consists of five regions, and each region was responsible for coding and updating their part of the network. The network was built for conducting transport analysis, and thus areas that are studied with the model will probably have more municipal roads coded. Having different levels of detail when it comes to the coding of municipal roads can impact emission calculations. The freight transport network was built from the network in the regional models, but some of the attributes have been given different meaning. As of February 2009 only preliminary documentation was available on the network.

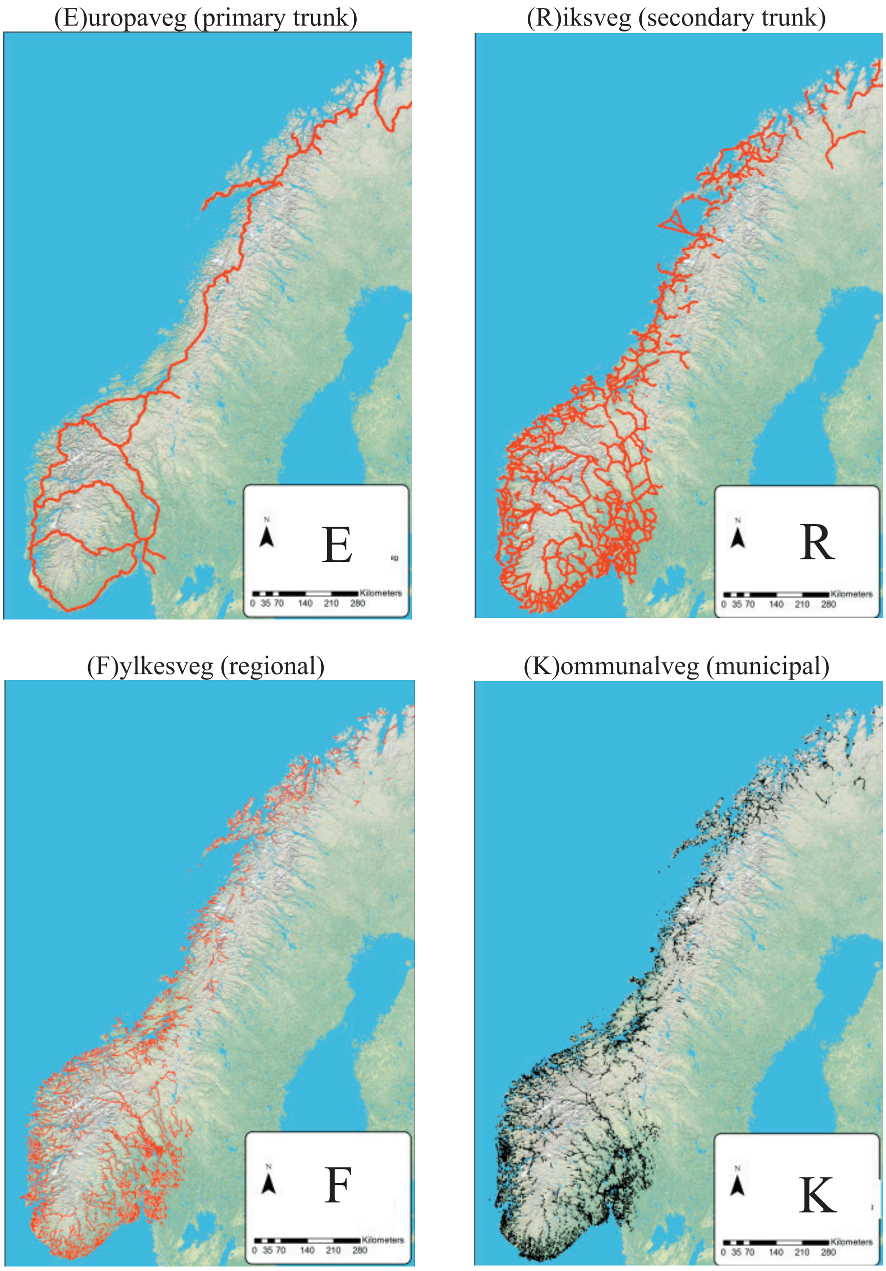


FIGURE 21 ROAD HIERACHY IN NORWAY

Another issue with the NTP road and freight transport network is the location of terminals. The sea terminal in Trondheim is located approximately 2.5 kilometers to the west of its actual position. According to the preliminary documentation the terminals are located according to their postcode. But looking at Figure 22 it is clear that there is an issue with this approach. The harbor terminal is missing or erroneously connected to the rail passenger terminal. There is placed a terminal in “Tonstadkrysset”. And there are no terminals coded in the Sandmoen area, but one terminal is coded on the Heimdal side of the E6. The level of detail in the RTM freight transport network is not adequate for freight transport emission studies. A manual check of terminals and terminal connectors would have to be conducted. Another weak spot of this network is turning restrictions and one-way restrictions. These restrictions are present in a format that is specific to the CUBE transport analysis software and would have to be converted into a format recognized by the ArcGIS software.

An alternative is to build the networks by using existing available geographic data, not existing networks. The national public roads administration has an extra digital road description derived from national road databank known as Elveg. This dataset includes the geometry and a set of linear referenced attributes. Linear referencing is a way to link attribute data as a measurement along a line. “The road is four meters wide from 200 meters from the road start and to 700 meters from the road start” is an example of linear referencing. The data is delivered as a SOSI file. SOSI is an acronym for the Norwegian words: “Samordnet Opplegg for Stedfestet Informasjon” (coordinated methods for geographic information). SOSI is an electronic interchange format defined by Statens kartverk[23]. The SOSI file is a national standard and thus the file format has limited support in off-the-shelf computer applications. Therefore a specialized computer application is needed to convert the SOSI file to other file formats supported by GIS systems. Geodata, a Norwegian firm, has created several commercial products for converting SOSI data into data formats used by ESRI (Environmental Systems Research Institute) products[24]. Shapefiles are a common interchange format that ESRI have developed and the shapefiles specifications have been released into the public domain in an ESRI whitepaper (ESRI, 1998).

[23] http://www.statkart.no/sosi/welcome.htm (page in Norwegian)
[24] http://www.geodata.no/Produkter/SOSI-produkter/ (page in Norwegian)

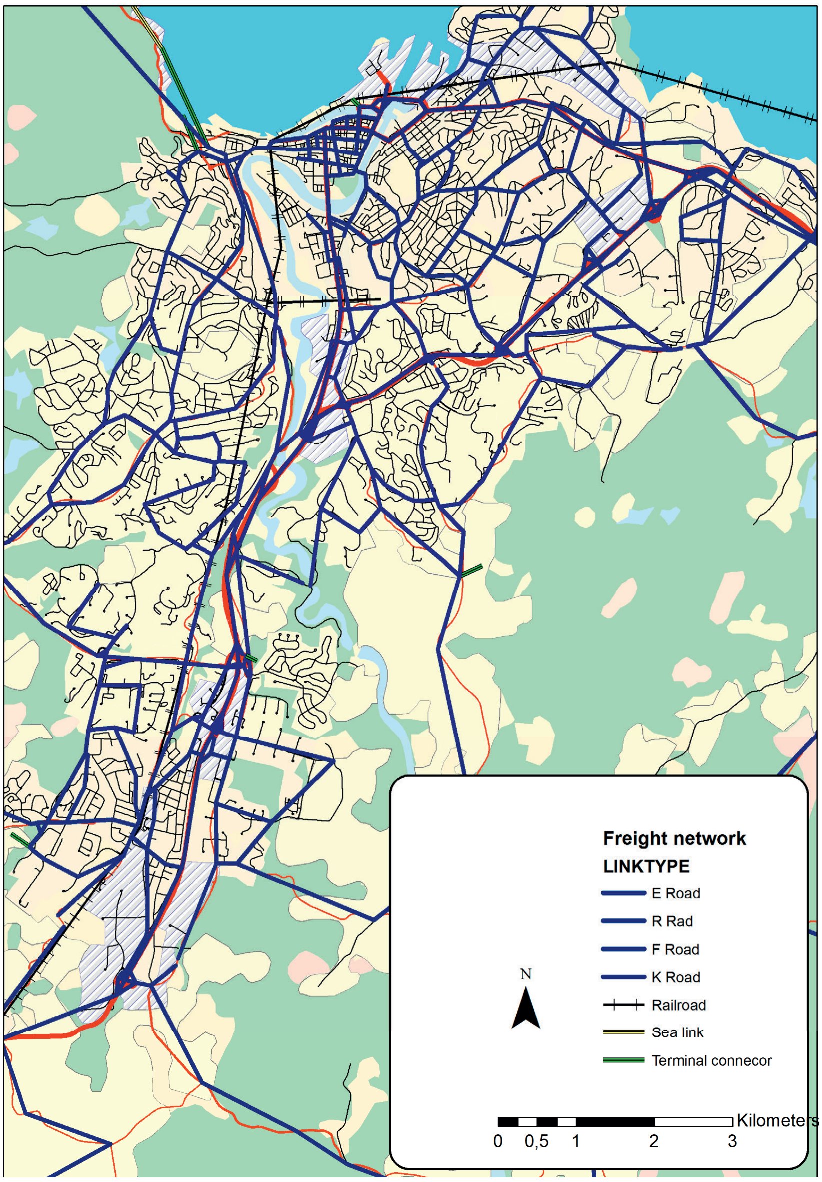


FIGURE 22 EXAMPLE OF FEIGHT NETWORK (TRONDHEIM), SOURCE: NTP, OSKAR KLEVEN

The Elveg dataset consists of eight files: two SOSI files and six text files. The two SOSI files contain road geometries and address markers, while the text files includes information on load restrictions, speed limits, height restrictions, direction restrictions, road blocks and turnings restrictions. A more detailed description of this data is found in Statens vegvesen and Statens kartverk (2008). The SOSI files are split into separate files for each municipality in Norway. To create a network for the whole of Norway 430 data files have to be merged as Norway has 430 municipalities. The SOSI converter handles merging of the SOSI.

Using Elveg has several desirable features:

- Speed limits for road transport are included. Ferries are coded as part of the road system.
- The road geometry is three dimensional; each vertex of the road has a z coordinate.
- Driving restrictions are included.
- Roads have address information encoded

Using Elveg as a source is beneficial because Elveg is under a management regime. The information in the Elveg dataset is maintained by two governmental agencies. This will remove the need for manually updating the network if new roads are built and old roads are closed. A workflow that can automatically build road network from standard Elveg files will remove the need for updating of the road network within the model. The Elveg data set has undergone a quality control before it is released (Statens vegvesen and Statens kartverk, 2008 p. 21).

It is possible to build a network using Elveg as a source in an automated fashion. The key to automation is the use of python scripting and model builder in ArcGIS. Scripts are created to accomplish small tasks; the tasks can then be linked together to form a larger computer application with the model builder. Building the road network consists of nine steps.

1. Convert SOSI data files to a shapefiles
2. Read Elveg text files into a database
3. Join road geometry (shapefile) with the technical data: barriers, height restrictions, load restrictions, one-way restrictions and speed limits
4. Export shapefile and table of forbidden turns
5. Run modified script “Create Turn Feature Class From Multi-Edge Turn Table” available from ESRI (ESRI, 2008)
6. Import the shapefile with turning movements from step 5 and update the geometry of the turning movements with the road features
7. Identify links with missing speed limits and calculate average speed dependent on road category to be used when the speed limit is missing
8. Update speeds on ferry links
9. Build the network
10. Conduct a manual check for gaps in the E road network

A feature in GIS nomenclature is one object that contains georeferenced information and has a common set of attributes. Points, lines and polygons are examples of vector-based feature types.

The conversion process in the first stage is done via Geodata's software for SOSI conversion. After import the dataset was reviewed. The Elveg dataset included public walkways and freestanding stairs. 1452 features of this type were removed from the dataset because they will not be used for freight transport purposes.

The second stage relies on scripting to extract data from the text files and enter them into a database. The amount of data extracted from the files is not sufficient to cause any worries. Caution is advised when data sets grow beyond 1GB. Different storage formats may have different limitations that are not well documented. The total freight network dataset was expected to grow beyond 1GB of data and this has to be taken into consideration when choosing the final storage solution. ESRI's file geodatabase is a good choice based on portability and size limitations. The file geodatabase is stored on disk as a directory structure and no files outside the directory structure are needed to use the database. This makes it easy to copy the database between computers. The file geodatabase has few limitations that will affect the routing and analysis tool; see Table 10 for the limitations.

TABLE 10 LIMITATIONS OF FILE GEODATABASE, SOURCE: ADAPTED FROM (CHILDS, 2009 P. 13)

Limitation	Value
File geodatabase size	Technically no limit
Table size	1 TB, optional 256 TB
Number of tables	2 147 483 647
Number of columns in table	65 534
Number of rows in table	4 294 967 295
Geodatabase name length	Operating system dependent
Table name length	160 characters
Column name length	64 characters
Character field width	2 147 483 647

The third stage is to use standard join operations to join attributes with the associated feature. A join operation is to link data from two tables together using a common identification string or number present in both tables. In this case TRANSID which is a 9-digit number is the key for the join-operations. The TRANSID is unique for each road segment.

The fourth and fifth stages are used to build a network with turning restrictions. Turning restrictions allows the user to code turning restrictions that might be encountered in the road network such as "no left turn." The problem was that there is no "off-the-shelf method" to take the turning restrictions from the Elveg dataset and turn them into a format that ArcGIS can use. One possibility was buying a prepared Elveg network from Geodata with the turning restrictions included. This was unsatisfactory because the cost for buying an updated network would be too high and one would be buying back one's own data. An alternative approach was to create a routine to build the turning restriction from the Elveg data source. From a computer science perspective this should be an easy task. The banned turning movements are stored in Elveg as a sequence of edges. The sequences of edges are used to create a banned turn feature that the GIS software can use as input to creating the turning restrictions. A white paper from Tele Atlas gave the first clue to a viable solution. The white paper describes building a network from map data acquired from Tele Atlas (Tele Atlas, 2009). In annex 1 of the paper the terms turntable and turn feature class are used interchangeably. This was interesting because the term turn table refers to a previous discontinued version the GIS software from ESRI ArcView 3.x. This was an indication that old style turntable could be converted into the new turn feature class. And within the standard ESRI tool there was a tool for converting old style data into the new format. The last missing piece on how to build the turn table was found in a set of slides from the ESRI 2009 international user conference. The trail from here leads to the ESRI developer's network where a script is available for building banned turn movements[25]. The Elveg dataset does not contain multi edge turns so the script was modified for this purpose. The script takes the list of banned turns, described as a set of edges, and turns them into a feature that is scaled to half the edge length around the central vertex. Figure 23 shows a T intersection as a sequence of edges numbers 1, 2 and 3. If arriving from edge 3 then the left turn is forbidden. In the Elveg data a sequence of edges describe the banned movement, in this case 1 - 3. The ESRI script finds both edges in the turn and the vertex they have in common. Then a new feature is created with parts of the two features joined in the common vertex. In Figure 23 the banned movement (BM1) is illustrated on the right. The routine to build the turntable is computationally intensive. For the Norwegian network the runtime was about four hours on a normal office computer.

The process of building a road network with turning restrictions from an Elveg dataset gave a valuable understanding of how building turning restrictions works. The knowledge acquired in this process could be used to build turning restrictions from other network sources. And updating networks based on the standard Elveg distribution could be done independent of a commercial product built from the same source.

[25] http://edn.esri.com/index.cfm?fa=codeExch.sampleDetail&pg=/arcobjects/9.1/Samples/NetworkAnalyst/CreateTurnFCFromMultiEdgeTurnTable.htm

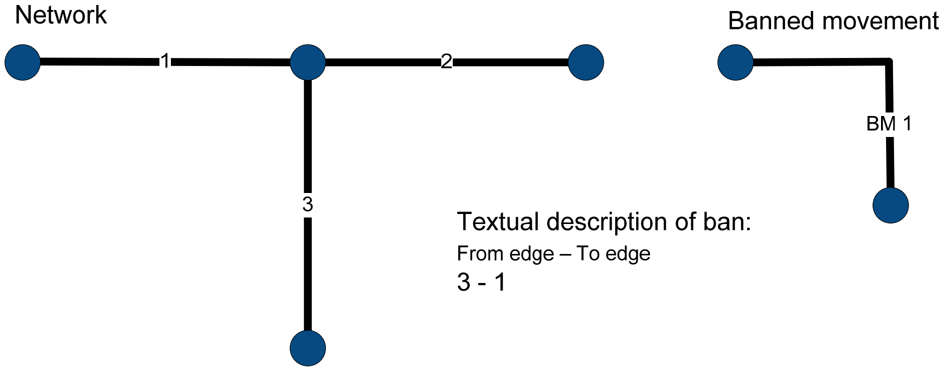


FIGURE 23 NETWORK AND BANNED TURNING MOVEMENTS

Developing a method for building turn movements from standard Elveg might seem a bit over the top. But it allows for greater freedom, if the Elveg dataset does have the attributes or quality required then other commercial datasets could be acquired. As mentioned in Tele Atlas (2009) turning movements are not included in their dataset, but can be built with the method described above.

The sixth stage is importing the turning movements back into the database, and updating the turning movements by geometry. This function updates the edge reference in the turn table using the geometry.

The seventh step is to identify links with missing speeds. There are two known reasons why speed limits might not exist (Statens vegvesen and Statens kartverk, 2008). The first is that Norwegian national road databank (NVDB) is an online database that can be edited at any time. The database does not guarantee that all technical data is completely registered before the road feature is saved in the database. The other reason is that it is unclear what the correct value is, in the case of municipal roads the speed limits are set by the municipality.

In the road network 1,206 features did not have a speed limit assigned to them. The total number of road features is 569,415, of which 0.2% of the features are without a speed limit. Road stretches served by ferries do not have speed limits. For road links of this type a ferry speed was calculated based on an assumption of average ferry speed of 15 knots.

Manual updating was not wanted because this procedure would have to be done each time the network was regenerated. An alternative was to build a simple model of speeds based on road category. Based on a simple model that there is a correlation between the road category and speed limit the average speed limit for each road category was calculated. The average speed was calculated as weighted average with the length of the road link as the weight. Table 11 gives an overview of the number of links missing speed limits and the length broken down by road category. The reason for the large percentage of length missing speed on R roads is that ferries are part of this category. Ferry stretches are on average longer than the road links in the Elveg data set.

TABLE 11 NUMBER AND LENGTH OF LINKS MISSING SPEED LIMITS

Road category	Road links	Road length (km)	Links missing speed	Length of links missing speed (km)	% of length missing speed
E	7133	35109	169	89	0.25
F	27446	131193	266	809	0.61
K	38504	294591	81	29	0.01
R	21448	108106	690	1446	1.33

Table 12 shows the results from the simplified model for predicting road speed based on road category. This model will be used to fill in the blanks when it comes to speed. An additional column of data was added to the road table to indicate if a predicted speed was used. This can be used for debugging purposes if strange routes occur. Ferries are coded with a speed of 15 knots (27.7 km/h); for the other links the speeds from Table 12 will be used.

TABLE 12 SIMPLE MODEL FOR SPEED BASED ON ROAD CATEGORY

Road category	Drive time (hours)	Length (km)	Calculated speed
E	94.4	7205.1	76.3
F	401.9	28247.4	70.3
K	861.3	38548.2	44.8
R	302.0	22878.5	75.8

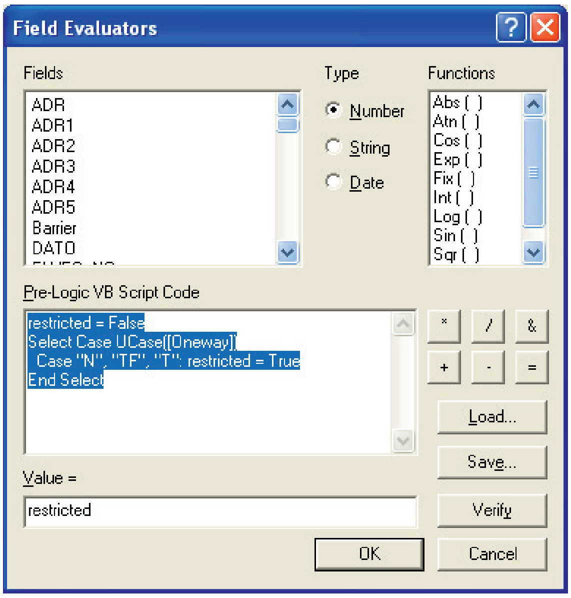


FIGURE 24 RESTRICTION EVALUATOR CODE

ESRI's network analyst has a predefined way to threat one-way restrictions on links. If an Elveg link has the code N or T then travel in both directions will be banned. If the code is TF (To-From) then travel in the direction that the link was created is restricted. On the other hand if the code is FT (From-To) then travel is restricted against the direction that link was created. Figure 24 shows the code for the one-way evaluator when traveling in the direction that the link was created.

In addition to turning restrictions and one way streets there can be other barriers. Barriers recorded in the Elveg xxxxSperr.txt files are barriers that physically block the road. These features are joined into the table with road links. For Norway there exist 12,157 such road blocks. Road based freight transport has to comply with these restrictions like any other passenger car. Bans are coded with the letter N. In network analyst an evaluator was created to look for the N in the barrier field and if found to restrict access to the link.

The gradient of the features in the road network are calculated from the 3-dimensional geometry. The calculation of gradients is done for every feature. The equation $(Z_{end} - Z_{start})/Distance$ is used to calculate the gradient for each line in the direction of the feature. For the reverse direction the gradient is multiplied by -1 to get the gradient in the opposite direction. The distance used is the 2-dimensional distance.

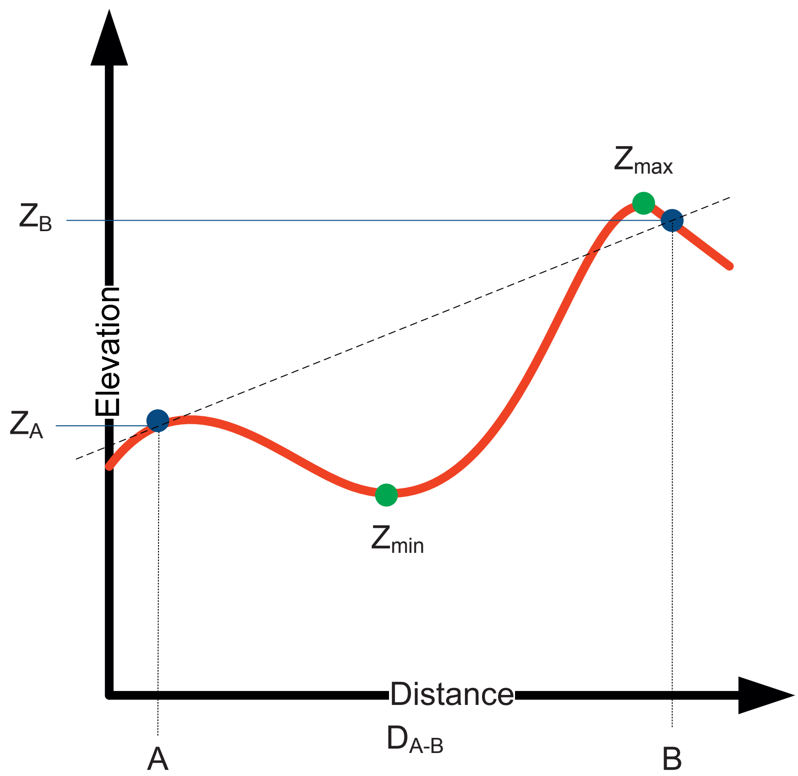


FIGURE 25 ILLUSTRATION OF GRADIENT CALCULATION

From Figure 25 one can see that the gradient calculated is an approximation of the roads real gradient. The dataset from the national road databank is not segmented by minimum or maximum height. Thus parts of the road may have different gradients than the average gradient calculated. The calculated gradient follows the striped line while the true gradient follows the red line. To identify road features where the average gradient is misleading can be done by identifying the global minimum and maximum elevation of the road, Z_{min} and Z_{max}. If there is a large discrepancy between (Z_{max}-Z_{min}) and (Z_B - Z_A) then there is a need to look at the road segment and split it into two roads. Submerged road tunnels that do not cross municipal boundaries are a typical example. The submerged tunnel in Tromsø is an example where the average grade is erroneous. The tunnel is a single road feature that stretches across Tromsøysundet. Z_a is at 0.5 Meters Above Sea Level (MASL) and Z_B is at 0.3 MASL and the distance is 6,871 meters. This gives an average gradient of 0.0029% which is flat. But Z_{max} is 0.5 MASL while Z_{min} is -100.29 MASL thus the average grade is misleading. The solution is to split the road feature at Z_{min} and recalculate the grades. After recalculation of the grades the Tromsø tunnel has an average grade of 2.96% down on the west side and 2.87% up on the east side. This method does not guarantee that there will not be any intermediate sections with higher grades on the same road feature. But this method identifies some road features where the average grade can be misleading.

The road network that is exported from the national road databank is not always topographically correct. During building of networks only features that share a common coordinate-pair are joined together. Statens kartverk has done a check for vertices that are closer than 10 centimeters and integrated these features. Integration in GIS terms takes two vertices and gives them the same coordinate-pair if the distance between them is less than a specified tolerance. The 10-centimeter tolerance set by Statens kartverk does not seem to be sufficient. Six places have been identified where primary trunk roads (E roads) are not connected, north of Alta, between Ulsberg and Berkåk, north of Storhovet (Lillehammer), north of Sarpsborg and west of Sandefjord. In each case the gap between the vertices was slightly over 10 centimeters.

Using a digital road network description as input to the emission function is an efficient way of calculating emissions along routes. But errors in the digital network will be reflected in the emission calculations. There are four prime sources of errors when using a network build on the Elveg dataset: speed; gradient; topology; and attribute errors.

The speed coded into the network is the speed limit. Using the speed limit as a proxy for the average speed is a very simplistic speed model. There is an ongoing project in Norway related to driving speeds of commercial vehicles (Børnes, 2008). The design of the emission model is set up so that when the speed model for commercial vehicles is available it can be implemented. It is beyond the scope of this Ph.D. project to build a speed model. Therefore it is assumed that average speed is equal to the speed limit. In chapter 5 a test of this assumption is presented.

From the literature we know the gradient has a major impact on heavy-duty vehicle emissions (Hassel and Weber, 1997). And thus it is important to check the digital network descriptions for erroneous gradients. Gradient issues arise from the segmentation of the digital road descriptions. If inflection points are used as segmentation criteria then the average grade problem will be lessened. The NPRA have commissioned a software solution that is to allow for user specified segmentation of the network. The commissioned solution is to deliver specialized simplified networks for analysis purposes. The solution is to build on Transport Network Engine (TNE) and deliver data in standard format available in ArcGIS. The name of the tender was: "Trafikklenker i transportnettverk og trafikkdatabase – fase II" (Traffic links in transportation networks and traffic database – phase II). Apart from the average grade problem there are problems with missing elevation data. Figure 26 shows a typical error in the network. The R road (Rv 33) running for north to south has an intersection with the municipal road (Kv 5356). In the intersection the R road and the municipal roads have the same height, but in the next vertex the height (Z) is 0. The length of the road feature is 3 meters, but the grade is 4196%.

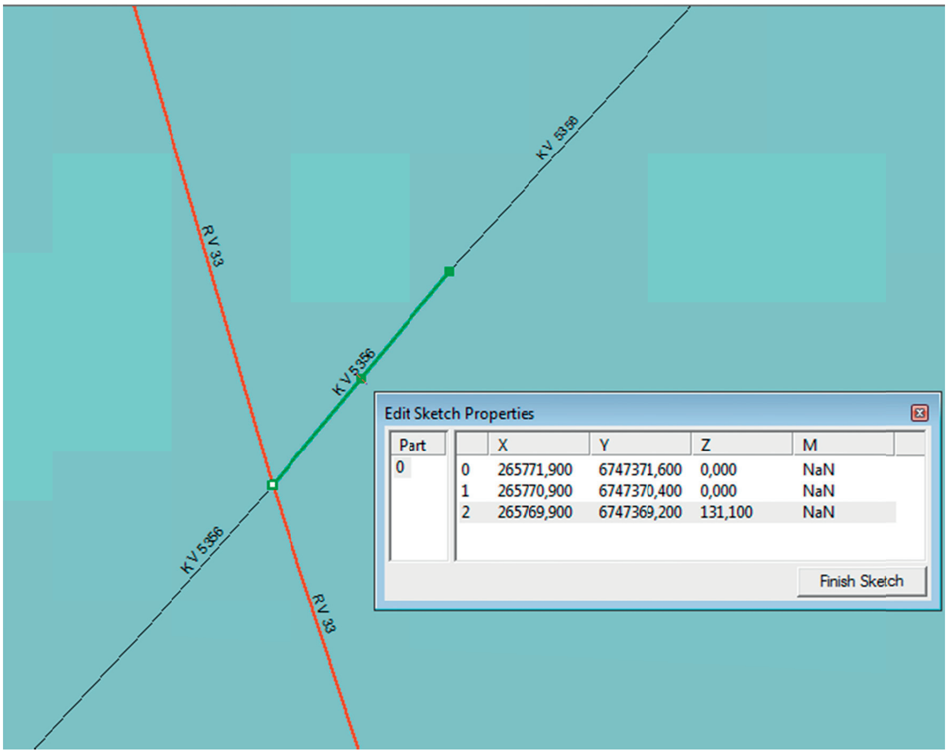


FIGURE 26 MUNICIPAL ROAD WITH ERRORS IN FEATURE VERTEX Z COORDINATES

0.34% of the total distance of the network has gradients greater than 15%. Table 13 shows a breakdown of believed erroneous gradient over road category. Most of the gradient errors are believed to be caused by elevation errors on municipal roads.

Road category	Feature count	Distance (km)	Feature length (m)
E	224	3.5	15.5
R	497	5.3	10.5
F	1087	12.5	11.5
K	5893	312.0	52.9

TABLE 13 COUNT AND LENGHT OF FEATURES WITH GRADES OVER 15%

The geographic distribution of features with grades over 15% is shown in Figure 27. Features with suspected gradient problems are spread out over the most of Norway, but there are concentrations around big cities; Oslo, Bergen, Stavanger and Trondheim. The primary reason for this is that there is a higher concentration of municipal roads in these cities.

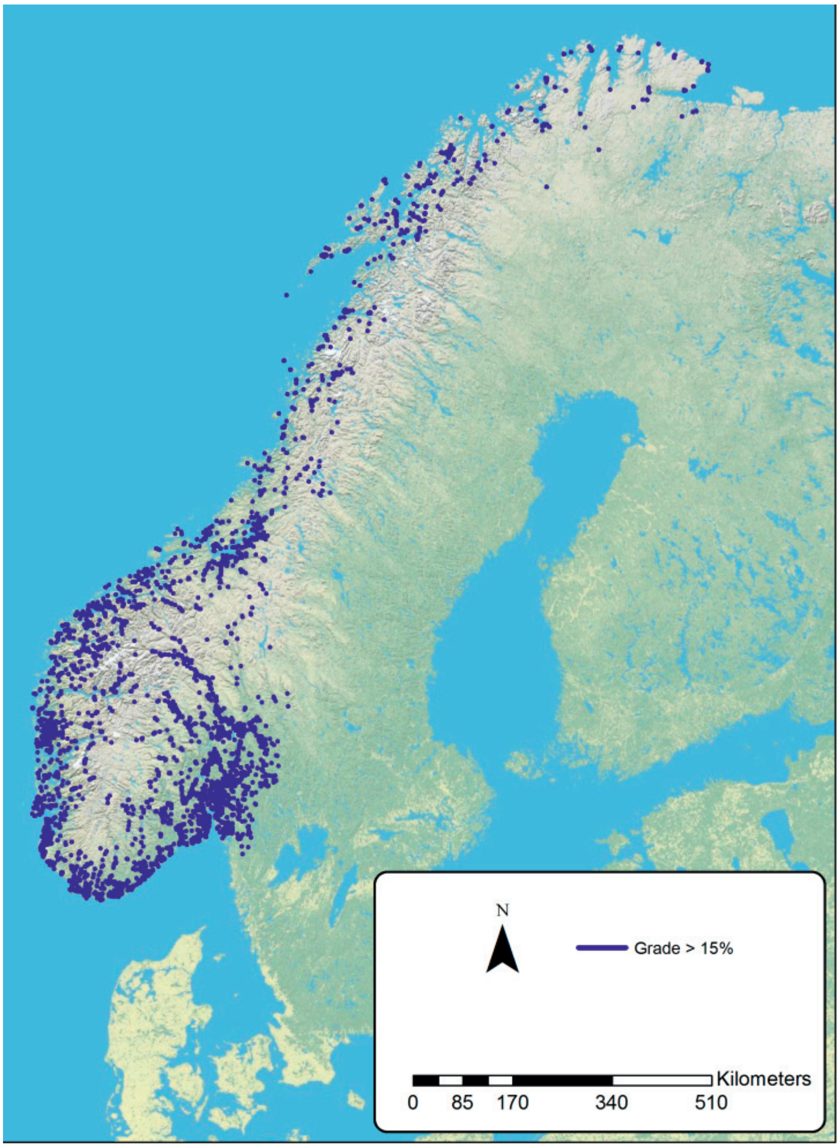


FIGURE 27 GEOGRAPHIC DISTRIBUTION OF ROAD FEATURES WITH GRADES OVER 15%

Statens vegvesen is responsible for the Elveg data and should therefore fix errors and release updated data. It is hard to say if the errors are present in the national road databank or if they appear during export of data to the Elveg dataset. Within the confinement of the Ph.D. project a gradient limitation is enabled to reduce the problem. Gradients are limited to ±12% in the calculation module. ±12% is the maximum gradient for new roads as defined in the road building standard for Norway.

Another source of errors is topological errors. These occur when road features are not overlapping. When viewed at a large scale the roads seem to be connected, but when one zooms in they are not connected. Figure 28 shows the two road segments on the E6 north of Alta. Looking at the roads on a scale of 1:500 the roads seem to be connected. But when zoomed in to a scale of 1:2 the roads are clearly not connected. The distance between the two endpoints is 10.4 centimeters. Had the lines been 5 millimeters closer than the endpoint would have been connected via Statens kartverk's integrate procedure.

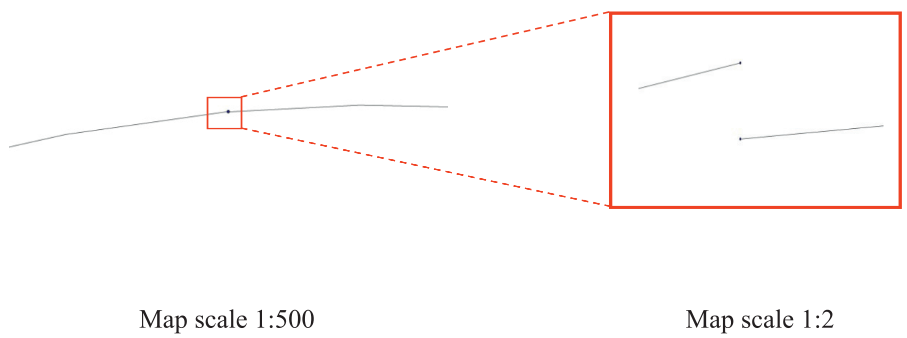


FIGURE 28 TOPOLOGY, UNLINKED ROADS NORTH OF ALTA (SCALE IS INCORECT FIGURES HAVE BEEN RESIZED)

With the most advanced versions of ArcGIS one can define geodatabase topology rules. The most useful topology rule to find breaks in the network is to use "Must Not Have Dangles" as described in the ESRI online documentation[26]. The problem with this rule is that it returns a lot of false positives. Every end of a road that is not connected to another road is flagged as an error. Thus the municipal roads are littered with false errors. This type of error is the responsibility of the dataset owner, the NPRA and should be fixed in national road database. A possible solution could be to increase the tolerance of the integrate function to 20 centimeters. This increase would remove the errors found on the E roads. The E roads are a part of the trunk road network in Norway, so the E roads were checked for breaks using the "Must Not Have Dangles" rule. The effect of topological errors could be severe. The break in the road network north of Alta

[26] http://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?TopicName=Topology_rules

caused the most northern part of the Norwegian road network to be disconnected from the rest of the network.

The last error type is attribute errors. Attributes are the pieces of information linked to the features. Speed limit is one such attribute that is manually entered when the feature is created or updated. Hence there is the possibility of human error when punching the data. But another cause of speed limit errors could be the lack of updating. All attributes can have potential errors and it is hard to find an error without local knowledge. If data is used frequently then it is more likely that errors in the data can be detected. Users must be able to report back to the data owner that they have found a potential problem. Such a strategy of updating the network will improve the network quality with use.

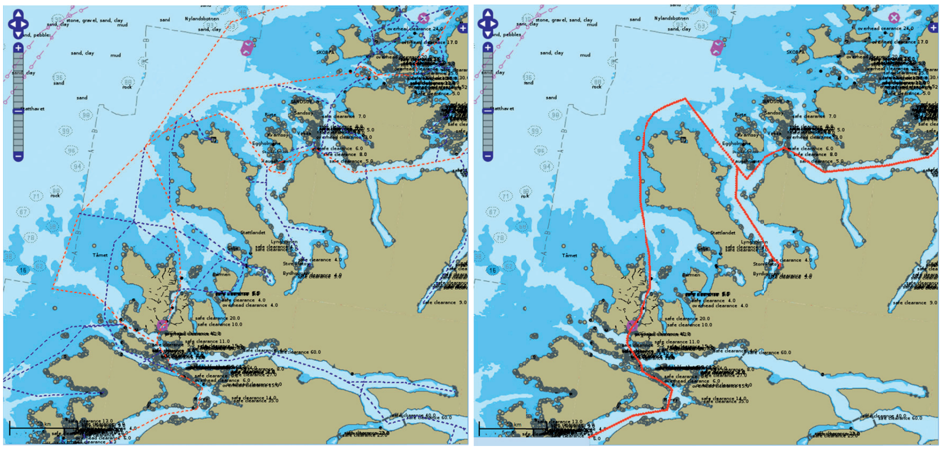
There are errors in the network that can affect the emission estimates. Most of the errors are attributed to quality of input data, except for speed. It is not speed in itself that is the problem but that speed limits are used as a proxy for average speed. Only the most serious errors stemming from input data quality have been fixed, such as gradients over ± 12% have been set to ±12% and the E roads have been checked for topology errors.

There is a need for further work on input data quality. The trend in Europe is that data collection financed by the government should be open for public use. The idea is that the government should make the data available and the users should create applications using the public data. In the UK a website was set up to distribute datasets collected by the government[27]. The web page title gives an idea of what the website creators want to achieve: "Unlocking innovation". If one selects a dataset a page with data about the dataset is presented with an all-important feedback link at the bottom. This allows data to be used by the public and a formal way to give feedback on the data to the data owners. Free use of digital infrastructure descriptions could be useful in several applications. And it is a way to get feedback on hard to catch attribute errors for the data owners. For the use in emission estimation the road network is believed to be good enough and it certainly represents a step beyond emission factors with denomination g/km.

3.4.3 THE SEA NETWORK

For both rail and road the vehicles have to follow a network, while boats are advised to follow the shipping lanes. Shipping lanes are defined by buoys, markers and lighthouses. There are some advised routes along the Norwegian cost. These routes are called main and secondary fairways. They provide a safe path along the coast. Figure 29 shows the main, secondary and the 2006 trunk fairway around Stad, one of the more challenging stretches along the Norwegian coast.

[27] http://data.gov.uk/

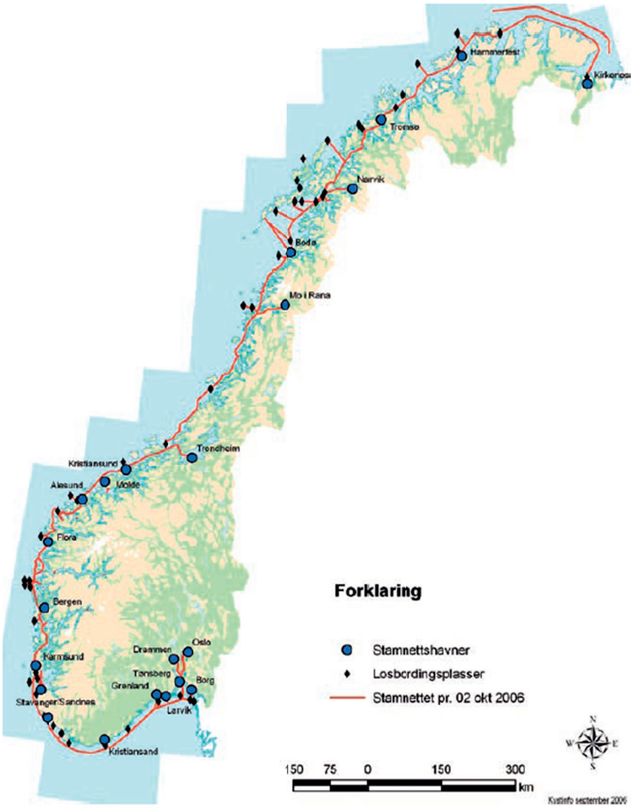


Main (red) and secondary fairways (blue) 2006 trunk fairway

FIGURE 29 MAIN, SECONDARY AND TRUNK NAUTICAL FAIRWAYS - STAD, SOURCE: (KYSTVERKET, 2010)

The nautical fairways in Figure 29 indicate that sea based travel is network based. Modern coastal navigation using GPS will tend to lead to a node/link type of network. GPS positions, waypoints, are set so that safe routes between waypoints are straight lines. Thus a trip is described as a set of points with straight lines between them.

The trunk fairway study of 2006 had some interesting priorities: safety and acute maritime pollution; reduced travel time; and costs associated with distance and removal of intermodal bottlenecks (Kystverket, 2006). Routing of the trunk fairway was based on these priorities. The trunk sea network links main harbors along the coast. Figure 30 shows the nautical trunk fairway for Norway. Important harbors are indicated with blue circles. The black dots represent pilot boarding locations. The pilot boarding locations show where ships can enter the Norwegian trunk fairway.



Main Coastal fairway ports:
(Listed from the North)

Kirkenes
Hammerfest
Tromsø
Narvik
Bodø
Mo i Rana
Trondheim
Kristiansund
Molde
Ålesund
Flora
Bergen
Karmsund
Stavanger
Sandnes
Kristiansand
Grenland
Larvik
Tønsberg
Drammen
Oslo
Borg

FIGURE 30 NAUTICAL TRUNK FARIWAY, SORUCE: (KYSTVERKET, 2006 P. 15)

Sea routing is more complex than road and rail routing. Route choice and whether or not to proceed is linked to the prevailing weather conditions, type of vessel, cargo and speed reductions due to weather. For challenging parts of the sea network, exposed areas combined with undesirable seabed topography can create extensive delays. The map in Figure 29 shows the area around Stad which is considered to be a challenging part along the Norwegian coastline. Stad is considered so challenging that studies have been conducted into building a tunnel through Stadlandet. In a report from the tunnel study to the ministry of fisheries and coastal affairs an insight into weather based routing can be gained (Kystverket, 2007). Some parts of the fleet cross anyhow, but with delays due to choosing an outer route and reduction of vessel speed. Type of cargo and potential for damage to freight and vessel is taken into account. There are differences between summer and winter months. The summer is less problematic than the winter. A more surprising statement is the assessment of risk and time of day. Some vessels will tend to delay crossing in bad weather to ensure a daylight crossing. Thus speed could be altered in other parts of the network to achieve a daylight crossing.

In other parts of the network normal shortest route decisions to save time and fuel are preferred. In the sea network bridges and power lines and available depth can affect routing. The available data sources for the fairways did not include height or depth restrictions. As of 2010 nautical fairways are published on the Norwegian coastal administration map server[28]. The dataset used is the official appendix to the regulation: Forskrift 30. September 2009 nr. 1477 farleder (Regulation of the 30 of September 2009, number 1477 nautical fairways).

The routes available from the Norwegian Coastal administration should cover all sea links in normal use for vessels involved in freight transport. The level of detail in the fairway network is satisfactory for the emissions functions available. But height and depth limitations are not given in the dataset. Historical AIS data can be used to track a ship's actual route.

Unlike road and rail, distances at sea are not constant in relation to the earth's crust. There are ocean-currents that can affect the distance traveled. Along the Norwegian coast line there is a current flowing in the north easterly direction. This is seen in Appendix E which shows a vector map of the ocean currents along the Norwegian coastline. The average speed of the current along the coast varies between 0.29 knots and 0.78 knots (Norges sjøkartverk, 1981). For a vessel moving at 16 knots this could result in a 2-5% change in traveled distance. There are local variations along the coast where the effect can be greater. Strong winds can contribute to different sailing speed. Winds from the stern can increase vessel speed, while headwinds can reduce vessel speed.

The effects of ocean currents and weather are not included in the sea network because they are hard to quantify and they differ between areas. The emission factors from ships described in Sjöbris et al. (2005) are too coarse to take these effects into consideration. And one should be aware of the effect of ocean currents and weather because at specific locations like Stad they can affect behavior.

3.4.4 The terminals

The model being developed has parts that are generic for all freight transport service providers and parts being specific for each actor. The rail, road and sea networks are general networks. The companies that use intermodal freight solutions or consolidate freight have terminals in their network. The terminals are key points where freight can change mode, be consolidated or split. Some terminals are used by many operators and some are used only by specific firms. The key to including terminals is to find the

[28] http://kart.kystverket.no/default.aspx?gui=100004&lang=2

terminals that are a part of the logistical network that is to be studied. The case for this Ph.D. project is TPG's logistical network. Thus the only firm-specific terminals included are those operated by TPG. All rail terminals are included and sea terminals that are served by the vessel MS Tege.

Terminals are quite challenging because insufficient information is available on them and their environmental impact. The lack of literature on terminal emission factors could be attributed to the diversity of terminals. There is quite a lot of different equipment used: forklifts; reach stackers; terminal tractors; cranes; and shunting locomotives to name a few.

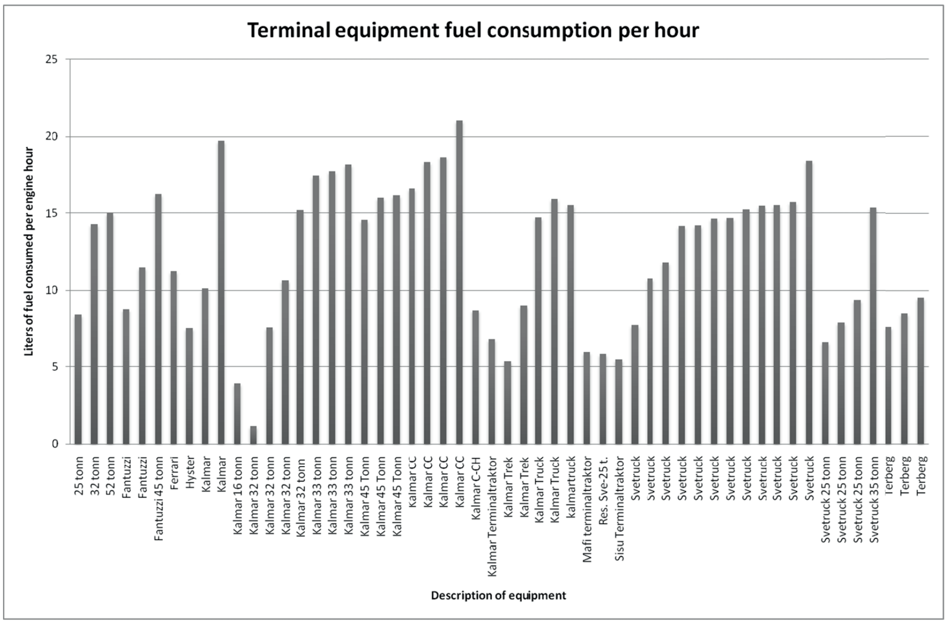


FIGURE 31 HOURLY FUEL CONSUMPTION FROM TERMINAL EQUIPMENT

Figure 31 shows hourly fuel consumption for forklifts at rail terminals for one operator in Norway. There are big differences between trucks that are reported as the same. One example is the Svetruck 25t, from 6.5 liters per hour to 9.3 liters. Fuel consumption for the Kalmar 32t forklift ranges from 7.5 to 15.2 liters per hour. The lowest data from the Kalmar 32t was 1.1 liters per hour. This is believed to be erroneous. A normal passenger car, Volkswagen Touran, reports 0.7 liters of diesel per hour when idling. There are differences between the terminals as seen in Figure 32 where fuel consumption is plotted against twenty-foot equivalent unit (TEU). Most of the freight passing through the terminals are stored in twenty-foot containers, but there are some trailers that are converted into TEU's. The numbers in parentheses are indications of terminal size in TEU's, and thus it can be seen that scale is not the only factors producing different consumption figures. The Bodø terminal is on par with the Alnabru terminal, and the Alnabru terminal is ten times bigger in volume. The figure indicated that consumption at the most inefficient terminal is about 1.7 times greater than at the most efficient one. The consumption figures should be used cautiously. This is because there are different physical terminal layouts and mixed use of terminal equipment. The Alnabru terminal has electrified cranes while the Trondheim terminal only has forklifts and reach-stackers.

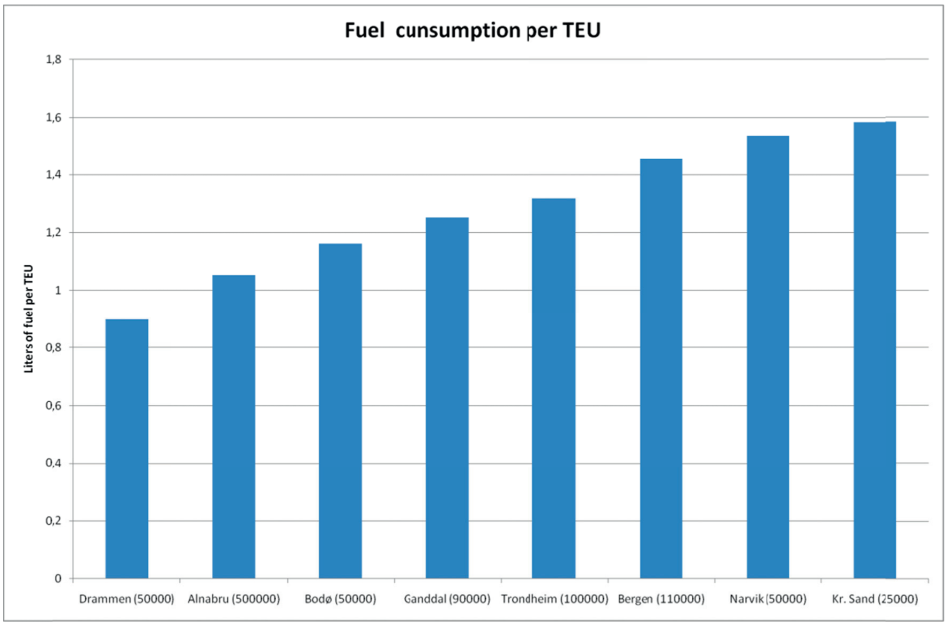


FIGURE 32 TERMINAL FUEL CONSUMPTION PER TEU

Figure 34 shows electrical energy consumption at terminals compared for two measures of volumes; number of parcels and weight. For the weight figures the difference is nine times between the most and least efficient terminals. When using parcels as a measure of volume the difference is more than 11 times.

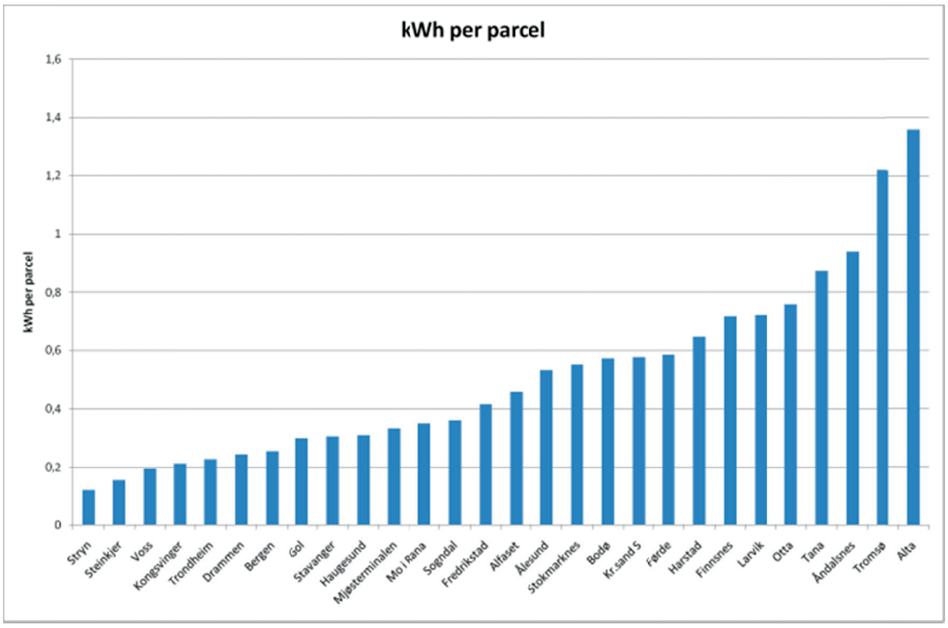


FIGURE 33 ELECTRICITY CONSUMPTION AT TERMINALS IN RELATION TO NUMBER OF PACKETS

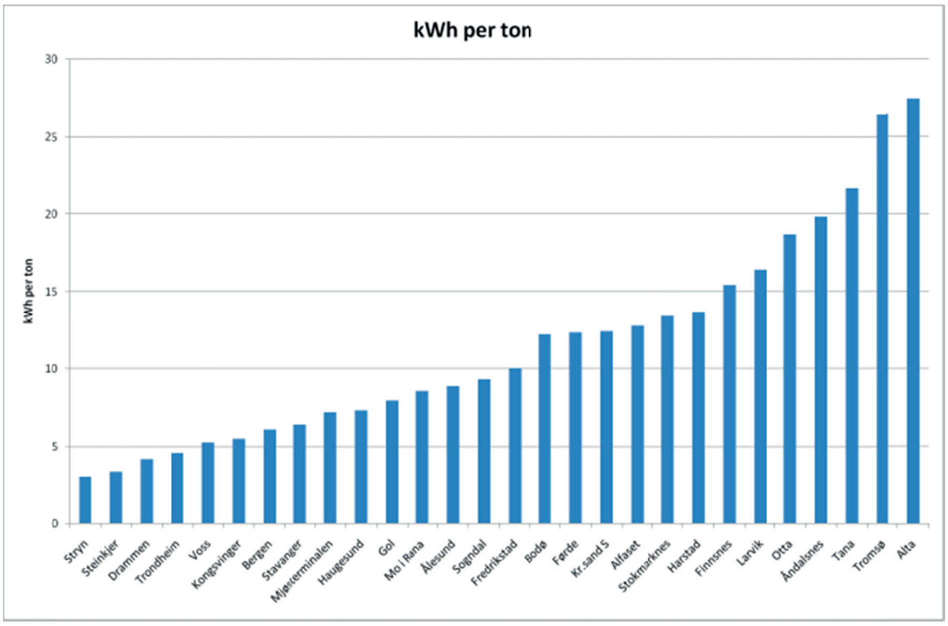


FIGURE 34 ELECTICITY CONSUMPTION AT TERMINALS IN RELATION TO FREIGHT WEIGHT

The data presented here was collected as part of the Green Freight Transport project. Their data certainly indicates that terminals have different energy consumption factors for both fuel and electricity even if the same company operates the terminals. Further studies should be undertaken to fully understand the differences between the terminals. Splitting energy consumption into that which is directly related to production and that which is not dependent on production would be interesting. The energy usage that is not related to production could be reduced by traditional energy saving techniques. For example, if a firm has their headquarters located at a terminal then this should not make the terminal less energy efficient. The split would justify comparisons between terminals. The large differences seen in terminal energy consumption, when related to production volume, indicate that there could be a potential for improvement.

The ideal solution would be to break down energy consumption over several production factors and find the most influential ones and use these for reporting. But such a study is outside the reach of this Ph.D. project. Energy reduction at terminals did not seem to be of high priority as the terminal operators had little information about energy consumption and fewer had energy performance indexes in relation to production. There were actors that had rental contracts that included energy, thus they did not know their electrical energy consumption. The Green Freight Transport project group did not believe that the terminal emissions were of such a scale that they warranted a significant amount of new registrations. The figures presented in Table 14 show emissions from a freight transport with CargoNet between Malmö – Jönköping.

TABLE 14 CO_2 EMISSIONS FROM A FREIGHT TRANSPORT AND TERMINAL EMISSION SOURCE: CARGONET

Direct road	Calculations according to EcoTransIT			CO_2 (kg) 720
Combined road and rail	Liter / 10 km	kilometers	factor	CO_2 (kg)
	5	29	2.6	377
Terminal	Malmö (liter)	Jönköping (liter)	Factor	CO_2 (kg)
	3	2	2.6	13

Historical fuel consumption data were used for the Malmø and Jönköping terminals. Diesel fuel used by trucks and shunting locomotives was included. CO_2 emissions related to the use of electrical energy was excluded. The emission from moving the freight between the terminals was twenty-nine times greater than the emissions at the terminals for combined road and rail. When a truck was used for the whole distance the difference is 55.4 times. These figures were used to argue that the terminal emissions in a freight transport chain are so small that they should be disregarded. On the other hand Table 14 shows that there is a difference between the Malmö and Jönköping terminals. The Jönköping terminal uses only two-thirds of the diesel per unit as the Malmö terminal. The difference is quite small, but this difference has to be multiplied by total number of units. The same was found for forklift usage at Norwegian rail terminals. The difference per unit between terminals was small, but when calculated over the total terminal production the emissions were considerable and there could be economic gains in the region of 240,000 Norwegian kroner (Levin and Sund, 2010).

There is not enough data available to estimate emissions from terminals in Norway. At present there are few good explanations as to why there are differences between terminals when it comes to emission efficiency. The registrations at the terminals are not detailed enough to be used to implement measures to enhance emission efficiency. For example it is hard to say if the differences between the terminals are due to the usage of electrical cranes for loading and unloading, forklift driving behavior or distance traveled by forklifts. There is a need for further studies in this area. From the data available it is not possible to conclude if terminals in Norway have optimal emissions.

Using economic gains as bait for getting companies to monitor their terminal energy consumption was assumed to be a viable approach. To structure the monitoring of energy consumption a simple marking scheme was proposed. The goal of the marking scheme was to ensure that terminal operators collect data that can be used to create emission factors for their terminals. The system is based on three green stars and each star has a unique meaning. The three-star systems can be included in the emission model, for each package an average number of stars could be presented based on the terminals used for that specific transport. Table 15 shows the three green stars, their meaning and a recommended unit of measure. Using a kilowatt-hour as a measure of energy consumption will allow for energy efficiency comparisons between terminals. Thus it could be possible to look at the energy efficiency of different terminal handling equipment based on real world data. This could be used when designing new terminals as to make them as energy efficient as possible, or at least it would allow for energy efficiency data to be included in the decision-making process.

TABLE 15 THE THREE GREEN STARS AND THEIR MEANING

Star	Description of stars	Recommended unit of measure
★	Total energy consumption is recorded (fossil fuel, electrical, heat, renewable)	Kilowatt hour (kWh)
★	Terminal production, volume moved through the terminal	Kilograms (kg)
★	Energy split between production dependent and independent emissions	Percentage (%)

The first star is awarded if the terminal records all energy consumption at the terminal. Thus energy consumption from outsourced activities such as snow clearance during the winter months is to be included even if a third party is providing the service. The second star is awarded if the terminal operator records a measure of production at the terminal. The final indicator of production is to be expressed at kilograms, but internally units like parcels, freight weight or TEU's can be used. The internally used measures then have to be multiplied by an average conversion factor to give a kilogram equivalent factor. This is because emissions in the rest of the emission model use weight to calculate emissions. The third star is awarded if the terminal operators are able to differentiate between emissions that are dependent and independent of production volume. The reasoning for this is that terminals can have activities that are not directly related to the specific terminals activity. For example the Norwegian administration of TPG is co-located at Alnabru. CargoNet has its administration located in downtown Oslo. Thus a measure for TPG to improve terminal efficiency could be to move the administration offsite. A more environmentally sensible approach could be to compare the energy efficiency for their offices to other office buildings and apply the appropriate measures to the building infrastructure.

A terminal that is awarded with three stars has the ability to generate its own emission factors. These factors can be used to compare terminals and find measures to improve the terminal's environmental performance. In the emission model we will not be able to identify the terminals with the best environmental performance, but terminals that have the ability to generate emission factors will be identified. The same type of concept has been used by the Norwegian food safety authority when classifying restaurants. The NFSA's usage of "smileys" does not tell the customer how good the food tastes, but rather gives the customer a likelihood of getting food poisoning.

Freight terminals in Norway are quite heterogeneous and thus establishing one general factor for all terminals makes it difficult to identify areas of improvement at terminals. The contribution of terminal emissions to the total emissions from freight transport was believed to be too low to warrant large scale registrations by the partners of the Green

Freight Transport project. Thus terminals will be included with a measure that indicates if they are able to estimate their own emissions. The practical implication for the emission tool is that the terminal links in the model will be assigned zero emissions, but the terminal node can contain the green star rating.

3.4.5 Summary of networks

There is data available for building transportation networks for rail, road and sea freight transport. The sources of data are government agencies. The Norwegian coastal administration data is available to the general public as downloads from their online map server. The road data is not publically available as downloadable data. The Norwegian public roads administration has an online map server, but is only able to export pictures and not feature data. Feature data was received as SOSI files from the NPRA. For rail data feature data was received as shapefiles. The received dataset contained elevation data, but all values were set to 0. After several unsuccessful attempts at getting rail feature data with elevations a simplified method had to be employed. Rail data with elevation information exists within the rail database, but elevation data was lost during the export.

The quality of the input data will affect the quality of the emission estimates. Usage combined with some sort of feedback routine could improve the data with time. The quality of the network built from the digital descriptions is sufficient for emission estimation, but there are errors and assumptions that could affect the results. Within the confines of a Ph.D. project it is not possible to find and fix all the errors in the networks. And one of the design ideas for the emission model was that data owners are responsible for data quality. Thus errors should be reported to the data owner for corrections. The model contains routines that can process updated data to build new networks with little human interaction.

The level of detail present in the freight network as described in this chapter is believed to be adequate to the emission functions found in the ARTEMIS project. For road there is a major concern with the speed limit being used as a proxy for driving speeds. The effect of this assumption is tested in a later chapter. For rail the network made available to the Green Freight Transport project and hence this Ph.D. project did not have high enough level of detail to use the energy emission scheme proposed in Lindgreen and Sorenson (2005b) and Lindgreen and Sorenson (2005a). During the development phase alternative ways of estimating rail emissions have to be considered. The sea network has adequate detail for estimating ship emissions, but the routes proposed by the calculation tool should be checked with the ship owners as routing at sea can differ from land based routing. Route choice could be more dependent on weather, exposure, and rough seas than on shortest distance. The terminals are built into the network but their emissions are set to zero. There is not enough data available to estimate terminal emissions. A scheme of assigning green stars is set up to promote data collection that later can be used to create terminal emission factors.

4 BUILDING AND USING SEMBA

SEMBA is an acronym for **S**INTEF **E**mission **M**odule **B**ased on **A**rtemis which became the name of the new model for estimating emissions from freight transport. The model is built around a GIS application developed by ESRI called ArcMap. For routing analysis the Network Analyst extension is used. The GIS application is the core module of the model, only input data like the transport network and the emission module are supposed to be changed. Networks can be updated when new data is available, and the same is true for the emission functions. This chapter documents how the freight transport network and state of the art emission functions are combined to estimate emissions directly related to vehicle movements.

The emission calculation routines are written as a Python module called SEMBA. This module has several sub modules, one for each mode. The parameters taken from ARTEMIS project are stored in the main module along with general functions. Such a design separates the different modes in separate modules. This design allows for changes in the sub modules independently. Energy conversion from Joule to kilowatt-hours and linear regression are examples of management functions stored in the main management module.

Emissions from passenger cars are included in the SEMBA module. There are two reasons for this: one is that they were available in the same form as the heavy-duty vehicle, which made the implementation simple, and thus the tool could be useful for non-freight applications. The second reason is for testing purposes, the author was more acquainted with passenger car fuel consumption and emissions. Euro emission factors for passenger cars are given as grams per kilometer. This makes it simple to check and debug general management functions. The passenger car module served as a debugging tool and is thus marked with a dotted line around the module in Figure 35.

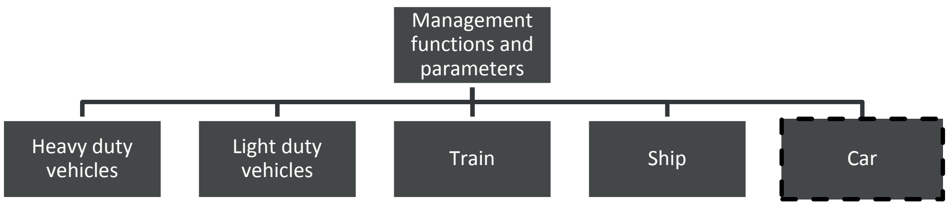


FIGURE 35 LAYOUT OF THE PYTHON SEMBA MODULE

The SEMBA module does not have any dependencies outside the Python standard library. There is however a test and debugging code inside the modules that require installation of Matplotlib[29] and NumPy[30] modules. Both NumPy and Matplotlib are open source and can be used free of charge. These modules are used to produce high quality plots. A total of 13,500 lines of code were written to complete the SEMBA module. The module does not contain any graphical user interface, only a set of Python callable routines.

The rest of this chapter will describe the calculations done in the sub modules, except for the passenger car module. The last part of the chapter will look at the GIS tool used in the calculations.

4.1 The heavy-duty vehicle module

There are nineteen different heavy-duty vehicles types in relation to vehicle maximum weight and configuration. Each of these vehicles are combined with six Euro standard classes to form the 114 heavy-duty vehicles defined in the ARTEMIS project. There are four sub-segments of vehicles: coaches; urban busses; rigid trucks; and truck-trailer/articulated-truck. Table 16 lists the vehicle types, maximum weight, their id number and Euro standard compliance.

TABLE 16 HEAVY-DUTY VEHICLE IDENTIFICATION NUMBERS

ID	Description	ID	Description	ID	Description	ID	Description
1	Coach Std <=18t 80ties	31	RT <=7.5t 80ties	61	RT >26-28t 80ties	91	TT/AT >34-40t 80ties
2	Coach Std <=18t Euro-1	32	RT <=7.5t Euro-1	62	RT >26-28t Euro-1	92	TT/AT >34-40t Euro-1
3	Coach Std <=18t Euro-2	33	RT <=7.5t Euro-2	63	RT >26-28t Euro-2	93	TT/AT >34-40t Euro-2
4	Coach Std <=18t Euro-3	34	RT <=7.5t Euro-3	64	RT >26-28t Euro-3	94	TT/AT >34-40t Euro-3
5	Coach Std <=18t Euro-4	35	RT <=7.5t Euro-4	65	RT >26-28t Euro-4	95	TT/AT >34-40t Euro-4
6	Coach Std <=18t Euro-5	36	RT <=7.5t Euro-5	66	RT >26-28t Euro-5	96	TT/AT >34-40t Euro-5
7	Coach 3-Axes >18t 80ties	37	RT >7.5-12t 80ties	67	RT >28-32t 80ties	97	TT/AT >40-50t 80ties
8	Coach 3-Axes >18t Euro-1	38	RT >7.5-12t Euro-1	68	RT >28-32t Euro-1	98	TT/AT >40-50t Euro-1
9	Coach 3-Axes >18t Euro-2	39	RT >7.5-12t Euro-2	69	RT >28-32t Euro-2	99	TT/AT >40-50t Euro-2
10	Coach 3-Axes >18t Euro-3	40	RT >7.5-12t Euro-3	70	RT >28-32t Euro-3	100	TT/AT >40-50t Euro-3
11	Coach 3-Axes >18t Euro-4	41	RT >7.5-12t Euro-4	71	RT >28-32t Euro-4	101	TT/AT >40-50t Euro-4
12	Coach 3-Axes >18t Euro-5	42	RT >7.5-12t Euro-5	72	RT >28-32t Euro-5	102	TT/AT >40-50t Euro-5
13	Ubus Midi <=15t 80ties	43	RT >12-14t 80ties	73	RT >32t 80ties	103	TT/AT >50-60t 80ties
14	Ubus Midi <=15t Euro-1	44	RT >12-14t Euro-1	74	RT >32t Euro-1	104	TT/AT >50-60t Euro-1
15	Ubus Midi <=15t Euro-2	45	RT >12-14t Euro-2	75	RT >32t Euro-2	105	TT/AT >50-60t Euro-2
16	Ubus Midi <=15t Euro-3	46	RT >12-14t Euro-3	76	RT >32t Euro-3	106	TT/AT >50-60t Euro-3
17	Ubus Midi <=15t Euro-4	47	RT >12-14t Euro-4	77	RT >32t Euro-4	107	TT/AT >50-60t Euro-4
18	Ubus Midi <=15t Euro-5	48	RT >12-14t Euro-5	78	RT >32t Euro-5	108	TT/AT >50-60t Euro-5
19	Ubus Std >15-18t 80ties	49	RT >14-20t 80ties	79	TT/AT >20-28t 80ties	109	TT/AT >14-20t 80ties
20	Ubus Std >15-18t Euro-1	50	RT >14-20t Euro-1	80	TT/AT >20-28t Euro-1	110	TT/AT >14-20t Euro-1
21	Ubus Std >15-18t Euro-2	51	RT >14-20t Euro-2	81	TT/AT >20-28t Euro-2	111	TT/AT >14-20t Euro-2

[29] http://matplotlib.sourceforge.net/index.html
[30] http://numpy.scipy.org/

22	Ubus Std >15-18t Euro-3	52	RT >14-20t Euro-3	82	TT/AT >20-28t Euro-3	112	TT/AT >14-20t Euro-3
23	Ubus Std >15-18t Euro-4	53	RT >14-20t Euro-4	83	TT/AT >20-28t Euro-4	113	TT/AT >14-20t Euro-4
24	Ubus Std >15-18t Euro-5	54	RT >14-20t Euro-5	84	TT/AT >20-28t Euro-5	114	TT/AT >14-20t Euro-5
25	Ubus Artic >18t 80ties	55	RT >20-26t 80ties	85	TT/AT >28-34t 80ties		
26	Ubus Artic >18t Euro-1	56	RT >20-26t Euro-1	86	TT/AT >28-34t Euro-1		
27	Ubus Artic >18t Euro-2	57	RT >20-26t Euro-2	87	TT/AT >28-34t Euro-2		
28	Ubus Artic >18t Euro-3	58	RT >20-26t Euro-3	88	TT/AT >28-34t Euro-3		
29	Ubus Artic >18t Euro-4	59	RT >20-26t Euro-4	89	TT/AT >28-34t Euro-4		
30	Ubus Artic >18t Euro-5	60	RT >20-26t Euro-5	90	TT/AT >28-34t Euro-5		

Figure 36 shows the two most used types of heavy-duty vehicles for long-haul freight transport. The coaches and busses are not used for freight transport, but are included in the python code. For each of these vehicles there exists a set of parameters: gradients (-6, -4, -2, 0, 2, 4, 6); emission components (FC, NO_x, PM, THC, CO) and three load situations (0%, 50%, 100%). FC is short for Fuel Consumption and is used for calculating CO_2 emissions. It is assumed that 99% of the carbon in the fuel is oxidized and conversions factors based on molecular weight can thus be used. Thus 1 kilogram of diesel produces 3.17 kilograms of CO_2. These calculations are in line with official recommendations from the NPRA[31].

Articulated truck

Rigid truck

FIGURE 36 TYPES OF HEAVY-DUTY TRUCKS (PHOTOS: STOCK.XCHNG)

The following python source code calculates emissions for a 34-40 tonne articulated truck with a Euro IV compliant engine. The listing shows the amount of code needed to calculate emissions for a heavy-duty vehicle given vehicle type, load, average speed and gradient. Each pollutant is calculated separately; in this case the fuel consumption "FC" is calculated.

31 http://www.vegvesen.no/Kjoretoy/Fakta+og+statistikk/Sikker+bil/Miljo/Miljoutslipp/Co2+utslipp

```
Import SEMBA.HDV as hdv

VehicleID = 95
Component= "FC"
AverageSpeed = 50
Gradient = 3.2
Load = 100

print hdv.CalculateHDV(VehicleID, Component, AverageSpeed, Gradient, Load)

RESULT:

(877.34700062484694, 'g/km', ['No Warnings'])
```

LISTING 1 SEMBA CALCULATE EMISSIONS FOR 34-40T TRUCK

The calculation function returns the amount of emissions, the unit in which the amount is returned and any warnings. Warnings will be issued if maximum positive grade is exceeded. The maximum grade is set at 12%. For all positive grades there seems to be a linear relationship between emissions and gradient at each speed. The emission factors developed in the ARTEMIS project are discreet for percentage values (-6, -4, -2, 0, 2, 4, 6). Gradients in the Norwegian road network are not discreet. Figure 37 and Figure 38 shows statistical overviews of the Elveg network to which the HDV emission functions will be applied. The first bar graph shows the road length for each category of road. The box plot shows the distributions road segment lengths. Most links in the road network are short; the median segment length is less than 100 meters. The mean segment length is around 200 meters except for the municipal roads (K).

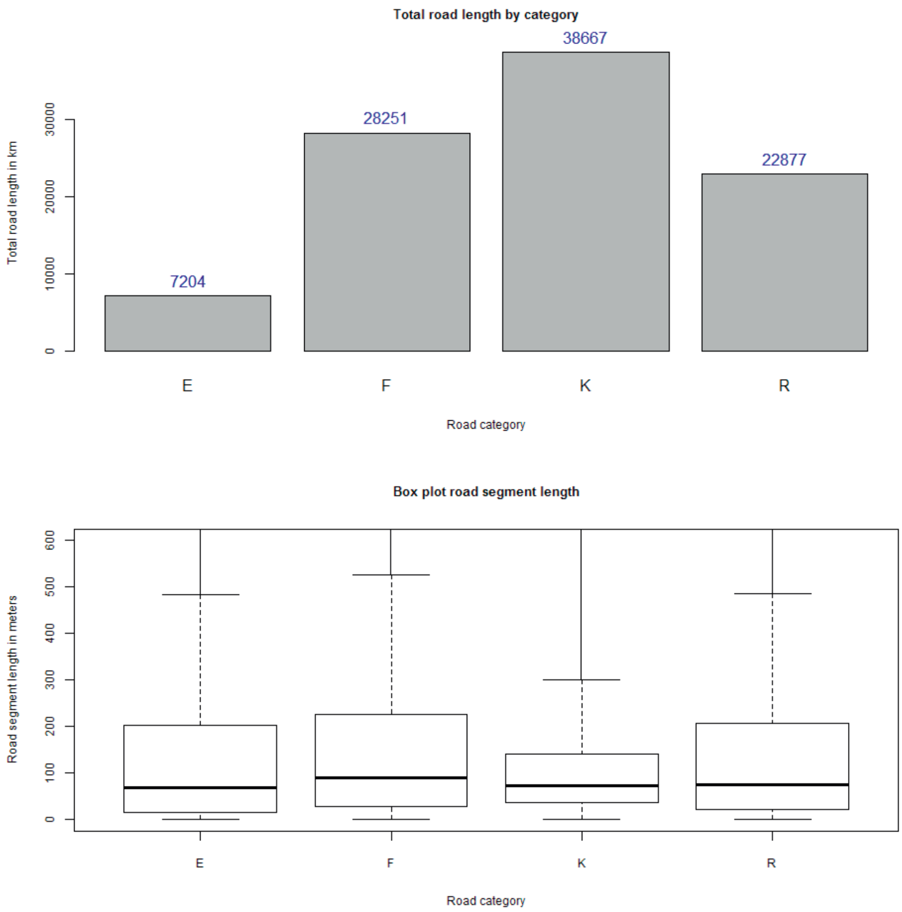


FIGURE 37 OVERVIEW OF THE NORWEGIAN ROAD NETWORK; ROAD CATEGORY LENGTH AND ROAD SEGMENT LENGTH

The gradient distribution is shown in the bottom part of the figure. Most of the distance in the complete road network is flat, under 1% absolute gradient. But there are quite a few meters of road that have absolute gradients larger than 6%. For the positive grades, a linear function is estimated for the specific speed. This allows for extrapolation of the gradients, and a maximum grade of 12% was chosen. According to the Norwegian road standards, a maximum grade of 8% is allowed for trunk roads (Vegdirektoratet, 2008 p. 66), but there exists roads with steeper gradients that are built before the standard came into effect or the roads are exempt from the standard. Many of the grades beyond 12% are believed to be errors in the network and maximum gradients are thus capped at 12%. When data quality of the road network is improved, and the number of links with erroneous grades is reduced, the gradient cap could be removed.

The plot in the lower part of Figure 37 is called a box plot, which is a quick way to communicate the median, upper and lower quartile, minimum and maximum value as well as an indication of which values are considered to be outliers. The letters (E,F,K,R) are encodings for the administrative road categories as shown in Figure 21.

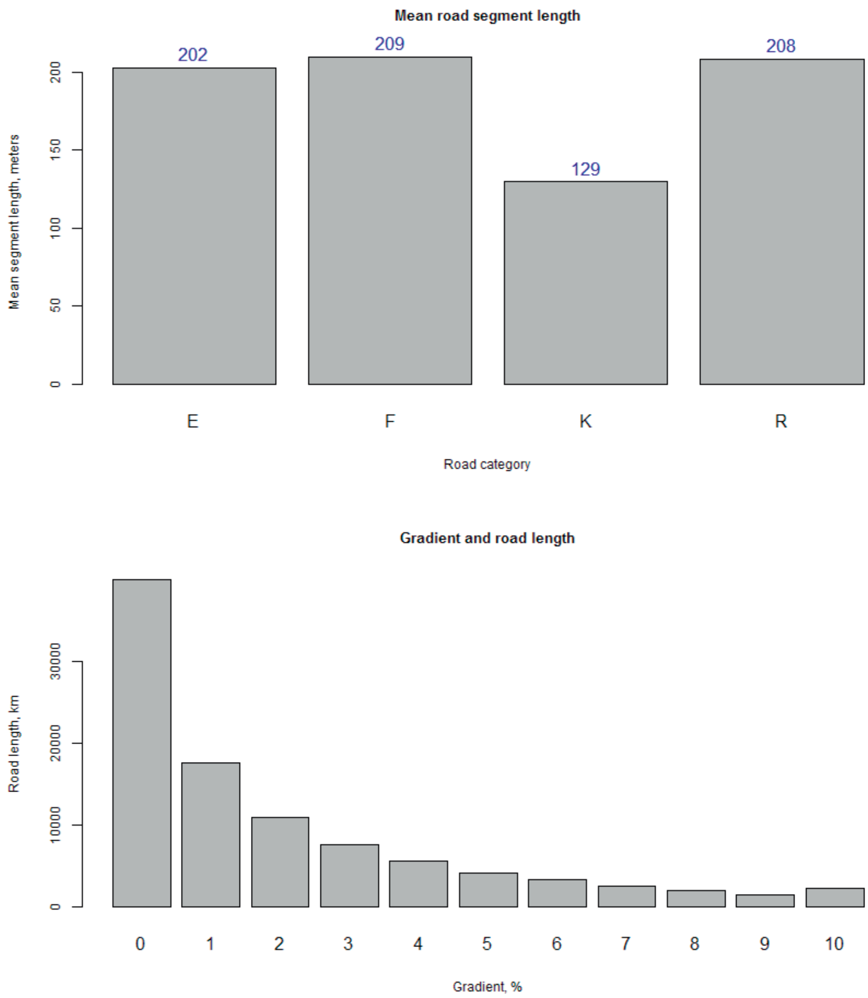


FIGURE 38 OVERVIEW OF THE NORWEGIAN ROAD NETWORK; ROAD LENGTH AND GRADIENTS

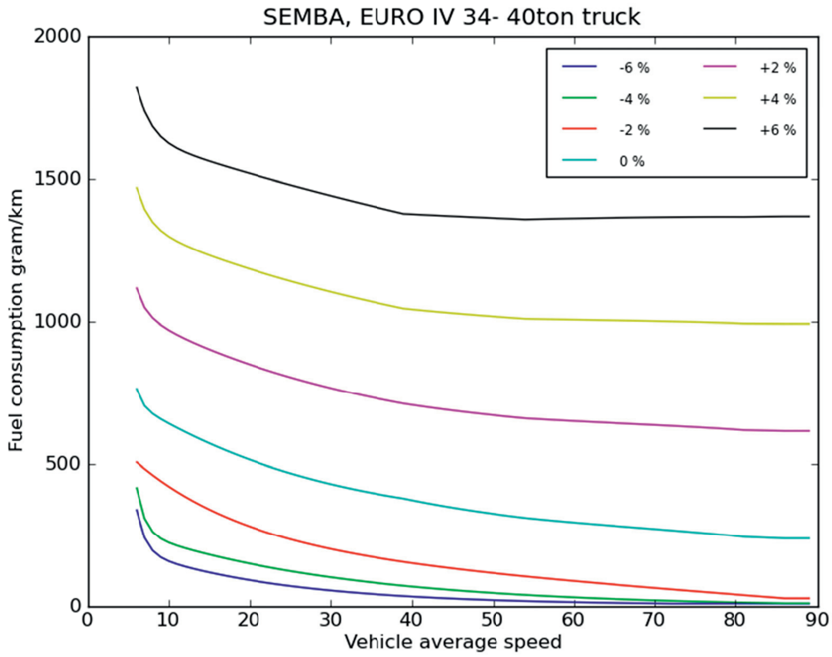


FIGURE 39 IMPACT OF GRADIENTS AT DIFFERENT AVERAGE SPEEDS FOR A FULLY LOADED 34-40T EURO IV TRUCK

For each link in the road network, emissions for every vehicle, pollutant and three degrees of vehicle loading is calculated. A naming scheme was introduced to keep track of the different emissions in a systematic way. For each link, columns are added with the following naming:

HDV_id_component_direction_load

- **HDV**: is a designation for heavy-duty vehicles. For light duty vehicles the designation is LDV.
- **Id**: is the vehicle identification number, for heavy-duty vehicles, see Table 16 Heavy-duty vehicle identification numbers.
- **Component**: the emission component or fuel consumption (FC, CO, CO_2, PM, THC, NO_x).

For each vehicle type (one vehicle id), 30 columns are added, thus a total of 3,420 columns are added to the feature class.

A python script was created for calculating the link emissions. And the script can be executed via the standard ESRI ArcToolbox interface. Figure 40 shows screenshots for entering input data and the calculation routines.

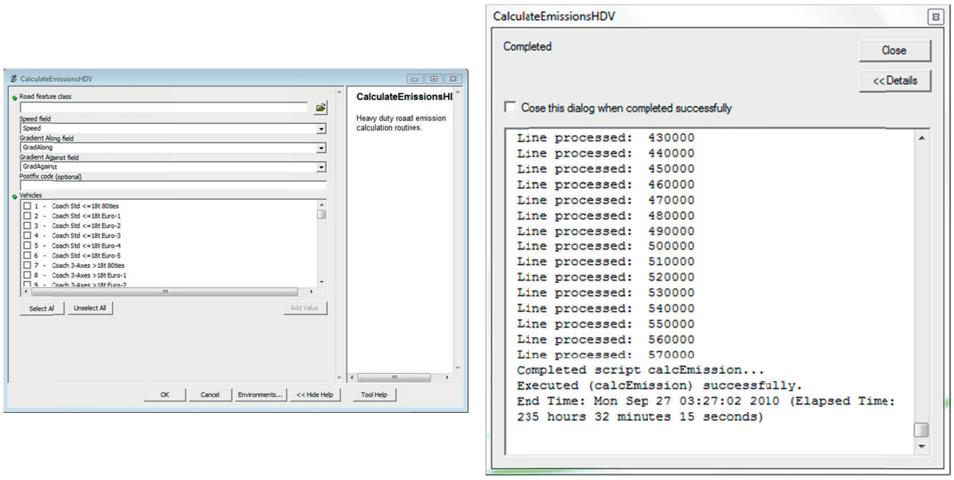


FIGURE 40 HDV LINK EMISSION CALCULATION

The calculation routine takes from under two hours to three and a half hours to complete. The runtime seems to be related to the size of the feature class storing the calculated values. Thus for the first vehicles the runtime is short while for the last vehicles the runtime is longer. For the 114 vehicle types, this results in a runtime of about 235 hours, or slightly less than ten days. This process is a onetime process each time the network is updated. And it is possible to run the emission calculation routine on only new or updated links in the network, thus reducing the computational time to seconds.

For each of the columns, an evaluator needs to be added to the network. An evaluator is a link between the columns in the feature class and the network solving routines. In short an evaluator allows for values in a column to be aggregated, thus emissions for all the links in a route can be added together.

4.2 THE LIGHT DUTY VEHICLE MODULE

Some vehicles below 3.5 tonnes are used for commercial freight. These vehicles are known under different names; light duty vehicles (LDV), light commercial vehicles (LCV) or light duty goods vehicles (LDGV). The term light duty vehicle (LDV) will be used in this thesis. These vehicles are used to deliver smaller amounts of freight and have different driving patterns from passenger cars and hence different emissions. The LDV emissions take vehicle loading into account, but gradients are not included. The vehicle groups combined with the Euro standard are assigned a vehicle ID. Table 17 shows the vehicle ID's that can be used in the SEMBA calculation. First one finds the fuel type of the vehicle, then the tare weight, and then one looks in the selected Euro standard column and finds the vehicles identification number to be used in the calculation routines.

TABLE 17 LIGHT DUTY VEHICLE CLASSIFICATION

Vehicle type			Euro 0	Euro 1	Euro 2
	N1-I	Tare weight less than 1305 kg	1	4	7
DIESEL	N1-II	Tare weight between 1305 and 1760 kg	2	5	8
	N1-III	Tare weight between 1761 and 3859 kg	3	6	9
	N1-I	Tare weight less than 1305 kg	10	12	
PETROL	N1-II	Tare weight between 1305 and 1760 kg	11	13	15
	N1-III	Tare weight between 1761 and 3859 kg		14	16

LDV emissions are calculated on a link by link basis like HDV emissions. There are fewer LDV vehicle types, thus calculation runtime is shorter. There are only sixteen LDV vehicle types as opposed to 114 HDV vehicle types. The LDV emission factors developed by the ARTEMIS project use only average speed and vehicle loading as input. For each function, a valid load range and emission range is defined.

```
import SEMBA.LDV as ldv

VehicleID = 6
Component= 'FC'
AverageSpeed=50
Loading = 50

print ldv.CalculateLDV(VehicleID, Component, AverageSpeed, Loading)

RESULT:
(149.40999999999997, 'g/km', ['No Warnings'])
```

LISTING 2 SEMBA LIGHT DUTY VEHICLE EMISSIONS MODULE

4.3 CALCULATION WARNINGS IN THE LDV AND HDV MODULE

The road emission functions from ARTEMIS have limitations regarding average speed. Results from the emission functions are only valid within a certain speed interval. For each function there is a minimum and maximum average speed. If average speed is outside this interval, a warning is issued. A warning is issued if the gradient cap is reached. The calculation does not fail if the values are outside the legal interval, but a warning is returned along with the value of the last legal value. If the maximum speed is 69 km/h and a value of 80 km/h is used, the result of a calculation with 69km/h is returned along with a warning that the maximum speed has been exceeded. An example of a calculation where the maximum speed is exceeded can be seen in Figure 39. Here the emissions calculated for a gradient of +6% is constant for all speeds over 55 km/h.

For light duty vehicles there are defined minimum emissions and an interval for load. If these conditions are violated, a warning will be issued and the closest legal value will be used.

4.4 THE RAIL MODULE

Work package 700 in the ARTEMIS project looked at train activity and emission factors. The outcome of WP 700 is a Microsoft Excel based model that includes railway data. The model available at the ARTEMIS documentation site has data for fifteen countries. The countries are: Austria, Belgium, Denmark, Finland, France, Germany, Great Britain, Greece, Ireland, Italy, Luxembourg, Nederland, Portugal, Spain and Sweden. Unfortunately, data for Norway is not included. This reduces the usefulness of the model developed in the ARTEMIS project. The ARTEMIS rail model first calculates the energy used and then multiplies the energy with energy specific emission factors. For diesel trains energy consumption is calculated then converted into fuel consumption and then converted to emissions via fuel specific emission factors.

Since input data was not available to use the ARTEMIS model, a simple model based on chapter 3 in Lindgreen and Sorenson (2005b) was implemented. Testing of the model gave low energy consumption for freight trains. One of the major problems with this model is that most of the potential energy is converted into kinetic energy except for what is lost to wind and rolling resistance. In the Norwegian rail network there are several stretches where breaks are applied to keep the train under the speed limit. This loss of energy is not modeled correctly in the SEMBA model. The SEMBA calculation model needs the following input data for each train configuration:

TABLE 18 INPUT VARIABLES TO SEMBA TRAIN ENERGY CALCULATION MODULE

Variable	Description
CL_{loco}	Locomotive air resistance coefficient
CL_{wagon}	Wagon air resistance coefficient
A_{norm}	Normal frontal area of the locomotive
M_{loco}	Mass of the locomotive
M_{wagons}	Mass of empty wagons
$M_{payload}$	Mass of total payload
Csv	Constant given in per thousand, found in Lindgreen and Sorenson (2005b) for Danish trains
C1	Constant given in per thousand, found in Lindgreen and Sorenson (2005b) for Danish trains
C2	Constant given in per thousand, found in Lindgreen and Sorenson (2005b) for Danish trains
Fsl	Initial value for locomotive driving resistance
Axels	Total number of axels
N_e	Energy efficiency

Each train configuration is stored in the SEMBA module with an accompanying ID number. A code example is not included, as an alternative method to calculate train energy usage was preferred.

Testing of the model gave low values for energy use per gross tonne kilometer when compared to official figures (Jernbaneverket, 2006 appedix 1, p. 2) that are used for calculating energy cost for trains without energy meters. Energy consumption was checked against rail energy consumption figures found in the EcoTransIT documentation (Knörr et al., 2010 Table 23, p 44). The calculations were to be compared with data collected by a freight rail operator. The rail operator did not manage to deliver sufficient amounts of data, and in addition they would not vouch for the quality of the data. The measurement system was implemented in 2010 and the rail freight transport service provider had limited experience with the system. This meant that it was not possible to test the SEMBA rail calculation results against observed data. Figure 41 shows the total energy consumption measured for nine trips with the same train from Alnabru to Dombås. The correlation between total energy usage and total train weight is weak, as an r-squared value of 0.27 was found. The low r-square value could indicate that there are important factors missing. At present only weight and distance are needed to describe freight train energy usage. If factors expressing driver behavior and number of stops were included a better model could perhaps be found. If detailed gradient and more observed values for energy consumption become available then the model could be improved significantly.

An alternative to using the SEMBA train model is to use energy consumption estimates that are used for billing the freight transport service providers that do not have energy meters in their locomotives. This is an improvement over the existing factor found in tools like EcoTransIT as the figures differentiate between different rail lines in Norway. The alternative energy consumption factors are only dependent on gross tonne kilometers.

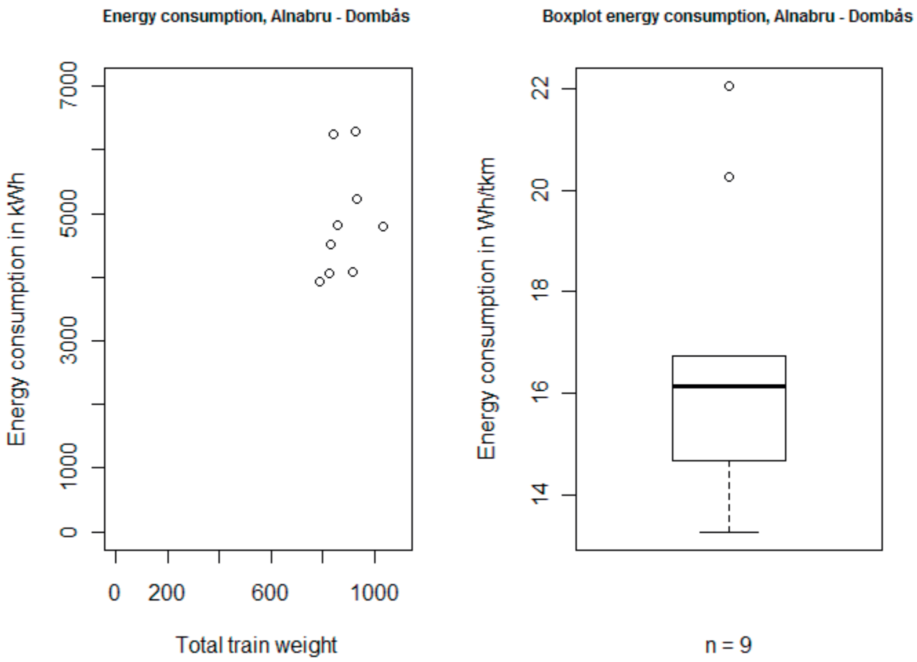


FIGURE 41 ENERGY CONSUMPTION FOR ELECTRIC TRAINS ALNABRU - DOMBÅS

Table 19 lists the expected energy usage per gross tonne kilometer for freight trains on different railroad sections in Norway. The measured data received from the rail freight transport service provider can be compared to the data for Dovrebanen. The median is approximately 16 Wh per gross tonne kilometer in the measured data while a value of 25 Wh per gross tonne kilometer was given by Norwegian National Rail Administration. The comparison is rather crude since the rail stretch from Alnabru to Dombås has a moderate grade, from 100 to 659 meters above sea level over 280 kilometers. After Dombås, the Dovrebanen starts to climb the Dovrefjell mountain pass, with the highest point being 1,204 meters and is located 40 kilometers after Dombås. Thus energy usage measured in Wh per gross tonne kilometer should be lower for the section between Alnabru and Dombås than for the whole stretch, Alnabru to Trondheim. This could indicate that there is an agreement between the measured values and those given by Jernbaneverket.

Both Table 19 and the measured energy consumption data collected by the rail freight transport service provider give energy usage at the point of consumption; it does not include losses in the catenary lines, phase converters and transmission lines.

TABLE 19 FREIGHT TRAIN ENERGY USAGE BY RAILROAD SECTIONS SOURCE: (JERNBANEVERKET, 2006 APPENDIX 1, P. 2)

Railroad sections	Wh / gross tonne kilometer
Bergensbanen	30
Dovrebanen	25
Sørlandsbanen (Oslo – Kr.sand)	27
Sørlandsbanen (Kr.sand - Stavanger)	30
Ofotbanen (westwards)	2
Ofotbanen (eastwards)	64

Table 20 gives the energy efficiency as seen from the public power grid with the most used types of locomotives. EL16 and EL14. The telefilter is a piece of technology that reduces the reactive load on the catenary and transmission lines so that the energy loss is reduced. According to the rail freight transport service provider, they have a commitment to have the telefilter engaged on all their locomotives unless there are equipment failures. Table 20 is calculated based on tables presented in appendix 3 of "Jernbaneverkets standardvilkar for avregning av 16 Hz energy" (The Norwegian National Rail Administration standard agreement for settlement of 16 Hz energy) (Jernbaneverket, 2006). Combining Table 19 and Table 20 will give energy consumption factors for Norwegian rail. The energy consumption should then be multiplied by the appropriate emission factors found in Table 6. After 2007 all energy bought by the national rail administration has certificates of origin that state the same amount of energy is produced from hydroelectric plants in Norway (Jernbaneverket, 2009 p. 12). The energy bought by the national rail administration is distributed to the rail operators.

TABLE 20 ENERGY EFFICIANCY MEASURED FROM THE PUBLIC POWERGRID

Area	Locomotive	Energy efficiency
Southern - Norway	EL 14	75 %
Southern - Norway	EL 16 with telefilter	75 %
Southern - Norway	EL 16 without telefilter	72 %
Ofotbanen	EL 14	69 %
Ofotbanen	EL 16 with telefilter	69 %
Ofotbanen	EL 16 without telefilter	66 %

4.4.1 Diesel trains

Since the model based on the ARTEMIS documentation is believed to underestimate energy consumption, an alternative method was needed for diesel trains. The rail operator did not have performance data for fuel consumption on Nordlandsbanen. Nordlandsbanen is a non-electrified stretch of railroad from Trondheim to Bodø and is extensively used for freight transport. An alternative approach was to use the TogKjør computer application. The computer application is decommissioned, thus the link between the national rail databank and the computer application was severed. But an employee of the national road administration built a dataset for Nordlandsbanen and ran energy calculations. A typical train for the relation was chosen and calculations were done with 0% and 100% utilization of the train based on weight. Maximum payload was set to 441 tonnes, and maximum total train weight was set to 900 tonnes. The tar weight of the train was 459 tonnes. The train was powered by one CD66 locomotive.

$$Diesel\ consumption({}^{liters}/_{ton\ km}) = \frac{16.10X\ (liter)\ + 2060(liter)}{441\ (ton) * \frac{X}{100} * 728.75\ (km)}$$

In the equation above, the X is the percentage utilized of the maximum payload weight. For a 50% utilized train this works out to 0.01 liters per tonne kilometer which is equal to 0.0269 kilograms of CO_2 per net tonne kilometer. The annual average for CargoNet, the rail freight transport service provider, is 0.04 kilograms of CO_2 per net tonne kilometer (Jernbaneverket, 2009). Several of the smaller rail freight transport service providers, in respect to net tonne kilometers, have annual emission factors in the range 0.02 – 0.01 grams of CO_2 per net tonne kilometer.

The diesel emission factors should be combined with the appropriate fuel specific emission factors given in Table 4. The column with the SSB 2001 data are believed to be best at reflecting the Norwegian diesel trains as they were specifically developed for Norway.

4.5 THE SEA MODULE

For sea transports, the model described in Sjöbris et al. (2005) was implemented. In the SEMBA calculation tool the user needs to enter the ship type, fuel type and either deadweight tonnage (DWT) or gross tonnes (GT).

TABLE 21 LISTS THE POSSIBLE SHIP TYPES THAT CAN BE USED IN THE CALCULATIONS, THE THREE FUEL TYPES AVAILABLE ARE PRESENTED IN

Table 22.

TABLE 21 SHIP TYPE NUMBERS

Ship type number	Description
1	Bulk H_SHIP
2	Dry cargo
3	Container
4	Ro-Ro
5	Reefer
6	Cargo ferry

7	Passenger ferry
8	High-Speed ferry
9	Tanker
10	Gas tanker
11	Cruise vessel
12	Vehicle carrier

TABLE 22 AVAIABLE SHIP FUELS

Fuel designation	Description
MDO	Marine diesel oil
MGO	Marine gas oil
RO	Residual oil

In addition to main engine emissions there are emissions from auxiliary power when the ship is laying in port and when the ship is loading or unloading. The ARTEMIS ship model has a separate model that calculates auxiliary engine emissions. An example of a ship energy calculation is presented below. First cruising energy consumption is reported in gram per kilometer then energy consumption auxiliary engines are reported as gram per hour. The first set of emission figures from the auxiliary module are for port operations, the last set is for hoteling in harbor.

```
import SEMBA.SHIP as ship

ShipID = 3
FuelType = 'FC'
EngineStrokes = 4
GrossTons = -1
DeadWeghtTons = 1278

print ship.CalculateShipSail(ShipID, FuelType, stroke= EngineStrokes, GT=
GrossTons, DWT= DeadWeghtTons)

RESULT:
[6660.9791051662942, 399.1146555801962, 31.681232367021618, 18.939867175936836,
6.5428632062327248, 21115.303763377153, 26.643916420665178, 'g/km', []]

print ship.CalculateAUX(ShipID, FuelType ,GT= GrossTons,DWT= DeadWeghtTons)

RESULT:
([21431.740925035472, 1403.8358497840707, 149.22212630574751, 70.019613112696902,
41.323050361591612, 67938.618732362447, 85.726963700141894, 'g/h'],
[10466.664172691742, 685.59425222012749, 72.875922149318541, 34.195625008526392,
20.1810245951959, 33179.325427432821, 41.866656690766973, 'g/h'])
```

LISTING 3 SEMBA EXAMPLE SHIP EMISSION CALCULATION

Emissions when sailing are a function of distance, while emission factors for auxiliary engines are a function of time. The components are reported in the following order: Fuel Consumption, NO_x, CO, HC, PM, CO_2, SO_2.

4.6 THE TERMINAL

It was originally planned to include calculation of terminal emissions in SEMBA. The final version of SEMBA does not include terminal emissions, as there was a lack of data to estimate terminal emission factors. A terminal emission module could be implemented in SEMBA when emission figures for terminals are available. The star system suggested in section 3.4.4 can be used to give the freight companies incentives to collect data that can eventually be used to create terminal specific emission factors.

4.7 SUMMARY OF SEMBA

The main goal of building SEMBA was to have a unified model for calculating emissions on transport links that could be used from within a GIS system. Using a dynamic programming language like Python is beneficial because programs/modules are primarily distributed as human readable code and not byte-compiled code. Distributing the source code makes it easier for third parties to find bugs or wrong assumptions in the program/module.

When building SEMBA it became evident that the level of detail, in emission calculations, was quite different between the modes. The road module has a higher degree of detail than the sea module. The road module uses more than 11,000 equations to describe emissions from the heavy-duty road fleet, while the ship module uses sixteen lookup tables to describe main engine emissions from the shipping fleet. The ARTEMIS rail energy calculations were not used since they depend on a speed acceleration matrix. No speed acceleration matrix was available for Norway and thus a simplified version of the energy calculation routine was built. Emissions from terminal operations are not included in SEMBA due to the lack of data to estimate specific emission factors for each terminal.

Over time there will be changes to the transport technologies used, as the design of SEMBA allows for new technologies to be included when calculation routines become available. Alternative calculation routines can be included and used to see the impact of different calculation strategies. SEMBA is made available as open source and posted on SourceForge[32]. This will give any interested parties the ability to use the tool and to contribute to the SEMBA project.

The large difference in level of detail between the modes has implication when doing comparisons between modes. In effect it means that one can get into gray areas when comparing modes where the emission difference is small. Thus care should be taken when trying to assess which mode is best when doing comparative studies. It is important to understand the impact the level of detail can have on the calculations for specific routes.

---

[32] `http://sourceforge.net/projects/semba/`

The implementation of SEMBA as a standalone unified calculation module allows for more possible uses of the new emission model. The SEMBA module could be extracted and used to test emission performance and the effect of network detail. In Levin and Norvik (2010) the SEMBA module was used to test the emission effect of using average gradients over long distances in contrast to using a detailed road network. The test showed that using average gradients can cause underestimation of emissions. The SEMBA module could thus be used for academic purposes to gain a better understanding of single vehicle emissions in relation to user defined infrastructure.

A challenge when using emission functions or any model is the question of transferability. The emission models taken forward in the ARTEMIS project are primarily developed for central Europe. But are models developed for central Europe useable in Norway? The next chapter presents an experiment designed to give insight into the question of transferability of the road model for heavy-duty vehicles.

5 Control of the road model assumptions

This chapter presents an experiment that was designed to gain knowledge about transferability of the ARTEMIS Average speed model for heavy-duty vehicles to Norwegian conditions. To validate the model under Norwegian conditions would require measuring emissions form running vehicles. The equipment to measure tailpipe emissions is very costly and designing full-scale measurement champagne to measure heavy-duty vehicle tailpipe emissions is a complete Ph.D. project by itself. An alternative is to test the underlying assumptions.

A key assumption that was made when designing the model was that using the speed limit was a good proxy for average driving speeds. Another key assumption was driving behavior used by the ARTEMIS project as driving cycles.

Collecting speed data and comparing it to the speed limit was a way of testing if the speed limit is a good proxy for driving speed. This could be done by using inexpensive GPS units. The Green Freight Transport project owner, TPG, found a company that was willing to let us collect data from their vehicles. The plan was to use GPS data units to record vehicle trips and to store this data for later analysis. Another ongoing research project, “A speed model for commercial vehicles,” wanted to record georeferenced speed data from heavy-duty vehicles. Thus data collection was combined for both projects as TPG was involved in both projects.

In addition there was an explorative study to see if engine performance data could be collected using a standardized access to the vehicle's engine control unit. This data could have been used as input to the detailed model used in ARTEMIS to create HVD emission functions, namely the PHEM model.

5.1.1 Design

The idea was to collect geo-referenced speed data which could be combined with the digital road network for analysis. Using low cost GPS equipment looked like a reasonable solution, as manufacturers of GPS data loggers indicate that speed can be reported within 1/10 of a meter per second. Low-cost GPS units have been found satisfactory for reporting ground speed. Keskin and Say (2006) used low-cost GPS for agricultural purposes, while Witte and Wilson (2004) looked at GPS speed accuracy when biking. The GPS has been used to create real-world driving cycles, and a methodology for developing real-world driving cycles based on GPS data is described in Kamble et al. (2009). Jagadeesh et al. (2004) reported two interesting observations about GPS errors. First, the error between two consecutive readings is smaller than the average error of the GPS; second, the distance between current and previous GPS positions is almost equal to the true distance between the points. The above-mentioned papers indicate that commercial grade GPS units could be satisfactory for road vehicle speed measurements.

In addition to the fact that GPS seems to be able to give good enough speed measurements, the recorded speeds are geo-referenced. This means that the measured speed data can be linked with the road infrastructure. A goal for the data collection was to compare the observed driving speed with the speed limits. This is because speed limits are used as a proxy for average driving speeds in the new emission model. The other goal is to look at driving behavior and compare with existing driving cycles for HDV's.

One way to verify GPS speed data is to simultaneously collect data from the vehicle's speedometer. A cost effective way of doing this is by using the vehicles OBD II (On Board Diagnostics) connector. The OBD II connector is a standard diagnostics plug that vehicle mechanics can use to locate faulty sensors in the vehicle. The standard that the vehicle manufacturers have to adhere to is ISO 9141:1989 (International Organization for Standardization, 1998). ISO 9141 is for the hardware level, while ISO 15031-5 is for the application level according to the OSI model. The OSI reference model is presented in Zimmermann (1980). Readers for the OBD II connector are available on the Internet for under $25. Most of the readers have software that is able to read emission-related diagnostics as defined in ISO 15051-5 (International Organization for Standardization, 2006).

The last requirement was that the registrations were to have minimal effect on the driver and vehicle. The Green Freight Transport project was warned by the project owner that some of their hired long-haul drivers were concerned about their vehicles. Thus fixing antennas to the roof and making permanent fixtures to their vehicles was out of the question due to the fact that the vehicles would have to be taken out of service for the fitting. The equipment was also to be temporary, so that it could be installed and removed quickly.

5.2 PILOT STUDY

In order to test if it was possible to have the GPS antennas inside the car, tests were performed. From past experience with handheld GPS units, it was presumed that getting a good GPS reception inside a vehicle could be difficult. There had clearly been a development in the GPS technology. The Holux M1000 receiver got a fix within a few seconds and maintained a fix from any position on the dashboard. This was far better than anticipated. The Holux M1000 was chosen because of its low cost, and that it had Bluetooth for communicating with data logger equipment. An OBD KEY Bluetooth edition[33] was acquired to read speed data from the test vehicle's OBD II connector. The

[33] http://www.obdkey.com/

test vehicle was a 2006 Volkswagen Touran with a diesel engine. A Qtek, windows mobile smart phone was programmed as a logging device.

5.2.1 TECHNICAL DETAILS OF THE LOGGING SOFTWARE

The software that came with the GPS and the OBD II reader did not work well for logging data due to the lack of a time stamp for recorded data. Thus a piece of software had to be developed to receive the data stream from the GPS and to pull data from the OBD II reader and time stamp data. The Python programming language was chosen for writing the logging application. The Python language has been ported to many different operating systems, thus Python code can be run on many different devices not only a PC. Python is open source, has good documentation and a vibrant user community that shares code and modules that they develop. The language is easy to learn, and there are online tutorials especially written for scientists[34].

The GPS unit produces a constant stream of data that is compliant with the NMEA 0183 standard[35]. To receive data from the OBD II reader a request for data has to be made. A multithreaded application was created. One thread was used for saving the incoming NMEA messages from the GPS. The other thread was used to request data from the OBD II reader and to store the answer. Incoming data was time stamped by both threads using the data-logger's clock. A new data file was created every time the logging application was started. The application has the ability to transfer the stored files on the device using File Transfer Protocol (FTP). FTP is a standard protocol for transferring files over internet. Files were then transferred to a server when the vehicle was in range of a known Wi-Fi network.

Figure 42 shows the equipment used in the pilot, to the left is the OBD II reader, the windows mobile logger is in the middle and the GPS unit is on the right.

[34] http://software-carpentry.org/
[35] http://www.nmea.org/content/nmea_standards/nmea_083_v_400.asp

OBD II datalоger Qtek windows mobile phone Holux M1000 GPS

FIGURE 42 EQUIPMENT USED IN THE PILOT STUDY

Figure 43 shows a schematic of the data collection setup. Only GPRMC and GPGGA messages were stored from the GPS unit. These two sentences contain information on position, speed, elevation, number of satellites, time and date.

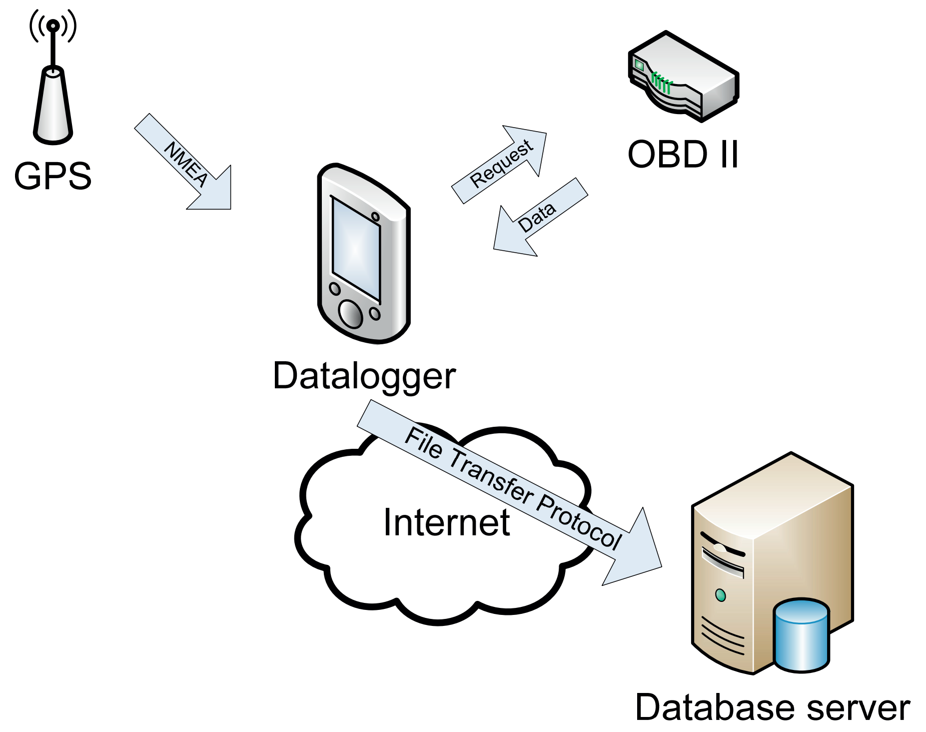


FIGURE 43 SCHEMATIC OF DATA COLLECTION SETUP

The data from the GPS and the OBD II reader are stored in a common log file. An example of a log file is shown in Listing 4. Each line has a prefix that includes a description of data type and a time stamp.

```
GPS_GGA,090105181424,$GPGGA,181040.0,6324.918941,N,01028.075949,E,1,06,2.0,173.5,M
,,,,*05
GPS_RMC,090105181424,$GPRMC,181040.0,A,6324.918941,N,01028.075949,E,15.6,297.4,050
109,,,A*57
OBD_RPM,090105181423,2048.0
OBD_Speed,090105181424,32
OBD_Load,090105181424,12.5490196078
GPS_GGA,090105181425,$GPGGA,181041.0,6324.920845,N,01028.066997,E,1,06,1.9,173.5,M
,,,,*01
GPS_RMC,090105181425,$GPRMC,181041.0,A,6324.920845,N,01028.066997,E,16.8,297.0,050
109,,,A*50
OBD_MAF,090105181425,23.38
OBD_RPM,090105181425,2185.0
OBD_Speed,090105181425,34
```

LISTING 4 SAMPLE DATA FROM THE LOG FILE

4 OBD II parameters were collected:

- RPM: Engine speed in revolutions per minute, PID $0C.

- MAF: Air used by the engine for combustion, PID $10.
- Load: Calculated engine load value, PID $04.
- Speed: Vehicle speed, PID $0D.

From the GPS the GPRMC and GPGGA sentences were stored. For a reference to the complete interpretation of the GPRMC and GPGGA sentences see chapter 8 in Zogg (2009).

5.2.2 Visual assessment of GPS positional quality

One way to quickly get a visual overview of the GPS positional quality is to draw the recorded points on top of a map. A small Python application was developed to read the GPS data from the log file and convert the latitude and longitude coordinates into UTM coordinates and save the data as an ESRI shape file.

Figure 44 shows the test route driven. The route was chosen so that there would be open landscape, sparsely developed areas, urban areas and to some extent urban canyons. An urban canyon is like a normal canyon but the sides are tall buildings instead of rocks. Urban canyons limit the view to the sky. It took under eighteen minutes to drive the complete route. The plotted GPS points follow the roads well, there is only one place where there is a large discrepancy. The purple circle (A) in the middle of the map shows the point where there is a discrepancy. This discrepancy consists of one reading that is clearly outside the other readings. The reason for this discrepancy is unknown.

A more detailed plot (circle B) is shown in Figure 45. On top of the vehicle track, the red line, the GPS vehicle speed is plotted. The speeds look reasonable and are in accordance with what one would expect. Compared to the driving notes the speeds through the roundabout seem a bit high at the give way line. This is thought to be because samples were taken once per second (1Hz). Thus collecting speed data at 1 Hz is not optimal for looking at a speed profile through a roundabout. But the purpose of the GPS speed data collection was to look at average driving speeds over longer road links found in the national road databank.

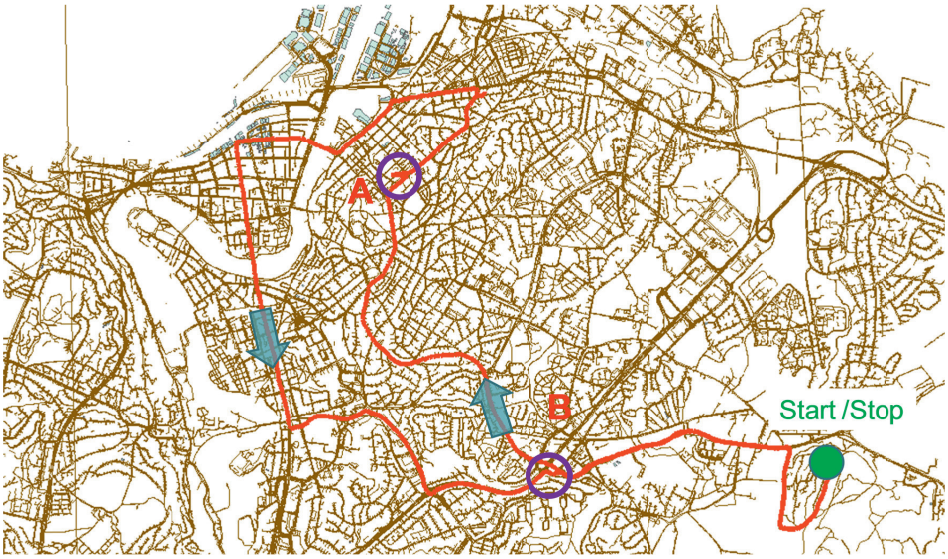


FIGURE 44 PLOT OF GPS TEST ROUTE, 1051 DATAPOINTS (1HZ)

Figure 46 shows the vehicle track from an urban canyon. The buildings in the city center of Trondheim are too low to create a real urban canyon, see photo in Figure 47. But along this route there are buildings on both sides of the vehicle that have three or more floors. There are two interesting points along this part of the route, the points A and B. In both points, the driving speed was reduced to less than 5Km/h due to traffic lights. The vehicle did not come to a complete stop, but the vehicle drove considerably slower than what the GPS reported. Again this shows that sampling at 1Hz is not fast enough for looking at behavior approaching intersections. But then again the GPS data will be used to calculate average driving speeds for road links in the trunk road network that is used by truck moving freight.

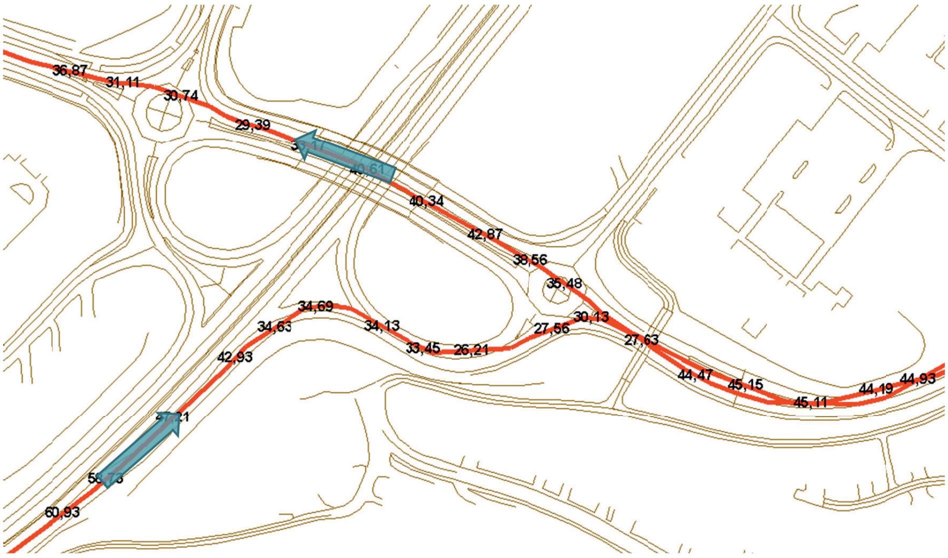


FIGURE 45 ZOOMED IN PLOT OF VISUAL GPS POSITIONAL QUALITY AT HIGHWAY INTERSECTION

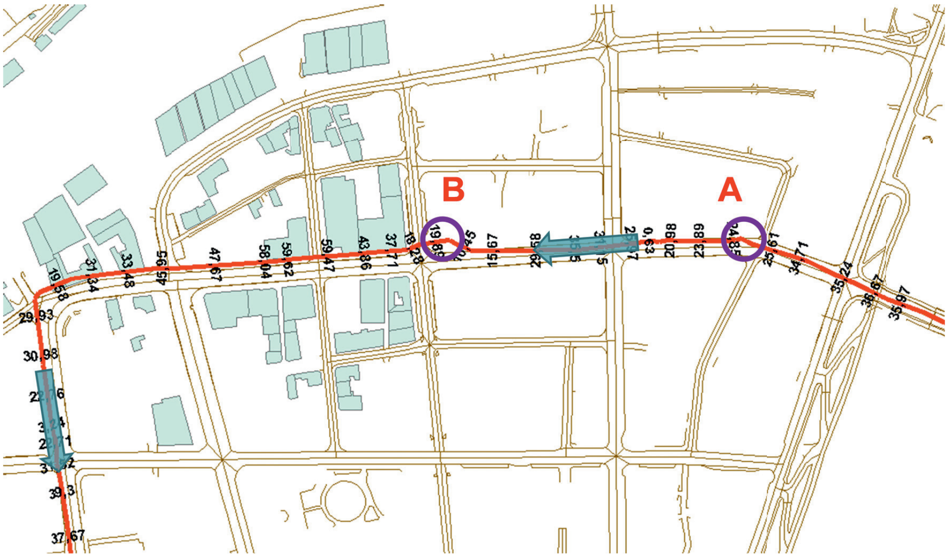


FIGURE 46 ZOOMED IN PLOT OF VISUAL GPS POSITIONAL QUALITY IN "URBAN CANYON"

FIGURE 47 PHOTO FROM GOOGLE'S STREET VIEW SHOWING THE URBAN CANYON IN TRONDHEIM FROM POINT A

The next step was to compare the speed measured by the vehicle (OBD) and the GPS. The result was surprising. Figure 48 shows a plot of speed against time from start of the trip. There is without a doubt a time shift present. By trial and failure a time shift of 17 seconds was found, the GPS data was recorded 17 seconds after the OBD data was recorded.

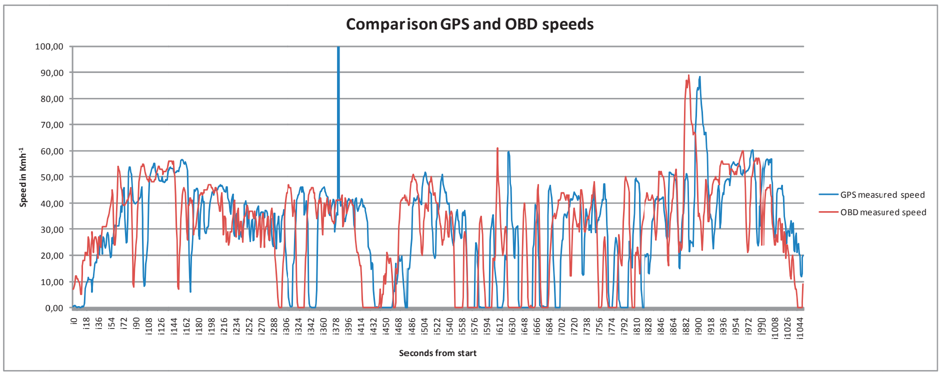


FIGURE 48 COMPARISON GPS AND OBD SPEED TIME SHIFT PROBLEM

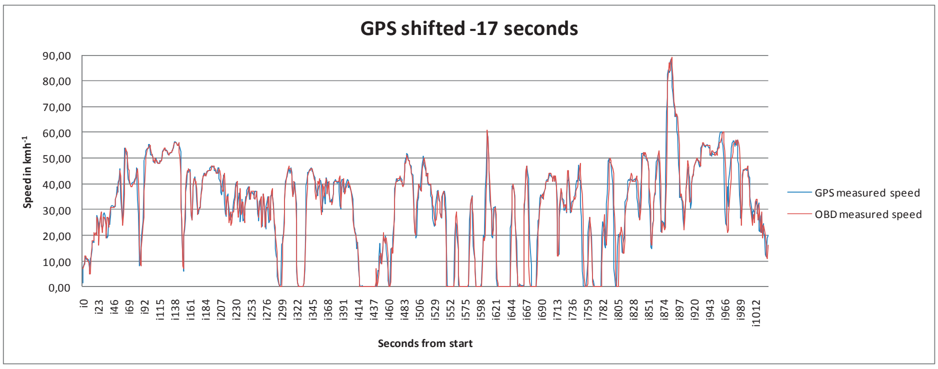


FIGURE 49 GPS SHIFTED -17 SECONDS, ONE OUTLAYER REMOVED

Several tests were performed to find the cause of the time shift, but without any luck. The time shift was not constant. If the GPS was powered up where the reception was bad, for example under a roof in an open garage, the time shift got bigger. If the GPS was started with a clear view to the sky, the time shift was reduced to a couple of seconds.

A new data logger was acquired, HP iPaq 914. The benefit of this unit was the integrated GPS, a faster processor and an updated version of the Windows Mobile platform (6.1). The main reason for choosing this phone was the integrated GPS. The same logging application was installed on the new device. A major difference was that now only one unit was connected via Bluetooth. The change to the new logger device solved the time shift problem. Thus the time shift problem was believed to stem from the hardware or the combination of hardware.

5.3 EQUIPMENT USED IN THE LARGE SCALE DATA COLLECTION

A trucking company operating fifteen rigid container trucks was recruited for data collection. The logger based on Windows mobile was tested, but was found unsatisfactory because the drivers did not use the unit. And when it came to collecting OBD data, the trucks had a 24-volt electrical system, which was incompatible with the OBD reader. After talks with the owners of the trucking company it became clear that we needed “black-box” loggers that required no interaction from the driver.

Worries about not placing the antenna on the roof were put to rest; it seemed that data collected with the GPS antenna behind the windshield was good enough for rural operations. Visual inspections of the GPS plots indicated that most of the observations were within 10 meters from the middle of the road. The comparison of GPS and OBD speeds gave no reason to move away from a plan of having the units within the vehicle.

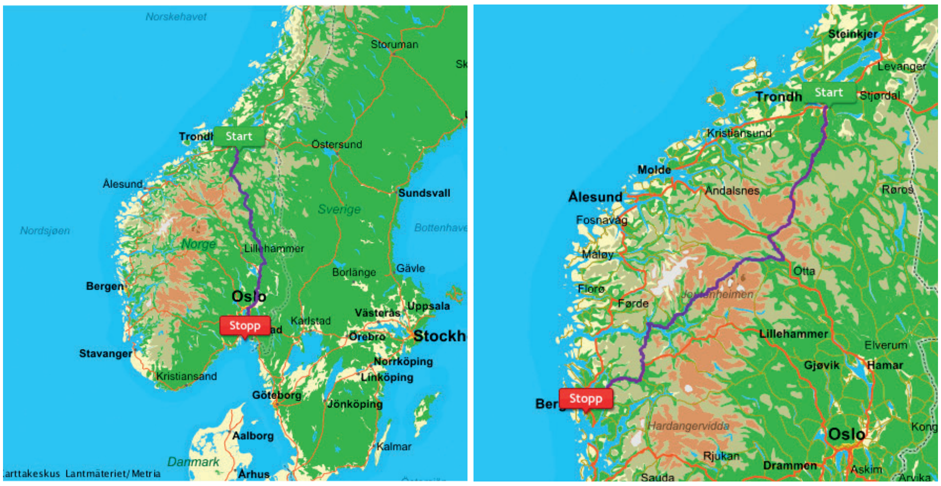
As part of the Green Freight Transport project and the Speed Model for Commercial Vehicles project a black box logger was commissioned. The logger was to log GPS data and OBD data at 1Hz and have the ability to transfer the logs via the cellular network to a storage server. The tech-staff at SINTEF Transport research bought 10 RTCU-MX2i pro units from LogicIO. The RTCU-MX2i is a piece of hardware that can be programmed by the customer. Thus a rather tedious process of creating a logger application was undertaken by SINTEF Transport research tech staff.

The final product did not live up to its expectations; the cellular part of the RTCU-MX2i was not able to transfer the GPS data at a high enough speed and recording and sending could not be done simultaneously. To get data from the CAN-bus one needed to know the vehicle's specific encoding. This reduced the usability of the logger to collecting GPS data only. The consequence of this was that the loggers had to be collected in order to download the data. The second consequence was that the loggers were not able to collect data from the vehicle's engine. Engine load and engine speed are key parameters that could be used to calculate emissions from engine maps as those seen in Figure 9. It would have been interesting to compare the emission estimated by the model with emissions calculated based on engine maps using engine speed and load. But this was unfortunately not possible since engine load and speed were not available from the full scale data collection.

5.4 Full scale data collection

A total of 10 RTCU-MX2i data loggers were used. The loggers were placed in trucks that were in real world operation. Two main freight routes from Trondheim were selected. The first route was between Trondheim and Moss which is in the south of Norway. The second route was between Trondheim and Bergen. The other loggers were placed in vehicles running from Åndalsnes to Oslo, Trondheim to Rørvik and in vehicles having regular routes on the Fosen peninsula.

Figure 50 shows routes served by 4 trucks, 2 in each route. Both of these two routes run on the trunk road network. Trondheim – Moss is 539.4 km and Trondheim - Bergen is 622.4 km. The routes drawn on Figure 50 show the shortest routes. The shortest routes are not always followed due to winter closings, extreme weather or driver changes.



Route: Tronheim - Moss Route Trondheim - Bergen

FIGURE 50 FREIGHT TRANSPORT ROUTES (MAP SOURCE: HTTP://KART.GULESIDER.NO/)

The registration period ran from February 2009 to February 2010. This resulted in 8.4 million GPS speed observations. Looking at the data from the trucks it became clear that they were used on different routes than those requested by the two research projects. This meant that the routines intended for map matching had to encompass the whole road network to utilize more of the data. In this thesis the term map matching is used to describe the method to connect the GPS data to the road network so that attributes like the speed limit can be compared with the observed speed. Details on the map matching used in this thesis are presented in section 5.6.3 and in Levin (2010). Figure 51 shows a map of Norway with the registrations plotted on top as purple points. Most of the trips are along the routes described earlier, but one can see that there are several “extra” trips in the Åndalsnes/Ålesund area and around Trondheim. This is because the vehicles are used for other assignments between the long-hauls. A small number of observations have been excluded because their positions were obviously wrong; they were located in the ocean west of Norway. The algorithm for linking GPS data points to the road network is able to remove these erroneous points. The impact of this finding was that the algorithms for analysis had to be able to exclude GPS data points if they were believed to be erroneous. This was accomplished via an exclusion criteria described in section 5.6.4 Analysis of driving speeds. Any GPS point further than 25 meters from the road was not used for further analysis.

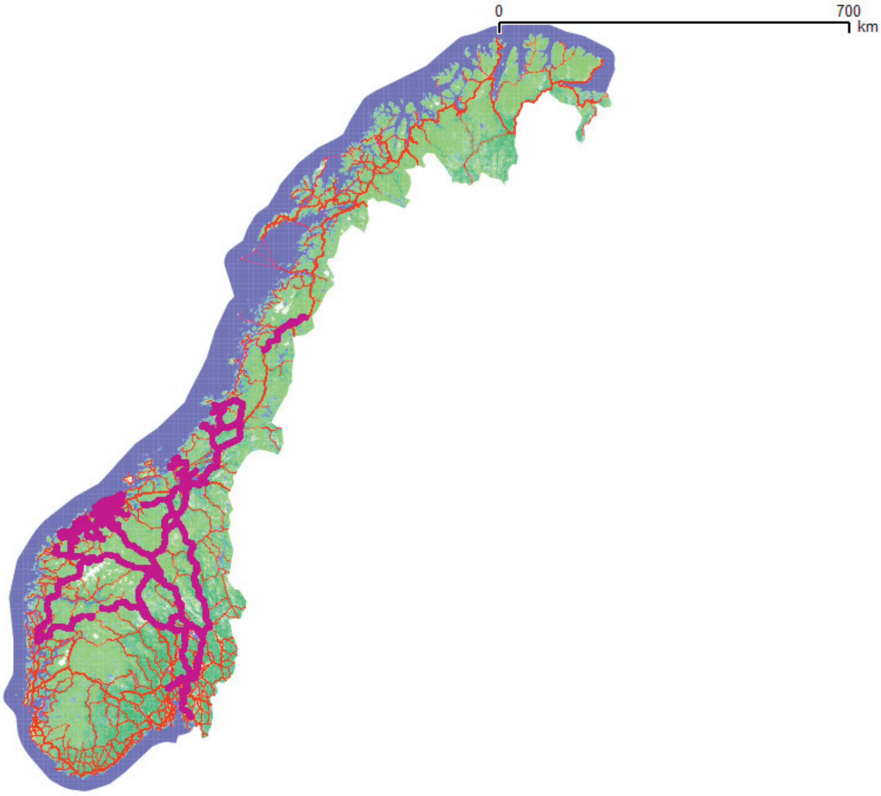


FIGURE 51 MAP WITH GPS REGISTRATIONS IN PURPLE

FIGURE 52 PLOT OF GPS DATA ALONG THE E6 AT HJERKIN (OPEN MOUNTAIN SUROUNDINGS)

Figure 52 shows a plot of GPS positions along the E6 at Hjerkin. The width of the plot trace is about 10 meters; this indicates that the positional quality is quite high. Figure 53 shows another plot along the E6 where positional quality is worse; the track is about 150 meters wide in some places. The cause of this is that the road is located in a canyon. The height difference between the contour lines is 100 meters. This is a clear example that the surroundings will influence the measurements at least when it comes to positional accuracy.

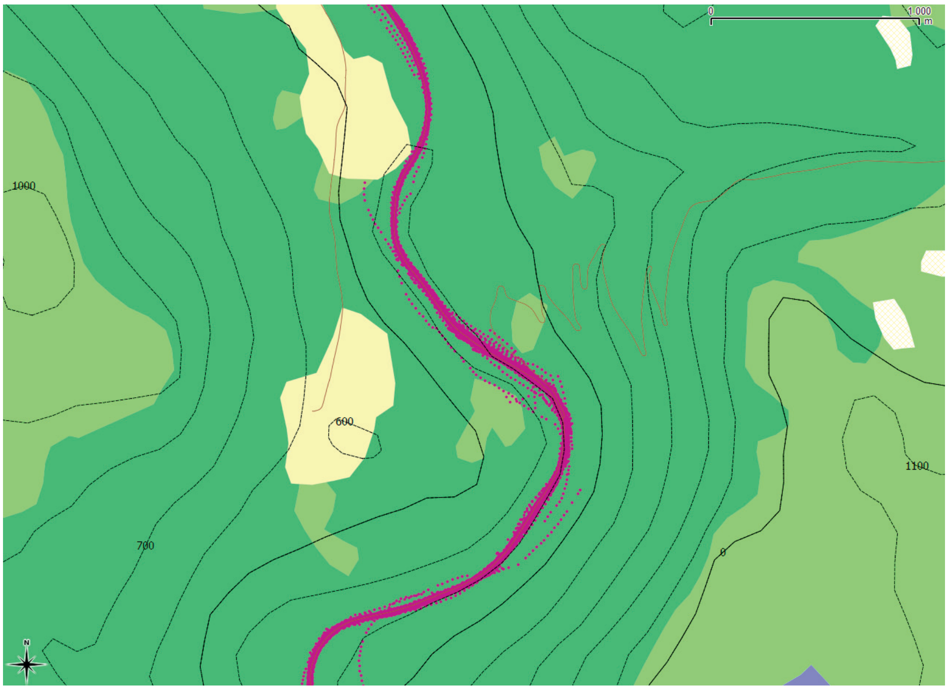


FIGURE 53 PLOT OF GPS DATA ALONG THE E6 IN A VALLY SOUTH OF DOMBÅS

5.5 TEST OF RTCU-MX2I

In order to get a clearer view of the implication of the placement and equipment choice, an experiment was set up. A probe vehicle was fitted with two GPS units placed behind the windshield and one GPS unit placed on top of the vehicle. The roof fitted VBOX 3i GPS is a GPS specifically made for measurement of racing cars. The unit has a capability of logging data at 100Hz, and costs about 100,000 NOK. Positional quality is given as 3 meters 95% CEP. 95% CEP (Circle Error Probable) means that the position readings will fall within a circle of the stated diameter 95% of the time. The RTCU-MX2i gives a CEP value of 2.5 meters 50%. It is hard to compare the two since the CEP is defined differently, but the VBOX 3i should be more accurate on average. The VBOX uses Doppler shift in the GPS carrier signal to calculate speed and direction. The RTCU-MX2i documentation does not mention if Doppler shift is used for the calculation of speed or direction. The alternative to Doppler speed calculations is distance moved between two positions divided by time, and direction as a vector between the two positions.

FIGURE 54 PLACEMENT OF GPS LOGGERS IN TEST VEHICLE

Figure 54 shows the location of the GPS antennas in the test vehicle. The VBOX antenna is placed about 2 meters to the rear of the RTCU-MX2i antennas. This was due to the fact that the VBOX needed a specific antenna that was permanently fixed to the vehicle. Figure 55 shows the two types of data loggers. Two identical units of the low cost units were used in the comparison.

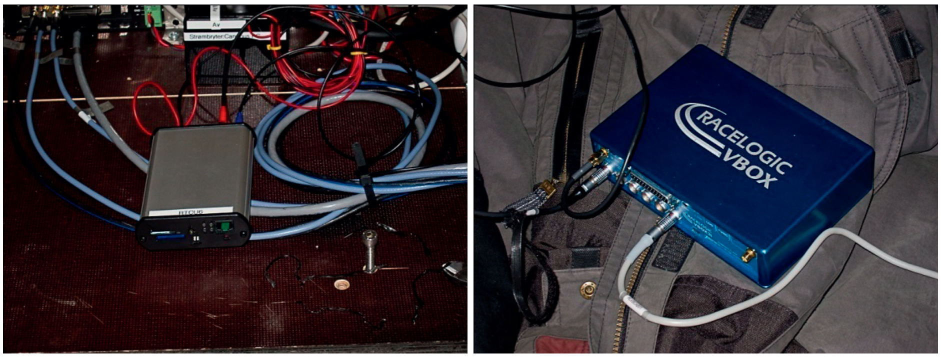


FIGURE 55 THE RTCU-MX2I ON THE LEFT AND THE VBOX GPS ON THE RIGHT

A test route was set up that would include both urban and rural surroundings, and a circular route was chosen to get a grip on the errors introduced by placing the RTCU-MX2i antennas inside the vehicle. The quality of GPS observations are dependent on the location of the satellites in relation to where the measurements are carried out. Satellite location was not taken into consideration for this test. A random day was chosen and the test was conducted in the middle of the day.

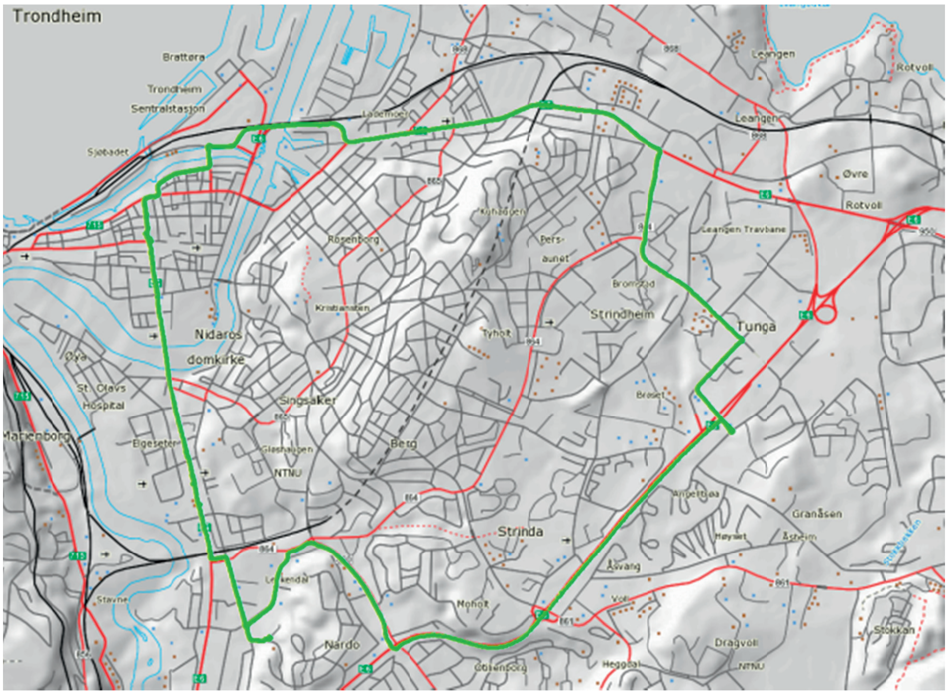


FIGURE 56 TEST ROUTE FROM THREE GPS UNITS PLOTTED AS A GREEN LINE(MAP SOURCE: STATENS KARTVERK)

Figure 56 shows a plot of the GPS positions on a map; it is not a green line but very closely spaced green dots. Data from all units are included in the figure. The VBOX was set to return data at 1Hz, the same rate as the two RTCU-MX2i units. The route takes under twenty-five minutes to drive. The route was driven twice. In addition, a stationary test was conducted, where the vehicle was parked close to a tall building.

For each observation the speed difference between the VBOX and the RTCU-MX2i units was calculated. The speed from the VBOX unit was used as the reference. A small difference between the speeds observed would indicate that the low cost units were suitable for measuring vehicle speed.

TABLE 23 DATA LOSS FROM THE DATA LOGGERS

Unit	Number of data points	% data lost
1 - VBOX	4428	0
2 - MX2i RTCU 2	3944	10.9
3 - MX2i RTCU 6	3977	10.2

During this experiment a bug was identified in the RTCU-MX2i software for logging. This bug caused loss of data from the RTCU-MX2i units. As seen in Table 23, the units are losing a significant amount of data, about 10%. This meant that the units that were out on the road were losing data. The data loss was regrettable, but was not believed to undermine the analysis for the collected data. It is assumed that the error was linked to the software in the unit. Methods for analyzing the data were designed to cope with the missing data. New technological platforms with greater possibilities have been developed in the last year. The Arduino[36] micro-controller platform is a likely candidate for future studies. A vehicle logger application has been developed based on the Arduino platform (Oxer and Blemings, 2009). This is a strong indication that alternative platforms for logging vehicle performance will come in the near future.

Table 24 shows the number of data points in each test. If there was no data loss then the row values should be equal to the first column.

TABLE 24 DATA SAMPLES IN EACH TEST

Test name	Number of data points		
	VBOX	**RTCU 2**	**RTCU 6**
D1 – dynamic test 1	1571	1407	1418
D2 – dynamic test 2	1656	1456	1480
S1 – static test 1	1201	1081	1079

[36] http://www.arduino.cc/

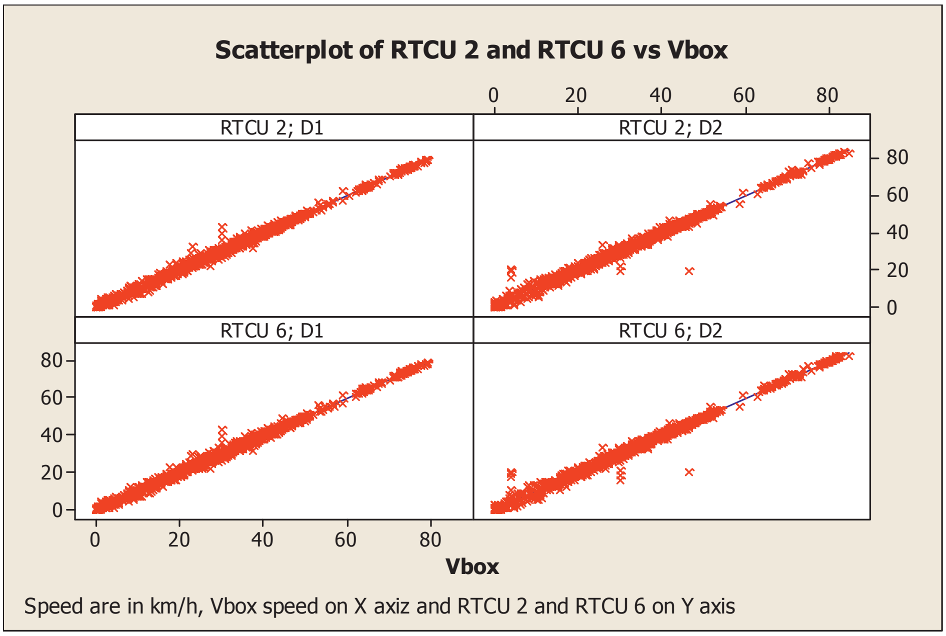


FIGURE 57 SCATTER PLOT OF VBOX AND GPS SPEED DATA

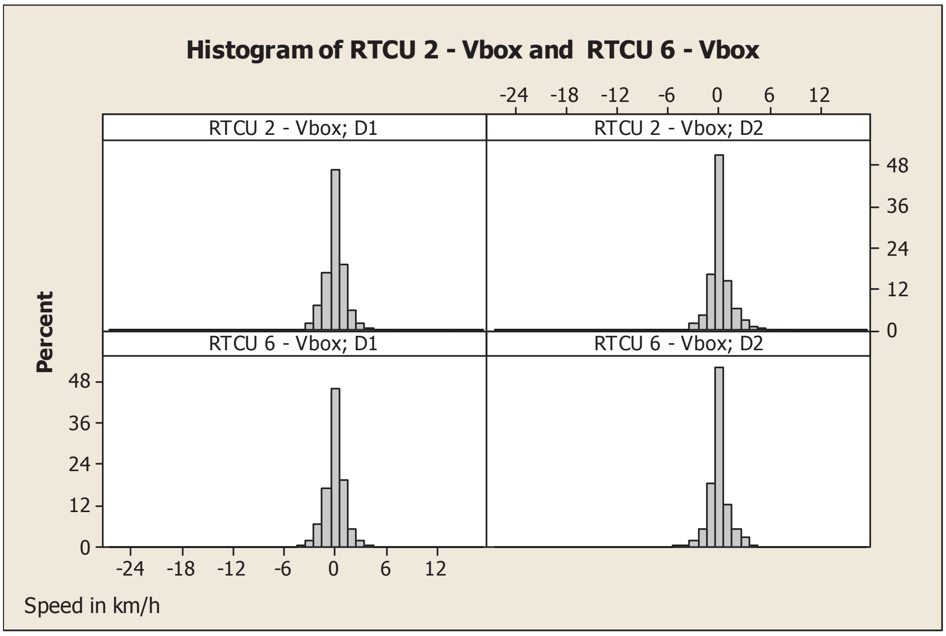


FIGURE 58 HISTOGRAM OF DIFFERENCE BETWEEN RTCU'S AND VBOX GPS

Figure 57 shows regression plots of the two RTCU units against the VBOX, the plots confirm that the speed measurements from the VBOX and the RTCU units are close to being equal. The histograms of differences between VBOX reported speed and speeds reported from RTCU 2 and RTCU 6 units are shown in Figure 58. The regression analysis gives the following results:

```
RTCU 2 = 0.261 + 0.994 VBOX
R-Sq = 99.5%

RTCU 6 = 0.106 + 0.997 VBOX
R-Sq = 99.4%
```

LISTING 5 RESULTS FROM MINITAB REGRESSION ANALYSIS

The regression equation indicated that the reported speed by the RTCU units is very close to being the same as reported by the VBOX. The R squared indicator is very high. More than 99% of the variation in VBOX speed can be explained by the speed reported by the RTCU units. Figure 57 shows that most data points are close to the regression line and that there are no large values controlling the line.

Some discrepancies are observed in dynamic test 2 (D2). A good thing about geo-referenced speed data is that one can find measurements that deviate significantly and look for causes geographically. From the dataset one can see that several observations in the same time frame differ quite a lot. Figure 59 shows a speed time plot for a period where large deviations are observed. It is quite clear that the VBOX GPS is returning data that seem unrealistic. If the VBOX was correct the vehicle should have accelerated with 11.8 m/s^2. This is highly improbable for any road vehicle. The map gives us some clues to why this could be happening. At 10:39.15 the VBOX speed is more than 25 km/h higher than the speed reported by the RTCU units, see Figure 59. This speed difference was observed under a railway bridge. It is possible that the bridge is blocking the view to the sky and hence causing the erroneous speed calculation in the VBOX. The VBOX is probably supplying raw speed data, while it is believed that the RTCU units have some sort of post processing to make them more usable in urban areas (UBLOX, 2006 p. 3).

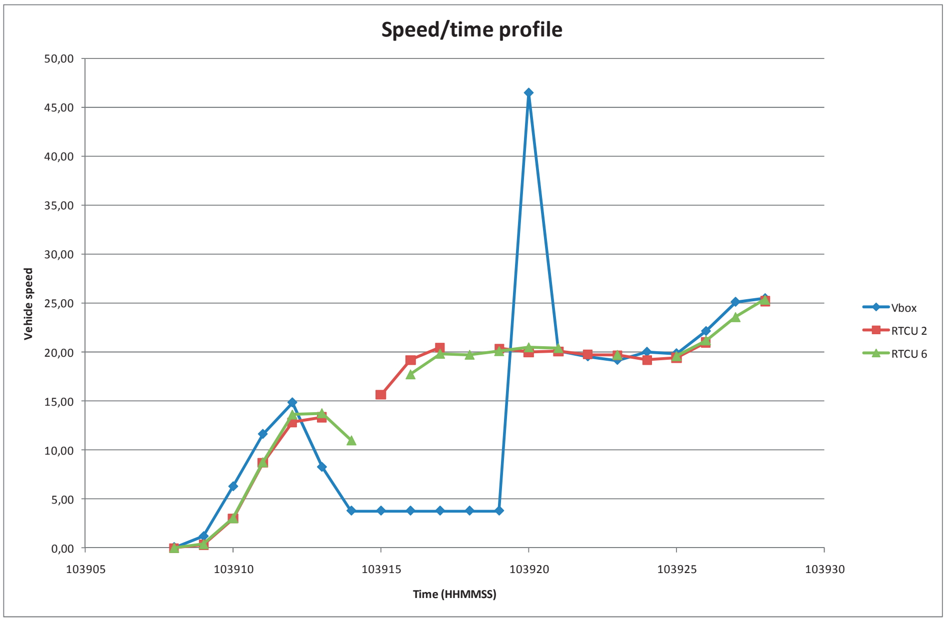


FIGURE 59 SPEED/TIME PROFILE FROM OBSERVATIONS WITH LARGE SPEED DIFFERENCE

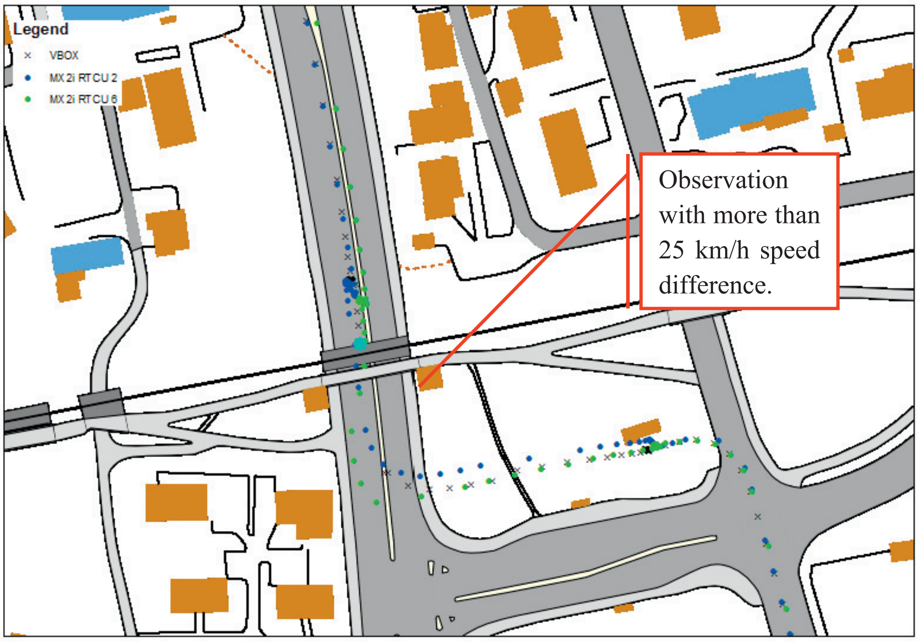


FIGURE 60 MAP OF AREA WITH LARGE DIFFERENCE BETWEEN OBSERVED VBOX AND RTCU SPEEDS

It should be noted that the map source is outdated. The road to the south of the railway has been moved since the map was updated. Thus the plots that seem to run across a piece of land are actually on the new road. An updated map source was not available in April 2010.

5.5.1 ACCESSING GPS STATIONARY QUALITY

Under moving conditions the speed difference between the GPS units are small. But how good is the GPS positional estimate when the vehicle is standing still? A small static test was carried out where the vehicle was parked close to a building. The vehicle was parked facing westwards. See Figure 61 for a map of the area and a zoomed in view of the data points. The building is blocking the view to the sky from the north, and to the south there is a hill. This could resemble a situation when a vehicle is parked at a terminal for loading/unloading. Here we can clearly see a difference in positioning capabilities. The VBOX exhibits a good dense cloud of black positional marks, while the RTCU 2 and RTCU 6 show traces that are wandering. From the plot alone one can see that the VBOX with its antenna placement has a better positional fix. But the spread of the points are not that bad for the RTCU units. A circle of 18 meters would be sufficient to encompass all RTCU observations with antennas behind the windshield. Such accuracy should be sufficient to identify if the vehicle is parked at a terminal or not. For the analysis of average driving speed only GPS data points with speeds over 3 km/h are used.

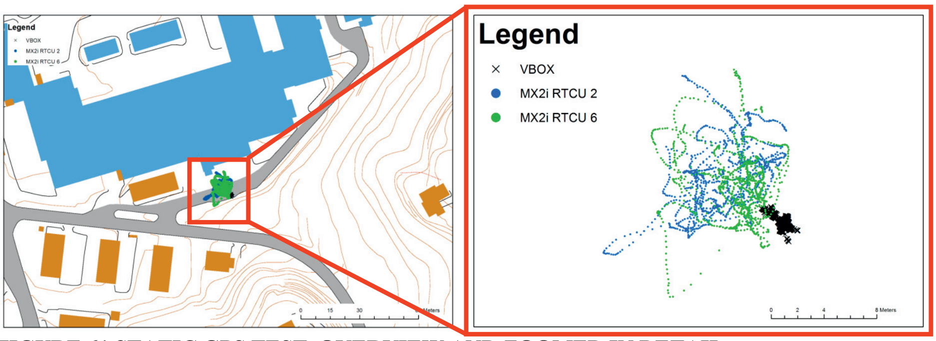


FIGURE 61 STATIC GPS TEST, OVERVIEW AND ZOOMED IN DETAIL

5.5.2 COMMERCIAL GRAD GPS UNITS AS A MEASUREMENT TOOL

Within the frame of this Ph.D. project GPS units are considered to be black boxes. We know that position is calculated on the basis of signals from satellites. Most GPS units return positional and speed data at a rate of 1Hz, but inside the units higher rates might be used and some form of smoothing operation may be applied. From the documentation of the RTCU-MX2i it was found that the unit used a "Ublox ANTRIS 4 GPS engine." According to the product documentation of this chip a max update frequency of 4Hz. This could allow the creators of the RTCU-MX2i to average 4Hz data or set the chip to return 1 Hz data. The strategy chosen by the creator is not documented in the documentation available online. This example illustrates that not all GPS units are alike and there can be some sort of post processing of the data smoothing or filtering. Thus accuracy and suitability to specific tasks can vary among different types of GPS units. Within the confines of this Ph.D. project not enough time or money was available to test GPS quality thoroughly, but simple tests were conducted to see if the GPS was good enough.

The test carried out shows that the units used and their placement give vehicle speeds that are on par with the ten times more expensive GPS unit meant for motorsports. The test revealed a bug in the logging software that can cause loss of up to 10% of the observation. This is regrettable, but methods for analyzing driving speeds can be set up to counter this problem. The test shows that speed data and positional data are not totally dependent on each other. This could be due to usage of Doppler calculations to find speed and direction. An interesting finding was that the railway bridge could have caused some strange speed observations from the GPS equipment which was perceived to be the best. The cheaper GPS units stopped reporting speed and heading data close to the bridge. This underlines the need for routines to remove data from the complete dataset that is perceived to be faulty, or have analysis routines that can sort out erroneous data.

5.5.3 SATELLITE AVAILABILITY, TIME OF DAY AND LOCATION

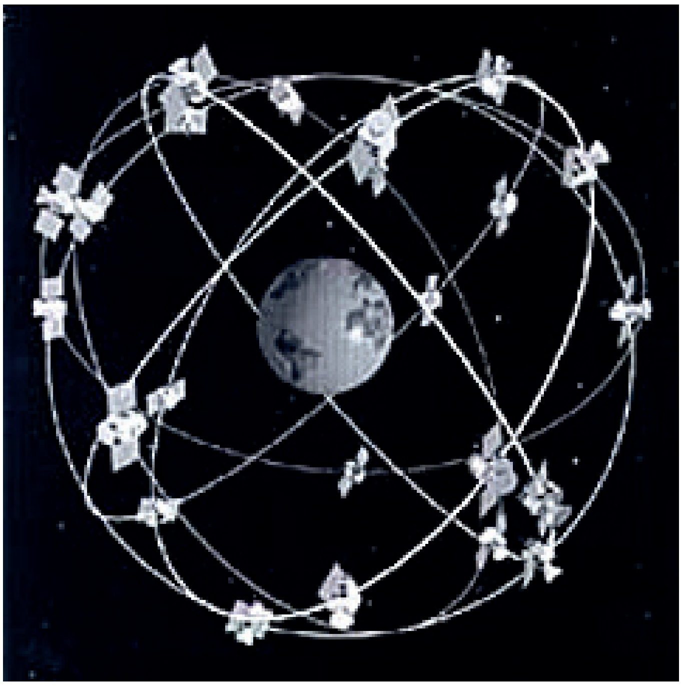


FIGURE 62 GPS SATELLITE ORBITS (SOURCE: NOAA)

The GPS system is based on satellites that orbit the earth at approximately 20 200 kilometer above the earth's surface (French, 1997). As of March 19, 2010, thirty-five GPS satellites were orbiting the earth, thirty of which were marked as healthy for users[37]. A healthy satellite is a satellite that has passed its own self tests and has concluded that signals from the satellite can be used by GPS receivers on the ground. Since GPS satellites are not in geostationary orbits they move across the globe, thus for one place on earth the number of visible satellites will change. Figure 62 shows GPS satellite orbits. The GPS receiver's positional accuracy will change with date and time of day because of satellite availability and satellite elevation. Trimble Navigation Limited has created a piece of software called Planning v 2.8 that gives the user the ability to "forecast" satellite availability. This software can show available GPS satellites at a specific location and time and calculate a probable dilution of position based on available satellites. DOP is an acronym for Dilution of Precision. A smaller DOP value indicates a smaller position error. DOP is a way of describing the important relationship between placement of the satellites in the sky and the receiver on the

[37] `http://pnt.gov/public/faq.shtml#satellites`

ground. This satellite-receiver relationship will affect the positional accuracy of the GPS measurement (Langley, 1999). For the test run in Trondheim one can see that there are two spikes in the DOP chart on the day of the test, one in the early morning and one in the evening. The test was run between 10:00 pm and 12:00 am. The Trimble software clearly shows that GPS measurements will be effected by the satellite constellations and that at certain times one may have unfortunate constellations that will affect GPS precision. The almanac for January 22 was downloaded from U.S. Coast Guard Navigation Center (U.S. Coast Guard, 2010).

Errors due to number of satellites and satellite constellations will add to the errors caused by satellite blockage from mountains, buildings or other infrastructure. Thus GPS positional quality is not only dependent on location and elements that may block the view to the sky, but also on the satellite constellation. Positional errors will not be stable for the same geographic place different error may change with time of day. Figure 63 shows the expected number of satellites visible over Trondheim on the day of testing the RCTU and VBOX GPS units.

FIGURE 63 GPS SATTELITE AVAILIBILITY AND DOP FOR TRONDHEIM 22.01.2010

Our measurements are continuous thus it is inevitable that we will take measurements under unfavorable conditions due to satellite constellations. One way to make measurements less prone to errors from poor satellite visibility is to ensure a high degree of replication of measurements on the same road stretches.

5.5.4 Conclusion of RTCU test

Even if the placement of the GPS units were not optimal, data seems to be sufficiently accurate for the study of driving speeds and calculation of average speeds on road segments. A mini trial comparing the RTCU units to the VBOX unit do not give an indication that speed data would be systematically erroneous. Using GPS to collect driving data is a simple way to get georeferenced speed data, but care should be taken when using consumer grade GPS units. There are also errors due to GPS satellite constellations that can affect the quality of GPS measurements. Consumer grade GPS units may use filtering and smoothing techniques to improve precision and it can be hard to find documentation of such routines.

GPS data is an affordable way to gather georeferenced vehicle speed data, but one should be aware that the quality of GPS data will be affected by the surroundings and satellite constellations. Averaging repeated observations is a way to reduce the influence of measurements errors.

5.6 Analysis

During the collection period a total of about 8 million GPS observations were collected. This data would be used to answer two questions:

1) What is the effect of using the speed limit as a proxy for truck driving speeds?

2) How do speed and acceleration levels in ARTEMIS compare to those we observed?

One challenge to answer the two aforementioned questions was the enormous amount of data, and that the observed data had to be paired with other data sources such as a digital road description for analysis. Manual methods were unfeasible due to the data volume. Thus software to automate the process for data storage and preparation had to be written.

5.6.1 GIS for data management and preparation

To be able to connect the data collected with the GPS units to the road network for analysis GIS functionality was needed. Due to availability the ESRI GIS platform was first chosen, but this decision had later to be revised because of data storage and runtime issues. Table 25 gives an overview of the file size storage limitations of different GIS storage systems tested.

TABLE 25 LIMITATIONS OF TESTED GIS DATA STORAGE SYSTEMS

Storage	File size limitation	Analysis tools
ESRI shapefile	Dbf and shp file cannot exceed 2GB	Any that offer ODBC connections
ESRI personal Geodatabase	Total file size cannot exceed 2GB	Any that offer ODBC connections
ESRI file Geodatabase	None, dataset is limited to 1TB by default, but can be se to 256TB	Proprietary ESRI products
PostGIS, spatial extension for PostgreSQL.	None, data set is limited to 32TB	Any that offer ODBC connections, open source drivers.

Only two products were viable for storing the data, the ESRI file geodatabase and PostGIS. Due to the fact that data in the ESRI file geodatabase can only be accessed through a limited set of ESRI functions the PostGIS alternative was selected because it allows generic access via ODBC. ODBC is an acronym for Open Data Base Connectivity. ODBC is a standardized way for computer applications to retrieve data from databases.

Performance became an issue; computer systems with less than 4GB of memory exhibited performance issues. An ESRI linear referencing tool used six days to process a dataset with 8.4 million GPS registrations running on a Windows XP 32-bit machine with 4GB of memory. After moving the database to PostGIS, running on a dedicated 64-bit FreeBSD server with 8GB of memory, the same operation took 9 minutes and 54 seconds. The performance increase is probably attributed to a combination of hardware, operating system and algorithm used for locating the GPS data points in relation to the road.

The downside of PostGIS is the user interface; commands are not sent to the database via a graphical interface like in ESRI's ArcMap, but through SQL sentences. SQL is an acronym for Structured Query Language. SQL is a computer language used for interacting with databases. The implication of this is that the user has to be proficient in SQL programming to create simple GIS operations that are a "point and click" in the ERSI tools. PostGIS[38] and PostgreSQL[39] are both open source software and are free to use. PostgreSQL is the underlying database the PostGIS extension uses. PostgreSQL and PostGIS can be run by many different operating systems.

[38] http://postgis.refractions.net/
[39] http://www.postgresql.org/

5.6.2 DATA MANAGEMENT

From the GPS logs the $GPRMC and $GPGGA sentences were collected and stored in tables in the database. During loading the GPS data was split into runs and trips. A run is synonymous with a log file, every $GPRMC and $GPGGA in a file will receive the same run identification number. A run is then split into trips using a function programmed into the database. The trip identification function reads the speed from the $GPRMC sentence, if the speed is below a threshold for a significant amount of time a new trip is created. For the creation of the database a speed of 3 km/h and 180 seconds was used. This seemed to be long enough that runs were not split into trips at signalized intersections. This gave a total of 151,103 trips in the database.

The road network that was prepared for the emission calculation routines was loaded into the database. The road network contains the speed limits on the road segments. This data allows for analysis of driving speeds compared to speed limits.

5.6.3 LINKING GPS DATA WITH ROAD DATA

The data from the RTCU units only have information derived from the GPS units. Information about the speed limit is stored in the road network. Techniques to link the GPS data points to road networks is called map matching. Several map matching algorithms are discussed in White et al. (2000). The algorithms range from simple mapping to closest point to advanced algorithms that take network topology into account. Quddus et al. (2007) gives an overview of map matching techniques and divides them into four categories: Geometric analysis; topological analysis; probabilistic and advanced map matching algorithms.

A simple and efficient way of analyzing data is using geometric methods. The database extension PostGIS offers routines for distance calculations between geographic objects in the database. Extensive documentation is available online at Refractions Research Inc. (2009). A link table between the road segment and the GPS points is established by using the PostGIS linear referencing function. The link table holds the GPS ID, road link ID and a number indicating the location of the GPS point measured in meters from the start of the road link. Then a window function is used to find the entry time and exit time on a link. A window function gives each row in the database the ability to use data from other specific rows or averaged data from parts of the table (Harada and Fetter, 2009). This is used to find the time when a trip enters a link and time of departure. In Figure 64 this would be the time at N and time at N+12. The difference in time between N and N+12 is equal to the travel time on the road segment. The next stage is to calculate the distance between N and N+12; this is accomplished through the use of linear referencing. A value from 0 to 1 is given to N depending on how far N is from the start of the line, the same is done for N+12. The difference between N and N+12 multiplied by the geometric length of the shape is the distance between N and N+12 along the road segment. The average speed on the road segment is then calculated from the distance traveled and time used.

The direction of travel in relation to the direction of the road segment had to be calculated. Road segment direction can be expressed in several ways. In Norway it is common to use the metered direction as road direction. Roads have a linear reference system where the direction is consistent with increasing metering values. Direction of digitalization is another way to describe direction. It was assumed that it would be safer to use the direction of digitalization as direction for the average speed analysis. This is because it will be unaffected by possible errors in the metering. Thus direction is defined as the direction of digitalization for road segments.

An algorithm to find if the vehicle traveled along or against the road segment direction was created. This idea is to create a vector between the first and last point of the road segment and compare this vector to a vector of the first and last point observed that are linked to the road segment. If the direction of the observed point vector deviates less than 45 degrees in either direction then the trip is considered to travel in the same direction as the road segment was coded. If the observed point vector deviates less than 45 degrees in each direction from the road segment vector +180 degrees then the trip is considered as running in the opposite direction. In Figure 64 the line GPS direction is the observed vector, while the road direction is the road segment vector. The direction is also drawn in Figure 64 and is the same as the road segment direction.

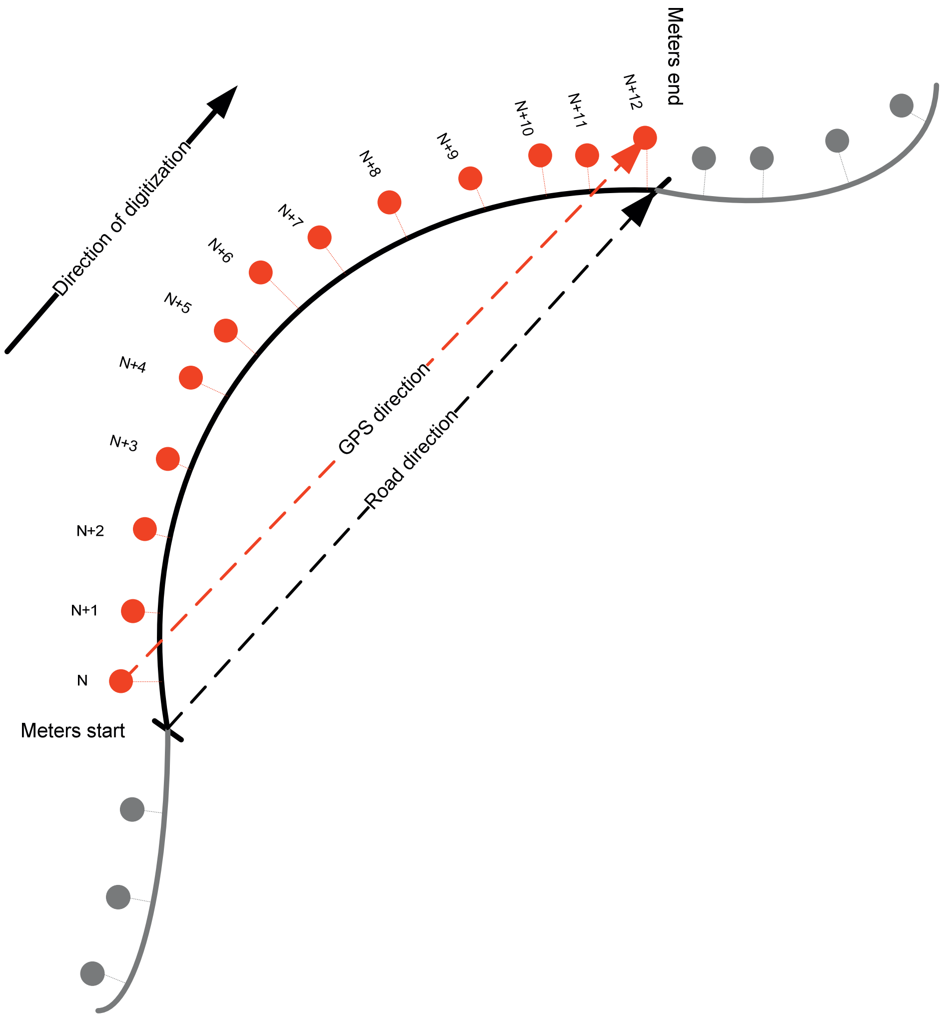


FIGURE 64 GRAPHIC OF MAP MAPMATCHING AND AVERAGE SPEED CALCULATION

Distances in the road network could be measured in either 2D or 3D. The use of 3D length is preferable because this is the true length along the road. But if the dataset has quality problems with the elevation data one could possibly introduce larger errors than the error of using 2D measurements instead of 3D measurements. Figure 65 shows two plots of 3D measured length divided by 2D measured length. One shows the full range of the index, the other limits the index to 1.4x longer 3D distance than 2D distance. The index is calculated as: measured 3D length divided by measured 2D length. From the plots it is clear that there are several road segments with erroneous elevation data. The plots are segmented based on road class. E and R roads are trunk roads while F roads are regional and K roads are municipal roads. Elevation data on municipal roads could be a problem. Quite a few municipal roads exhibit an index value that indicates gradients of over 20 degrees.

TABLE 26 AVERAGE DIFFERENCE BETWEEN 3D AND 2D LENGTH GROUPED BY ROAD CATEGORY

Road category	Index
(E)uropaveg	1.0020
(R)iksveg	1.0025
(F)ylkesveg	1.0055
(K)ommunal veg	1.0258

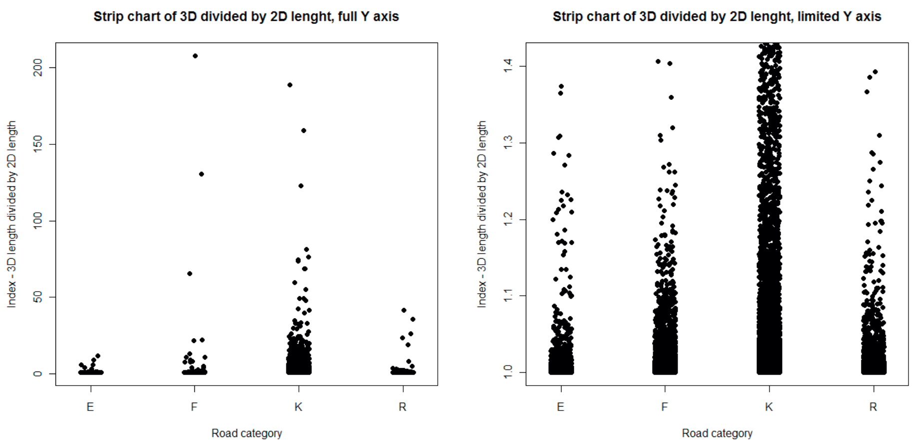


FIGURE 65 PLOT OF 3D DIVIDED BY 2D MEASURED LENGTH

Table 26 lists the calculated difference between 2D and 3D length. For the trunk road categories the difference is on average less than 0.26%. The difference between 2D and 3D length is a measure of road gradient and/or varied vertical curvature. For municipal roads the length difference between 2D and 3D is 2.58%. Figure 65 indicates that there are some roads with extreme and most probably erroneous grades that cause the difference in length. In some cases the length of the 3D road was more than fifty times longer measured than the 2D distance in the calculation of average speed. Based on the data above, 2D length was chosen as a measure of distance. This is accordance with the findings when looking at the suitability of the Elveg 2008 network in section 3.4.2. The net result of this is that the average speeds could become slightly higher than the true speed. But this error is much smaller than the errors that would be observed if 3D length was used.

5.6.4 ANALYSIS OF DRIVING SPEEDS

Average speed was calculated for each trip on the relevant road segment. Direction of travel was calculated and gradients were grouped into 9 groups (<-8,-6,-4,-2,0,2,4,6,8<). The map matching routine could return erroneous matching if the positional quality of the GPS data is low. An alternative to using more complex matching routines was to remove erroneous data after it was matched. The focus for the analysis was average speed on the rural trunk road network. The bullet points below list the exclusion criteria used for the analysis.

Criteria used to select data for final analysis:

- The road is not in city municipality, here identified by the 4 digit municipality number: (0219,0220,0301,1001,1102,1103,1201,1601)
- The road segment is a normal road: v_vegstatus='V'
- The road segment is not a municipal road: v_vegtype in ('E','R','F')
- That the road segment is not a ferry, tunnel or bridge: v_medium IS NULL
- The length of the road segment is over 200 meters: v_length > 200
- There is not a large minima or maxima on the road link, see Figure 25: v_local_min_max_index > 0.75
- The observations cover +-25% of the road segment length: 0.75 < vg_dist_diff < 1.25
- The average speed is under 110 km/h: g_average_speed_time_based < 110
- The speed limit is equal or greater than 50 km/h: v_fartsgrense >= 50
- There are more than 3 speed observations on the link: observations_on_link >3

The exclusion process reduced the number of GPS speed data points from 7,025,070 to 2,998,398. The 2.9 million points are distributed over 123,919 road links.

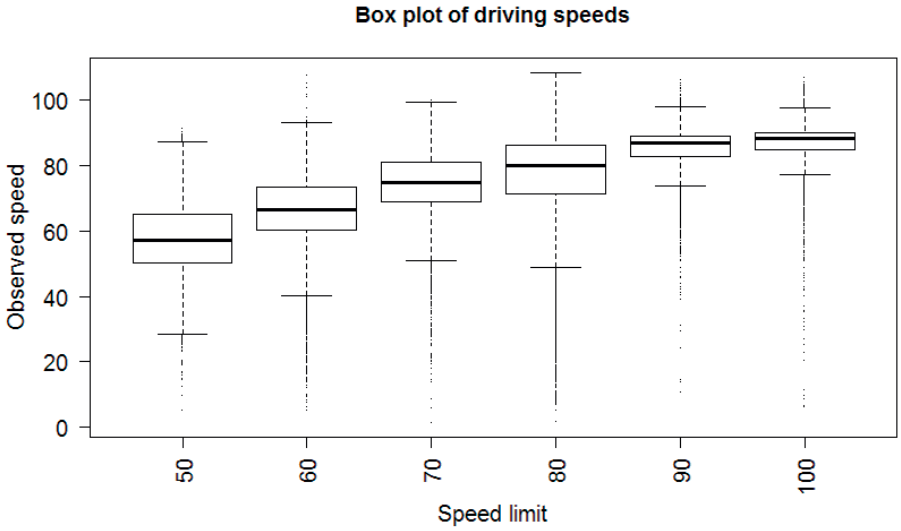


FIGURE 66 BOXPLOT OF SPEEDLIMIT AND DRIVING SPEED

TABLE 27 TABLE OF SPEEDLIMITS AND OBSERVED SPEEDS, KM/H

Speed limit	Mean observed speed	Standard Deviation	95% CI
50	57.8	11.9	57.4 - 58.2
60	66.4	11.2	66.2 – 66.6
70	74.6	9.3	74.5 – 74.8
80	77.4	11.4	77.3 – 77.5
90	85.1	6.48	85.0 – 85.2
100	86.6	8.49	86.3 – 86.9

The reason for calculating the observed average speeds on the rural road links was to understand the error introduced into emission estimates when using the speed limit as a proxy for the real average speed. Figure 67 shows fuel consumption for Euro IV trucks at different average speeds. From this figure one can see that using a speed limit of 50 km/h for vehicles that are driving at an average speed of 57.8 km/h will slightly overestimate emissions. The curves for all vehicles level off after 50 km/h and thus the error will be reduced. The speed model for commercial vehicles is assumed to give better driving speeds and these should be used for average driving speed in the future. The methodology to calculate average speed on links developed within this Ph.D. project was used by the speed model for commercial vehicles project. The GPS speed registrations were shared between the projects, but the speed model project used a more detailed road network for their analysis.

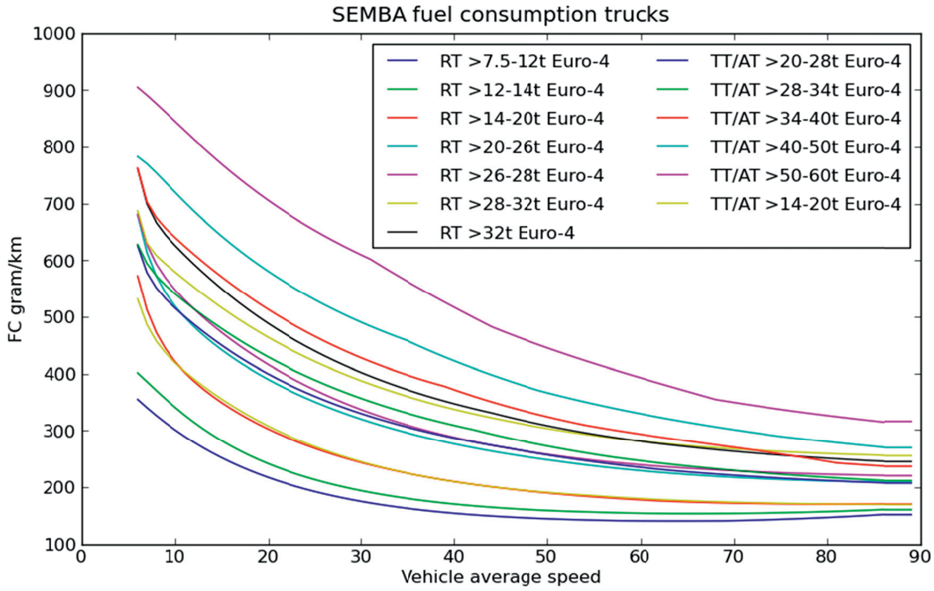
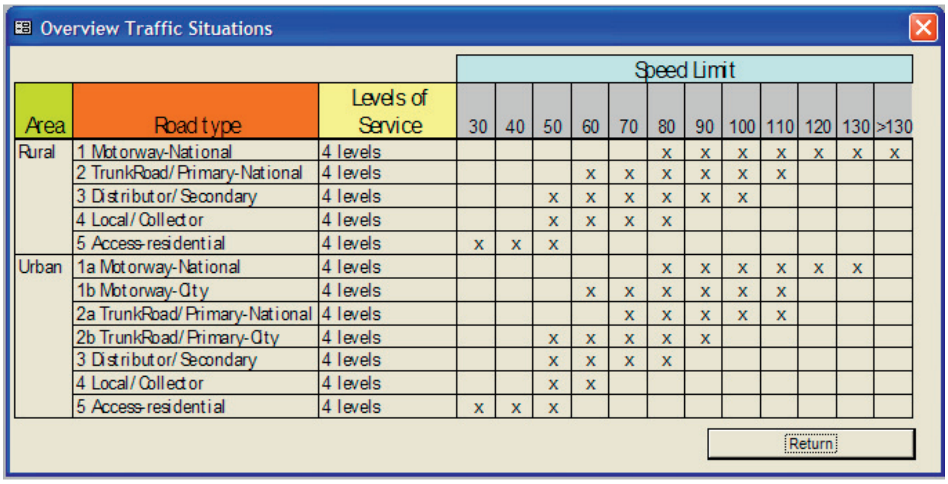


FIGURE 67 FUEL CONSUMPTION FOR EURO IV TRUCKS AT DIFFERENT AVERAGE SPEEDS

Thus until the results from the speed model for commercial vehicles is available then speed limits will be used as input to the emission calculations.

5.7 Assessment of observed and ARTEMIS driving patterns

Driving cycles are the foundations of the average speed curves and emission curves. A set of driving cycles representing a vehicle class for different average speeds are combined into the average speed emission curves. The large scale GPS data collection was done in part to be able to look at the underlying assumptions of the emission functions. Speed and acceleration choices are important and influence emissions. Within the time frame of this Ph.D. project it has not been possible to develop Norwegian driving cycles. Looking at the driving behavior in terms of accelerations was a possibility to compare driving behavior. As part of the ARTEMIS project a computer program for calculating road emissions was developed, and the ARTEMIS road model software is available from the INRETS ARTEMIS webpage. It is possible to get access to the traffic situations used, and to look at the driving cycles used. In Figure 68 an overview of the traffic situations are presented. Thus it was possible to extract the data that ARTEMIS used to build the emission curves, and the extracted data could be compared to measured data in Norway.

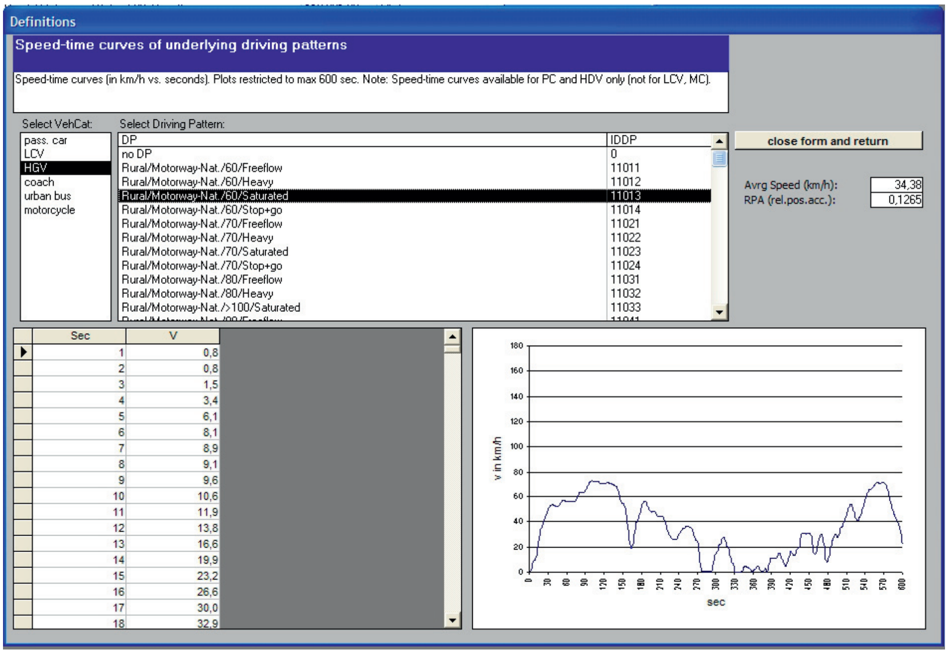


Overview Traffic Situations

Area	Road type	Levels of Service	30	40	50	60	70	80	90	100	110	120	130	>130
			Speed Limit											
Rural	1 Motorway-National	4 levels						x	x	x	x	x	x	x
	2 TrunkRoad/Primary-National	4 levels				x	x	x	x	x	x			
	3 Distributor/Secondary	4 levels			x	x	x	x	x	x				
	4 Local/Collector	4 levels			x	x	x	x						
	5 Access-residential	4 levels	x	x	x									
Urban	1a Motorway-National	4 levels						x	x	x	x	x	x	
	1b Motorway-City	4 levels				x	x	x	x	x	x			
	2a TrunkRoad/Primary-National	4 levels					x	x	x	x	x			
	2b TrunkRoad/Primary-City	4 levels			x	x	x	x	x					
	3 Distributor/Secondary	4 levels			x	x	x	x						
	4 Local/Collector	4 levels			x	x								
	5 Access-residential	4 levels	x	x	x									

Return

FIGURE 68 OVERVIEW OF TRAFFIC SITUATIONS IN THE ARTEMIS ROAD MODEL COMPUTER PROGRAM SOURCE: (KELLER ET AL., 2007)



Sec	V
1	0,8
2	0,8
3	1,5
4	3,4
5	6,1
6	8,1
7	8,9
8	9,1
9	9,6
10	10,6
11	11,9
12	13,8
13	16,6
14	19,9
15	23,2
16	26,6
17	30,0
18	32,9

FIGURE 69 SCREENSHOT OF DRIVING PATTERN IN THE ARTEMIS COMPUTER PROGRAM SOURCE: (KELLER ET AL., 2007)

The traffic situations are combinations of different driving patterns. Figure 69 shows an example of a driving pattern for a Highway in rural area with 60 km/h speed limit and saturated driving conditions. The graph in the lower right corner of the screen shot shows second-by-second speeds for the first 600 seconds.

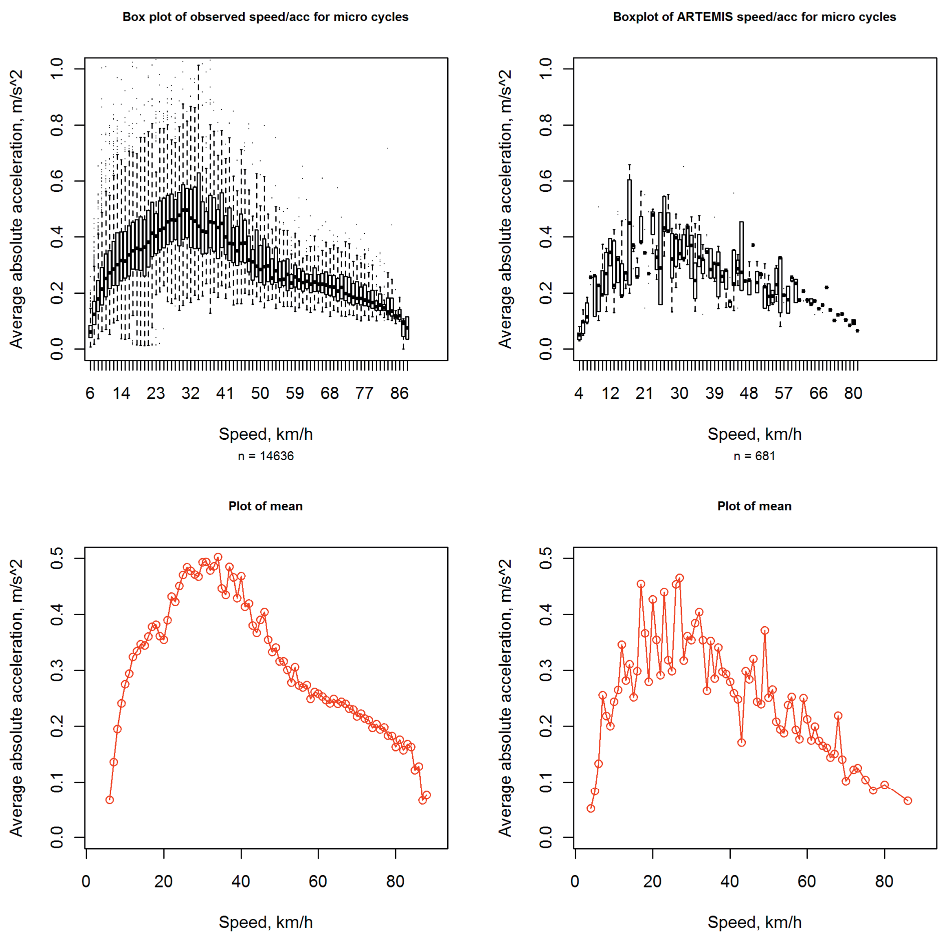


FIGURE 70 COMPARISON OF OBSERVED AND ARTEMIS MICRO TRIPS

Data from the table in the lower left was extracted and entered into a database for comparison with the data collected from the GPS registrations. 173 driving patters were extracted and divided into micro trips. A micro trip is a speed time profile that start at 0 km/h and ends at 0 km/h. For our sample a cut off value of 3 km/h was select both for the ARTEMIS micro tips and the micro trips from the GPS registrations. This resulted in 1,371 micro trips from the ARTEMIS computer program for HDV and 21,230 micro trips from the GPS observations. For each micro cycle the average speed was calculated and cycles were binned in 1 km/h groups. Figure 70 shows box plots of micro trip absolute acceleration on the top and average absolute accelerations in the bottom part of the figure. The shape of the box plots and the mean are quite similar for the observations and ARTEMIS driving patterns. The scale of the accelerations seems to be quite similar.

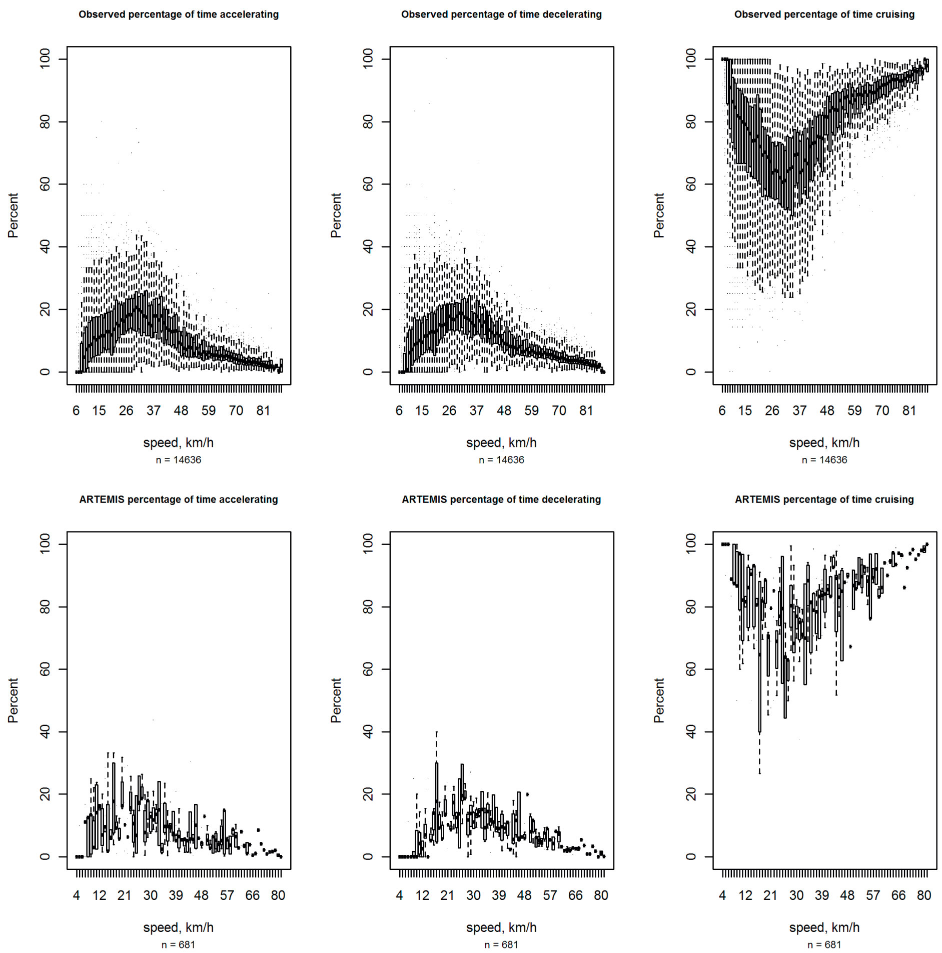


FIGURE 71 MICRO TRIPS TIME IN DIFFERENT MODES

Another way to assess a driving cycle is to look at the amount of time spent in acceleration, deceleration and cruising. Figure 71 shows a comparison of time in acceleration, deceleration and cruising. Again it looks like the observations have the same shape for the median over the speed range. But there seems to be a small shift in where the minimum time is in cruising mode. In the observed GPS data the minimum seems to be around 35 km/h. For the ARTEMIS data the picture is a bit more unclear, but a minimum seems to be at around 25 km/h.

In a 2001 study Ericsson found that relative positive acceleration RPA was a way to describe variations in driving cycles in relation to fuel use and exhaust emissions (Ericsson, 2001). RPA was calculated from the observed micro trips and the micro trips found in the ARTEMIS road model program. Figure 72 shows the same plots as Figure 70 but with RPA on the Y axis. RPA is defined as the integral of instantaneous speed and positive accelerations divided by driving cycle length.

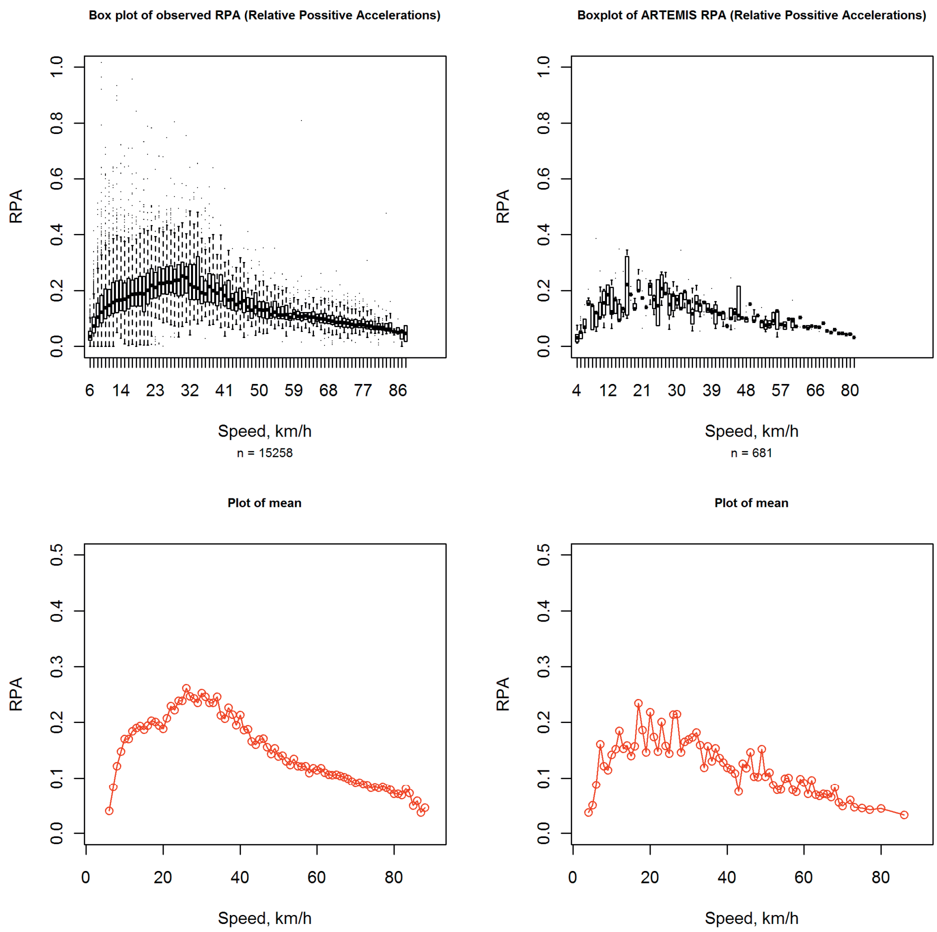


FIGURE 72 RELATIVE POSITIVE ACCELERATIONS FOR MICRO TRIPS

$$RPA = \frac{\int_0^T (v_i * a_i^+) dt}{x}$$

RPA was calculated for each micro trip, and micro trips with the same average speed were grouped together.

Figure 72 shows a comparison of RPA values from the observed and Artemis micro trips. Once again the shape of RPA when plotted against micro cycle average speed is similar.

TABLE 28 RELATIVE POSITIVE ACCELERATIONS

Micro cycle	RPA Average	RPA SD
Observed HDV	0.158	0.108
Artemis HDV	0.119	0.062

Table 28 shows that the average observed RPA was higher than the RPA found in the Artemis micro cycles.

A regression analysis of the average RPA data reveals that there is indeed a connection between measured and ARTEMIS RPA values. The dot plot in Figure 73 shows a linear regression line Y= 0.05 + 0.95x. The R squared value is 0.65.

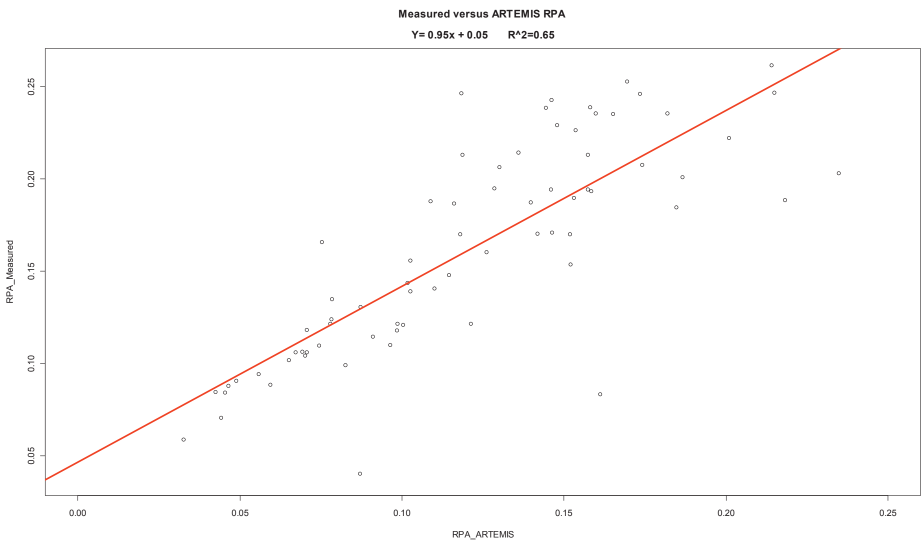


FIGURE 73 DOT PLOT OF MEASURED VERSUS ARTEMIS RPA VALUES

Based on Figure 72, Figure 73 and the regression analysis there is a link between RPA in the micro trips found in the ARTEMIS database and the measured values. But Table 28 presents evidence that the accelerations found in the measured data are higher than the accelerations found in the ARTEMIS database. The ARTEMIS database has data for the whole trucking fleet. There are two probable reasons why we observe higher accelerations. The first reason is a bias in the observed fleet, the vehicles observed cannot be said to represent the fleet accurately. Six of the eight observed vehicles were relative modern container trucks, Euro III and Euro IV. The mean weight was 11.4 tonnes based on loading data from 174 container trucks with cargo; this works out to an average weight utilization of 60% assuming three axel trailers for dual container transports. Thus the power to weight ratio is believed to be greater than for vehicles transporting bulk goods. Traffic conditions can be the second reason for why acceleration rates are higher in the observed fleet than in the ARTEMIS data. Most of the road network used for long-haul operations is uncongested; this is certainly true for night-time movements which are common for freight transports on many main relations. The reasons for the accelerations might be due to the road geometry. It is believed that the average speed is influenced more by road geometry than by traffic conditions for commercial vehicles on the Norwegian trunk road network. It is believed that when driving in quite heavy traffic accelerations are probably lower due to the fact that there is most probably a vehicle in front that will influence the acceleration rate.

5.8 SUMMARY

The main goal of this chapter was to see if there were ways to check if it was reasonable to transfer the ARTEMIS heavy-duty vehicle emission model to Norwegian conditions. First an experimental study was conducted to see if inexpensive consumer hardware could be used for tracking freight vehicles and collect data from the vehicle's engine. The prototype based on a windows mobile hardware and internal GPS units worked. But when this solution was placed in the commercial vehicles it became clear that the units became a hassle to the drivers and they did not use the units as described. The prototype was replaced with units that did not require user intervention, but could be disabled by the user by removing the power. This gave the drivers the possibility to disable tracking at their own discretion. The engine logging functionality did not work with the new black box units, thus engine parameters were not collected. The problem was related to the technology used and that it was not mature enough. At present new and more flexible technology is available for building more robust data loggers based on the Arduino microcontroller platform. An example of a vehicle telemetry platform is described in chaper 15 of Oxer and Blemings (2011).

In addition to collecting data, data analysis routines were developed to handle the volume of data; the raw data contained 4.78 gigabytes of data spread over 4,733 files. The GPS speed observations were extracted, georeferenced and stored in a database as geographic objects and linked to the road network. Details on this are given in Levin (2010). The collected data was compared with data extracted from the ARTEMIS database (Keller et al., 2007). Regression analysis was performed on relative positive accelerations and a positive correlation was found. The data did not indicate that it would be erroneous to use the European ARTEMIS emission functions for heavy-duty vehicles. The higher observed average acceleration could possibly be explained by a bias in the observed vehicle fleet or by the impact of road geometry on driving speeds.

The advances in vehicle data availability through fleet management systems open possibilities for georeferenced fuel consumption measurements. But this is a topic for further studies and requires cooperation from the vehicle producers to get nonstandard OBD-II data from the vehicles. This would allow for more detailed studies of vehicle fuel consumption and further the understanding of the factors that influence fuel consumption in real world driving conditions.

Using the speed limit as a proxy for average driving speed on the trunk road network showed that there were systematic differences. At speeds below 70 km/h trucks had an observed speed over the speed limit. At speeds above 80 km/h the trucks had average speeds lower than the speed limit. The net result of this should be that a model using the speed limit would slightly underestimate road emissions.

The comparison of driving behavior and relative positive acceleration values indicate that there is a connection between the observed behavior and the driving behavior used as driving cycles to create the average speed emission functions.

Thus this chapter has documented that using the ARTEMIS heavy-duty vehicle average speed functions should yield plausible emission and energy consumption results for Norwegian driving conditions. The last step in making the new emission model usable for everyday freight transport operations is to make the model into a tool that is usable for freight transport service providers. This is done in the result management module of the new emission model where results are aggregated to a level where freight transport service providers can use the results to create an emission calculation tool.

6 RESULT MANAGEMENT

This chapter presents the steps taken to make the detailed emission calculations usable for freight transport service providers. The aggregation routines are described along with tests of the routines. There are also some recommendations on how to use the emission database that is created by the aggregation routines.

So far the three bottom triangles of the Green Freight Transport triangle have been presented, see Figure 17. In the results management triangle the focus is on bridging the gap between detailed calculation routines and giving the freight companies a useful tool. At present companies have emissions factors that are dependent on distance and weight. And it is this type of simplicity that the result management module seeks to give the freight transport service providers. It became clear from several project meetings that using GIS tools to calculate emissions would become too cumbersome; hence reducing the chance that freight transport service providers would use the final tool. One idea that was consistent with the framework structure of the model was to develop a final stage after the core calculation routines that would aggregate and store data that could later be fed into existing company production systems.

Meetings with the TPG IT department gave insights into the existing productions systems used by TPG. The most useful bit of information for ensuring a successful shipment was the postcode in addition to a company name. Most of the shipments in TPG's production databases contained the postcode for sender and receiver. It became clear that there was enough information stored in the production databases to reconstruct which packages were loaded on the same vehicle. Thus it could be possible to calculate the weight on each vehicle and to allocate the emissions to the individual packages. Not all packages in the TPG system have physical weight recorded, but all packages have a volume-weight recorded. The Norwegian term for volume-weight is "fraktberegningsvekt" which is used to calculate the cost of shipment by the freight transport service provider. Volume-weight is the biggest value of physical weight or volume multiplied by a factor. The factor is a weight corresponding to 1 cubic meter. In the TPG system this factor is subject to negotiation with the customers, thus different customers can have different factors. In the new TPG production system Transport 2010 a new volume-weight notation is introduced, with "framføringsvekt"—the factor between volume and weight—will be fixed for all customers.

Based on the information gained from meetings with the TPG IT department a scheme for transforming detailed calculations into a database with emissions between postcodes was born. Based on address point data from the Elveg 2008 dataset postcode centroids were built. These centroids were then connected to the closest link on the road network. Figure 74 shows an example of a centroid built from points.

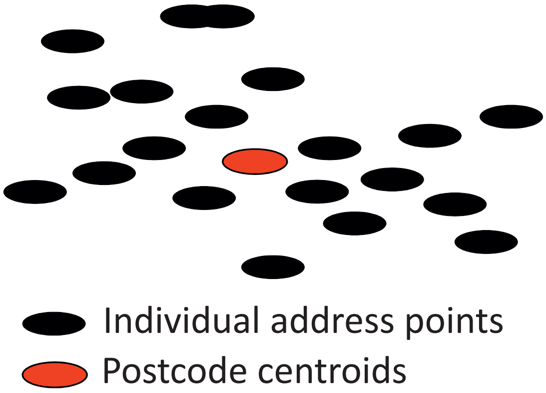


FIGURE 74 POSTCODE CENTROID

Centroids for address points with the same postcode were calculated in a GIS application. None-weighted building of centroids may not yield the optimal results. This is because the centroid is to express the average geographic place where freight is picked up or left. Address points may have different functions, some address points are single houses while others may be high-rise buildings with apartments or offices. If knowledge about activity (business or residential) at the address point was known then one could create a weighting scheme to get a better centroid location.

Postcodes are quite heterogeneous and thus sizes of postcode areas differ. Figure 75 shows the spread of postcode centroids in Norway. It is easy to see the outline of Norway. Then there is a zoomed in area to the west of Trondheim, the city of Trondheim is the large concentration of black dots in the south east. The cut-out shows that the postcodes are denser in the urban areas. This is beneficial to freight calculations because it is assumed that there is more freight going to urban areas than to rural areas.

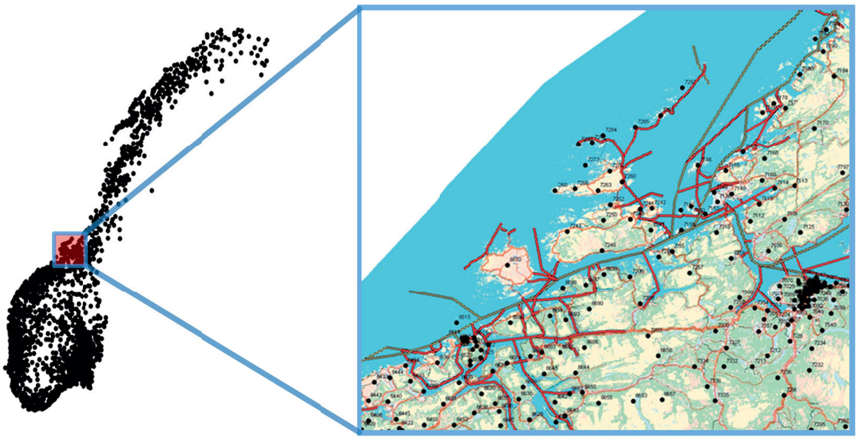


FIGURE 75 DISTRIBUTION OF POSTCODE CENTROIDS IN NORWAY

The cut-out was created to diagnose problems with islands that are not connected to the mainland with ferries, but served by smaller vessels carrying only passengers. The actual freight routes to these islands are most probably not the direct shortest path. Freight to smaller villages is usually collected by third-party operators that collect freight from several of the larger freight companies and aggregate it into a shipment. It is hard to calculate the emissions of these routes because they are under the control of a third party. The third party freight company usually consolidates freight from several large freight service providers. Thus actual routes taken and amount of freight in the vehicles that the third party transport provider uses is not known for the buyers of this transport. But fortunately the volumes to remote areas are quite small. And it is possible for the third party freight mover to calculate the emissions from the final transport because they have the necessary information on the shipment. The workaround for the large freight companies is to calculate emissions to the closest postcode that is on the mainland or islands that have a regular ferry service. This method has to be implemented by the freight transport service providers. In the Green Freight Transport project TPG has an algorithm to find the closest or best matching postcode based on name and postcode number.

The final observation from Figure 75 is the postcode that seems to be placed inside Sweden (north east of the cut-out). This point ended up here because of a faulty grid reference. The coordinates of the address points were said to be given in UTM 32 North, but were actually given in UTM 33 North. This caused a coordinate conversion where the point was moved eastwards. This was corrected in the final dataset.

6.1 CREATING EMISSIONS FACTORS FOR ALL POSTCODE RELATIONS

Building a database of emissions functions between all postcode relations seemed like good solution to integrate new emissions functions into the existing production system.

But building the database became quite a challenge if it was to be done within a reasonable time frame. The problem is the massive amounts of calculations needed to build the emission database. The bullet points below show some facts about the input to the final emission database.

- 3031 post codes
- 5 components (Fuel consumption, NO_x, CO, PM and HC)
- 84 vehicle types
- 3 loadings (0%, 50% and 100%)

Thus 9,186,961 route calculations have to be made. For each link in a route 1,260 emission calculations have to be processed. The number of links in each route will vary with route length. Figure 38 shows that the average link length is about 200 meters, thus for every kilometer emissions for five links have to be calculated.

The first try was to use ESRI's network analyst to build an OD-matrix of emissions. It was possible to set 1,260 network evaluators, but it was impossible to build the network for analysis. There exists no documentation that there was a limit on the number of evaluators that could be set. The software producers at the Norwegian support division were challenged with finding a workaround. Meanwhile a plan B was formed, the idea was to move the calculations over to a true 64-bit operating system running 64-bit software. The error messages posted by the software indicated that there was not enough memory available. The software was running on a Windows 7 PC with 8 gigabytes of RAM, but the operating system only reported application memory usage of 800 megabytes at the time of failure. A FreeBSD 64-bit server installation was chosen as an operating system. The ESRI software does not run on this operating system nor is the software in itself 64-bit. Thus alternative software had to be found for network analysis. The GIS applications available on the FreeBSD platform did not have mature enough GIS and network analysis software. PostgreSQL with the POSTGIS extension could provide GIS analysis and storage, but the PGRouting [40] extension to the PostgreSQL/POSTGIS did not work.

Plan C became to use an alternative software library for network analysis, NetworkX[41]. NetworkX is a general software library for working with graphs. Road networks can be seen as special cases of graphs with nodes and edges being road segments and intersections. NetworkX is a python module and thus it was simple to export the road network from the Windows based ESRI software to a plain text format that could be read by the NetworkX library and built into a graph for analysis.

To create a network that was readable by NetworkX, nodes had to be created and road links given for starting and end nodes. Integer values of X and Y coordinates were used

[40] http://www.pgrouting.org/
[41] http://networkx.lanl.gov/overview.html

as node identification. Thus linking roads together with start and end coordinates. A link table for postcodes to nearest road link was exported.

The runtime of the first network analysis and emission estimation prototype was unacceptable. Based on progress after four days the estimated time to completion was ten years. Plan D was to try to buy a new server with more memory to eliminate memory swapping to disk. A server with an Intel Core I7 950 processor running at 3.07GHz with 24 gigabytes of memory, compared to an AMD 965 3.4 Ghz processor with 8 gigabytes seemed to only cut about a year of the computation time.

Plan E was to profile the Python application and to see if it was possible to optimize by rewriting the code to allow for parallelization. The current Python application was single threaded and did not utilize more than one of the cores available in the processor. Python and parallelization with a large shared memory space did not look promising due to the way Python is implemented. At the Python Conference 2010 in Atlanta, David Beazley gave a talk on the challenges with multithreaded Python applications, Understanding the Python GIL[42]. Based on the information gained about the Global Interpreter Lock (GIL) plan E was rejected.

Plan F was further profiling of the emissions calculating code in relation to the input data. The profiling of the Python application indicated that calculating emissions on each link took most of the time. To make the Python application useful in the real world it became apparent that data reduction techniques had to be applied before link calculations took place.

On a long route from Oslo to Hammerfest there was around 10,000 links to be calculated (1978 kilometers). Thus if this could be reduced significantly, then the computation time would be reduced. Road gradient and the speed limit and road length are the parameters used in the emissions calculation. A simple data reduction technique is to group similar data in bins and use these bins in the analysis. Road speed limits were grouped into the following bins (30, 50, 60, 70, 80, 90, 100) and the gradients were grouped into the following bins (12, 10, 8, 6, 4, 2, 0, -2, -4, -6, -8, -10, -12). The speed bins are closely related to the available speed limits, while the gradient bins are grouped in classes of two percent points. The ARTEMIS heavy-duty vehicle functions are given in bins of twp percent points, thus this seemed to be a reasonable grouping. The result is a matrix with ninety-one cells that can be used to describe all road links. After each path is found a matrix is built and the values of the cells are set to the kilometers in each bin. For the Oslo - Hammerfest example this would reduce the number of emission calculations from about 10,000 to ninety-one. This routine could be further optimized by exchanging the emissions calculation of the ninety-one cells by multiplication of an emission matrix calculated for 1-kilometer bins. For one relation

[42] `http://us.pycon.org/2010/conference/schedule/event/76/`

this would not give much of an advantage, but this calculation would be done more than 9 million times. Energy and CO_2 emissions calculations were no longer calculated as these can be calculated afterwards based on the fuel consumption. Regression analysis was used to build a linear emission function from the three available loads available from the ARTEMIS emissions functions. The emission function has the following format:

$$Y_{component} = Ax_{Component} + B_{Component}$$

Ax is the slope of the function and *B* is the intercept. *Y* is the emission in the given component for the trip between two postcodes. The emissions are given in grams.

In the meantime the support division for the ESRI GIS application had found a workaround based on sequential runs. Emissions would be calculated from a single postcode to all other postcodes and then this process would be repeated for all origin postcodes. This solution was investigated as plan G. There were problems with this solution; first three parallel processes had to be run to get all the needed emissions factors. The ESRI software seemed to be limited to about 200 evaluators for network analysis. The second problem was expected run time; estimates based on profiling done by the support division indicated a runtime of three years. So this plan was dropped.

After twenty-one days plan F failed due to memory issues, the problem was that the paths were stored in memory. A path is essentially a list of links that are traversed on a specific postcode relation. The most efficient shortest path algorithm in the NetworkX library returns all paths from one postcode to all other postcodes. This problem was not discovered because the postcodes were sorted. Postcodes are roughly sorted from the south of Norway and to the north as an increasing number. The postcode density is greater in the south compared to the north. Thus paths from postcodes in the north to all other postcodes will consume more memory. The hardware bought for building the emission database had a maximum memory capacity of twenty-four gigabytes. The most cost effective solution became to buy a solid state hard drive (SSD) to use as swap space. Peak memory consumption was 56 gigabytes for the most northeastern postcodes.

The result from the Python application was a 246 gigabyte large text file with the following format:

```
From;To;Vehicle_Type;Component;Distance;Ax;B;R^2
1405;1409;31;FC;16.7853163724;3.1985295965;1907.29524316;0.998878219876
1405;1409;31;NOx;16.7853163724;0.11187123902;73.8360576771;0.999988362662
1405;1409;31;CO;16.7853163724;0.0659631673207;26.4507864474;0.969687929584
1405;1409;31;PM;16.7853163724;0.00892881072381;4.68631397528;0.961322117782
1405;1409;31;THC;16.7853163724;-0.011828328362;14.3442473665;0.999610952024
```

LISTING 6 EXERPT FROM THE GREEN FREIGHT TRANSPORT DATABASE

The column layout is as follows:

1. Origin postcode
2. Destination postcode
3. Vehicle type integer number from 31 to 114 corresponding to a vehicle and Euro emission standard, a list of vehicle types is given in Table 16
4. Component, possible values (FC, NO_x, CO, PM, THC)
5. Distance between origin and destination in kilometers.
6. *Ax*, slope of the emissions function based on vehicle loading
7. *B*, intercept of the emission function based on vehicle loading
8. R-squared value for regression function based on the three loadings; 0%, 50% and 100%

Plan H was to transform the large text file into a format that was more suitable for loading into a database. The first step is to understand how the database will be used and to transform the data according to this. The R –squared number was used to check if it was suitable to use regression to interpolate emission factors for weight loading between 1 and 100%. Typical values are in the 0.98 – 0.96 range indicating that there is indeed a positive linear relationship between amount emitted and weight moved by the vehicle. But in some cases the R-squared values were lower. A typical example of this problem is shown in textbox below.

```
From;To;Vehicle_Type;Component;Distance;Ax;B;R^2
1405;1404;59;FC;12.9352881597;12.6791945652;2346.14522123;0.999994175527
1405;1404;59;NOx;12.9352881597;0.194675968254;44.9264986537;0.998967614403
1405;1404;59;CO;12.9352881597;-7.40712337986e-05;1.33116088872;0.00481588906512
1405;1404;59;PM;12.9352881597;-3.99634421837e-05;0.28688832521;0.27756432994
1405;1404;59;THC;12.9352881597;-8.89620172887e-05;0.175830585523;0.708111913951
```

LISTING 7 EXCERPT FROM DATABASE WHERE CO AND PM EMISSIONS HAVE LOW R-SQUARED VALUES

The distance between postcode 1405 and 1404 is about 13 kilometers. For fuel consumption and NO_x the R-squared values are good. But for CO, PM and THC the R-squared value indicate that the weight transported and amount of these emissions are not correlated. The vehicle used (ID=59) is a rigid truck with a maximum weight of 26 tonnes with a Euro IV engine. The scale of the emissions with low R-squared values is small and the slope estimate is very small, this was common for the values inspected. This could indicate that when the scale of an emission is small and the estimated slope is small, then the slope could be ignored and the emission held constant over all loadings.

The new format of the text file is shown below:

```
From; To; Vehicle_type; Distance_km; FCa;FCb;NOxa;NOxb;COa;COb;PMa;PMb;THCa;THCb
1405;1409;31;16.79;3.1985;1907.30;0.1119;73.84;0.0660;26.45;0.0089;4.69;-
0.0118;14.34
1405;1409;32;16.79;3.1161;1624.97;0.0885;52.90;0.0195;8.93;0.0039;1.85;0.0010;3.16
1405;1409;33;16.79;3.2071;1564.77;0.0751;54.12;0.0070;7.42;0.0013;0.89;0.0006;1.99
1405;1409;34;16.79;3.1985;1640.14;0.0638;40.05;0.0074;7.68;0.0007;0.81;-
0.0001;1.77
```

LISTING 8 EXCERPT OF FINAL DATABASE LAYOUT

The restructured text file is smaller at 63 gigabytes; most of the reduction comes from rounding to four decimals for A and B, while distance is rounded to two decimal places. The final calculated emission value should be presented as integer values of grams.

The final part of plan H was to load the text file into a couple of different databases and see if performance was acceptable. PostgreSQL, MySQL and SQLite databases were tried. Loading of the data and indexing according to origin, destination and vehicle type took from four to eight hours. Lookup of a single relation took less than 0.1 seconds. The SQLite database was put on an external USB disk drive and hooked up to a normal office laptop computer and a single lookup still took under 0.1 seconds. This was a clear indication that it was possible to use the large emission database as input to the production systems in freight transport companies. The SQLite database takes 99.5 gigabytes of disk space. The conclusion of the last exercise was that it was plausible for freight transport service providers to utilize the database as input to their production systems.

6.2 Tests of the result management module

The move from ESRI’s network analyst to a self-tailored NetworkX application has the potential to induce errors in the emission calculations. The simplification procedure that made it possible to calculate emissions in advance had the possibility to introduce new random or systematic errors.

The first check was to test if distance calculations done on ESRI’s ArcMap platform differ from those done with the self-tailored NetworkX application. Eleven cities were selected and a postcode within the city limits was chosen. The following cites were selected:

- Oslo - 1081
- Fredrikstad - 1608
- Drammen - 3045
- Sandnes - 4322
- Kristiansand - 4611
- Bergen - 5011
- Ålesund - 6002
- Trondheim - 7042

- Bodø - 8012
- Tromsø - 9019
- Kirkenes - 9900

These cities were chosen on the basis of city size and location, there is at least one city in each part of Norway. The postcode is a random postcode within the city limits. From the eleven cities a distance matrix was created and routes between the cities were calculated. Figure 76 shows a scatter plot of the distances measured with the two routing applications. The GIS application that was originally intended to be used is labeled ArcMap, while the application created because of the limitations is labeled NetworkX. The eleven cities give 110 routes with distances that are plotted in the figure. A simple regression analysis of the data gives a linear function y = 1.007x + 2.439. This means that the distances reported by the NetworkX application is a bit longer, on average 0.7% longer. The R-squared value for the NetworkX and ArcMap distances is 0.9999 which is very good. The boxplot to the right in the figure shows that 50% of the differences between the NetworkX length calculations and the ArcMap length calculations are within a distance of 20 kilometers. Again the boxplot shows there is a bias towards longer distances calculated with the NetworkX application.

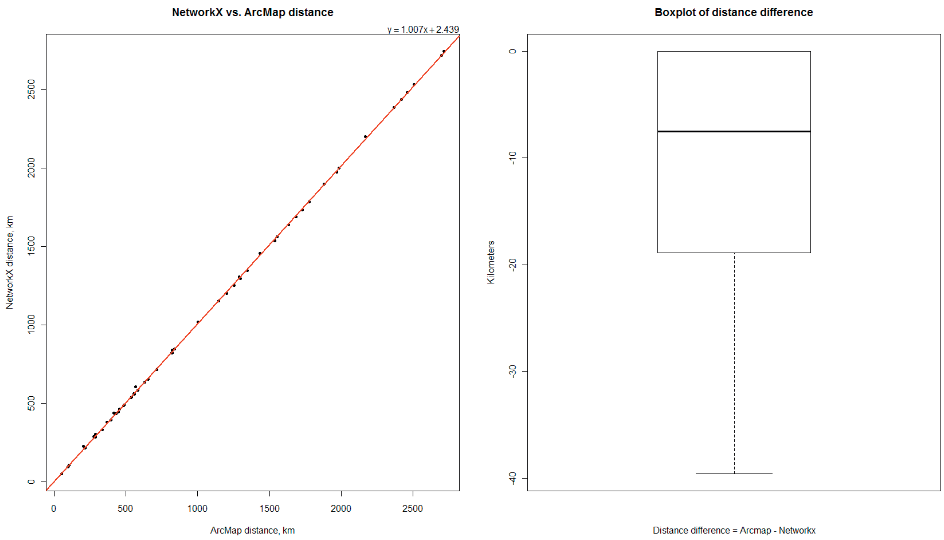


FIGURE 76 NETWORKX VERSUS ARCMAP DISTANCES

It is not surprising that there are some differences with the distance calculations. The first reason is that ArcMap snaps start- and end-points perpendicular to the road link and calculates the partial length of the first and last road link. The NetworkX application is not a true GIS application; it uses a predefined list to link postcodes to the closest road link. The full distance of that road link is then used in the calculation. A

GIS tool needs to link the postcodes to the road segments; ArcMap was used to do this. The second reason for differences is the road network. The road networks are not the same. An export application was written for the road links stored in the ArcMap software. Road links were given start- and end-nodes that correspond to the integer value of their X and Y coordinates combined. Thus road links that share common coordinates, when converted to integers, are linked together. The network used in ArcMap has turning restrictions while there are no turning restrictions in the NetworkX network. There are differences between the ArcMap and NetworkX networks, but they are not greater than expected due to the differences in methodology used. And the impact on the emission estimates will be minor.

If one starts with a topological network with node indicators on the lines then it should be possible to build the exact same networks if one excludes banned turns. And if the next version of the ESRI software allows for more than 600 evaluators and improves execution speed then there is the possibility to remove the export step completely. Then one could use ESRI's network analyst that builds on ArcMap to create the emission database. An alternative is to move the GIS functionality to a PostgreSQL/PostGIS platform with the new experimental network solving routines known as pgRouting. pgRouting is an extension to the PostgreSQL/PostGIS applications that allow for routing based on networks stored in the PostgreSQL/PostGIS database. To find the best future option an explorative study should be undertaken. The study should focus on the ability to handle large networks with more than 1 million links. For this Ph.D. project it is believed that the solution found using an export to a NetworkX network is good enough.

The second control that needs to be undertaken is to check the impact of simplifying the calculation routines to reduce calculation time to a reasonable level. As mentioned the detailed calculation routines gave indicated a runtime of 10 years. So a faster solution had to be found. At the time the simplification algorithm was developed it was known that simplification of the calculations could lead to underestimation (Lervåg, 2009). But there was no alternative to simplification if one was to deliver a road emission database for all postcode relations. Emissions were calculated for the 110 routes between the eleven cities. A simple regression analysis confirms that there is difference between the detailed calculations and the simplified calculations. According to Figure 77 a difference of about 10% is present.

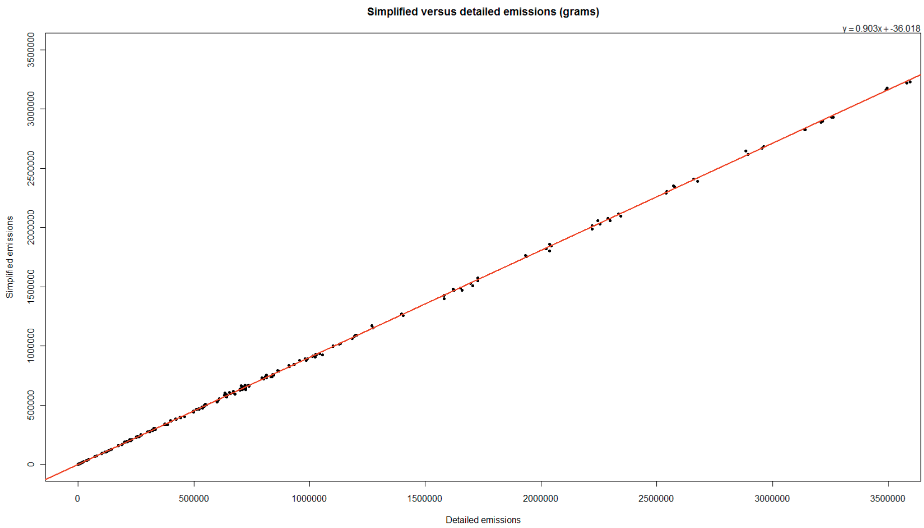


FIGURE 77 SIMPLIFIED VERSUS DETAILED EMISSIONS

One problem with this analysis is that it uses all emission figures for all pollutants. Thus pollutants with large emission values will dominate the regression curve. CO_2 is one such component. An alternative analysis is to look at each component separately. Figure 78 shows scatter plots of the simplified and detailed calculations along with an ideal regression line (intercept= 0 and slope=1). All components exhibit the same underestimation of emissions, all data points are below the ideal regression line.

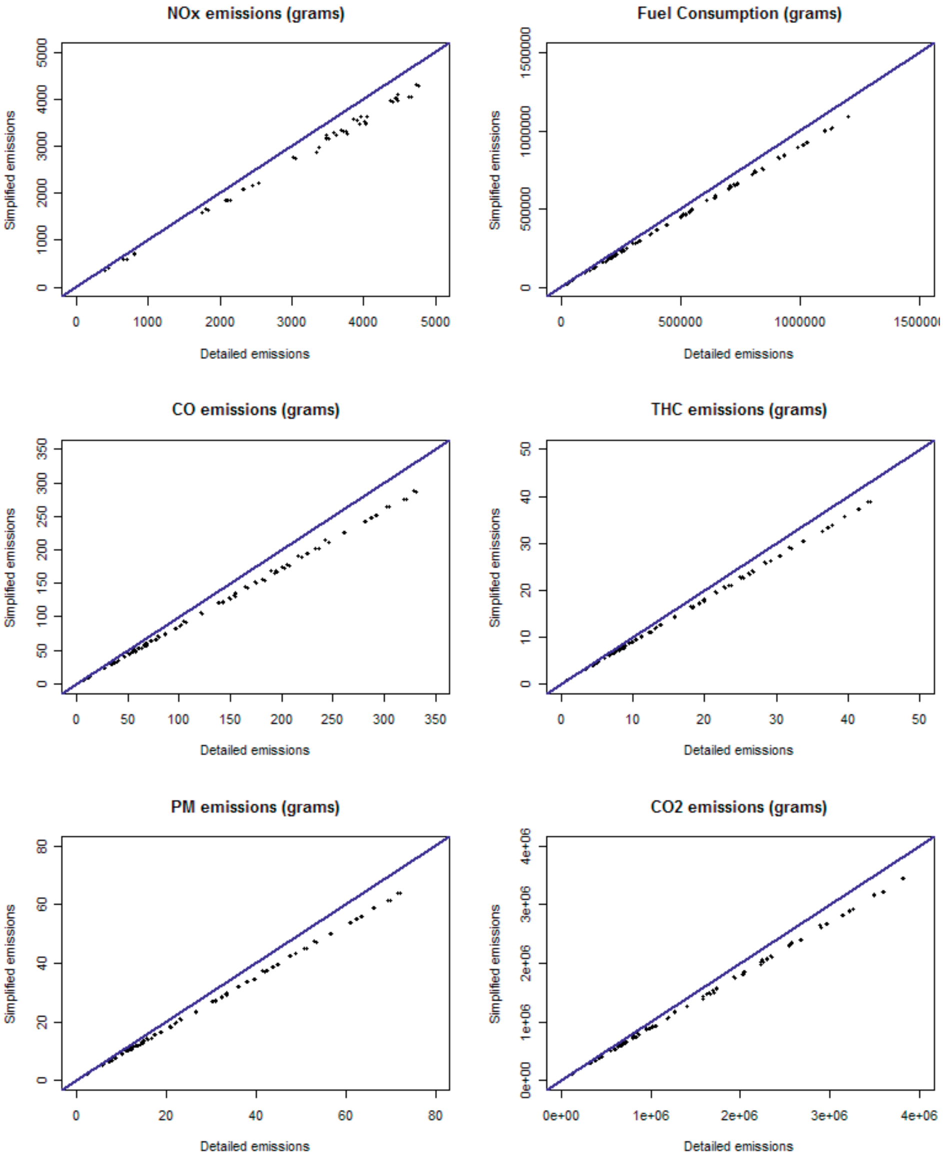


FIGURE 78 SCATTER PLOTS OF SIMPLIFIED AND DETAILED CALCULATIONS BY COMPONENTS WITH IDEAL REGRESSION LINE

The intercept and slope for the regression lines for the different components are presented in Table 29.

TABLE 29 SLOPE AND INTERCEPT FOR REGRESSIONLINE BETWEEN SIMPLIFIED AND DETAILED CALCULATIONS

Pollutant / Energy	Intercept	Slope
NO_x	1.4966870	0.8940984
Fuel consumption	-72.6529397	0.9034066
CO	0.1745728	0.8639436
THC	0.01074546	0.89949968
PM	0.02498749	0.88495361
CO_2	-230.3098190	0.9034066

All components have slopes below 1, from 0.86 to 0.90 based on the 110 routes calculated in the test dataset. The grouping function was studied and debugged and no faults were found. The python grouping algorithm is presented in the following textbox. Speeds and gradients are put into different bins according to their original value.

```
def classify(speed, grade):
  #First element is 0 so it can be used for indexes in in matrices
  S=-1 #Speed class
  G=-1 #Grade class
  #find speed class along x axis
  if speed >0 and speed <= 40:
    S=0
  if speed >40 and speed <=55:
    S=1
  if speed >55 and speed<=65:
    S=2
  if speed >65 and speed<=75:
    S=3
  if speed >75 and speed<=85:
    S=4
  if speed >85 and speed<=95:
    S=5
  if speed >95:
    S=6
  #find grade along Y axis
  if grade>11:
    G=0
  if grade>9 and grade <=11:
    G=1
  if grade>7 and grade <=9:
    G=2
  if grade>5 and grade <=7:
    G=3
  if grade>3 and grade <=5:
    G=4
  if grade>1 and grade <=3:
    G=5
  if grade>=-1 and grade <=1:
    G=6
  if grade<-1 and grade >=-3:
    G=7
  if grade<-3 and grade >=-5:
    G=8
  if grade<-5 and grade >=-7:
    G=9
  if grade<-7 and grade >=-9:
    G=10
  if grade<-9 and grade >=-11:
    G=11
  if grade<-11:
    G=12
```

```
    return S,G
```

LISTING 9 ORIGINAL SPEED AND GRADIENT GROUPING FUNCTION

An alternative view of the grouping function is given in Table 30 and Table 31 along with the value used in the emission calculation for each group.

TABLE 30 SPEED GROUPING

Speed (v): Value range	0 < v <= 40	40 < v <= 55	55 < v <= 65	65 < v <=75	75 < v <= 85	85 < v <= 95	v > 95
Group number:	0	1	2	3	4	5	6
Value used	30	50	60	70	80	90	100

TABLE 31 GRADIENT GROUPING

Gradients (g): Value range	g > 11	9 < g <=11	7 < g <= 9	5 < g <=7	3 < g <= 5	1 < g <= 3	-1 <= g <= 1	-3 <= g < -1	-5 <= g < -3	-7 <= g < -5	-9 <= g < -7	-11 <= g < -9	g < -11
Group number:	0	1	2	3	4	5	6	7	8	9	10	11	12
Value used	12	10	8	6	4	2	0	-2	-4	-6	-8	-10	-12

In practical terms it is not possible to calculate difference for the whole data, as this would take more than ten years. But a simulation was set up to select 5,000 routes based on randomly selected links from the road network. For each route a random number of links between 100 and 10,000 were chosen and emissions calculated on these links with the detailed method and simplified method. To reduce runtime two simulations were run in parallel on servers calculating 2,500 routes each. A different random seed was set on the two servers to avoid building the same datasets.

The simulation again showed an underestimation of the emissions for all components and fuel consumption. Table 32 shows the intercept values and slope values for the simulated routes, 5,000 in total. They show a systematic underestimation of 5-6%.

TABLE 32 INTERCEPT AND SLOPE OF REGRESSINLINE FOR SIMULATED ROUTE DATA ORIGINAL ALGORITHM

Pollutant / Energy	Intercept	Slope
NO_x	-0.719	0.941
Fuel consumption	-43.778	0.943
CO	0.001	0.935
THC	0.001	0.946
PM	0.001	0.943
CO_2	-138.775	0.943

A graphical presentation of the data in Table 32 is presented in Figure 79.

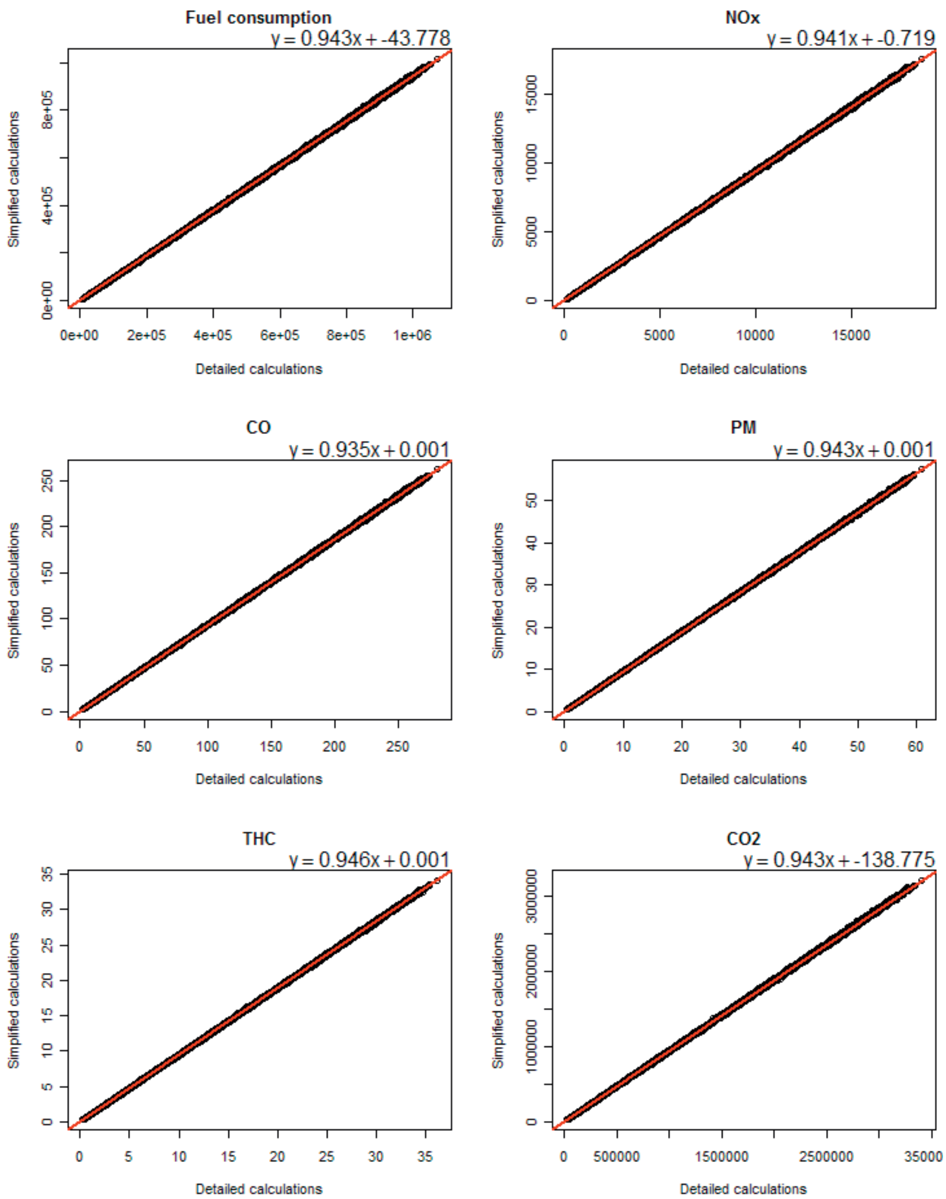


FIGURE 79 COMPARISON SIMPLIFIED AND DETAILED CALCULATIONS WITH ORIGINAL ALGORITHM

One possible explanation for the observed underestimation is that the distribution of gradients in the road network is not uniform. Figure 80 shows that the distribution of gradients is not uniform; more of the road network has small gradients than larger gradients. The creation of groups could cause an underestimation. At present all grades below 1% are calculated as flat, gradient used is 0%. But 40% of the length of the road network has links with less than 1% gradients and thus these will be calculated with gradient 0%. This could be the part of the reason why the simplified calculation routine underestimates emissions.

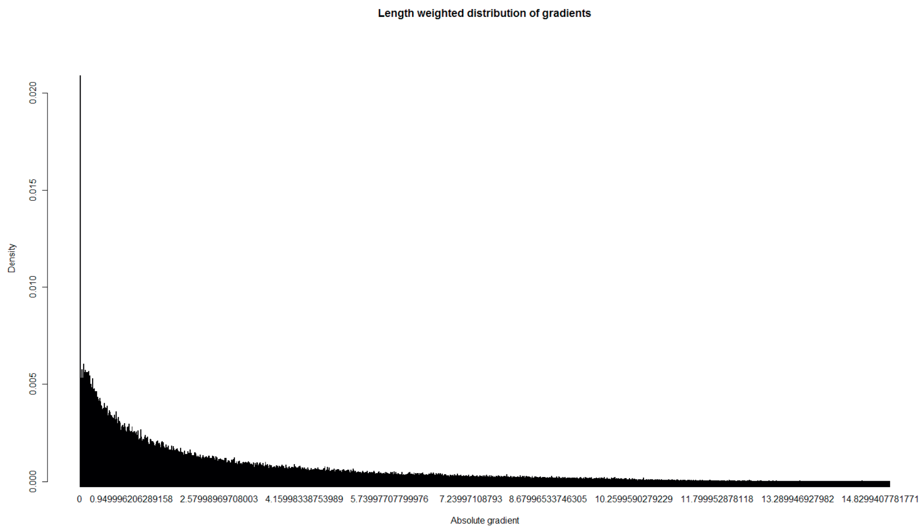


FIGURE 80 LENGHT WEIGHTED DISTRIBUTION OF GRADIENT IN THE 2008 ELVEG NETWORK

A slightly modified algorithm was created to capture more of the small gradients. The original bin for low gradients used to range from ±1 and was calculated with a value of 0. In the modified algorithm this range was decreased to ±0.5 and the next bin that used to range from (1…3) or (-1…-3) was shifted to (0.5…3) and (-0.5…-3) and calculated with a gradient value of 1.75%. This seemingly small change had a major effect when applied to the same simulation dataset. Table 33 shows that the modified simplification algorithm overestimated emissions by between 2 and 4% depending on component. Finding a better simplification function would be a process of trial and error. The under- and overestimation seemed to be linear and thus a correction factor could be used.

TABLE 33 INTERCEPT AND SLOPE OF REGRESSINLINE FOR SIMULATED ROUTE DATA MODIFIED ALGORITHM

Pollutant / Energy	Intercept	Slope
NO_x	1.257	1.035
Fuel consumption	72.056	1.035
CO	0.018	1.027
THC	0.002	1.021
PM	0.003	1.025
CO_2	228.416	1.035

Figure 81 gives a graphical presentation of the values given in Table 33. There is a strong correlation between the detailed results and the simplified results. The R – squared value for all components for both the original and modified algorithm is 0.9999.

Based on the test conducted, the simplified emission calculation routine lead to systematic underestimation of all pollutants. A correction factor can be applied since the underestimation appears to be linear in the test of the real data and for the synthetic test data.

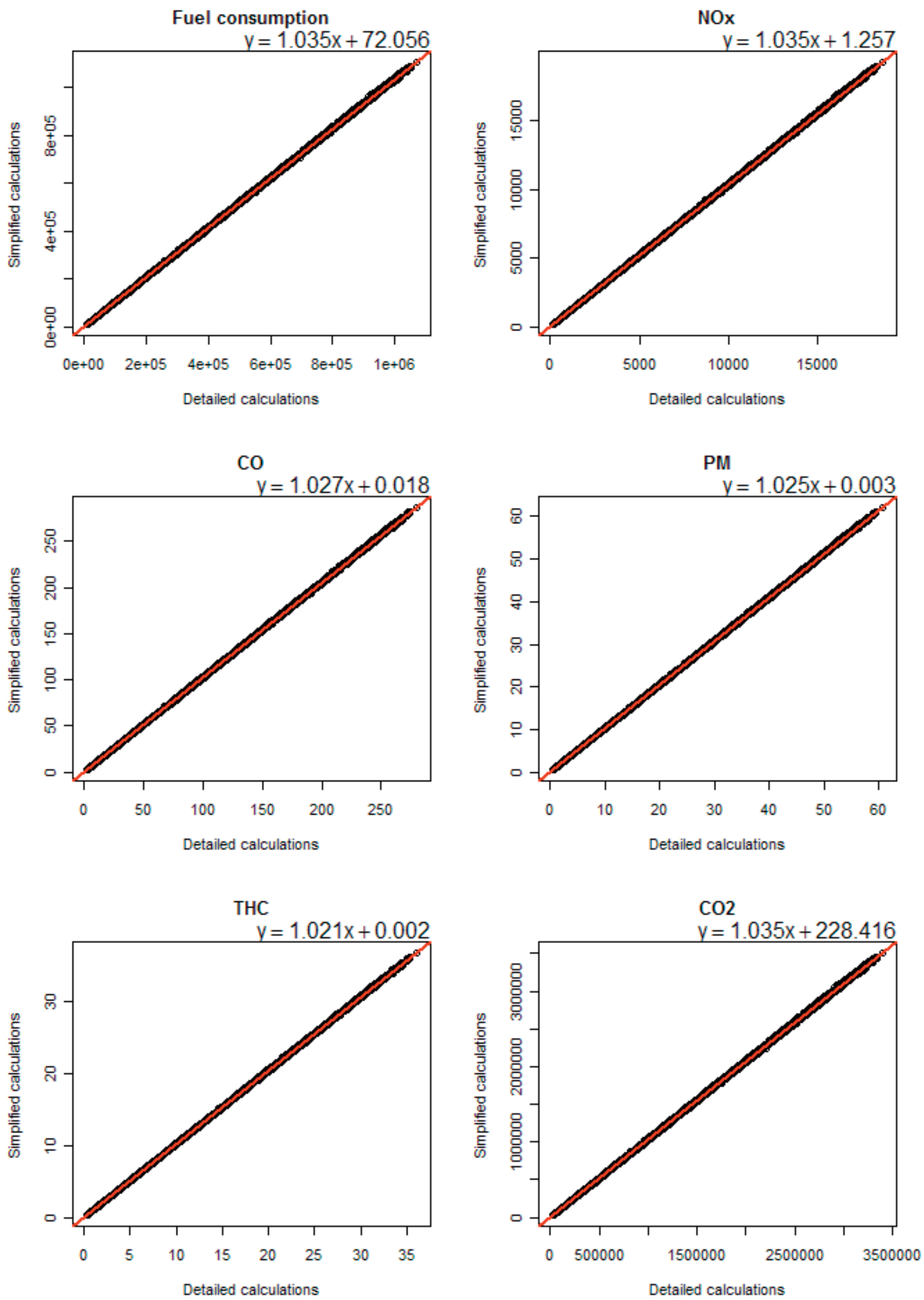


FIGURE 81 SIMPLIFIED AND DETAILED CALCULATIONS WITH MODIFIED ALGORITHM

6.3 Correction factors for road emission database

The ideal situation would be to use the detailed calculation routine to generate the emissions database. But the calculation time, ten years, makes this unusable. The simplified approach that was applied to create the postcode emission database reduced the computational time to thirty-one days. But the algorithm that was created induced a bias towards underestimation because of the groupings chosen and the distribution of gradients in the road network. A simulation test confirmed that the bias was induced because of the grouping of small gradients, a small change in the range definition of the groups cause a shift to overestimation. Further work on the simplification algorithm could reduce the calculation error. One possible solution could be to use a grouping that reflects the distribution of grades. Thus the ranges are smaller in the lower end of the gradient scale where most of the roads are. 40% of the length of the Elveg 2008 road network has gradients less than 1%. Alternative simplification algorithms should be developed if the limitations of the ERSI software are not solved within the near future. If ESRI solves the problems with the limitations in Network Analyst then there is no need for the simplification algorithm.

Due to time and financial limitations of the Ph.D. project it was not possible to spend more time on finding a better algorithm. But the study has shown that the errors are linear. Thus is should be possible to adjust the calculations with a correction factor. The original algorithm when tried on the eleven cities in Norway showed a constant underestimation, ranging from 10 - 16% depending on the component. In the simulated dataset where road links are drawn randomly and assembled into routes indicate a systematic underestimation of about 6%. The results from the study of the routes between the eleven cities is assumed to give better correction factors as they are based on real routes. The intercept values are so small that they could be ignored. Correction factors to be applied to the final database are given in Table 34.

TABLE 34 CORRECTION FACTORS FOR THE FINAL DATABASE

Component	Correction factor
NO_x	1.1184
Fuel consumption	1.1069
CO	1.1575
THC	1.1117
PM	1.1300
CO_2	1.1069

6.4 Practical use of the model

Available data, not knowing the environmental consequences of measures, and the company lacking the necessary knowledge were identified as the biggest barriers against implementation of an environmental management system (Lervåg, 2009). The new model allows freight transport service providers to test measures under their control by using more detailed emission functions. The model was built to estimate emission from a single vehicle given a set of input parameters. Vehicles in this context can be a train, ship or truck including any container or trailer that is loaded onto the vehicle. The resulting management module was built as a way to interface the new emission model with the firm's own production system. In Levin and Sund (2010) four stages of bottom-up calculations were identified. The first stage is collecting input relating to infrastructure descriptions and turning them into transportation networks that can be used as input to emission calculations. The next step is structuring emission functions so that they can be used in conjunction with the network. In our case this is the GIS application. The third step is the aggregation step which closely resembles the result management module. The fourth and last step is the result presentation step. All steps are shown in Figure 82.

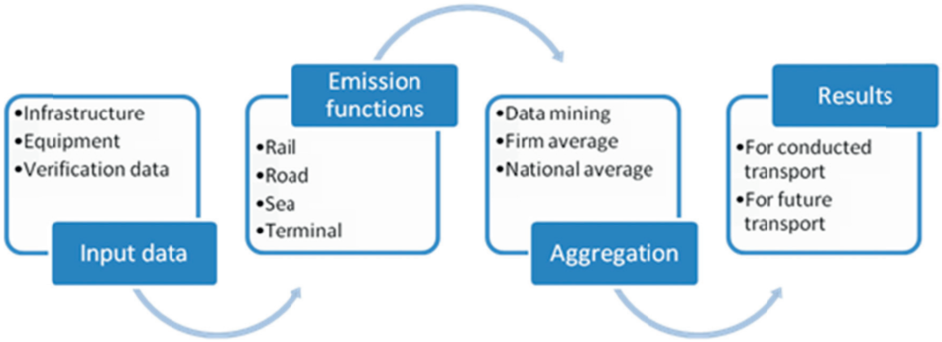


FIGURE 82 THE FOUR STAGES OF BOTTOM-UP EMISSION CALCULATIONS SOURCE: (LEVIN AND SUND, 2010)

The key concept in the aggregation stage is to look at data available in the company's production system. In the Green Freight Transport project a pilot "emission estimation tool" was to be installed at TPG. One advantage with TPG is that they have created their own production system. This meant that TPG was open for alteration to the system in order to build a scientifically sound emission estimation routine. But as the Green Freight Transport project was a user-controlled research project there was a clear focus on making the routines usable in terms of run time and load on the production system. The final database with the correction factors are believed to be satisfactory for use in conjunction the freight transport company's production system. TPG began to implement the emission database into their production system in the beginning of 2011.

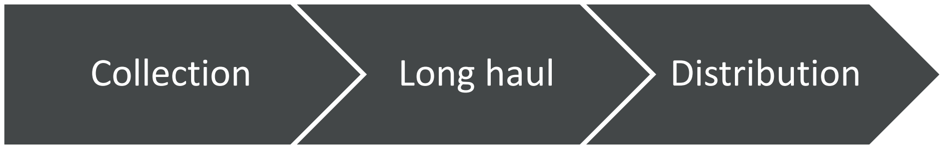


FIGURE 83 THE THREE PHASES OF A SHIPMENT

Figure 83 shows the three phases of a shipment in the TPG system. The first stage is when freight is collected from different origins. The freight is then moved to a terminal where it is sorted and packages going to the same destination terminals are combined into containers. The containers are then moved to the distribution terminal in the long haul phase. Rail, road and sea modes and combinations of these are available in the TPG system. At the distribution terminals the freight is then sorted again and loaded onto vehicles for their final destination. The rest of the chapter will look at how emissions can be allocated to the freight.

6.4.1 ALLOCATING EMISSIONS

Until now focus has been on calculating emissions from a single vehicle. For the emission calculations to be meaningful for the freight transport service providers the emissions have to be allocated to the freight moved. When estimating emissions the weight of the vehicle including the container or trailer used is to be included in the total weight. Thus if a container is used on a truck then the extra emissions resulting from the container is to be allocated over the freight sent in the container. If a trailer from a truck is put on a train, then the extra emissions associated with that trailer should be added to the freight inside the trailer. This is in line with the product category rules (PCR) prepared by NTM for: Basic module: Freight transport service[43].

A challenging question was how do freight transport service providers allocate the emissions among the packages on the same vehicle? The answer is not clear cut and further research is needed to find the best way to do it. The simplest way could be to allocate emissions based on physical weight. A problem with this method is associated with the density of the freight. Low density freight can “fill” the vehicle before the physical weight limit is reached. If there are capacity issues low density freight will force the use of extra vehicles to move the freight. If 30 tonnes are to be moved from Trondheim to Oslo then if the density is high then all of the 30 tonnes can be moved by one truck. If the density is low then two trucks would be needed and if the density was very low then the freight could need three trucks to be moved. Below is a calculation

[43] http://www.environdec.com/en/Product-Category-Rules/Detail/?Pcr=5862

example for 30 tonnes moved between Trondheim and Oslo with varying utilization of the trucks.

TABLE 35 IMPACT OF FREIGHT DENSITY ON EMISSIONS

Number of vehicles	1	2	3
Vehicle load	**100%**	**50%**	**33%**
Fuel consumption (g)	170292	264062	357066
NO_x (g)	2971	4841	6700
CO (g)	49	101	152
PM (g)	11	22	32
THC (g)	7	13	19

Table 35 shows the emission impact if the 30 tonne load had to be split onto more vehicles. If two trucks have to be used the fuel consumption increases by 55%. And if three trucks have to be used the fuel consumption increases by 210%. The other emissions increase in a similar fashion.

An alternative way to allocate emissions is to use the same factors used when calculating the price of shipment. TPG uses a pricing scheme that reflects the density of the freight as a freight weight that is calculated based on a volume density factor set by TPG. The benefit of using the same allocation function for economic aspects and environmental aspects is that it can link some environmental and economic goals. For example a customer could be given a discount because the shipment pattern of the client helps TPG achieve better utilization on certain routes. As seen in Table 35 better utilization reduces emissions and is thus positive. In the Green Freight Transport project an allocation function based on the way customers are charged is used.

But as stated earlier allocation functions for emissions between customers should be looked at in more detail in order to make sure that the allocation gives incentives to environmentally friendly behavior.

6.4.2 Collection and distribution

The collection and distribution phases are different from the long haul phase as freight can be picked up and dropped off during a trip. The vehicle weight utilization will change over the duration of the trip. Thus the amount of emissions the vehicle emits will change between the stops even if driving conditions are equal. To reflect this in the emission calculations a calculation scheme called package sequence was developed. In the package sequence the key concept is to split a collection or distribution trip into a set of stops between postcodes. And emissions between the stops can be calculated with the appropriate load factor. Then the emission would be allocated to the freight in the vehicle between the stops, and finally summed up for each package at the end of the trip.

6.4.3 Long haul

For road vehicles, emission calculations are simpler because vehicle load is constant for the whole trip. To some extent the same is true for rail, as the rail operator that TPG uses, CargoNet, runs mostly system trains. A system train is a train where the train configuration stays the same independent of loading and the train does not stop to pick up or drop off freight on the way between origin and destination. But there are some examples where the train picks up or drops off several wagons at a few stations. Another challenge with the train is that it is operated by an external company. Thus they do not have information about the other freight onboard the trains. The factors used to convert between emissions based on gross-tonnes to net-tonnes is only known by the rail operator. The problem with the conversion factor between gross-tonnes and net-tonnes is that for system trains it is basically a measure of utilization. And to some extent this information can be viewed as business sensitive information. But according to the Green Freight Transport project user needs assessment, companies were willing to share information if it would improve their environmental performance (Lervåg, 2009). Thus the freight transport companies who use the train should be able to ask the rail operator for train specific factors for converting net-tonnes into gross-tones. For the Green Freight Transport project SINTEF received data to build conversion factors. These factors were then applied to specific train routes and directions so that energy consumption for rail was related to net-tonnes.

For sea born transport the total emissions are independent of the amount of freight onboard the ship. This is because the state-of-art emission model does not use weight of freight as a variable. Thus a conversion factor between gross-tonnes and net-tonnes does not make sense. But a simple volume share could be used that describes the company's share of emissions between two ports. In the example of TPG the ship problem is minimal since the whole ship is chartered by TPG. But the shipping route that Tollpost operates resembles pickup and distributions routes, because freight will be loaded and unloaded along the route. Thus the emission share has to be calculated for every leg of the ship transport.

6.4.4 Special cases

In an ideal world there would be no special cases, there would be full and complete knowledge about every packet and vehicle used. But unfortunately there are many special cases, data is missing or simplifications have to be made due to various reasons. And if the TPG prototype is to be implemented by other freight transport service providers then other issues may arise because data is not collected in the same way or with a different level of detail.

Thus a strategy to cope with special cases was established. It consists of the four stages listed in Figure 84.

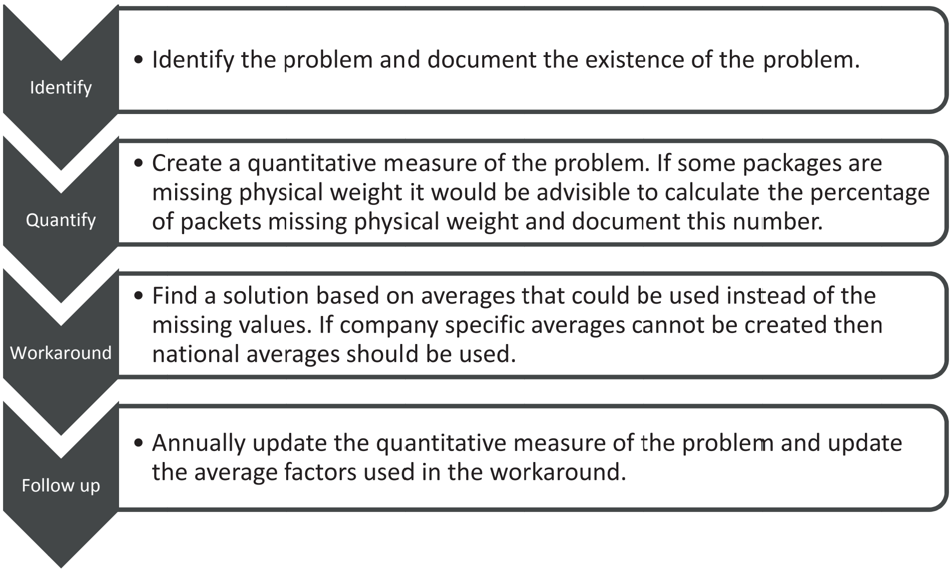


FIGURE 84 STRATEGY FOR COPING WITH SPECIAL CASES

The idea behind the strategy is transparency and periodic updates of factors used in the workaround and measures to quantify the problem. In the case of TPG some shipments were missing physical weight, but the freight weight was given. The scale of this problem was quantified and the proposed workaround was to calculate an average factor between freight weight and physical weight and to use this to calculate physical weight. It was acceptable for TPG to update the quantitative measure annually.

If the measure to quantify a problem is small enough, then this could warrant the workaround to ignore the problem. In the case of TPG it was decided to use shipments as the most detailed level. A shipment can consist of several packages, but these packages can be split across different vehicles and in some extreme cases split between different modes, for example rail/road. When the issue of split shipments on different modes was quantified the number was so small that the workaround was to ignore the problem. But the issue will still be followed up annually to see if there is a change in proportion.

Another special case is the use of “Charter” contracts for road transports. A charter contract is different from the other contracts that TPG has because it is a one-way contract. TPG only pays for the outward transport, and has no responsibility for the return transport. TPG has no knowledge about how the truck returns to its origin or if the truck is actually on a return trip. A simple but robust technique is needed as a workaround for this issue. After discussions with TPG the following workaround was proposed: For the outward trip the emission is calculated with an average utilization for charter trucks. The brokers dealing with the charter vehicles are probably the best at estimating this utilization factor. This factor should be the same for every freight transport service provider that uses charter transports. In addition to emissions from the outward trip emissions for an empty return trip is added to the freight that was sent with the charter vehicle. The rationale behind this is that the use of charter transport is not believed to be as environmentally friendly because charter is used to temporarily increase capacity in the logistic network. It is believed that the goods could be moved at a later time without expanding the capacity of the logistic network temporarily. Thus environmentally friendly customers could have contracts that state "no use of charter" and the calculation of emissions would reflect this. The customers would then have to accept that the freight might be delayed, but they have contributed to a better utilization of the existing logistic network.

The strategy for special cases tries to balance the cost of implementing the new model with estimation accuracy. If special cases are documented by every freight transport service provider that implements the new model then it should be possible to track down issues relating to special cases that cause systematic differences. If the model is implemented by more freight transport service providers then more special cases would appear, which will have to be dealt with. However, it is important that knowledge is documented and shared; it would be beneficial for the companies to form a network where these issues could be discussed.

6.5 Summary

The result management module is important if freight transport service providers are to use the results from this project because it allows for a simple interface to emission calculations. The database can be linked with a freight company's production system to calculate emissions based on actual weight and utilization of the vehicle, but creating this database was computationally intensive. Off-the-shelf commercial software had hidden limitations that made it impossible to calculate emissions, a workaround was proposed by the producers of the software, but the calculation time was estimated to be in the neighborhood of three years. A self-made detailed calculation routine would take ten years to complete. But the introduction of a simplification algorithm reduced the calculation time to thirty-one days. But the simplification routine underestimated emissions when compared to detailed calculations for routes between eleven Norwegian cities. The error is not caused by a bug in the algorithm, but that an algorithm with equal groups does not seem to be a good match for the distribution of gradients found in the road network. Further work could be conducted to find a better simplification algorithm, but this is not possible within the economic and time frame of this Ph.D. project. The error is fairly constant and a scaling factor can be to used give results in line with the detailed calculations, especially for the main freight routes between the biggest cities in Norway. Table 34 presents a set of suggested correction factors.

The resulting management module reduces the precision of the calculations by introducing postcodes as origins and destinations and not geographic coordinates as can be used in the GIS tool. Postcodes were chosen as they are commonly used by the freight industry to designate origins and destinations for transports. The database offers the benefit of full integration into the company production system. In the beginning of 2011, TPG started to implement routines for linking the model to their production system. When it comes to practical use of the model for emission estimation several practical issues became evident. Some possible solutions were described, but the full extent of the issues will not be known until implementation is completed by several freight transport providers.

Documentation of how the emission model is implemented is needed if one is to compare emissions for specific transports between companies. Before a set of best practice routines can be established more experience with implementation of the emission estimation model is needed. The special cases and allocation functions presented in this chapter should be seen as a starting point for a further discussion when more experience with usage of the tool becomes available.

The final step in testing the new emission model for freight transport is to assess model results and compare them to results from existing tools and measured values if available.

7 RESULTS FROM THE NEW MODEL

Within the confines of the Ph.D. project it was not possible to verify results from the new model against measured values. For road-based transport there was an attempt at checking driving behavior to see if the driver behavior used by the ARTEMIS calculations is radically different than the behavior observed. The analysis showed that there was a good correlation between observed positive accelerations in Norway and those found in the ARTEMIS database. For rail, attempts at collecting energy usage measurements did not succeed; not enough data was made available and the little data that was available showed large variations. For sea, there were attempts at getting the fuel accounts and documentation of NO_x emission measurements, but this data was never received. Thus it is not possible to verify the estimation results. The alternative approach was to compare the results from the model to existing emission factors or emission tools to check the plausibility of the new model.

7.1 TEST OF ROAD RESULTS

To check road energy consumption we had four months of fuel logs from vehicles running mainly between Bergen and Trondheim. The vehicles were to some extent used to move freight in the Trondheim region. The tare vehicle weight was 10,500 kilos. And the maximum payload was 16,700 kilos, but the vehicle could be configured to tow a trailer.

Of the 178 trips between Trondheim and Bergen we have weight data for 145 trips that were run with one container and twenty-eight trips that were run with two containers as payload. This data should be treated with care, because even if there was only one recorded container there could be two containers on the vehicle or an empty trailer could be towed. This is because the TPG production system used to only record containers with freight in them. Containers that were relocated would not be recorded in the old production system. Thus this analysis will be more an indication of scale than a real comparison, but it is based on the best data that was available.

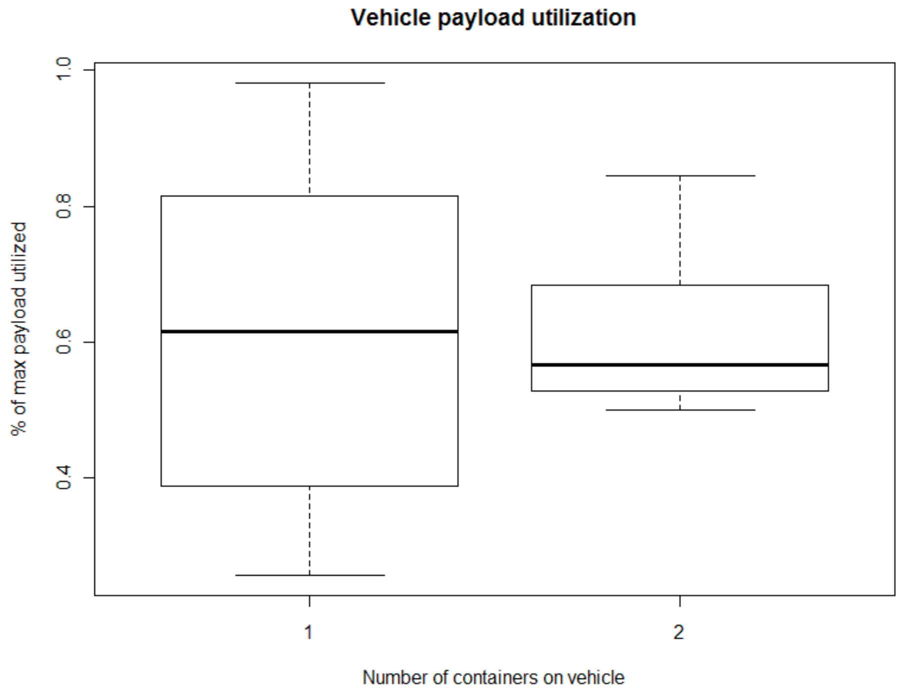


FIGURE 85 VEHICLE PAYLOAD UTILIZATION (ONE VEHICLE FIXED ROUTE TRONHEIM/BERGEN)

Figure 85 shows vehicle payload utilization for one vehicle with one and two container configurations. The mean weight utilization for both one and two container configurations was 60%. The printout below shows emissions estimates for the Trondheim/Bergen route taken from the database created by the result management module of the new model. The weight of the container(s) was taken as the average weight from the actual 145 with one container and 28 trips with 2 containers.

```
From Trondheim to Bergen: 1 container on rigid truck
Fuel consumption :  205946 gram   326.26 gram/km    54.38 gram/tkm
Fuel consumption :     242 liter   0.38 liter/km     0.06 liter/tkm
CO2 emission     :  652849 gram  1034.23 gram/km   172.37 gram/tkm
NOx emission     :    3629 gram     5.75 gram/km     0.96 gram/tkm
CO emission      :      76 gram     0.12 gram/km     0.02 gram/tkm
PM emission      :      16 gram     0.03 gram/km     0.00 gram/tkm
THC emission     :       9 gram     0.01 gram/km     0.00 gram/tkm

From Bergen to Trondheim: 1 container on rigid truck
Fuel consumption :  205545 gram   325.62 gram/km    54.27 gram/tkm
Fuel consumption :     242 liter   0.38 liter/km     0.06 liter/tkm
CO2 emission     :  651578 gram  1032.22 gram/km   172.04 gram/tkm
NOx emission     :    3614 gram     5.73 gram/km     0.95 gram/tkm
CO emission      :      75 gram     0.12 gram/km     0.02 gram/tkm
PM emission      :      16 gram     0.03 gram/km     0.00 gram/tkm
THC emission     :       9 gram     0.01 gram/km     0.00 gram/tkm
```

```
From Trondheim to Bergen: 2 containers on articulated truck
Fuel consumption :  235158 gram   372.53 gram/km   21.91 gram/tkm
Fuel consumption :     277 liter   0.44 liter/km   0.03 liter/tkm
CO2 emission     :  745450 gram  1180.93 gram/km   69.47 gram/tkm
NOx emission     :    4238 gram     6.71 gram/km    0.39 gram/tkm
CO emission      :      80 gram     0.13 gram/km    0.01 gram/tkm
PM emission      :      17 gram     0.03 gram/km    0.00 gram/tkm
THC emission     :      10 gram     0.02 gram/km    0.00 gram/tkm

From Bergen to Trondheim: 2 container on articulated truck
Fuel consumption :  234966 gram   372.23 gram/km   21.90 gram/tkm
Fuel consumption :     276 liter   0.44 liter/km   0.03 liter/tkm
CO2 emission     :  744843 gram  1179.97 gram/km   69.41 gram/tkm
NOx emission     :    4229 gram     6.70 gram/km    0.39 gram/tkm
CO emission      :      80 gram     0.13 gram/km    0.01 gram/tkm
PM emission      :      17 gram     0.03 gram/km    0.00 gram/tkm
THC emission     :      10 gram     0.02 gram/km    0.00 gram/tkm
```

LISTING 10 RESULTS FROM THE NEW MODEL FOR A TRANSPORT BETWEEN TRONDHEIM AND BERGEN

For the vehicle running mainly on the same route a fuel log for four months (January, February, May and June) was obtained. The fuel consumption for each of the four months is presented in Table 36.

TABLE 36 FUEL CONSUMPTION FOR VEHICLE IN FIXED ROUTE TRONDHEIM/BERGEN

Month	Average fuel consumption (liter/km)
January	0.44
February	0.48
May	0.40
June	0.41

The freight company does not keep records of the weight of the loads hauled so their only fuel indicator is based on kilometers driven. A weighted average of the 173 trips between Trondheim and Bergen gives 0.3897 liter/km. While the weighted average from the fuel log gives 0.43 liter/km. This gives a difference of about 10 %. It is not surprising that the reported fuel consumption is higher because that fuel consumption figure includes emissions due to congestion, idling and required stops. The two vehicles used in this comparison were both Euro IV vehicles. It is not possible to compare the other emissions as no data on them are available. But the emissions could be compared to existing emission factors.

Table 2 presented the emission figures used by TPG. From this table we can see that the long haul road CO_2 emission factor is 52.71 gram/tkm. While in our estimation the rigid truck with one container and 10 tonnes of freight has an emission factor of 172 gram/tkm. It should be noted that the weight of the container is not included in the payload by which the total emissions are divided. The average weight of the container is about 4 tonnes. For the articulated truck configuration with two containers the emission factor is 69 grams per tonne kilometer, which is closer to the factors used by TPG.

Another tool to compare the results to of the new model is the EcoTransIT calculator[44]. Figure 86 shows the input parameters to the EcoTransIT calculation.

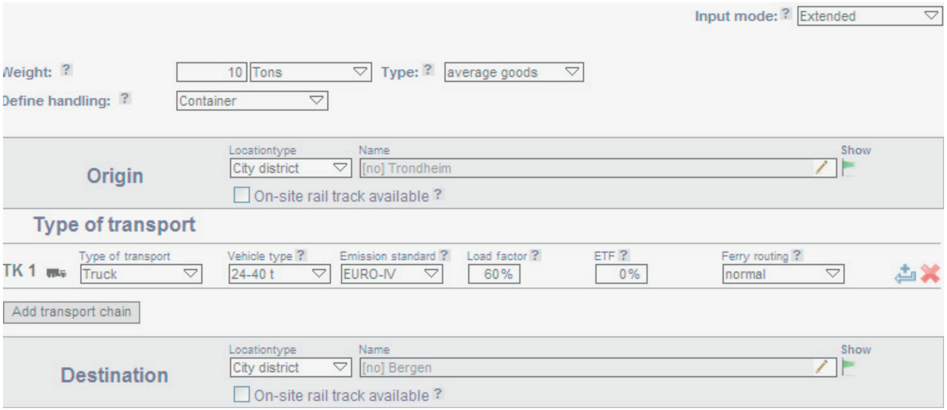


FIGURE 86 INPUT PARAMETERS TO THE ECOTRANSIT EMISSION CALCULATOR

TABLE 37 RESULTS FROM ECOTRANSIT CALCULATION (TANK TO WHEEL)

Component	Total (gram)	per tkm (gram)
Fuel(calculated via energy)	145.63 liters	0.034 liters
NO_x	1690	0.39
PM	14	0.0032
HC	13	0.00

Table 37 presents tank to wheel figures for emissions that can be compared with the one-container estimates from the new model. EcoTransIT does not report fuel usage, but it reports energy used. Using a typical figure for the energy density of diesel is 37.3 Mega Joule per liter[45] a total fuel consumption of 144.63 liters of diesel was calculated. The product Shell Diesel Extra sold at Norwegian gas stations has an average energy density of 37.2 Mega Joule per liter[46]. The routing module in EcoTransIT uses a different route than the routes used by the new model. The route chosen by the new model is 631 kilometers long (excluding ferries), while the EcoTransIT route is 721 kilometers. The route choice differences can be attributed to the level of detail in the network and any weighting function that EcoTransIT may apply. According to the EcoTransIT documentation motorways are weighted lower than other roads, thus making motorways preferable (Knörr et al., 2010 p. 30). It is surprising that EcoTransIT calculates lower fuel consumption than the new model: 0.04 liters per tkm compared to 0.06 liters per tkm. Part of the explanation could be that topography is included in the

44 http://www.ecotransit.org/ecotransit.en.phtml
45 http://en.wikipedia.org/wiki/Energy_density
46 http://www.epc.shell.com/documentRetrieve.asp?documentId=76748179

new model while it is not included in EcoTransIT. Choosing motorways will tend to give roads with less challenging topography. The NO_x Emissions are also underestimated: 0.39 gram/tkm compared to 0.96 gram/tkm. One explanation could be the impact of gradients. EcoTransIT classifies countries into three categories when it comes to gradients: flat, hilly and mountainous. For flat countries energy and emissions are reduced by 5% while for mountainous countries 5% is added to energy and emission calculations. No correction factor is used for hilly countries. It is not surprising that the existing emission factor that TPG uses is higher because it does not differentiate between the different Euro emission standards and uses a fleet average. The Euro 4 truck PM emissions are lower for the EcoTransIT calculations, 0.0032 grams as compared to 0.0042 grams for the new model. Again the explanation could be because of the topography as for NO_x.

Thus for the specific route between Trondheim and Bergen energy consumption from the fuel logs was higher than the new model. The new model results for fuel consumption were higher than the EcoTransIT tool.

The Network for Transport and Environment (NTM) offers a simple calculator for non-members on their homepage[47]. The simplified version does not differentiate between the different Euro emission standards and is thus not as useful for comparing emissions regulated by the Euro standard. But the energy consumption figure can be used as it has been quite stable between the different Euro standards. Figure 87 shows a plot of fuel consumption for a 34-40 tonne articulated truck at different speed. The plot was produced by SEMBA and it confirms that there has been little change in the fuel consumption over the emission standards except for when the Euro emissions were introduced, between Euro 0 and Euro I.

Using the same 10 tonne container with 6 tonnes of goods NTMCalc gives 206.7 grams of CO_2 per tonne kilometer, which equates to a diesel consumption of 65.2 g/tkm. The equivalent truck from the new model had a fuel consumption of 54.4 g/tkm, while EcoTransIT gives 28.9 g/tkm. Thus the new model fuel consumption model is between the values reported by two existing tools.

[47] http://www.ntmcalc.org/index.html

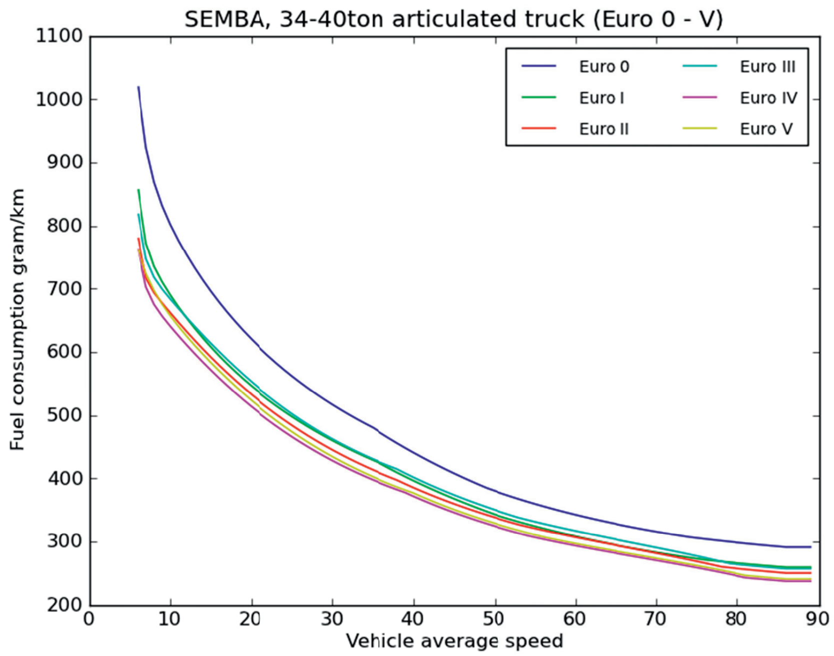


FIGURE 87 CHANGE IN FUEL CONSUMPTION OVER DIFFERENT EURO EMISSION STANDARDS

7.2 TEST OF RAIL RESULTS

7.2.1 ELECTRIC FREIGHT TRAINS

For Bergensbanen the new model has an energy consumption factor of 40 Wh/gross tonne kilometer. While for Dovrebanen the new model has an energy consumption factor of 33 Wh/gross tonne kilometer. These energy consumption figures include losses in transmission lines, catenary lines and transformers. Table 38 shows the energy consumption for different train sizes taken from the EcoTransIT documentation. Typical Norwegian freight trains have a total weight between 500 and 1000 tonnes. Thus the new model will give higher energy consumption for electric trains than the average values found in EcoTransIT.

The existing TPG emission factors did not focus on energy and thus no energy data is available.

TABLE 38 ENERGY CONSUMPTION FACTORS FOR ELECTRIC RAIL SOURCE: (KNÖRR ET AL., 2010 TABLE 23)

Train Type	Final Energy Consumption			
	Train	Freight		
		Bulk	Average	Volume
Unit	Wh/Gtkm	Wh/Ntkm		
Light Train (500t)	25.5	42.7	49.5	63.9
Average Train (1000t)	16.6	27.8	32.2	41.5
Large (1500t)	12.9	21.6	25.0	32.3
Extra Large (2000t)	10.8	18.1	20.9	27.0
Heavy (>2000t)	10.0	16.8	19.4	25.1
Source: Railion 2007, IFEU 2008				

The next test is to look at energy usage at the point of consumption, energy meter values from actual trains are compared to energy consumption factors without losses in the transmission lines, catenary lines and transformers. The National rail administration delivered energy consumption data for three trains on Bergensbanen, Dovrebanen and Sørlandsbanen. The energy consumption figures are presented in Table 39 along with train weight data. From and to destinations are coded with the letters: B = Bergen; A = Alnabru; T = Trondheim; S = Stavanger; and D = Drammen.

TABLE 39 ENERGY CONSUMPTION FOR 3 TRAINS

Train ID	Date	Loco	From	Start time UTC	To	End time UTC	kWh	Loco weight	Wagon weight	Cargo weight	Train Weight	Distance km	Energy consumption kWh/Gtkm	Average line consumption kWh/Gtkm	Consumption factors used by the new model
5506	20091012	EL14	B	12:05	A	22:40	8360	130	330	263	723	503	0.023		
5506	20091111	EL14	B	18:35	A	03:30	8806	130	342	89	561	503	0.031	**0.026**	**0.030**
5506	20091117	EL14	B	12:20	A	22:40	7186	130	342	89	561	536	0.024		
5707	20091012	EL14	A	18:10	T	03:30	10518	130	373	523	1026	549	0.019		
5707	20091111	EL14	A	18:35	T	03:30	8860	130	372	478	980	549	0.016	**0.017**	**0.025**
5707	20091117	EL14	A	18:20	T	03:30	8902	130	369	516	1015	549	0.016		
5814	20090310	EL14	S	18:45	D	02:55	7504	130	176	430	736	524	0.019		
5814	20091118	EL14	S	18:35	D	04:30	8100	130	176	411	717	524	0.022	**0.023**	**0.028**
5814	20091124	EL14	S	18:35	D	04:00	9712	130	176	387	693	524	0.027		

The table shows that the model overestimates energy consumption to some extent. But the variation between each train is large. For Bergensbanen the difference is about 25% between the trains and 13% between measured train value and the value used by the new model. For Dovrebanen the difference between the new model and the average measured value is larger than the variation between the different trains. The new model is able to reflect the difference between the railway lines where Bergensbanen has higher energy consumption than Dovrebanen and Sørlandsbanen. The amount of data available is too little to make a solid conclusion. Three data points are too few to get a perception of the variation, but remembering back to Figure 41, the ten energy consumption factors were quite spread for the same train and distance.

The third test is to look at energy consumption per net tonne kilometer. Energy consumption per net tonne kilometer is reported by the rail freight transport service provider. The annual average electricity consumption for CargoNet is 0.06kWh per net tonne kilometer. This is at the high end of the scale when looking at Table 38, only a small train (<500t) carrying volume freight has a higher consumption factor.

To summarize the new model the model result for electrical rail energy is somewhat higher that observed values, but not unreasonable given the variation seen in the available data. The model is able to differentiate between the different rail lines, the same trend is seen in the measured data. The annual average values for a specific rail freight transport service provider shows that energy consumption on Norwegian railways is higher than the average values used in EcoTransIT.

7.2.2 Diesel freight trains

CargoNet provided one year of weight data from the trains on Nordlandsbanen grouped by train number and subsections. Based on this data a weight utilization of 69.8% was calculated. This weight utilization was used as input to estimate the emissions for a freight train from Trondheim to Bodø. 70% utilization gives 308 tonnes of freight on the train and the distance is 728.75 kilometers.

TABLE 40 DIESEL TRAIN EMISSIONS ESTIMATED BY THE NEW MODEL ON NORDLANDSBANEN

Component	Diesel (kg)	CO_2 (kg)	CO (kg)	NO_x (kg)	SO_x (kg)	PM (kg)	HC (kg)
Total	2706	8578	29.7	127.2	2.2	10.3	10.8
Per tkm	0.012	0.038	0.132 (g)	0.567 (g)	0.010 (g)	0.046 (g)	0.048 (g)

CargoNet reported an annual average of 0.04 kilograms CO_2 per net tonne of freight (Jernbaneverket, 2009 p 14) which is quite close to the 0.038 kilograms of CO_2 that the new model estimated for a train from Trondheim to Bodø. Table 41 shows the emission values calculated by the EcoTransIT calculator.

TABLE 41 EMISSIONS FROM FREIGHT TRAINS CALCULATED BY ECOTRANSIT

Component	Total	per tkm
Fuel(calculated via energy)	1358 (kg)	0.006 (kg)
NO_x	67 (kg)	0.2976 (g)
PM	1.85 (kg)	0.008 (g)

HC	6.3 (kg)	0.028 (g)
SO_2	28 (g)	0.0001 (g)

Figure 88 shows that the EcoTransIT calculates lower emissions per net tonne kilometer than the new model. From the figure it is quite clear that the emissions calculated by EcoTransIT for rail are lower than the emissions estimated by the new model.

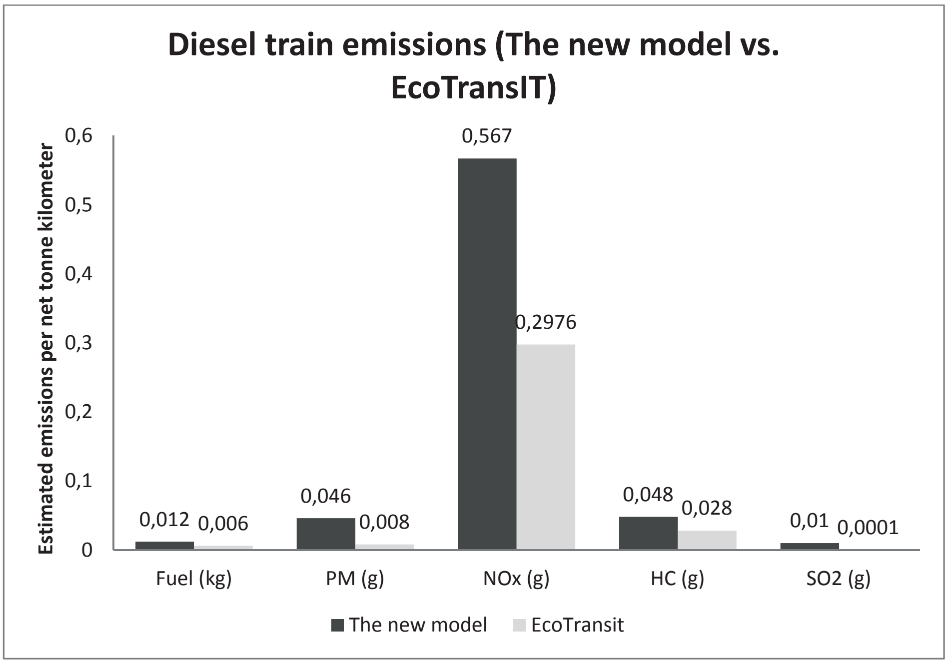


FIGURE 88 COMPARISON OF RAIL EMISSIONS FOR DIESEL FREIGHT TRAINS

The differences are quite big, for diesel rail the emission factor from the model is twice the emission factor found by using the EcoTransIT calculator. For the truck there was a big difference, the new model gives 1.7 times higher diesel consumption. The comparison is based on tank to wheel emissions and energy consumption.

The simplified NTMCalc cannot be used for rail as it does not report energy consumption as only electric trains are available.

The new model results for diesel trains were compared to annual averages for the main Norwegian rail freight transport service provider and found to be in very close. But the new model produces significantly higher emission values than values calculated from EcoTransIT. Again this indicates that there are issues with energy performance for freight trains on Norwegian rail lines. Single track rail lines and the resulting stops for passing trains could be an explanation for the big differences.

7.3 TEST OF SEA RESULTS

Using the EcoTransIT tool to calculate ship emissions did not work, the correct route was selected from Bodø to Tromsø, but the energy calculation failed and gave a result of 0. In the EcoTransIT documentation there is an example table of emissions factors based on 4% speed reduction 80% engine load and average container load of 10.5 tonnes.

TABLE 42 EMISSION FIGURES FOR CONTAINER FEEDER VESSEL SOURCE: (KNÖRR ET AL., 2010 P 91)

CO_2 (g/tkm)	NO_x (g/tkm)	SO_x (g/tkm)	HC (g/tkm)	PM (g/tkm)
26.99	0.70	0.40	0.0262	0.0579

The emission factors from EcoTransIT include the use of auxiliary engines and port operations. The new model splits ship operations into three groups, cruising, laying in port and loading/unloading operations. Thus to give a good comparison a specific sea route is chosen, Bodø – Tromsø with one hour for loading and unloading and two hours laying in port, which is labeled 360-1-2. 360-2-8 means 360 kilometers, 2 hours loading/unloading and 8 hours lying in port. The last line is for a trip between Trondheim and Bodø which is 560 kilometers. The calculations are based on a ship much like MS Tege, which TPG uses, 60% utilization of a container capacity of sixty containers each with 10 tonnes of freight in them.

TABLE 43 NEW MODEL EMISSIONS IN GRAMS PER TONNE KILOMETER FOR DIFFERENT ROUTE CONFIGURATIONS

Route	Fuel (g/tkm)	CO_2 (g/tkm)	NO_x (g/tkm)	CO (g/tkm)	HC (g/tkm)	PM (g/tkm)	SO_2 (g/tkm)
360-1-2	18	57	1.08	0.09	0.05	0.02	0.07
360-2-2	18	57	1.09	0.09	0.05	0.02	0.07
360-2-8	19	59	1.12	0.09	0.05	0.02	0.07
560-1-2	18	56	1.07	0.09	0.05	0.02	0.07

The emission factors available from EcoTransIT are lower for CO_2 than the emission factor that the new model uses. The difference is quite large. The emission estimates from the new model which stem from the ARTEMIS project are 2.1 times larger. The emission factors extracted from the EcoTransIT documentation include 4% slow steaming, which could account for some of the difference. NO_x emissions are 1.5 times larger; HC emissions are 1.9 times larger than the EcoTransIT emissions. The new model gives lower values for particulate matter and SO_x emissions. The table shows the impact of the laying time in relation to the trip length. It can be seen that the cruising emission factor quite clearly dominates over the loading/unloading and lying in port emissions, but this can be used to describe a ship transport in more detail and understand ship emissions better.

The simple NTMCalc was used to calculate fuel consumption for a container vessel. The simple NTMCalc does not have a suitable ship definition; there is no definition of such small container feeder ships. The smallest container ship available for calculation had a capacity of 1,400 TEUs, while MS Tege has a capacity of 63 TEUs. The fuel consumption of the 1,400 TEU container vessel available in NTMCalc was 5.7 g/tkm. Thus the simple NTMCalc could not be used.

7.4 EMISSIONS IN RELATION TO FUEL CONSUMPTION FOR ROAD TRANSPORT

Can freight transport service providers test if their own road emissions are reasonable? For single vehicles the freight transport service providers have the possibility to check their fuel usage in relation to the freight moved. This allows them to check the plausibility of the fuel/energy calculations. But what about the values for the rest of the pollutants, are these values plausible? To give insight into this the emission database produced by the result management module was used to simulate truck trips between fifteen places in Norway, the eleven cities and four other places that that had an elevation over 150 meters. The aim of the simulation was to test the correlation between fuel consumption and pollutants emitted using actual road topography. If there is a strong correlation between fuel accounts for a single vehicle and fuel usage estimated from the new model then the freight transport service providers could be confident that their emission statements are correct for road vehicles.

For rail and sea, the emission factors used in SEMBA are directly linked to the fuel consumption. For heavy-duty vehicles the relationship between fuel consumption and emissions is not straight forward as emissions are influenced by gradient, load and speed. To get a better grasp of the relationship between fuel consumption and emissions, fifteen places in Norway were chosen and emissions calculated between these cities for two vehicle types. For each vehicle type, rigid truck 26-28 t and articulated truck 34-40t, five runs were made to represent the different Euro emissions standards, 0 – V. In addition three load utilizations were used, 0%, 50% and 100% of the allowed weight. This results in 7,560 trips between the fifteen places.

A naïve plot of all results is shown in Figure 89, where NO_x, CO, PM and THC emissions are regressed against fuel consumption. The naïve model seems to have quite poor explanatory capabilities, the R-squared values ranges from 0.45 and 0.73. But the plots show signs of banding for all components, which indicates that better models exist that takes other factors into account.

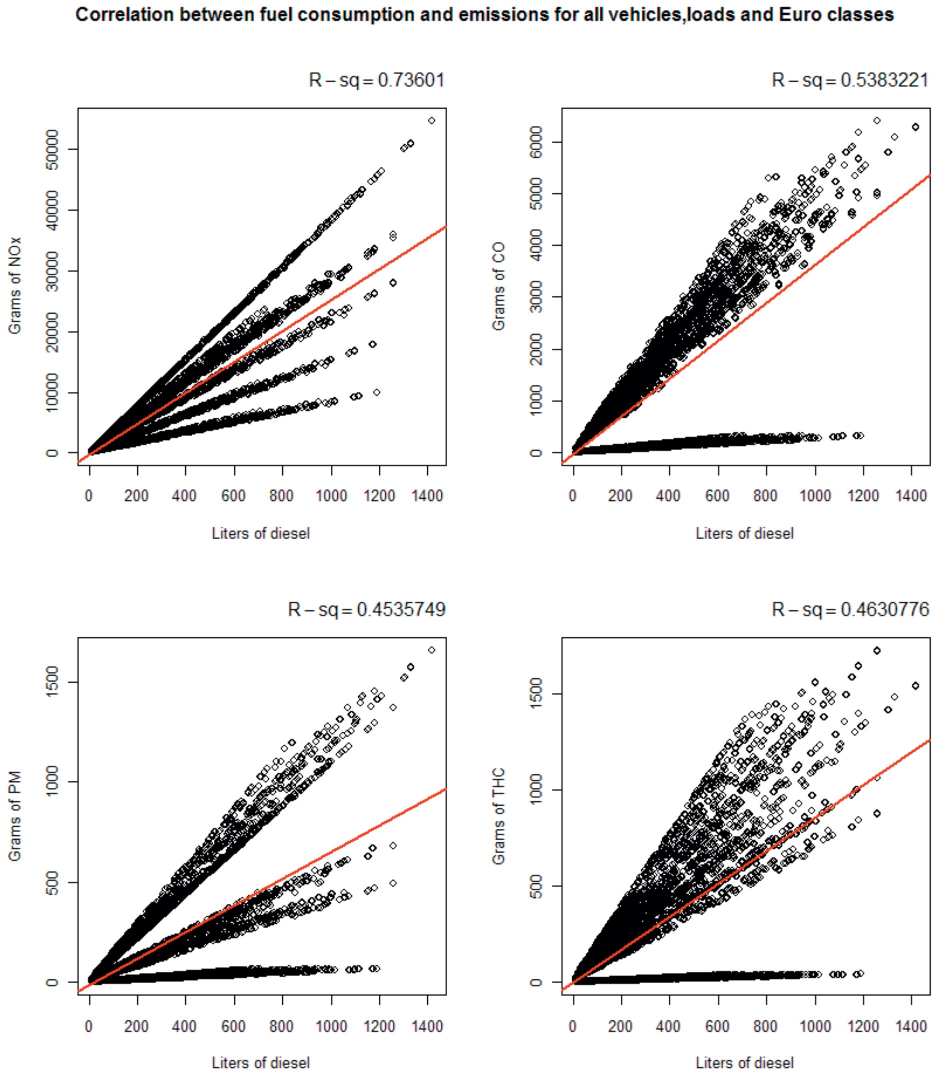


FIGURE 89 CORRELATION BETWEEN FUEL CONSUMPTION AND EMISSIONS FOR ALL VEHICLES, LOADS AND EURO CLASSES

If the data set is reduced and only Euro IV vehicles are studied we get the plots shown in Figure 90. Here we see a dramatic increase in the explanatory capability if we add the Euro emission standard as an explanatory variable. The plots for the other Euro classes (0, I, II, III and V) show the same pattern, R-squared values in the 0.9 region, but there are still signs of banding. There seems to be three bands which could represent the different loads (0%, 50%, 100%).

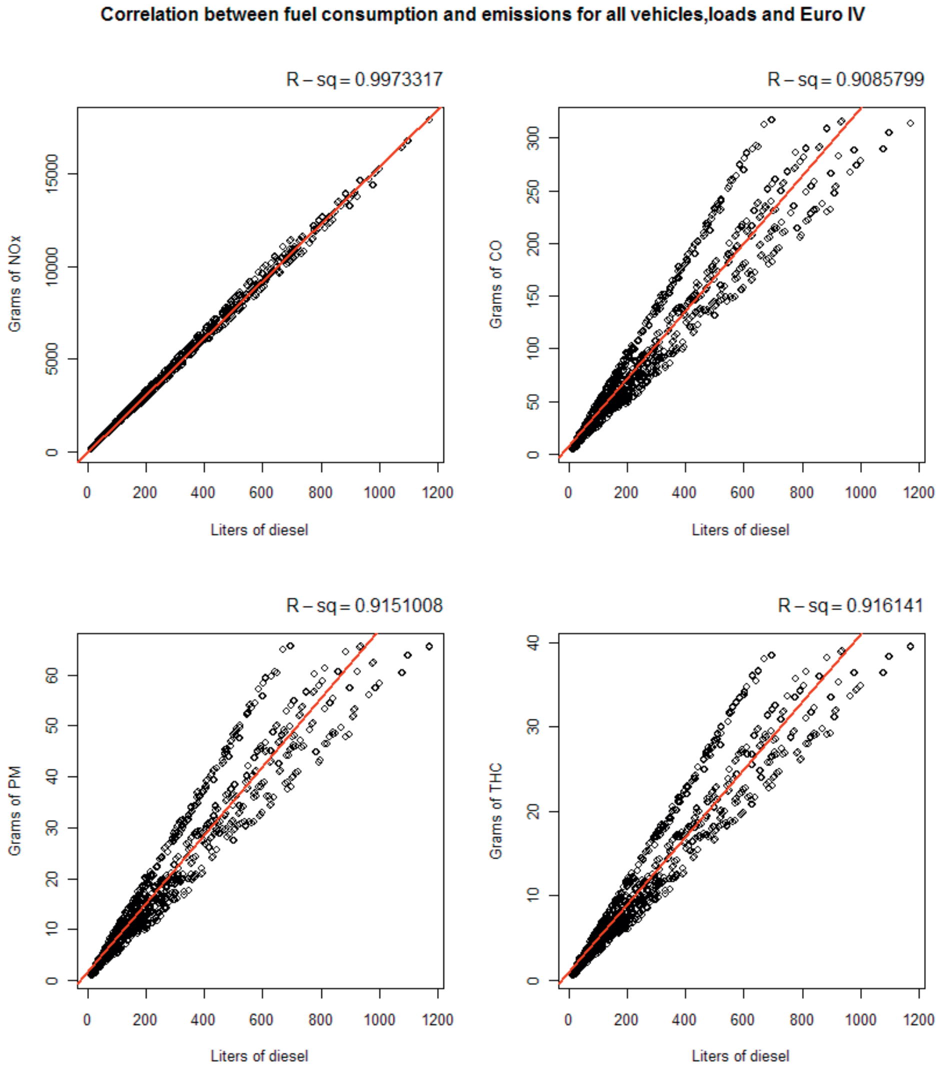


FIGURE 90 CORRELATION BETWEEN FUEL CONSUMPTION AND EMISSIONS FOR ALL VEHICLES, LOADS AND EURO IV

Figure 91 shows the correlation between fuel consumption and emissions for the two vehicles, with Euro IV engines and loaded to 50% of their weight capacity. The R-squared value is 0.99 for all emission components. It is not surprising that the R-squared value increases as we look at two vehicles with same Euro classification and running with a similar load. The important piece of information gained by this simulation was that there seemed to be a linear relation between fuel consumption and emissions when vehicle type, Euro standard and load is given and the emission functions are used on real-world routes between fifteen places in Norway.

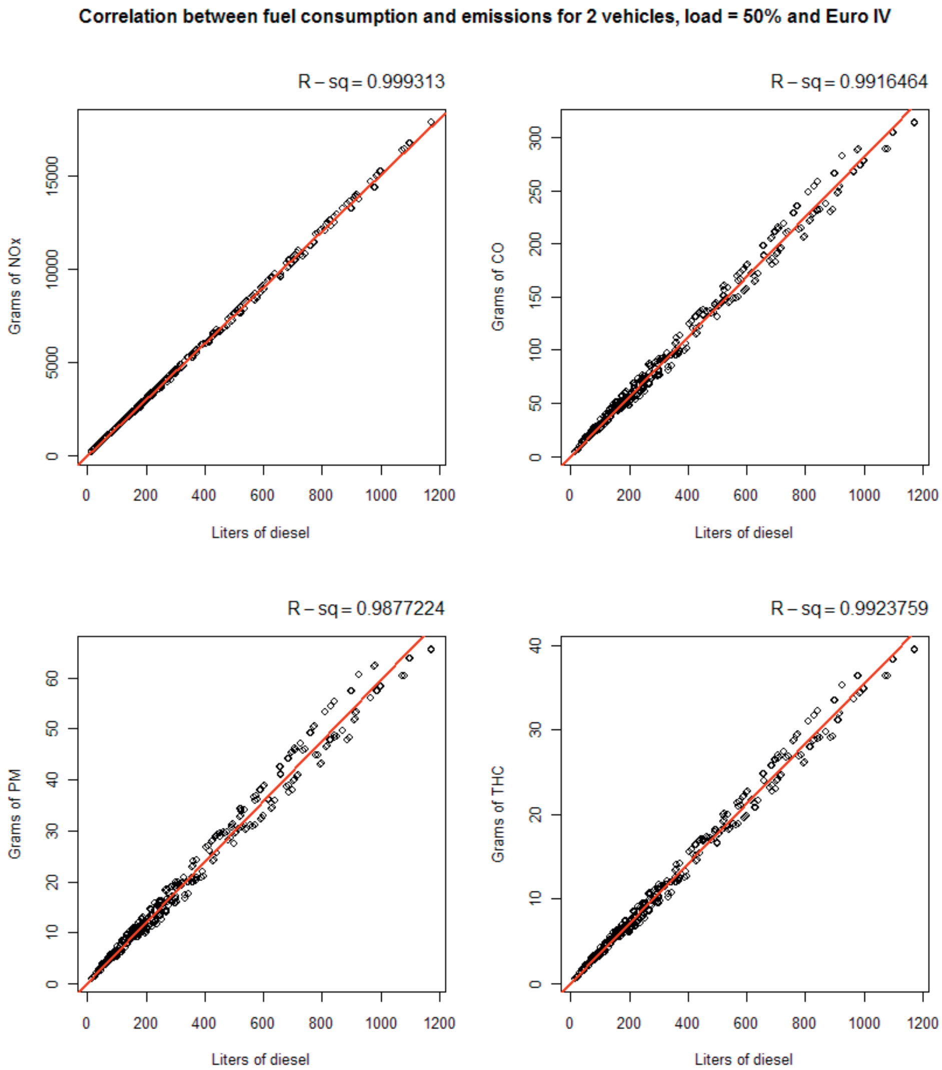


FIGURE 91 CORRELATION BETWEEN FUEK CONSUMPTION AND EMISSIONS FOR 2 VEHICLES, LOAD = 50% AND EURO IV

The implication of a linear relationship between fuel consumption and the amount of pollutants emitted is interesting. If individual companies measure their fuel consumption and find it to be close to the estimated value from the new model then there is a high probability that the emission estimates are correct if they have used the correct load utilization, and Euro classification of the vehicle. The simulation also indicates that truck size has little effect on the amount of pollutants emitted in relation to fuel used. Thus different truck sizes have different fuel consumption, but the pollutants per gram fuel burned seem to be constant given that Euro class and vehicle loading were used in the calculation of fuel consumption.

7.5 SUMMARY

It was not possible to verify the emission estimates of regulated components (NO_x, CO, HC and PM), as measurement equipment is costly for this Ph.D. project. In this Ph.D. project the proposition was not to develop emission functions, but to use state of the art emissions functions and to use these in conjunction with digital infrastructure descriptions. Thus one assumes that the emission functions are correct, but the emission estimates for the actual trips have to be checked. This was checked by estimating emissions on specific relations and comparing the estimates with other sources. EcoTransIT was used as a reference because the online calculator is said to be able to calculate emissions in Norway. Focus was on energy calculations because it is easier for practitioners to relate to the liters of fuel used rather than the grams of NO_x emitted etc. And it is considerably easier to measure fuel consumption than CO, HC, PM and NO_x emissions.

For trucks EcoTransIT reported lower energy consumption and NO_x, HC and PM emissions. Comparisons to fuel logs, from a local trucking firm running the same route, showed that the new model underestimated fuel consumption by about 10%. The NTMCalc tool reported higher fuel consumption than the new model. It was expected that the new model would underestimate energy consumption and emissions to some extent, because the speed used by the new model was the speed limit. But real world traffic is affected by congestion which increases energy consumption and emissions. The routing in the new model uses shortest time as the routing criteria and the impact of start and stops for mandatory rests are not included.

For rail the EcoTransIT calculator underestimates energy consumption for electrified and diesel rail when compared to the new model. For electric rail the new model reports 2.4 times higher energy consumption. When the new model estimates are compared to the few registrations available it seems like the new model estimates are high between 15 % and 47%. But care should be taken when using these figures as they are based on the average of three observations. For diesel rail the new model estimates twice the energy consumption. When the CO_2 emission estimated by the new model was compared to the annual average reported by the CargoNet in 2009 there was a good match. CargoNet reported 0.04 g/net tonne kilometer compared to the new model estimate of 0.038 g/ net tonne kilometer.

For ships, the EcoTransIT calculation did not work, but data from an example table in the EcoTransIT documentation was used for comparison. The energy consumption figures from the EcoTransIT documentation overestimated energy by a factor of 1.5 when compared to the new model estimates. The ship emission factors in EcoTransIT take empty returns into account; this could partially explain why the emissions were lower.

The testing of the new model has revealed that the emissions are of the same scale, but there are differences. The test to check the relationship between calculated energy usage and heavy-duty road vehicle emissions revealed a strong correlation. Thus freight transport service providers can assess the quality of their emission statements based on vehicle fuel logs.

The new model is able to calculate freight transport emissions quite well, where measured data was available the model results were comparable or reasonable explanations for the differences could be found based on model design. Comparison to an existing tool shows that this tool underestimated emission values for all emissions and modes when compared to the new model and measured data. Thus it is believed that the new model is a step forward and has the ability to test measures under the control of single firms.

8 CONCLUDING REMARKS

This chapter presents concluding remarks on the model design, digital network descriptions, emission functions and factors, routing and analysis, result management and use of the new model.

8.1 MODEL DESIGN

The main purpose of the Ph.D. project was to build a model to estimate emissions from freight transport that can be used at company level to reduce emissions. The Green Freight Transport project user-needs assessment showed that environmental issues were seen as important for the companies. But it is hard to say if this a genuine wish to reduce the environmental consequences from freight transport, or if it is a marketing effort to be viewed as being environmentally-friendly. This view was strengthened by discussions in the Green Freight Transport project group where there was a wish for a tool that was better than the existing tools, but only if the new tool caused marginally more work. But there was an important exception to this view and that was from TPG the project owner: more work could be accepted if it was automated. This opening was used to the full extent as very detailed emission functions are used in the new model. But input data needed for the calculations are collected from the freight transport provider's production system. A database of emissions by postcodes is linked into the production system so that emissions from transports can be calculated automatically. This means that detailed emission calculations can be done at vehicle level without requiring more manual work than the previous calculation routines.

The scope of the new model was narrowed to domestic freight in Norway. The reason for this narrowing was to create a detailed enough model to make it sensitive to measures under control of single firms. The other more practical reason for the narrowing was the expected computational issues due to network size. This narrowing of scope does not exclude the model from being used in other countries, but it will require the user to find the appropriate digital infrastructure data. The model design caters for linking together all countries into one or several databases. In a value chain perspective the Norwegian perspective might seem limiting as only a fraction of the transport distance is within Norway. But since the model does not use average values and calculates emissions for specific trips that can be compared to fuel logs it has the potential to be used by the Norwegian freight transport industry to reduce domestic CO_2 emissions without large scale infrastructure investments.

If the tool was to be used there had to be some benefit for the companies when using this tool. When talking to freight transport service providers they say that they have an interest in environmental performance, but this interest seems to be connected with marketing or customers demanding environmental performance figures. When trying to get firms to implement new routines, it is always good to have the answer to questions such as, “what is in it for me?” The link between energy consumption and emissions is useful because energy costs money and thus reducing emissions could reduce energy costs. There is also money to be saved if one understands where emissions originate from and how they can be reduced. Thus energy calculations were included in the new model to make it possible for firms to calculate direct monetary costs/gains from emission reduction schemes.

The new model uses a bottom-up approach to estimating emissions and energy usage. A challenge with the bottom-up approach is that only activities that are included in the model will generate emissions and use energy. This is different to the existing emission factors used which start with the total energy consumption and divides energy usage and emissions over activities in the model. If an important activity is emitted from the model the emissions associated with this activity is spread across all other activities. In the new model developed within this Ph.D. project the total emissions will be lower if important factors are left out. The effect of congestion is one example. In the bottom-up approach congestion could be modeled as reduced speed, but data on reduced speed was not available for this Ph.D. project thus it was not possible to model the effect of congestion. And thus the emissions estimated by the new model will be lower because the excess emissions due to congestion are not included. While in the traditional top-down approach excess emissions from congestion will be included even if there is no data available on the effect of congestion. The excess emissions that are generated by congestion are spread over all other activities. And thus the results from the traditional emission factors as those used by TPG were expected to be higher than emissions estimated by the new model, but this was not the case for CO_2 figures when tested on a specific route (Trondheim – Bergen) the new model produced higher emissions than the existing factors used. But the new model could recreate the same emissions if the weight utilization of the container was increased. An alternative could be to choose a freight route with a less challenging topography. Thus it is believed that the new model could work quite well but it is challenging to compare model results for specific routes to average national factors.

The new model allows for more credible comparisons with real world fuel usage. In Chapter 7 the road module of the new model was tested for an actual route against monthly fuel logs for a vehicle traveling this route. The comparison showed that the new model estimated about 10% lower energy usage than the fuel logs showed. It is believed that the difference found could be related to the missing effect of congestion, the effect of mandatory rest stops or idling. Thus the model could be used to calculate what the energy usage should have been, and when compared to the fuel logs this could show the potential for reductions in energy usage and thus emissions. Thus the tool can be used to look at the potential CO2 savings from better utilization, route choice and congestion avoidance. But if the tool is used unwisely, drivers could be chasing an energy usage goal that is unreachable because of congestion and effects of mandatory stops. It is important to remember that the model results are best case and are estimates based on assumptions.

The new model is designed so that the effects of congestion and mandatory stops could be included if data was available. One way to incorporate the effect of congestion is to use transportation models to get average speeds on network links. In these models speed flow curves are used to calculate link travel time, if model results were available these could be linked into the digital network descriptions. But there would have to be minor changes to the assignment and analysis model, because the calculations have to be time dependent. On-peak or off-peak link speed have to be chosen on the basis of time of day. Thus a vehicle leaving Trondheim late in the evening would use off-peak speeds out of Trondheim, but on-peak speeds when entering Oslo because it would be entering Oslo in the morning rush hour.

The new model focuses on getting good estimates for emissions per vehicle, whether it's a truck, train or ship. But the customers of the freight industry want to know the emissions from their package. To tackle this challenge an emission allocation scheme had to be set up. In section 6.4.1 a simple and crude allocation method was described. The main advance with the new model is that utilization of freight vehicles will affect the emissions not as an average number, but as a number based on the freight in the actual vehicle. More work needs to be undertaken on the allocation of emissions, but using the scheme proposed in this Ph.D. project is a starting point. There are special cases that need further attention if transport to and from Norway is to be assessed. But these special cases were not investigated, as this Ph.D. project was only to look at domestic transport. One such special case was the ferries from the southern part of Norway to Denmark or Germany. These ferries transport cars, trucks and passengers. The ARTEMIS sea module allows us to estimate the emissions from the ferry, but how does one allocate the emissions between passengers, cars and trucks? It is important that the freight industry finds a common standard for allocating emissions to freight. The work started by The Network for Transport and Environment (NTM) with creating product category rules (PCR) can serve as a starting point. A PCR is a guidance document to be used when collecting data and calculating greenhouse gas emissions in order to create a climate declaration.

The original plan was to have a core module consisting of a routing and analysis based on ESRI's ArcMap with the Network Analyst extension. The plan was that this core would stay unchanged and that only input to this part of the model would change. The ESRI ArcMap with Network Analyst was chosen because it was available to the Ph.D. candidate, and the limitations of the software seemed to be able to cope with the envisioned amounts of data. A single computation of a truck route from Trondheim to Bergen takes one second to complete if link emissions from the specific vehicle had been estimated. Using a GIS system for emission calculations has benefits for the experienced GIS user. But interfacing the GIS system with the freight companies' production systems was believed to be too challenging and costly, thus the plan to estimate emissions between all postcodes and store them in a database for later use was born. The results from the routing and analysis module were stored in a database in the resulting management module as a database of emissions between postcodes for different vehicle types. It was believed that a database would be simpler to interface with the existing production systems.

Limitations of the Network Analyst extension were discovered and this led to the development of an alternate routing and analysis platform based on software used to analyze graphs. Thus an extension to the routing and analysis module was developed for building the emission database that was to be used by the companies. There were two problems associated with the move to an alternative routing and analysis method. First, banned turns were not transferred, and the second problem was that the graph had to be built using integerized X and Y coordinates to form a nodes that could be used to create a topologically correct network. The networks used by the two different routing and analysis methods gave small differences as described in section 6.2. It would be better to have only one way to generate the database of emissions. And it would be beneficial to have a method that worked within the ESRI platform as this is also used for data management.

To build the new model a total of 22 Python script files, totaling 3,265 lines of code and comments were written. Another 1,457 lines of SQL mixed with Python code was written to analyze the collected GPS data. The problem with writing this much code is that errors could be present. Some software errors are relatively easy to find while other errors are harder to catch. Care was taken when writing the code, and tests were created to check important calculations, but there is still the possibility that errors could be present. Publishing the source code as open source allows for third party review of the code, this could further reduce the possibility of errors. The SEMBA python module used to calculate link emissions is published on http://sourceforge.net under the name SEMBA. SEMBA is released under a BSD type of license. The BSD type of license was chosen as it allows for both open source or closed source implementations of the code. This means that companies can make software using the code found in SEMBA and charge for the software as long as credit is given to the copyright holder. The license is included as Appendix F. The database with estimated emissions between postcodes is published under the same license. The idea behind such a liberal license is to remove any obstacles from implementing the software in the transport companies' production systems.

The coming sections will present each module in the model; strengths, weaknesses and possible further developments.

8.2 DIGITAL NETWORK DESCRIPTIONS

The challenge with the digital network descriptions was to find sources of data that meet the needs of the emission functions. The emission functions for the different modes had different data requirements. The sea mode uses only distance from the network, speed is not a property of the network, but of the vessel. The rail uses distance and railway line identification, while the road functions use distance, speed and gradient. But even if network data was available there were issues with data quality. There were cases where speed limits were missing and on these links average data was used. Another big issue with the road network was missing Z-coordinates, and height data. The Z-coordinates were used to calculate gradients, and thus erroneous gradients were calculated. The problems with the elevation data should be solved by the data owner because then all users this data could get new and updated road descriptions with correct elevation data in the next update.

Vehicle speed was challenging because there is very little data available on vehicle speeds in the road network. Thus proxies have to be found, for trucks the speed limit was used. Another concurrent research project was developing a speed model for commercial vehicles; this speed model could in the future be used instead of the speed limit. If the speed model for commercial vehicles is used there will still be problems with driving speeds in urban areas as these are not included in the speed model. Transport models could be used to add on-peak and off-peak link speeds to the road network. This is a possible development for the future. To get the full benefit of off-peak and on-peak vehicle speeds then a time-dependent routing function for the long-haul trips needs to be implemented. But distribution and collection routes could use on and off-peak speeds if trips are run within the on-peak or off-peak period. Mid-day vehicle speeds for urban areas should be studied more closely as these are probably lower than the speed limits. Existing fleet management systems could give information on urban travel speeds. New hand terminals were said to contain GPS units, and thus could be used to record driving speeds and stop times. This data could give valuable information on emissions from distribution and collection if models could be built from this data and included in the digital network descriptions.

Getting data on railways was challenging. The data existed in the railway databank, but there were challenges associated with exporting the data to formats that could be used by the GIS application. From an outsider's point of view it seemed like the national rail databank used proprietary protocols for exchanging data with in-house software applications. It is believed that it would be possible to get the exact data requested from the national rail databank, but then a custom computer application had to be created. The final rail model ended up only using distance and route specific factors. Thus there was no need for a detailed network. But if one is to estimate a new energy consumption model for Norwegian rail based on measurements then a detailed rail network would be important, especially to understand the effects of gradients and speed limits and overtaking sections.

The single most important factor when using digital network descriptions for network analysis is that the networks are topologically correct. Topological errors can cause routing errors or in the worst case can make certain destinations unreachable. The Norwegian Public Roads Administration has a current project that makes it possible to export a topologically correct road network. The name of the project tender was: "Trafikklenker i transportnettverk og trafikkdatabase – fase II." If they succeed then one would expect to see less routing errors due to roads not being connected.

8.3 EMISSION FUNCTIONS AND FACTORS

At the outset of this project it was planned to find existing emission factors and see if these could be used to estimate emission from freight transport in Norway. A major find was the ARTEMIS project (Boulter and McCrae, 2007) that has emission functions for all the modes that this Ph.D. project was to cover: road; rail; and sea. But the difference in level of detail in the emission functions between the modes was surprising. Road emission functions were more detailed than the other modes. The rail module was the most challenging; the ARTEMIS rail model did not have input data for Norway. A simple energy calculation model was implemented in SEMBA, but results from this model indicated low energy consumption when compared to data found in the EcoTransIT documentation. A major problem with the simplistic rail energy model was that it did not account for energy loss when braking so as not to exceed the speed limit when going downhill. Thus energy consumption factors used for billing rail operators were used. This is problematic because the energy consumption factors for locomotives without energy meters are probably a bit higher than they should be because a rough driving pattern was used for creating these factors (Jernbaneverket, 2006 Appendix 1, p. 1). Thus when comparing energy usage one should be aware that the module for electric rail energy consumption is biased towards higher usage. The impact on the emission estimates is limited because the Norwegian National Rail Administration buys electrical energy with origin certificates from hydroelectric power. Thus the direct emissions from electric trains are said to be 0 grams per kilowatt hour for PM, NO_x, CO, HC and CO_2. The data on energy consumption from running freight was inconclusive, as too little data was available. In the last few months of 2009 CargoNet begun to install energy meters in their locomotives. This data can be used to develop new energy consumption factors for Norwegian electric rail. The energy measurements are done for 5-minute intervals and are georeferenced; thus it could be possible to find where the most energy is used along the rail line. For the future it would be recommended to look into the energy usage figures and see if they can be combined with activity data to generate specific energy emission figures for the Norwegian rail lines.

For diesel train energy consumption the situation is different, here a drive time and energy estimation model (TogKjør) has been used to estimate the energy consumption and normal driving conditions were used. Thus emissions from diesel trains should not be biased towards higher energy consumption. The diesel locomotives did not have flow meters installed so no data was available on fuel consumption. CargoNet did not have any fuel consumption figures except for an annual average presented in the Norwegian National Rail Administration 2009 environmental report. There are technological changes that can impact the energy consumption and emissions from rail. In 2009 new locomotives were introduced that have regenerative braking possibilities for electric rail (CE 119). In the summer of 2010 CargoNet introduced new diesel locomotives (CD 312) with more powerful engines thus more cargo could be moved. Rail data has only been available from one of six railway companies that haul freight. CargoNet has about a 62 % share of the net tonne kilometers run with electric locomotives (Jernbaneverket, 2009 p. 14), and 90% of the net tonne kilometers run with diesel trains (Jernbaneverket, 2009 p. 14). If the rail companies monitor their energy consumption then they could develop their own energy consumption factors that could be used in generating emission factors. The state of the art emission factors for rail are directly related to fuel consumption using gram pollutant per gram of fuel emission factors.

For sea, the Green Freight Transport project was informed that Norwegian ship emission model was actively being developed. The new ship emission model used AIS data and data from the ships engine certificates to estimate emissions from Norwegian ships in Norwegian waters. We tried to get access to this model, but use of the model required a letter of consent from the ship owner. The Green Freight Transport project never succeeded in getting a letter of consent for the ship that was part of the Green Freight Transport project. Thus it was not possible to explore the emission model created by the Norwegian Coastal Administration.

The road emission functions are the most detailed emission functions. The average speed emission functions created in the ARTEMIS project are based on real world driving cycles that are fed into an emission model known as PHEM (Passenger car and Heavy-duty Emission Model). The driving cycle data was extracted from the ARTEMIS emissions database and split into micro trips. Driving behavior from trucks in regular freight routes was collected and split into micro trips and compared to the micro trips found in the ARTEMIS driving cycles. A regression analysis showed a relationship between the ARTEMIS and observed relative positive accelerations (RPA) for the micro trips. Relative positive acceleration is a proxy measure that is believed to be linked to emissions (Ericsson, 2001). Thus it was believed that RPA could be used as an indicator for fuel consumption and emissions. But the last sentence in the conclusion of another paper by Larsson and Ericsson (2009) points out that "Rate of acceleration is therefore not the only parameter affecting fuel consumption." Thus the power of using RPA as a means to compare ARTEMIS driving behavior and the recorded driving behavior was reduced. But when designing the new model there was a focus on energy consumption because it's fairly easy to measure average fuel consumption. Thus the model results could be checked against real world fuel consumption figures. The drivers could check their fuel usage against the fuel usage estimated from the new model. If there was a good match then that result could indicate that European emission functions could indeed be used for studying freight trucks in Norway.

An exploratory study of the onboard diagnostics II protocol was conducted to see if instantaneous fuel consumption could be read from the vehicles in a standardized way. Prototype software to log georeferenced data read from the OBD II connector on the vehicle was developed. But building a black box setup to log this data did not succeed, due to limitations in the purchased black box equipment. Even if the tapping of the vehicle internal communication bus (CAN bus) via the OBD plug failed, it is quite clear that reading data from the vehicle has great potential. In February 2011 the truck manufacturer Scania visited SINTEF and gave a presentation on data that was available from their trucks. Aggregated fuel consumption, NO_x and PM emissions were said to be available from the vehicles fitted with the C200 device. The C200 device[48] is equipped with GPS, digital tachograph, GPRS for data communication and interfaced with the vehicle computers. This could allow for very detailed emission estimates and energy estimates. The drawback of using the C200 is that it is a Scania specific product, while the OBD II standard should be equal for all vehicles. The positive aspect of the C200 and other vehicle specific interfaces is that other non-standard data is available. According to the representatives from Scania, the new Scania trucks can calculate total vehicle weight +- 100 kilos, based on the air suspension. There exists a Fleet Management Systems (FMS) standard that should allow for safe integration of third-party equipment that used data from the vehicle (Logicom GMBH, 2011). The following manufacturers have agreed to a common protocol to give third-parties access to vehicle data: Daimler; MAN; Scania; DAF Trucks; IVECO; Volvo Trucks; and Renault Trucks. This could allow for inexpensive real-world data collection on a large scale, and allow for new detailed emissions models to be estimated. But the technology could be used to report the actual environmental impact from freight transport, which would make for very robust and accurate emission accounting.

8.4 Routing and analysis

A key input to the routing and analysis module is digital infrastructure descriptions. Norway has digital infrastructure descriptions for road and rail stored in national databanks. The challenge was not finding the data, but getting the data from these databanks in formats that were useable by standard GIS applications. Another issue was the segmentation of the road network, the 2008 Elveg dataset had a defined segmentation resulting in over 570,000 road features. The Norwegian Public Roads

[48] `http://www.scania.com/products-services/services/fleet-management/index.aspx`

Administration is working on creating a routine for dynamic segmentation of the network. With dynamic segmentation of the road network it should be possible to reduce the number of road features to improve network analysis operations. And if the networks are topologically correct then routing errors due to network errors should be reduced. In general a strategy to fix network errors at the source should be applied because this will ensure that other users can get access to the corrected networks. The challenge is how to report errors back to the data owners so that they can correct the data. The UK website for releasing public datasets has contact and feedback routines for each dataset[49]; this could be one possible way to get structured feedback.

To find the correct route is not only dependent on having a correct network, but to have the correct impedance function. The impedance function is a measure of resistance for choosing the link that is the route between two points in the network that has the lowest total resistance, which can be found using shortest path algorithms. The two simplest impedance functions are link length and link travel time. In this Ph.D. project the link travel time is used as the impedance function. But there exists alternative formulations that can give more realistic routes. In the Freight Analysis Framework version 2 (FAF^2) prepared for the Federal Highway Administration, an impedance function that takes several road characteristics into account is presented (Alam et al., 2007). Number of lanes, urban bypass, truck restrictions, truck route designation, tolls and reliability all impact the relative attractiveness of the link. The EcoTransIT world calculator has impedance functions that are linked to the road hierarchy. There are five levels where the motorway is most preferred (weight 1.0) while small city street is least preferred (weight 5.0). In Norway the research project "Speed model for commercial vehicles," is being developed that takes road geometry into account when assessing vehicle speed. Thus the travel time estimates could be improved for rural operations. Further studies should be conducted to identify impedance functions that can be used to find the most realistic routes for road freight transport.

If there is to be routing in a multimodal network that contains rail, road and sea links then rail and sea routing have to be investigated. For rail routing train schedules should be implemented as they impact travel time and train speed. Sea routing is more complex, routes may be chosen based on weather and wave conditions. It would be interesting to study if small coastal freight ships change route in relation to weather in and around exposed areas like Stad. One possibility to assess the impact of weather on sea routing is to combine AIS and metrology data. Shortest distance was used as the impedance function for the Green Freight Transport Project. And the main fairways laid out by the Norwegian Coastal Administration were used as a sea network.

It was originally planned to have a single routing and analysis module based around the ESRI ArcMap platform with the Network Analyst extension. For analyzing a single

[49] `http://data.gov.uk/dataset/gb-road-length-statistics-2008/feedback`

route and using the GIS user interface the ESRI product is a good choice. But the software was not able to build the database needed to interface with the freight transport companies' productions systems. Alternative routing and analysis software was thus developed based on software intended for the study of graphs. This "homemade" software solution is not ideal even if it gets the job done. The biggest problem is that the software is not a true GIS client as it lacks basic GIS capabilities. Another issue is the user interface which does not offer a graphical client for viewing the network or routes.

In addition effort should be put into improving the impedance functions in order to create more realistic routes. There is ongoing development of a routing extension to PostgreSQL & PostGIS that could be an alternative to ESRI's Network Analyst. This work could be interesting because the combination of PostgreSQL and PostGIS proved to be very powerful to analyze large amounts of GPS data (Levin, 2010).

8.5 RESULTS MANAGEMENT

The final module in the model is the results management module. This module is an extension to the routing and analysis module that transforms calculation results into a usable form for the freight transport companies. The routing and analysis module of the model estimates emissions for single vehicles, whether they are trucks, trains or ships. The results management module is to allocate the emissions generated by the vehicles to the freight. The idea of separating estimating emissions and allocating emissions is to make the process of emission estimation more transparent. One problem with comparing emission estimates is that assumptions can influence the results, especially vehicle utilization (McKinnon, 2008 p. 13). The result management module was designed to use data from the company's production system and aggregate data so that the actual value of vehicle weight utilization is used. The routines to allocate the emission to the freight have to be expressed as mathematical functions that use aggregated data from the company's production system. A key concept is to use input values to the allocation function from the production system, but there will be cases when data is not available. If data is not available then it should be treated as an exception. For each exception it is important to document the scale of the problem so that it could periodically be measured and a workaround should be described. This documentation should allow for better comparison between companies, as it can identify why estimates differ. In Levin and Sund (2010) the result management module is described as the process of aggregating data from the companies production databases.

The result management module is not a computer application, but a set of routines to tie the emission database from the routing and analysis module to the company specific production system. The implementation will be different for every freight transport service provider because it is based on the data available in the company production system. But the key message is to document with mathematical formulae how the estimated emissions are allocated based on data found in the production system.

There is no correct way to allocate emissions like the laws of physics. In this Ph.D. project a simple principle of allocating all direct emission from the transport to the freight is used. Emissions were allocated according to the freight weight that takes the volume of packages into account as well as the weight of the package. The key message when it comes to allocating emissions is that the allocation function should promote sound energy and environmental performance. The suggestions set forward in this Ph.D. project should be seen as a starting point, further investigation into allocation routines should be made to ensure that these allocation functions are generally accepted. It would be interesting to look at a full year of operation and see the impact of different allocation functions. It is hoped that separating estimating emissions and allocation of emissions could make it simpler to compare emissions relating to freight transport between companies.

8.6 USE OF THE NEW MODEL

One measure of success for the new model is that the model will be used by companies involved in freight transport. The new model could be used to account for emissions from conducted transports. From discussions in the Green Freight Transport project group it would seem that this was the primary purpose for the new model. It is hard to judge if the freight transport service providers only want an emission figure so that they can relay this to their customers, or if they want to use the figure to improve their environmental performance. McKinnon (2010) makes a point out of this skepticism and thus it would be beneficial if there would be some other gains than pure environmental gains from using the new emission estimation model. In Levin and Sund (2010) the relationship between emissions, energy usage and economic gains is suggested as a means to get the freight transport operators more interested in reducing emissions. By reducing energy usage from freight operations then emission would be reduced and a financial gain could be achieved. Thus having a detailed understanding of what causes emissions could help freight transport service providers find ways to reduce emissions and calculate possible impacts. The routing and analysis module of the model will give advanced users the ability to do detailed analysis, while the results management module should allow for automated emission estimation routines.

The new model could be used to analyze impacts of infrastructure improvements, but only the direct emissions from vehicles using the infrastructure before and after the improvement are covered. The new model was tested to see the impact of details when estimating emissions, and results showed over simplification with respect to road gradients could lead to underestimates of about 15% based on real world routes (Levin and Norvik, 2010).

The scope of the new model could be seen as quite limiting, as only Norwegian domestic transport was covered. But there are two reasons for why this was a smart narrowing. The first is the computational challenges involved. In the beginning it was assumed that having a model encompassing the whole Norwegian infrastructure would be computationally challenging. This proved to be true as the candidate arrived at plan H before having one successful run to produce the database for the result management database. Another reason for narrowing the scope was to enable the users of the new model to test alternatives to see if they were able to reduce their emissions and by how much. Having a single global model would mean reducing the level of detail and it would be extremely challenging to test the model. Inputs to the emission functions are context sensitive, thus one had to look into and understand driving behavior in for example Nepal and India in addition to emission regulation. Thus it is more sensible to create emission models for single countries or regions where there is a limited variation in the context, and then link the models together in a global model. Thus building a model for Norway and enabling freight transport service providers to find possible environmental optimization's within Norway makes sense. This thesis has shown that it is possible to build a detailed emission model that can be moved to a different context, but new input data has to be found, both network and emission functions. But the model design and the internal framework of the model could remain the same. For countries within the EU the most prominent changes to the model would be the digital infrastructure descriptions. While for American, Asian and African countries the emission factors would have to be changed.

8.7 Has the research question been answered?

The main result of this Ph.D. project has been a new emission model for freight transport emissions at the vehicle level. The new model is sensitive for measures under the control freight transport service providers and is thus a step forward. The model has an extension (the result management module) that allows for a simple integration into the freight transport service providers production system.

The research question was: *How to develop a detailed emission model to be used in everyday freight transport operations?* This thesis documents the design and implementation of a new emission model for freight transport developed by the Ph.D. candidate. As mentioned the new model is capable of analyzing measures under the control of freight transport service providers. The project owner Tollpost Globe has implemented the new model as their emission calculation tool. Given the data available in their production system they are able to see the emission impact related to daily operations. TPG's implementation of the tool gives customers three alternative uses[50]:

1. Find the impact of the customers' transports (for inventory purposes).

[50] http://www.tollpost.no/nb/E-tjenester/Sider/Miljøkalkulator.aspx

2. Simulate the effect of changing the pickup and delivery frequency.
3. Calculate emissions alternatives for different routes that could be used.

This shows that a tool built from the new emission model is used by a single freight transport service provider. In addition a Transnova initiative is under way to establish a network to implement the new model as a tool for the four biggest freight transport service providers in Norway[51]. Common for all implementation cases is that the new emission model developed within this Ph.D. project will be used. Tollpost Globe was awarded the Norwegian Logistics and Freight Association environmental price for their work in taking forward a tool based on the new emission model[52]. The Research Council of Norway posted an article on their web site that says, “Transportation giants come together to save the environment.” The article was in relation to the implementation of the new model as the environmental calculator in four competing freight transport service providers. The fact that the new model is being implemented as a tool in other competing freight transport service providers shows that the new emission module is useable for the firms even if the calculations are very detailed. A key to this success is the design of the model that incorporates a result management module and an emission database that allows for simple integration into the production systems.

A new emission model has been developed, and the new model has gained the trust of the large actors in the Norwegian freight transport industry. Four sub-questions were stated to guide the development of the new model to as to make it as detailed as possible but yet useable to the practitioners. The four questions were:

1. Is it possible to find emission functions and factors that could be used to calculate emissions from a single vehicle that are sensitive to measures under the control of single firms?
2. Is needed input data for the emission functions available and how to structure emission calculations?
3. How can the new model be integrated into a freight transport service provider’s production system to become a useful tool?
4. Is it possible to check transferability of emission function by collecting vehicle data to compare with data used to create the emission functions?

The answer to the first sub-question is a definite yes. Single vehicle emissions have been studied in a European context. And results from different research projects are available. The ARTEMIS project proved to be a valuable source of emission factors and functions. The different modes of freight transport have a different level of detail. Road emissions have been more studied than sea and rail. We failed at finding credible emission factors for terminal emissions. The little data that we managed to collect

[51] http://www.transnova.no/project/nettverk-for-gronn-godstransport
[52] http://www.ltl.no/article.php?articleID=939&categoryID=112

showed quite a lot of variance in relation to energy consumption (Levin and Sund, 2010). The terminal is a fascinating place that deserves more attention, the heterogeneity and age composition of equipment used at the terminals are immense. The best piece of advice offered to terminal operators is to monitor energy consumption in relation to production and try to reduce the energy consumption per unit produced. Quick calculations made by the Green Freight transport project partners showed that terminal emissions were only a small part of the total emissions from a freight transport (Table 14).

The second question looks into two problems, the first being to find needed input data to fully utilize the emission factors found by the previous question. To answer this question digital infrastructure descriptions were explored and tested. The detailed data exists, but there are quality issues. The thesis shows which sources were used and which quality issues were discovered. A detailed exploration of infrastructure descriptions is essential in order to achieve the highest quality emission calculations. The second part looks into how to structure emission calculations. A unified calculation model that is to be long lived requires some careful design. Model design using modules that plug into an internal framework of the model is the key. Such a design allows for modifying and improving parts of the model without having to program the whole model. The final design had four modules: digital infrastructure descriptions, emission functions and factors, routing and analysis and result management.

The third sub-question looks into how the complex emission model could be made useful. The challenge of having a detailed emission model is that it requires a large amount of input data and the user needs to understand what the model is doing. The challenge was to find simplification that still made the model capable of showing changes related to measures under the control of single firms. The end result was to create a database of pre-calculated emission functions on a postcode to postcode basis. The end result of this process became a database of over 713 million emission functions. Proof in the pudding would be if freight transport service providers decided take this emission function database and build it into a tool by integrating it in their production system.

The fourth sub question looks into collecting data for testing the new emission model. The initial idea was to look into how an even more detailed model could be used to verify the emission results. But due to technical challenged this was not possible within the constraints of this Ph.D. project. An alternative approach was to test the underlying assumptions about driving behavior and see if Norwegian truck driving behavior resembles the behavior used to create the emission functions. An experiment using commercial grade GPS units was conducted and the results indicated that it was plausible to transfer the truck emission functions from the ARTEMIS project to Norwegian conditions.

The answers to the four sub-questions have served as a basis for generating documentation on how to develop a new emission model. The knowledge acquired in the process of answering the questions has enabled the candidate to build a new emission model for freight transport that can be used for everyday freight operations. It should be noted that the model has to be integrated into the company's production system. The information on flow of goods and which shipments are on the same vehicle are crucial if the model is to show emission impacts of changes in shipment strategies like increasing utilization. It is the candidate's belief that the research question has been answered with this thesis.

8.8 FURTHER RESEARCH AND DEVELOPMENT

There are several areas where the model could be improved by research or further development of existing routines for constructing input data. When it comes to further research there is the question of binging the emission functions up to the same level of detail as the road emission functions. The search for emission functions in chapter 2 revealed that there exists a potential for creating more detailed emission functions for sea and rail building on available data. Input data should also receive some further investigations. The rest of this section highlights some of the more interesting topics to look into.

8.8.1 SEA

For ship there is the emission inventory that the Norwegian Coastal Administration is developing using AIS data and ship certificates. Combining this data with detailed freight data for single ships could create mode detailed emission functions for ships. There is also the question of ship routing, which factors are involved in ship-based routing and can they be recreated in GIS routing systems.

8.8.2 RAIL

It would be interesting to estimate energy consumption for running freight trains. Such research could further the understanding of the observed variability in energy consumption estimates. If passenger trains are included in the analysis, then it would be a valuable contribution to priority discussions since most rail lines in Norway are single track.

8.8.3 ROAD

For road transport a comparative study between emission estimates from the new model and from advanced fleet management systems like Scania's C200 could give useful insight into activities not currently covered by the new model. The impact of mandatory stops and route choice could be studied. For passenger vehicle the extra emissions of cold starts are believed to have a major impact on emissions. Using the engine sensors it could be possible to further study the extra emissions related to cold starts. One particular interesting development that could create a wealth of new knowledge is the vehicle's ability to weigh itself. Knowing the vehicle weight for all trips without having to search the transport documents or the transporter's productions systems will be a great advance for creating road based freight transport statistics.

8.8.4 The terminal

The terminal is the missing link in multimodal freight transports. The Green Freight Transport Project has shown that there is a considerable energy usage at the terminals and that there are variations between terminals. Understanding the differences would be useful to give the terminal operators clues to how they can reduce their emissions by being more energy efficient. A second stage could be to create terminal emission factors that could be included in the new model.

8.8.5 Digital infrastructure descriptions

The digital infrastructure descriptions are important in detailed emission studies. Finding the optimal level of detail in the infrastructure description is important as this could reduce the computational time while providing the emission functions with all necessary data. There is also a great potential for further development of accessibility to the digital infrastructure sources. At present, more knowledge exist in the sources than what the existing applications are able to export to the outside world. There is also the problem of how errors should be communicated back to the data owners and fixed. And finally there is the possibility to implement results from other research projects. Using the speed model for commercial vehicles could improve average driving speed estimates and thus produce better emission estimates.

8.8.6 Establishing a best practice for allocation of emissions

The last arena for research that I would like to focus on is the allocation of emissions. This Ph.D. project provided a starting point for the discussion of how emissions are to be allocated between shipments on the same vehicles. After gaining some experience with results from the new model it would be advisable to look into the allocation rules.

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10 Appendix

APPENDIX A STATEMENT OF PH.D. CANDIDATE'S ROLE IN THE GREEN FREIGHT TRANSPORT PROJECT

SINTEF

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To whom it may concern

Your ref.	**Our ref.**	**Project No. / File code**	**Date**
Levin, PHD	Grønn Godstransport PhD	503738	2012-04-13

Statement of PHD candidate's role in the Green Freight Transport project

Tomas Levin, hereby referred to as the PHD candidate, was actively involved in the research project Grønn Godstransport. The topic of the candidates PHD project was directly linked to several of the work packages in the research project.

The candidate held the academic lead on 3 of the 11 work packages in the project:

- Calculation tool for environmental accounts
- System development
- Technical evaluation

In the final report the PHD candidate had academic lead for the work done and was responsible for the following chapters:

Kapittel 2.3: Beregningsmetodikk *(Calculation methodology)*
Kapittel 3: Grønn Godstransport - beregningsverktøy *(Calculation tool)*
Kapittel 4: Utslipps funksjoner *(Emission functions)*
Kapittel 5.4: Implementering i Transportbedrifter *(Implementation in transportation firms)*
Kapittel 5.5: Proof of concept
Kapittel 5.6 : Verktøy tilgjengelighet *(Tool accessibility)*
Kapittel 6: Teknisk evaluering *(Technical evaluation)*
Kapittel 8: Videre forskning og utvikling *(Further research and development)*

The final report can be downloaded from:
http://www.sintef.no/Publikasjoner-SINTEF/Publikasjon/?pubid=SINTEF+A18830

A four page brochure of the project can be downloaded from:
http://www.gronngodstransport.no/

Sincerely,

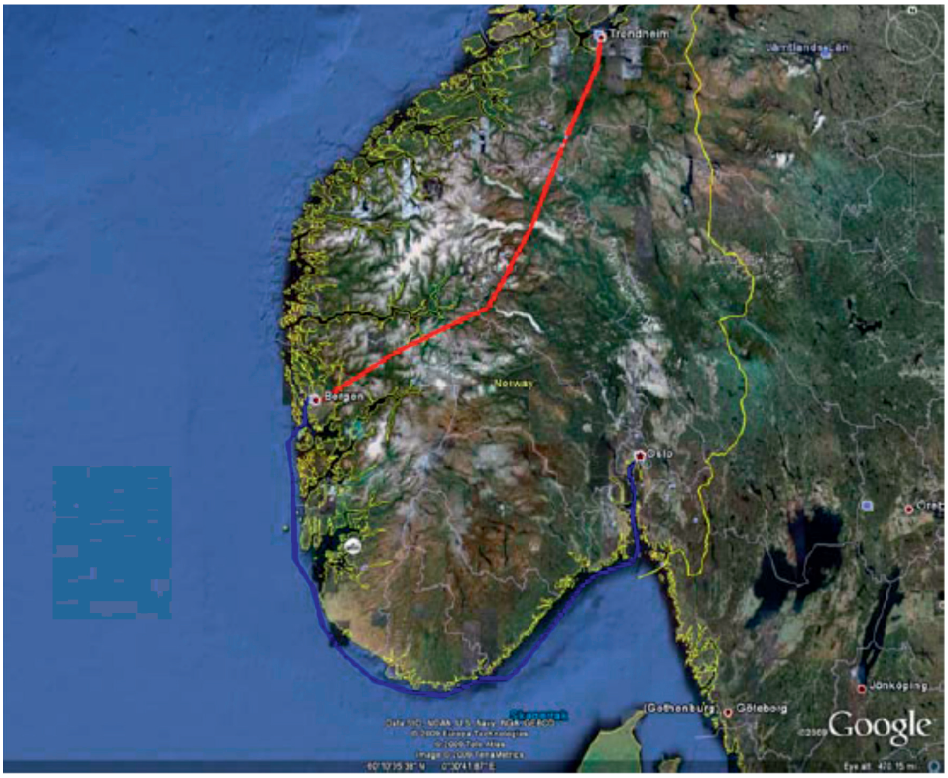
Roar Norvik

Roar Norvik
Green Freight Transport project manager

PROJECT NO. / FILE CODE
503738

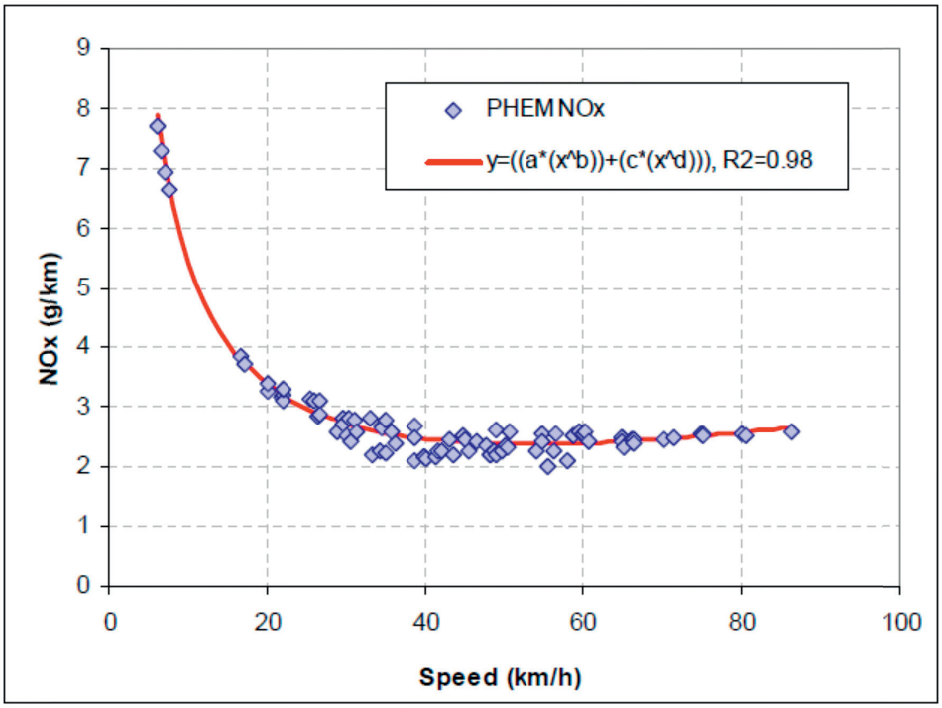
1 of 1

APPENDIX B VISUALIZATION OF ROUTING ERROR



The figure shows how a faulty infrastructure description gives a strange rout for a requested transport with ship from Trondheim to Oslo. The goods is first put on a truck and driven to Bergen, then transferred to a ship for transport to Oslo. The correct would have been a direct ship route from Trondheim to Oslo. The figure is taken from Toftegaard and Knudsen (2009).

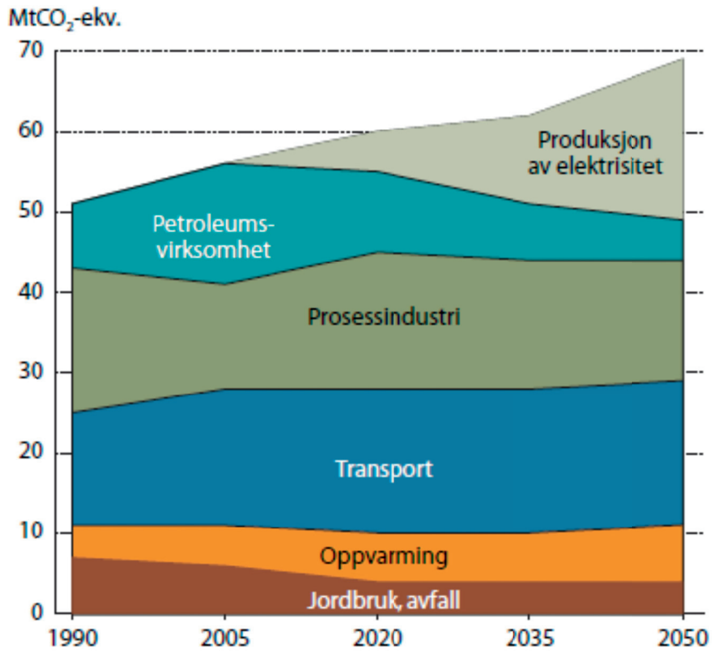
APPENDIX C EXAMPLE OF AVERAGE SPPED EMISSION FUNCTION



Source: (Boulter and Barlow, 2005 p.9)

The blue dots on the figure show the data points that have been used to estimate the average speed emission function. It should be noted that the speed given here is traffic dependent. The speed value of the blue dots is an average speed for the driving cycle used.

APPENDIX D PROJECTED CO_2 EMISSIONS BY SECTOR



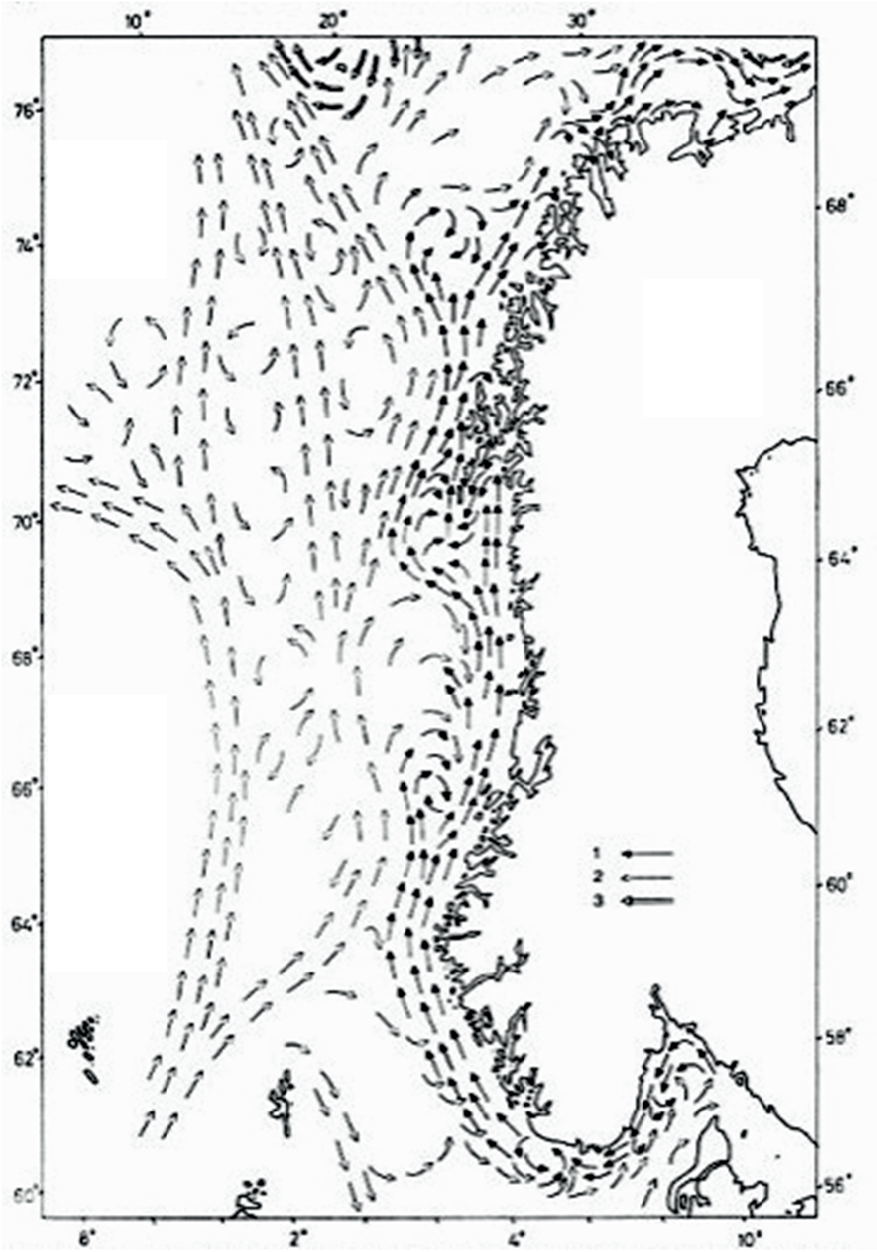
The figure shows the projected sources of CO_2e emission by sector (Lavutslippsutvalget, 2006 p. 52)

Translation:

Produksjon av elektrisitet : Production of electricity
Petroliumsvirksomhet: Petrolium activety
Prosessindustri: Process industry
Transport: Transport
Oppvarming: Heating
Jordbruk, avfall: Farming and waste

The interesting thrend in this figure is the assumption that production of electricity will add to the CO_2e emissions. Thus in laymans terms one can no longer, after 2005, say that norwegian electricity is CO_2 free hydro electric power. This should be taken into consideration if large scale electrification of the freight transport sector is undertaken.

APPENDIX E VECTOR MAP OF CURRENTS ALONG THE NORWEGIAN COASTLINE, SOURCE: (NORGES SJØKARTVERK, 1981 P. 54)



The vector map of sea currents along the Norwegian coastline shows the direction of currents along the Norwegian coast line. Thus it should be more energy efficient to travel northwards than southwards. To assess the impact of the tidal currents measurements of speed over ground could be compared to vessel speed through the water. For example by comparing GPS based vessel speed with vessel's log speed. And finally compare the result with the vector map of currents.

APPENDIX F SOFTWARE LICENCSE FOR SEMBA AND THE EMISSION DATABASE PRODUCED BY SEMBA

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APPENDIX G ACRONYMS USED IN THIS THESIS

Below is a list of acronyms used in the thesis and a very short description of their meaning. This appendix has been included primarily as a help to the reader. Links to formal organizations have been included. For other acronyms internet links have been included as to give the reader a possible starting point for exploring the topics. The sites listed should not be seen as scientific sources, but as starting points for getting an overview. For detailed and verified information the traditional scientific publications should be utilized.

Acronyms	
AIS	Automatic Identification System; a tracking system for ships both used between ships and ship to shore. AIS transponders are required for larger ships in international shipping - http://www.kystverket.no/en/EN_Maritime-Services/Reporting-and-Information-Services/Automatic-Identification-System-AIS/
API	Application Programming Interface; a set of routines to allow computer programs to communicate with each other.
ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems; a large research project looking at single vehicle emissions for different modes. The project goal was to create a harmonized method to calculate emissions. Project deliverables are available from the following website: http://www.inrets.fr/ur/lte/publi-autresactions/fichesresultats/ficheartemis/artemis.html
ATB	Air Transport Bureau; is part of the International Civil Aviation Organization and has a focus on quantification of environmental effects of air transport. http://www.icao.int/secretariat/air-transport/Pages/default.aspx
CARB	California Air Resource Board; the California Air Resource Board was establishes to improve air quality in California by research and focusing on motor vehicles. http://www.arb.ca.gov/homepage.htm
CLRTAP	Convention on Long-range Trans boundary Air Pollution; a convention that has focus on air pollution in Europe. The convention is today signed and ratified by 51 parties. http://www.unece.org/env/lrtap/
CO	Carbon Monoxide; an odorless gas emitted from combustion that can cause suffocation.

CO_2	Carbon dioxide; a gas produced by combustion that is believed to be a prime causer of global warming.
COST	European Cooperation in Science and Technology; a European instrument to create scientific networks. - http://www.cost.esf.org/
DOP	Dilution Of Precision; a measure of the inaccuracy of a GPS positional estimate.
DWI	Direct Water Injection; a method to reduce the temperature in the engine cylinder by injecting water into the cylinder before combustion, this reduces the amount of NO_x produced.
DWT	Deadweight tonnage; a measure for how much weight a ship can safely carry
ECE	United Nations Economic Commission for Europe; the aim is to promote one economic Europe - http://www.unece.org
EEA	European Environment Agency - http://www.eea.europa.eu/
EPA	United Stated Environment Protection Agency - http://www.epa.gov/
EPD	Environmental Product Declaration; a scheme to provide information about the environmental impact from goods and services - http://www.environdec.com/
ERESS	European Railway Energy Settlement System – a database that is used to track and bill rail operators based on energy meters onboard electric locomotives - http://www.eress.eu/
ESRI	Environmental Systems Research Institute – a company that has created GIS software which is widely used in Norway - http://www.esri.com/
ETA	Estimated Time of Arrival; an estimate of when something is expected to arrive, passengers or goods.
FC	Fuel Consumption; often found in technical reports relating to emissions.
FTP	File Transfer Protocol; a protocol for transferring files over the internet published in 1985 - http://www.faqs.org/rfcs/rfc959.html
GGT	A research project called Grønn Gods Transport (Green Freight Transport) - http://www.gronngodstransport.no/
GIL	Global Interpreter Lock (Python implementation); a design issue with the

	Python programming language to simplify access to low level routines like memory. Ensures that no threads are run in parallel. - http://wiki.python.org/moin/GlobalInterpreterLock
GIS	Geographic Information System; usually refers to tools that are created to manipulate that have a geographic meaning. For an online introduction to GIS please visit the following website - http://www.ccdmd.qc.ca/en/gis/
GPGGA	NMEA 0183 Fix information sentence; a line of text communicated over the NMEA protocol that gives GPS receiver's position and height and an estimate of the error - http://www.nmea.org/
GPRMC	NMEA 0182 recommended minimum data for gps; a line of text communicated over the NMEA protocol that gives GPS receiver's position, speed and course - http://www.nmea.org/
GT	Gross tonnage, value used to classify ship in relation to internal volume - http://www.imo.org/About/Conventions/ListOfConventions/Pages/International-Convention-on-Tonnage-Measurement-of-Ships.aspx
HDV	Heavy-duty Vehicle; a vehicle used to carry goods with a reference mass of over 2610 kg (M1,M2, N1, N2) and all M3 and N3 vehicles as defined in annex II of Directive 2007/46/EC - http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:263:0001:01:EN:HTML
ICAO	International Civil Aviation Organization - http://www.icao.int/
IMO	International Maritime Organization - http://www.imo.org/
INRETS	The French National Institute for Transport and Safety Research; one of the research partners in the ARTEMIS project - http://www.inrets.fr/
IPCC	Intergovernmental Panel on Climate Change - http://www.ipcc.ch/
KLIF	The Climate and Pollution Agency in Norway - http://www.klif.no/
LCA	Life Cycle Assessment; a way to assess the environmental impact of a product by looking at production, usage and dismantling is a systematic way - http://www.epa.gov/nrmrl/std/lca/lca.html
LCV	Light Commercial Vehicle (same as LDV); a vehicle used to move goods under 3.5 tonnes total weight.
LDGV	Light Duty Goods Vehicle (same as LDV); a vehicle used to move goods under 3.5 tonnes total weight.

LDV	Light Duty Vehicle; a vehicle used to move goods under 3.5 tonnes total weight.
LPG	Liquefied Petroleum Gas; a gas that can be used as engine fuel.
MASL	Meters Above Sea Level; a measure of elevation where mean sea level is set at 0 meters.
MGO	Marine Gas Oil; a fuel used by ships that resembles diesel used for road vehicles.
NPRA	Norwegian Public Roads Administration - http://www.vegvesen.no/en/Home
NNRA	Norwegian National Rail Administration - http://www.jernbaneverket.no/en/Startpage/
NCA	Norwegian Coastal Administration (Kystverket) - http://www.kystverket.no/
NEDC	New European Driving Cycle; a European legislative driving cycle used to measure vehicle emission compliance - http://www.dieselnet.com/standards/cycles/ece_eudc.php
NFSA	Norwegian Food Safety Authority (Mattilsynet) - http://www.mattilsynet.no/
NIS	Norwegian International Ship Register; a register for Norwegian vessels in international waters - http://www.nis-nor.no/
NOR	Norsk Ordinært Skipsregister; a register for vessels over 15 meters - http://www.nis-nor.no/
NO_x	Nitrogen Oxides; a common term for nitrogen oxides produced from combustion of fuel.
NTE	No-To-Exceed (US EPA heavy-duty diesel regulation); a new type of legislation in relation to emissions, where engine producers cannot exceed an emission curve at any point - http://www.dieselnet.com/standards/cycles/nte.php
NTNU	The Norwegian University of Science and Technology - http://www.ntnu.no/
NTP	The Norwegian National Transport Plan; a political road map for the transportation sector in Norway - http://www.ntp.dep.no/

NVDB	Nasjonal Vegdatabank, (The Norwegian digital road database) - http://www.vegvesen.no/Fag/Teknologi/Nasjonal+vegdatabank/In+English
OBD	On Board Diagnostics; a system to monitor emission related information from a vehicle - http://www.dieselnet.com/standards/us/obd_ca.php
ODBC	Open Data Base Connectivity; a standardized way to access structured data in, typically relational databases - http://support.microsoft.com/kb/110093
PCR	Product Category Rules; rules specifying how emissions related to products or services should be conducted - http://www.environdec.com/
PM	Particulate matter; particles emitted from a vehicle tailpipe. Other typical variants include PM_{10} and $PM_{2.5}$, where the numbers relate to the size of the particles.
RPA	Relative Positive Accelerations; a measure for aggressive driving that is correlated to emissions and energy consumption.
RTM	Regional Transport Model; a set of 4-stage passenger transportation models that splits Norway into 5 regions - http://www.ntp.dep.no/transportanalyser/rapporter.html
SQL	Structured Query Language; a programming language for relational database. SQL is used to create a data structure as well as to query data - http://www.iso.org/iso/iso_catalogue/catalogue_ics/catalogue_detail_ics.htm?csnumber=53681
SSB	Statistics Norway (Statistisk sentralbyrå); Norway's official source of statistical data - http://www.ssb.no/
SSD	Solid State hard Drive; a device to store data that does not use rotating platters, but flash memory and has a higher data transfer capacity than normal hard drives.
TEU	Twenty-foot Equivalent Unit; a measure that relates to the size of a twenty-foot container.
THC	Total Hydro Carbons; a pollutant from combustion, typically uncombusted fuel.
TNE	Transport Network Engine; a commercial product that contains functions that can be used to extract data from the national road databank and modify it for a specific purpose -

	http://www.triona.se/appl/exec/NetPublisher/browse/236
TPG	Toll Post Globe AS; a large company in the Norwegian freight transport industry - http://www.tollpost.no/
TRL	The UK's Transport Research Laboratory; a partner in the ARTEMIS project - http://trl.co.uk/
UIC	International Union of Railways; an organization that promotes rail transport - http://www.uic.org/
UNFCCC	United Nations Framework Convention on Climate Change; the 1992 treaty that focuses on what nations could cooperatively doe to dampen global warming - http://unfccc.int

11 PUBLISHED PAPERS DURING THE COURSE OF THIS PH.D.

Paper 1:

Implementing new transport solutions in existing transport models: Paper presented at Trafikdage på Aalborg Universitet conference 25th-26th of August2008, Aalborg (Peer review).

Paper 2:

Environmental inventory for freight transport companies: Paper presented at the ITS World Conference 2009”, 21th – 25th September 2009, Stockholm.

Paper 3:

Green freight – every penny counts: Paper presented at the World Conference on Transport Research, 11th – 15th of July 2010, Lisbon (Peer review).

Paper 4:

Greening freight – do details matter?: Paper presented at the European Transport Conference 2010, 11th – 13th October 2010, Glasgow.

Paper 5:

A methodology for inexpensive GPS data storage and analysis: Paper presented at at Trafikdage på Aalborg Universitet conference 23th-24th of August2010, Aalborg (under review).

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