Optimal measures in order to reduce total emissions from non-road mobile machinery in a national and economic perspective

-Annual emissions from the non-road mobile machinery sector in Sweden for 2006 to 2020

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ABSTRACT

In this report future annual emissions amounts of gaseous pollutants, particulate matter (PM_{10}) and noise from the non-road mobile machinery sector in Sweden were estimated. The estimates over future emissions amounts were conducted for each year from 2006 to 2020. Special focus has been taken to the impact of European and national legislations, the age distribution of different types and sizes of machinery and measures to reduce the annual emissions. Besides different measures to reduce emissions, corresponding costs were also estimated. The study comprises fuel consumption and emissions of CO_2, carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), and noise from non-road mobile machinery equipped with diesel engines with a rated engine power of 37 to 560 kW. Non-road mobile machinery for example includes tractors, wheel loaders, excavators, articulate haulers, mobile cranes, combined harvesters, forestry machinery and trucks.

The current report was a supplementary study to a report describing a methodology for estimating annual fuel consumption and emissions from the non-road mobile machinery sector in Sweden for year 2006. Inventory data of the year 2006 study was obtained from the Swedish machinery testing institute's machinery inspection operation, statistics of sale returns from trade organisations and the Swedish motor-vehicle register. The number of machinery and annual fuel consumption and emissions amounts for year 2006 is presented in table S1.

Table S1. Number of machinery and annual fuel consumption and emissions amounts for year 2006

	Annual amounts, tonne year^{-1}
Number of machinery	290 000[a]
Fuel consumption	880 000
CO_2	2 800 000
CO	6 000
HC	2 200
NO_x	23 000
PM	1 000

[a] number of units

Besides estimates of annual fuel consumption and emissions amounts, emissions of noise was also derived both at a national level and for a specific construction site. For the case study the results showed that it was possible to reduce the average noise level with more than 3 dB(A) compared with the base scenario just by choosing the machinery fulfilling the strictest noise limits, i.e. Stage II which was mandatory for most machinery from 2006. Other measures simulated included various types of retrofit of noise reduction packages. The specific cost for the different measures to reduce average noise emissions from the specific construction site varied from 4 000 up to more than 500 000 SEK dB^{-1}.

For the estimate of future fuel consumption and emissions amounts various simulations were conducted, each with a different measure for reducing the annual amounts. Five main emission reduction measures or programs were studied:

- Scrappage program
- Alternative fuel program
- Voluntary emission regulation program
- Retrofit of aftertreatment program
- Noise reduction program

The impact on engine exhaust gas emissions and noise of the current European emission and noise regulations, Stage I to IV and Stage I to II for emissions and noise respectively were common for all simulations or programs. Besides the impact of European regulations, annual work was set to a fixed value for each type of machinery and year simulated, thus eliminating any potential changes of the state of the market. The result of the baseline scenario "Business as usual" (BAU), i.e. only taking account to the impact of European regulation, is presented in table S2 for four different years

Table S2. Number of machinery and annual fuel consumption and emissions amounts for four different years

	Annual amounts, tonne $year^{-1}$			
	2006	2010	2015	2020
Number of machinery	290 000 [a]	250 000 [a]	250 000 [a]	250 000 [a]
Fuel consumption	880 000	880 000	890 000	900 000
CO_2	2 800 000	2 800 000	2 800 000	2 800 000
CO	6 000	5 600	5 500	5 500
HC	2 200	1 800	1 400	1 000
NO_x	23 000	16 000	10 000	4 900
PM	1 000	810	550	300

[a] number of units

Both fuel consumption and emissions of CO_2 remains fairly constant as an effect of the assumption that the annual work was set at a fixed value. However, emissions of especially NO_x and PM showed a major reduction due to the tighter and tighter regulations.

All programs simulated were able to reduce the emissions compared with the BAU scenario with exceptions for emissions of nitrogen oxides, which increased in some of the alternative fuel programs. Both the absolute reduction and cost varied significantly between and within the various programs. Reduction of NO_x varied from an accumulated increase in emissions of 25 000 tonne to an accumulated reduction of 22 000 tonne for the studied period from 2006 to 2020. At the same time the accumulated cost for the programs varied from a few hundred million SEK to more than 60 000 million SEK.

In table S3, specific reduction cost for each pollutant in SEK kg^{-1} for eight typical emission reduction programs are presented.

Table S3. Specific costs for reduction of gaseous emissions compared with BAU

Simulation	Specific reduction cost, SEK kg^{-1}			
	CO	HC	NO_x	PM
Scrappage program 2	2 600	2 800	280	4 300
Scrappage program 8	2 700	3 200	340	4 700
Scrappage program 13	3 000	3 800	330	5 400
Alt. fuel program 6	10 800	10 200	-	32 500
Alt. fuel program 9	4 200	9 300	5 200	56 400
Voluntary emission program 2	-	1 300	60	1 800
Retrofit program 2	660	2 100	-	4 400
Retrofit program 9	1 600	6 100	760	39 200

The results showed that the most economically favourable alternative for reducing emissions from non-road mobile machinery was the voluntary emissions regulation program, i.e. early introduction of machinery fulfilling coming emission limits. Another important result was that the introduction of alternative fuels as a mean of emissions reduction was associated with rather high costs compared to the actual reduction in emissions. For emissions of nitrogen oxides the specific reduction cost varied from almost 100 SEK kg^{-1} up to a few hundreds of SEK kg^{-1} except for the alternative fuel programs, which resulted in a considerable higher cost.

SAMMANFATTNING

Denna rapport är en slutrapport för projektet EMMA 7 Samhällsekonomiskt optimala åtgärder för reducering av emissioner från arbetsmaskiner inom Emissionsforskningsprogrammet (EMFO). Bränsleförbrukning och emissionsmängder från arbetsmaskinsparken i Sverige har beräknats för varje år från och med 2006 till och med år 2020. Vid beräkningarna har hänsyn tagits till befintliga och kommande lagkrav för utsläpp från arbetsmaskiner i Europa samt den Svenska maskinparkens sammansättning avseende typ av maskin, storlek, åldersfördelning. Förutom bränsleförbrukning och emissioner har olika åtgärder för att minska utsläppen från arbetsmaskiner studerats inklusive de kostnader som är associerade med dessa åtgärder.

Projektet var begränsat till större dieseldrivna arbetsmaskiner, d.v.s. mobila maskiner med en motoreffekt över 37 kW men under 560 kW. Mobil maskiner eller arbetsmaskiner omfattar bland annat traktorer, hjullastare, grävmaskiner, dumpers, mobilkranar, skördetröskor samt skogsmaskiner. Dessutom avgränsades utsläppen till att, förutom bränsleförbrukning, omfatta emissioner av CO_2, kolmonoxid (CO), kolväte (HC), kväveoxider (NO_x), partiklar (PM) samt buller.

Denna rapport var en fortsättning på en tidigare rapport (A methodology for estimating annual fuel consumption and emissions from non-road mobile machinery - Annual emissions from the non-road mobile machinery sector in Sweden for year 2006) inom projektet vilken beskrev en metod för att beräkna årlig bränsleförbrukning och emissioner från arbetsmaskinsparken i Sverige för år 2006. Indata för år 2006 erhölls från SMP Svensk Maskinprovning AB:s besiktningsverksamhet, försäljningsdata från branschorganisationer, Fordonsregistret samt en mindre del litteraturdata. Antalet maskiner samt årlig bränsleförbrukning och emissioner för år 2006 redovisas i tabell S1.

Tabell S1. Antal maskiner samt årlig bränsleförbrukning och emissioner för år 2006

	Mängd, ton $år^{-1}$
Antal maskiner	290 000[a]
Bränsleförbrukning	880 000
CO_2	2 800 000
CO	6 000
HC	2 200
NO_x	23 000
PM	1 000

[a] antal

Förutom bedömning av årlig bränsleförbrukning och emissioner beräknades även utsläpp av buller på både nationell nivå och för ett en specifikt byggprojekt, en s.k. case study. För case-study visade resultaten att det var möjligt att minska den genomsnittliga bullerstörningen med mer än 3 dB(A) jämfört med grundscenariet genom att endast välja maskiner som uppfyller de i dagsläget strängaste bullerkraven, d.v.s. Steg II vilket är den obligatoriska nivån för de flesta maskiner från och med år 2006. Andra studerade åtgärder omfattade olika typer av eftermonterade ljuddämpningssatser, både för maskin och motor/avgasljud. De specifika kostnaderna för olika åtgärder för att minska emissioner av buller från det specifika byggprojektet varierade från 4 000 kr dB^{-1} upp till mer än 500 000 kr dB^{-1}.

För bedömningar av framtida bränsleförbrukning och emissionsmängder samt effekter av olika åtgärder för att minska dessa nivåer genomfördes en rad olika serier av simuleringar (program). Totalt genomfördes fem olika program, endast en åtgärd för att minska bränsleförbrukning och emissioner studerades per program. Följande program studerades:

- Utskrotning
- Alternativa drivmedel
- Premiering av förtida uppfyllande av kommande emissionskrav
- Eftermontering av utrustning för avgasefterbehandling
- Bullerdämpning

Förutom ovan angivna program studerades även effekterna på bränsle förbrukning, avgasemissioner och buller av att inte genomföra några åtgärder alls. Detta motsvarade ett ”business as usual” (BAU) scenario vilket även användes som referens för samtliga övriga simuleringar eller program. Effekterna på avgasemissioner emissioner och buller av befintliga och kommande avgas och bullerkrav för arbetsmaskiner i Europa, d.v.s. Steg I till IV för avgasemissioner och Steg I till II för bulleremissioner, var gemensamt för samtliga simuleringar eller program. Dessutom sattes årligt utfört arbete för varje maskintyp till ett fixt värde, nivån för år 2006 användes för samtliga år mellan 2006 och 2020 för att inte inkludera effekterna av konjunktursvängningar i resultaten. Resultatet för basscenariot ” ”business as usual” redovisas i tabell S2 för år 2006, 2010, 2015 och 2020.

Tabell S2. Antal maskiner samt årlig bränsleförbrukning och emissioner för år 2006, 2010, 2015 samt 2020

	Mängd, ton år^{-1}			
	2006	2010	2015	2020
Antal maskiner	290 000 [a]	250 000 [a]	250 000 [a]	250 000 [a]
Bränsleförbrukning	880 000	880 000	890 000	900 000
CO_2	2 800 000	2 800 000	2 800 000	2 800 000
CO	6 000	5 600	5 500	5 500
HC	2 200	1 800	1 400	1 000
NO_x	23 000	16 000	10 000	4 900
PM	1 000	810	550	300

[a] antal

Både bränsleförbrukning och emissioner av CO_2 resulterade i en relativt konstant nivå för samtliga år, vilket var förväntat eftersom årligt utfört arbete var satt till en konstant nivå. Årliga emissionsmängder förändrades kraftigt, speciellt för NO_x och PM, från år 2006 till 2020 som en effekt av allt hårdare avgaskrav på nya arbetsmaskiner i kombination med en naturlig omsättning av arbetsmaskinsparken.

Samtliga studerade program eller åtgärder resulterade i lägre årliga emissionsmängder jämfört med BAU för samtliga emissioner förutom för kväveoxider vilka ökade i vissa fall med alternativa drivmedel (RME). Både den absoluta emissionsminskningen och kostnaderna för de olika programmen varierade kraftigt. Den ackumulerade effekten på utsläppen av kväveoxider från år 2006 till 2020 varierade från en minskning med 22 000 ton till en ökning av 25 000 ton. Samtidigt varierade den ackumulerade kostnaden för de olika programmen från några hundra miljoner kr till mer än 60 miljarder kr.

I tabell S3 redovisas specifik reduktionskostnad för samtliga emissioner i kr kg^{-1} för åtta olika åtgärder för att minska utsläppen från arbetsmaskiner i Sverige. Kostnaderna är inte viktade mellan de olika emissionerna utan motsvarar ett fall där hela programmet kostnad lades på en enda emissionskomponent i taget.

Tabell S3. Specifik reduktionskostnad för avgasemissioner jämfört med BAU

Simulering	Specifik reduktionskostnad, kr kg^{-1}			
	CO	HC	NO_x	PM
Utskrotningsprogram 2	2 600	2 800	280	4 300
Utskrotningsprogram 8	2 700	3 200	340	4 700
Utskrotningsprogram 13	3 000	3 800	330	5 400
Alternativbränsleprogram 6	10 800	10 200	-	32 500
Alternativbränsleprogram 9	4 200	9 300	5 200	56 400
”Förtida uppfyllande av kommande krav” program 2	-	1 300	60	1 800
Eftermonteringsprogram 2	660	2 100	-	4 400
Eftermonteringsprogram 9	1 600	6 100	760	39 200

Resultaten visade att det mest kostnadseffektiva alternativet att minska utsläppen från den Svenska arbetsmaskinsparken var att stimulera införandet av maskiner som uppfyller kommande lagkrav i förtid. Ett annat viktigt resultat var att användandet av alternativa drivmedel som en åtgärd för att enbart minska emissionerna var associerat med relativt höga kostnader jämfört med den uppnådda utsläppsreduktionen. För emissioner av kväveoxider varierade den specifika reduktionskostnaden från knappt 100 kr kg^{-1} upp till några hundra kronor kg^{-1} förutom vid användandet av alternativa drivmedel vilket resulterade i betydligt högre kostnader. Samtliga bedömningar har utförts ur ett rent emissionsminskande perspektiv, övriga eventuella effekter så som tillgänglighet, sysselsättning, resursutnyttjande mm har inte inkluderats.

CONTENT

1. NOTATIONS

A_1, A_2, A_3	Maintenance constants for CDPF
b	Base year
Be	Brake specific fuel consumption or emissions, g kWh-1
C_C	Cost for engine certification, SEK unit^{-1}
C_E	Cost for equipment for emission control, SEK unit^{-1}
C_{IIIA}	Investment cost in order to comply with stage III A emission regulation, SEK unit^{-1}
C_{IIIAF}	Fixed cost for stage IIIA in the voluntary emission program, SEK
C_{IIIB}	Investment cost in order to comply with stage III B emission regulation, SEK unit^{-1}
C_{IIIBF}	Fixed cost for stage IIIB in the voluntary emission program, SEK
C_{IV}	Investment cost in order to comply with stage IV emission regulation, SEK unit^{-1}
C_{IVF}	Fixed cost for stage IV in the voluntary emission program, SEK
C_M	Cost for material for emission control, SEK unit^{-1}
$C_{O\&M}$	Cost for maintenance of diesel particle filters, SEK kg^{-1} fuel
C_R	Cost for machinery redesign, SEK unit^{-1}
$C_{R\&D}$	Cost for R&D for emission control, SEK unit^{-1}
C_T	Cost for tooling for emission control, SEK unit^{-1}
Cv_p	Purchase price of new machinery, SEK
Cv_{ret}	Total cost for all machines actively retired, SEK
Cv_{y2}	Purchase prise of new machinery at year y2, SEK unit^{-1}
d	Slope constant
E	Fuel consumption or emissions, g
E_{blend}	Fuel consumption or emissions of the blend relative to EC1 fuel
E_{ISO}	Absolute emissions based on the ISO 8178 C1 regulation, g h^{-1}
$E_{real\text{-}use}$	Absolute emissions based on the real use of non-road mobile machinery, g h^{-1}
fsa	Fraction sound absorbing soil
h	Difference in altitude between machinery and observer, m
h_m	Height of machinery, m
h_o	Height of observer, m
Hr	Annual use, h
i	model year
k	Equipment dependent slope constant
L_A, L_B, L_C	Topography dependent reduction factors, dB(A)

Lf	Load factor
L_P	Noise level, dB(A)
LS_{WAR}	Total noise level, dB(A) $1pW^{-1}$
L_W	Average noise level at construction site, dB(A)
L_{WAi}	Permissible noise level, dB(A) $1pW^{-1}$
m	equipment dependent constant
N	Number of units
N_{IIIA}	Number of machinery anticipated for recovery of fixed cost for stage IIIA
N_{IIIB}	Number of machinery anticipated for recovery of fixed cost for stage IIIB
N_{IV}	Number of machinery anticipated for recovery of fixed cost for stage IV
P	Rated power, kW
p_p	Portion of machines participating, %
r	Distance, m
RME_{rel}	Fuel consumption or emissions of the pure RME fuel relative to EC1 fuel
S_p	Relative scrappage payment
veh_i	Number of machines of model year i
veh_{ret}	Number of actively retired machines annually
$W_{real\text{-}use}$	Correction factor for emissions based on the real use of non-road mobile machinery
x	Average lifetime, year
y	Year
z	Share of RME fuel in the fuel blend
α	Interest of investment, %
β	Advancement of emission limit in the voluntary emission program, years
δ	Minimum age of machinery participating in the scrappage program
θ	Number of subcategories of non-road mobile machinery
φ	Fraction of units still in service

2. INTRODUCTION

Non-road mobile machinery is a common element in today's society, they operate both within cities with construction and maintenance work and on the countryside with agricultural production for example. However, non-road mobile machinery is almost exclusively equipped with diesel engines due to the high fuel economy. Diesel exhaust gas emissions contain several unwanted by-products such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) particulate matter (PM) and various other toxic and mutagenic substances (Bosch, 1996, Scott et al., 2005).

In Europe, non-road mobile machinery accounts for approximately 15 to 20% of the total emissions of nitrogen oxides (EEA, 2005). Diesel exhaust can be hazardous to the environment and toxic to humans thus causes cardiovascular and respiratory problems and premature deaths. In order to reduce the air pollutions from vehicles and machines equipped with internal combustion engines the European union, USA, Japan and other countries has adopted emission regulations. Emission regulations will reduce the overall emissions from the assembly of machinery as old units are replaced with new ones. Due to the rather long lifetime of most non-road mobile machinery the full effect of new emission regulations will lag in time for tenths of years. In Sweden, about 40% of all agricultural tractors still in service are 25 years old or older (SCB, 2004).

However, it is important to study the effects and costs of other measures to reduce emissions from non-road mobile machinery and consequently improve the air quality. The three Rs of emission reduction is often used as an example of possible measures to reduce emissions from the current assembly of machinery (DTF, 2003; Scott, 2005). Those measures are Replace, Refuel and Retrofit.

Replacing entire vehicles or just the engine with the best available technology might be most suitable solution for the oldest and highest polluting machinery. Replacing of the engine only, repowering, is a rather cost effective measure to improve the emission characteristics of the machinery. However, the machine might still have poor efficiency thus causing the engine to operate in a higher power region compared with a corresponding new machine.

Refueling means the use of fuels with better emissions characteristics such as ultra-low sulphur fuels or many alternative diesel fuels. For most engines refuelling is a suitable measure that only affect the fuel cost if no modifications of the engine are necessary. Today ultra low sulphur fuels, fuels with less than 15 ppm sulphur, syntetic diesel fuels i.e. FTD, and biodiesel blends commercially available and suitable for use in most diesel engines.

Retrofit, the installation of exhaust gas emission aftertreatment equipment, could be used to remove one or many specific substances from the exhaust. Different technologies are suitable for different types of equipment, operations and pollutants. Diesel oxidation catalyst mainly reduces the amounts of CO and HC in the exhausts. NO_x control systems include for example adsorbers, traps and selective catalytic reaction catalysts. The third and last main categories of retrofit equipment are diesel particulate filters.

Besides emissions of gaseous substances emission of noise is an increasing problem today, especially in densely populated areas. The need to reduce noise from non-road vehicles has previously been identified by the Swedish EPA in their inventory of emissions and mitigation options for non-road vehicles (SEPA, 1999). Noise is defined as unwanted sounds, and will vary between individuals considering sources and levels and vary during time of the day. Absence of noise is necessary for a high quality of life.

The sound level experienced depends both on sound pressure and frequency spectra. The range that the human ear can catch is very wide; spanning from barely hearable up to the pain threshold in approximately 100 billion times, leading to a need for logarithmic scales (dB). To grasp the influence of sound frequencies on the ear's experience of sound levels, weighted filters have been constructed. The A-filter (dBA) is used for common sound levels and frequencies, such as traffic noise, whereas the C-filter (dBC) is constructed for low frequency sounds and vibrations.

The ability of noise to act disturbing is related to its level as well as its frequency spectra and time-distribution. Hearable tones increase the degree of disturbance, and noise dominated by low frequencies has a tendency to act tiring. Noise that varies in level and character is usually considered as more disturbing than constant noise (Swedish Work Environment Authority, 2005:16). Information to neighbouring citizens regarding type and timeframe of a planned construction enterprise can improve the attitude against the disturbing noise (SEPA, 2004).

Noise is included in three of the Swedish environmental quality objectives:

1. A Good Built Environment
   - Sub target 3, Noise: The number of people exposed to traffic noise above the recommended levels assigned by the Swedish parliament for noise in residential buildings shall be reduced by 5 % by the year 2010 compared to the level of 1998.
2. A Balanced Marine Environment, Flourishing Coastal Areas and Archipelagos (boats)
3. A Magnificent Mountain Landscape (snowmobiles)

This study is one part in a large Swedish research program on emissions (EMFO). EMFO is a sector-wide competence to develop vehicles and vehicle components with emission levels that are sustainable in the long term. The programme is to contribute to producing knowledge and making this knowledge available for use in research, development and education. Members of this programme include: Saab Automobile AB, Scania CV AB, AB Volvo, Volvo Car Corporation AB, Scandinavian Automotive Suppliers AB, the Swedish Energy Agency, the Swedish National Environmental Protection Agency, VINNOVA (Swedish Agency for Innovation systems) and the Swedish National Road Administration.

The purpose of the current project was to study the effects and corresponding costs of different measures to reduce emissions from the assembly of non-road mobile machinery in Sweden for the period of 2006 to 2020.

3. MODEL

With non-road mobile machinery this report refers to any mobile machine not intended to carry goods or passengers on the road in which a compression ignition engine, diesel, is installed. The following types or categories of non-road mobile machinery were included in the study:

Tractors

- Agricultural and forestry tractors
- Residential tractors
- Industry tractors

Combined harvesters

- Combined harvesters

Forestry machines

- Forwarders
- Harvesters

Construction equipment

- Wheel loaders
- Backhoe loaders
- Crawler excavators
- Wheeled excavators
- Skid steer loaders
- Articulated haulers
- Mobile cranes
- Trucks
- Other

Furthermore, each category was divided into 3 different groups depending on net power ranging from 37-75 kW, 75-130 kW and 130-560 kW except for crawler excavators. For crawler excavators a fourth power range was also include, less than 37 kW. Many of the crawler excavators used within the construction sector has an engine power less than 37 kW, thus still equipped with a diesel engine (Wetterberg et al., 2007). Crawler excavators with a rated engine power less than 37 kW are often called or classified as miniature excavators. The power interval was chosen to harmonise with the net power presented in European emission regulations.

Both the total number of non-road mobile machinery and the age distribution for each type of machinery or the number of machines of different model years was estimated for each model year from 1982 to 2006. All machines older than 25 years, with a model year of 1981 or less, was consolidated into the model year 1982 group thus causing that group to represent machines with and age of 25 years or more. In total the project included 46 different categories of machines divided into 25 model years thus resulting in 1 150 different sub-categories of non-road mobile machinery.

For each sub-category *i.e.* type of machine, power region and model year, annual hours was estimated based on inventory data obtained within the project. The calculations of fuel consumption and emission amounts were individually performed for each sub-category rather than just for an average value, which normally is the case due to limited amounts of data. All individual calculations were conducted in agreement with the detailed approach according to CORINAIR (EEA, 2005). The following basic equation is used for deriving fuel consumption and emissions (E) in gram:

$$E = N \times Hr \times P \times Lf \times Be \qquad \text{Equation 1}$$

where N was number of vehicles, Hr was annual use in hours, P was rated power in kW, Lf was annual average load factor and Be was brake specific emissions and fuel consumption in g kWh^{-1}.

Though the approach with age dependent sub-categorise all individual variables in equation 1 could be exactly match to the different prerequisite in the individual sub-categories, for example annual work hour is strongly dependent on both type of machine and the age of the machine while emission factors shows a major dependency to the model year of the machine.

Instead of executing thousands of individual calculations the proposed model was based on several matrices, one for each variable in equation 1. Figure 1 illustrates how the different matrices were connected to each other.

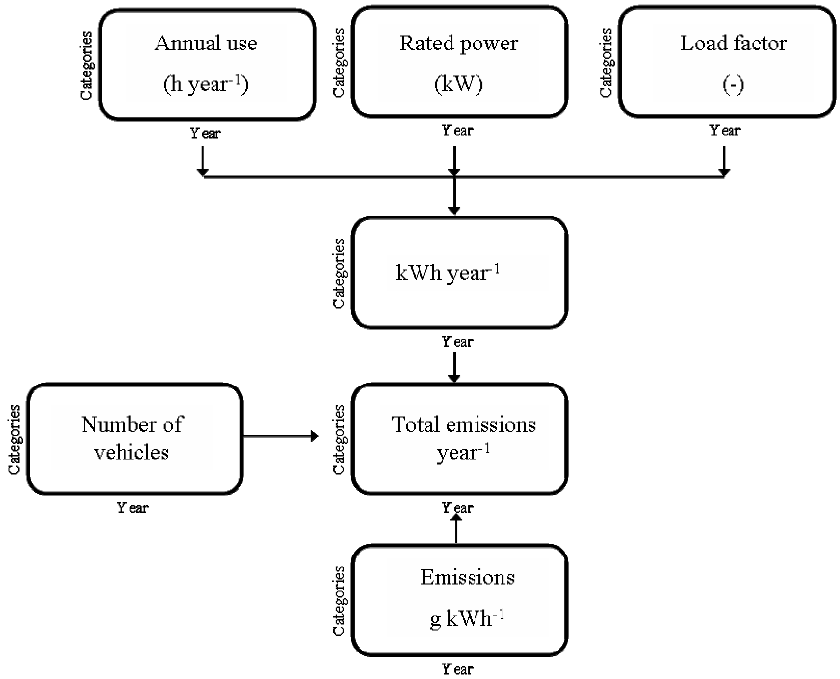

Figure 1. Structure of fuel consumption and emission model.

Each row in the matrices described different types or categories of non-road mobile machinery and each column an age category or model year, see table 1 for an example of a matrix representing number of different categories of non-road mobile machinery.

Table 1. Example of matrix describing the number of different categories of non-road mobile machinery

Category	Net power			Model year			
	kW	1982	1983	1984	1985	…	2006
Agr. tractor	37-75	42 929	2 939	3 395	3 276		1 223
Agr. tractor	75-130	3766	452	450	562		705
Agr. tractor	130-560	255	47	28	26		171
…							
Mobile crane	130-560	9	9	11	13		93

The annual amount of emissions and fuel consumption from the included non-road mobile machinery were calculated as the sum of the product of matrices describing number of non-road mobile machinery, specific emissions, annual use, rated power and load factor. The model including presentation of input data are thoroughly described by Lindgren (2007).

For each year passing in the model, a fraction of the present assembly of machinery was removed from duty or scrapped. The fraction of machinery of each model year still in service was calculated based on a scrappage function presented by USEPA (2005).

$$\varphi_i = 1 - \frac{1}{1 + \left[\frac{i}{b - x} \right]^d} \qquad \text{Equation 2}$$

where φ_i was the fraction of units of model year *i* still in service at base year *b*, *i* was model year, *x* was the average lifetime in years and *d* was a dimensionless slope constant. The dimensionless slope constant, *d*, was set to a fixed value of 1 500. Estimated average lifetime for different non-road mobile machinery, based on adjustments of the individual variables in equation 2 to inventory data, is presented in table 2.

Table 2. Estimated average lifetime in year for different non-road mobile machinery

Construction equipment	37-75 kW	75-130 kW	130-560 kW
Agricultural tractor	21	22	19
Residential tractor	20	21	12
Industrial tractor	11	11	8
Combined harvester	20	20	20
Forwarder		8	8
Harvester		8	8
Wheel loader	8	8	9
Backhoe loader	19	19	17
Miniature excavator	23[a]		
Crawler excavator	10	10	11
Wheeled excavator	9	10	9
Skid steer loader	20		
Articulated hauler		14	16
Mobile crane		8	9
Truck	11	11	12
Other	12	11	13

[a] rated engine power of less than 37 kW

The number of units sold in year 2007 and forthcoming years was derived from the assumption that the annual work was constant for each sub-category i.e. type of non-road mobile machinery and power region. However, the model rendered it possible to also include variations in the state of market. The calculations were preformed in different steps.

1. calculation of annual work produced at base year *b* with all machinery from model year *b-24* to model year *b* for each sub-category individually,
2. recalculation of age distribution of machinery of different model years still in service at year *b+1* in accordance with equation 2 above except for units that are 25 years old or older which was set to a fixed value *i.e. b-23* was set to *b-24*,
3. calculation of annual work produced at year *b+1* with all machinery from model year *b-23* to model year *b* for each sub-category individually, and
4. calculation of requisite number of machinery to produce the calculated difference in work between point 1 and 3.

For each year simulated a few machines were scrapped. However, the amounts of work produced by those machines were replaced with the same amount of work produced by new machines.

4. EMISSIONS

4.1. Brake specific emissions and fuel consumption

Emission data presented in table 3 are based on the European legislation to regulate emissions from non-road mobile machinery, Directive 97/68/EC and Directive 2000/25/EC with amendments (EU, 1997; 2000; 2004a; 2004b; 2005).

Non-road mobile machinery is used for a variety of different operations and the real fuel consumption and emission amounts are dependent on the actual use of the engine (Lindgren, 2004). Hansson et al. (1998) has also shown that emission values cannot be reasonable accurately calculated from average emission factors such as data presented in table 3 or by the Emission Inventory Guidebook without account being taken of the type of load on the engine.

Table 3. Emission standards for non-road mobile machinery and agricultural and forestry tractors

Net power kW	Implementation date	CO	HC	NO_x g kWh^{-1}	PM
Stage I					
37≤ P< 75	1999.04/2001.07[a]	6.5	1.3	9.2	0.85
75≤ P< 130	1999.01/2001.07[a]	5.0	1.3	9.2	0.70
130≤ P< 560	1999.01/2001.07[a]	5.0	1.3	9.2	0.54
Stage II					
37≤ P< 75	2005.01/2004.01[a]	5.0	1.3	7.0	0.4
75≤ P< 130	2003.01/2003.07[a]	5.0	1.0	6.0	0.3
130≤ P< 560	2002.01/2002.07[a]	3.5	1.0	6.0	0.2
Stage III A					
37≤ P< 75	2008.01	5.0		4.7[b]	0.4
75≤ P< 130	2007.01	5.0		4.0[b]	0.3
130≤ P< 560	2006.01	3.5		4.0[b]	0.2
Stage III B					
37≤ P< 56	2013.01	5.0		4.7[b]	0.025
56≤ P< 75	2012.01	5.0	0.19	3.3	0.025
75≤ P< 130	2012.01	5.0	0.19	3.3	0.025
130≤ P< 560	2011.01	3.5	0.19	2.0	0.025
Stage IV					
56≤ P< 130	2014.10	5.0	0.19	0.4	0.025
130≤ P< 560	2014.01	3.5	0.19	0.4	0.025

[a] Agricultural and forestry tractors
[b] sum of HC and NO_x

The emission data for stage III B, net power interval 37 to 75 kW are equal to the data given in the Stage III B net power interval 56 to 75 kW in order for the emission data to harmonise with net power intervals given in the model. A similar approach is used for the emission data for stage IV. In the model, emission data corresponding to stage IV, net power intervals 37 to 75 kW and 75 to 130 kW are equal to the amounts given in table 3, stage IV net power interval 56-130 kW.

Fuel consumption data and emissions data for uncontrolled non-road mobile machinery, i.e. pre-stage I engines, was derived from Emission Inventory Guidebook (EEA, 2005). Moreover, fuel consumption data for stage I to stage II engines was also obtained from the Emission Inventory Guidebook and presented in table 4. Fuel consumption data for stage III A to stage IV was set to the same value as for stage II.

Table 4. Fuel consumption data in g/kWh for uncontrolled engines and for stage I to IV engines

Net power kW	Uncontrolled	Stage I	Stage II	Stage III A	Stage III B	Stage IV
			g kWh^{-1}			
37≤ P< 75	265	265	265	265	265	265
75≤ P< 130	260	260	260	260	260	260
130≤ P< 560	254	254	254	254	254	254

Uppenberg et al. (2001) has shown that for each MJ of diesel fuel, environmental class 1, combusted 73 g of carbon dioxide (CO_2) is released to the surrounding air. The average energy density of an environmental class 1 diesel fuel from Preem Petroleum (Preem, 2006) is 43.1 MJ kg^{-1} fuel, thus results in 3146 g of carbon dioxide per kg of fuel combusted. Emission data in g kWh^{-1} for uncontrolled engines is presented in table 5.

Table 5. Emission data for uncontrolled engines in g kWh^{-1}

Net power kW	CO	HC	NOx	PM
		g kWh^{-1}		
37≤ P< 75	5.1	2.3	14.4	1.51
75≤ P< 130	3.8	1.7	14.4	1.23
130≤ P< 560	3.0	1.3	14.4	1.10

Emissions of carbon monoxide are lower for the uncontrolled engine compared with the stage I engine. The Emission Inventory Guidebook (EEA, 2005) recommends using the same carbon monoxide emission level for both categories of engines. In this study the stage I value has been chosen despite the higher emission. However, all emission levels are adjusted before use as shown below.

The basic emission data presented in tables 3 and 5 were modified several times due differences:

1. in the characteristics of the reference diesel fuel specified in the type approval process and the diesel fuel used in Sweden, i.e. differences in cetane number, density, sulphur content and aromatics,
2. between the emission amounts stipulated in the emission regulations and emission amounts obtained during engine type approval, and
3. in the engine load characteristics between the test cycle used stipulated for use in the emission regulation and the actual use of the vehicle.

Furthermore, a degradation factor was included in order to comply with the effects of wear and aging on both fuel consumption and emission. The degradation factors used were obtained from the Emissions Inventory Guidebook (EEA, 2005), see table 6 and figure 2.

Table 6. Degradation factor for fuel consumption and emissions

	FC	CO	HC	NO_x	PM
Degradation factor (% $year^{-1}$)	1	1.5	1.5	0	3

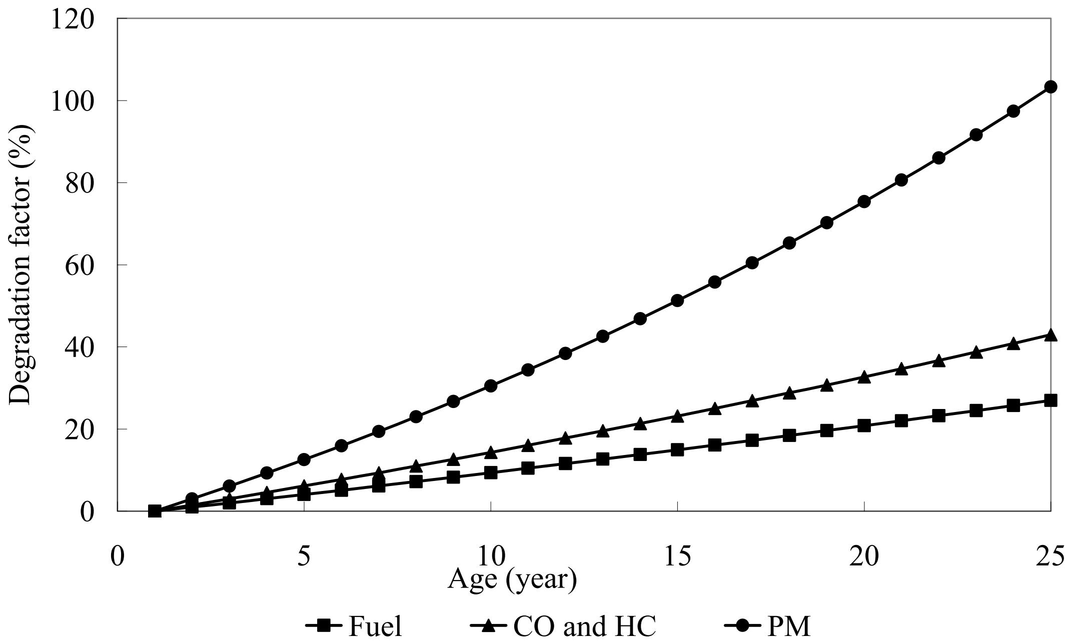

Figure 2. Degradation factor in percent for fuel consumption, emissions of particulate matter (PM), CO and hydrocarbons (HC) as a function of age

4.1.1 Fuel

Baseline emission data for uncontrolled diesel engines as presented by the Emissions Inventory Guidebook (EEA, 2005) and regulated emission amounts stipulated in the emission regulation for Stage I, II and III A were modified due to the differences in fuel quality or specification between the reference fuel and the fuel used during real-use of the vehicle, se table 7 for fuel specifications.

Table 7. Fuel specification for reference diesel fuel used in stage I, II, III A and Swedish environmental class 1 diesel fuel (EC 1)

	Stage I-II	Stage III A	Stage III B and IV	EC 1
Cetane number	45-50	52-54	<54	52
Sulphur content (ppm)	1500	300	<10	10
Aromatics (ppm)	20-30	-	-	5
Polycyclic aromatics (ppm)	3-6	3-6	3-6	0.02
Density (kg m^{-3})	835-845	833-837	833-837	800-820

For stage I and stage II specifications for reference diesel fuel stipulated for use at the type approval is regulated in Directive 97/68/EC (EU, 1997). According to Directive 2004/26/EC the sulphur content of the reference fuel for stage III B and stage IV should be reduced and the definition of the reference fuel must reflect the fuel market situation in the member states at the time for different emission stages to be forced in (EU, 2004a). A maximum sulphur content of 10 ppm was set for both stage III B and stage IV (EU, 2004a).

According to data presented by Volvo (Mårtensson, 2003) and Euromot (Stein, 2002) fuel quality plays an important role on the resulting emission amounts. The relative effects on engine exhaust gas emissions when changing from the different reference diesel fuels to Swedish environmental class 1 diesel fuel are presented in table 8.

Table 8. Relative effects on engine exhaust gas emissions between reference diesel fuel and Swedish environmental class 1 diesel fuel (EC 1)

	Stage I-II	Stage III A
CO	1	1
HC	1.05	1.05
NOx	0.93	0.93
PM	0.7	0.8

The differences in specifications between Swedish EC1 diesel fuel and the non-road mobile machinery reference diesel fuel for type approval to meet stage III B and stage IV limit values *i.e.* cetane number and sulphur content were only of minor importance and thus it was assumed that the emissions would be comparable.

4.1.2 Engine certification

The emission regulations stipulate a maximum amount of emissions that must not be exceeded. However, most engines emit less pollutants and the difference can be significant. Based on about 16 500 engine certification data for non-road compression ignition engines presented by the US environmental protection agency from 1998 to 2006 weighting factors for regulated emissions has been derived for Tier 1 to 3 (US EPA, 2006) and adopted for European conditions. The weighting factor presented in table 9 was derived as the quotient between certification and legislation values as a function of net power for each step in the emission regulation.

Regulatory authorities in the European Union and in the USA are cooperating in order to harmonise the emission standards. The US regulation Tier 1 and 2 are in parts harmonised with European regulation Stage I and II while the US Tier 3 and 4 limits are almost fully harmonised with the European Stage III and IV limits. Therefore, the engine certification data obtained from the US EPA where transferred to the European Stage I to III A regulations. Weighting factors for Stage III B and IV was assumed to be equal to one *i.e.* recorded emissions would be equivalent to the type approval limits except for carbon monoxide, which was set to the same level as for stage I to III A.

Table 9. Weighting factors for baseline emission data for stage I to IV

Net power	Observations	Stage I	Stage II	Stage III A	Stage III B	Stage IV
Hydrocarbons						
37-75	770	0.50	0.40	0.70	1.00	1.00
75-130	518	0.40	0.35	0.70	1.00	1.00
130-560	2615	0.30	0.25	0.40	1.00	1.00
Nitrogen oxides						
37-75	1704	0.80	0.80	0.95	1.00	1.00
75-130	848	0.80	0.80	0.95	1.00	1.00
130-560	2609	0.80	0.80	0.95	1.00	1.00
Carbon monoxide						
37-75	778	0.30	0.30	0.30	0.30	0.30
75-130	514	0.30	0.30	0.30	0.30	0.30
130-560	2512	0.30	0.30	0.30	0.30	0.30
Particulate matter						
37-75	737	0.50	0.70	0.85	1.00	1.00
75-130	492	0.40	0.70	0.85	1.00	1.00
130-560	2439	0.40	0.70	0.85	1.00	1.00

Baseline emission data for uncontrolled engines was adjusted with the same weighting factors as used for stage I.

4.1.3 Engine load characteristics

The ISO 8178 standard stipulated for use in Directive 97/68/EC and Directive 2000/25/EC with amendments are not representative for the real use of non-road mobile machinery (ISO, 1996; EU, 1997; EU, 2000; EU 2004a; EU 2005). Data on average use of different non-road mobile machinery are reported by Hansson et al. (2001) and Lindgren et al. (2002) for agricultural tractors. Lindgren et al. (2002) also presents data on average use for several other non-road mobile machinery. Furthermore, in Stage III B a transient test cycle, the non-road transient cycle (NRTC) will be used for measurements of particulate matter. The NRTC is based on real-use engine load characteristics for several different operations and vehicles. The operations and vehicles studied are presented by Starr et al. (1999) and Ullman et al. (1999) and represents typical operations with non-road mobile machinery. By combining the engine load characteristics presented by Lindgren et al. (2002), Starr et al. (1999), and Ullman et al. (1999) for the different vehicles included in the model real-use emission factors can be calculated. Real-use emission factors are then compared with emission weighted according to the ISO 8178 standard as shown in equation 3:

$$W_{real-use} = \frac{E_{real-use}}{E_{ISO}} \qquad \text{Equation 3}$$

where $W_{real-use}$ is a dimensionless correction factor, $E_{real-use}$ is absolute emissions in g h^{-1} during average use of the vehicle and E_{ISO} is absolute emissions in g h^{-1} weighted according to the ISO 8178 standard for the same engine. The correction factors for real-use of the vehicle are presented in table 10.

Table 10. Correction factors for real-use different non-road mobile machinery

	Fuel	CO	HC	NOx	PM
Tractor	1.07	1.27	1.18	1.00	1.07
Combined harvester	1.12	1.05	1.26	0.92	1.08
Forwarder	1.15	1.18	1.08	1.11	1.10
Harvester	1.15	1.18	1.08	1.11	1.10
Wheel loader	0.94	1.06	1.10	1.09	1.01
Backhoe loader	1.12	1.71	1.65	1.17	1.21
Crawler excavator	1.12	1.12	1.07	1.09	1.03
Wheeled excavator	1.12	1.12	1.07	1.09	1.03
Skid steer loader	1.18	1.75	1.83	1.09	1.28
Articulated hauler	1.06	1.83	1.34	1.01	1.10
Mobile crane	1.12	1.12	1.07	1.09	1.03
Truck	1.10	1.30	1.23	1.06	1.09
Other	1.10	1.30	1.23	1.06	1.09

Table 10 shows that emission regulations based on the ISO 8178 standard underestimates both fuel consumption and pollutants from non-road mobile machinery in most cases.

4.2. Emissions of noise

Besides fuel consumption and emissions of CO, HC, NO_x and PM, which has been described by Lindgren (2007) emissions of noise from the Swedish assembly of machinery was included in the present study.

Noise from non-road vehicles can arise both from the engine (engine noise) as well as from the interaction between the working tool and the treated material (tool noise), i.e. location 1 and 2 in figure 3 respectively. The noise from several types of machines is regulated by legislation.

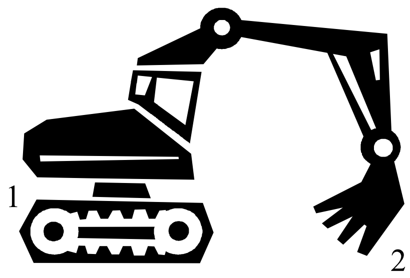

Figure 3. Example of point of origion of different types of noise.

Noise from non-road vehicles is primarily regulated in the legal act SFS 1998:1707 (Ministry of Environment, 1998); "Non-road vehicles should be constructed and equipped as to not emit more noise, exhaust emissions or other contaminants than can be acceptable from a health- and environmental perspective". The Swedish legal act in based on European directives as explained below.

4.2.1 Legal requirements regarding noise levels

Noise-emission from construction plants and equipment has been subject to directives within EC since 1978 (directive 79/113/EEC, published 19 December 1978). Agricultural and forestry tractors were excluded from the scope.

79/113/EEC was the frame directive, which was followed by 86/662/EEC for excavators, dozers, loaders and excavator-loaders. The noise limits were as follows:

Table 11. Noise limits according to directive 86/662/EEC

Net installed power kW			Permissible sound-power level dB(A) $1pW^{-1}$
	P	≤ 70	106
70 <	P	≤ 160	108
160 <	P	≤ 350	112[a]
			113[b]
350<	P		118

[a] excavators
[b] other

The directive was amended by directive 89/514/EEG and 95/27/EC and the noise limit was lowered in two steps as presented in table 12 and 13.

Table 12. Noise limits from 30 December 1995 until 29 December 2001, "Step 1"

Equipment	Noise limit, L_{WA} dB(A))
Tracked machine (except excavators)	87 + 11 log P[a]
Wheeled dozer, loader, excavator-loader:	84 + 11 log P[a]
Excavators	83 + 11 log P[a]

[a] net installed power

Table 13. Noise limits from 30 December 2001, "Step 2"

Equipment	Noise limit, L_{WA} dB(A))
Tracked machine (except excavators)	84 + 11 log P[a]
Wheeled dozer, loader, excavator-loader:	81 + 11 log P[a]
Excavators	80 + 11 log P[a]

[a] net installed power

The second step was, in practice, not implemented since the directive was repealed by 2000/14/EC, which came into effect 3 January 2002.

2000/14/EC was published on 8 May 2000 and contained noise limits for the same categories of machinery as the old directives. In addition, noise limits for new categories, such as compactors, welding and power generators, dumpers, graders, lift trucks and hydraulic power packs, were given.

The noise limits were almost the same as in the old directives, but in practice the new directive led to significantly lowered limit-values, due to a new definition of noise level. The new directive uses the term "guaranteed value" while the old directives only mentioned a measured value on a single machine. In order to state a "guaranteed value" the manufacturer must allow for uncertainty in the measurements and also for variations in the production. The manufacturer has the possibility to guarantee values with 90% or 95% confidentiality. When the manufacturer has acquired a lot of noise data, a K-factor at 90% confidentiality of 1 dB or less can be achieved.

A traditional uncertainty-calculation will give a much higher value (> 3 dB) for the uncertainty than the value accepted by the directive and the interpretation of the directive.

The noise limits in the new directive were to be implemented in two steps; one step that came into effect 3 January 2002 and a second step that came into effect 3 January 2006. In step 2, the noise limit was lowered 3 dB in comparison with step 1 for the majority of the machines. Some categories of machinery were excluded from stage 2 in the last minute since "state of the art" for these machines was not considered to be such that the limit-values could be fulfilled. For example, tracked machines create so much noise due the track itself, that there is no possibility to decrease noise level further. Other types of machinery that were considered unable to fulfil the new limit were big industrial trucks and vibratory plates. The noise limits in step 2 are presented in table 14

Table 14. Noise limits according to directive 2000/14/EC

Type of equipment	Net installed power P, kW	Permissible sound power level, dB pW^{-1} Stage I[a]	Stage II[b]
Compaction ma- chines (vibrating rollers, vibratory plates, vibratory rammers)	$P \leq 8$ $8 < P \leq 70$ $P > 70$	108 109 $89 + 11 \lg P$	105 [d] 106 [d] $86 + 11 \lg P$ [c]
Tracked dozers, tracked loaders, tracked excavator-loaders	$P \leq 55$ $P > 55$	106 $87 + 11 \lg P$	103 [d] $84 + 11 \lg P$ [c]
Wheeled dozers, wheeled loaders, wheeled excavator-loaders, dumpers, graders, loader-type landfill compactors, combustion-engine driven counter-balanced lift trucks, mobile cranes, compaction machines (non-vibrating rollers), paver-finishers, hydraulic power packs	$P \leq 55$ $P > 55$	104 $85 + 11 \lg P$	101 $82 + 11 \lg P$ [c]
Excavators, builders' hoists for the transport of goods, construction winches, motor hoes,	$P \leq 15$ $P > 15$	96 $83 + 11 \lg P$	93 $80 + 11 \lg P$

[a] as from 3 January 2002
[b] as from 3 January 2006
[c] The figures for stage II are indicative only for the following types of equipment: Dozers (steel tracked); Loaders (steel tracked > 55 kW); Combustion-engine driven counterbalanced lift trucks and Compacting screed paver finishers

Definitive values in table 14 will depend on amendment of the Directive following the report required in Article 20(1) (EC, 2000). In the absence of any such amendment, the data for stage I will continue to apply for stage II. Moreover, The permissible sound power level shall be rounded to the nearest whole number (less than 0.5 use lower number; greater than or equal to 0.5 use higher number).

The noise directive contains requirements also for a lot of equipment for which no noise limits apply. For such equipment the manufacturer is obliged to establish the noise level, to guarantee the noise level, to inform the Commission and the member state in question about the guaranteed value, and to mark the equipment with the guaranteed value. The idea with these requirements was to collect noise-data that would facilitate for a future limit-value to be set. So far, the Commission has not collected and analysed such data in the intended way.

According to the EU Commission Directive 2000/14/EC (EC, 2000) noise from certain equipment for use outdoors (e.g., compressors, dozers, excavating-loaders, mobile cranes and lawnmowers) shall have a guaranteed sound power level, whereas other equipment are subject to noise marking only (e.g., chain saws, concrete mixers, refuse collection vehicles). The directive has been implemented in two steps, in January 2003 and January 2006 respectively, where the permissible sound power level is sharpened over time.

The manufacturer of a machine is responsible for fulfilling the provision of Machines and certain other Technical Appliances (AFS 1994:48). In this, noise is treated as: Machines should be constructed and manufactured so that risks related to emissions of airborne noise are reduced to lowest possible level, taking into consideration technical advances and availability of appliances to reduce noise, primarily at the source.

4.2.2 Recorded noise levels

Typical noise levels recorded at type approval has been complied by The Swedish machinery testing institute for different types of non-road mobile machinery. For tractors the current directive for noise emissions came into force in 1974 and has not been amended since then. Recorded noise levels in "A" weighted sound power level (L_{WA}) for tractors for different model years are presented in figure 4. The data were based on measurements preformed according to the regulation stipulated by the Organisation for economic co-operation and development (OECD) and thus recalculated from the originally recorded sound pressure level.

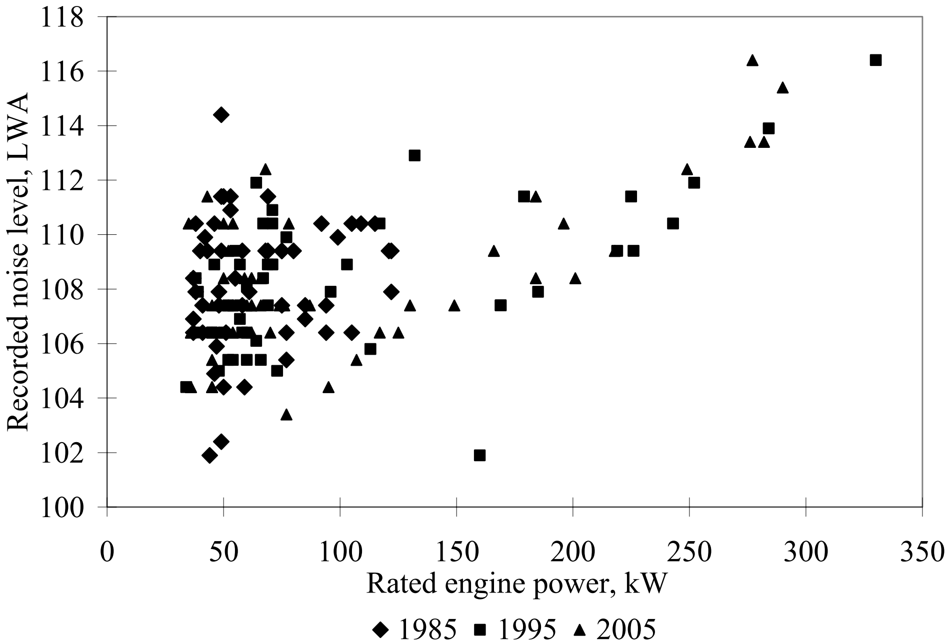

Figure 4. Recorded L_{WA} noise levels for tractors of model years 1985, 1995 and 2005.

Based on the data in figure 4, a second-degree polynomial was derived and further used for estimations of noise levels within the present study. It was assumed that the emissions of noise from tractors were independent of the age of the machinery. Emissions of noise from combined harvesters and harvesters were set to the same level as tractors on account of limited amount of data available for combined harvesters and harvester. Furthermore, emissions of noise from forwarders were approximated with the noise emissions from an articulated hauler, a construction equipment used for transportation of materials in similar manners as forwarders.

In contrast to tractor construction equipment has been subject to noise directives including amendments the past 20 years. However, the present compilation of recorded noise levels only extends over the time period from 1995 to present time. Recorded noise levels pre-1995 were assumed to be 3 dB higher compared with the 1995 level for all types of construction equipment. In table 15 to 20, recorded noise levels are presented for various types of construction equipment and power ranges.

Table 15. Recorded noise levels for wheel loaders

	Rated engine power range		
Model year	37-75 kW	75-130 kW	130-560 kW
1995-1996	103	105	107
1997-1998	103	106	108
1999-2000	100	103	106
2001-2005	102	105	107
2006-	100	101	106

Table 16. Recorded noise levels for backhoe loader

	Rated engine power range		
Model year	37-75 kW	75-130 kW	130-560 kW
1995-2000	103	107	-
2001-2005	102	102	-
2006-	99	103	-

Table 17. Recorded noise levels for crawler and wheeled excavators

	Rated engine power range		
Model year	37-75 kW	75-130 kW	130-560 kW
1995-2000	100	102	107
2001-2005	100	103	106
2006-	98	101	106

Table 18. Recorded noise levels for articulated haulers

	Rated engine power range		
Model year	37-75 kW	75-130 kW	130-560 kW
1995-2000	-	108	114
2001-2005	-	105	111
2006-	-	102	108

Table 19. Recorded noise levels for mobile cranes

	Rated engine power range		
Model year	37-75 kW	75-130 kW	130-560 kW
1995-2000	-	103	104
2001-2005	-	103	104
2006-	-	101	101

Table 20. Recorded noise levels for trucks

	Rated engine power range		
Model year	37-75 kW	75-130 kW	130-560 kW
1995-2000	105	109	111
2001-2005	102	106	108
2006-	102	106	108

Recorded emissions of noise from skid steer loaders were assumed to correspond to recorded emissions of noise from wheel loaders with a rated engine power of less than 75 kW. The category of other machinery was approximated with the average value of all construction equipment.

4.2.3 Annual emissions of noise

Annual emissions of noise from the Swedish assembly of machinery were derived according to a modified method presented by Johansson et al., (2002) as presented in equation 4

$$LS_{WAR} = 10\lg\sum_{i=1}^{\theta} veh_i \frac{Hr_i}{8760} 10^{0.1L_{WA_i}} \qquad \text{Equation 4}$$

where LS_{WAR} was total sound power level in dB(A) 1pW^{-1}, veh_i was number of machines, Hr_i was annual use in hour, L_{WAi} was permissible sound power level per machinery in dB(A) 1pW^{-1} and θ was number of subcategories.

The resulting sound power level from equation 4 gave an abstract noise level as the non-road mobile machinery included were scattered in both time and space. However, the equation could be utilised to study relative effects on the resulting sound power level of different measures to reduce the permissible sound power level for specific types or model years of non-road mobile machinery. Besides the study of total sound power level from the entire Swedish assembly of machinery, a case study of a specific construction site was conducted.

4.2.4 Case study noise

The case study was performed during the spring 2007. Observations of non-road mobile machinery were recorded at two times in mid March; one Friday and one Tuesday. The construction work was at this time focused on the underground passage, linking the east and west side of the train station. The nearest residential buildings were situated 80 - 150 m from the excavation pit.

The observed non-road vehicles were thereafter classified and assigned a rated engine power and a noise level representing an average type and age of machinery. The defined noise from each vehicle was aggregated into a single noise level emitted from the construction site, assuming the vehicles were close enough to each other to be included in the same point source of noise.

The Uppsala travel centre is one of the largest construction projects ever in the city of Uppsala, aiming to modernize the city's central railway station and bus terminal. The purpose of this reconstruction is to increase traffic capacity, enhance passenger safety and availability as well as to fit in new buildings in this central area. A map describing the construction site is presented below in figure 5.

The construction work started during the autumn 2005 and will continue until December 2011. The project has a commitment to disturb neighbouring citizens and travellers as little as possible. Another intention of the project is to carry out the work in an environmentally friendly manner, and for this purpose the municipality of Uppsala has produced an environmental management plan. In this, targets are defined relating to different areas:

- Emissions to air, soil and water
- Noise and vibrations
- Management of chemicals and waste
- Protection of ground water aquifers
- Protection of wild life
- Verification of target fulfilment

The target for Noise and vibration is divided into some sub-targets:

- Measurements of noise and vibrations should be carried out during the entire construction phase
- Noise and vibrations should not exceed recommended levels defined by the Swedish Rail Administration (Banverket)
- Noisy work, such as excavation, pole driving and grooving should be performed on work days between 07:00 and 18:00
- Transport roads should be maintained in good condition; pot holes should be filled in order to decrease noise

Figure 5. Site plan of Uppsala travel centre.

The results from the observations are presented below in table 21. The activity at the constructions site was generally much higher during the Tuesday than the Friday, when many construction workers had left for the weekend.

Table 21. Observations of non-road vehicles at the case study construction site.

Time of observation	No. of vehicles	Type of machinery
Friday, 9 March, 2007; 13:00	3	Crawler excavator
	1	Wheel excavator
	1	Wheel loader
	2	Mobile crane
Tuesday, 13 March , 2007; 12:30	3	Crawler excavator
	5	Wheel excavator
	2	Articulate haulers
	1	Wheel loader
	2	Mobile crane

The observation site was situated at a residential building approximately 100 meters from the construction site and 5 meters above the ground.

Besides the observations of machinery activity and number a second study was performed at the Uppsala travel centre construction site. Two independent measurements of A-weighted sound power level were conducted on an ordinary workday and on a weekend, Tuesday and Saturday respectively. A sound level meter from Brüel and Kjær was utilised and one-minute integrated sound level was logged for at least 24 hour at each occasion. The measured sound level was utilised for both establishing background noise levels and verifying the theoretical calculated sound level based on the observations described above.

5. EMISSION REDUCING MEASURES

Lindgren (2007) has described a method for estimating annual fuel consumption and emissions from non-road mobile machinery in Sweden for year 2006. By employing the model presented by Lindgren (2007) fuel consumption and emission amounts can be estimated for forthcoming years. In the present study estimates of annual fuel consumption and emission amounts were conducted for the period from 2006 to 2020. The estimates were for example based on current and forthcoming emission regulation and the age and number distribution of different types of non-road mobile machinery. Several different measures can be conducted in order to affect the annual fuel consumption and emissions amounts. The following approaches were studied:

- Scrappage program
- Alternative fuels
- Voluntary emission regulation program
- Exhaust gas aftertreatment equipment
- Noise reduction measures
  - Vamil
  - Bauer Engel

The active scrappage approach effected the age and number distribution of machinery while the other three approaches had an effect on the brake specific emissions and fuel consumption matrices. Depending on the solution chosen and the timescale for implementation the various approaches will result in different reduction potential and costs. Only the additional cost associated with each approach were calculated, for example only the scrappage incentive cost were included thus not the replacement of new machinery.

5.1. Scrappage program

All machines, independent of age within the population of non-road mobile machines as presented above contributes to the overall emissions. Furthermore, older machines emits more pollutants per kWh work produced compared with newer machines due to both less strict emission regulations and to increased wear of the engine. For example, in 2014 an 17 years old engine, model year 1998, will emit up to about 30 times as much particulate matter and nitrogen oxide as a new engine that fulfils the emission regulation according the stage IV.

By active retirement or hasten the scrappage of older machines, the overall emissions from the non-road mobile machine sector can be reduced. In a study of the vehicle population in southern California Dixon and Garber (2001) showed that vehicles older than 15 years contributed to about 40% of the overall pollutants from the vehicle population. Moreover, vehicles older than 15 years only accounted for approximately 11% of the total mileage travelled.

One way to introduce active retirement or scrappage of machines is a voluntary accelerated vehicle retirement programs as described by BenDor and Ford (2006). Such programs could use fees imposed on new vehicle sales to finance the scrappage payment. Within this study only the scrappage payment is considered. The effect of a scrappage program is closely related to both the age distribution of the vehicle fleet under consideration and the portion of potential participants. Alberini et al. (1996) has estimated the portion of vehicle owners that will participate in a scrappage program as a function of scrappage payment. At a scrappage payment of $1300 or approximately 5% of the purchase price of the vehicle when it was new, roughly half of the vehicle owners will agree to scrap their vehicles (Alberini, 1996; Kavalec and Setiawan, 1996). A 10% scrappage rate correspond a scrappage payment of 2.5% of the price of the new vehicle.

The amount of vehicle scrappage as a function of relative payment within the model was derived from a payment response curve derived from Alberini (1996), see figure 6. The relative payment was calculated as payment divided by the purchase price of the machine when it was new. The relation described is only valid for machines already written off.

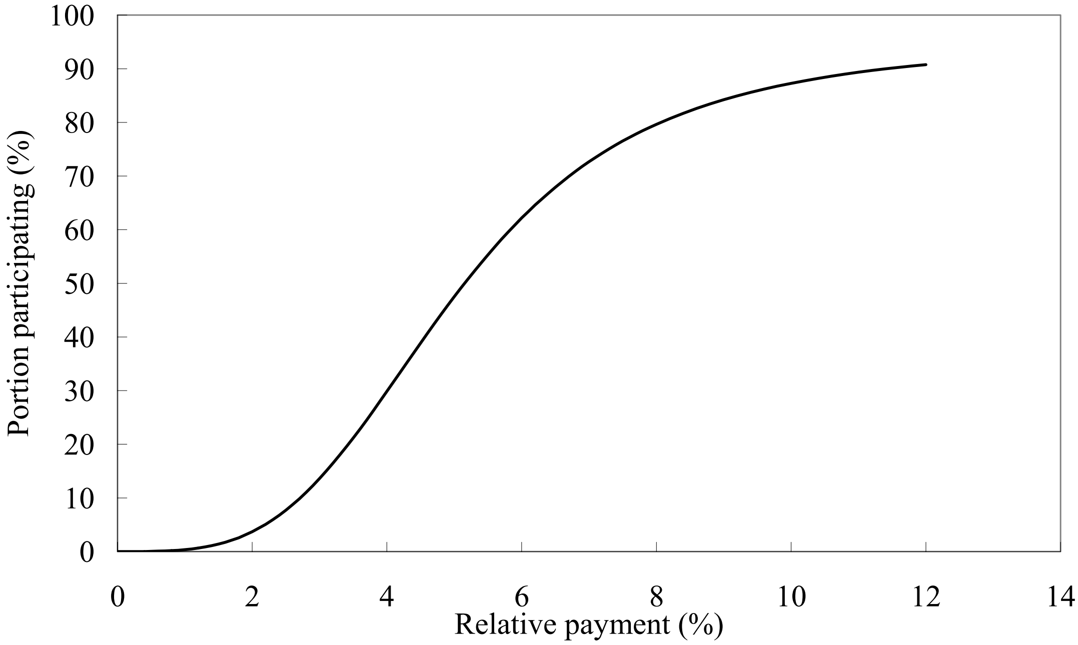

Figure 6. Portion of participating machine owners in a scrappage program as function of relative payment.

The number of actively retired machines annually veh_{ret} was calculated by:

$$veh_{ret} = \sum_{i=y-24}^{y-\delta} veh_i \times p_p \qquad \text{Equation 5}$$

where veh_i was the number of machines of model year i still in service at year y, δ was minimum age of the machine to be entitled to the scrappage payment and p_p was portion of participating machine owners in percent.

The total payment for all machines actively retired Cv_{ret} in SEK was calculated as:

$$Cv_{ret} = veh_{ret} \times S_p \times (Cv_p)_i \qquad \text{Equation 6}$$

where Cv_p was purchase price of a new machine of model year i in SEK. The relative payment S_p was derived by:

$$S_p = 0.05 \times \left(\frac{95}{95 - p_p} - 1 \right)^{\frac{1}{3.5}} \qquad \text{Equation 7}$$

Within the model, the amount of work produced by the active retired machines was entirely replaced by new machine. However, only the scrappage payment for the active retired machines was calculated not the investment in new machinery.

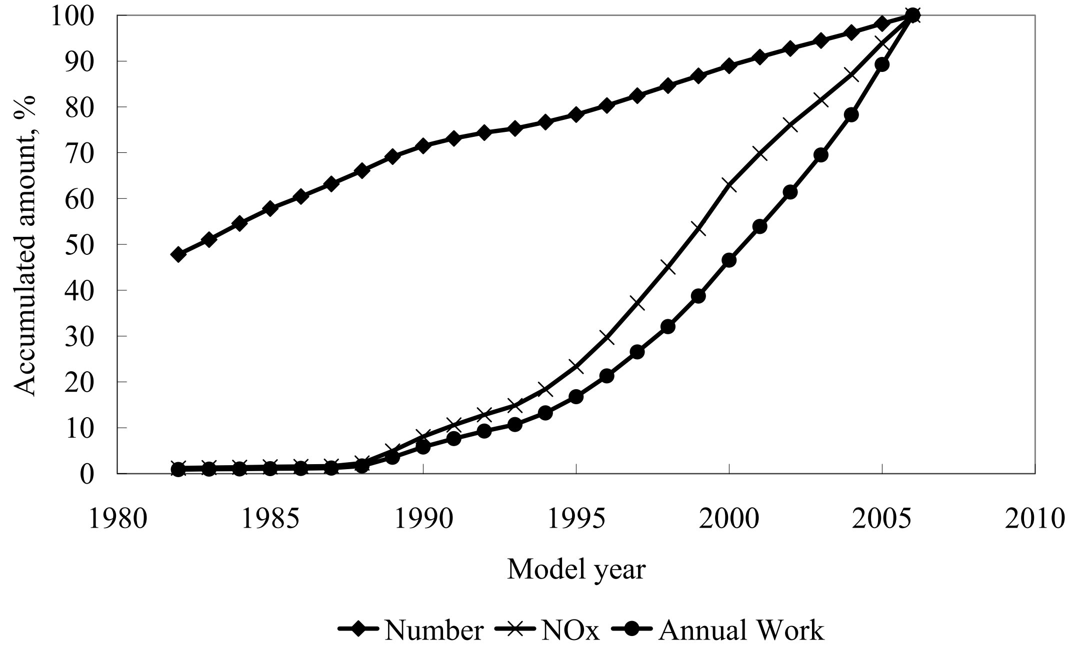

Figure 7. Accumulated amount of number of units, emissions of NO_x and annual work as function of model year for agricultural and forestry machinery including other types of tractors

However, for non-road mobile machinery the situation was different compared with on-road vehicles, especially for agricultural and forestry machinery including other tractors. Approximately 75% of all agricultural and forestry machinery including other types of tractors has an age of 15 year or more as shown in figure 7. The corresponding portion of construction equipment was only 32%.

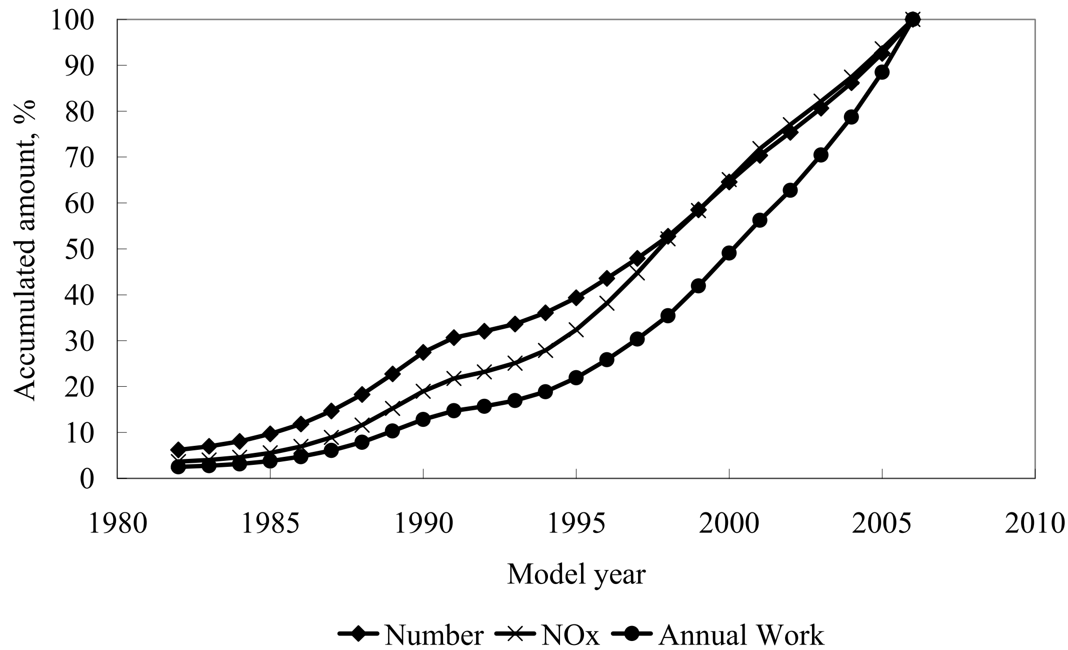

Figure 8. Accumulated amount of number of units, emissions of NO_x and annual work as function of model year for construction equipment

The portion of the overall annual work from agricultural and forestry machinery including other types of tractors produced by machinery of an age of 15 year or more accounted for less than 10%. For construction equipment machinery older than 15 year accounted for almost 16% of the overall annual work as shown in figure 8. The share of the annual work produced by machinery older then 15 years was similar to the annual mileage travelled by on-road vehicles as described above. However, there were a large difference in the contribution to the overall emissions from non-road mobile machinery and on-road vehicles. While on-road vehicles with an age of 15 years or more accounted for approximately 40% of the overall emissions, the corresponding data for their non-road counterparts was only around 20%.

The active scrappage function described above might result in that a significant number of non-road mobile machinery is taken out of duty. However, old machinery will most likely be overrepresented and thus might results in a high cost and low effect as old machinery only marginally contribute to the overall emissions from the entire assembly of machinery.

A secondary scrappage function was developed with an aim to increase the rate of turnover of machinery, i.e. reduce the average lifetime in order to increase the introduction of new machinery with increased emission performance. In the model, this was done by reducing the estimated average lifetime employed in the scrappage function described in equation 2. In figure 9 the scrappage function for a crawler excavator with a normal average lifetime of 10 years are presented together with a corresponding scrappage function where the average lifetime has been reduced with one year.

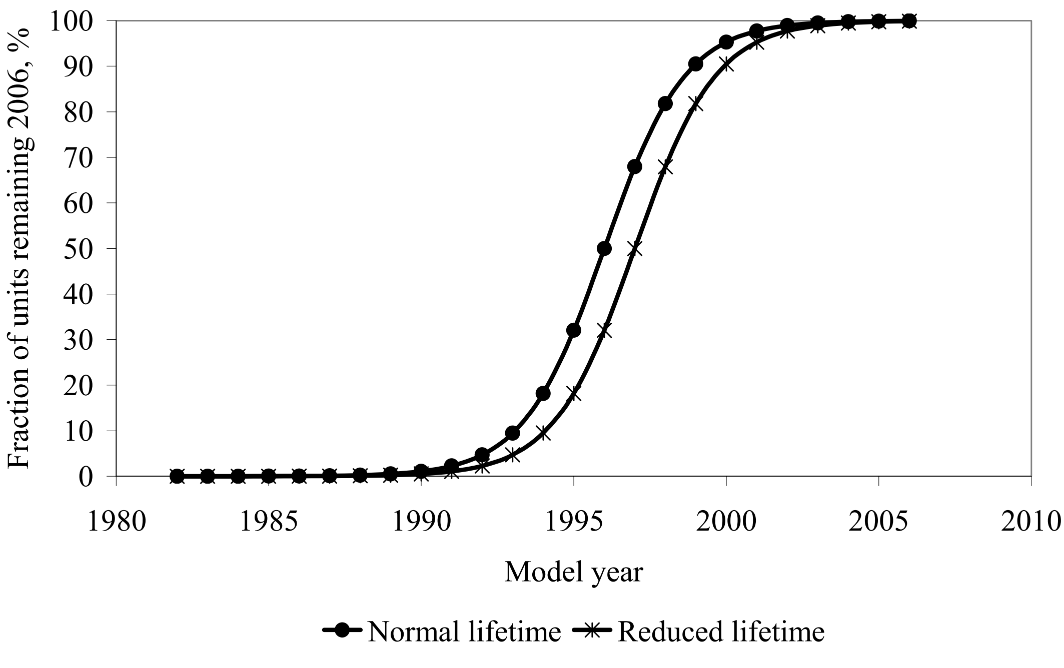

Figure 9. Fraction of remaining units of different model years at year 2006 for two different average lifetimes

By reducing the average lifetime, an increased portion of machinery at an intermediate age will be removed prematurely compared with the previously described scrappage program. The means of control of such a program would probably be some type of tax relief or investment subsidy for new machinery. No literature concerning governmental subsidy programs for non-road mobile machinery has been identified and thus the same relative payment function as described above was employed.

5.1.1 *Vehicle purchase price*

In order to calculate the payment for actively retired machines, the purchase price of new machines of different model years had to be estimated. Within the yearbook of agricultural statistics in Sweden average annual purchase price for agricultural tractors are presented (Statistics Sweden, 2005). Data over average annual purchase price were obtained for each year from 1980 to 2004 (Statistics Sweden, 1981 to 2005).

The average annual purchase price of an agricultural tractor had increased from about 100 000 SEK in 1980 to approximately 500 000 SEK in 2004, a fivefold increase. Moreover, the annual purchase prices of tractors from 1980 to 2004 were recalculated into the money value of year 2006, which was the base year of the study. As shown in figure 10, the difference in average annual purchase price between 1980 and 2004 was only about 200 000 SEK, barely a 100% increase in price. Especially between 1980 and 1990 there was a marked difference between the annual purchase price and the purchase price recalculated in the money value of 2006.

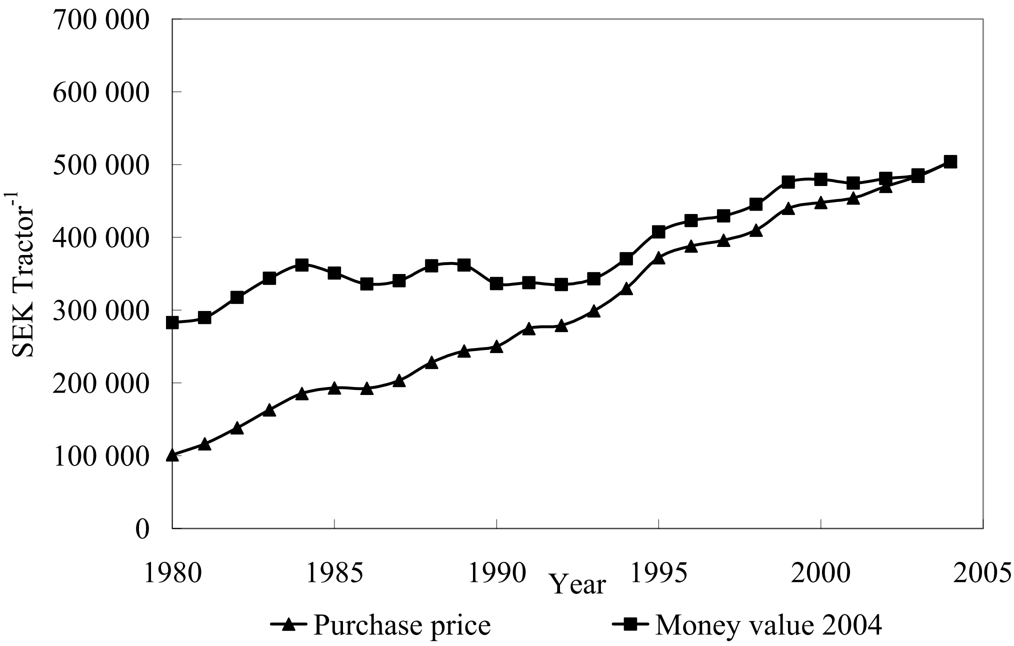

Figure 10. Average purchase price for agricultural tractors for the period of 1980 to 2004 both as annual price and in the money value of 2006.

However, during the period of 1980 to 2004 the average rated power of agricultural tractors has shown a minor increase, about 30 kW or 1.2 kW per year. Average purchase price per kW rated engine power in the money value of 2006 were calculated by combining the data in figure 10 above with data about average rated engine power and number of machines. Figure 11 shows average annual purchase price per kW rated engine power and a linear trend.

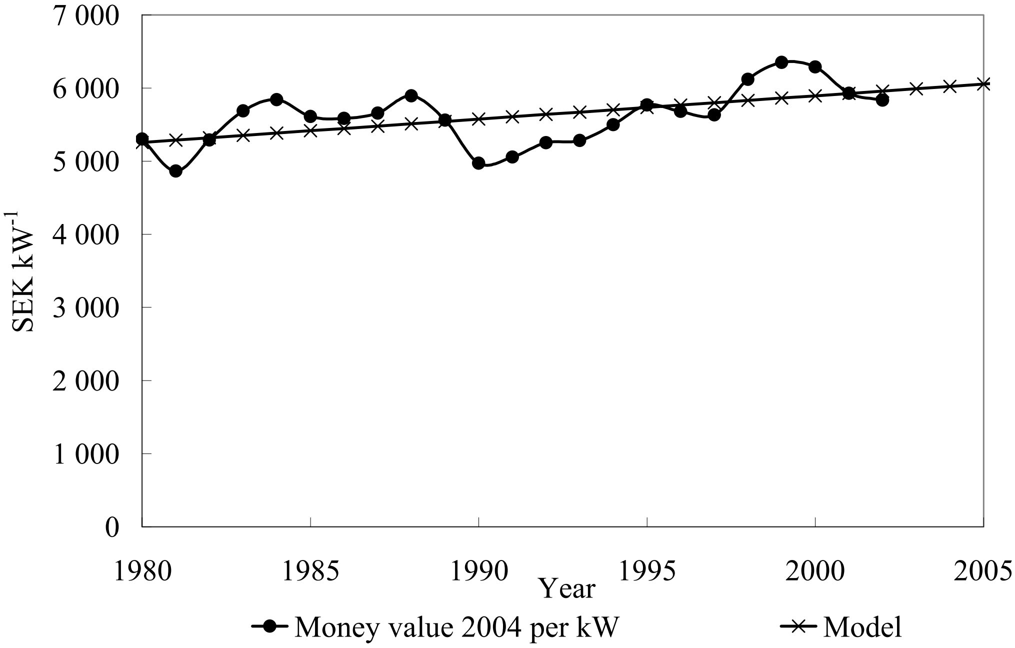

Figure 11. Average annual purchase price in SEK per kW rated engine power.

The linear trend was used as a model to estimate the average purchase price in SEK per kW for different rated engine power and model years as function of model years. The increase in cost per kW with time was for example an effect of increased cost of labour, material and more technically advanced machines.

Moreover, The model was adapted to estimate the annual purchase price for any type of machine and model year between 1982 and 2020 provided that the annual purchase prices was known for one optional year as shown in equation 8.

$$Cv_p = \frac{32 \times (1982 + y_1 - 1) - 57960}{32 \times y_2 - 57960} Cv_y \qquad \text{Equation 8}$$

where Cv_p was purchase price in SEK unit^{-1} at year y_1, and Cv_y was purchase price in SEK unit^{-1} at year y_2.

5.2. Alternative fuels

One method to affect the emissions from non-road mobile machines is to introduce alternative fuels, both from a fossil and renewable origin (BIOFRAC, 2006; EUCAR, 2006).

The aim of the Commission of the European community's Green Paper 'Towards a European strategy for the security of energy supply' is that alternative fuel will supersede conventional fuel based on fossil raw materials by 20% by the year 2020 (EU, 2003). Within Directive 2003/30/EC it is also stipulated that the member states should ensure that a minimum proportion of biofuels and other renewable fuels is to be found on their markets (EU, 2003). By the year 2006 a minimum of 2%, based on energy content should be on the market. Corresponding proportions by the year 2011 is 5.75%. This could be realized by introducing either pure biofuels, high concentrations in mineral oil derivatives or as biofuels blended in mineral oil derivatives in accordance with the fuel regulation EN590:2004 (EU, 2003).

Within this project, the effects of the following alternative diesel fuel or fuel blends were investigated. Firstly, a bio diesel based on either a 2% or a 5.75% fatty acid methyl ester (FAME) blend in conventional diesel fuel. The FAME in consideration was rapeseed oil.

Secondly, a unblended FAME fuel produced from rapeseed oil, RME, and finally, a synthetic diesel fuel, which have been produced from biomass. Fuel consumption and emission amount relative to conventional diesel fuel of environmental class 1 from the pure RME and the synthetic diesel fuel is presented in tables 22 and 23, respectively.

Emission data for the use of rapeseed methyl-ester (RME) in heavy-duty vehicles was presented by Uppenberg et al. (2001), STEM (2001), Hansson et al. (1998), Åsman (2005) and Aakko et al. (2000). However, the result form Uppenberg at al. (2001) and STEM (2001) were based on a lifecycle perspective i.e. all emissions from the well to the wheel were included while the other studies reported engine emissions only. The data in table 22 shows that the production of the feedstock and subsequent production of the RME fuel considerably contributes to the overall emissions thus makes the resulting emissions from RME to exceed the emissions amount from EC1 diesel fuel. Therefore, only the engine emissions were included in the model. However, in a global perspective lifecycle emissions would be more appropriate.

Table 22. Emissions from RME relative to EC1-diesel fuel

	Lifecycle emissions		Engine emissions			
	Uppenberg et al. 2001	STEM, 2001	Hansson et al. 1998	Åsman 2005	Aakko et al. 2000	Model
Fuel	1.00		1.17		1.15	1.16
CO	1.00	2.38	1.00	0.83	0.75	0.86
HC	1.00	0.95	0.56	0.45	0.38	0.46
NO_x	1.15	1.21	1.19	1.27	1.33	1.26
PM	1.00	1.08		0.67	0.54	0.60

Engine exhaust gas emissions or tailpipe emissions of CO_2 from the use of RME were derived through a life cycle perspective. About 3.87 g of CO_2 was produced per MJ of RME consumed or about 1/19 of that of conventional diesel fuel according to Bernesson (2004). Most bio diesels, such as RME, contain virtually no sulphur at all (Knothe et al., 2005). However, according to the product specification of a Swedish commercial RME fuel the maximal sulphur content is less than 10 ppm, which is comparable with commercial diesel fuel (OKQ8, 2006a).

Emission data for the RME and diesel blend was weighted from the data in table 22 and the share of RME in the biofuel mix as shown in equation 9.

$$E_{blend} = 1 - z + zRME_{rel} \qquad \text{Equation 9}$$

where E_{blend} is the emission of an optional pollutant relative to a conventional diesel fuel for the biodiesel blend, z is the share of RME in the biodiesel blend and RME_{rel} is the emissions of the same pollutant relative to a conventional diesel fuel for a pure RME fuel.

Emission data for emissions from a FTD fuel were derived from two Swedish studies (Nord and Haupt, 2002; Wetterberg et al., 2003) and two international studies (Clark et al., 1999; Schaberg et al., 2000). In both Swedish studies conventional diesel fuel of environmental class 1 was used as a reference fuel, while Schaberg et al. (1999) and Clark et al. (1999) used California diesel fuel as a reference fuel. Emissions from the California diesel fuel were modified due to the differences in fuel quality or specification compared with Swedish diesel fuel of environmental class 1.

Wetterberg et al. (2003) studied the effects of FTD fuel on three different engines for non-road mobile machinery. The engines differed in model year, displacement, fuel injection system, number of cylinders and power. However, Wetterberg et al. (2003) only find minor effects of FTD fuel on emissions and fuel consumption compared with conventional diesel fuel, thus the average data for the three engines are presented in table 23. The most pronounced difference was on particulate matter emissions from one of the engines, which was much lower compared with the other tests.

Table 23. Fuel consumption and emissions from FTD relative to EC1-diesel fuel

	Wetterberg et al. 2003	Nord & Haupt 2002	Schaberg et al. 2000	Clark et al. 1999	Model
Fuel	0.99		0.99	0.99	0.99
CO	1.00	0.97	0.67	0.82	0.86
HC	0.88	0.85	0.78	0.57	0.77
NO_x	0.98	0.93	0.96	0.95	0.95
PM	0.95		0.85	0.94	0.91

Emissions of CO_2 per MJ of Fischer-Tropsch diesel fuel consumed were according to Clark et al. (1999) 70 600 mg. Corresponding data for conventional diesel of environmental class 1 was 74 000 mg MJ^{-1} (Uppenberg at al., 2001). However, in a life cycle perspective emissions of CO_2 from a FTD fuel based on a biomass feedstock would be much lower. An analysis of a commercial Fischer-Tropsch fuel in Sweden showed that the sulphur content was 1 ppm or 50% of that normally occurring in conventional diesel fuels in Sweden (Wetterberg et al., 2003). The fuel price including taxes and VAT for the different fuels are presented in table 24.

Table 24. Fuel price including taxes and VAT

Fuel	Fuel SEK $litre^{-1}$
Diesel, EC1	11.16
RME	10.45
FTD	12.99

All data in table 24 is based on the buyers purchase price at the filling station on the 22 of March 2006 (OKQ8, 2006b; SVJ, 2006). Taxes and VAT is based on Swedish laws and includes both carbon dioxide and energy taxes (SFS, 1994). Currently, alternative fuels based on a renewable feedstock such as RME could apply for tax relief, thus reduces the cost to a level comparable with conventional fuels. For RME the lost revenue for taxation for the Government would correspond to approximately 4.58 SEK $litre^{-1}$ including VAT compared with EC1 fuel, which has been included in the simulations.

The price for the RME and diesel blend was weighted together from the price of pure RME and conventional diesel fuel as shown in figure 12.

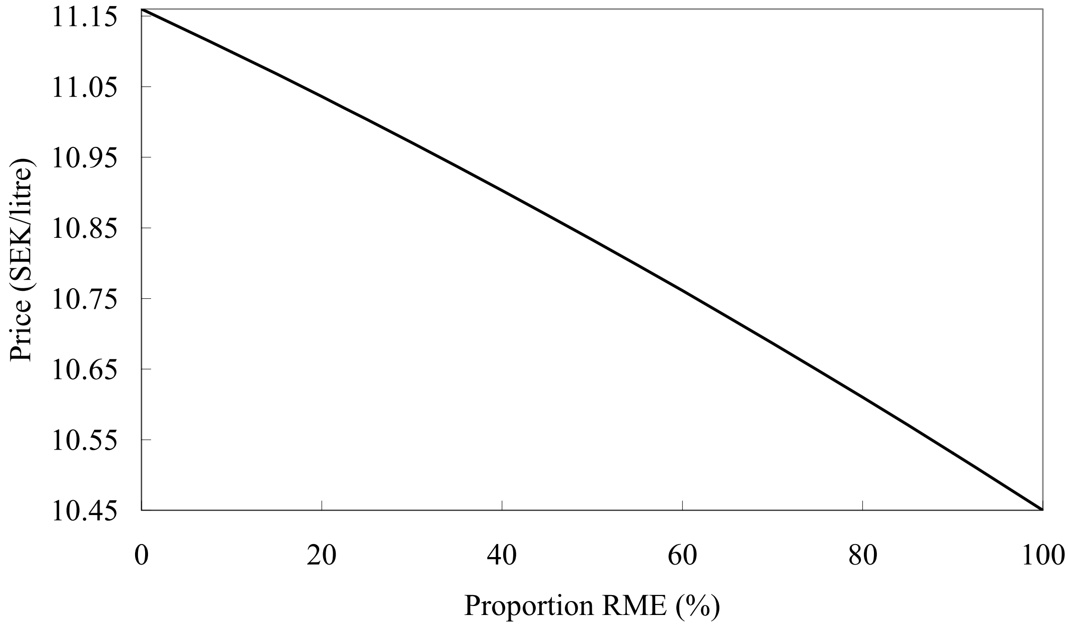

Figure 12. Estimated price of the RME diesel blend as a function of blending condition.

5.3. Voluntary emission regulation program

Engine exhaust gas regulations are an effective way to control and reduce the emissions amounts from different vehicles and engines. Thus by forcing parts of the non-road mobile machinery fleet enter the different steps in the emission regulation in advanced, the overall emissions amounts would be reduced. However, new engine and emission-control technologies are associated with extensive research and development activities and thus costs.

The costs considered within this voluntary emission regulation program were divided into different events associated with the production of new engines and engine equipment to comply with forthcoming emissions regulations. Those events were

- Research and development
- Adjustment of engine production line and tooling
- Certification
- Exhaust gas aftertreatment equipment
  - NO_x control system
  - Catalytic diesel particulate filter (CDPF) system
  - CDPF regeneration system
  - Diesel oxidation catalyst (DOC)
  - Exhaust gas recirculation system
- Machine redesign
- Engine operating
  - CDPF maintenance
  - CDPF fuel economy impacts
  - NO_x control reductant

5.3.1 Research and development costs

The research and development costs are manufacturer related costs for both engine and emissions control equipment. These costs can be further divided into different categories depending on the necessary technology and emissions control equipment to comply with the forthcoming emissions regulation. The different categories were

- Diesel oxidation catalyst (DOC) and engine-out R&D
- Catalysed diesel particulate filter (CDPF) R&D
- NO_x control R&D

The engine-out research and development includes those emissions control technologies that manufacturers are believed to use in order to meet the emissions regulations, such as exhaust gas regulation and improved fuel injection systems. The research and development costs for the above-described categories are described by the US Environmental Protection Agency for different engine sizes (USEPA, 2004b). The data used were based on the total estimated revenues incurred by the manufacturers over the time period stated in the emission regulation divided by the estimated amounts of engine sold over the same period. Moreover, the data were divided on different power categories and emission control technologies. Based on the data presented by the USEPA (2004b) an equation was developed for deriving the R&D costs per engine in SEK as a function of rated engine power for NO_x control.

$$C_{R\&D} = \left(3.23 \times 10^{-2} \times P^2 - 4.32 \times P + 483\right) \qquad \text{Equation 10}$$

where $C_{R\&D}$ was R&D costs for NO_x control in SEK unit^{-1} and P was rated engine power in kW. It was assumed that the average R&D for CDPF was approximately half of that invested in R&D on NO_x control only. Furthermore, it was also assumed that the average R&D for DOC and engine-out was just about half that of CDPF or one fourth that of NO_x control. Figure 13 presents the costs associated with research and development in SEK per unit as function of engine power for research and development in NO_x control equipment, CDPF and DOC/Engine-out respectively.

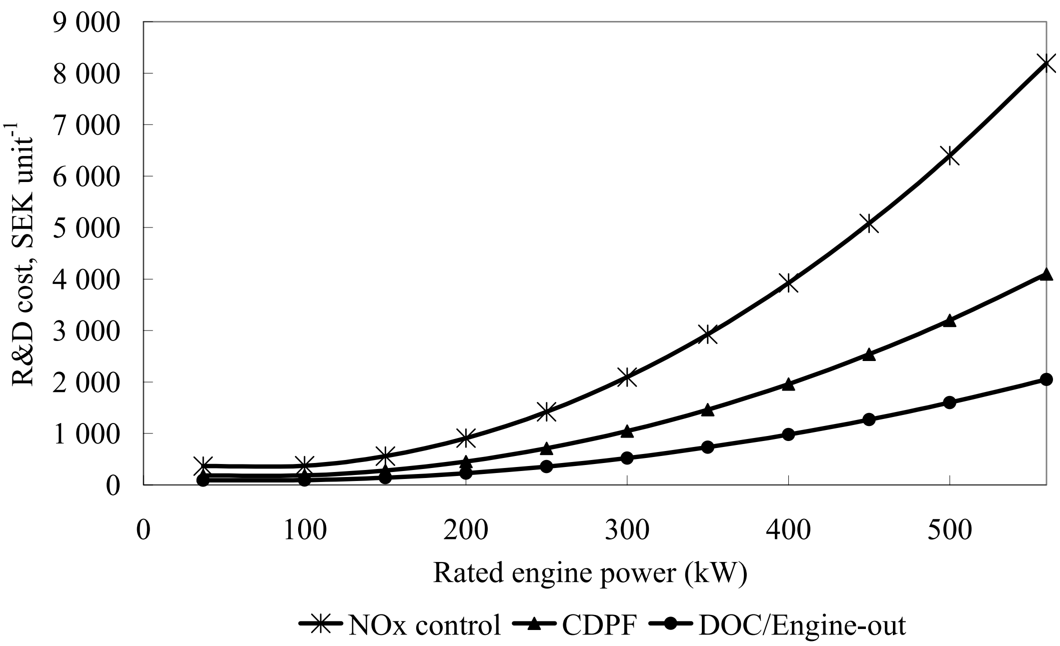

Figure 13. Research and development costs in SEK per unit.

The increased costs with engine size are probably an effect of the limited production numbers of larger machines. For example, according to the USEPA (2004b) less than 3 000 units were sold in the net power region of 450 to 560 kW compared with more than 100 000 units in the net power region of 56 to 75 kW.

5.3.2 *Adjustment of engine production line and tooling*

Besides the research and development of a new engine or engine equipment, adjustments of the engine or equipment production line including new tooling is necessary in order to adapt the construction of the new engine.

It was assumed that the adjustment and tooling related costs were assigned equally between engines with NO_x control and CDPF system (USEPA, 2004b). The tooling costs related to production lines for engines only requiring DOC and engine-out modification was assumed to be half that of NO_x control or CDPF systems.

Based on the data presented by the USEPA (2004b) an equation was developed for deriving the tooling related cost per engine in SEK as a function of rated engine power for NO_x control.

$$C_T = 370 - \frac{310}{1+\left(\frac{P}{-125}\right)^6} - 0.0185(35-P) \qquad \text{Equation 11}$$

where C_T was tooling related costs for NO_x control in SEK $unit^{-1}$ and P was rated engine power in kW. Figure 14 shows that the tooling costs per engine rise rapidly with engine size up to about 200 kW. That is most likely a combined effect of both the number of units sold in different engine sizes and that some manufacturers operates in both the non-road market and the highway market.

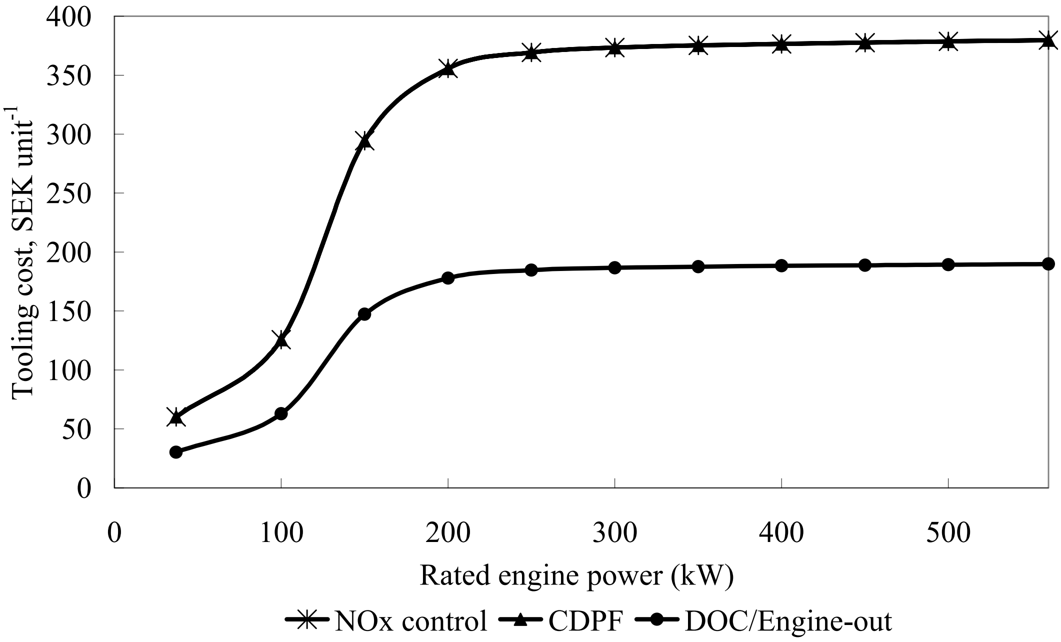

Figure 14. Tooling cost in SEK per unit for NO_x control, CDPF and DOC or engine out modifications

For manufacturers operating in both the non-road and highway market the tooling costs are split on both segments. Those kinds of combined product lines are decreasing with engine size because the largest engines for non-road applications have no highway counterparts.

5.3.3 Certification

The US environmental protection agency has estimated the engine certification cost for each manufacturer to $60 000 for each type of engine or engine family while applying steady state test procedures (USEPA, 2004b). The cost covers both testing and administrative costs and is independent of engine size. In order to comply with transient test procedures an additional $31 500 cost is estimated by the USEPA (2004b). Furthermore, it is assumed that the use of NO_x control and CDPF only coincide with emissions regulations that stipulate the use of a transient test procedure.

Based on the data presented by the USEPA (2004b) an equation was developed for deriving the certification costs per engine in SEK as a function of rated engine power for NO_x control.

$$C_C = \left(1.79\times10^{-8}\times P^4 - 1.45\times10^{-5}\times P^3 + 3.43\times10^{-3}\times P^2 + 1.19\times10^{-1}\times P + 72.2\right) \quad \text{Equation 12}$$

where C_C was engine certification related costs for transient test procedures in SEK unit^{-1} and P was rated engine power in kW.

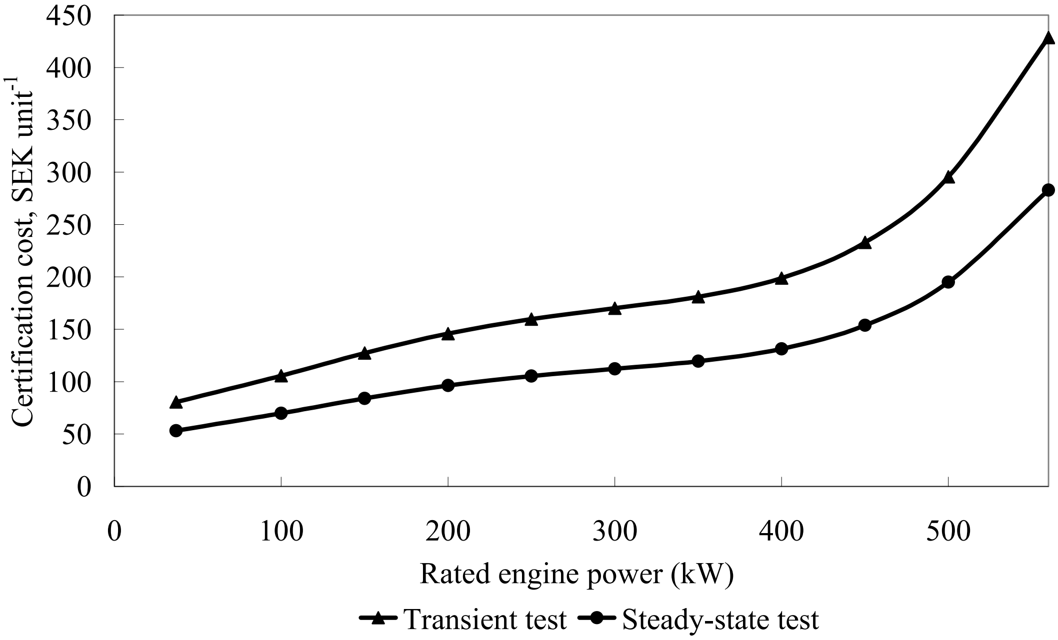

Figure 15. Certification cost in SEK per unit for transient test procedures i.e. NO_x control and CDPF and steady state procedures i.e. DOC or engine out modifications.

The cost associated with steady state test procedures was assumed to be 2/3 of the costs related to the transient test procedure described in equation 12. The resulting certification cost for both a transient and a steady-state test procedure for various rated engine powers are presented in figure 15.

5.3.4 Exhaust gas aftertreatment equipment

Exhaust gas aftertreatment equipment costs were those costs related to new equipment necessary to comply with forthcoming emissions regulations such as NO_x control and catalytic diesel particulate filter systems. There exist a variety of different technologies for reduction of NO_x in the exhaust, for example NO decomposition, selective catalytic reduction (SCR) with ammonia or hydrocarbons and NO_x adsorber-catalyst systems. According to a study by Schittler (2003) a urea-SCR system would be the most cost effective system, taking both equipment and operational cost components such as fuel penalties, urea consumption and maintenance into consideration. In this study only one type of NO_x control system was considered, a urea-SCR. The system consists of

- an oxidation catalyst,
- a hydrolysis catalyst,
- a NO_x reduction catalyst,
- a reductant metering system for ammonia,
- a carrier substrate for the washcoat, and
- a housing material.

As with the NO_x control, there exist many different technologies for reducing particulate matter emissions from diesel engines. However, they all operate according to the same principal, capturing particulate matter emissions through some filtration mechanism. For the diesel particulate filter to function properly the backpressure or the soot load must be kept at a rather low level. In order to keep the backpressure at a low level some kind of regeneration method must be applied.

According to a joint study by the Engine manufacturers association (EMA) and the European association of internal combustion engine manufacturers (EUROMOT) particulate matter filter systems must be fully integrated with the engine and require regeneration that is independent of machine and duty application (EMA, 2002). The regeneration should also be passive *i.e.* occur without the involvement of the operator of the machine. However, the exhaust gas temperature, which is an essential parameter in passive filter regeneration, or the duration of periods with sufficiently high temperatures are too low to support passive filter regeneration for many non-road mobile machinery applications (EMA, 2002; Lindgren et al., 2002; USEPA, 2004b). In order to secure regeneration in all possible non-road mobile machinery applications and duty cycles some form of active regeneration system is necessary. The catalytic particulate diesel filter used for this study consist of

- an oxidation catalyst,
- an active regeneration system,
- a carrier substrate for the washcoat, and
- a housing material.

For less strict emissions regulations i.e. stage III A a diesel oxidation catalyst in combination with exhaust gas recirculation might be a conceivable method. A diesel oxidation catalyst is used in order to reduce the amount of harmful emissions of carbon monoxide, gas phase hydrocarbons and the organic fraction of diesel particulate matter in the exhausts while exhaust gas recirculation can reduce the emissions of nitrogen oxides.

The equipment costs to the buyer for NO_x control, catalytic diesel particulate filter and diesel oxidation catalyst system presented by the US environmental protection agency was assumed to follow a linear trend with rated engine power according to equation 13 (USEPA, 2004b).

$$C_E = kP + m \qquad \text{Equation 13}$$

where C_E was costs for new gas aftertreatment equipment required to comply with new emissions regulations in SEK unit^{-1}, P was rated engine power in kW, k was an equipment dependent slope constant and m was an equipment dependent constant. Cost for material, labour, labour overhead, carrying costs for both manufacturers and dealers were included in the exhaust gas aftertreatment equipment cost.

The equipment dependent slope constant and constant in equation 13 is presented in table 25 for NO_x control, catalytic diesel particulate filter and diesel oxidation catalyst. Both near term and long term costs are presented.

Table 25. Equipment dependent slope constant and constant

Equipment		Slope constant k	Constant m
NO_x control	Near term	46.0	2 036
NO_x control	Long term	36.7	1 772
CDPF	Near term	65.3	977
CDPF	Long term	49.9	745
CDPF regeneration	Near term	4.5	1 481
CDPF regeneration	Long term	3.6	1 119
DOC	Near term	8.2	1 215
DOC	Long term	7.8	1 149
Cooled EGR	Near term	19.1	726
Cooled EGR	Long term	14.7	538

The differences between long and near term cost are due to the fact that manufacturers gain experience in production with time and with increasing series. The gain in experience allows the manufacturers to simplifying both tooling and assembly procedures as well as reducing the complexity of the equipment or parts of the equipment. It was assumed that the near time costs were more accurate for the costs associated with early introduction of exhaust aftertreatment devices while the long time costs were considered to be representative for series production of machines equipped with exhaust after-treatment devices. Therefore, near term costs were used for all equipment studied within the voluntary emission regulation program.

Besides the equipment costs, some other equipment related costs were considered in the total cost analysis *e.g.* cost for bracket, bolts and labour. The total cost related to the mounting of exhaust gas aftertreatment equipment were presented by the US environmental protection agency and derived through equation 14

$$C_M = 1.03P + 95.9 \qquad \text{Equation 14}$$

where C_M was the costs related to mounting of devices for NO_x control in SEK $unit^{-1}$ and P was rated engine power in kW. Costs related to mounting of devices for CDPF was assumed to be equivalent to the costs for NO_x control. Furthermore, the DOC and engine-out equipment related costs were assumed to be negligible *i.e.* the DOC was assumed to replace the existing muffler *etc* (USEPA, 2004b).

5.3.5 Machine redesign

The engine exhaust gas aftertreatment equipment necessary in order to comply with the emission regulation will occupy considerable space within the machine. In order to incorporate the aftertreatment equipment as an integrated part some redesign of the machine will be necessary. Machinery redesign costs were estimated from the expected recovery revenues presented by USEPA (2004b) divided on different aftertreatment technologies and power categories. Estimated machine redesign costs per unit were derived by dividing the total revenues by the expected number of machines sold, equation 15.

$$C_R = 2.69\times10^{-2}\times P^2 + 1.98\times P + 510 \qquad \text{Equation 15}$$

where C_R was non-road mobile machinery redesign recovery costs for NO_x control in SEK $unit^{-1}$ and P was rated engine power in kW. It was assumed that the average redesign cost for CDPF was approximately two-thirds of the recovery cost for NO_x control only. Furthermore, it was also assumed that the average redesign cost for DOC and engine-out was just about one-eights that of NO_x control.

5.3.6 Engine operating costs

With new emissions control technologies the engine operating costs are likely to increase due to increased maintenance, increased fuel consumption or the need of some external reductant. The engine operating costs were regarded as a running cost during the whole lifetime of the machine, while the investment costs described above were considered to be once-for-all costs.

For urea-SCR systems it have been shown that the consumption of 32.5% urea solution is approximately equivalent to 0.67% by volume relative to the fuel consumption for each g kWh^{-1} of NO_x reduced (Tiax, 2003). In the same study, they estimated that the price of urea solution should be comparable to the price of diesel fuel including production, distribution and profit (Tiax, 2003). However, according to Volvo the price of urea solution will be significant lower than the diesel price, about 7.5 SEK $litre^{-1}$ including VAT (TRB, 2005).

It was assumed that the average reduction of NO_x was equivalent to the difference in NO_x emissions between stage III B and stage IV according to the European emission legislation (EU, 2004a). Emission levels for stage III B, stage IV and the assumed reduction of NO_x for different ranges of rated engine power is shown in table 26.

Table 26. NO_x reduction with Urea-SCR system

		37-75 kW	75-130 kW	130-560 kW
Stage III B	g kWh^{-1}	3.3[a]	3.3	2.0
Stage IV	g kWh^{-1}	0.4[b]	0.4[b]	0.4
Reduction	g kWh^{-1}	2.9	2.9	1.6

[a] Based on the 56-75 kW power range
[b] Based on the 56-130 kW power range

Moreover, the fuel consumption will decrease with the use of urea SCR compared with previous engine technologies. The decrease is equivalent to the use of urea by volume (Acea, 2003). The reduction of emissions of carbon monoxide, hydrocarbons and particulate matter for a urea-SCR system with a diesel oxidation catalyst was assumed to be equivalent to the reduction necessary to comply with stage IV.

A catalytic diesel particulate filter can reduce the amount of particulate matter in the exhaust with up to 95%. However, it usually varies between 60 and 95% depending on soot load and the relation between the fraction of carbonaceous, sulphate and organic particulate matter (Majewski, 2005). Besides, a CDPF also reduces the emissions of carbon monoxide and hydrocarbons with about 85% and 65%, respectively (DECSE, 2000). The CDPF devices usually consist of a monolith with many small, parallel channels connected through porous walls, which acts as filters. As the exhausts are forced through the filter they will induce a pumping loss corresponding to an increase in fuel consumption with 1% (USEPA, 2004b). It is also assumed that the CDPF system is equipped with a back-up system for active regeneration in order to secure regeneration during extensive periods of low engine load and thus low exhaust gas temperatures. The fuel penalty for the active back-up system was set to 1% analogous with estimates by the US environmental protection agency (USEPA, 2004b). Besides the fuel penalty, maintenance costs will also be added to the overall engine operation costs for CDPF. Catalytic diesel particulate filters should be maintained every 3 000 or 4 500 hours at the most depending on engine size. The maintenance cost was calculated by equation 16

$$C_{O\&M} = A_1P^2 + A_2P + A_3 \qquad \text{Equation 16}$$

where $C_{O\&M}$ was costs for CDPF maintenance in SEK kg^{-1} fuel consumed, P was rated engine power in kW and A_1, A_2 and A_3 were dimensionless constants. Table 27 shows the values of the dimensionless constants in equation 16 for various engine sizes.

Table 27. Maintenance constant for various engine sizes

Engine size	Maintenance constants		
kW	A1	A2	A3
37-130	6.69×10^{-6}	-1.30×10^{-3}	8.05×10^{-2}
130-560	4.14×10^{-8}	-3.48×10^{-5}	9.14×10^{-3}

The diesel oxidation catalyst (DOC) was assumed to have no effects on the fuel consumption. However, a DOC reduced the emissions of carbon monoxide, hydrocarbons and particulate matter with 80%, 60% and 20%, respectively (Harayama et al., 1992; Mogi et al., 1999). Parallel with the use of DOC, exhaust gas recirculation (EGR) was assumed to be utilised to reduce the emission to desirable amounts. An EGR system can reduce the amounts of nitrogen oxide emissions significantly (Khair, 1997).

However, the reduction of nitrogen oxides with EGR has some disadvantages, emissions of carbon monoxide and hydrocarbon and particulate matter emissions increased significantly, unless used in combination with a DOC (Khair, 1997; Abu-Hamdeh, 2003; Khair and Sharp, 2004; Majewski, 2005b). By setting the reduction of NO_x to 55% i.e. the reduction necessary for a stage II engine to comply with the NO_x regulation according to stage IIIA the emissions of carbon monoxide and hydrocarbons increased with approximately 10% each and emissions of particulate matter increased 1.5 times (Khair, 1997; Wagner et al., 2000; Abu-Hamdeh, 2003). However, by combining the EGR with a DOC and engine-out modifications i.e. injection timing control it was assumed that a 55% reduction of NO_x could be obtained while emissions of CO, HC and PM would be as low as with a DOC alone.

No measurable effects on the fuel consumption could be observed compared with previous emission control technologies due to the more favourable trade-off for NO_x-fuel penalty with EGR compared with injection timing alone (Khair, 1997; USEPA, 2000; Majewski, 2005b).

5.3.7 Use of after treatment devices

The uses of after treatment devices are dependent on both regulated emissions levels and the manufacturers choice of technology to meet those emission levels. In order to reduce the number of potential solution or combinations it was assumed that only one type of device or combination of devices will be use for each stage in the European non-road emission regulation. For stage I and II none of the aftertreatment device describe will be used due to the limited need for aftertreatment devices in order to comply with stage I and II. Moreover, at present time both stage I and stage II has already been incorporated. For stage III A it is assumed that the manufacturers will use a combination of engine-out modification, cooled exhaust gas recirculation in combination with a diesel oxidation catalyst. Stage III B introduces a 90% reduction in particulate matter emissions, a limit of 0.025 g kWh^{-1} for all engines from 37 to 560 kW. It is believed that a particulate filter is necessary to comply with the regulation *i.e.* a catalytic diesel particulate filter.

In the most stringent emission regulation so far for non-road mobile machinery, stage IV, NO_x emissions is restricted to a maximum of 0.4 g kWh^{-1} thus it is expected that some type of NO_x after treatment will be utilised. In table 28, assumptions regarding the use of different exhaust gas after treatment devices are shown.

Table 28. Assumptions regarding the use of various emission control technologies

Emission regulation	Emission control technology	Test cycle
Stage I & II	None	Steady-state
Stage III A	Cooled EGR and DOC	Steady-state
Stage III B	CDPF incl. regeneration	Transient
Stage IV	NO_x control	Transient

As shown in table 28 the steady-state test cycle, analogous with the 8-mode ISO 8178 C1 test cycle, will be used for stage III A while the non road transient cycle will be applied for stage III B and stage IV besides the static one (ISO, 1996; EU, 1997; 2000; 2004a; 2004b; 2005). The data in table 28 will be used for deriving all costs associated with the implementation of different engine exhaust gas after treatment devices *i.e.* research and development, tooling, certification, equipment and engine operating costs.

5.3.8 Total costs

The total costs were derived as the sum of the fixed and variable costs. Fixed costs included costs that were independent of the number of machinery participating in the voluntary emission regulation program for example research and development, tooling and certification. The manufacturers needs to bring their entire research and development plan forward in order to be able to fulfil the voluntary emission regulation program independently of the number of units intended to be sold. Furthermore, the actual production costs, i.e. equipment, redesign and operation and maintenance are direct proportional to the number of units sold thus were classified as variable costs.

5.3.8.1 Fixed cost

The fixed costs associated with the voluntary emissions regulation program were derived by the additional costs for the early implementation of different emissions regulations i.e. interest of the total investment. An early introduction of a stage III A engine gives rise to the following additional cost C_{IIIAF} in SEK.

$$C_{IIIAF} = \left(\frac{1}{4}C_{R\&D} + \frac{1}{2}C_T + \frac{2}{3}C_C\right)N_{IIIA} \times \alpha \times \beta \qquad \text{Equation 17}$$

where N_{IIIAF} was number of machinery needed for recover the investment, α was the interest in % and β was the advancement of the emission legislation in years. The fixed costs associated with fulfilling stage III B and stage IV were derived according to the same principals, see equation 17 and 18.

$$C_{IIIBF} = \left(\frac{1}{2}C_{R\&D} + C_T + C_C\right)N_{IIIB} \times \alpha \times \beta \qquad \text{Equation 18}$$

$$C_{IV} = \left(C_{R\&D} + C_T + C_C\right)N_{IV} \times \alpha \times \beta \qquad \text{Equation 19}$$

N_{IIIA}, N_{IIIB}, and N_{IV} was derived as the number of machinery sold during the year of implementation and the following 4 years except for stage IV where the following 6 years were included. This approach was based on the anticipated recovery time for manufacturers according to USEPA (2004b).

5.3.8.2 Variable cost

The variable costs were based on the production and labour costs for equipment and were proportional to the number of units participated in the voluntary emission program. The variable costs for stage IIIA, stage IIIB and stage IV in SEK $unit^{-1}$ are described in equations 20 to 22.

$$C_{IIIA} = C_E + \frac{1}{8} C_R \qquad \text{Equation 20}$$

$$C_{IIIB} = C_E + C_M + \frac{2}{3} C_R \qquad \text{Equation 21}$$

$$C_{IV} = C_E + C_M + C_R \qquad \text{Equation 22}$$

Besides the cost accounted for in equation 21, the cost for the maintenance demands associated with CDPF must be added. The maintenance cost was considered as a running expense and not an investment unlike the other entries in equation 21.

The use of an urea-SCR are also associated with a running expense in form of urea, which must be added to the overall costs. For a 100 kW engine, the resulting cost for fulfilling stage IV, i.e. NO_x control, was about 8 500 SEK $unit^{-1}$. The majority of that cost was associated with equipment and mounting costs, and only a minor part of the overall cost was attributed to research and development and other costs related to the research and adaptation of the production line. However, the research and development cost per machinery are strongly associated with the total number of units produced.

5.4. Retrofit of aftertreatment equipment

One method to reduce harmful pollutants, often considered as cost effective, from old combustion engines is retrofit (Scott et al., 2005). According to the USEPA, the term retrofit includes several different activities such as incorporation of pollution control aftertreatment equipment; upgrading an existing certified engine to a cleaner certified engine; repower older machines with new certified engines and; the use of cleaner fuels. However, within this study retrofit was limited to the incorporation of exhaust gas aftertreatment equipment into existing machinery.

As soon as a new technology is available existing certified engines can be retrofitted. However, the effects in terms of reduced amounts of engine exhaust gas emissions will probably be insignificant and thus costly. By equipping an older, high polluting engine with a device for pollution control, major emission reductions can be obtained.

Two of the technologies described in the voluntary emission regulation program section above were studied in terms of retrofit, namely catalytic diesel particulate filter with active regeneration and selective catalytic reduction. Cooled EGR was not considered as a suitable technology for retrofit. The estimated reduction potential for different verified exhaust aftertreatment technologies are presented in table 29 (Scott et al., 2005; USEPA, 2005b)

Table 29. Reduction potential for aftertreatment equipment

		CO	HC	NOx	PM
CDPF	LCC [a]	60-90	60-90	-	90
	Scott [b]	90	90	-	90
	USEPA [c]	90	93	-	89
	Average	83	84	-	90
SCR	LCC [a]	50-90	50-90	90	30-50
	Scott [b]	70-90	50-90	60-80	25
	USEPA [c]	50-90	50-90	60-90	10-30
	Average	73	70	76	25

[a] LCC, 2005
[b] Scott et al., 2005
[c] USEPA, 2006b

The reduction potential data presented in table 29 are in agreement with the reduction necessary in order for an engine to comply with coming emission regulations. For example for a stage III A engine to comply with the stage III B regulations, emissions of particulate matter must be reduced by approximately 90% which is in alignment with the reduction potential of a CDPF. Moreover, the reduction potential of a SCR is almost 80% of the NO_x, which is in the order of the reduction necessary for a stage III B engine to fulfil the stage IV regulations.

The use of different engine exhaust gas technologies was matched to the engine technology of the machine to be retrofitted. For example if the machine to be retrofitted already fulfils the engine exhaust regulations according to stage III B, *i.e.* CDPF, it would only be possible to retrofit an SCR-system not a second CDPF-system. Retrofit of CDPF would only be possible on pre-stage III B machines and for engine fulfilling stage IV retrofit would not be feasible with any included equipment.

In the model, it would be possible to equip a pre-stage III B engine with both a CDPF and a SCR or only one of them. The emission amounts of PM and NO_x for a pre-stage III B engine equipped with both a CDPF and a SCR would be reduced with approximately 90% and 80% respectively.

5.4.1 Purchase and installation cost

The same cost analysis as presented in the voluntary emission regulation program section couldn’t be used in this section due to different circumstances. The voluntary emission regulation program was based on large production volumes and only accounted for the additional cost for the buyer. Retrofit on the other hand was based on smaller production volumes and installation of exhaust aftertreatment equipment in existing machines not originally designed for that purpose. This was assumed to be associated with higher cost both concerning purchase price and installation cost.

The federal office for the environment (FOEN) in Switzerland has described the cost associated with retrofit of diesel particulate filters for non-road mobile machinery divided in range of engine power (FOEN, 2003). The USEPA and several other organisations have calculated the purchase price for NO_x control systems (McKinnon, 2000; LCC, 2005; Scott et al., 2005; USEPA, 2006c). Average data on the mean cost to user in SEK for different exhaust gas aftertreatment devices are presented in table 30.

Table 30. Mean purchase cost for retrofit of diesel aftertreatment equipment in non-road mobile machinery

		37-75 kW	75-130 kW	130-560 kW
CDPF	SEK machine^{-1}	43 000	59 400	101 600
NO_x control	SEK machine^{-1}	106 000	121 000	151 000

The installation cost including labour, brackets and bolts for retrofitting of a diesel particulate filter in non-road mobile machinery were presented by the FOEN (FOEN, 2003). Moreover, the data presented was divided in range of rated engine power. Installation cost for a NO_x control system was assumed to be equal to that of a CDPF system, see table 31.

Table 31. Installation cost for retrofit of exhaust aftertreatment equipment in non-road mobile machinery

Installation cost		37-75 kW	75-130 kW	130-560 kW
CDPF	SEK machine^{-1}	9 400	12 500	15 600
NO_x control	SEK machine^{-1}	9 400	12 500	15 600

5.4.2 Engine operating costs

Engine operation costs for retrofit of NO_x control and catalytic diesel particulate filters were assumed to be equal to the engine operation costs described above for the voluntary emission regulation program.

5.5. Noise reduction measure

Disturbance of noise from on-road vehicles mainly derives from two sources, firstly engine and transmission noise and secondly road tire noise, including steel tracks. For non-road mobile machinery road tire interaction are of secondary importance due to the rather low transportation velocities of non-road mobile machinery. From steel tracked machinery road tire noise can make a considerable contribution to the overall noise levels from the machinery. Still, noise from the engine and transmission is considered to be the largest problem for non-road mobile machinery besides tool noise or noise arising from the operation of the machinery. However, tool noise is usually not included in the directive regulating noise from non-road mobile machinery (EU, 2000).

Most manufacturers utilises some sort of encapsulating of the engine and transmission in order to reduce noise levels. However, for the purpose of this study the technology used for noise reduction measures were of minor importance. Instead, the interests were centred on the effects and corresponding costs. Several different national and international voluntary noise certification systems exist in Europe whereas two has been used as examples within this study, Blauer engeln and Vamil.

5.5.1 Blauer engel

Blue Angel (Blauer Engel) is a German voluntary tool of environmental policy. Blue Angel for construction machinery is used rather often in public procurements, when work shall be carried out in sensitive urban areas.

For construction machinery it is focused on low noise. In the Ecolabel Jury's roadmap from 2004 to mid-2007 it has the following values compared to 2000/14/EC. In table 32 noise limits for both directive 2000/14/EC and Blauer engel are presented.

Table 32. Noise limits for Directive 2000/14/EC and Blauer engel

Machinery	Directive 2000/14/EC	Blauer engel
Tracked machinery (except for excavators)	87+11 log P	80+ 11 log P Max 101 dB
Graders, loaders, dumpers, mobile cranes.	82 + 11 log P	79 + 11 log P Max 101 dB
Compaction machinery (vibration rollers)	85 + 11 log P	82 + 11 log P Max 101 dB
Excavators	80 + 11 log P	78 + 11 log P Max 101 dB
Welding and power generators	95 + log P	91 dB
Garbage compressors	No value	79 + 11 log P
Road finishing machinery < 300 t h^{-1}	No value	90 dB/ 100 dB
Road finishing machinery > 300 t h^{-1}	No Value	94 dB/104 dB
Mobile concrete mixers < 8 m^3	No value	95 dB
Mobile concrete mixers > 8 m^3	No value	100 dB
Concrete pumps	No value	
< 50 kW		99 dB
> 50 kW		101 dB

The big difference for tracked machines implies that no steel tracked machines can have Blue Angel, except excavators. Tracked dozers and loaders are measured travelling and the tracks create too much noise in itself so the limit value will be exceeded. Excavators is measured stationary only so the track will not have influences on the noise level.

In order to simplify the simulation model it was assumed that the Blauer engel noise certification system reduced the noise levels from non-road mobile machinery with 3 dB in average independently of type of machinery and engine size. Based on information from a large manufacturer of non-road mobile machinery the additional cost for the customer for a midsize wheel loader to fulfil the Blauer engel were almost 20 000 Euro or approximately 1% of the purchase prise. It was further assumed that the cost for reducing the noise level of a non-road mobile machinery with 3 dB corresponded to 1% of the purchase prise of the machinery independently of type and size of the machinery.

5.5.2 Vamil

The Accelerated Depreciation of Environmental Investments Measure (Vamil) was a system in The Netherlands, during the years 1991 to 2003, to give benefit for investments in environmental friendly technologies. It is a tax facility offering companies the opportunity to apply accelerated depreciation on environmentally-friendly operating assets.

Low noise emission on construction machinery was such environmentally-friendly operating asset. The Vamil noise certification system basically aims to reduce the noise limits for European stage II noise limit with one dB. It was assumed that the additional cost for reducing the noise level corresponded to 0.1% of the purchase prise of the machinery. In figure 16 noise limits for European directives together with Blauer engel and Vamil is presented for different engine sizes.

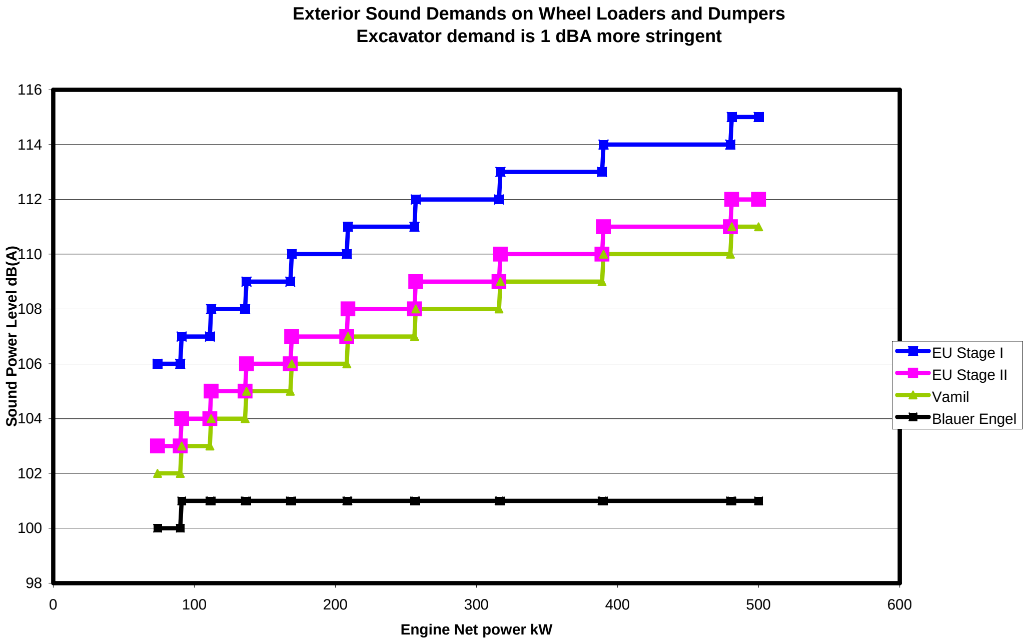

Figure 16. Noise limits for European directive and voluntary noise certification systems.

5.5.3 Noise propagation and costs

For the case-study resulting noise levels at a specific distance away from the construction site, L_p, was calculated based on equation 23 (Johansson et al., 2002).

$$L_p = L_w - \left(10\lg\left(2\pi r^2\right) + L_A + L_B + L_C\right) \qquad \text{Equation 23}$$

where L_w was average noise level at construction site in dB(A), r was distance between construction site and observer and L_A, L_B and L_c was topography dependent reduction factors in dB(A) described in equation 24 to 26 respectively.

$$L_A = 0.035 \times r^{0.75} \qquad \text{Equation 24}$$

$$L_B = fsa\left(2 + 4\left(1 - e^{-0.04r}\right)e^{-0.65h} + e^{-0.65(h_m + 0.75)}\right) \qquad \text{Equation 25}$$

where fsa was fraction sound absorbing soil, h was difference in altitude between machinery and observer in m, and h_m was height of the machinery. For sand, concrete and other high reflecting surfaces normally occurring at construction sites fsa was set to zero.

$$L_C = 3.5 - 3.5e^{-0.04r/(h_m + h_o + 0.75)} \qquad \text{Equation 26}$$

where h_o was the height of the observer site in m.

The average noise level, L_w, for the construction site was calculated in accordance with equation 27

$$L_W = 10\lg\sum_{i=1}^{N}\frac{Hr_i}{8760}10^{0.1L_{WA_i}} \qquad \text{Equation 27}$$

where Hr_i was average annual working hours for machinery i, and L_{WAi} was permissible noise level from machinery i in dB(A).

The resulting costs for retrofitted noise reduction measures were derived based on annual write-off costs together with an assumed write-off period. Besides the cost associated with different noise reduction "packages" noise levels could also by reduced by replacing older unit with high noise levels with new units with lower emissions of noise. The cost for replacement of machinery was derived as the annual surplus cost for the owner of the machinery i.e. as the difference in annual write-offs between the replaced and new machinery. The write-off periods for the machinery were assumed to correspond to the average lifetime while the write-off period for the 1 and 3 dB noise reduction packages were assumed to be one year.

6. SIMULATIONS

Annual fuel consumption, emission amounts, both gaseous emissions and noise, from the Swedish assembly of non-road mobile machinery were calculated for the period of 2006 to 2020. Several different situations were studied.

1. Business as usual
2. Scrappage
   2.1. one year program
   2.2. continuously program
   2.3. reduced average lifetime
3. Alternative fuels
4. Voluntary emission program
5. Retrofit of aftertreatment equipment
6. Noise reducing measures

6.1. Business as usual

In the business as usual (BAU) scenario no active measures to reduce emissions were conducted except for already decided emission regulations such as directive 97/68/EC and 2000/14/EC with amendments (EC, 1997; EC, 2000). The BAU scenario was utilised as a reference scenario, which all other simulations were compared against. The costs for fulfilling the BAU scenario was set to zero SEK and thus costs for all other simulations were derived as excess costs compared to the BAU scenario.

6.2. Scrappage program

Three different scrappage programs were tested. The first was based on a short-term scrappage program only effective one single year, a selective measure. The year to enforce this short term scrappage program could be set to any year between 2006 and 2020 and the portion of machinery participating could be set to an optional level between 0 and 100%. Moreover, the minimum age of machinery participating in this program could be set to any age between 1 and 25 year. In this program focus was on active scrappage of older machinery not to reduce the average lifetime. In table 33 is the value of the variables presented.

Table 33. Values of variables for simulation of scrappage program

Simulation	Year	Portion %	Minimum age year
Scrappage program 1	2010	15	12
Scrappage program 2	2015	15	12
Scrappage program 3	2010	5	12
Scrappage program 4	2010	25	12
Scrappage program 5	2010	15	8
Scrappage program 6	2010	15	15

The second scrappage program tested was based on a continuously program running from 2006 to 2020. Only the portion of machinery participating and the minimum age of the machinery participating could be changed all other variables were fixed. As for the first scrappage program, the program was directed towards the reduction of older units. The variables changed are described in table 34.

Table 34. Values of variables for simulation of scrappage program

Simulation	Portion %	Minimum age Year
Scrappage program 7	5	12
Scrappage program 8	15	12
Scrappage program 9	25	12
Scrappage program 10	15	8
Scrappage program 11	15	15

The third scrappage program was based on a reduction of the average lifetime and designed as a continuously program. All variables except reduction in average lifetime and the portion of machinery participating in the program were set to a fixed value.

Table 35. Values of variables for simulation of scrappage program

Simulation	Portion %	Reduction in average lifetime Year
Scrappage program 12	5	1
Scrappage program 13	15	1
Scrappage program 14	25	1
Scrappage program 15	15	3
Scrappage program 16	15	5

6.3. Alternative fuels

The effects of three different types of alternative fuels on the annual emissions from the assembly of non-road mobile machinery in Sweden were studied within the current project, RME-diesel blend, pure RME and FTD.

For the RME-diesel blend two different blends and two different shares of the market were examined as shown in table 36.

Table 36. Values of variables for simulation of RME-diesel blend

Simulation	RME blend %	Market share %
Alternative fuel program 1	2	25
Alternative fuel program 2	2	50
Alternative fuel program 3	5	25
Alternative fuel program 4	5	50

The second type of alternative fuel program included the usage of pure RME fuel. The effects on emissions and corresponding costs of three different shares of the market for RME were studied as shown in table 37.

Table 37. Values of variables for simulation of RME-diesel

Simulation	Market share %
Alternative fuel program 5	5
Alternative fuel program 6	25
Alternative fuel program 7	50

For the FTD fuel, the same variables as for the pure RME fuel were studied, table 38.

Table 38. Values of variables for simulation of FTD fuel

Simulation	Market share %
Alternative fuel program 8	5
Alternative fuel program 9	25
Alternative fuel program 10	50

All alternative fuel programs were introduced already in 2006 and were into force for the entire studied time frame, i.e. to 2020.

6.4. Voluntary emission regulation program

The voluntary emission regulation program was based on the possibility for manufacturers to fulfil the European emission regulations one or several years in advance, early introduction of engines and machinery that comply with future emission regulations. The costs associated with the voluntary emission program were calculated as surplus costs for the customer.

All emission regulations not already into force were covered by the voluntary emission program. All regulations were brought forward with the same number of years and the portion of non-road mobile machinery participation was also set to constant level. In table 39, the variables utilised in the voluntary emission program is presented.

Table 39. Values of variables for the voluntary emission program

Simulation	Years	Portion participating, %
Voluntary emission program 1	1	25
Voluntary emission program 2	1	50
Voluntary emission program 3	1	75
Voluntary emission program 4	2	50
Voluntary emission program 5	3	50

6.5. Retrofit of aftertreatment equipment

Retrofit of aftertreatment equipment included only two different technologies, catalytic diesel particulate filters and NO_x control equipment i.e. selective catalytic reduction technology by ammonia or urea. The retrofit program was based on three variables for each type of aftertreatment equipment, namely age of the machinery when the equipment must be installed, initial year of the program and portion of the machinery participated in the program. In table 40, the variables for retrofit of CDPF are described.

Table 40. Values of variables for the retrofit program for CDPF

Simulation	Age of machinery	Initial year	Portion participating, %
Retrofit program 1	8	2008	5
Retrofit program 2	8	2008	15
Retrofit program 3	8	2008	25
Retrofit program 4	8	2010	15
Retrofit program 5	8	2012	15
Retrofit program 6	6	2008	15
Retrofit program 7	10	2008	15

The same variables as used for CDPF were also tested for NO_x control as shown in table 41. However, the initial year for the introduction of the retrofit program was delayed with 4 years compared with CDPF, corresponding to the difference between emission regulation Stage III A and Stage III B. Besides, the initial year for retrofit program 11 was set to 2008.

Table 41. Values of variables for the retrofit program for NO_x control equipment

Simulation	Age of machinery	Initial year	Portion participating, %
Retrofit program 8	8	2012	5
Retrofit program 9	8	2012	15
Retrofit program 10	8	2012	25
Retrofit program 11	8	2008	15
Retrofit program 12	8	2016	15
Retrofit program 13	6	2012	15
Retrofit program 14	10	2012	15

6.6. Noise reduction program

For studying the effects of different measures to reduce emissions of noise two different European voluntary noise certification systems were utilised. Both certification systems were slightly simplified in order to make the simulations more straightforward. The first voluntary noise certification systems aimed to reduce emissions of noise from individual non-road mobile machinery with 1 dB whereas the target for the second system was a 3 dB reduction of noise. Several simulations were executed as shown in table 42. Only new machinery was considered, no retrofit of machinery already in use.

Table 42. Values of variables for the noise reduction program

Simulation	Reduction per machinery, dB	Portion participating, %
Noise reduction program 1	1	5
Noise reduction program 2	1	50
Noise reduction program 3	1	100
Noise reduction program 4	3	5
Noise reduction program 5	3	50
Noise reduction program 6	3	100

6.6.1 Case study noise

As a complementary study to the above-described noise reduction program a case study was performed. Both the effects of different model years or ages of the individual machinery and the effects of different noise reducing measures were studied. As a base scenario average type of machinery was utilised as shown in table 43 except for annual work hour, which corresponded to new machinery. The total noise level arising from the construction site at the immission point was derived by equations 20 to 24.

Table 43. Variables for an average Swedish non-road mobile machinery

Machinery	Model year	Rated engine power	Annual work hour
Crawler excavator	2001	120	1 300
Wheeled excavator	1999	100	1 350
Wheel loader	2001	150	1 400
Articulated hauler	1998	200	1 750
Mobile crane	2000	230	1 750

The following simulations were conducted for both for the first observed compositions of non-road mobile machinery at the construction site Uppsala travel centre:

1. All machinery were of model year 2006,
2. All machinery were of model year 2003,
3. Mobile cranes were of model year 2006 whereas the model years of the remaining machinery were in accordance with table 43.
4. A 1 dB reduction of emissions of noise from 3 crawler excavators,
5. A 3 dB reduction of emissions of noise from 3 crawler excavators,
6. A 3 dB reduction of emissions of noise from one wheeled excavator and 2 mobile cranes, and
7. A 3 dB reduction of emissions of noise from one wheel loader.

Observation 2 covered almost 50% more machinery than observation 1, principally some articulated haulers and more wheeled excavators. The simulations conducted for observation 2 are presented below.

1. All machinery were of model year 2006,
2. All machinery were of model year 2003,
3. Articulated haulers were of model year 2006 whereas the model years of the remaining machinery were in accordance with table 43.
4. A 3 dB reduction of emissions of noise from 3 crawler excavators,
5. A 3 dB reduction of emissions of noise from one wheeled excavator and 2 mobile cranes, and
6. A 3 dB reduction of emissions of noise from 2 articulated haulers, and
7. A 1 dB reduction of emissions of noise from all machinery.

7. RESULTS AND DISCUSSION

For the reference scenario, business as usual, no modifications were conducted besides current European emission regulations for gaseous emissions and noise and a natural replacement of old machinery. In table 44 absolute annual emissions amounts including average annual noise are presented for the years 2006, 2013 and 2020.

Table 44. Calculated absolute annual emissions in tonne year^{-1} for year 2006, 2013 and 2020 for the Swedish assembly of machinery

Substance	2006	2013	2020
Number[a]	290 000	250 000	250 000
Fuel	880 000	890 000	900 000
CO	6 000	5 500	5 500
HC	2 200	1 500	1 000
NO_x	23 000	13 000	4 900
PM	1 000	670	300
SO_x	1.8	1.8	1.8
CO_2	2 800 000	2 800 000	2 800 000
Noise[b]	147	146	146

[a] Number of units
[b] dB

The results shows a modest reduction in number of units and a minor increase in both fuel consumption and emissions of CO_2 and sulphur oxides. The reduction in number of units was an effect of increase in average engine size with model year, the average engine power of new machinery was higher than for old units. During the period of 2006 to 2020 the average engine power were assumed to increase with approximately 5%.

For emissions of CO, HC, NO_x, and PM the results shows a major decrease with time, especially for emissions of NO_x and PM. In figure 17 relative annual emissions for the studied period are presented.

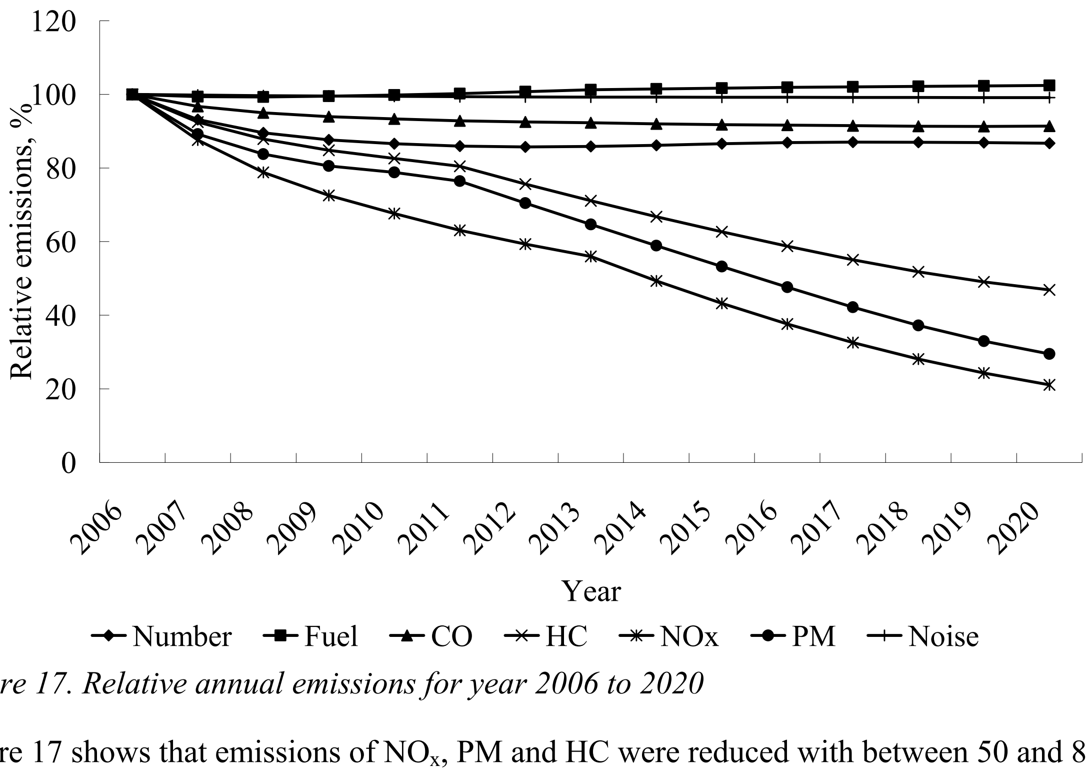

Figure 17. Relative annual emissions for year 2006 to 2020

Figure 17 shows that emissions of NO_x, PM and HC were reduced with between 50 and 80% during the period of 2006 to 2020 as a result of the already stipulated European emission regulations. Stage IIIB and Stage IV according to the European emission regulations has noteworthy effects on the annual emission amount from non-road mobile machinery in Sweden. However, the results also show that the effects of the increasingly tighter and tighter regulations take several years before they reach full impact. Stage IV that would come into force 2014 will not reach full impact during the studied period. According to emission regulation emissions of NO_x and PM will be reduced with more than 90% during the studied period, which should be compared with the calculated reduction of 79 and 70% respectively.

Non-road mobile machinery consists of several different types of machinery, such as agricultural and forestry machinery and construction equipment e.g. wheel loaders, excavators, articulated haulers and road maintenance equipment, which all are used for a wide range of different operations with varying engine load characteristics. In figure 18 to 20 relative contributions to total amounts for different types of non-road mobile machinery for year 2006, 2013 and 2020 are presented.

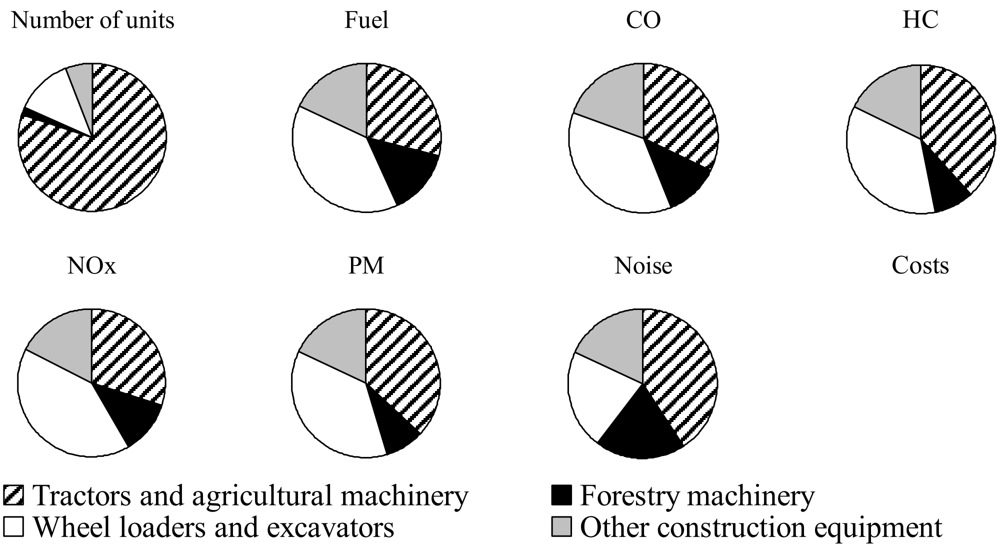

Figure 18. Relative contribution to total amounts for different types of non-road mobile machinery year 2006 for the BAU scenario

The results in figures 18 to 20 shows that tractors and agricultural machinery were responsible for the majority of units, more than 75% of all non-road mobile machinery both today and in 2020. Besides the high number of agricultural machinery the relative contribution to the overall emissions year 2006 were rather low, between 30 and 40% as shown in figure 18. Construction equipment only accounted for less than 20% of the overall number of units. Despite the low number of units, construction equipment were responsible for more than 50% of all emissions from non-road mobile machinery in Sweden year 2006. The contributions to the overall emissions from forestry machinery were between 10 and 20%, although forestry machinery only represented about 2% of the total units of non-road mobile machinery.

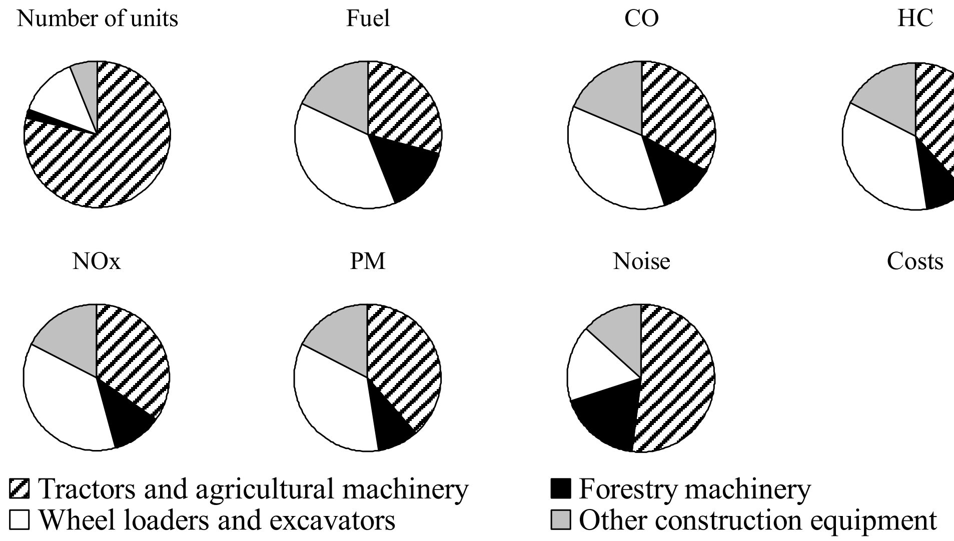

Figure 19. Relative contribution to total amounts for different types of non-road mobile machinery year 2013 for the BAU scenario

The contribution of emissions of noise from agricultural machinery showed an increasing trend for the studied period. The relative contribution increased from 40 to 55% from 2006 to 2020. The relative increase in emissions of noise from agricultural machinery was a result of non-existent noise emission regulations for agricultural tractors. According to the input data used, emitted noise levels from agricultural tractors have been kept at a constant level since 1985, while most other non-road mobile machinery has been subject to emission regulations for noise. Besides emissions of noise, the results did not showed any significant changes in relative contribution to the overall amounts between yean 2006 and 2020. All non-road machinery included within the current study was covered by the same emission regulations except for agricultural and forestry tractors. However, since year 2006 i.e. Stage III A, the emission regulations for agricultural and forestry tractors and other non-road mobile machinery are completely harmonized in both time an emission levels except for emissions of noise.

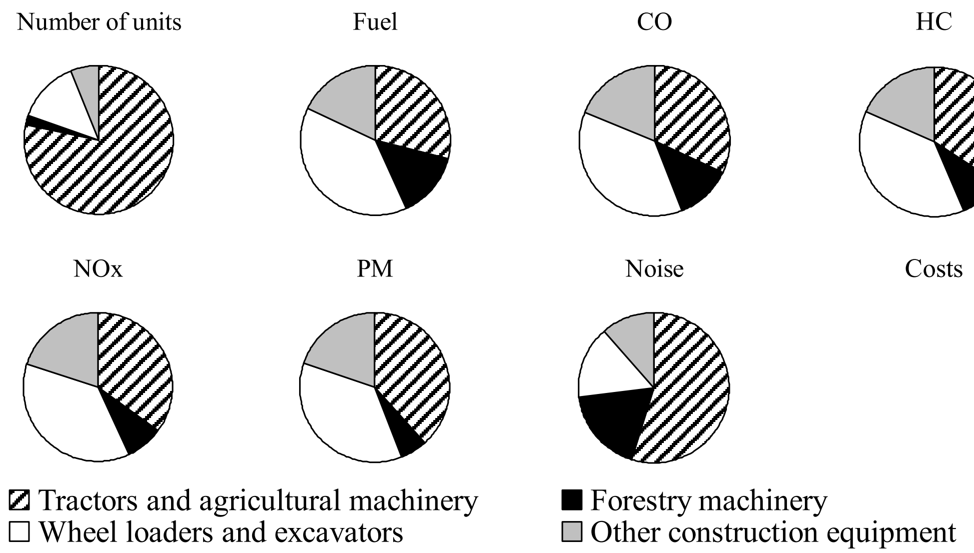

Figure 20. Relative contribution to total amounts for different types of non-road mobile machinery year 2020 for the BAU scenario

7.1. Scrappage program

Three different scrappage programs were studied, a one-year program and two different continuously programs with slightly different approaches. All results were presented relative to the BAU scenario except for economical data. Economical data were expressed as accumulated costs in the monetary value of year 2020 based on a 6% rate of interest.

7.1.1 One-year scrappage program

All the studied one-year programs had a marked impact on the number of non-road mobile machinery as shown in figure 21. The effects also last for the entire period, thus with a minor tendency to increase the years after the initiation of the program. Scrappage program 4, which covered 25% of all non-road mobile machinery with an age of 12 years or more showed the most pronounced reduction in total number of machinery. However, scrappage program 4 also resulted in the highest cost over the studied period as shown in figure 21.

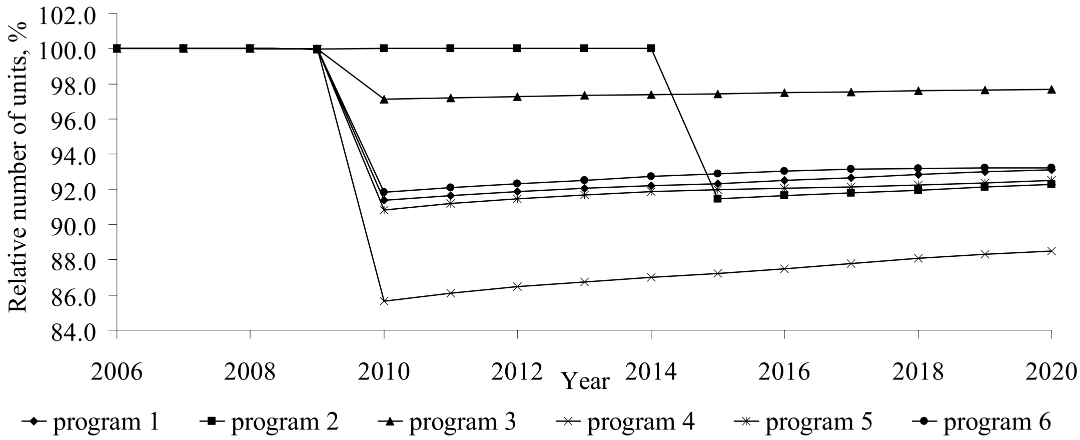

Figure 21. Relative number of units compared with BAU for scrappage program 1 to 6

Emissions of CO were reduced compared with BAU for all scrappage programs as shown in figure 23. However, the effects were not as pronounced as for number of units. An almost 20% reduction in total number of units only resulted in a 1.5% reduction in emissions of CO. Scrappage program 4 and 5 had the highest effects annual emissions of CO, a maximum reduction of about 1 to 1.5% the same year as the scrappage program came into force. The results also showed that the effects on emissions of CO of a one-year scrappage program slightly petered out with time. At 2020 the effects had almost completely diminished.

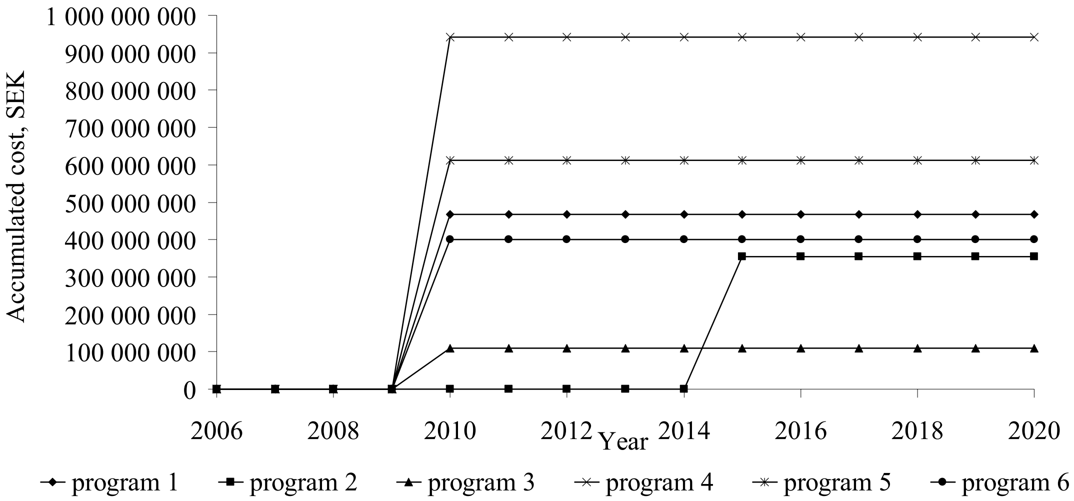

Figure 22. Accumulated costs for scrappage program 1 to 6

In terms of cost per kg of CO reduced over the entire studied period scrappage program 3 was the most efficient closely followed by scrappage program 5 with approximately 1 600 and 1 700 SEK per kg CO reduced, respectively. Scrappage program 6, which had the third lowest total cost as shown in figure 22 resulted in the highest specific cost per reduced kg of CO.

The results of fuel consumption showed the same trend as emissions of CO did. However, the effects were considerably lower, a maximum reduction of less than 0.5% compared with BAU.

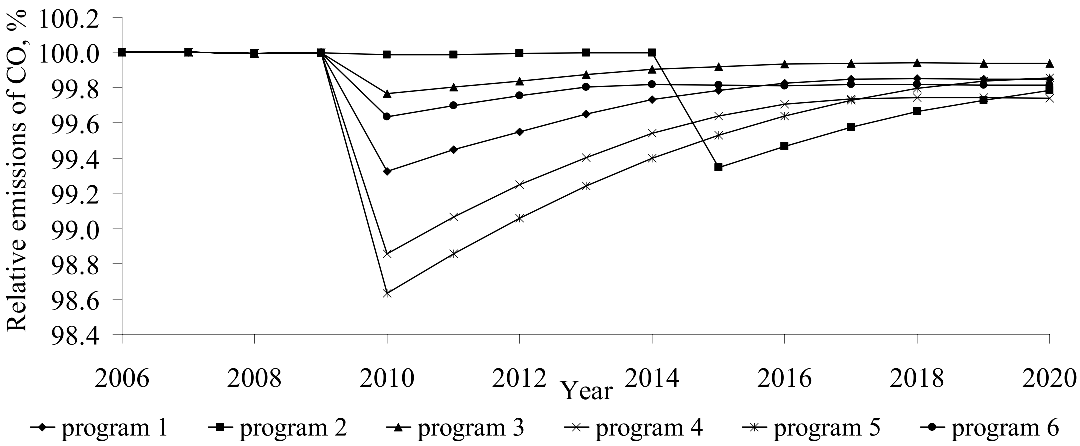

Figure 23. Relative emissions of CO compared with BAU for scrappage program 1 to 6

The results of scrappage program 1 to 6 on emissions of NO_x compared with BAU showed that the most marked effects were obtained with scrappage programs 2, 4 and 5 as shown in figure 24. The results also indicate that the effects of the scrappage programs will have a long term effects on the annual emissions of NO_x compared with BAU. The difference in annual emissions between BAU and the scrappage programs seems to increase beyond year 2020, which was the final year for this study. For the studied period scrappage program 3 and 5 had the highest economical efficiency with an approximate specific cost of 220 and 250 SEK per reduced kg of emissions of NO_x, respectively.

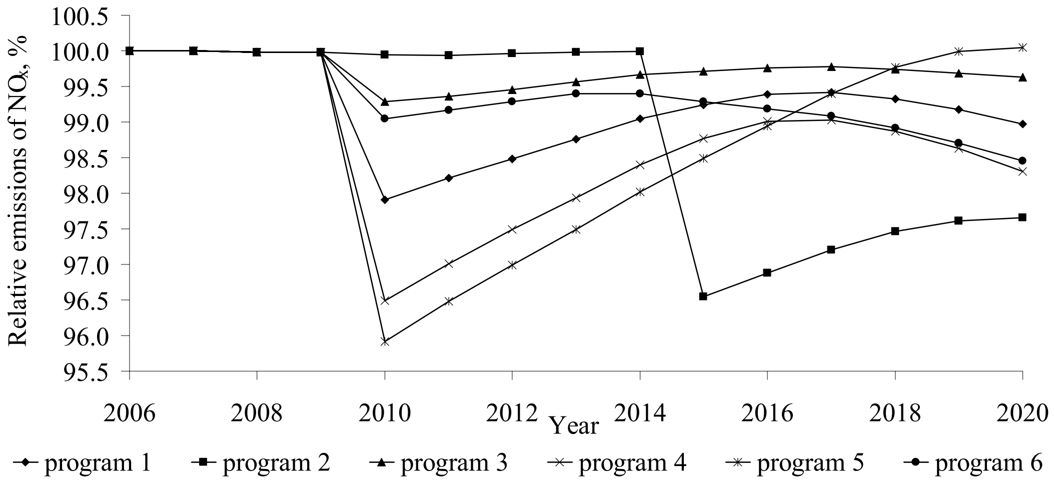

Figure 24. Relative emissions of NO_x compared with BAU for scrappage program 1 to 6

For emissions of PM scrappage program 5 resulted in an almost 4% reduction in 2010. However, at the end of the studied period emissions of PM for scrappage program 5 had increased with 2% compared with BAU as shown in figure 25. Those effects could be explained as a combination of the age distribution of non-road mobile machinery and the European emission regulation. A reduction of 15% of all non-road mobile machinery with an age of more than 8 years in 2010 will result in a rather large reinvestment of new machinery fulfilling the current emission regulation, i.e. Stage III A. Compared with Stage III B emissions of PM in Stage III A was 10 to 20 times higher. This new assembly of machinery will be in service for several years and thus contribute to the overall emissions of PM. Scrappage program 3 was still the most economically favourable program while scrappage program 5 was the least favourable with a specific cost of 4 200 and 8 400 SEK per kg emissions of PM reduced, respectively. Similar, less pronounced, effects could be seen on the results of emissions of HC.

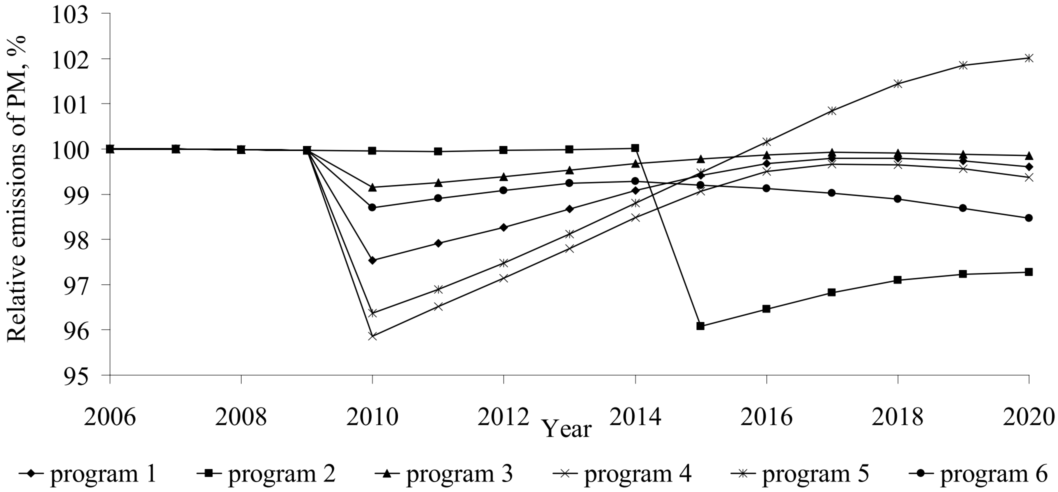

Figure 25. Relative emissions of PM compared with BAU for scrappage program 1 to 6

The results indicated that scrappage program 3 was the most cost efficient program of the above studied programs. In figure 26 the relative contribution to total emissions and corresponding costs are presented. The results showed that 80% of the accumulated total costs for scrappage program 3 was attributed to tractors and agricultural machinery. However, tractors and agricultural machinery only accounted for about 30 to 40% of the overall emissions, while for example forestry machinery accounted for between 10 and 20% of the total emissions in 2020. The accumulated costs for forestry machinery was negligible compared with the overall costs. The same principle applied to construction equipment, a high portion of the emissions and a low quantity of the costs.

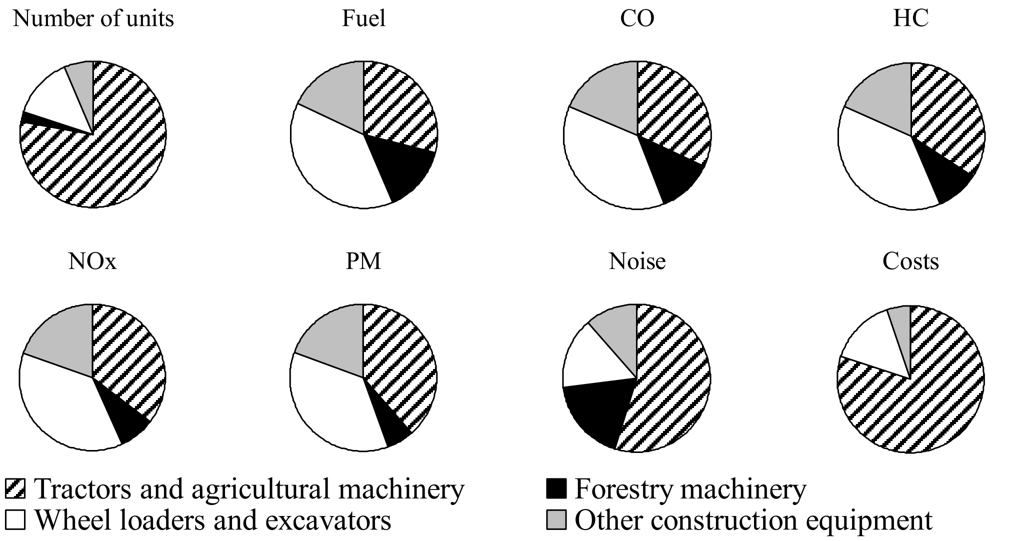

Figure 26. Relative contribution to total amounts for different types of non-road mobile machinery year 2020 for scrappage program 3

7.1.2 Continuously scrappage program 1

The first of two continuously scrappage programs was based on the same scrappage incentive as the one-year program but in force each year from 2006 to 2020.

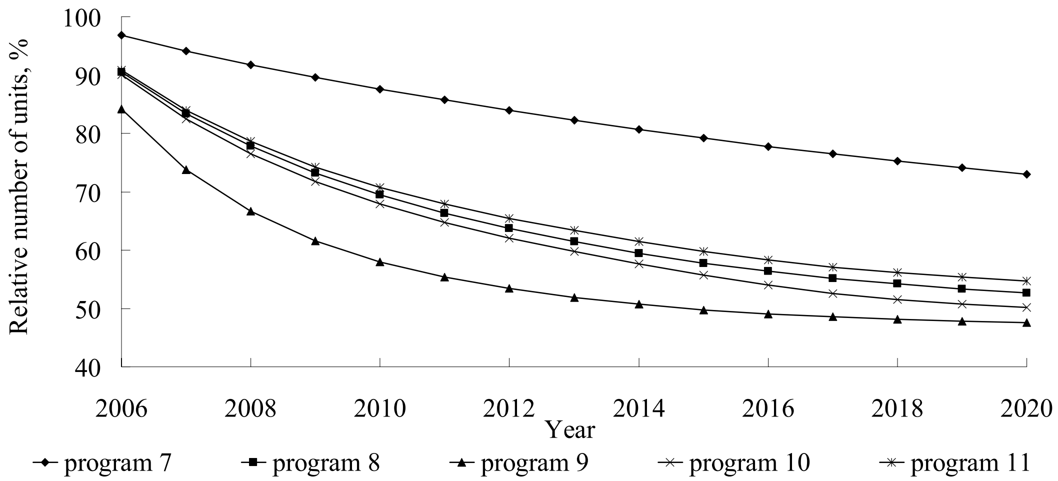

Figure 27. Relative number of units compared with BAU for scrappage program 7 to 11

The continuously scrappage programs 7 to 11 all resulted in significantly reduced number of units, between 25 and 50% of the machinery were removed from service compared with BAU, figure 27.

The accumulated costs associated with each scrappage program were rather high as shown in figure 28. The costs showed a major increase during the first few years of the program as a consequence of the high number of presumptive non-road mobile machinery. Scrappage program 8 and 11 showed a modest increase in accumulated costs compared with scrappage program 9 and 10 in relation to reduced number of units.

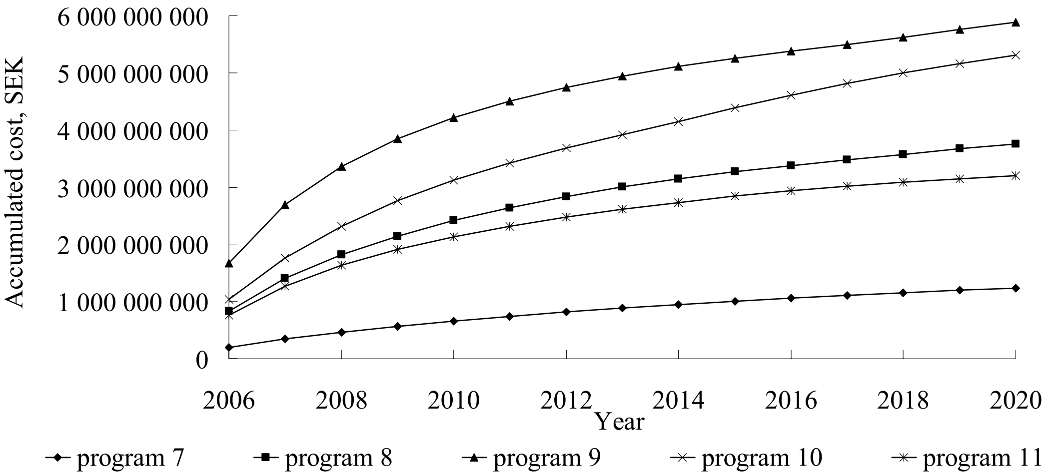

Figure 28. Accumulated costs for scrappage program 7 to 11

The reduction in emissions of NO_x compared with BAU was most pronounced for scrappage program 10, a reduction of approximately 25% at year 2020. As shown in figure 29, the results indicates that scrappage programs 7 to 11 had long term effects on the reduction of emissions of NO_x. All programs studied showed a clear trend of increasingly reduced emissions of NO_x during the period of 2006 to 2020. Scrappage program 10 showed the second highest accumulated cost as shown in figure 28 and still the lowest specific cost with 240 SEK per kg of emission of NO_x. The least favourable scrappage program was program 11 with a specific cost of 470 SEK per kg.

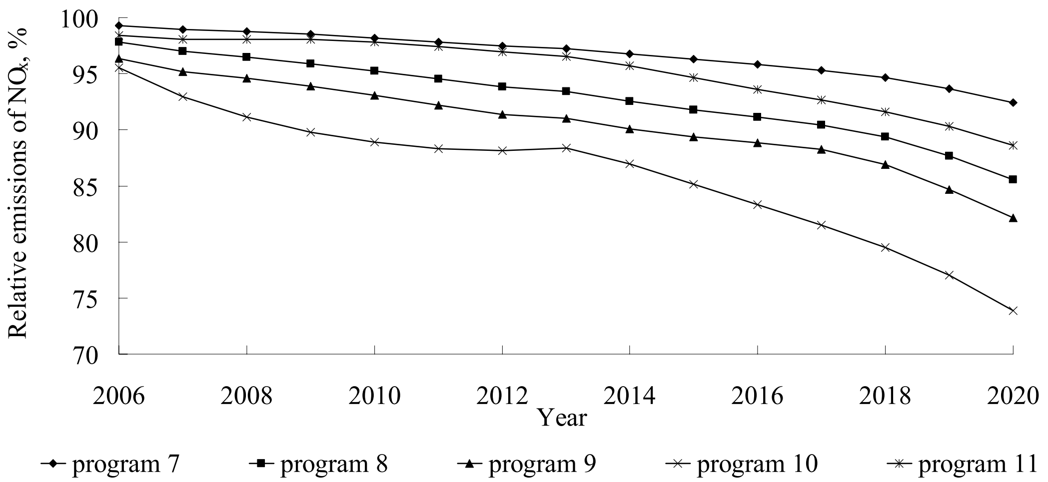

Figure 29. Relative emissions of NO_x compared with BAU for scrappage program 7 to 11

Scrappage program 7 to 11 only resulted in modest reductions in emissions of CO whereas program 10 resulted in the highest reduction rates with almost a 4% reduction compared with BAU. Still program 10 was the most economically favourable program with a specific cost of 2 000 SEK per kg CO compared with almost 3 500 SEK per kg.

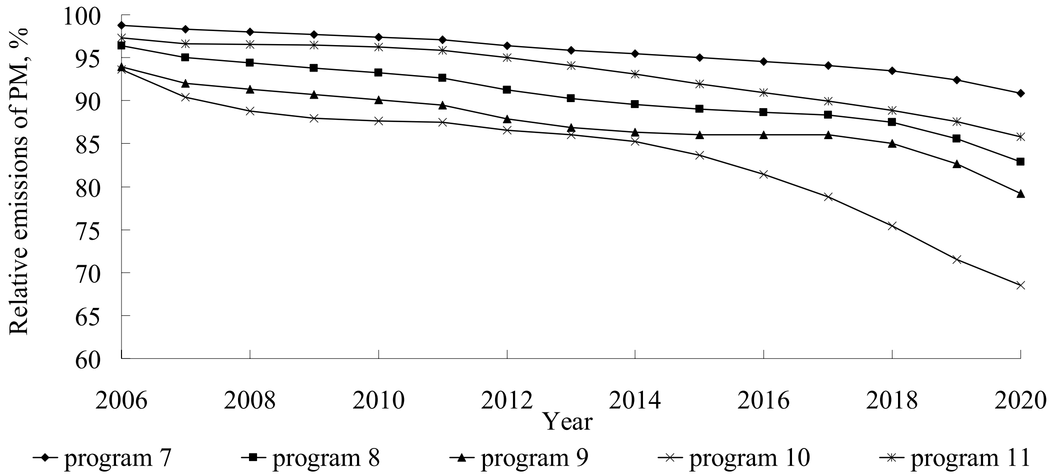

Figure 30. Relative emissions of PM compared with BAU for scrappage program 7 to 11

As with emission of NO_x, scrappage program 10 resulted in the highest reduction of emission of PM compared with BAU as shown in figure 30. The results also show a significant increase in the reduction of emission of PM from scrappage program 10 for the period of 2015 to 2020. Scrappage program 7 resulted in the lowest reduction of emission of PM, about 10%. However, scrappage program 7 resulted in the lowest specific reduction cost with 3 500 SEK per kg of emission of PM reduced closely followed by program 10 with a cost of 3 800 SEK per kg.

7.1.3 Continuously scrappage program 2

The second continuously scrappage program was based on a reduction of the average lifetime in contrast to the previous continuously scrappage program which was designed to remove the oldest units. This program aimed to increase the rate of turnover of the entire assembly of machinery.

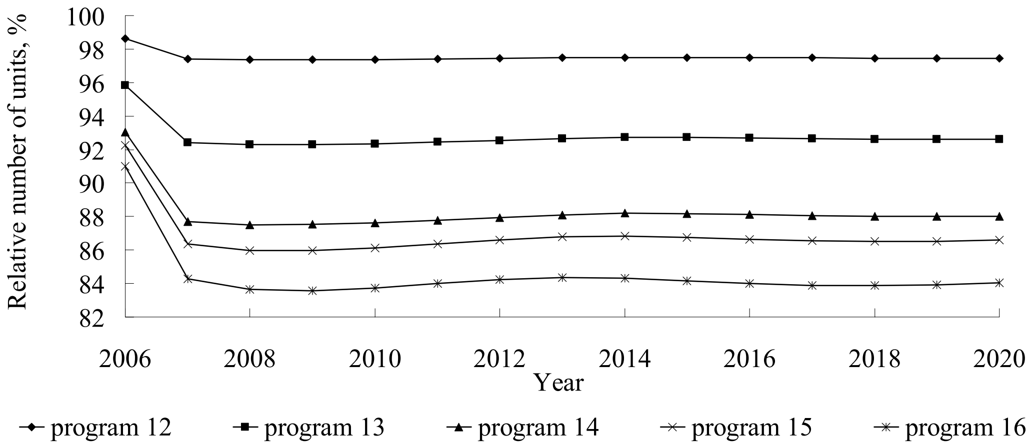

Figure 31. Relative number of units compared with BAU for scrappage program 12 to 17

According to the results, scrappage program 16 resulted in a steady reduction of number of units with 16% compared with BAU while the corresponding data for scrappage program 12 was 2% as shown in figure 31.

In figure 32 accumulated costs for scrappage program 12 to 16 are presented. All programs showed a linear increase in accumulated costs with time. Program 16 showed the highest increase while program 12 resulted in the lowest increase in accumulated costs.

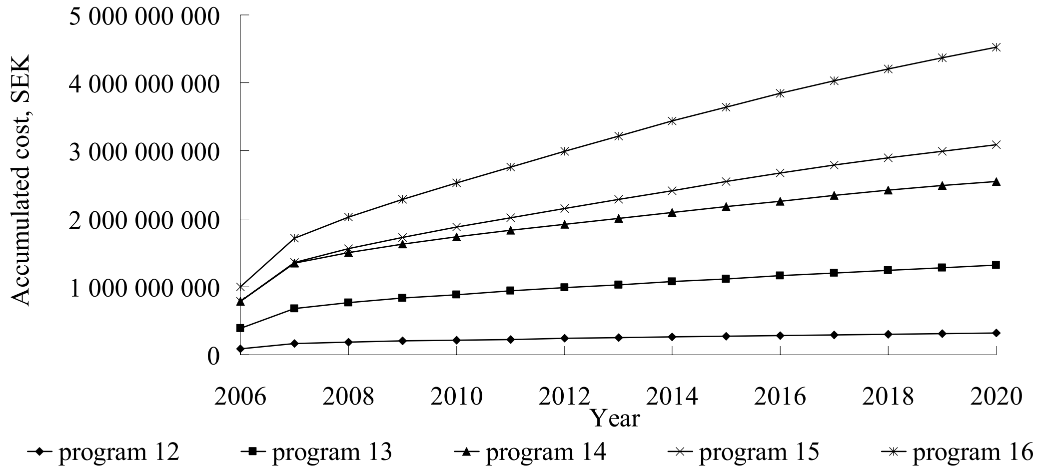

Figure 32. Accumulated costs for scrappage program 12 to 17

The results only showed minor effects on fuel consumption of the studied scrappage program. The maximum effects were less than 1% for any of the programs tested. The low effects in fuel consumption were probably a consequence of the assumed specific fuel consumption, which showed no differences between different model years of non-road mobile machinery. However, the degradation factor included in the model still resulted in an overall reduction in fuel consumption when old units were replaced by new.

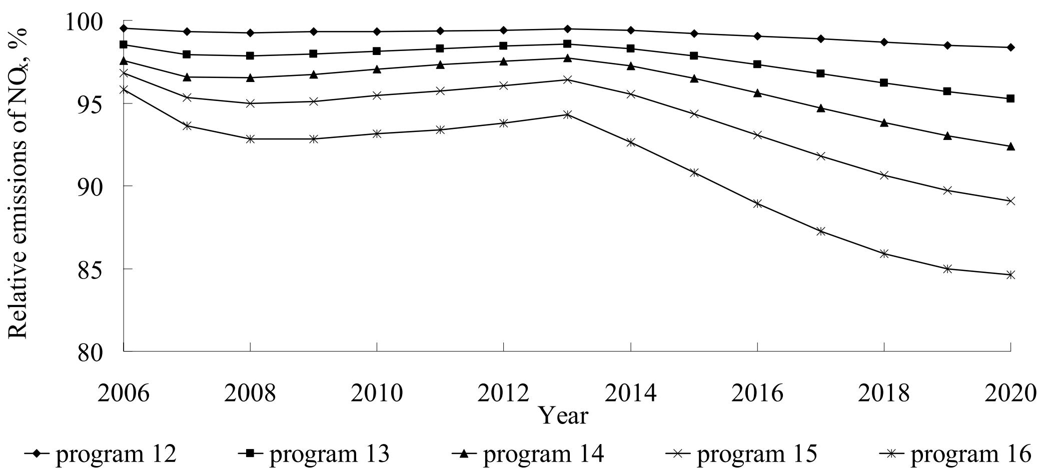

Figure 33. Relative emissions of NO_x compared with BAU for scrappage program 12 to 17

Scrappage programs 12 to 16 showed a rather stable reduction of emissions of NO_x between 1 and 7% during the first 7 years of the programs. After year 2013, all scrappage programs resulted in increased reductions of emissions of NO_x compared with BAU as shown in figure 33. Scrappage program 16 showed the highest reduction rate with approximately 25% in 2020. However, program 12 resulted in the lowers specific cost with 220 SEK per kg of NO_x reduced over the studied time period followed by program 16 with 310 SEK per kg.

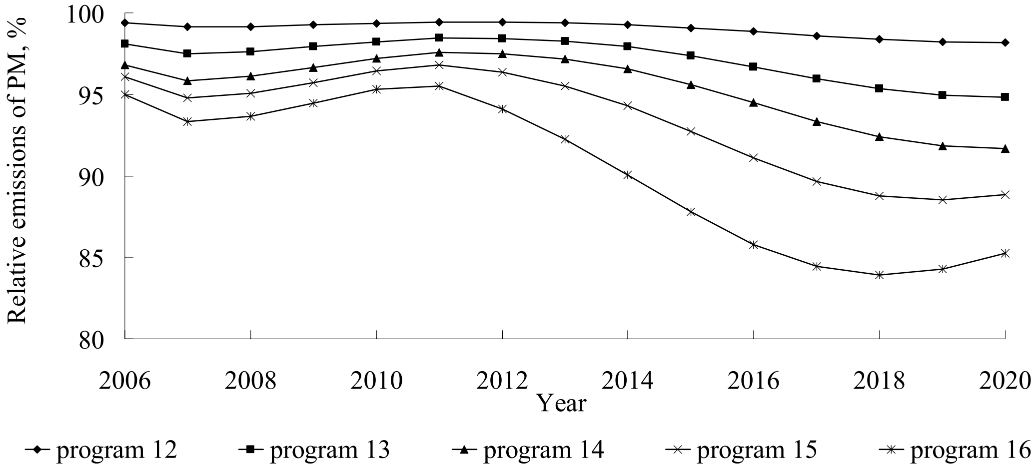

Figure 34. Relative emissions of PM compared with BAU for scrappage program 12 to 17

Figure 34 shows the result of relative emissions of PM for scrappage program 12 to 17 compared with BAU. The reduction rates for emissions of PM showed the same trends as for emissions of NO_x for the various scrappage programs. However, the results indicated that the effects of scrappage programs 12 to 16 would diminish after year 2020 especially for program 15 and 16. The most economically favourable scrappage program was program 12 with a specific cost of 3 800 SEK per kg PM compared with more than 5 500 SEK per kg for the other programs.

The most economically favourable individual scrappage programs of each of the three types of scrappage programs studied are compiled in table 45.

Table 45. Accumulated amounts of emissions reduced for three different individual scrappage programs compared with BAU

Emissions reduced	Scrappage program		
Tonne	3	10	12
Fuel	4 800	160 000	10 000
CO	67	2 600	160
HC	39	2 200	120
NO_x	500	22 000	1 400
PM	26	1 400	84
Cost[a]	110	5 300	320

[a] MSEK

The results showed that there were a large difference in both amounts of emissions reduced and the corresponding accumulated costs. Scrappage program 3 was according to the results the most economically favourable method to reduce emissions of NO_x. However, the difference between the three programs listed in table 3 was less than 10%. Similar results were obtained for emissions of PM where scrappage program 12 resulted in the lowest specific costs. For emissions of CO and HC the difference among the various scrappage programs in table 45 were more pronounced, between 15 and 25%. Neither of the scrappage programs tests had any noteworthy effect on emissions of noise compared to BAU, the largest effect obtained was just fractions of a percent. Furthermore, the results also showed that it is possible to reduce 500 or 22 000 tonne of NO_x for similar specific costs, all depending on the total budget and desired result.

7.2. Alternative fuels

All effects of the alternative fuel programs on emissions were linear proportional to the amount of alternative fuel used, thus independent of time. Accumulated reductions in emissions compared with BAU for all alternative fuel programs are presented in table 46 together with accumulated costs.

Table 46. Accumulated reduction in emissions for alternative fuel programs compared with BAU

Alternative fuel program	Accumulated reduction in emissions ktonne CO_2	Tonne CO	HC	NO_x	PM	Accumulated cost MSEK
1	200	59	62	-250	19	580
2	400	120	120	-500	39	1 200
3	500	150	160	-620	49	1 500
4	990	290	310	-1 200	97	2 900
5	2 000	590	620	-2 500	190	6 300
6	9 900	2 900	3 100	-12 400	970	31 700
7	19 800	5 900	6 200	-24 800	1 900	63 500
8	97	590	270	480	44	2 500
9	480	2 900	1 300	2 400	220	12 400
10	970	5 900	2 700	4 800	440	24 700

The results showed that all programs including pure RME or RME-diesel blends resulted in elevated levels of emissions of NO_x, while the FTD fuel resulted in reduced amounts of emissions of NO_x compared with BAU. Furthermore, the results showed that the emissions of CO_2 could be reduced considerable by the introduction of high shares of RME or FTD. However, the emissions of CO_2 from alternative fuels were strongly dependent on the lifecycle of the fuel in question including process and feedstock. If natural gas was used as feedstock in the production of FTD emissions of CO_2 from alternative fuel programs 8 to 10 would be much closer to that of BAU than what shown in table 46.

According to the results, alternative fuel programs based on RME or RME blends i.e. program 1 to 7 resulted in the most economically favourable programs for reductions of PM emissions. For the other pollutants, alternative fuel program 8 to 10 resulted in lower costs. As the fuel prize and revenues of taxation were the only costs included in the alternative fuels sub model, the economical results and the actual market penetration of each fuel would be sensitive to variation in fuel prize. Furthermore, the assumed relative emissions for RME and FTD compared with the conventional EC1 fuel also have a major influence on the results. For example, according to the literature sources used emissions of particulate matter from RME only amounts to approximately 60% of that of EC1 while the corresponding data for FTD was 90%.

7.3. Voluntary emission program

The voluntary emission program was based on early introduction of the European emission regulation with one or several years. The accumulated costs for the voluntary emission programs showed an increasing trend with increasing portion of machinery participating and number of years the regulations were brought forward. Program 5 resulted in the highest accumulated costs while program 1 had the lowest as shown in figure 35.

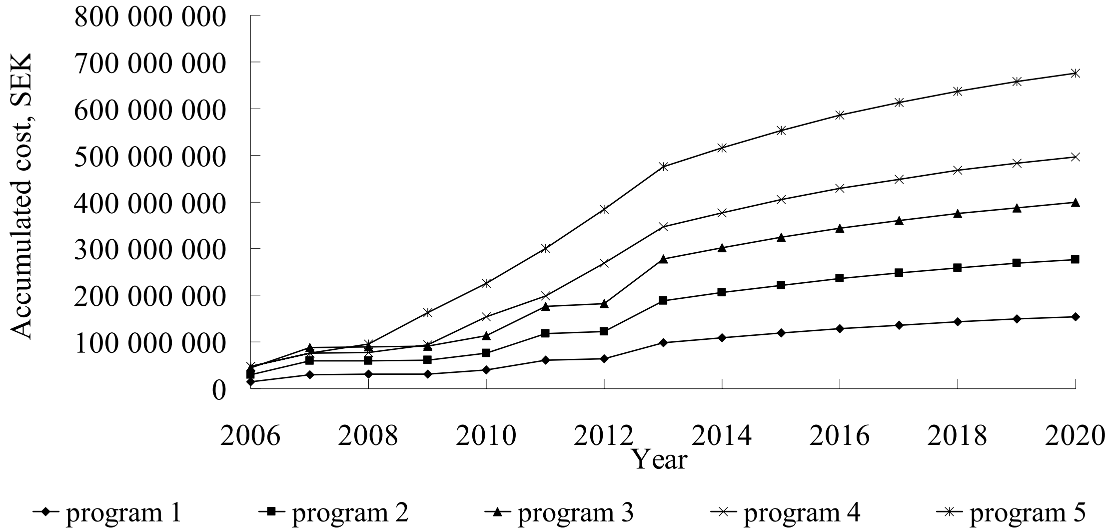

Figure 35. Accumulated costs for voluntary emission program 1 to 5

The results from the voluntary emission programs showed no or negligible differences in annual fuel consumption and emissions of CO compared with BAU. However, the infinitesimal effects of emissions of CO were expected, as there were no differences in the emission regulations for CO except for power region 37-75 kW between Stage I and II and that the voluntary emission programs only affects the emissions characteristics of new machinery, the existing assembly of machinery was unaffected.

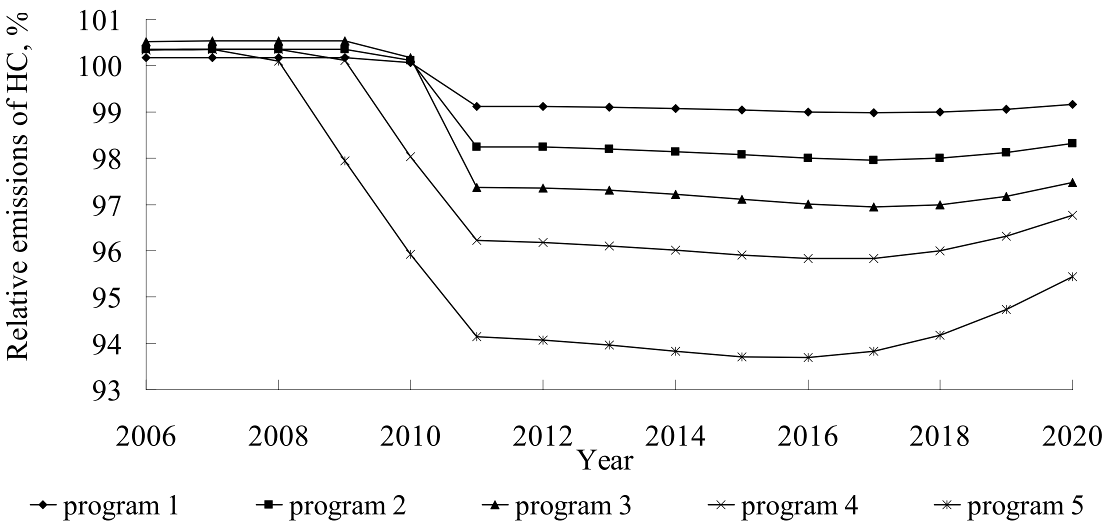

Figure 36. Relative emissions of HC compared with BAU for voluntary emission program 1 to 5

For emissions of HC the results showed a maximum reduction of almost 4% for voluntary emission program 5 as shown in figure 36. The results also indicated that the effects of the voluntary emission programs would diminish as the portion of non-road mobile machinery fulfilling Stage IV increases. Voluntary emission program 5 was most economically favourable with a specific cost of 760 SEK per kg of emissions of HC reduced compared with BAU. The remaining programs resulted in a slightly higher specific cost of approximately 1 000 to 1 400 SEK per kg.

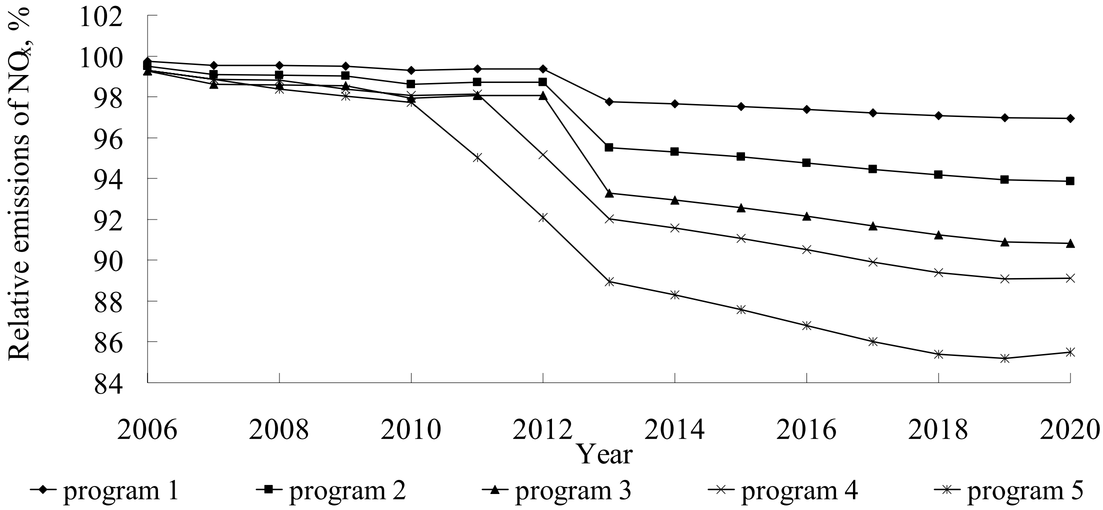

Figure 37. Relative emissions of NO_x compared with BAU for voluntary emission program 1 to 5

Compared with emissions of HC, the voluntary emission programs resulted in a more pronounced effects on emissions of NO_x as shown in figure 37, especially beyond year 2012. Still, program 5 resulted in the highest effects with a maximum reduction of around 15%. The results also indicated that the effects of the voluntary emission programs had a relatively long duration, probably due to the rather large reduction in emissions of NO_x between Stage III B and Stage IV. All the voluntary scrappage programs showed low specific costs with between 55 and 65 SEK per kg of emission of NO_x reduced compared with BAU.

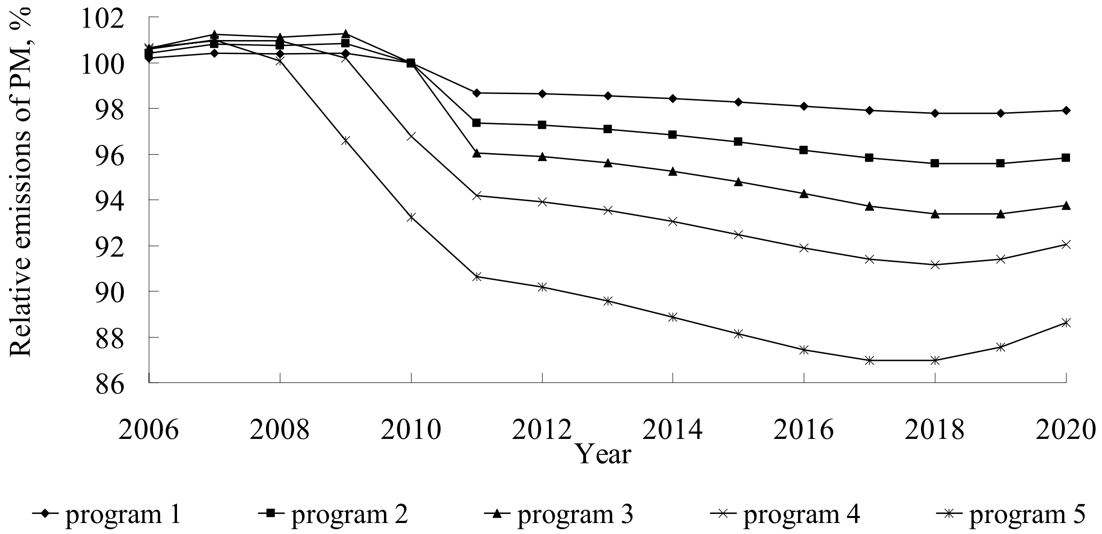

Figure 38. Relative emissions of PM compared with BAU for voluntary emission program 1 to 5

Relative emissions of PM for voluntary emission program 1 to 5 compared with BAU are presented in figure 38. The results for emissions of PM showed the same trend as emission of both HC and NO_x. Voluntary emission program 5 was the most economically favourable with a specific cost of 1 000 SEK per kg of emission of PM reduced compared with BAU closely followed by the other programs with approximately 1 300 to 2 000 SEK per kg.

7.4. Retrofit of aftertreatment equipment

Retrofit of aftertreatment equipment included the installation of catalytic diesel particulate filters or equipment for NO_x control in existing machinery in contrast to in-line mounting of aftertreatment equipment during production of the machinery.

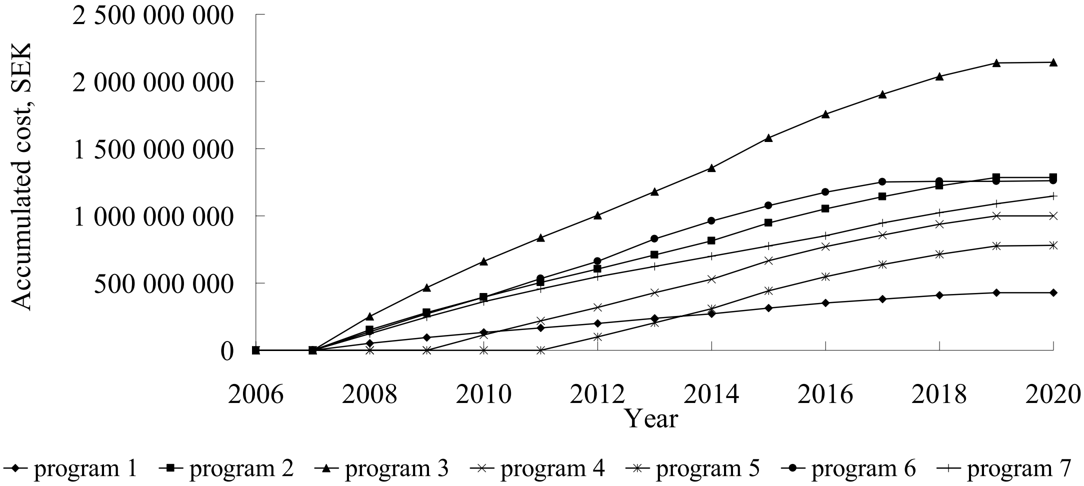

Figure 39. Accumulated costs for retrofit program 1 to 7

Figure 39 shows that the accumulated costs for retrofit program 1 to 7 range from approximately 500 to 2 000 MSEK. The results also showed that the accumulated cost became stagnant about year 2019 except for programs 6 and 7. Retrofit program 6, which encouraged 6 years old machinery to retrofit CDPF became inoperative around year 2017, because in 2017 the majority of 6 years old machines already were equipped with CDPF i.e. complied with emission regulation according to Stage III B. Furthermore, the accumulated costs for retrofit program 7 would become stagnant year 2021.

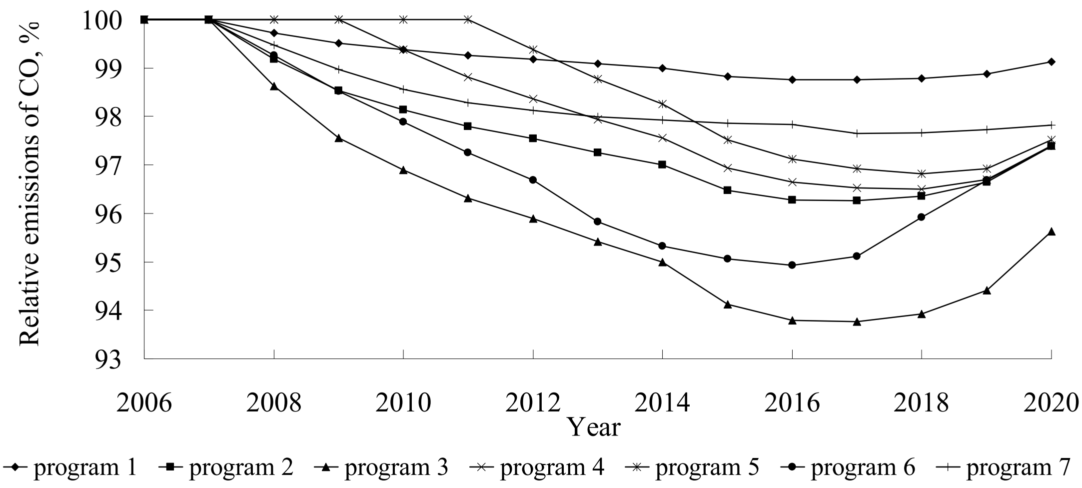

Figure 40. Relative emissions of CO compared with BAU for retrofit program 1 to 7

The results showed that retrofit of CDPF reduced the emissions with between 1 and 6% compared with BAU as shown in figure 40. The accumulated reduction of emissions of CO varied from 650 up to 3 200 tonne for retrofit program 1 and 3 respectively. However, retrofit program 6 was the most economically favourable with a specific cost of 520 SEK per kg of emissions of CO reduced compared with BAU while the corresponding data for program 7 was almost 900 SEK per kg. The results also indicated that the effects on emissions of CO of retrofit program 1 to 7 had a maximum reduction around year 2016 to approach BAU the following years. In year 2020 retrofit program 2, 4, 5, and 6 all showed similar results on emissions of CO despite large initial differences.

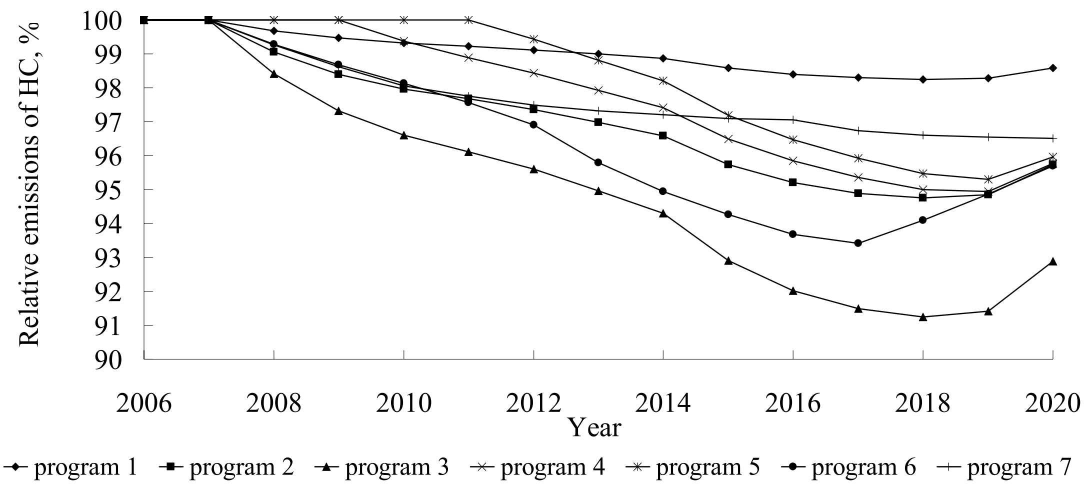

Figure 41. Relative emissions of HC compared with BAU for retrofit program 1 to 7

The relative effects on emissions of HC were similar to those of emission of CO. Figure 41 shows that retrofit program 3 resulted in a maximum reduction of emissions of HC with 9% or an accumulated reduction of 1 000 tonne compared with BAU. However, despite the large accumulated reduction the specific cost for retrofit program 3 amounted to 2 100 SEK per kg of emissions of HC reduced while the corresponding cost for program 6 only amounted to 1 800 SEK per kg.

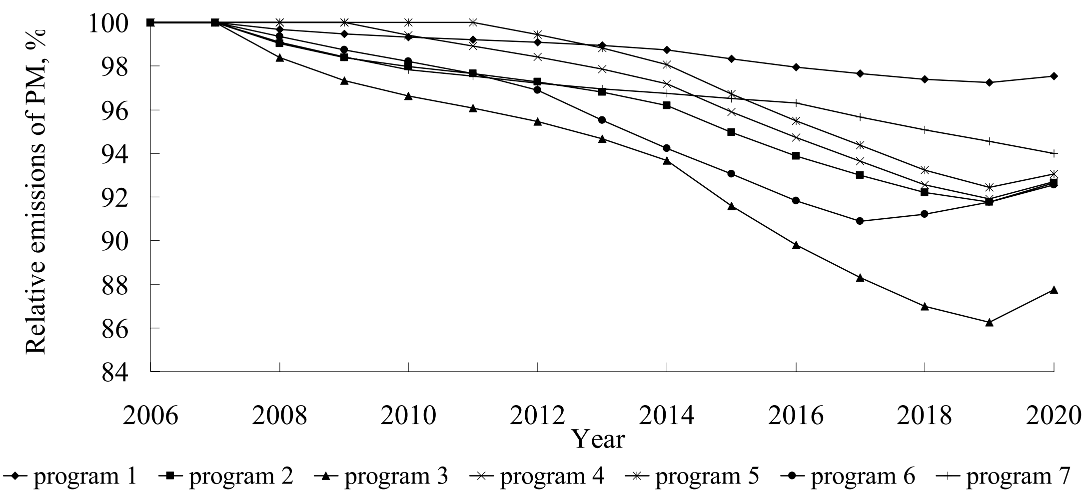

Figure 42. Relative emissions of PM compared with BAU for retrofit program 1 to 7

Retrofit of CDPF resulted in considerable reduction of emissions of PM compared with BAU as shown in figure 42. For retrofit program 3 emissions of PM in 2019 were reduced with almost 15% or 50 tonne per year. Furthermore, retrofit program 1 to 3 all resulted in a specific cost of 4 400 SEK per kg of emissions of PM reduced. However, the corresponding cost for retrofit program 6 was only 3 700 SEK per kg. The accumulated reduction of emissions of PM for retrofit program 6 compared with BAU was 340 tonne. As for the other pollutants, the results indicated that the effects of retrofit program 1 to 7 on emissions of PM would diminish beyond year 2020.

Retrofit program 1 to 7, i.e. retrofit of CDPF, only resulted in indeterminable effects on emissions of NO_x, noise or fuel consumption and thus not further reported.

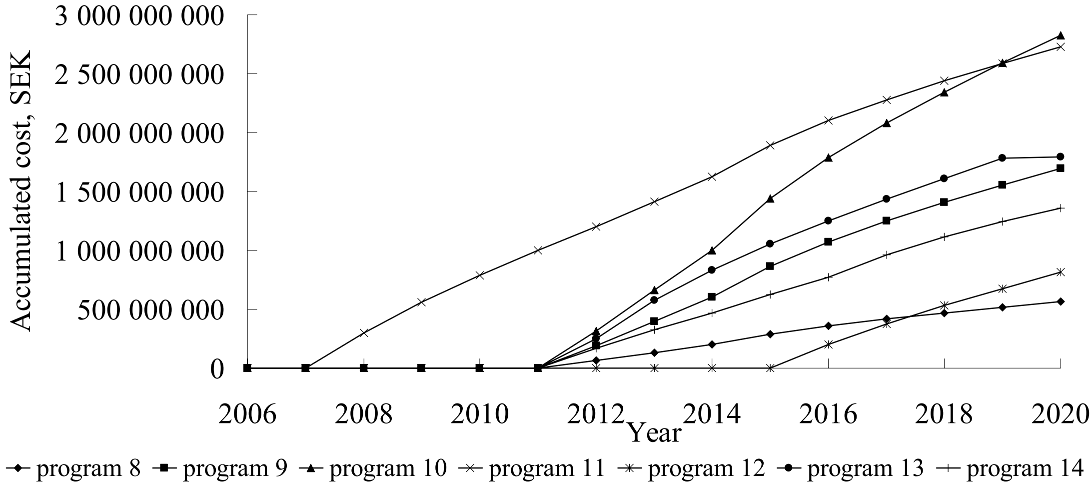

Figure 43. Accumulated costs for retrofit program 8 to 14

The accumulated costs for retrofit program 8 to 14, i.e. retrofit of NO_x control, are presented in figure 43. Retrofit program 10 showed the steepest increase in accumulated cost with almost 310 MSEK annually and thus the highest total cost with 2 825 MSEK. The accumulated cost for the retrofit program would level out sonly after year 2020 as indicated by the plateau in 2020 for program 13.

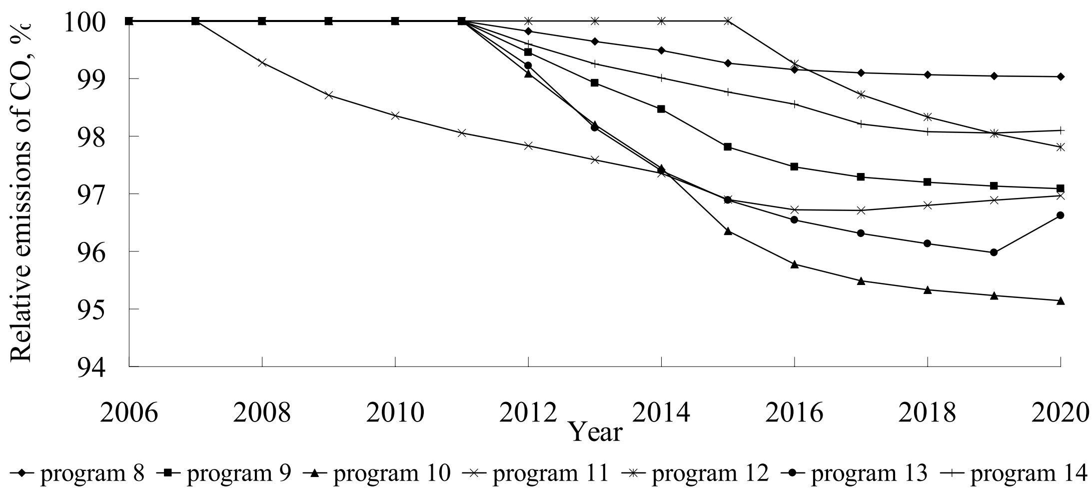

Figure 44. Relative emissions of CO compared with BAU for retrofit program 8 to 14

Retrofit program 10 resulted in the highest relative reduction compared with BAU and the highest accumulated reduction of emissions of CO, around 1 800 tonne, together with program 11 which was introduced already in 2008 compared with 2012 for most of the other programs. Figure 44 also shows that the effects in 2020 and beyond were rather independent of the initial year of the retrofit programs, i.e. program 9, 11, and 12. The effects of retrofit program 13 on emission of CO were considerably reduced in 2020 as also was indicated by the plateau in accumulated costs for the same program. Still, retrofit program 13 resulted in the most economically favourable specific cost with 1 200 SEK per kg of emissions of CO reduced.

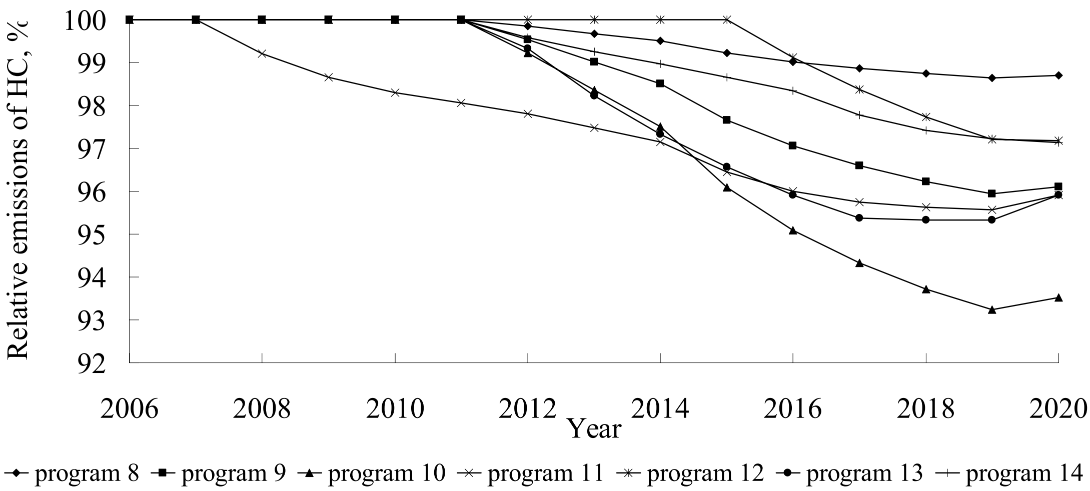

Figure 45. Relative emissions of HC compared with BAU for retrofit program 8 to 14

The effects of retrofit program 8 to 14 on emissions of HC resembled the results for emissions of CO as shown in figure 44 and 45. However, the relative reduction rates were more pronounced for emissions of HC. Furthermore, the specific costs for reductions of a kg of emissions of HC were rather high, almost 5 000 SEK per kg and above.

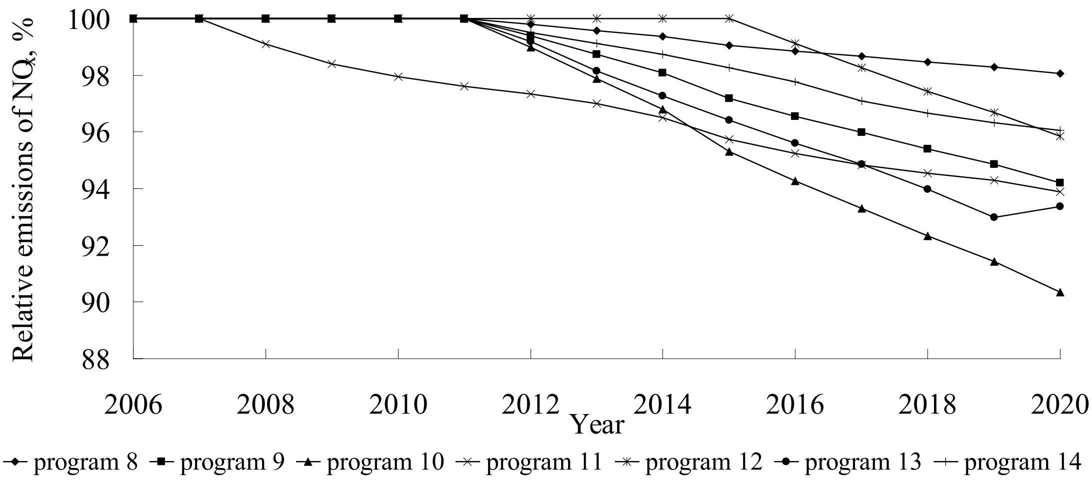

Figure 46. Relative emissions of NO_x compared with BAU for retrofit program 8 to 14

The results on emissions of NO_x of retrofit program 8 to 14 showed a marked reduction compared with BAU for all programs. Figure 46 shows an almost 10% reduction of emissions of NO_x for retrofit program 10 in 2020. Furthermore, the results indicated the reduction of emissions of NO_x compared with BAU would continue to increase beyond year 2020. Retrofit program 10 showed the most pronounced reduction of emissions of NO_x. However, program 10 had the highest share of machinery participating. Program 11, which was introduced in 2008 resulted in both the highest absolute reduction amounts and lowest specific costs with 4 500 tonne and 610 SKE per kg of emissions of NO_x, respectively. The specific costs for retrofit program 8 to 10 were almost identical, thus rendered it possible to relatively free set a maximum absolute cost for reduction of emissions of NO_x or a desired reduction target in tonne and still be able to assess the cost with fairly good accuracy.

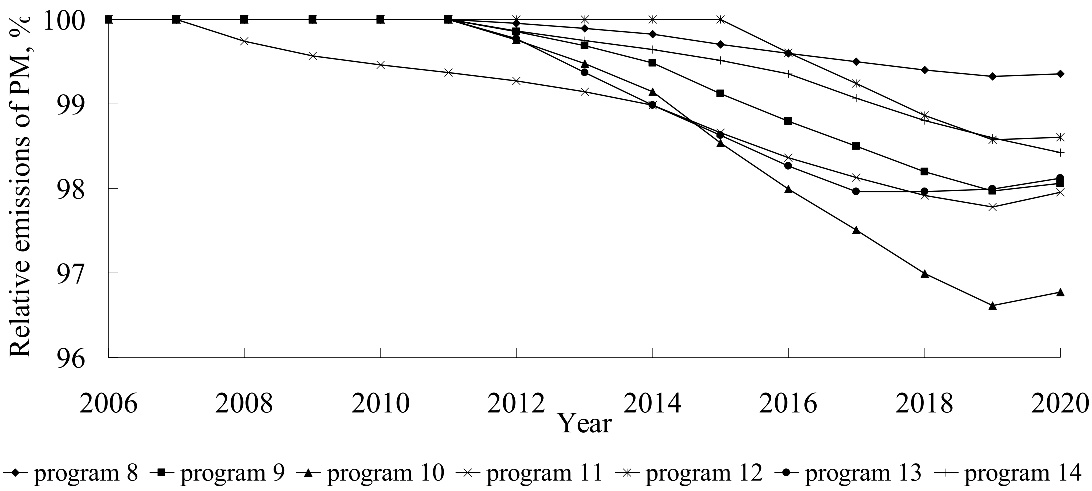

Figure 47. Relative emissions of PM compared with BAU for retrofit program 8 to 14

The results showed a fairly good reduction of emissions of PM considering that the retrofit program was based on introduction of equipment for NO_x control. As with the other pollutants, program 10 resulted in the highest relative reduction rates with a maximum reduction of slightly more than 3% as shown in figure 47. However, the specific cost for reduction of emissions of PM for retrofit program 8 to 14 were quite high, between 31 000 and 47 000 SEK per kg.

7.5. Noise reduction program

As shown in figure 48, the average annual emissions of noise from the entire assembly of non-rods mobile machinery slowly reached a fixed value depending on the desired target of the noise reduction program. Even 15 years after the initiation of the program, the full potential had not been reached according to the results. The reduced effectiveness of the program was a consequence of boundaries of the program, only new machinery was included in the program yet all active machinery contributed to the overall emissions.

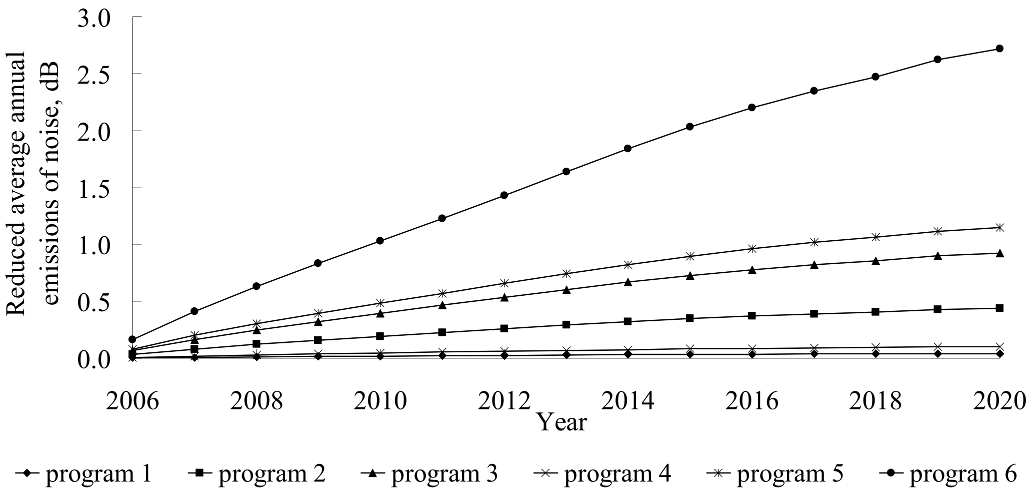

Figure 48. Reduced average annual emissions of noise compared with BAU for noise reduction program 1 to 6 for the entire assembly of non-road mobile machinery

The accumulated costs for the noise reduction program were rather high, especially for programs with a high share of machinery participating as shown figure 49. The accumulated costs for noise reduction programs 5 and 6 were considerably higher compared with the other programs. However, programs 5 and 6 covered between 50 and 100% of all new machinery and aimed to reduce the emissions of noise for each machinery with 3 dB, thus a costly measure.

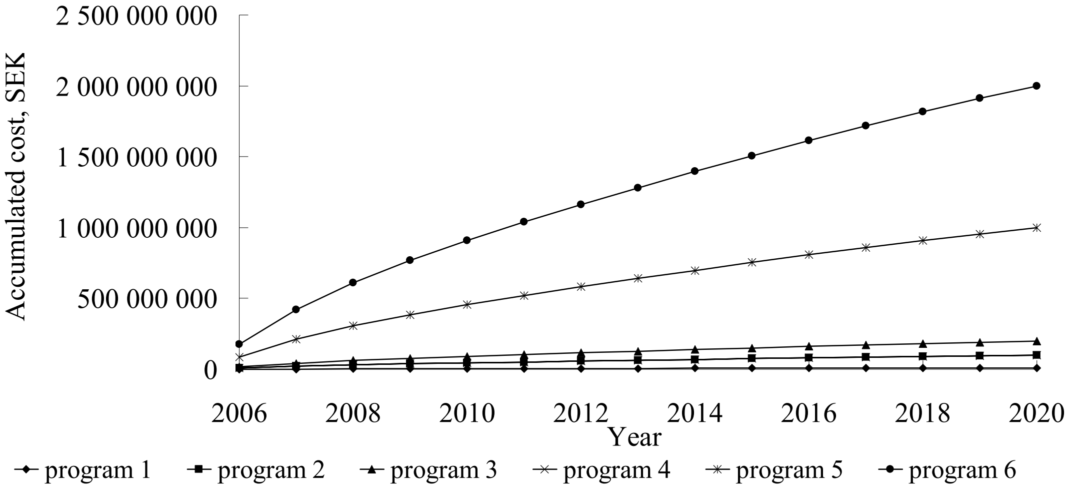

Figure 49. Accumulated costs for noise reduction program 1 to 6 for the entire assembly of non-road mobile machinery

The specific annual costs for noise reduction programs 1 to 6 is shown in figure 50. The specific cost were derived as the accumulated costs divided by the annual reduction of averages emissions of noise from the entire assembly of machinery. As shown by the results, program 4 to 6 had a significantly higher specific cost compared with program 1 to 3. However, the result was quite obvious as the individual cost for a 3 dB reduction amounted to 1% of the purchase prise of the machinery while the corresponding cost for a 1 dB reduction only was 0.1%. Furthermore, the results indicated that it would be more economically favourable to choose a one-dB reduction program compared with a 3-dB program considering the average emissions from the entire assembly of machinery.

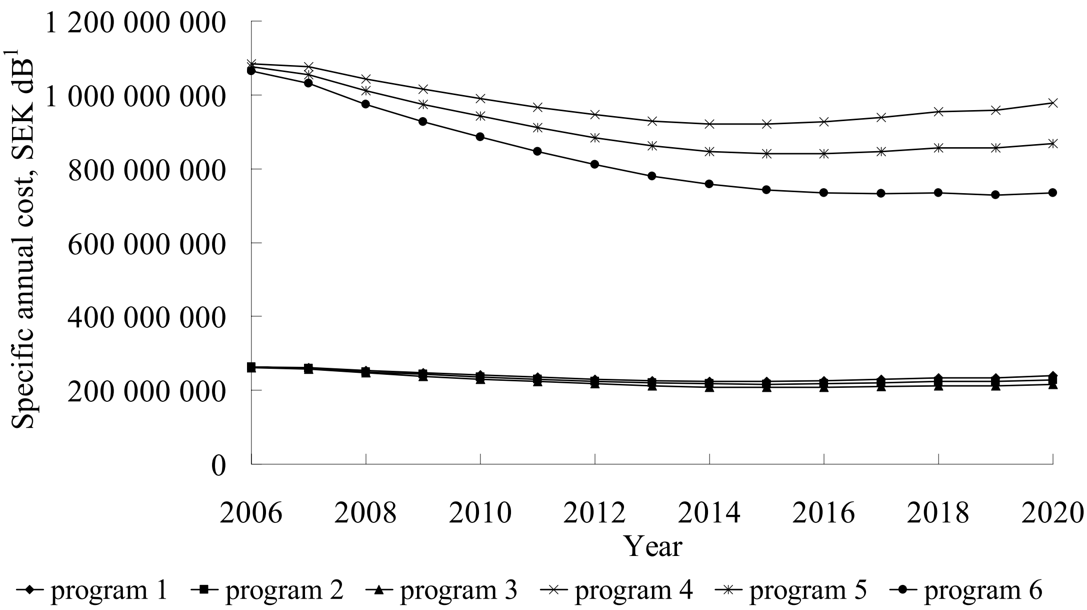

Figure 50. Specific annual costs for noise reduction program 1 to 6 for the entire assembly of non-road mobile machinery

Disturbance of noise from non-road mobile machinery is more closely connected to the operation of specific machinery of local assemblies of machinery and not to the entire assembly of machinery in Sweden. Moreover, agricultural machinery and other machinery operated outside densely populated areas significantly contributed to the overall emissions of noise, yet not really a proposed a major source of disturbance of noise for the population in average.

For a specific construction site it would probably be more effective to only target on specific machinery with high emissions of noise. The effects on the level of disturbance of emissions of noise from a specific construction site have been studied through a case study.

7.5.1 Case study noise

For this case study observations of non-road mobile machinery operation at the construction site Uppsala travel centre were utilised. Two different observations or compositions of machinery were studied which resulted in a calculated sound level of 54 and 61 dB respectively. Besides the observation, sound level was also measured at the construction site at two separate occasions, an ordinary workday and a weekend day.

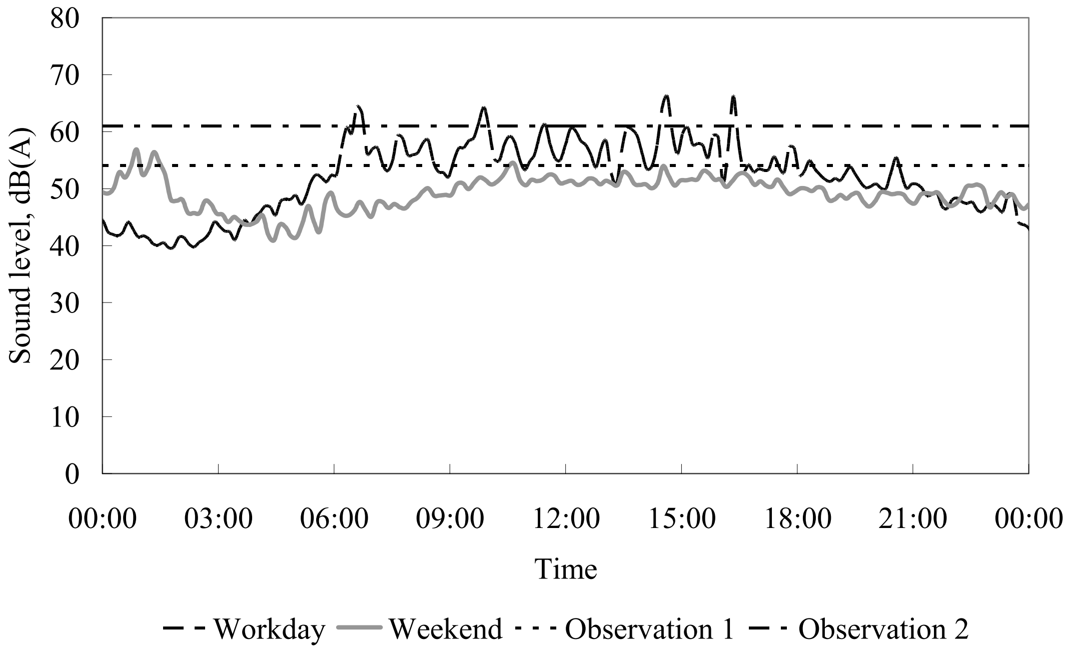

Figure 51. Measured and calculated sound level at Uppsala travel centre construction site

The results in figure 51 shows a fairly good correspondence in measured and calculated sound levels. During daytime, the resulting sound level during weekends was 5 to 7 dB lower compared with the average sound level during a normal workday, thus was assumed to represent the background sound level at the construction site. Furthermore, the sound level at the weekend, i.e. Saturday, showed a higher value between midnight and 3 o'clock in the morning compared with the corresponding time at an ordinary workday. The increased sound level was probably an effect of a nearby bus and train station in combination with an increased amount of people going home after a late night on the town.

In table 47 and 48 the effects of different noise reduction measures on average emissions of noise and the corresponding costs are presented for observation 1 and observation 2, respectively.

Table 47. Effects on emissions of noise of different reduction measures and corresponding cost for observation 1

Case	Average emissions of noise, dB	Cost, SEK	Specific cost, SEK dB^{-1}
Base	54.0	-	-
1	52.1	58 000	30 000
2	54.1	26 000	-
3	53.2	34 000	41 000
4	53.7	5 300	19 000
5	53.3	53 000	76 000
6	52.9	107 000	102 000
7	53.3	15 000	23 000

Table 48. Effects on emissions of noise of different reduction measures and corresponding cost for observation 2

Case	Average emissions of noise, dB	Cost, SEK	Specific cost, SEK dB^{-1}
Base	60.8	-	-
1	56.5	93 000	22 000
2	59.0	47 000	26 000
3	57.4	12 000	4 000
4	60.7	53 000	390 000
5	60.6	107 000	540 000
6	58.9	43 000	22 000
7	59.8	28 000	28 000

The results showed the lowest average emissions of noise from case 1 for both observation 1 and observation 2. In both instances, case 1 represented the most modern assembly of machinery, i.e. model year 2006. For observation 1 average emissions of noise were lower for the base case than for case 2, in spite of the more modern assembly of machinery. The base-case consisted of machinery with a model year of 1998 to 2001 depending on type of machinery while all the machinery in case 2 were of model year 2003. However, for wheeled excavators the lawful level of emissions of noise for the engine size in question were lower for the years 1995 to 2000 than for the years 2001 to 2005 thus reduced the emissions of noise for the base-case compared with case 2 despite newer machinery.

According to the results, replacement of individual machinery with considerably higher emissions than the average level would be economically favourable. In case 3 for observation 2, the replacement of 2 articulate haulers with an individual noise level of 114 dB with new machinery with a noise level of 108 dB resulted in a 3.5 dB reduction of the average emissions of noise to a total cost of 12 000 SEK or 4 000 SEK per dB. Retrofit of highly effective noise reduction package i.e. 3 dB reduction, on machinery with comparatively low individual noise levels would result in rather limited effects and high specific costs as shown in table 47 and 48 for cases 5, and 6, for observation 1 and cases 4 and 5 for observation 2. The specific cost for cases 5 and 6 for observation 1 was between 75 000 and 100 000 SEK per dB while the corresponding cost for cases 4 and 5 for observation 2 was between 400 000 and 550 000 SEK per dB. If the same amount of money as was used in case 4, observation 2, instead was utilised for retrofitting the machinery with highest levels of noise with a 3 dB reduction package, case 6 observation 2, the average noise level would be reduced with approximately 2 dB compared with 0.1 dB thus reducing the specific costs from almost 400 000 to slightly more than 20 000 SEK per dB.

For both observation 1 and 2, replacement of machinery usually resulted in noticeable reductions in average emissions of noise to a fairly low cost. Similar effects could be obtained by pinpointing and retrofit the machinery with the most substantial effect on the average emissions of noise with highly efficient noise reduction packages.

The results indicated that restrictions of maximum age of the machinery or enforcement of specific noise reduction measures probably would be a viable method to reduce the disturbance of noise within sensitive areas, in resemblance with method used for the environmental zones used in the biggest cities in Sweden.

The estimated costs for the 1 and 3 dB reduction package utilised in the noise reduction program were based on assumptions with rather high uncertainties and thus the results should be interpreted with caution. For example, the cost associated with a 1 dB reduction in emissions of noise from machinery not previously subjected to noise reducing measures would not impose any problems or render any significant costs. However, for a machine already fulfilling the strongest noise regulations the costs for a reduction of an additional dB could be considerable. Furthermore, the costs for noise reduction probably show a dependency to type of machinery, size and several other aspects not included in the present work. Still, the results from this study gave an indication of the effects and associated costs of different measures for reducing emissions of noise from non-road mobile machinery.

The results from both the noise reduction program and the case study implied that it would be more cost-effective to target on emissions of noise from specific construction sites or similar than to reduce the average emissions of noise from the entire assembly of non-road mobile machinery. Furthermore, the results showed that the compositions of machinery at the specific construction site played an important roll in the overall effects and costs. According to the results the best results were obtained when targeting on the machinery with the highest levels of emissions of noise. However, machinery with high levels of emissions of noise might also be the most difficult ones to reduce emissions on.

8. GENERAL DISCUSSION

The results showed that it was possible to reduce the engine exhaust gas emissions from the non-road mobile machinery sector. However, the entire non-road mobile machinery sector consists of several types of machinery not included in this study, such as small hand-held and non hand held machinery often with positive ignition, railway propulsion engines and engines for inland waterway vessels. Moreover, the majority of the fuel consumption and emissions, especially emissions of NO_x and PM, arises from the land based non-road mobile machinery equipped with heavy-duty diesel engines, and thus covered by this study.

The results also showed that the model was suitable for estimating and study annual emissions from non-road mobile machinery. However, the proposed model to estimate annual emissions was not suitable for emissions of noise, thus the case-study.

The results from the emission reduction programs indicated that the most economically favourable alternative was based on early introduction of machinery already fulfilling coming limit values for all studied emissions except for emissions of CO where the effect was negligible as shown in table 49. The least economically favourable methods were introduction of alternative fuels. However, increased use of alternative and preferable renewable fuels could have other positive effects such as reduced emissions of greenhouse gases and replacement of conventional fuels based on a fossil feedstock (ref).

Table 49. Specific costs for reduction of gaseous emissions compared with BAU

Simulation	Specific reduction cost, SEK kg^{-1}			
	CO	HC	NO_x	PM
Scrappage program 2	2 600	2 800	280	4 300
Scrappage program 8	2 700	3 200	340	4 700
Scrappage program 13	3 000	3 800	330	5 400
Alt. fuel program 6	10 800	10 200	-	32 500
Alt. fuel program 9	4 200	9 300	5 200	56 400
Voluntary emission program 2	-	1 300	60	1 800
Retrofit program 2	660	2 100	-	4 400
Retrofit program 9	1 600	6 100	760	39 200

In average the relative cost in SEK per kg was reduced with approximately 20% when the age were reduced from 8 to 6 years for retrofit programs 1 to 14. To increase the age of the machinery subjected for the retrofit program swiftly made it less economically favourable as those machinery only produced a minor part of the overall annual work from the entire assembly of machinery. Annual working hours were greatly reduced with increasing age of the machinery as showed by Wetterberg et al. (2007) and Lindgren (2007). However, the current project only examined the effects of different measures to reduce emissions on annual emission amounts from the assembly of non-road mobile machinery in Sweden from year 2006 to 2020. Many of the measures studied would still generate significantly reduced levels of emissions compared with BAU even after year 2020. By excluding the potential reduction of emissions beyond year 2020, emission programs with a high reduction rate would be disadvantaged compared with programs fully implemented in 2020.

The alternative fuel program 5 to 7 resulted in a fairly high specific cost for reduction of all pollutants except for emissions of NO_x. Emissions of NO_x increased with increasing portion of RME. However, it is important to consider the system boundaries for all alternative fuel programs when interpreting the results. For RME only engine emissions were included, which were significantly lower than the conventional EC1 fuel except for emissions of NO_x. However, for emissions of CO_2 a life cycle perspective was employed thus only CO_2 emissions with a fossil origin were included. If a lifecycle perspective would be used instead of engine emissions for all emissions, all pollutants would correspond to or exceed the emission amounts from EC1 except for emissions of CO_2. If all emissions from well to wheel were included the resulting overall emissions would have increased compared with BAU except for CO_2.

The results, in economic terms, were strongly dependent on the data used and assumptions made. For engine exhaust gas aftertreatment equipment the data clearly indicated that it was more economically favourable with in-line production compared with retrofit due to the difference in price of the equipment. For a 100 kW engine a diesel particulate filter and a urea-SCR costs approximately 140 000 and 70 000 SEK respectively when retrofitted. Corresponding data for in-line production were less than 20 000 SEK thus making the in-line alternative much more cost effective. Moreover, during in-line production the entire system including engine, control system and aftertreatment equipment could be optimised in terms of both emissions characteristics and fuel consumption. During retrofit the possibilities to modify the entire vehicle are strictly limited (DTF, 2003). The highly heterogeneous and divers non-road mobile machinery market augments this problem (Mayer, 2007).

Furthermore, is was assumed that all retrofitted engine exhaust gas aftertreatment equipments operated as intended during the whole lifetime of the vehicles. It has been shown that this is a questionable assumption, as some retrofitted equipments operates at a reduced performance especially for older technology. Mayer (2007) and LCC (2005) has shown that the failure rate of retrofitted particulate filters has decreased from more than 10% pre year 2000 application to down to about 2-6% for the last few years. In the same study Mayer (2007) showed an effective reduction of the number of particles with 90 to 99.9% after a field test that lasted for two years and an accumulated operation time of between 1 500 and 7 000 hours. However, the reduction in particle mass was considerable lower, ranging from only 3% up to almost 90% filtration rate.

As shown for agricultural tractors, there were a trend towards larger and lager machinery, which probably also could be found for the remaining part of the non-road mobile machinery sector. There are potential risks that an increased average size of the machinery will cause higher overall emission amounts. However, larger machinery has the potential to carry out the same amount of work on less time compared to smaller machinery. Provided that the machinery fulfils comparable emissions regulations the resulting absolute emission amounts should, theoretically, be equivalent.

If the trend of larger engines results in a major increase of the portion of engines with a rated power above 560 kW the effects on overall emissions could be significant. Engines for non-road mobile machinery with a rated engine power above 560 kW are currently not covered by any European emission regulation, which results in much higher emission amounts. However, in the future engines with a rated power exceeding 560 kW would probably be included in the same directive as engines with a rated power between 37 and 560 kW. Theoretically, overall emission amounts should decrease with increasing size of machinery provided that the overall work is constant. For an engine fulfilling the stage IIIB emission regulation, permissible emission of NO_x and CO per kWh are 65% and 40% higher for an engine of less than 130 kW compared with an engine with rated power above 130 kW, respectively.

Instead of engine sizes, the demand for work in the future will probably have a much more pronounced effect of the overall emission amounts from the non-road mobile machinery sector.

The data in table 49 indicated that the voluntary emissions regulation program followed by the diesel particulate filter retrofit program were the most economically favourable alternatives. However, no consideration has been taken to the relative importance of different pollutants. For example, the use of RME has positive effects in terms of reduced emissions of CO, HC and PM while emissions of NO_x increased. The increased emissions of NO_x have no visible effects in the results presented above. In order to make an estimate of the overall effect or cost-effectiveness of the above-described measures to reduce emissions some weighting factors for different pollutants could be applied. The Swedish institute for transport and communications analysis (SIKA) has developed a method for estimation of the cost of different pollutants in a national economical perspective i.e. ASEK values (SIKA, 2005). SIKA has estimated the value of the effects of different pollutants in a national perspective as shown in table 50.

Table 50. Estimated value of different pollutants in Sweden 2001

Region	Estimated value in SEK kg^{-1}				
	CO_2	SO_2	NO_x	HC	PM
National	1.5	21	62	31	0
Mid-size town	1.5	81	70	43	2 030
Large-size town	1.5	275	30	56	9 500

The data in table 50 were based on three different regions depending on the density of the population. A national perspective corresponds to the Swedish condition in average, while the mid and large-size towns were utilised to estimate the cost-effectiveness in more densely populated areas. The mid-size town corresponding to a town with a populations of approximately 40 000 while the large size town represented the three major cities in Sweden i.e. more than 200 000 people. The estimated values were recalculated to the monetary value of 2006 according to the same principle used for the vehicle purchase price.

In figure 52, the cost effectiveness of the various emissions reduction programs are presented for three different locations, rural areas, medium sized town and large sized town. The cost effectiveness were derived by dividing the reduced national costs due to decreased amounts of pollutants with the technical cost for the corresponding emissions regulation program, thus the index 100 indicated a breakeven cost between reduced costs of the society and the technical costs for the program. The technical costs were derived as explained above, and corresponded the differences in purchase/running cost between a machine participated in the emissions reduction program and a similar machine that not participated. Cost for administration, control and realisation of the program was not included.

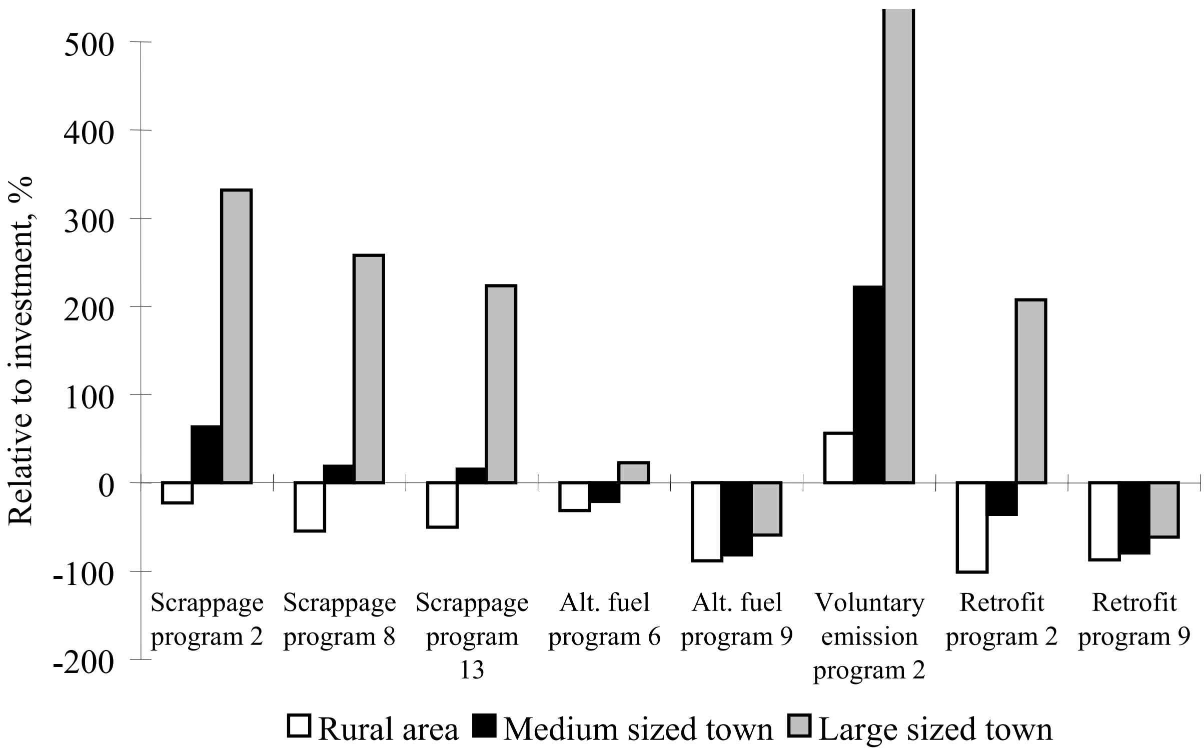

Figure 52. Reduced costs for the society for various emission reduction programs compared with the investment cost

The result in figure 52 shows that there were large differences in cost effectiveness of different measures to reduce emissions from non-road mobile machinery. Furthermore, the effects were also strongly dependent on the location i.e. rural or urban environments. According to the result, only the voluntary emissions reduction program resulted in a overall reduced cost for rural areas, for all other measures the technical cost for the various program were higher than the reduced costs for the society due to lower emissions. According to the results, retrofit of diesel particulate filters on machinery solely operated on the countryside would result in increased costs of the society mainly due to the low ASEK value for PM in rural areas together with the assumed increased fuel consumption and thus emissions of CO_2.

For the proposed model cost effectiveness could also been derived for different types and applications of machinery e.g. agricultural tractors or various construction equipment. However, in order to derive the accurate cost effectiveness of different measures to reduce emissions from sub-sectors of non-road mobile machinery, assumptions, simulations and aggregation of results must be adapted for that specific purpose. Furthermore, the data in table 50, estimated value of different pollutants in Sweden 2001, should also be subject to further investigation before too detailed results are derived. Still, the results in figure 52 could be used as an indication of the suitability of different measures. For example, the use of synthetic diesel seems to be associated with too high costs compared with the potential reduction of emissions while the voluntary emissions reduction program appeared to be applicable. Another result was that, considering the limited production capacity, RME was better used within cities compared with rural areas. An overall result was that measures to reduce emissions for non-road mobile machinery should primarily be focused on machinery principally operated within cities and not on machinery solely operated in rural areas such as combined harvesters, harvesters and forwarders.

Besides the above described measures, several other events could occur that either increases or decreases the annual emissions from non-road mobile machinery. One obvious event would be the state of the market, increased development of the construction sector would have direct effects on the emissions from non-road mobile machinery. That would probably lead to an increased investment in new machinery, and the resulting effects on the annual emissions would be dependent on the current emission legislation i.e. Stage III B or Stage IV. However, an increased development in the construction sector could also lead to a increased use of old machinery, which currently are used sparsely, thus a major increase in overall annual emissions.

Another presumptive effect could be the extension of the flexibility scheme in the European emission regulation for non-road mobile machinery (EU, 2004). A manufacturer could be granted by an approval authority to place a limited number of engines on the market that do not comply with the current stage of emissions values. However, the engine s placed on the market must comply with the previous stage of emissions values. In directive 2004/26/EC the number of engines placed on the market shall not exceed 20% of the manufacturers average annual sales volumes for one year (EU, 2004). The flexibility could for example be used as 20% in one year or as 10% per year in two years. In the current revision of Directive 97/68/EC with amendments several manufacturers proposes an increase of the flexibility to 50% of the average annual sales for engines that should fulfil emission regulation according to Stage III B and Stage IV (EU, 1997). In figures 53 and 54, the effects of three different flexibility schemes, 20, 50 and 100% of the annual sales in one year, on emissions of NO_x and PM are presented, respectively. For Stage III A a maximum of 20% flexibility was employed.

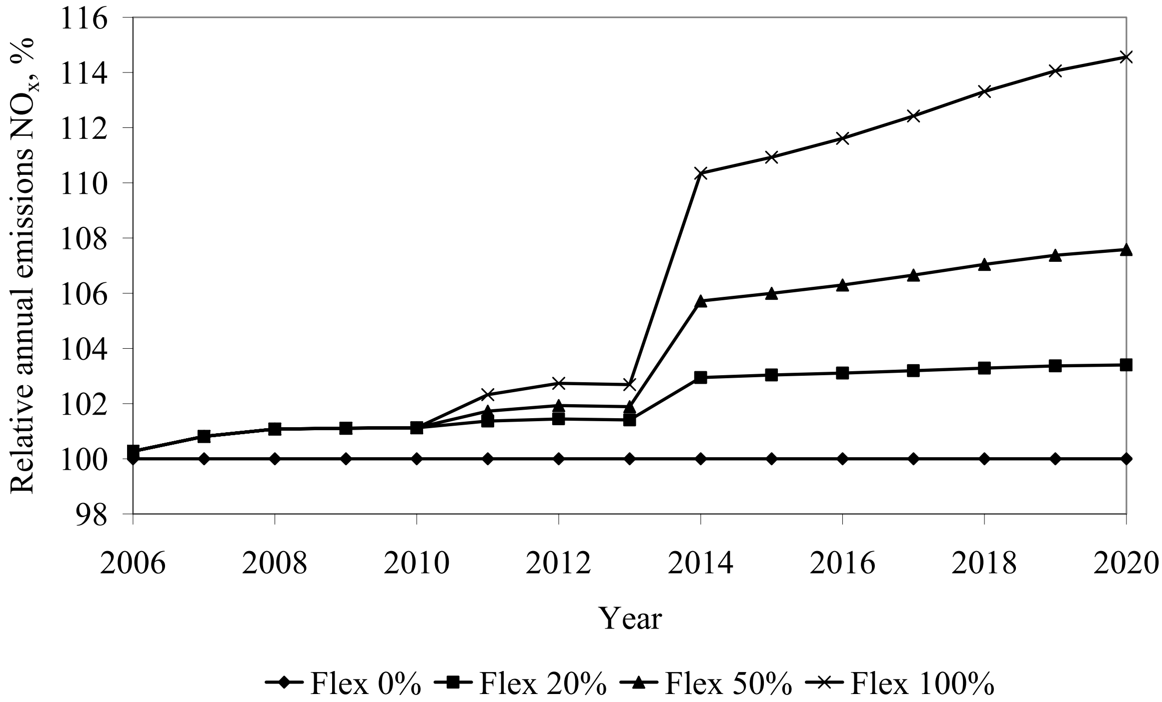

Figure 53. Relative emissions of nitrogen oxides for various flexibility schemes compared with no flexibility

The results showed that an increased flexibility scheme could increase the emissions of NOx with 3 and 7% in 2020 for the 20 and 50% flexibility respectively. For the 100% flexibility, i.e. delaying the introduction of a new emissions Stage with one year, could result in a significant increase in emissions. The effect of a flexibility scheme for Stage III B and Stage IV would result in long lasting increased levels of emissions of NO_x, even beyond 2020. Compared with no flexibility, a 100% flexibility effective in one year would increase the emissions of NO_x from non-road mobile machinery in Sweden with 6 700 tonne during the period 2011 to 2020.

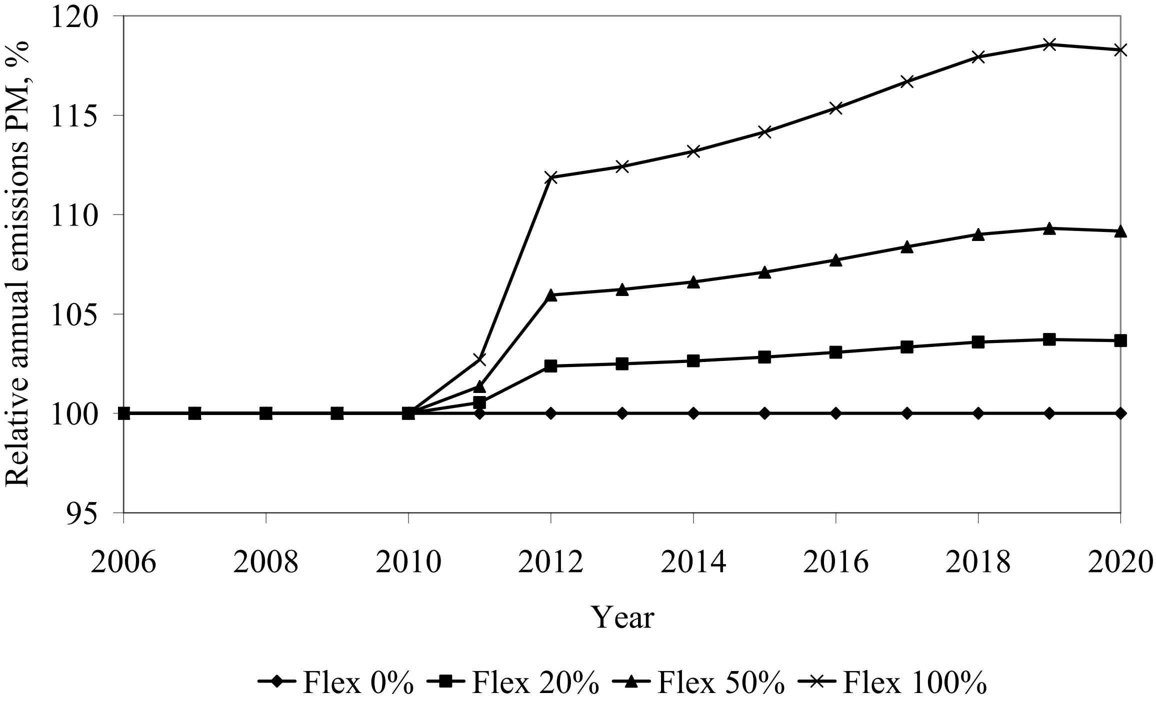

Figure 54. Relative emissions of particulate matter (PM_{10}) for various flexibility schemes compared with no flexibility

For emissions of particulate matter the effects of a flexibility scheme was comparable with the effects for NO_x. The relative increase in annual emissions compared with no flexibility showed a major increase, a maximum increase of 19% compared with 14% for NO_x. However, the effects of a 50% flexibility scheme only resulted in minor increases, corresponded to 3 and 6% of the overall emissions during the period of 2011 to 2020 for NO_x and PM, respectively.

Compared with the above described measures to reduce emissions from non-road mobile machinery, an increase in the flexibility scheme from the existing 20% to 50% for Stage IIIB and IV would in year 2015 result in an increase in emissions of PM and NO_x with 23 and 300 tonne year^{-1} respectively. Corresponding data for year 2020 were 17 and 200 tonne year^{-1}.

This roughly corresponds to the reduction capacity achieved by the various emissions reduction programs as shown in figure 55 and 56 for emissions of particulate matter and nitrogen oxides respectively.

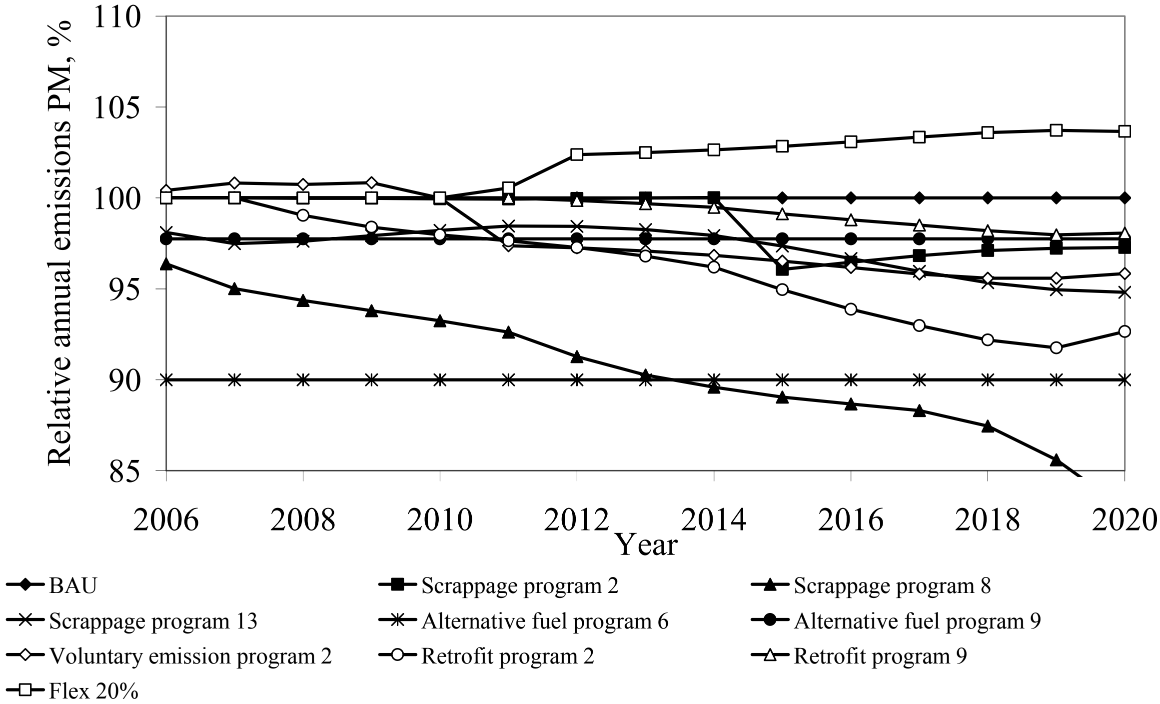

Figure 55. Relative emissions of particulate matter (PM_{10}) for various emissions reductions programs including the effects of a 20% flexibility scheme

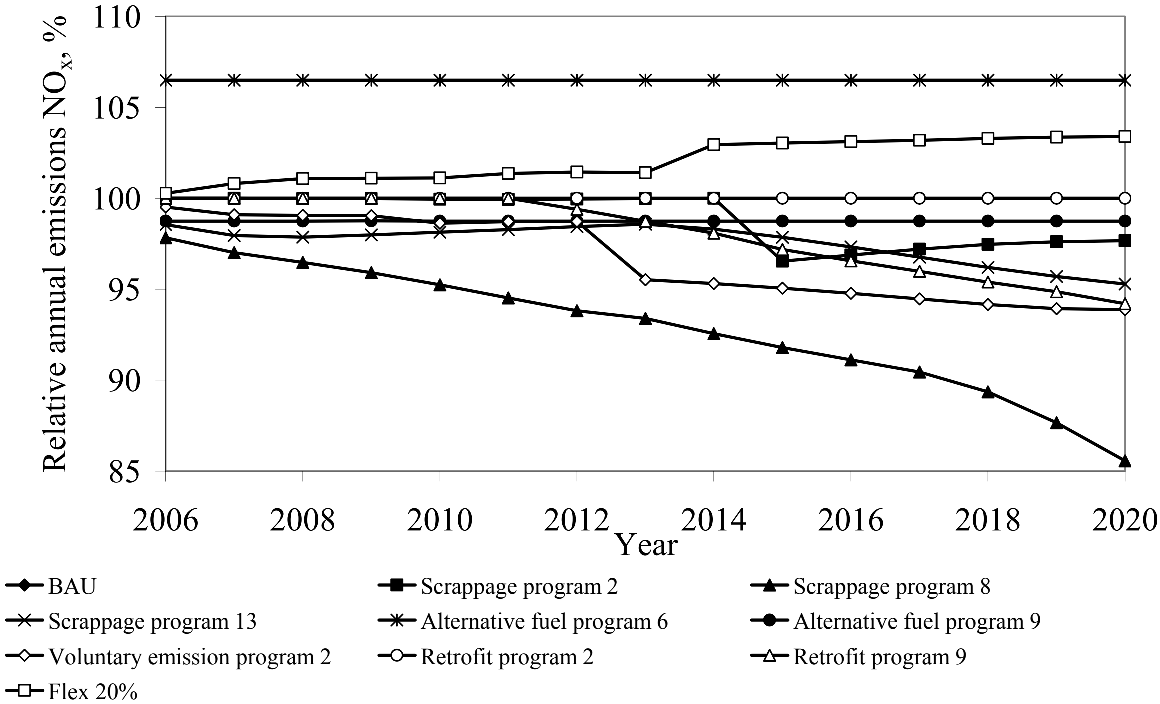

Figure 56. Relative emissions of nitrogen oxides for various emissions reductions programs including the effects of a 20% flexibility scheme

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