Emissions from Rail Transport Activities in the Urban Area of Copenhagen

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Abstract

This paper explains a detailed time-activity based emission inventory for rail transport activities made with diesel fuelled IC3 coupled train sets (IC3 trains) and ME locomotive hauled trains (ME trains) during train movement, at train stops and during service preparation, in a 5 km range inventory circle around Copenhagen Central Station.

Trains during running (percentage shares in brackets) is the largest source of fuel consumption (74 %) and NO_x (67 %), PM (65 %), CO (67 %) and HC (69 %) emissions. The fuel consumption*[NO_x, PM, CO, HC]* percentage shares are 22 %*[28 %, 31 %, 29 %, 26 %]* for train service preparation. Emission contribution shares for trains at station are in all cases 4 %. ME trains account for most of the NO_x (87 %), PM (96 %), CO (89 %) and HC (80 %) emissions, due to relatively high emission factors and a fuel consumption share of 65 %. The installation of emission abatement kits on ME locomotives completed in autumn 2013 is expected to cut down the total NO_x and PM emissions from rail transport by 26 % and 29 %, respectively.

The use of more accurate emission factors simulated for the specific train driving patterns and during engine idle combustion, would improve the precision of the emission inventory, reason being that trains during running in this work are found to be the largest emission source, and emissions during engine idle will most likely differ substantially from emissions at driving specific engine power loads.

Keywords: Trains, ME, IC3, NO_x, PM, CO, HC

1. Introduction

In 2012 a project was made by the Danish National Center for Energy and Environment (DCE) on behalf of the Danish Environmental Protection Agency in order to examine the influence on urban air quality from railway activities and the use of non road mobile machinery (Olesen et al., 2013). Two circular 5 km range areas around the central train stations of Copenhagen and the city of Aarhus were selected as investigation areas in the project.

This paper explains the baseline emission inventory for rail transport activities made with diesel fuelled IC3 coupled train sets (IC3 trains) and ME locomotive hauled trains (ME trains) during train movement, at train stops and during service preparation, in the inventory circle around Copenhagen Central Station, as input for subsequent air quality dispersion modelling.

Emission results for NO_x and PM will be shown for trains during train movement, at train stops and during service preparation. Results will also be shown for CO and HC as well as spatially distributed results for the inventory area. The emission effect of using an emission kit to reduce ME NO_x and PM emissions will be assessed, and the results from rail transport will be set in relation to the emissions from other sources, e.g. road transport, power plants, residential wood combustion and non road mobile machinery.

2. Method

Figure 1 (left) shows the 5 km range inventory circle around Copenhagen Central Station ("København H"). The investigation area include three railway line segments; Copenhagen-Airport ("Kbh H-Airport", green color, 7.2 km), Copenhagen-Østerport ("Kbh H-Østerport", blue color, 5.7 km) and Copenhagen-Valby ("Kbh H-Valby", yellow color, 6.1 km).

Inside the investigation area, trains on the airport line stop at the "København H" and "Ørestad" stations and trains on the Valby line stops at "København H" and at the "Valby" station. On the Copenhagen-Østerport line "København H" and "Østerport" are included as stoppage stations in the survey[1].

The train service preparation center "Belvedere" is located between "Dybbølsbro" and "Sydhavn" on Figure 1 (right). Service preparation center Copenhagen ("KGC København") is located between "København H" and "Dybbølsbro".

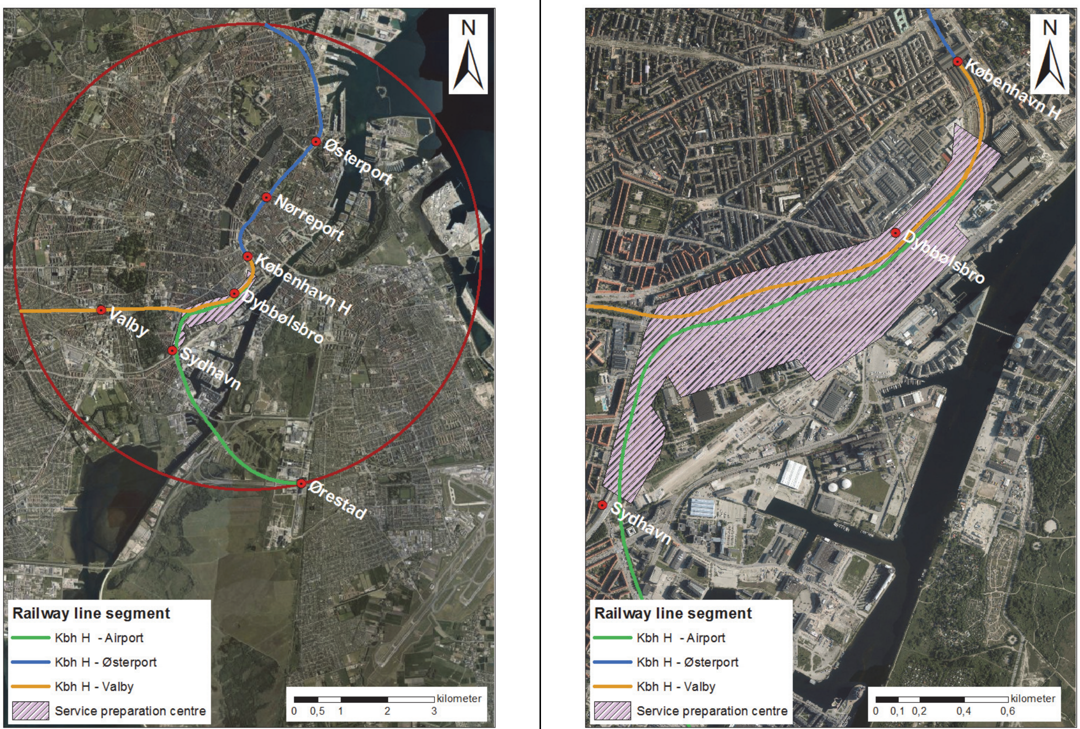

Figure 1: Map of 5 km range inventory circle around Copenhagen Central Station and a detailed map showing the location of the train service preparation centers

[1] Nørreport st. ("Nørreport T") is also a train station on this line. However, Nørreport st. is an underground station and the railway line pass through a tunnel in short sections on both sides of the station. For simplification (e.g. to exclude specific ventilation spots in the calculations) the trains are considered to move without stop between Kbh H and Østerport, and are treated as a line source of emissions.

2.1. Activity data

Activity data for passenger trains are provided by the Danish Railways (DSB) for a workday (a typical Wednesday) in 2012 with normal railway traffic on the three railway line segments inside the inventory circle. For each train running (by train number code) data consist of arrival and departure time at stations, train Litra type, and number of interconnected train sets (DSB, 2012).

The IC3 litra train type ("IC3 trains") runs on all three railway lines, and is the sole train type used on the railway connection between Copenhagen and the airport. The IC3 trains consist of separate train set units that can be coupled up in order to meet the varying passenger transport demand during a day. The ME locomotive type hauls four coaches ("ME trains") on the Copenhagen-Oesterport and Copenhagen-Valby lines.

The train number codes are also used to classify each train departure into to express, intercity and regional connection types, for which DSB also provided information of stoppage time at the different stations. Regardless of train connection type, the stoppage time is one minute at the Ørestad, Valby and Østerport stations. At København H the stoppage times are; Express (IC3, five minutes), Intercity (IC3, eight minutes) and Regional (IC3 or ME, three minutes)

Figure 2 shows the number of trains during the day inside the inventory circle, per line segment and train type.

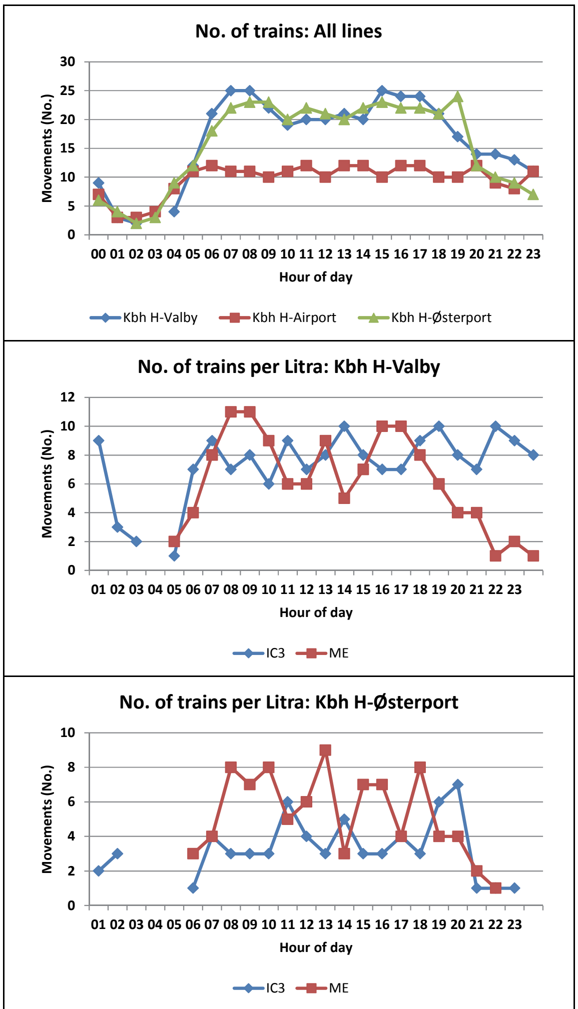

Figure 2: No. of trains per line segment and per Litra (avg. working day)

Data for service preparation of trains are also provided by DSB, and include time of arrival and departure, litra type and service time durations at the two train service preparation centers Belvedere (only ME types) and KGC København (only IC3 types). Arrival and departure service time durations are 45 minutes for Belvedere, and 5 and 20 minutes, respectively, for KGC København. Figure 3 shows the number of serviced train sets at arrival and departure at Belvedere and KGC København during the day.

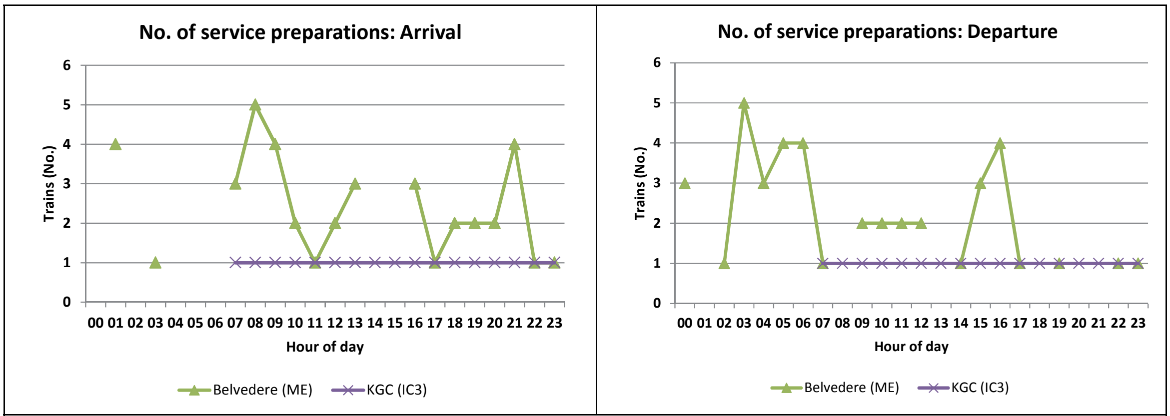

Figure 3: No. of train sets (arrivals/departures) at Belvedere and KGC Copenhagen.

2.2. Emission factors

The fuel consumption and emission factors for the IC3 and ME trains are measured by DSB. The factors are published in the Danish TEMA2010 model as average factors for the express, intercity and regional train trips made in the Danish rail network (TEMA2010). In the current project it was not possible to obtain emission factors for the specific driving patterns of the trains used on the railway lines inside the inventory circle. As an approximation in this project TEMA2010 emission factors for regional trips was chosen, which represent the lowest trip speeds of the three available train trip products offered by DSB. The selected emission factors are shown in Table 1.

Further, it was not possible to gather specific emission data for ME and IC3 trains during engine idle at station and service preparation centers in this project. Instead fuel related emission factors are derived from the km based fuel consumption and emission factors shown in Table 1. For IC3 the estimation of the idle factors make implicit that two of four engines are being switched off during the stay at stations and in the service centers.

Table 1: Emission factors during running (per seat km) and stop (per min and train set).

Litra	Fuel	CO	HC	NO_x	PM	Capacity
	MJ/seat km	g/seat km	g/seat km	g/seat km	g/seat km	seats/train set
IC3	0.219	0.012	0.006	0.091	0.0008	144
ME	0.286	0.065	0.017	0.421	0.0138	360
	MJ/min*	g/min*	g/min*	g/min*	g/min*	l/min*
IC3	4.782	0.262	0.131	1.987	0.0175	0.133
ME	17.934	4.076	1.066	26.399	0.8641	0.5

*) per train set

2.3. Calculation method

For each train during running the emissions are calculated as:

$$E = N \cdot L \cdot EF \quad (1)$$

Where E = emissions, N = number of train sets per train (= 1 for ME trains), L = length of railway line (km), EF = emission factor per train set (g/km).

For each train at station or during train service preparation emissions are calculated as:

$$E = N \cdot \Delta t \cdot EF \quad (2)$$

Where Δt = time duration (minutes), EF = emission factor per train set (g/min).

3. Results

Table 2 shows the fuel consumption and the emissions of NO_x, PM, CO and HC per line segment for trains during running, at train stops and during service preparation for the inventory area. The calculated emission results are generally explained by the size of the emission factors (Table 1), and the number of train set km driven (during running), number of stops and stoppage time (at station), and the number of service preparations and the service time durations as explained in section 2.1.

Table 2: Emission results for trains during running, at station and during service preparation, as totals and per litra for Copenhagen (one normal workday).

Activity	Line segment	Litra	No. Trains	Train set km	Fuel (MJ)	CO (g)	HC (g)	NO_x (g)	PM (g)
Running	Kbh H-Valby	IC3	169	1607	50685	2777	1389	21061	185
	Kbh H-Valby	ME	124	712	73283	16655	4356	107874	3531
	Kbh H-Valby	Total	293	2319	123967	19432	5745	128935	3716
	Kbh H-Lufthavn	IC3	66	852	26882	1473	737	11170	98
	Kbh H-Østerport	IC3	66	690	21759	1192	596	9041	79
	Kbh H-Østerport	ME	90	556	57209	13002	3401	84214	2756
	Kbh H-Østerport	Total	156	1246	78968	14194	3997	93255	2836
	Total travel	IC3	301	3150	99326	5443	2721	41272	363
	Total travel	ME	214	1267	130492	29657	7757	192088	6287
	Total travel	Total	515	4417	229818	35100	10478	233361	6650
Stops	Station	Litra	No. of stops	Train set mins	Fuel (MJ)	CO (g)	HC (g)	NO_x (g)	PM (g)
	Kbh H stop	IC3	152	1436	6868	376	188	2854	25
	Kbh H stop	ME	107	326	5846	1329	348	8606	282
	Kbh H stop	Total	259	1762	12714	1705	536	11460	307
	Valby stop	IC3	43	65	311	17	9	129	1
	Valby stop	ME	60	60	1076	245	64	1584	52
	Valby stop	Total	103	125	1387	262	72	1713	53
	Ørestad stop	IC3	34	59	282	15	8	117	1
	Østerport stop	IC3	33	55	263	14	7	109	1
	Østerport stop	ME	45	45	807	183	48	1188	39
	Østerport stop	Total	78	100	1070	198	55	1297	40
	Total stop	IC3	262	1615	7724	423	212	3209	28
	Total stop	ME	212	431	7730	1757	459	11378	372
	Total stop	Total	474	2046	15453	2180	671	14587	401
Service	Preparation center	Litra	No. of train sets	Train set mins	Fuel (MJ)	CO (g)	HC (g)	NO_x (g)	PM (g)
	KGC Kbh. Departure	IC3	17	340	1626	89	45	676	6
	KGC Kbh. Arrival	IC3	17	85	407	22	11	169	1
	Belvedere Departure	ME	41	1845	33088	7520	1967	48707	1594
	Belvedere Arrival	ME	41	1845	33088	7520	1967	48707	1594
	Total Service	IC3	34	425	2033	111	56	845	7
	Total Service	ME	82	3690	66176	15040	3934	97414	3189
	Total Service	Total	116	4115	68209	15151	3989	98258	3196
All	Grand total	IC3			109082	5977	2989	45326	398
	Grand total	ME			204398	46454	12150	300880	9848
	Grand total	Total			313480	52431	15138	346206	10247

Trains during running (percentage shares in brackets) is the largest source of fuel consumption (74 %) and NO_x (67 %), PM (65 %), CO (67 %) and HC (69 %) emissions (Figure 4). The fuel consumption*[NO_x, PM, CO, HC]* percentage shares are 22 %*[28 %, 31 %, 29 %, 26 %]* for train service preparation. The emission contribution share for trains at station is in all cases 4 %.

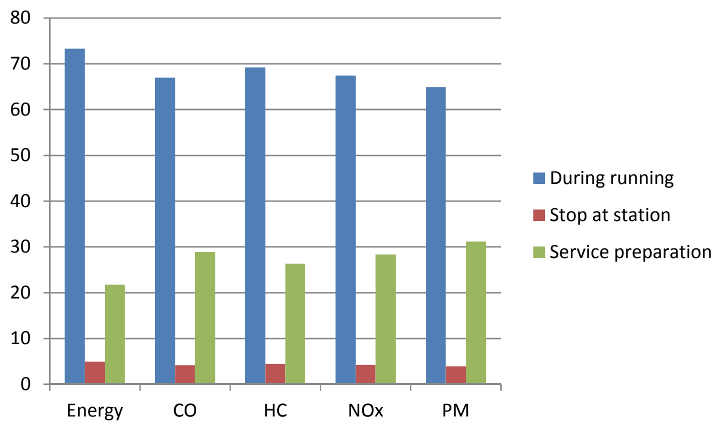

Figure 4: Percentage share of fuel consumption, NOx, PM, CO and HC emissions for trains during running, stop at station and during train service preparation.

Figure 5 shows the percentage shares of fuel consumption, NO_x, PM, CO and HC broken down into line segment, train station, and service preparation center contributions.

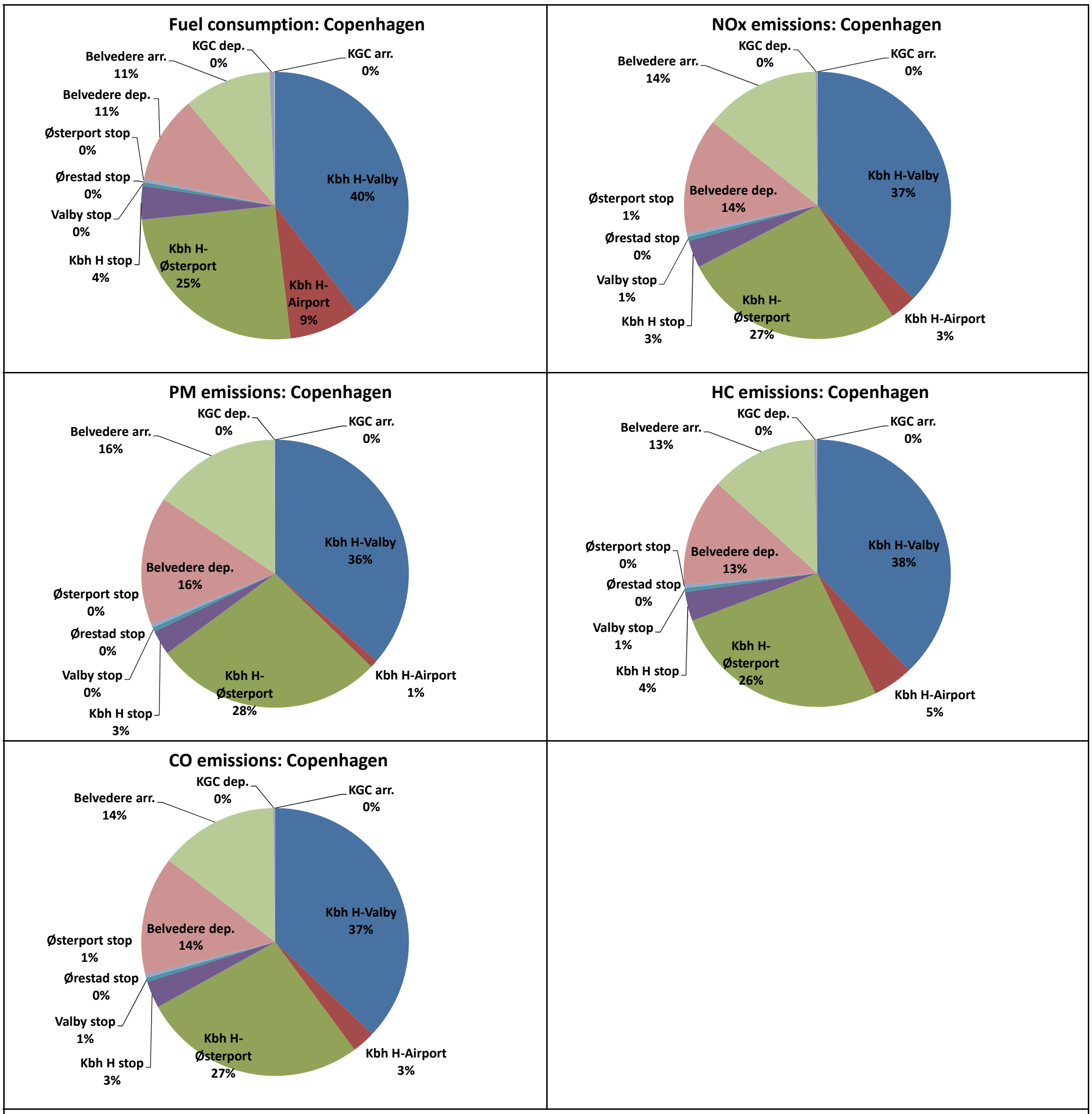

Figure 5: Inventory results for railways activities in Copenhagen broken down into line segment, train station, and service preparation center contributions.

Per train type, the ME train is by far the most dominant source of fuel consumption, NO_x, PM, CO and HC emissions; the shares are 65 %, 87 %, 96 %, 89 % and 80 %, respectively. More emission explanations will be given in the following.

Hourly emission results

Figure 6 shows the hourly NO_x and PM emissions per line segment for trains during running. For the Kbh-Valby and Kbh H-Airport lines litra specific emission results are also shown. Needless to say, for ME and IC3 trains the emissions in Figure 5 are directly proportional with the number of train set km's driven (Figure 2), this proportionality, though, being most visible for ME trains due to their relatively high emission contributions. The NO_x and PM emissions from ME trains on the Kbh-Valby and Kbh H-Airport lines are high compared with the emission contributions from IC3, due to the large emission factors for the ME train type (Table 1).

Reversely, the IC3 emissions are relatively low during running, and the NO_x and PM shares amount to 18 % and 5 %, respectively of the total emissions during running. The IC3 emission factors are 22 % and 6 %, for NO_x and PM, respectively, compared with those of ME (Table 1). The IC3:ME emission factor ratios are the same as the total emission ratios (derived from Table 2), in fact the two train types produce almost the same number of seat km in the inventory area.

The fuel consumption, CO and HC contributions for IC3 trains are 43 %, 16 % and 26 %, respectively, of the totals for running trains. For ME trains, the fuel consumption, NO_x, PM, CO and HC emission shares are 57 %, 82 %, 95 %, 84 % and 74 %, respectively. For the Valby*[Østerport, Airport]* lines fuel shares are 54 %*[34 %, 12 %]*. Emission shares for CO, HC, NO_x and PM are 56 %[40 %, 4 %], 55 %[38 %, 7 %], 55 %[40 %, 5 %] and 56 %[43 %, 1 %].

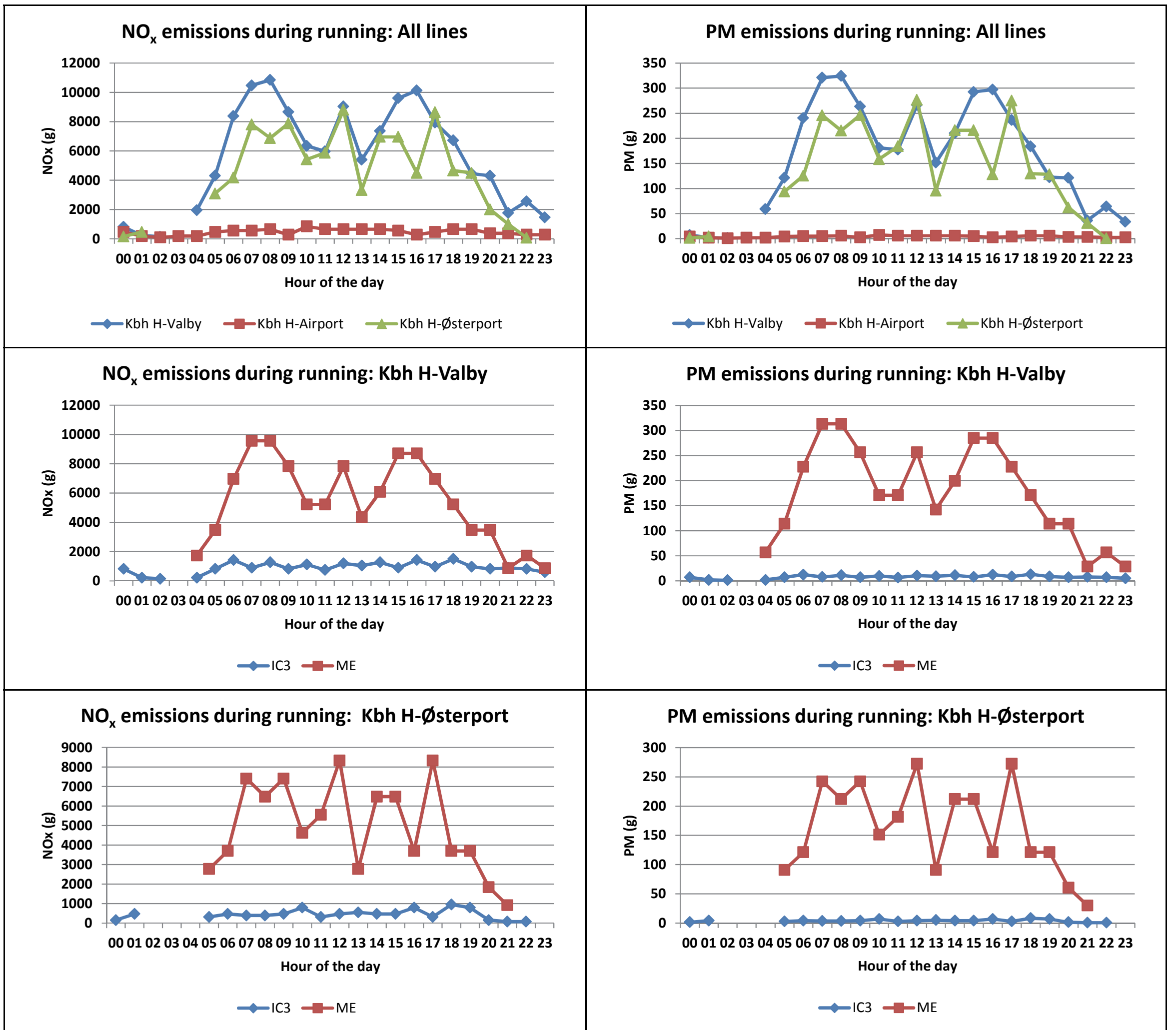

Figure 6: NO_x and PM emissions during running for line segments and per litra for Kbh H-Valby and Kbh-Østerport.

Figure 7 shows the hourly NO_x and PM emissions during train service preparations at the Belvedere and KGC service centers. The emission developments in Figure 7 directly reflect the development in the train service activities in Figure 3 combined for arrivals and departures. The fuel consumption share for ME service at Belvedere is as high as 97 % of total train service fuel consumption, and for NO_x ,PM, CO and HC emissions the shares are even higher; 99.1 %, 99.8 %, 99.3 % and 98.6 %, respectively (derived from Table 2). The high emission shares are explained by the high time related emission factors for ME compared with IC3 (Table 1), and the total service time used at each service preparation location (train set mins, Table 2).

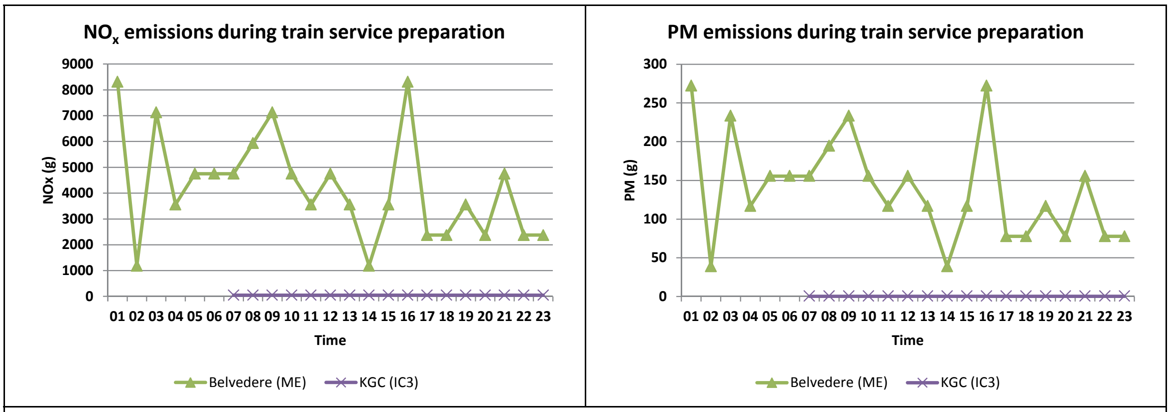

Figure 7: NO_x and PM emissions during train service preparations (arrivals and departures) at Belvedere and KGC Copenhagen service preparation centers.

Emissions from other sources

Table 3 shows the emissions of NO_x and $PM_{2.5}$ in the inventory area made up with the Danish SPREAD model; a database GIS model that allocates the Danish emission inventories[2] in a spatial resolution of 1 x 1 km (Plejdrup et al., 2011).

Table 3: Emissions of NO_x and $PM_{2.5}$ for all sources in the inventory area.

Source	NO_x	% of total	$PM_{2.5}$	% of total
Public electricity and heat production	988	26	16	3
Residential heating	97	3	341	55
Road	2236	59	180	29
Rail, this project scaled to year[3]	107	3	3.2	0.5
Other transport	31	0.8	0.3	0.0
Non road machinery	257	7	26	4
Miscellaneous sources	85	2	56	9
Total	3802	100	623	100

For NO_x, the largest emission sources are road transport and heat and power production at large heat and power plants. For $PM_{2.5}$ most of the emissions comes from residential wood burning and road transport. The residential heating $PM_{2.5}$ estimate is regarded with some uncertainty due to uncertainties in the emission calculations and their allocation. Also the allocation of non road mobile NO_x and $PM_{2.5}$ in this specific city area is regarded with some uncertainty. Although rail transport emissions depending on wind direction and other ambient atmospheric conditions can be a big environmental nuisance to humans close to the railway lines where the emissions occur, it must be stressed that trains only contribute with 3 % of total NO_x and 0.5 % of total $PM_{2.5}$ for the inventory area as a whole.

[2] For other sources than rail transport, estimates are for the year 2010.
[3] For rail, the one-day emission totals are scaled to year with a factor of 310 (DSB, 2012), and show a good correspondence with SPREAD 2010 NO_x (116 tonnes) and $PM_{2.5}$ (3.9 tonnes).

Spatial emission distribution

Figure 8 shows the spatial emission distribution for rail transport activities in the inventory area. The highest emissions are seen on the railway lines passing through the service preparation areas. As previously explained most of the emissions come from ME trains and these trains are also the predominant source of emissions on the Valby and Østerport lines. A dim emission trail is visible on the Airport line between Sydhavn and Ørestad due to the relatively small emissions from the IC3 trains.

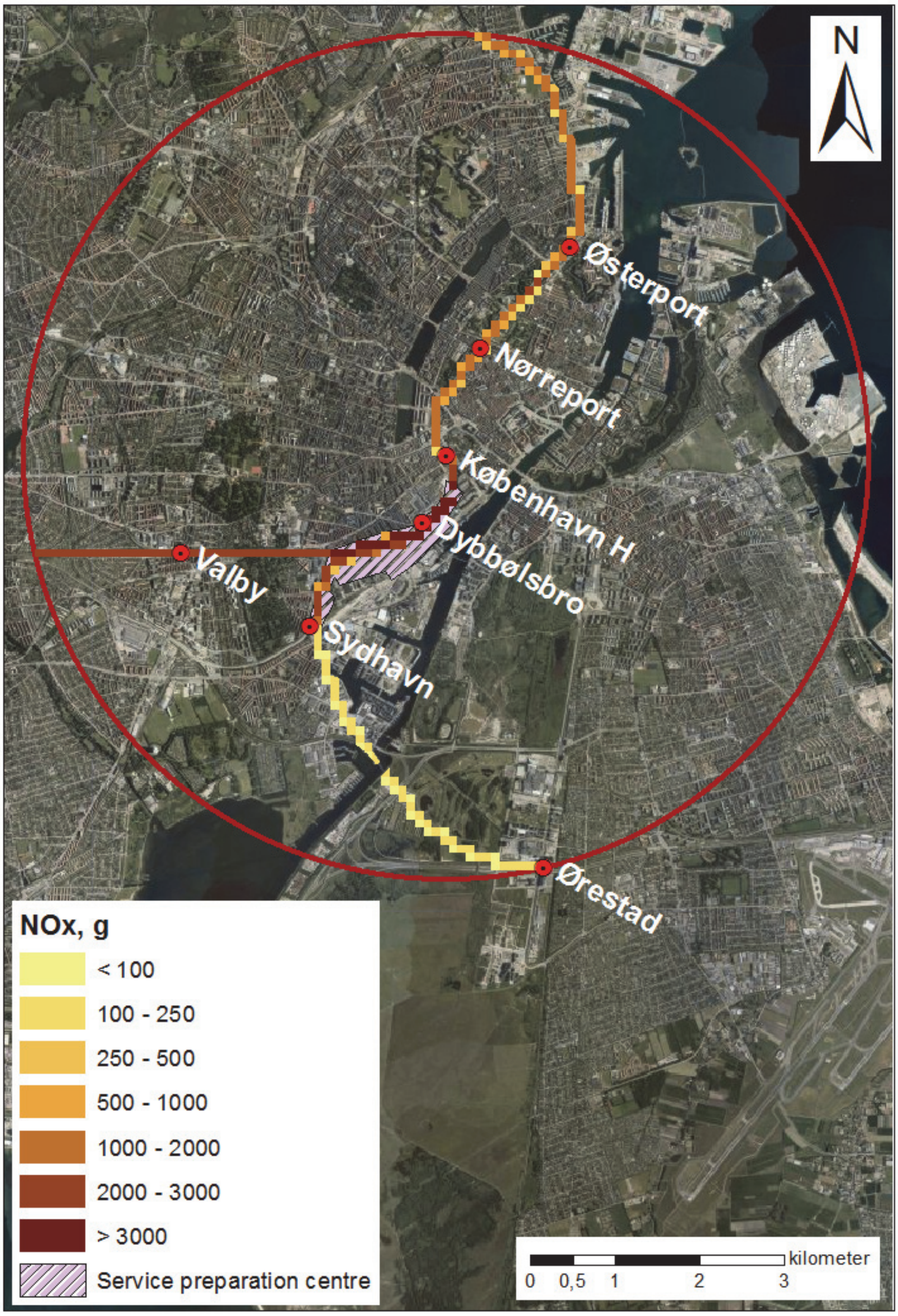

Figure 8: Spatial distribution of NO_x emissions (100m x 100m) from rail transport activities in the 5 km inventory circle around Copenhagen Central Station.

Emission consequences of ME emission abatement kit

In 2011 DSB began the installation of emission abatement kits on all ME locomotives in their fleet in order to cut down NO_x and PM emissions. The emission abatement kit used by DSB consist of more emission effective fuel injection nozzles, fuel pump and exhaust gas after cooler which on average reduce the NO_x and PM from ME locomotive engines by approximately 30 % (Skafte Nielsen, 11/7 2014). The retrofit program was completed in autumn 2013, however, due to the timeline of the project the positive effect on the emissions from trains was not included in the calculations from the beginning in this project.

Subsequently the expected emission consequences of the installation of emission abatement kits on ME locomotives used in the inventory circle can be assessed. In total the NO_x and PM emission reductions from railway activities achieve 26 % and 29 %, respectively. For trains during running, at train stops and during service preparation the NO_x*[PM]* emission reductions become 25 %*[28 %]*, 30 %*[30 %]* and 23 %*[28 %]*, respectively; the listed emission reduction variations rely on the changes in ME emission importance in the different source categories.

4. Conclusions

This paper explains the baseline emission inventory for rail transport activities made with diesel fuelled IC3 coupled train sets (IC3 trains) and ME locomotive hauled trains (ME trains) during train movement, at train stops and during service preparation, in a 5 km range inventory circle around Copenhagen Central Station. Time specific activity data per train type (no. of trains per line segment, time duration at station) and time per train type during train service preparation are provided by the Danish Railways for a typical work day in 2012. Emission factors (g/km, g/s) measured for IC3 and ME trains come from the TEMA2010 model, based on average driving.

Trains during running (percentage shares in brackets) is the largest source of fuel consumption (74 %) and NO_x (67 %), PM (65 %), CO (67 %) and HC (69 %) emissions inside the inventory circle. The fuel consumption*[NO_x, PM, CO, HC]* percentage shares are 22 %*[28 %, 31 %, 29 %, 26 %]* for train service preparation, whereas the emission contribution shares for trains at station are in all cases 4 %. ME trains account for most of the NO_x (87 %), PM (96 %), CO (89 %) and HC (80 %) emissions, due to relatively high emission factors and a fuel consumption share of 65 %. The installation of emission abatement kits on ME locomotives completed in autumn 2013 is expected to cut down the rail transport related NO_x and PM emissions by 26 % and 29 %.

The use of more accurate emission factors simulated for the specific train driving patterns inside the inventory circle and during engine idle combustion would improve the precision of the railway inventory estimates. The reasons are that trains during running are found to be the largest emission source in this work, and emissions during engine idle will most likely differ substantially from emissions at driving specific engine power loads.

Acknowledgements

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