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Mobile Emission Factor Determination through Ambient Air Monitoring - MEDAM Project

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SUMMARY

Emissions from mobile sources form a major factor in defining urban air quality. The emission factors for mobile sources function as a prerequisite in enabling the evaluation of possible abatement measures and the forecast of urban air quality. Furthermore, emission factors for mobile sources are used for evaluating the health risk associated with particulate matter for which traffic is considered a relevant source.

A recent review on emission factors has shown large discrepancies for the particulate matter emission factors for mobile sources between published values and those currently used for model assessments using CAR and OPS and based on RIM+ data. The uncertainty about these factors has been further increased by an observation in the Dutch National Air Quality Monitoring Network indicating a possible overestimation of the factors.

To address this uncertainty a limited monitoring campaign was designed to confirm one of the emission factors cited in the recent review. For nine days during the winter of 1996 particulate matter (PM_{10} and $PM_{2.5}$), along with the co-pollutants CO and NO_x, were measured in different streets in Amsterdam. The measurement results were used to estimate the emission factors for light duty (LDV) and heavy duty verhicles (HDV) on the basis of the co-pollutants' emission factors.

The estimated emission factors for PM_{10} were 0.2 ± 0.7 g/km and 16.3 ± 6.9 g/km for LDV and HDV, respectively, while for $PM_{2.5}$ the values were more accurate: 0.13 ± 0.07 and 3.2 ± 1.1 g/km, respectively. The meteorological conditions and the possible presence of other sources, including the application of de-icing salt on the road, affected the PM_{10} measurements to such a degree that no conclusive confirmation could be found. For $PM_{2.5}$, however, the results suggested to replace the currently used factors by those based on the review.

The limited number of measurements from this campaign and the restrictions in the design will not allow to estimate the emission factors but do offer a tool for confirmation or falsification within certain margins. To obtain more representative data the study should be repeated during other periods of the year, using better attuned instrumentation and possibly other co-pollutants including organics.

SAMENVATTING

De luchtkwaliteit in steden wordt voor een belangrijk deel bepaald door de emissies van verkeer. Om de invloed van voorgenomen emissiereducerende maatregelen te kunnen evalueren en de luchtkwaliteit in steden te kunnen voorspellen zijn de emissie factoren van verkeer een eerste vereiste. Voor de evaluatie van het gezondheidsrisico geassocieerd met fijn stof, waarvoor verkeer als een belangrijke potentiele bron wordt gezien, worden fijn stof emissie factoren toegepast.
De op grond van een literatuur onderzoek voorgestelde emissie factoren van verkeer en de factoren die gebruikt werden in model berekeningen (CAR en OPS) voortkomend uit RIM+ werden relevante discrepanties geconstateerd. De onzekerheid omtrent de emissiefactoren werd versterkt door de observaties in het Landelijk Meetnet Luchtkwaliteit die een mogelijk overschatting van de toendertijd gehanteerde emissie factoren aangaven.
Om deze onzekerheid terug te dringen werd een beperkte meetcampagne opgezet voor de bevestiging van een van de twee voorgestelde factoren. Op 9 dagen in de winter van 1996 werd PM_{10} en $PM_{2.5}$ gemeten parallel aan CO en NO_x in verschillende straten in Amsterdam. Aan de hand van de meetresultaten werden de emissie factoren van personen- en bestelautos (LDV) en van vrachtverkeer (HDV) bepaald relatief ten opzichte van de emissiefactoren van CO en NO_x. De geschatte waarden voor PM_{10} waren 0.2 ± 0.7 g/km en 16.3 ± 6.9 g/km voor respectivelijk LDV en HDV. Voor $PM_{2.5}$ waren de waarden: 0.13 ± 0.07 en 3.2 ± 1.1 g/km. De meteorologische condities en de mogelijke toepassing van zout voor het ijsvrij houden van de wegen of de aanwezigheid van andere bronnen hebben de metingen dusdanig verstoord dat geen positieve bevestiging voor de voorgestelde PM_{10} emissiefactoren kon worden gegeven. Voor $PM_{2.5}$, echter, werd geconcludeerd dat de op grond van de literatuur studie voorgestelde factoren werden bevestigd door de resultaten van deze studie.
Het beperkt aantal metingen van deze meetcampagne en de beperkingen in de opzet laten niet toe dat met de resultaten de emissiefactoren kunnen worden vastgesteld maar bieden een mogelijkheid om de waarden binnen bepaalde onzekerheidsgrenzen te bevestigen dan wel te falsifiëren. Om meer representatieve gegevens te verkrijgen dient de studie over een langere periode te worden uitgevoerd waarvoor eveneens de mogelijkheid voor een beter afgestemde combinatie van instrumenten en luchtverontreinigende componenten, inclusief organische componenten, kan worden onderzocht.

CONTENTS

1. Introduction

Traffic in cities is regarded as an important source of air pollution. One of the emitted pollutants, particulate matter, is currently under close scrutiny as it is suspected to contribute to the public health risk.

To assess the contribution of mobile sources to air pollution and to enable the evaluation of envisioned abatement measures, model calculations are mandatory. Emission inventories, a prerequisite for these approaches, are based on compiling geographically desaggregated activities, such as the combustion of fuel in mobile sources and the emissions that accompany these processes. In most cases the emission factors of mobile sources are estimated by measuring the concentration in emitted gas streams of vehicles operating under standardized and non-standardized driving conditions, such as the FTP, UDC and EUDC cycles (Van den Brink, 1996). These cycles mimic the actual driving conditions of the fleet. However, the emissions from mobile vehicles depend heavily on the state of maintenance, but this is usually not included in the testing procedures. The emission factors derived from emission measurements obtained under standardized maintenance and performance conditions might be expected to underestimate the emissions of the fleet cruising the streets.

Measurements of PM_{10} in 1992 through the Dutch National Air Quality Monitoring Network (NAQMN) produced data that suggested an overestimation of the emissions of mobile sources. This observation led to the adjustment of the emission factor for mobile sources used at that time for estimating the contribution of mobile sources to air pollution by model calculations (CAR and OPS).

In a recent review of the emission from mobile sources, Van den Brink (1996) proposed factors mostly adopted from the Dutch Bureau of Statistics (CBS, 1992) but showing discrepancies with the adjusted factors.

To address the uncertainty signaled by the various sources of information, a limited measurement campaign was designed to confirm the emission factors to be used in the various ongoing assessments of particulate matter in the Netherlands. In this campaign the emission of the fleet cruising the streets of Amsterdam was evaluated by comparing the concentrations of some air pollutants, including PM_{10} and $PM_{2.5}$, in heavy traffic streets with those encountered at a nearby city background station. $PM_{2.5}$ was, in particular, included because information on $PM_{2.5}$ mobile source emissions is rather rare. This approach is a further attempt in addition to previous ones (not published data) to use ambient concentration data to evaluate emission factors.

Chapter 2 describes the experimental design of the campaign, including the assumptions on which the design was based, and the selection of the locations and measurement periods. Chapter 3 details the methods used for measuring the pollutants and the method for calculating the emission factors, as well as their uncertainty in the obtained results. In Chapter 4 the results are presented and discussed. Finally, in Chapter 5, the conclusions and recommendations for further research are formulated.

2. Experimental Design

The monitoring campaign was designed to apply ambient monitoring techniques for estimating emission factors of a single source contributing substantially to emission. The advantage of this design over emission measurements for the source traffic is that the emission of the current fleet cruising the streets is assessed. On the other hand, it has the disadvantage that other unknown sources are not monitored directly. By including two other major emittants from traffic (CO and NO_x) and given the slight difference in emission factors for these compounds for the two important classes, light-duty vehicles (LDV) and heavy-duty vehicles (HDV), sufficient information can be gathered to assess the particulate matter emission factors for both classes. This chapter stipulates the assumptions used for the design, and the experimental conditions and methods.

2.1. Assumptions

Firstly, the current approach assumes that the air quality on roads with heavy traffic is determined by two major factors: (i) the city-background concentration, representative for the large-scale dispersion of pollutants emitted inside and outside the city on which (ii) the contribution of traffic is superimposed. Secondly, the composition of the air pollution in heavy-traffic streets reflects the composition of the background pollution mixed with the different compositions of emissions from the various types of vehicles. This implies a stable composition (no chemical or physical reactions occur) a short while (a few seconds) after the pollutants leave the tailpipe. In these few seconds the emittants condense and react, taking on the form (chemical composition and size) that is measured at the emission testing sites using dilution samplers as well as at the selected sites. Thirdly, the composition of emissions from light duty vehicles (LDV) differs significantly from heavy duty vehicles with respect to particulate matter, carbon monoxide and nitrogen oxides.

The determination of the PM emission factors depends heavily on the emission factors for CO and NOx and hence the accuracy of the PM emission factors relies on the accuracy of the emission factors of these pollutants. Finally, it is assumed that the selected city background monitoring site is representative for the entire city.

2.2. Locations

The city background monitoring site selected was the site previously used in various other monitoring programmes in Amsterdam (CHEAP, Bloemen et al., 1995). It was located behind the Revaliadatie Centrum Amsterdam (RCA) building at the edge of the Vondel Park. The sighting to the east was free for several kilometers, from the west it was nearly completely obstructed by the built-up area of the Overtoom, a heavy traffic street in West Amsterdam. Only a narrow canyon-type alley between the monitoring site and the Overtoom exists. In the CHEAP study, this site proved to be a typical background location.

Eleven different heavy traffic streets were selected as based on the information provided by OMEGAM, Amsterdam and documented in Traffic-Environment Maps supplemented by information obtained during local inspections. The monitoring equipment housed in a van was parked at the curbside, when possible on the downwind side. The selected streets are listed in Table 1. The streets were categorized as for the CAR model (Eerens et al., 1993), describing the type of built-up area bordering the streets, as well as the average speed of the traffic flow.

2.3. Measurement periods

For practical reasons the measurements were performed between 08:00 and 18:00 hours. The period was limited due to the limited operational time of the battery-powered equipment. The measurement dates are given in Table 1.

Table 1: Street monitoring sites

No.[1]	*Street name*	*Measuring date*	*CAR type*	*Speed*[2] *class*	*Meteorological conditions*
1	Overtoom	16/1/96	3b	c	low wind speed
2	Vijzelstraat	17/1/96	3b	c	low wind speed, fog
3	Overtoom	18/1/96	3b	c	low wind speed
4	Ceintuurbaan	19/1/96	3b	c	low wind speed
5	Amsteldijk	23/1/96	4	b	high wind speed (6 m/s)
6	Stadhouderskade	24/1/96	4	d	moderate to high wind speed
7	Vijzelstraat	25/1/96	3b	c	sunny, high wind speed
8	Raadhuisstraat	26/1/96	3b	c	snow, moderate wind speed
9	Weesperstraat	30/1/96	3b	e	sunny, moderate wind speed
10	Jan van Galenstraat	31/1/96	4	b	sunny, low wind speed
11	Stadhouderskade	1/2/96	4	d	clear, low wind speed
12	Erasmusgracht (near A10)	2/2/96	1	a	fog, drizzle, low wind speed
13	Stadhouderskade	6/2/96	4	d	sunny, low wind speed
14	Weesperstraat	8/2/96	3b	b	high wind speed
15	Haarlemmerweg	15/2/96	4	e	overcast, low wind speed

[1] The observations obtained on the days 1-5 were not complete and consequently could not be included in the evaluation.

[2] Speed classes are defined in the CAR model as: a - 100 km/h; b - 44 km/h; c - 19 km/h; d - 13 km/h; e - 26 km/h.

3. Material and Methods

3.1. Measurements

3.1.1. Housing

At the city background site the equipment was housed in the VOCCARe, a 12-m trailer equipped with air conditioning and parked in the parking bay of the RCA, which was very rarely used for other vehicles. The particulate matter monitors had their own inlet in the roof of the trailer at a height of approximately 3 m. The monitors for the gaseous pollutants CO and NO_x used one central inlet at the same height.
The equipment used at the traffic site was installed in a van parked at the curbside of the street. The particulate matter monitors had their own inlet in the roof of the van at a height of approximately 3 m. The gaseous monitors used one central inlet, also at the same height. Power was supplied from batteries, charged every night. The limited power supply restricted the measurement duration to approximately 10 hours.
Data acquired with a personal computer equipped with A/D converters and other interfaces were stored on the harddisk of the PC until transferred to floppy disks and transported to the laboratory for further processing.

3.1.2. PM monitoring

Two size selections were measured; PM_{10} and $PM_{2.5}$. Two TEOM 1400 (Rupprecht and Patashnick Co. Inc., Albany, NY) were used at the city background site; one was equipped with an Andersen 246B PM_{10} inlet and one with a URG $PM_{2.5}$ head (3 l/min) (University Research Glassware, Chapel Hill, NC). Filters were replaced every 10 days.
At the street site two FAG-B monitors (FH62I-N) (FAG Kugelfisher, Erlingen, Germany) were used, one equipped with an Andersen 246B PM_{10} inlet and one with a URG PM2.5 head (16.6 l/min) (University Research Glassware, Chapel Hill, NC). Both the inlets were heated to 50°C. The FAG monitors were calibrated weekly with the standard supplied by the manufacturer. The TEOMs were not calibrated during the course of the project. The TEOMs and the FAG monitors were intercompared at the end of the project period by stationing the van at the city background site for two different days. The measurement results showed the monitors to be interchangeable at the levels observed in the city: ratio TEOM/FAG 82 ± 14% and 93 ± 16% for PM_{10} and $PM_{2.5}$, respectively

3.1.3. CO monitoring

Carbon monoxide was measured with the Thermo Electron model 48 at a range of 20 ppm full scale. The span of the monitors was checked every second day and the zero every day. Corrections for both the span and zero were made for the CO monitor at the city background site; for the CO monitor in the measuring van, corrections for zero and span were done weekly.

3.1.4. NOx monitoring

Nitrogen oxide (NO_x) was measured with a Tecan Ecophysics CLD700 AL monitor. The range at the city background site was not fixed but the instrument was mainly operated at a span of 1 ppm. A range of 1 ppm was used at the street site. At the city background site the span and zero were checked every day with zero air and a standard of 780 ppb. The monitor in the van was checked (span and zero) every week with a standard of 300 ppb. Corrections for adjusting span and zero were necessary for both monitors.

3.2. Emission factor calculation

3.2.1. Calculation scheme

The contribution to the concentration of a pollutant in streets for which traffic is a major source (C_t) is assumed to be the accumulation of the city background level and the contribution of passing cars.

$$C_t = C_{street} - C_{background} \qquad [1]$$

The contribution to the concentration of traffic can also be described by:

$$C_t = N * E_f * f_{disp} \qquad [2]$$

where N is the number of cars passing during a given time, E_f the emission factor and f_{disp} a dispersion factor explaining the dilution of the emitted pollutants in the street.

In general light duty (LDV) and heavy duty vehicles (HDV) emit pollutants in different amounts and it is of interest to distinguish between these types of vehicles. Their contribution can be described by:

$$C_t = N * \{f_h * E_h + [1 - f_h] * E_l\} * f_{disp} \qquad [3]$$

where f_h is the fraction of HDV, and E_h the emission factor of HDV and E_l of LDV.

The concentrations of nitrogen oxides (NO_x) and of carbon monoxide (CO) can be treated in this way.

$$NO_{xt} = N * \{f_h * E_hNO_x + [1 - f_h] * E_lNO_x\} * f_{disp} \qquad [4]$$

$$CO_t = N * \{f_h * E_hCO + [1 - f_h] * E_lCO\} * f_{disp} \qquad [5]$$

where E_hCO and E_lCO are the CO emission factors for HDV and LDV, and E_hNO_x and E_lNO_x the emission factors for NO_x.

Eliminating the unknown f_{disp} and N by rearranging [4] and [5] gives the fraction of HDV:

$$f_h = \frac{E_lNO_x - E_lCO * (NO_{xt}/CO_t)}{(E_hCO - E_lCO)(NO_{xt}/CO_t) + E_hNO_x - E_lNO_x} \qquad [6]$$

By analogy the emission factor of traffic for PM can be described by:

$$E_tPM = f_h * E_hPM + (1- f_h) * E_lPM \qquad [7]$$

and in relation with the NO_x emission factors by:

$$E_tPM = [f_h * E_hNO_x + (1 - f_h) * E_lNOx] * PM_t/NO_{xt} \qquad [8]$$

Rearranging [7] and [8] gives another expression for f_h:

$$f_h = \frac{E_lNO_x * PM_t/NO_{xt} - E_lPM}{E_hPM - E_lPM + (E_lNO_x - E_hNO_x) * PM_t/NO_{xt}} \qquad [9]$$

Combining the equations [6] and [9] to eliminate f_h gives [10]which is the equation of the linear regression line [11].

$$\frac{PM_t}{CO_t} = \frac{E_hNO_x * E_lPM - E_hPM * E_lNO_x}{E_hNO_x * E_lCO - E_lCO * E_hCO} + \frac{E_hPM * E_lCO - E_hCO * E_lPM}{E_hCO * E_lCO - E_lNO_x * E_hCO} * \frac{NO_{xt}}{CO_t} \qquad [10]$$

$$(PM_t/CO_t) = p + q * (NO_{xt}/ CO_t) \qquad [11]$$

of which the parameters p and q can be calculated using least square regression. The PM emission factors for traffic are then extracted as:

$$E_hPM = p * E_hCO + q * E_hNO_x \qquad [12]$$

and

$$E_lPM = p * E_lCO + q * E_lNO_x \qquad [13]$$

3.2.2. Uncertainty analysis

The uncertainty in the estimated emission factor depends on the source. Based on the calculation scheme mentioned above, the contributions to the overall uncertainty are the uncertainty (i) in the emission factors for CO and NO_x for both the LDV and HDV and (ii) in the regression factors p and q of [11]. The propagation of uncertainty is calculated as the square root of the sum of squares of the relative standard errors.

3.3. CO and NO_x emission factors

The emission factors for CO and NO_x are extracted from the RIM+ database. These factors vary with speed. As the actual speed at the monitoring site was not well known and the number of observations fairly limited, the average emission factors for the range 13 to 44 km/h are used to calculate the emission factors for PM. The variance for the CO and NO_x emission factors used in the error calculation for the PM emission factor is based on this range (Table 2). Other uncertainties in the CO and NOx emission factors, as well as uncertainties caused by factors not considered here, were assumed to be irrelevant compared to the uncertainties in these emission factors.
Ambient conditions will influence the combustion in mobile sources and hence the emission factors will show a seasonal-dependent variation. The seasonal dependency of the emission of the pollutants CO and NO_x is estimated by the evaluation of levels measured at three different sets of street stations and regional background stations of the NAQMN (Table 3). The seasonal correction factor ($F_{season,X}$) is calculated by:

$$F_{season,X} = \frac{X_{traffic,campaign}}{X_{traffic,year}} \qquad [14]$$

where $X_{traffic,\ campaign}$ is the contribution of traffic to the level in the street for the periods and times when measurements were performed (approximately 08:00-18:00), calculated according to [1]; $X_{traffic,year}$ is the contribution of traffic during the entire year at the same time of the day. The seasonal dependency of CO and NO_x was estimated with the measurement results obtained at three station sets (street–rural); the average seasonal correction factors, calculated according to [14], are given in Table 3.
The corrected emission factors of CO and NO_x used for the calculation of the emission factors for PM are given in Table 5. The uncertainty of these emission factors appears to be mainly caused by the speed dependency of the emission factors. The correction factors for LDV and HDV areassumed to be identical.

Table 2: Emission factors for CO and NOx where annual averages for each speed class and the speed of average emission factors are corrected for seasonal variations

Speed	*E_lNOx*	*E_lCO*	*E_hNOx*	*E_hCO*
(km/h)	(g/km)	(g/km)	(g/km)	(g/km)
13	0.87	10.1	17.9	10.4
19	0.87	8.5	15.6	8.0
26	0.87	4.7	14.0	4.8
44	0.79	2.5	11.8	2.6
Average	0.85	6.5	14.8	6.5
Range	0.08	7.6	6.1	7.8
Rel Variance (%)	5	60	40	60
Corrected*	1.0 ± 0.3	9.5 ± 6.0	17.4 ± 5.8	9.5 ± 5.8

* See Table 3 for correction factors.

Table 3: Seasonal correction factor for three selected station sets

Street station	*Background station*	*Factor CO*	*Factor NO_x*
LML236	LML230	0.75	0.93
LML639	LML633	0.78	1.02
LML728	LML722	0.51	0.59
	Average	0.68 ± 0.15	0.85 ± 0.22

3.4. Reference emission factors

3.4.1. LDV emission factor

The reference PM emission factor for LDV is a composite of the emission factors published in the review by Van den Brink (1996) and the relative urban performance of the various LDV types in Dutch cities in 1995 (CBS, 1996). In the review mentioned, the emission from the tailpipe is assumed to be smaller than 1.0 µm and hence the tailpipe emissions for PM_{10} and $PM_{2.5}$ are identical. The contribution of the tires, brakes and road dust to the PM_{10} emissions of total emitted particulate matter are estimated at 55%, 100% and 50%, respectively. For $PM_{2.5}$ these fractions are 5%, 40% and 10% of the given values (Table 4). It is worth noting that the contribution of diesel-fueled cars and delivery vans is approximately 70% of the total emission of LDVs.

3.4.2. HDV emission factor

The reference emission factor for HDV is calculated in a similar way. It is assumed that no dust filters were used. The emission factors for buses were assumed to be similar to the factor for lorries. The composite emission factors are given in Table 5.

Table 4: LDV emission factor calculation based on data published in Van den Brink (1996)

	Urban performance	*Tailpipe*	*Tires*	*Brakes*	*Road dust*	*EpPM10*	*EpPM2.5*
Type	%	g/km	g/km	g/km	g/km	g/km	g/km
Passenger car, Petrol, catalytic converter	25.3	0.005	0.004	0.008	0.030	0.0076	0.0029
Passenger car, Petrol	26.0	0.030	0.004	0.008	0.030	0.0144	0.0095
Passenger car, Diesel	15.0	0.200	0.004	0.008	0.030	0.0338	0.0310
Passenger car, LPG	12.7	0.018	0.004	0.008	0.030	0.0055	0.0031
Delivery van, Petrol, catalytic converter	1.9	0.030	0.005	0.010	0.030	0.0011	0.0007
Delivery van, Petrol	1.9	0.053	0.005	0.010	0.030	0.0015	0.0011
Delivery van, diesel	16.1	0.300	0.005	0.010	0.030	0.0528	0.0495
Delivery van, LPG	1.1	0.017	0.005	0.010	0.030	0.0005	0.0003
Emission factor						0.12	0.10

Table 5: HDV emission factor calculation based on data published in Van den Brink (1996)

	Urban performance	*Tailpipe*	*Tires*	*Brakes*	*Road dust*	*EpPM10*	*EpPM2.5*
Type	%	g/km	g/km	g/km	g/km	g/km	g/km
Medium duty lorries	35.7	1.400	0.020	0.040	0.030	0.5228	0.5064
Heavy duty lorries	45.5	2.200	0.020	0.040	0.030	1.0318	1.0108
Buses	18.8	1.400	0.014	0.028	0.030	0.2728	0.2660
Emission factor						1.83	1.78

4. Results and Discussion

4.1. Phenomenology

4.1.1. Meteorology

The meteorological conditions of the project period are characterized by the low temperature (-9.6 °C to 4.2 °C), occasionally high wind speeds (6 m/s) and snowfall (see Table 1). The freezing conditions probably (no confirmation could be obtained) led to the application of de-icing salt.

4.1.2. NO_x ,CO

The NO_x and CO levels measured at the city background and the street site are presented in Figures 1 and 2. The large variation of the concentrations in the street is caused by the meteorological conditions and further depends on the type of the streets characterized by the CAR parameter (Table 1).

4.1.3. PM_{10} and $PM_{2.5}$

For estimating the emission factor for PM_{10} and $PM_{2.5}$ only the days for which a complete data set of measurements was available could be used. This applied to 9 out of 15 days. Normalized PM_{10} and $PM_{2.5}$ concentrations were used for the evaluation on these days. The PM concentrations due to traffic emissions (PM_t) were normalized by the CO concentration due to traffic emissions (CO_t): (PM_x/CO). CO was selected because the CO emission factors of LDV and HDV are identical.

The nine selected days are presented in Figures 3 and 4, the levels of PM_{xt}/CO_t on various days reflecting the different conditions on those days. Two consecutive days (24 and 25 January - days 6 and 7) show high normalized PM_{xt}/CO_t levels, most pronounced for PM_{10}. This indicates an excess of coarse material. The concurrence of high wind speeds suggests resuspended dust.

Normalized levels of PM_{10} on day 8 are low compared to the majority of the days (9, 10, 11 ,12 and 14). Snowfall occurred on day 8 during the morning and the temperature was well below zero (-8.4 °C to -9.0 °C). It is assumed (no visual confirmation was obtained) that due to the traffic flow most of the snow had disappeared in the afternoon. For normalized $PM_{2.5}$ these low levels were less pronounced than for PM_{10}. Here the snow coverage might have reduced the mechanically induced resuspension of coarse material.

On day 13 (6 February) moderate to high normalized levels were observed. This was a sunny day with low temperatures (-0.1 °C to -4.3°C) and low relative humidity (63%-69%).

On day 15 (15 February) the normalized levels of PM_{10} and $PM_{2.5}$ were moderate compared to the other days. On this day the humidity (78%-84%) was high and the temperature moderate (0.3 °C to 3.5 °C).

These observations suggest that resuspension modified by snow coverage and high relative humidity played an important role in the contribution of traffic to the PM concentrations. The results of all these days were used to calculate the emission factor for PM_{10} and $PM_{2.5}$.

4.1.4. Ratios $PM_{2.5}/PM_{10}$

The contributions of $PM_{2.5}$ to PM_{10} are given in Figure 5. The overall average ratios for the city background station and the mobile station are 0.59 $\pm$ 0.15 (N=379) and 0.53 $\pm$ 0.18 (N=132), respectively.

4.2. Emission factors

The emission factors are calculated on the basis of linear regression analysis according to [11]. The regression plots are given in Figures 6 and 7. The high scatter for PM_{10} ($R^2 = 0.70$) might be related to the observations mentioned above (days 6,7,8,13). The scatter of the $PM_{2.5}$ regression plot is considerably less ($R^2 = 0.925$). This points to active PM_{10} sources other than tailpipe, such as tyre and road deterioration, mechanically induced resuspended dust or Aeolian dust.

The negative intercept of both regression lines leaves part of the regression curve non-existent: no negative (normalized) concentrations can occur and if there is no NOx emitted by traffic there can be no traffic-related PM_{10} either. Plausable causes of this phenomenon are to be found among the non-linear emission rates with speed and possible over- or undercorrection for urban background concentrations at street level. For PM_{10} measurements, the difference in instrumentation might be a reason.

Table 6 presents the calculated PM_{10} and $PM_{2.5}$ emission factors for both LDV and HDV along with the reference emission factors used in RIM+ (Van den Brink, 1996) and those used in the CAR model at the time of the study of Van der Brink. No standard variation for the latter has been published and a 50% relative variation was assumed in line with the variation in the other emission factors.

The overall error in the $PM_{2.5}$ emission factor for both LDV and HDV ($E_lPM_{2.5}$ and $E_hPM_{2.5}$) is quite acceptable (approximately 40%), given the limited number of measurements. The LDV emission factor obtained in this study does not significantly differ from the reference factor. The CAR LDV emission factor represents only 26% of the MEDAM factor, a significant difference. The same applies for the CAR HDV factor (only 18% of the MEDAM factor). The MEDAM HDV factor itself is approximately twice as large as the reference factor.

The reference and MEDAM LDV PM_{10} factors (E_lPM_{10}) are in the same range (0.12 and 0.21 g/km, respectively) and due to the large error in the MEDAM factor (>300%) the actual difference is not significant. For the HDV PM_{10} emission factor the difference between the MEDAM and reference factor is even more than for $PM_{2.5}$: a ratio of approximately 9. The ratio of the reference and the CAR HDV factors is approximately 3.

Table 6: PM emission factors for LDV and HDV (in g/km)

	$E_l PM_{2.5}$	$E_h PM_{2.5}$	$E_l PM_{10}$	$E_h PM_{10}$
MEDAM (this study)	0.13 ± 0.07	3.15 ± 1.11	0.21 ± 0.68	16.3 ± 6.9
Van den Brink (1996)	0.10 ± 0.05	1.78 ± 0.89	0.12 ± 0.06	1.83 ± 0.92
CAR adjusted	0.034 ± 0.017	0.58 ± 0.29	0.038 ± 0.019	0.64 ± 0.32

The emission factors for $PM_{2.5}$, LDV and HDV obtained in this study are not significantly different from those used in RIM+ (Van den Brink, 1996). The factors used in the CAR model seem to be lower than in this study.
The LDV emission factor for PM_{10}, calculated from the measurement results of this study, shows no significant difference with either the reference or the CAR factor. The reference factor, though, is more in the range of the obtained factor than the adjusted CAR factor is. The MEDAM PM_{10} emission factor for HDV is much higher than the RIM+ factor or the CAR factor. Given the fact that the MEDAM $PM_{2.5}$ emission factors do not differ largely from the reference factor, the discrepancy must be sought in the coarse fraction. The emission factor for PM_{coarse} can be evaluated by:

$$E_x PM_{coarse} = E_x PM_{10} - E_x PM_{2.5} \qquad [15]$$

The $E_l PM_{coarse}$ factor is 0.1 ± 0.7 g/km, about the same order of magnitude as the $E_l PM_{10}$. $E_h PM_{coarse}$ is 13.2 ± 7.0 g/km, which accounts for 80% of the total PM_{10} emissions by HDVs.
An emission factor of resuspended dust is very hard to come by. USEPA has proposed a formula in which the silt loading of the road (mass of particles smaller than 75 $\mu m/m^2$ of road surface) and the weight of the vehicle are important factors (Quality of Urban Air Review Group, 1996). However, the range of silt loading of 0.01 - 30 g/m^2 measured in the USA will possibly not be appropiate for wetter conditions such as those in the Netherlands.
In a recently published study (Moosmuller et al., 1998) an emission factor was found for fast travelling large vehicles (lorries, semitrailers and vehicles pulling trailers) of 8 ± 4 g/km. This emission was related to the entrainment of material from the shoulders of the road due to the turbulence in the wake of vehicles. The measurements were carried out under dry conditions (June) on a typical rural road with unpaved shoulders in California, USA. Emissions from smaller vehicles (cars, vans and sport utility vehicles) were negligible. Both studies support the findings of the MEDAM study in that the concentration due to resuspension is mainly caused by large vehicles.
For this source, relevant for the PM_{10} levels, is very hard to estimate with the current tools further investigation needed. Complications here are the difficulty in assessing the state of the road, such as silt loadings and paved or unpaved shoulders of the road, the presence of sources (typical for the street) emitting, in particular, coarse material and the influence of the meteorological conditions. Finally, the extrapolation of the findings to the road system of the investigated area is also difficult.

5. Conclusion and Recommendations

The approach followed in this study shows potential for acquiring information on emission factors for pollutants emitted by mobile sources in use through limited measurement campaigns. The advantage of this approach is that the actual emission factor averaged over the fleet cruising the streets is assessed. A disadvantage is that the dependency on other emission factors might be marked and hence the quality of these factors are relevant.
The limited number of measurements from this campaign and the restrictions in the design will not allow an estimate of the emission factors but can only function as a tool for confirming them.
The measurement campaign was completed during the winter with low temperatures and either low relative humidities or heavy precipitation. Under these conditions the PM_{10} levels show a large variation, possibly due to strongly varying resuspension of material deposited by road and tire wear, applied de-icing salt and other unknown sources. This may have made the PM_{10} emission factor determination somewhat erroneous. The uncertainty in the PM_{10} emission factors obtained is also caused by the uncertainties in the other factors: emission factors of NO_x and CO, and the seasonal correction factor. The $PM_{2.5}$ emission factors were obtained with a lower uncertainty, although the uncertainty in the other factors still contribute substantially.
Therefore the results can be concluded to confirm the reference emission factors for $PM_{2.5}$ for both LDV and HDV. For the PM_{10} LDV factor, results are inconclusive. The high PM_{10} emission factor for HDV suggests that other sources, possibly resuspension, are active.
The period during which measurements were carried out is certainly not representative for one year. Changes in tailpipe emissions caused by difference in temperature and changes in resuspension caused by different available silt loadings might lead to other observed emission factors. To obtain more representative data to derive emission factors, the study should be repeated during other periods of the year, using better attuned instrumentation and possibly other co-pollutants including organics.

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Appendix 1 Figures

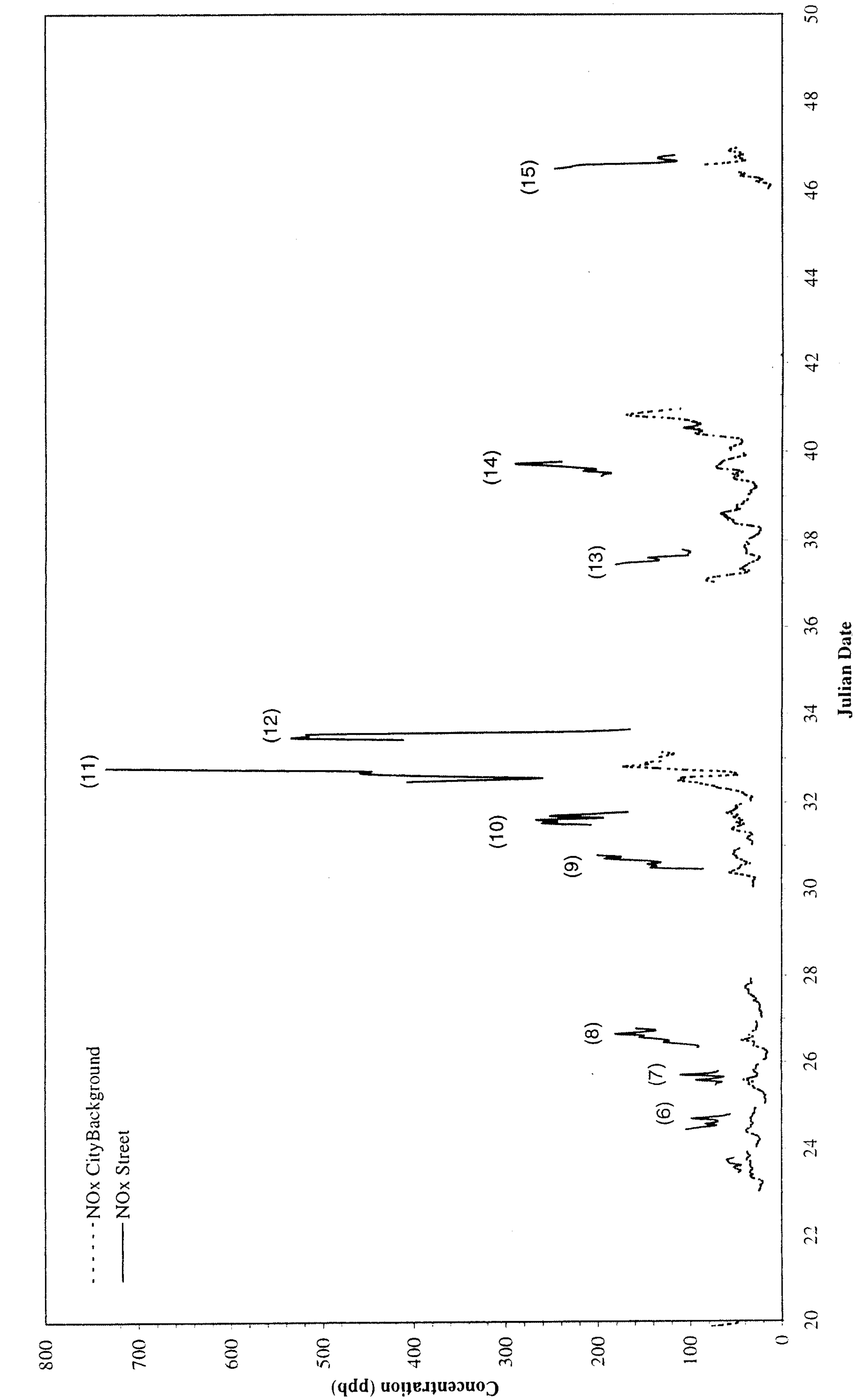

Figure 1: NOx concentrations at citybackground and street sites. Numbers correspond with Tabel 1.

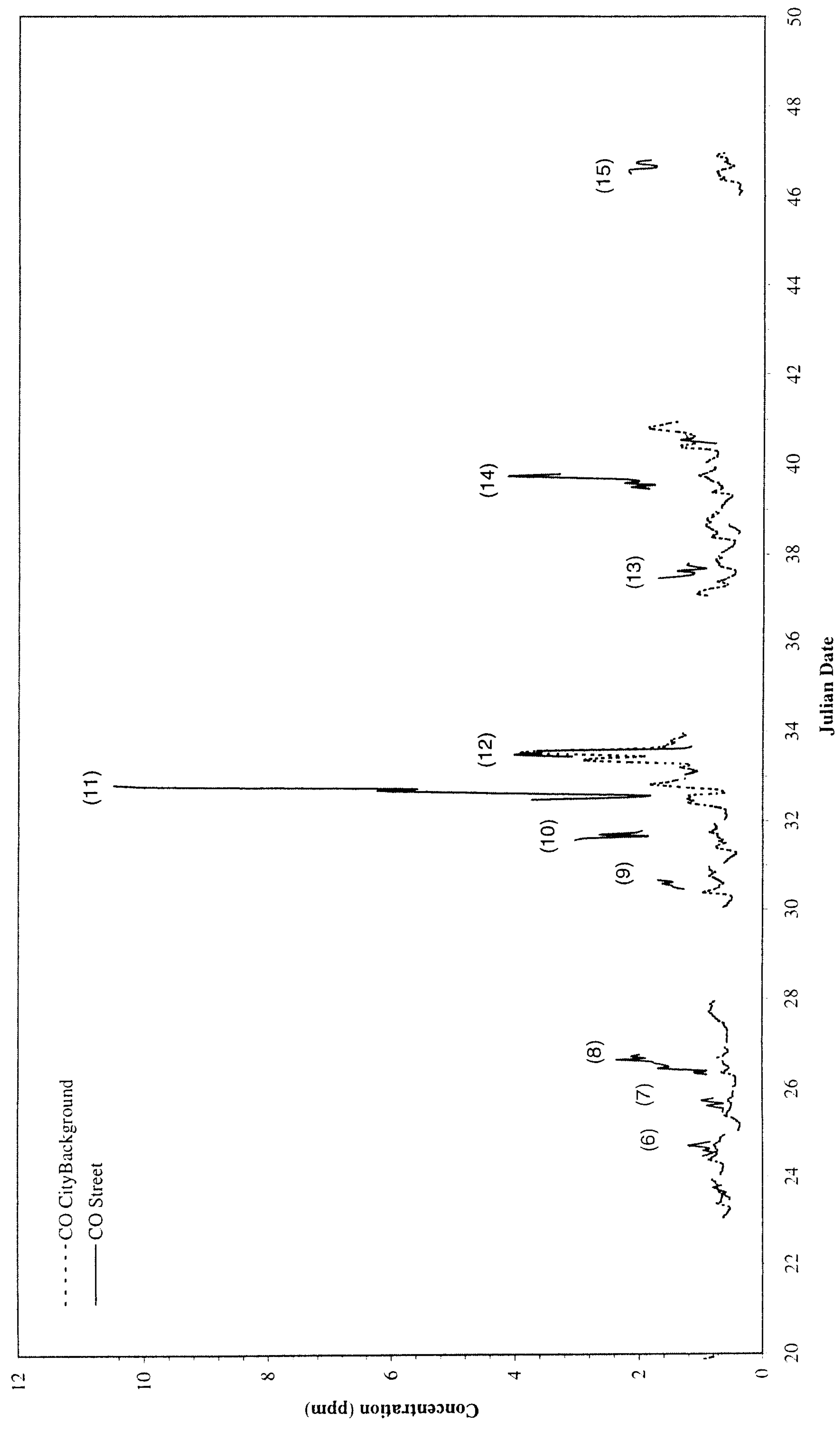

Figure 2: CO concentrations at citybackground and street sites. Numbers correspond with Tabel 1.

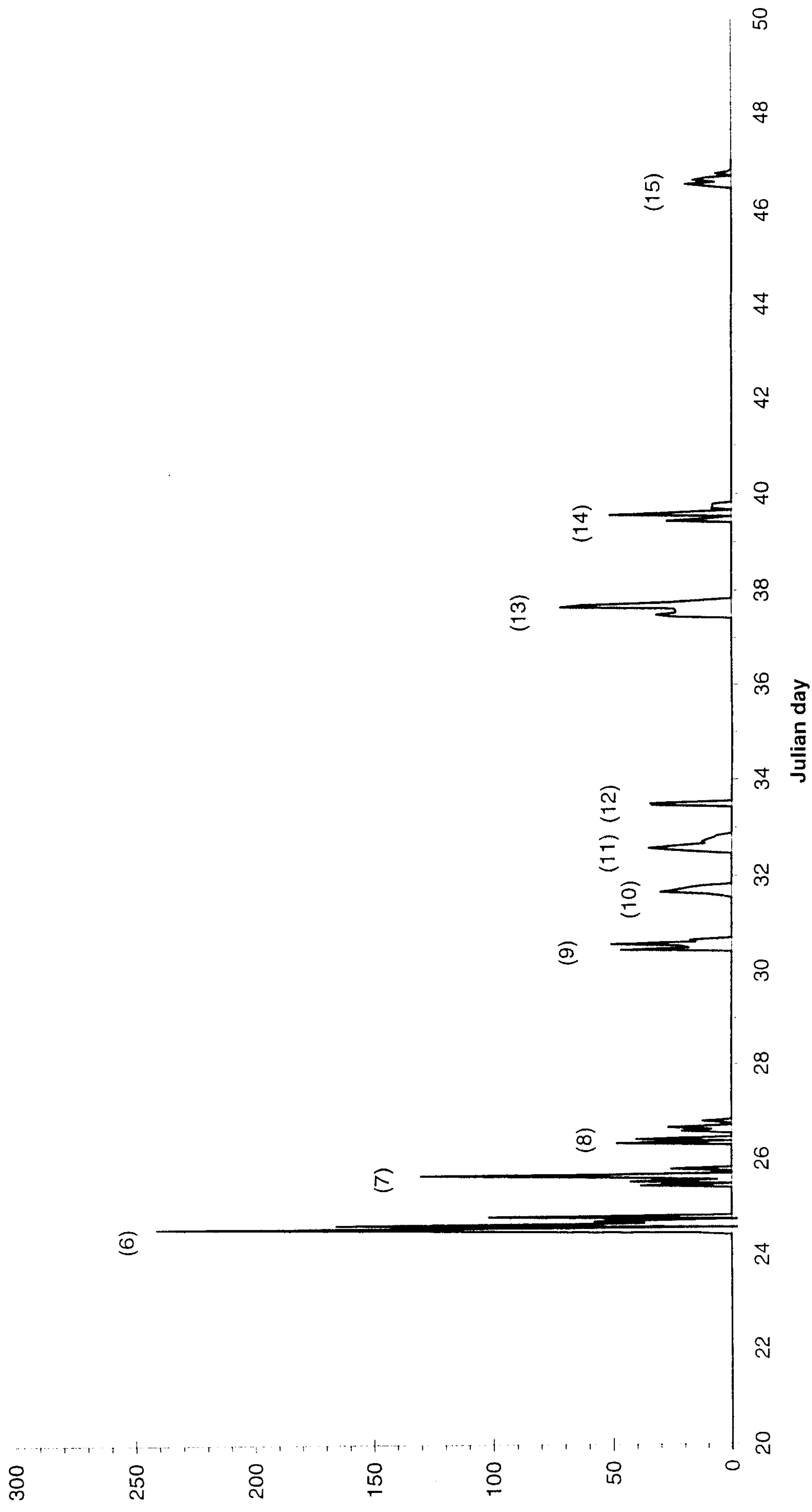

Figure 3: Normalized PM2.5 concentrations for each measurement day (number corresponds with Tabel 1)

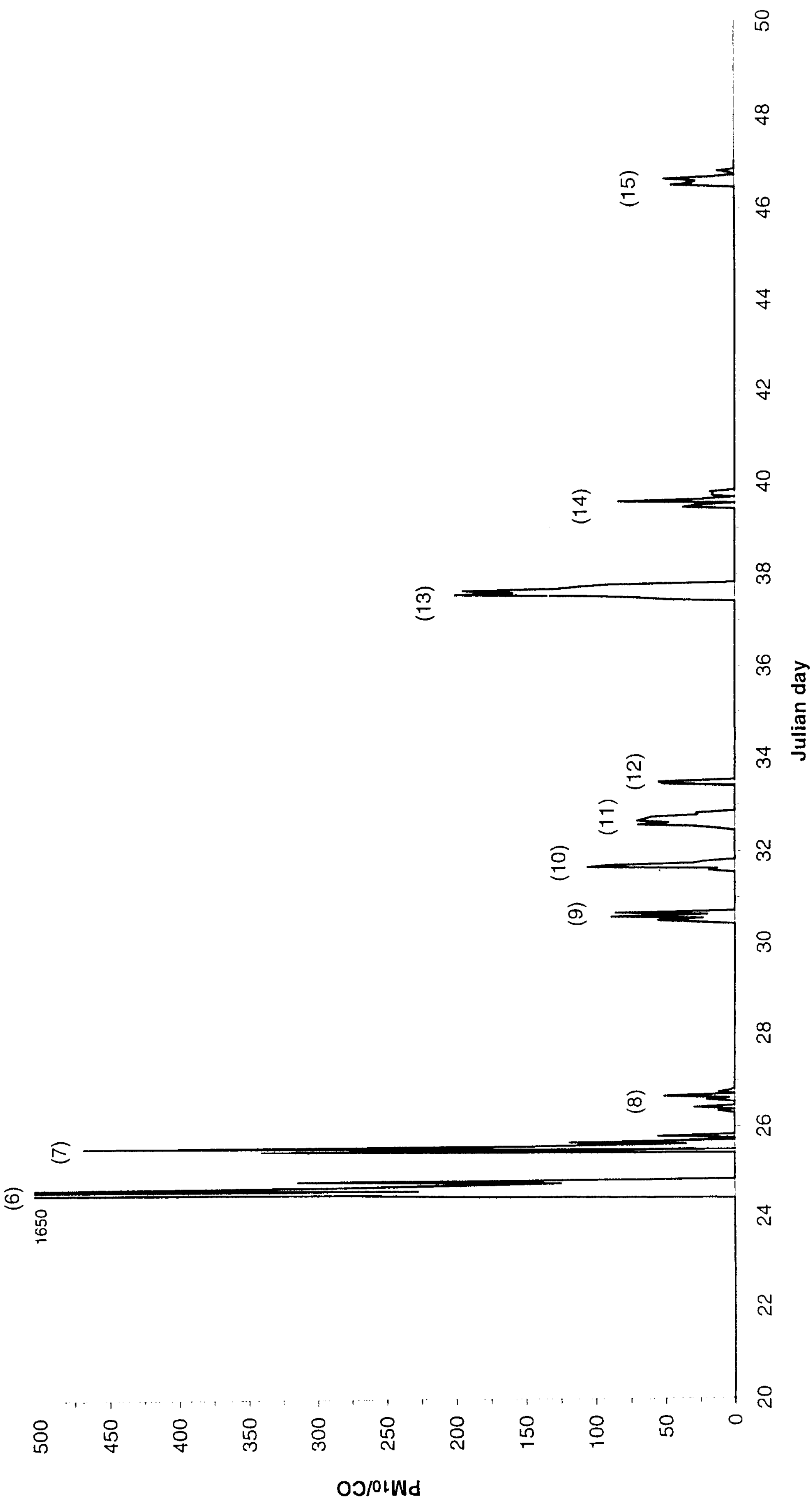

Figure 4: Normalized PM10 concentrations for each measurement day (number corresponds with Tabel 1)

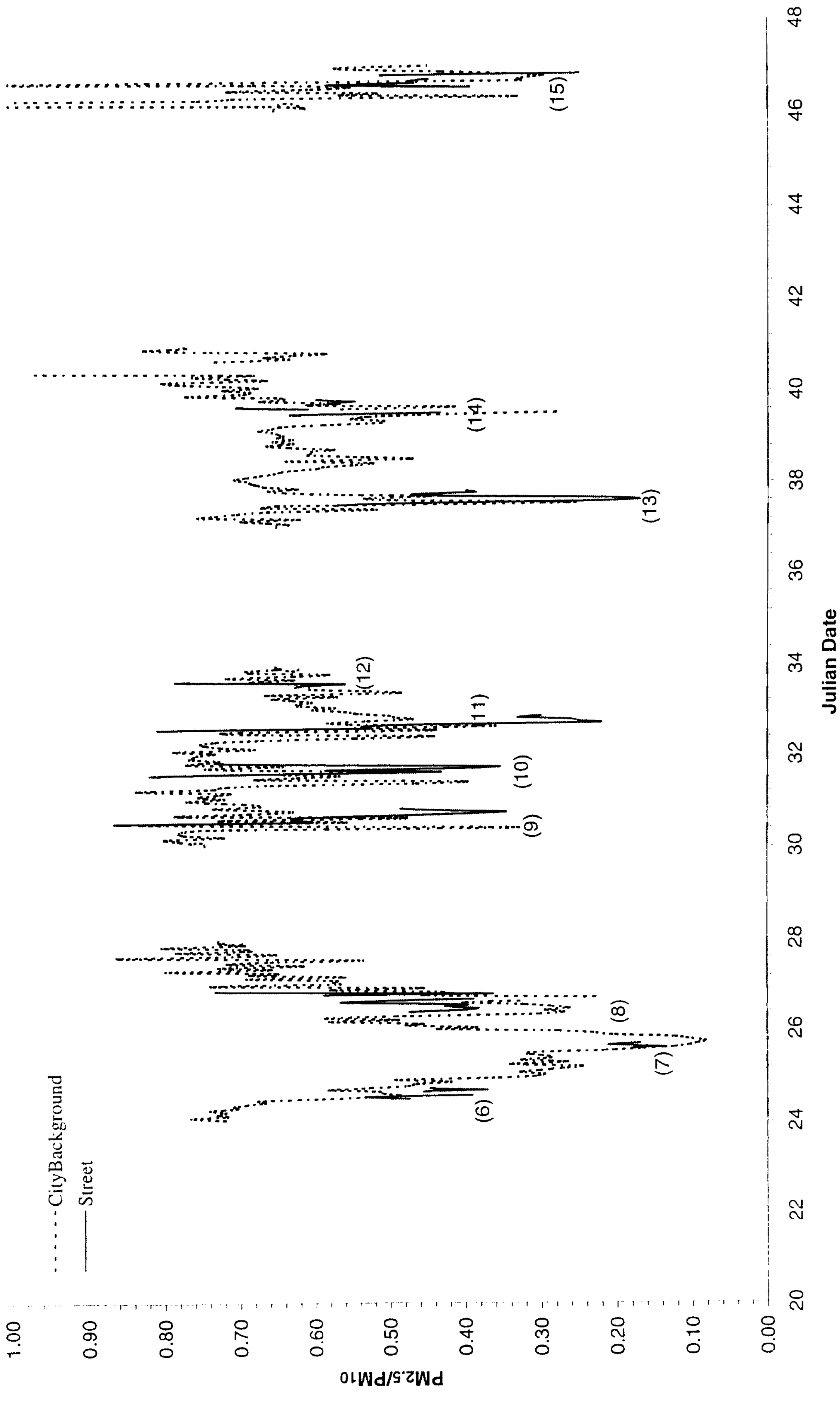

Figure 5: PM2.5/PM10 ratio for the city backround site and the street. Numbers correspond with Tabel 1.

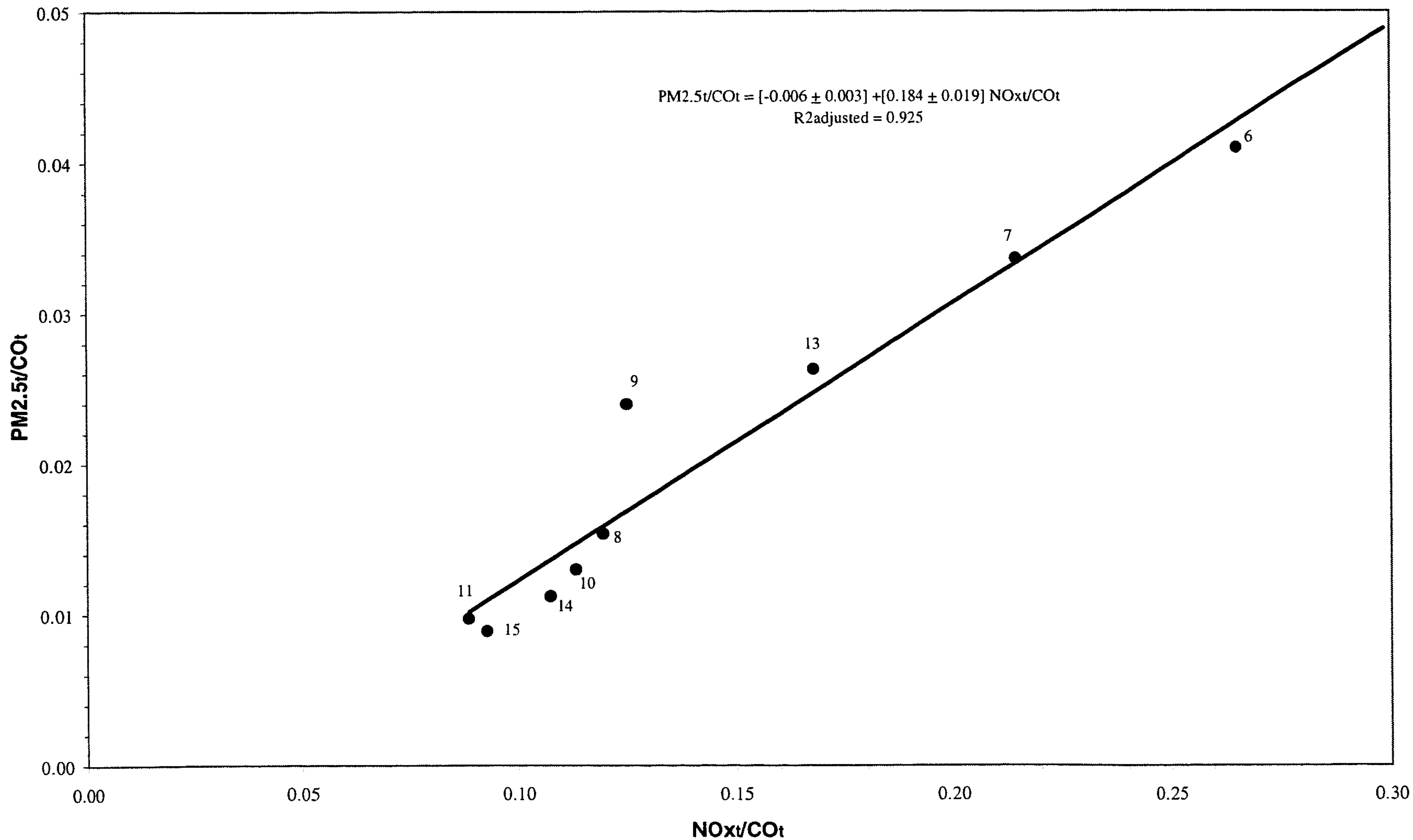

Figure 6: Regression of PM2.5t/COt on NOxt/COt. Numbers correspond with Tabel1

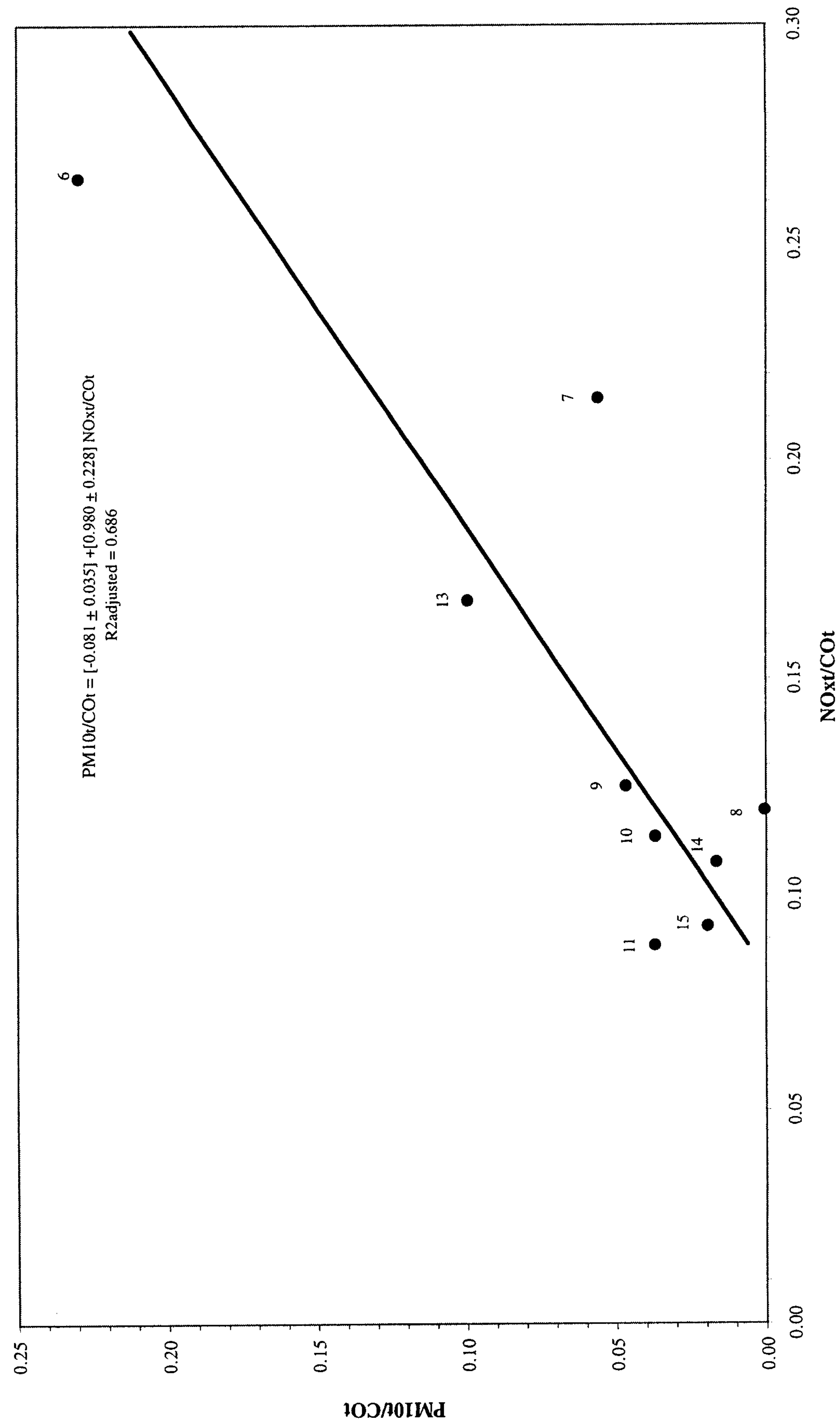

Figure 7: Regression of PM10t/COt on NOxt/COt. Numbers correspond with Tabel1