Aalborg Universitet

Papers

Volume 8: 2008-2014

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Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Thoft-Christensen, P. (2014). *Papers: Volume 8: 2008-2014*. Department of Civil Engineering, Aalborg University.

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CHAPTER 150

STOCHASTIC MODELLING OF TRAFFIC AIR POLUTION[1]

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ABSTRACT

In this paper, modeling of traffic air pollution is discussed with special reference to infrastructures. A number of subjects related to health effects of air pollution and the different types of pollutants are briefly presented. A simple model for estimating the social cost of traffic related air pollution is derived.Several authors have published papers on this very complicated subject, but no stochastic modelling procedure have obtained general acceptance. The subject is discussed basis of a deterministic model. However, it is straightforward to modify this model to include uncertain parameters and using simple Monte Carlo techniques to obtain a stochastic estimate of the costs of traffic air pollution for infrastructures.

1. INTRODUCTION

Important progress has been made in Life-Cycle Cost-Benefit (LCCB) analysis of infrastructures. Due to the large uncertainties related to the deterioration, maintenance, and benefits of such structures, analysis based on stochastic modelling of all significant parameters seems to be the only relevant modelling. However, a great number of difficulties are involved, not only in the modelling, but also in the practical implementation of the models developed at present. The main purpose of this paper is to present and discuss some of these problems from a user and a social point of view.

In paper the importance of including all (negative as well as positive) benefits in life-cycle cost-benefit analysis for infrastructures is stressed. Benefits may be positive as well as negative from a user point of view. In the paper negative benefits (user costs)

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[1] Proceedings of ICOSSAR 2013, New York, USA, 2014, pp. 3539–3545.

are discussed in relation to air pollution costs. Several investigations clearly show that user costs often completely dominate the total costs.

To understand why LCCB is seldom used in design and maintenance of infrastructures, it is necessary to look at the modelling techniques used. Usually, when designing new infrastructures the resources are very limited. Therefore, it is of great interest to be able to estimate the total expected costs for new infrastructures and to try to minimize the total costs in the expected lifetime of the new infrastructure.

It is a fact that user costs are usually not included when optimal design and maintenance strategies and decisions are made, although authors mention that user costs ought to be included. The life-cycle costs are often sought minimized for the considered infrastructure without considering the often significant costs for the users of the infrastructure and even without considering the long-term effects of the decision. Unfortunately, the decisions are often political decisions that are not easy to accept for the community. There is clearly a need to convince the decision-makers that user costs should be considered when major decisions are made.

To illustrate the importance of including user costs in an LCCB analysis of an infrastructure, the costs related to traffic pollution is discussed in this paper. When user costs are included in an analysis a deterministically modelling is usually used, although user costs are always very uncertain. Therefore, user costs must be modelled by stochastic variables or stochastic processes. However, a deterministic modelling based on statistic documentation is a good starting point for a stochastic modelling of user costs.

It is a well-known fact that traffic pollution has an important influence on the health especially in major cities. The air pollution is caused by vehicles travelling on the traffic network. It is shown in a large number of papers that long-term exposure to traffic pollution is an important risk factor for mortality; see e.g. Finkelstein et al. (2004). In a cancer study by the American Cancer Society, it is shown that fine particulate and sulphur oxide-related pollution is closely related to lung cancer and cardiopulmonary mortality; see Pope et al. (2002).

2. TRAFFIC AIR POLLUTION

Air pollution is a very complex mixture of fine particles produced by e.g. burning of fossil fuels. Air pollution due to traffic is a reactive form of oxygen consisting of noxious gases such as sulphur dioxide, nitrogen oxides and carbon monoxide.

The health effects of traffic related air pollution have been extensively studied in the last fifty years. Serious effects are asthma, cardiovascular diseases, changes in lung function, and death.

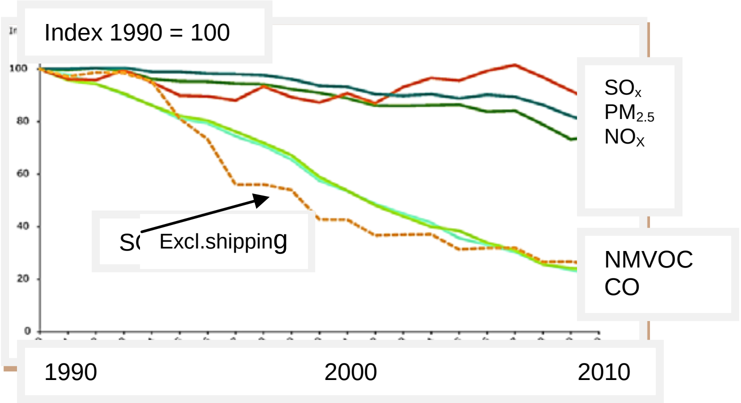

Figure 1. Trend in emissions of air pollutants from transport. NMVOC's are Non-methane Volatile Organic Chemicals.

PM is the general term used for a mixture of suspended particles in air, with a wide range in size and chemical composition. $PM_{2.5}$ refers to 'fine particles' that have a diameter of 2.5 micrometres or less. PM_{10} refers to particles with a diameter of 10 micrometres or less. It includes the 'coarse particles' (relatively large airborne particles) fraction in addition to the $PM_{2.5}$ fraction; see EEA (2012).

The EEA (2010) report includes the first assessment of progress towards target set out in key transport- and environmental policy and legislation in EU. As shown in Figure 1, substantial progress is made from 2000 to 2010.

Sahsuvaroglu & Jerret (2007) have estimated the premature mortality from particulate matter PM_{10} on basis of data from Hamilton, Canada using a methodology set by Pengelly et al. (1997, 2000). In general, a 10 μm increase in the PM_{10} level is associated with an average 0-7% increase in mortality. Based on the Hamilton data the increase in mortality is estimated to 79 premature deaths for the year 1995, which is a 2% increase.

A detailed description of individual pollutants is given by Brook et al. (2004):

- NO_x refer to compounds nitrogen dioxide NO_2, nitrogen trioxide N_2O_4,and dinitrogen pentoxide N_2O_5. Most research has been concentrated on CO_2.
- Carbon monoxide CO is a pollutant from incomplete combustion of carbon-containing fuels.
- Sulphide Dioxide SO_2. The principal sources of SO_2 include combustion of sulphur-containing fuels in e.g. diesel engines.
- Ozone O_3 is associated with electrical discharges. It is the principal component of photochemical smog.

Walker (2010) has in detail investigated probabilistic modelling of air pollution from road traffic in order to predict hourly average concentrations of NO_x with estimated uncertainty. The investigation is based on a deterministic pollution dispersion model by Walker (2008) capable of estimating such hourly average concentrations of e.g. NO_x up to 200-300 m from roads. Probabilistic models are then obtained by coupling this deterministic model with four stochastic models. The conclusion of this investigation is that more work on defining distributions of the involved parameters is needed to obtain good agreement with roadside observations at three monitoring stations at Norbysletta, Norway.

Air pollution is not only due to traffic, but traffic air pollution seems to be the dominant pollution form at least neat roads. This is clearly documented in a study of long-term average particulate air pollution in the Netherlands, Germany, and in Sweden by Brauer et al. (2003).

CO_2 pollution has a significant effect on the climate, but only little or no effect on the user of the infrastructure.

3. HEALTH EFFECT OF AIR POLLUTION

It is well documented in the literature that air pollution has a serious effect on the public health; see e.g. Seaton et al. (1995), Künzli et al. (2000), and Levy (2004). However, the fact that there are many different types of air pollution makes it difficult to quantify the effect of a specific pollutant.

It is difficult to estimate the health effects caused by traffic pollution. A great variation is observed city to city and from country to country. As an example, data from Denmark are shown in Table 1; see The Danish Ecocouncil (2004).

Health effects per year	Heavy vehicles	Vans	Taxies
Mortality	800	475	15
Hospitalisation	875	525	20
Chronic bronchitis	800	475	15
Acute bronchitis	2,800	1,650	60
Asthma attack	30,600	22.950	650
B-days	435,000	260.000	9.250

Table 1. Health effects by ultrafine particles from different vehicles categories in Denmark. B-days are days with decreased productivity due to illness.

In Table 1 only the health effects from ultrafine particles are estimated. Health effects from larger particles are not included. The traffic distribution in Copenhagen is shown in Table 2; see The Danish Ecocouncil (2004). It is important to observe than the heavy vehicles (4% of the traffic) cause 30 % of the pollution.

Traffic distribution	%	*NO_x pollution %*
Cars	77	49
Taxies	8	8
Vans	11	13
Heavy vehicles	4	30

Table 2. The traffic distribution in Copenhagen in 2010.

Laden et al. (2000) has shown that particulate matter PM from combustion sources was associated with increased mortality in six U.S. cities namely Boston, St. Louis, Knoxville, Madison, Steubenville & Topeka. They concluded that particulate matter from mobile sources and coal combustion were associated with increased mortality but mortality was not associated with coarse particles between 2.5 and 10 µm.

They also estimated the increase in daily deaths associated with a 10 $\mu g/m^3$ increase in mass concentration in the six U.S. cities, 1979–1988, see table 3.

Boston	St. Louis	Knoxville	Madison	Steubenville	Topeka
59	55	12	11	3	3

Tabel 3. Increase in mean daily deaths associated with a 10 µg/m3 increase in mass concentration in six U.S. cities.

The European Environment Agency EEA (2010) has estimated the years of life lost due to the harmful effect of fine pollution particles; see Figure 2. There is a big variation in the European countries. The average years of life lost is about 50 to 100 years per 100 km^2. However in some parts of Europe the years of life lost is higher than 100 years per km^2.

The premature mortality per year attributable to fine particles $PM_{2.5}$ in Europe has been estimated by de Leeuw & Horálek (2009); see Figure 3. The as-sessment concludes that there are 492 000 premature deaths per year in Europe, inclusive 297000 prema-ture caused by cardiopulmonary diseases, and 54500 premature deaths and 457000 attributable to lung cancer.

The problem whether air pollution mortality should be interpreted by the number of deaths or by years of life lost has been discussed by Rabl (2003).

Most of the impact of air pollution is not instantaneous but the cumulative result after years of expose. Therefore, the total number of deaths is not observable. Rabl (2003) shows that the number of deaths is not meaningful measure for air pollution effects, whereas loss of life expectancy is an appropriate impact indicator

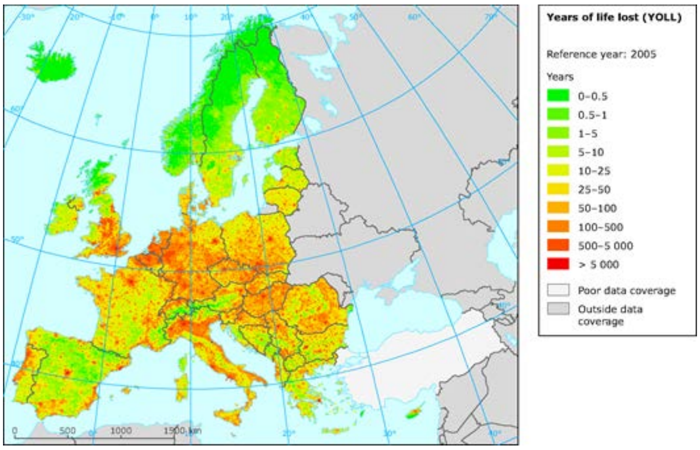

Figure 2.
Years pr. 100 km^2 of life lost due to pollution with fine particles in 2005.The green colour indicates 0-0.5 years lost, the orange colour 25-50 years lost, and the red colour 5000 years lost per 100 km^2.

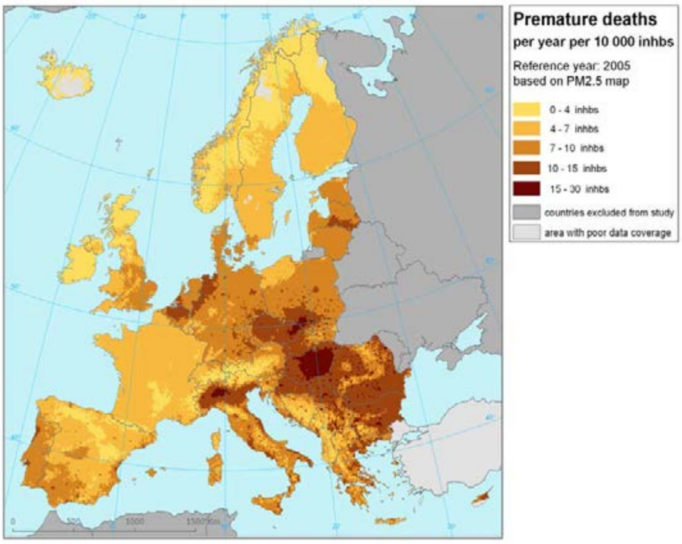

Figure 3.
Premature mortality in years per 10.000 attributable to PM$_{2.5}$ exposure.

4. SOCIAL COSTS OF TRAFFIC RELATED AIR POLLUTION

DKK per km. 2006	Symbol	Country side L_1	Smaller town L_2	Large city L_3
Passenger cars				
- petrol	V_1	0.04	0.06	0.09
- diesel	V_2	0.04	0.10	0.25
Buses (diesel)	V_3	0.52	0.80	1.31
Vans (petrol)	V_4	0.08	0.10	0.14
Vans (diesel)	V_5	0.08	0.17	0.41
Trucks (diesel)	V_6	0.43	0.61	1.09

Table 4. Social cost of air pollution six vehicle categories.

The variation of social costs caused of traffic related air pollution is large and varies with geographical and the different vehicle categories. The estimated social costs (DDK/km) of air pollution from road traffic per kilometer in Denmark is shown in Table 4, see Jensen et al. (2010).

5. DETERMINISIC MODELLING PROCEDURE

5.1 *Step 1. Division of road*

Evaluation of the pollution of a new infrastructure element such as a planned motorway with a length of L kilometers should be based on a division of the motorway in three types of distances according to the pollution extends.

1. Minor pollution. The distances of this type are typically in the open space where the surroundings contain only sparse populations. Although the pollution in each of these distances are low, the total pollution may be high since the total length L_1 of these distances may be high compared to the total length L of the motorway.
2. Medium pollution. Distances with medium pollution are often distances though minor towns and in the neighborhood of major cities. Let the total length of this type of distances be L_2.
3. Severe pollution. Distances with severe pollution are distances though major cities. Let the total length of this type of distances be L_3. Then $L=L_1+L_2+L_3$.

5.2 *Step 2. Time dependency*

Most of the significant variables such as the traffic intensity and the traffic pollution vary strongly with time. Therefore, to obtain a reasonable estimate of the total social costs in the planned life time of the infrastructure, the planned life time must be divided into smaller time intervals e.g. 1, 5, or to 10 years' time intervals. In each of these time intervals, the time dependent variables are kept constant.

In most of the developed countries, the pollution from a single car is decreased drastically in last 10 years due to new strict emission laws. On the other hand, the number of cars is growing in all countries, especially in undeveloped countries.

5.3 *Step 3. Estimation of traffic intensity and distribution*

The traffic intensity and the traffic distribution vary during the day and during the year for all relevant vehicle categories, e.g. the 6 categories V_1-V_6 defined in Table 4.

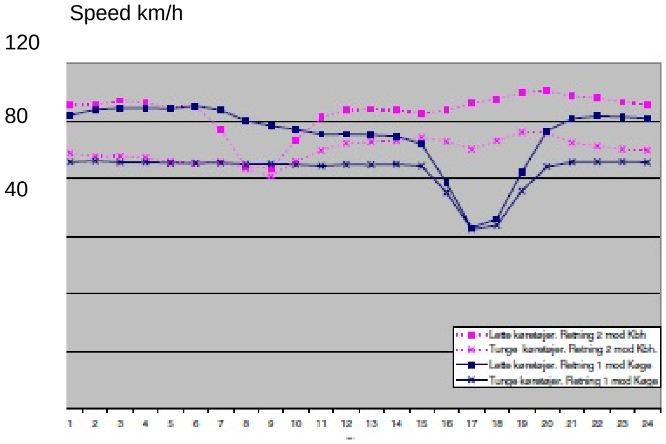

Figure 4. The speed distribution during one day (24 hours).

In a Danish study, Jensen et al. (2004) estimate the daily vehicle speed distribution on motorway near Copenhagen on basis of a manual counting; see Figure 4. The two red curves are for light vehicles from and towards Copenhagen, and the two blue curves are for heavy vehicles from and towards Copenhagen. The curves shown are only for weekdays. The speed distribution is important since the pollution is increased with increasing speed.

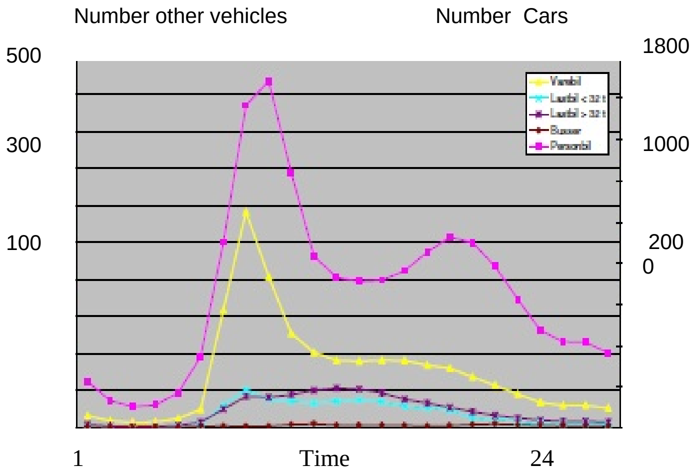

Figure 5. Daily number of different types of vehicles.

The numbers for five different categories of vehicles are shown in Figure 5. The red curve (top curve) is for cars and the yellow curve for vans. The other three curves are (from top) heavy trucks, light trucks, and buses.

The average number of vehicles for the same five types of vehicles in the whole year 2003 is shown in Table 5.

	Weekdays.	*Saturdays*	*Sundays*
Cars	86670	67244	65341
Vans	10048	7466	6942
Trucks, light	2647	991	697
Trucks, heavy	3412	616	427
Buses	389	155	113
Total	103166	76471	73520

Table 5. Average number of vehicles in 2003 for different types of vehicles.

5.4 *Step 4. Estimation of air pollution*

An effective assessment of the traffic air pollution is essential for estimating the health effect of the pollution. Several deterministic and stochastic methodologies have been developed in recent years. Most of them are deterministic and based on observations or previous experience from similar situations. The uncertainty of the significant variables (parameters) can usually be treated by a stochastic modeling.

Li et al. (2008) suggest handling uncertainties, which cannot be modeled by probabilistic distributions, using fuzzy membership functions. This approach is based on Monte Carlo simulation for the pollutants, quantification of evaluation criteria using fuzzy membership functions, and risk assessment based on fuzzy-stochastic information. This methodology is applied by Li et al. (2008) to a study of regional air quality management, regional environmental management, and urban planning.

In the study by Jensen et al. (2004) the average emission of NO_x in µg/m/s is estimated for the same types of vehicles as in table 2. The result is shown in Table 6 where the emissions from both directions are added.

	NO_x, µg/m/s.
Cars	960
Vans	343
Trucks, light	274
Trucks, heavy	570
Buses	72
Total	2.221

Table 6. Average NO_x (µg/m/s) for different types of vehicles.

5.5 ***Step 5. Estimation of air pollution costs***

Let the cost of air pollution per kilometer for vehicle category V_i. $i = 1,\ldots,6$ and the distance category L_j, $j = 1,..,3$ be C_{ij} , then the total pollution for the motorway is

$$C_{total} = \sum_{j=1}^{3} C_j = \sum_{j=1}^{3}\left(\sum_{i=1}^{6} C_{ij}\right) \tag{1}$$

where C_j , j=1,..,3 is the total pollution costs of L_j distance intervals.

It is important to note that all distances in the same distance category do not normally have the same pollution data. Therefore, the pollution costs in each of such internals must be added to obtain the total pollution cost for the distance interval in question.

A simple (deterministic) example of the estimation of the total pollution costs of a motorway can be performed using the cost data in table 4 combined with the following simplified data for the distance categories:

L_1=20 km,
L_2=10 km,
L_3=5 km,

and for the traffic intensity per year:

T_1=60.000,
T_2=40.000,
T_3= 8.000,
T_4= 8.000,
T_5=16.000,
T_6=30.000.

The calculated result of this simple estimation is

$C_{total} = \sum_{j=1}^{3} C_j$ = 459.600+716.4000+1.325.200 = 2.501.200 DKK/year
or approx. 350.000 EURO/year.

In preparation to the WHO Ministerial Conference on Environment and Health, London 1999, a tri-lateral project was carried out in Austria, France and Switzerland.

The project assessed the health costs of road traffic related air pollution in the three countries; see Sommer et al. (1999).

The main task was to estimate the exposure of the population to the ambient concentration of the annual mean value of PM_{10}. PM_{10} was chosen as an important and useful indicator for the health risk of air pollution. The annual mean values of PM_{10} due to rad traffic in the three countries were: Austria 8.0, France 8.9, and Switzerland 7.4 $\mu g/m^3$.

In this project willingness to pay (WTP) is used in the monetary valuation of mortality due to traffic air pollution. A basic value of 1.4 million EUR is adopted for the further monetization of the value of preventing a statistical fatality.

The health costs in 1996 due to road traffic-related air pollution based on the willingness-to-pay approach are shown in Table 7.

Million EURO	Austria	France	Switzerland	All three countries
Mortality	2.170	15.866	1.586	19622
Morbidity	722	5.t49	630	7100
Total	2.892	21.615	2.216	26.723

Table 7. Estimated health costs due to traffic air pollution.

It is interesting to note that the road traffic-related health costs per capita only a little: France 371 EURO, Austria 359 EURO, and Switzerland 313 EURO per capita.

6. STOCHASTIC MODELLING

In the simple example shown in section 5.5 only deterministic data are used. However, most of the variables are so uncertain that a stochastic evaluating must be used to obtain reliable estimations. The main problem is that probabilistic information on the significant variables in most cases dose not existing. If probabilistic information including the correlation between the variable can be obtained, then the uncertainty of C_{total} may easily be obtained using simple Monte Carlo calculation.

As indicated above, a large number of variables are involved in estimating the life cycle costs related to traffic air pollution. A major problem is to obtain relevant data for these variables especially because there is a high degree of uncertainty involved. Very little useful information is available in the literature.

Huijberegts (1998) has published two papers on “Application of Uncertainty and Variability in Life Cycle Analysis”. Uncertainty analysis is complicated by a lack of knowledge of uncertainty distributions and correlations between parameters. Various methods have been proposed to make uncertainty operational in life cycle analysis due to parameter uncertainty. The most promising technique is using a stochastic modeling where the parameters are modeled as uncertainty distributions. This technique is widely used in structural reliability analysis.

Two types of uncertainty are relevant in this content. Epistemic uncertainty is the uncertainty due to imperfect knowledge and can be reduce when more information and data is available. Stochastic uncertainty is due to inherent variability and is therefore non-reducible.

Cyrys et al. (2005) used stochastic modeling to predict NO_2 and fine particles $PM_{2.5}$ levels at 1,669 addresses in Munich. Alternatively, a Gaussian multisource dispersion model was used to estimate the annual mean values for NO_2 and total suspended particles (TSP). The aim was to compare the measured NO_2 and $PM_{2.5}$ levels with the levels predicted by the two modeling approaches and to compare the results of the stochastic and dispersion modeling for all study infants.

NO_2 and $PM_{2.5}$ concentrations obtained by the stochastic models were in the same range as the measured concentrations, whereas the NO_2 and TSP levels estimated by dispersion modeling were higher than the measured values. However, the correlation between stochastic- and dispersion-modeled concentrations was strong for both pollutants.

Exposure to the two traffic-related air pollutants was modeled for two ongoing birth cohort studies. A total of 1,757 infants were selected for this purpose. For the stochastic modeling a 1-year measurement program for NO_2 and $PM_{2.5}$ was conducted. The annual average air pollution concentrations measured and estimated for the 40 measurement sites are shown in Table 8 and 9.

NO_2 µg/m^3	*Mean*	*Minimum*	*Maximum*	*S.D.*
Measured	28.8	15.9	50.6	7.8
Stochastic	28.8	20.6	42.1	6.1
Dispersion	40.2	24.3	63.8	8.6

Table 8. Measured and modeled values for NO_2.

$PM_{2.5}$	*Mean*	*Minimum*	*Maximum*	*S.D.*
Measured	13,6	11.2	19.7	1.8
Stochastic	13.6	12.2	17.0	1.3
Dispersion, TSP	42.8	35.8	64.5	5.5

Table 9. Measured and modeled values for PM_{25}/TSP.

The NO_2 and $PM_{2.5}$ values predicted by the stochastic model are strongly correlated with the corresponding NO2 and TSP concentrations predicted by the dispersion model.

7. CONCLUSION

There is a general agreement that doing a life-cycle cost-analysis in infrastructure context is incomplete unless user costs are included. User cost can be di-vided in direct user costs and social costs. Direct user costs are costs which concern the individual user of the infrastructure such as repair costs, congestion costs, and accidents costs. The social costs are costs which concerns everybody not just the user of the infrastructure.

Costs related to traffic air pollution is one of the most import social costs with regard to infrastructures. It is a concern for everybody. It is also of great importance for the society. In this paper CO2 is not discussed although it is of great important for the global warming. In this paper only particle pollution is discussed since particle pollution has health effects not only in in a short-term but also in a long-term.

There is no valid argument for not including traffic air pollution in life-cycle cost analysis of infrastructures. It is correct, that sufficient data to make a fully satisfactory estimation of the costs of traffic related pollution does not exists, but this is also true for some of the other terms such as maintenance costs.

In this paper, it is shown how a simple deterministic modeling of the costs of traffic pollution can be performed on basis of data from similar pollution situations. Such data is of course uncertain, but the added uncertainty may in some cases give good arguments for choosing stochastic distributions for the uncertain variables and then perform a stochastic modeling.

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