LCA Methodology

Generic Spatial Classes for Human Health Impacts, Part II:

Application in an Life Cycle Assessment of Natural Gas Vehicles

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Preamble. This series made up of two articles is devoted to a new method for the spatially differentiated assessment of the impacts of primary airborne pollutants on human health within Life Cycle Assessments. The first part [Int J LCA 6 (5) 257 – 264 (2001)] describes the method and provides exemplary results for site-dependent exposure efficiencies. The second part [Int J LCA 6 (6) 334 – 338 (2001)] deals with the application of the method within a Life Cycle Assessment of natural gas vehicles.

Abstract. Within a Life Cycle Assessment of the fuel supply and the operation of cars fueled by natural gas, diesel and gasoline, the impacts of airborne pollutants on human health were assessed in a spatially differentiated way. Country average impacts were used for secondary sulfate and nitrate aerosols. The use of country average impacts also turned out to be sufficient for the primary pollutants emitted from most processes of the fuel supply. For emissions of primary pollutants from the vehicles and from some processes of the fuel supply, the low to moderate emission height and the high local population density in urban areas needed to be taken into account. In these cases, the method of generic spatial classes presented in Part I was applied. The spatially differentiated impacts were compared with the results of a generic impact assessment based on average European damage factors. The generic impact assessment overestimates the human health impact of the fuel supply by about a factor of 2, since many of the upstream processes take place in very sparsely populated countries, and underestimates the impact of the primary particles emitted by the diesel cars in large cities by about a factor of 2.

Keywords: Airborne pollutants; diesel; human toxicity; Life Cycle Impact Assessment (LCIA); natural gas; gasoline; spatial differentiation; transportation

Introduction

A new method for the spatially differentiated assessment of the impacts of primary airborne pollutants on human health was introduced in Part I of this series. Its practical feasibility and usefulness is examined within a Life Cycle Assessment of cars fueled by natural gas, diesel and gasoline. Both the vehicle operation and the upstream processes associated with the extraction, processing, transport and distribution of the fuels were considered. With regard to the fuel supply, the method was used to take into account that the various emissions are located in countries with widely diverging population densities ranging from Siberia and the OPEC countries, on the one hand, to Germany, on the other hand. Concerning the vehicle emissions, it was used to identify regions within Germany where natural gas vehicles should be introduced with priority from a human health perspective. The primary pollutants considered in the case study and their characterization in terms of selected impact categories are shown in Table 1. The extraction of abiotic resources was considered in addition to the pollutant-related impact categories[1].

Table 1: Characterization of the airborne pollutants considered

primary pollutant	impact category				
	climate change	human toxicity[a]	photo-oxidants	acidification	nutrification
CO_2	X				
CH_4	X		X		
N_2O	X				
PM 10 / PM 2.5		X			
NO_x		X	X	X	X
SO_2		X		X	
NMVOC[b]		X	X		
benzene[b]		X			
formaldehyde[b,c]		X			
acetaldehyde[b]		X			
benzo[a]pyrene[b,c]		X			
1,3-butadiene[b]		X			

[a] The impact of ozone on human health was subsumed under the category of human toxicity. In order to avoid double counting, the category of photooxidants therefore only refers to effects on natural ecosystems.

[b] Contribution to climate change from CO_2 as a degradation product of these substances was neglected compared to the much larger direct emissions of CO_2.

[c] A significant share of the total health impact of formaldehyde and benzo[a]pyrene is due to uptake of food and drinking water (Hofstetter 1998), which is not considered here.

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[1] For a discussion of the selection of pollutants and impact categories and the definition of system boundaries, see (Nigge 2000).

The emission factors and fuel consumptions for the cars were taken from (Bach et al. 1998) (**Table 2**). The fuel consumption of the natural gas cars is increased by 10% compared to gasoline and by 14% compared to diesel. Except for methane, the emissions of all pollutants are significantly lower for the natural gas cars than for their diesel and gasoline counterparts. The inventory data for the fuel supply were taken from the GEMIS database (Rausch et al. 1998), with some additions and updates being made as described in (Nigge 2000) (**Table 3**). The high resource demand (in terms of the Cumulative Energy Demand) for gasoline is mainly due to refining.

Table 2: Energy demands and emissions [g/km] of the cars (Bach et al. 1998)

	diesel	gasoline	natural gas
energy demand [MJ/km]	3.19	3.32	3.65
CO_2	238	248	201
CH_4	0.010	0.020	0.500
N_2O	0.0 E+0	0.0 E+0	0.0 E+0
CO_2-equivalents[a]	238	248	212
PM 2.5	0.050	9 E-5	3 E-5
NO_x (as NO_2)	0.500	0.140	0.060
SO_2	0.046	0.031	0.0 E+0
NMVOC	0.120	0.380	0.080
benzene	0.003	0.022	0.0 E+0
formaldehyde	0.020	0.002	0.0002
acetaldehyde	0.007	0.001	0.0001
benzo[a]pyrene	0.0 E+0	0.0 E+0	0.0 E+0
1,3-butadiene	0.002	0.003	0.0 E+0

[a] with Global Warming Potentials from Houghton et al. (1996)

Table 3: Resource demands and emissions [g/km] for the supply of the fuels in Germany (Rausch et al. 1998, modified according to Nigge 2000)[a]

	diesel	gasoline	natural gas
$(CED-H_{low})/H_{low}$ [%]	8.8	21.4	9.4
CO_2	20	48	20
CH_4	0.050	0.087	0.622
N_2O	4.0 E-04	8.9 E-04	7.3 E-04
CO_2-equivalents[b]	22	50	33
PM 10	0.0037	0.0061	0.0046
PM 2.5	0.0049	0.0056	0.0 E+00
NO_x (as NO_2)	0.071	0.110	0.050
SO_2	0.074	0.117	0.015
NMVOC	0.056	0.505	0.027

CED Cumulative Energy Demand, H_{low} lower calorific value of the supplied fuel

[a] emissions of the individual carcinogenic NMVOC listed in Table 1 can be neglected (see section 1.1)

[b] with Global Warming Potentials from Houghton et al. (1996)

1 Human Health Impacts

In order to assess the impact on human health of the emissions contained in the inventory, the exposures to primary pollutants were calculated as described in Part I. Exposures to secondary sulfate and nitrate aerosols formed from SO_2 and NO_x, respectively, were also considered. Unlike in the case of primary pollutants, the exposure to these secondary pollutants is insensitive to emission height and only varies with the population density at a subcontinental scale. This is due to their slow formation over several tens to hundreds of kilometers away from the source. Similar to the long-range exposure to primary pollutants, the total exposure to sulfates and nitrates can therefore be approximated by a constant value for all emission sites within one country. It was calculated with the EcoSense software (IER 1998) described in Part I as a mean value over several emission sites spread evenly across each country. Exposures to ozone formed from emissions of NO_x and VOC were calculated in a generic manner according to Hofstetter (1998). Their spatial differentiation is desirable in principle, but it turns out that ozone does not play a significant role in this case study.

Population exposures were transferred into incidences of mortality and morbidity and furthermore aggregated into Disability Adjusted Life Years (DALY, without age-weighting and discounting). On the basis of this aggregation, the direct effects of SO_2 and NO_x can be neglected compared to the effects of the secondary nitrate and sulfate aerosols. The same applies to the carcinogenic effect of diesel soot particles, compared to their impact on the respiratory tract (Hofstetter 1998).

1.1 Fuel supply

Regarding the pollutants to be considered, the upstream emissions of the individual carcinogenic pollutants can be neglected. This can be concluded from the fact that their contribution turns out to be negligible for the vehicles (see section 1.2), even though the transportation sector is the main source of NMVOC emissions (Krüger et al. 1997). This leaves PM 2.5 and PM 10 to be considered as primary pollutants, and sulfate and nitrate aerosols as secondary pollutants.

Each fuel supply chain consists of several hundred individual processes. Most of them, however, contribute only very small amounts to the overall emissions of each individual pollutant. For the purpose of a spatially differentiated impact assessment, a cutoff criterion was therefore applied: For each pollutant, only the impact of emissions contributing by more than 1% to the overall upstream emissions of that pollutant was assessed in a spatially differentiated way. These emissions come from between 8 and 14 unit processes and account for between 73% and 96% of the total upstream emissions of each pollutant. Emissions below the 1% threshold take place at several hundred different sites spread widely across Europe (and other continents in some cases). Spatial variations of their impacts per emitted mass, therefore, cancel each other out to a large extent. Their spatially differentiated treatment would only yield few additional insights in disproportion to the required effort. Their impact was therefore assessed in a generic way using average European damage factors.

When combined with the results of the spatially differentiated impact assessment, it turns out that the emissions above the 1% threshold contribute between 63% and 93% to the overall impact for each pollutant. Hence, the cutoff criterion is reasonable in that it captures the largest share of the overall impact while the number of individual processes to be considered still remains small enough.

The spatially differentiated impact assessment of the emissions of primary pollutants (PM 2.5, PM 10) above the 1% threshold was based on the following observations regarding location and emission height: Extraction, processing and long distance transport of natural gas and crude oil take place outside of cities. According to Fig. 7 in Part I, the associated population exposures can therefore be reasonably approximated by country averages for the respective emission heights. The use of country averages is furthermore appropriate for emissions from national power plant mixes and for compressor stations along national pipeline systems, since these processes are distributed over a large number of locations across the country. Spatial differentiation of the impacts of these processes is therefore due to differences in country average population densities, ranging from Russia (9 persons/km^2) at the low end to Germany (230 persons/km^2) at the high end. The emission height only has a weak influence on the country average impacts (see Part I, Fig. 7). It was therefore sufficient to consider three discrete classes of emission heights. All vehicles, as well as diesel generators for power supply, were assigned an effective emission height of 5 m. Power plant emissions were assumed to be released at an effective emission height of 200 m. The effective emissions height of all remaining processes such as compressor stations, refineries and burners for processing heat was approximated by a value of 50 m [2].

For two upstream processes, the use of country average impacts was not adequate, i.e. intra-country variations of the population density needed to be considered and emission height had a stronger influence on the impacts: The truck transport of diesel and gasoline to the fuel stations (over a distance of 100 kilometers) takes place to 50% within cities, which were represented by central cities in urbanized regions. The low emission height (5 m) in combination with the high population density in the cities increases the impact of the associated PM 2.5 emissions by 24% over the country average for traffic emissions. Furthermore, some of the 14 refineries in Germany are located close to densely populated areas. Based on their capacity-weighted distribution across the nine settlement structure classes, impacts from refinery emissions of PM 10 were found to be 22% higher than the country average for emissions at an effective height of 50 m.

The average damage factor (health impact per emitted mass) for the supply of each fuel determined in this way is shown in Table 4. Multiplication with the emission factors from Table 3 yields the spatially differentiated upstream impacts on human health shown in Fig. 1. For each fuel, the main contributions come from secondary sulfate and nitrate aerosols. The supply of gasoline is associated, by far, with the highest impact. This is mainly due to the high energy demand of the refining process which furthermore takes place in Germany with its high population density.

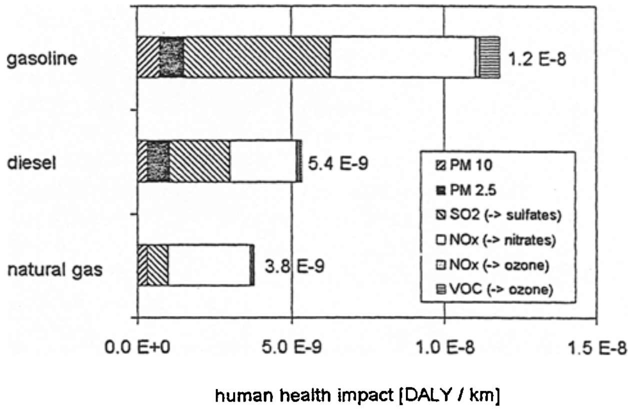

Fig. 1: Human health impact of the fuel supply (spatially differentiated assessment)

In order to test whether the spatially differentiated assessment has an effect on the final result, a generic impact assessment was also conducted. For this purpose, generic damage factors from Hofstetter (1998) were used since they are equivalent to the spatially differentiated damage factors used here in all respects except for the determination of the population exposures. The population exposures in Hofstetter (1998) refer to emissions from high stacks and an average location within Western and Central Europe (Fig. 2).

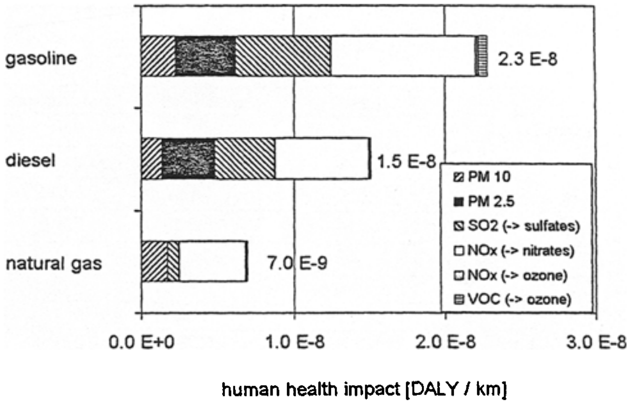

Fig. 2: Human health impact of the fuel supply (generic assessment)

Table 4: Damage factors [DALY/kg] for fuel supply and vehicle operation used in the case study

primary pollutant	secondary pollutant	fuel supply			vehicle operation		
		gasoline	diesel	natural gas	large city	normal city	small city
PM 10		1.2 E-4	8.4 E-5	7.6 E-5	N/A	N/A	N/A
PM 2.5		1.4 E-4	1.5 E-4	N/A	1.3 E-3	8.9 E-4	7.4 E-4
NO_x (as NO_2)	nitrates	4.3 E-5	3.1 E-5	5.7 E-5	7.4 E-5	7.4 E-5	7.4 E-5
NO_x (as NO_2)	ozone	1.3 E-6	1.3 E-6	1.3 E-6	1.3 E-6	1.3 E-6	1.3 E-6
SO_2	sulfates	4.1 E-5	2.7 E-5	5.4 E-5	7.4 E-5	7.4 E-5	7.4 E-5
NMVOC	ozone	1.3 E-6	1.3 E-6	1.3 E-6	1.3 E-6	1.3 E-6	1.3 E-6
CH_4	ozone	1.3 E-8	1.3 E-8	1.3 E-8	1.3 E-8	1.3 E-8	1.3 E-8
benzene		N/A	N/A	N/A	4.3 E-6	2.9 E-6	2.5 E-6
formaldehyde		"	"	"	4.2 E-6	2.1 E-6	1.4 E-6
acetaldehyde		"	"	"	7.9 E-7	4.0 E-7	2.7 E-7
benzo[a]pyrene		"	"	"	4.7 E-2	2.8 E-2	2.2 E-2
1,3-butadiene		"	"	"	1.0 E-4	5.1 E-5	3.6 E-5

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[2] The effective emission height is the sum of the stack height and the final value of the plume rise due to mechanical impulse or thermal effects (see Part I).

A comparison of Fig. 1 with Fig. 2 shows that the spatially differentiated impacts are about a factor of 2 lower than the generic values for each fuel. This is because the generic damage factors refer to Western and Central Europe, while a significant share of the upstream emissions actually occurs in areas with much lower population densities, such as Russia (Siberia), the OPEC countries or at sea. This effect is most pronounced for the diesel supply chain, where spatially differentiated impacts are a factor of 2.8 lower than generic ones, compared to a factor of 1.8 for natural gas and a factor of 1.9 for gasoline. Concerning the relation of the impacts between the fuels, diesel therefore moves closer to natural gas if spatial differentiation is taken into account.

1.2 Vehicle Operation

With regard to the vehicle emissions, the method presented in Part I was used to identify regions within Germany where natural gas vehicles should be introduced with priority from a human health perspective. Only inner-city driving was considered since natural gas cars are, at present, typically used within urban fleets (e.g. taxis) due to the lack of a widespread infrastructure of fuel stations. A differentiation was made between cities of three different sizes within Germany:

1. Large cities in agglomerations ('large cities')
2. Cities in urbanized regions ('normal cities')
3. Densified districts in urbanized regions ('small cities')

These three of the five generic spatial classes established in Part I can be used to represent the spatial variation of the human health impacts of traffic emissions of primary airborne pollutants within cities in Germany. Of the remaining two classes, the highly densified districts in agglomerations can be subsumed under 'normal cities', since the impacts of traffic emissions are similar for both classes (Part I, Fig. 7). The class of low density rural districts in rural regions was not considered due to the limitation to inner-city driving.

The damage factors for the vehicle emissions (spatially differentiated where applicable) are listed in Table 4. Fig. 3 shows the total impact for the three fuels on human health per kilometer of driving. The aggregated contribution of the fuel supply and the contributions of the individual pollutants emitted by the vehicles are indicated. The latter vary by more than 4 orders of magnitude. The effects of the individual carcinogenic NMVOC and of ozone formed from VOC are negligible and are therefore not visible. Small contributions come from sulfate aerosols and from ozone formed from NO_x. The main contributions to the health impact of the vehicles come from secondary nitrate aerosols and, in the case of diesel cars, also from primary diesel soot particles.

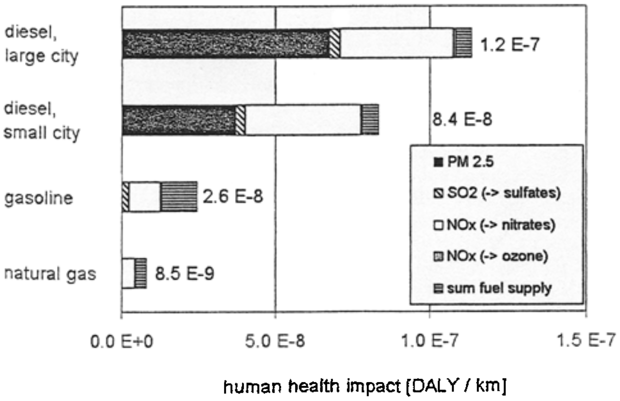

Fig. 3: Human health impact of vehicle operation and fuel supply (spatially differentiated assessment)

Due to the contribution of the primary particles, the total health impact of the diesel cars varies by about a factor of 1.4 between the cities of different sizes[3]. In large cities within agglomerations, it is 14 times as high as that of natural gas cars. In small cities, it is 10 times as high. The total health impact of gasoline cars is 3 times as high as that of natural gas cars. For both gasoline and natural gas, the impact is independent of the size of the city. In terms of the amount of avoided health impact, the substitution of natural gas for diesel in large cities therefore ranks first. Second, ranks the substitution of natural gas for diesel in small cities, which avoids a higher amount of health impact than the substitution of natural gas for gasoline in large or in small cities.

Fig. 4 shows the total health impact for the three fuels if assessed in a generic way according to Hofstetter (1998). A comparison with Fig. 3 demonstrates that the generic assessment underestimates the impact of the primary diesel particles (PM 2.5) by a factor of about 2 for large cities by disregarding their emission at low heights to high local population densities. At the same time, the upstream impacts are overestimated by about a factor of 2-3 in the generic assessment, as discussed above. The contributions of the fuel supply to the total health impacts are therefore overestimated as 16 (16)%, 61% and 56% for diesel in large (small) cities, gasoline and natural gas, respectively, compared to 5% (6%), 46% and 45%, if spatial differentiation is taken into account. Furthermore, the generic impact assessment would not allow one to differentiate the impacts of the diesel vehicles between an operation in cities of different sizes.

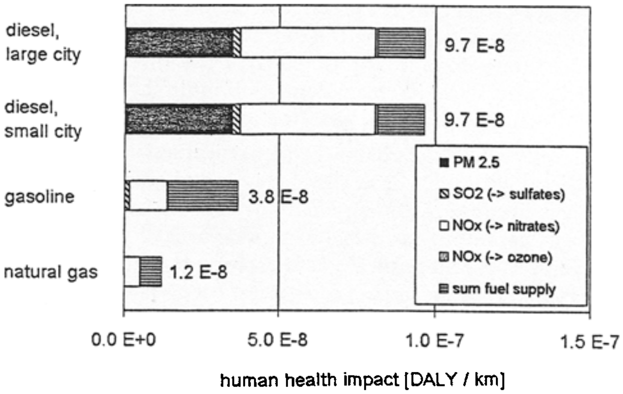

Fig. 4: Human health impact of vehicle operation and fuel supply (generic assessment)

2 Other impact categories

For the remaining impact categories, aside from human toxicity, standard generic impact assessment methods and reference values for normalization were used (Table 5). Fig. 5 shows the normalized indicators for all impact categories including human toxicity. The impacts of the natural gas cars in the categories of acidification, nutrification and ozone

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[3] The impact of the diesel particles alone varies by a factor of 1.8 between large and small cities. This difference is statistically significant compared to the intra-class variability of ± 40% (Part I, section 1).

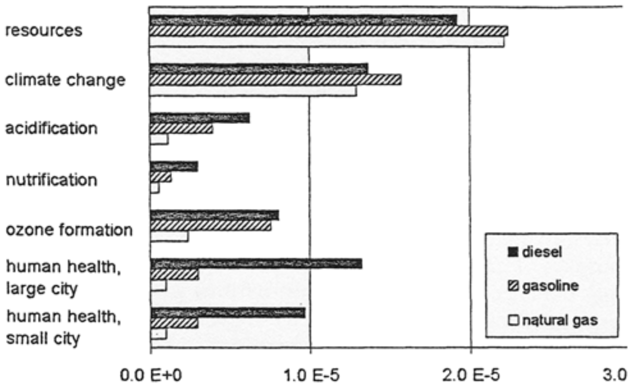

Fig. 5: Normalized impacts of vehicle operation and fuel supply

Table 5: Impact assessment methods used in the case study

category	indicator and method	normalization
abiotic resources	Cumulative Energy Demand (VDI 1997)	VDI 1998
climate change	Global Warming Potential (Houghton et al. 1996)	Hauschild and Wenzel 1998
human toxicity	Disability Adjusted Life Years (Hofstetter 1998)	Hofstetter 1998
photooxidants	Photochemical Ozone Creation Potential* (Derwent et al. 1996, 1998)	Hauschild and Wenzel 1998
acidification	Acidification Potential (Hauschild and Wenzel 1998)	Hauschild and Wenzel 1998
nutrification	Nutrification Potential (Hauschild and Wenzel 1998)	Hauschild and Wenzel 1998

* including NO_X according to Hofstetter (1998)

formation are about a factor of 5 lower than those of diesel cars and about a factor of 3 lower than those of gasoline cars. The upstream contributions are in the range of 10-20% for diesel and in the range of 20-60% for gasoline and natural gas. Concerning the extraction of abiotic resources and climate change, the impacts of the three fuels are of similar size, with upstream contributions in the range of 10% for diesel, and 20% for gasoline and natural gas.

The only slight disadvantage of natural gas occurs relative to diesel with regards to the extraction of abiotic resources. This is because the energy demand is 14% higher for natural gas cars than for diesel cars. The overall preference between diesel and natural gas therefore depends on the relative weights of the impact categories. An overall disadvantage for natural gas results if the extraction of abiotic resources is attributed a weight of at least 12 times the sum of the weights for human toxicity, acidification, nutrification and ozone formation. Under the assumption that this is unrealistic, natural gas performs most favorably among the three fuels with regards to the considered impact categories.

3 Conclusion

Within a Life Cycle Assessment of the fuel supply and the operation of cars running on natural gas, diesel and gasoline, the impacts of airborne pollutants on human health were assessed in a spatially differentiated way. The impacts of secondary sulfate and nitrate aerosols do not depend on emission height and local population density and were spatially differentiated on the basis of country average impacts. The use of country average impacts, which are rather insensitive to emission height, also turned out to be sufficient for the primary pollutants emitted from most upstream processes, since these processes either take place in areas with low to average population density outside of cities or are located at many different sites across a country (e.g. national power plant systems). This is contingent upon the specific product systems that were considered and does not necessarily apply to other cases.

The impacts of primary pollutants emitted from some processes of the fuel supply, and most importantly from the vehicles themselves, could not have been adequately addressed on the basis of country average impacts, however, since they take place in densely populated urban areas at low to moderate emission heights. In these cases, the method of generic spatial classes presented in Part I was applied. Most importantly, this showed that a generic impact assessment would have underestimated the impact of the primary particles emitted by the diesel cars in large cities by about a factor of 2.

Generally speaking, the method of generic spatial classes is likely to be beneficial compared to a spatial differentiation based on country average population densities in LCAs where a large share of the primary pollutants is emitted at low to moderate emission heights in or close to urban areas. This may, for example, be the case in LCAs of transportation systems involving diesel vehicles, or in studies of product systems where the transportation of goods by diesel vehicles is a significant part of the background processes.

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References

Bach C et al. (1998): Wirkungsorientierte Bewertung von Automobilabgasen. Bericht Nr. 160'928'2. Eidgenössische Materialprüfungs- und Forschungsanstalt (EMPA), Dübendorf

Derwent RG et al. (1996): Photochemical Ozone Creation Potentials for a Large Number of Reactive Hydrocarbons under European Conditions. Atmospheric Environment 30 (2) 181-199

Derwent RG et al. (1998): Photochemical Ozone Creation Potentials for Organic Compounds in Northwest Europe Calculated with a Master Chemical Mechanism. Atmospheric Environment 32 (14/15) 2429-2441

Hauschild M, Wenzel H (1998): Environmental Assessment of Products, Volume 2 – Scientific Background. Chapman & Hall, London

Hofstetter P (1998): Perspectives in Life Cycle Impact Assessment. A Structured Approach to Combine Models of the Technosphere, Ecosphere and Valuesphere. Kluwer Academic Publishers, Boston

Houghton JT et al. (1996): Climate Change 1995 – The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Krüger R et al. (1997): Alternative Kraftstoffe. Möglichkeiten zur Minderung der VOC-Emissionen im Straßenpersonenverkehr von Baden-Württemberg. ecomed publishers, Landsberg

Nigge K-M (2000): Life Cycle Assessment of Natural Gas Vehicles. Development and Application of Site-Dependent Impact Indicators. Springer-Verlag, Berlin

Rausch L et al. (1998): Gesamt-Emissions-Modell Integrierter Systeme (GEMIS) v. 3.08 (software). Öko-Institut, Darmstadt

VDI (1997): Guideline 4600, Cumulative Energy Demand. Terms, Definitions, Methods of Calculation. Verein Deutscher Ingenieure (VDI) – Gesellschaft Energietechnik. Beuth Verlag, Berlin

VDI (1998): Jahrbuch 98. Verein Deutscher Ingenieure (VDI) – Gesellschaft Energietechnik. VDI-Verlag, Düsseldorf

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