Evaluation of Emissions Factors based on Tunnel Measurements with Key Aspects on Heavy Metals and PM10 Non-Exhaust

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Motivation

Due to persisting high particulate matter concentrations in areas of Austria the determination of the influence of specific sources gains more and more importance. Especially in order to set actions for particulate matter reduction and to estimate their effects on air quality, source dependent emission quantities must be calculated and compared. With respect to traffic, the exhaust emission is well known, but for non-exhaust sources only approximate estimations are available. The main purpose of the investigation was to estimate PM10 non-exhaust emission factors. Therefor measurement campaigns in the Plabutsch road tunnel in the year 2012 and 2013 were performed and in addition NOx and Heavy Metal emission factors were determined.

Measurement Setup

The Plabutschtunnel is part of the A9 highway and is located in the western pheriphery of the city of Graz. Both tubes are about 10 km long with unidirectional traffic and approximately 20.000-30.000 vehicles per day in both directions. The tunnel itself has a roof profile with a maxima point sightly northern of the middle and to both portals a 1 % grade. The Plabutschtunnel has a fully transvers ventilation available but because of the piston effect of vehicles a longitudinal stream of 3 m/s to 7 m/s is induced and the mechanical ventilation rarely used. For analysis only periods without mechanical ventilation were taken into account. Speed limit is set to 100 km/h and section control within the tunnel is enforced.

In **Figure 1** the set-up of the measurement location is schematically shown. Two air quality measurement containers were positioned in two brake-down bays which are 3364 m apart. 985 m after the last measurement position the end of the tunnel is reached. Traffic counting is positioned outside the tunnel, 332 m after the north portal. The vehicles need about two minutes to pass the distance between the two measurement points and less the one additional minute to pass traffic counting point. All measurement data (air quality measurement, traffic counting and sir velocity) have a resolution of on minute, but for calculation the usage of a moving ten minutes average was proved to be best.

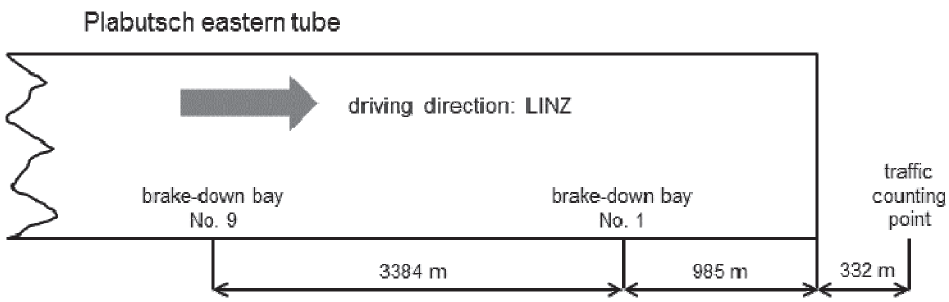

Figure 1: Schematically overview of the measurement setup.

For heavy metal detection the measurement distance was extended to the maximum (brake-down bay No. 17 to brake-down bay No. 1 distance 7180 m) to get detectable heavy metal differences between the two measurement points. For the estimation of heavy metals filters were clogged and in the following chemical analyses were performed by the Laboratorium für Umweltanalytik GesmbH with a Zeemann Graphitepipe AAS (Perkin Elmer 5100). So the measurement of heavy metals is discon-tinuous with a low temporal resolution. Filter samp,ing was performed during two periods per day, covering the morning and evening traffic peak (5:00 to 8:00 a.m. and p.m.). Overall nine filterpairs (one in each break-down bay) with a detectable heavy metal load were collected.

Calculation of emission factors

Based on the measurement data for NOx, PM10, longitudinal air velocity and traffic volume emission factors for NOx und PM10 were calculated. The longitudinal velocity is measured to estimate the dilution of the emissions and further on for back calculating the measured air quality concentrations to traffic emissions. The applied equations are given below.

$$flow\ rate_{\text{dilution}}\left[\frac{m^3}{s}\right] = longitudinal\ velocity\ \left[\frac{m}{s}\right] \cdot cross\ section\ [m^2] \tag{1}$$

$$amount\ of\ emission\ \left[\frac{g}{km}\right] = \frac{air\ quality\ concentration\ \left[\frac{\mu g}{m^3 \cdot minute}\right] \cdot 10^6 \cdot flow\ rate\ \left[\frac{m^3}{s}\right] \cdot 60\ [s]}{driving\ distance\ [km]} \tag{2}$$

The calculation of the emission factors (EFA) is based on multiple linear regression of the traffic amount, splitted in passenger cars (PC) and heavy goods vehicles (HGV), and the amount of emission (see equation (3)).

$$amount\ of\ emission\ \left[\frac{g}{km}\right] = EFA_{\text{PC}}\left[\frac{g}{km}\right] \cdot number_{\text{PC}} + EFA_{\text{HGV}}\left[\frac{g}{km}\right] \cdot number_{\text{HVD}} \tag{3}$$

To assess the quality of the calculated emission factors statistic indicators are given in the tables with the results. These indicators refer to the PM emission factor, including exhaust and non-exhaust all together. As the PM measurement does not allow any distinction between exhaust and non-exhaust PM a second information concerning one of these two shared is needed. In this study it is assumed that the PM exhaust part can be calculated based on the traffic data collected in the tunnel. Under the assumption that PM exhaust can be calculated with sufficient accuracy, the PM non-exhaust fraction can than simply be derived by subtraction from the PM total value.

The calculation of heavy metal emission factors is based on a discontinuous measurement (two three hour periods a day). So the amount of vehicles and the dilution rate were added over this time period. This procedure results in a reduced amount of data compared with NOx and PM10. Hence for heavy metals only vehicle emission factors were calculated and no differentiation between passenger car and heavy goods vehicle was made.

Results

The NOx emissions were mainly used to check the quality of the dataset, but as a side action NOx emission factors for real driving in terms of enforced speed limits on motorways were calculated and compared to HBEFA 3.1 (Umweltbundesamt, 2010) and NEMO (Rexeis, Hausberger, 2005).

Table 1: Measurement based NOx emission factors in Plabutschtunnel including the 95 % confidence interval compared to HBEFA 3.1 and NEMO

Year	Type of vehicle	NOx [g/km]	HBEFA 3.1 [g/km]	NEMO [g/km]
2012	PC	0,30 ± 0,01	0,27	0,35
	HGV	3,15 ± 0,06	2,24	4,53
2013	PC	0,28 ± 0,01	0,26	0,46
	HGV	3,31 ± 0,02	2,21	3,54

The measured emission factors for passenger cars fit quite well to the model calculated results from the HBEFA 3.1 those for heavy good vehicles are slightly better represented by the model NEMO. Summarizing the results the measured emission factors are in between the two emission models. To notice is the fact that it is not possible to consider the road gradient properly with the HBEFA 3.1, as it is limited within the step width of ± 2 %, ± 4 % and ± 6 %. For the correct road gradient (-0,5%) the factors were interpolated linearly.

Based on this datasets PM10 emission factors were calculated. These estimated emission factors contain PM exhaust and PM non-exhaust. When subtracting the model-calculated exhaust emission factors it was found that in tunnels the PM10 non-exhaust content is very low (see **Table 2**).

Table 2: PM10 emission factors in Plabutschtunnel including the 95 % confidence interval compared to HBEFA 3.1 and NEMO exhaust.

Year	Type of vehicle	PM10 [g/km] exhaust + non-exhaust	HBEFA 3.1 exhaust	NEMO exhaust
2012	PC	0,0219 ± 0,0016	0,007	0,015
	HGV	0,0954 ± 0,0086	0,032	0,051
2013	PC	0,0157 ± 0,0002	0,006	0,014
	HGV	0,0741 ± 0,0007	0,024	0,055

Already the sum of exhaust and non-exhaust out of the measurement is lower than the non-exhaust emission factor, compared to established emission factors for open road motorways (eg. Boulter, 2005). This indicated clearly, that in tunnel PM non-exhaust emission factors differ strongly from the commonly known and widely used factors described in literature (eg. Gehrig et al., 2004, Lohmeyer et al., 2011…). These established emission factors for motorways are based on open land measurements.

Due to the fact that the Plabutschtunnel is very long (about 10 km), has a quite high longitudinal air velocity (up to 7 m/s) and a high traffic volume the available data also show that there is an influence of traffic volume on the simple linear emission factors for passenger cars (PC) and heavy goods vehicles (HGV). When adopting the linear multiple regression with a sort of interaction term (PC×HGV, see equation (4)) the emission factor for this traffic term becomes negative, in return the emission factors for passenger cars and heavy duty vehicles rise.

$$amount\ of\ emission \left[\frac{g}{km}\right] = EFA_{\mathrm{PC}}\left[\frac{g}{km}\right]\cdot number_{\mathrm{PC}} + EFA_{\mathrm{HGV}}\left[\frac{g}{km}\right]\cdot number_{\mathrm{HVD}} + EFA_{\mathrm{PC\times HGV}}\left[\frac{g}{km}\right]\cdot (number_{\mathrm{HVD}}\cdot number_{PC}) \tag{4}$$

Table 3: PM10 emission factors with interaction term in Plabutschtunnel including the 95 % confidence interval compared with HBEFA 3.1 and NEMO exhaust.

Year	Type of vehicle	PM10 [g/km] exhaust + non-exhaust	HBEFA 3.1 exhaust	NEMO exhaust
2012	PC	0,0287 ± 0,0017	0,007	0,015
	HGV	0,1449 ± 0,0100	0,032	0,051
	PC × HGV	-0,0046 ± 0,0006		
2013	PC	0,0157 ± 0,0001	0,006	0,014
	HGV	0,0738 ± 0,0014	0,024	0,055
	PC × HGV	+0,00017 ± 0,00008		

As seen in **Table 3** data retrieved from the measurement campaign in the year 2013 in Plabutschtunnel don't show the need of an interaction term. Comparing the two emission factors for passenger cars (PC) and heavy good vehicles (HGV) hardly any differences between with and without interaction term could be seen. Also the value of the interaction term is very low. The cause is the distribution of the data (Hinterhofer, 2014). While in 2012 both a lot of traffic and little traffic has equal share within the measured dataset, in 2013 clearly more data have a traffic amount of less than ten vehicles per minute. So the calculated regression is clearly more influenced by little traffic.

The interaction term from the measurement campaign in the year 2012 shows that at the point of 35 vehicles per minute, with a heavy traffic share of 17,5 %, the calculated emission amount won't rise any more. This would cause a base traffic amount of around 50.000 vehicles per day and tube. For the Plabutschtunnel this traffic amount is not realistic. From 20 vehicles per minute the calculated emission amount with interaction term is lower than calculated with the emission factors without interaction term (given in **Table 2**). However, it has to be mentioned that the value of the interaction term depends strongly on the characteristics of the tunnel (length, number of traffic lanes, amount of traffic, velocity speed).

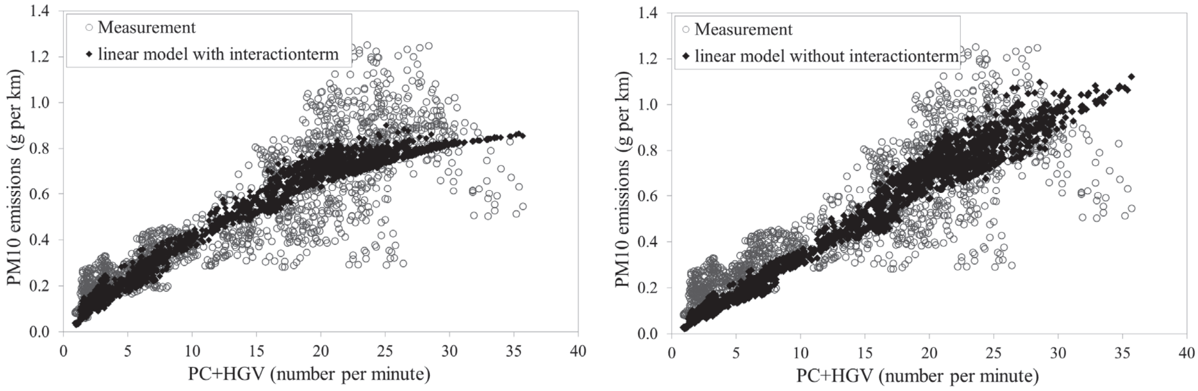

Figure 2: Comparison between measured data and model recharged emissions with and without interaction term.

Regardless of whether taking the interaction term into account or not, already the calculated emission factors for PM10 (exhaust and non-exhaust) are throughout lower than the PM10 emission factors for only non-exhaust content found in literature (eg. Lohmeyer et al., 2011)

In addition to the NOx and PM10 emission factor investigations in the year 2013 also filter analysis for heavy metals (Sb, Cu, Cr, Pb, Ni, As, Cd) have been performed. The filter load of arsenic and cadmium was below detection limit. All other substances were analysed and evaluated. The results are given in the Table below.

Table 4: Heavy metal emission factors Plabutschtunnel including the 95 % confidence interval plus average, minimum value, maximum value and median in [mg/km], 17,2 % havey traffic share implicit.

Substance	emission factor	average	minimum value	maximum value	median
Sb	0,0029 ± 0,0009	0,0030	0,0018	0,0047	0,0027
Cu	0,0635 ± 0,0164	0,0646	0,0410	0,0991	0,0637
Cr	0,0056 ± 0,0015	0,0057	0,0038	0,0093	0,0053
Pb	0,0009 ± 0,0003	0,0009	0,0003	0,0014	0,0009
Ni	N.A.*	0,0009	0,0001	0,0018	0,0008

* The scatter plot of the nickel emission amount related to the vehicle kilometre doesn't show a good correlation why a linear regression wasn't made.

The results show that the heavy metals emission load due to traffic is low. Because of the continuous traffic flow, brakes and clutch are rarely used. Compared with measurements in the Kaisermühlentunnel (Urban et al., 2006), a tunnel with frequent congestions the emission factors are lower by at least one-third.

Discussion

In the light of the results given above, the model calculated emission factors for NOx represent the real time emissions quite accurate. For PM10 the measured emissions cover almost all exhaust emissions that have been calculated with the two models HBEFA 3.1 (Umweltbundesamt, 2010) and NEMO (Rexeis, Hausberger, 2005). So the share of PM10 non-exhaust must be very low. The measured PM10 non-exhaust results are, compared to established emission factors (e.g. Lohmeyer et al., 2011), clearly lower than so far supposed. Hence especially for tunnels the commonly used emission factors should be decreased.

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References

Boulter, P.G. (2005), A review of emission factors and models for road vehicle non-exhaust particulate matter. *TRL Report PPR065*. TRL Limited, Wokingham, UK

Gehrig, R.; Hill, M.; Buchmann, B.; Imhof, D.; Weingartner, E.; Baltensberger, U. (2004): PM10 emission of road traffic from abrasion and resuspenion processes, Paper *PM Emission Inventories scientific Workshop*, Milan, Italy, 18. October 2004

Hinterhofer, M. (2014) Anteil der verkehrsbedingten PM10 und PM2,5 Emissionen aus Abrieb und Wiederaufwirbelung an der Feinstaubbelastung in Österreich, *Dissertation University of Technology Graz*

Lohmeyer A., Schmidt, W. and Düring, I. (2011) Einbindung des HBEFA 3.1 in das FIS Umwelt und Verkehr sowie Neufassung der Emissionsfaktoren für Aufwirbelung und Abrieb des Strassenverkehrs, *Projekt 70675-09-10*

Rexeis, M. and Hausberger, S. (2005), Calculation of Vehicle Emissions in Road Networks with the model “NEMO”; *Transport and Airpollution Conference*; ISBN: 3-902465-16-6, Graz

Umweltbundesamt (2010), Handbuch Emissionsfaktoren des Straßenverkehrs (HBEFA 3.1), Wien

Urban, H., Ellinger, R., and Hübner, C. (2006) Ermittlung von aktuellen österreichischen Kfz-Flotten-Emissionsfaktoren für limitierte und nicht limitierte Schadstoffkomponenten im Tunnel Kaisermühlen, *Projekt Nr.: 927a05,* Wien