Dr. Marlene Hinterhofer, Ao.Univ-Prof. Dr. Peter Sturm, Ing. Thomas Nöst,
Graz University of Technology

"NO_x, PM_{10} and heavy metal emission factors based on current tunnel measurements"

Abstract

Due to persisting high particulate matter concentrations in areas of Austria the determination of the influence of specific sources gains more and more importance. To improve the appraisal of traffic concerned PM_{10} and NO_x current fleetspecific emission factors were determined in the Plabutsch Tunnel. It has been shown that, especially in relation to PM_{10} non-exhaust, driving in tunnels leads to a significantly reduced amount of emissions, compared with field routes. For this reason, much lower emission factors have to be set for road sections in tunnels. Due to the length and traffic density in Plabutschtunnel a decrease in PM_{10} emission rate can be observed at high transport speeds. Taking this observation into account and adapting the regression model using an interaction term ($amount_{PC} \times amount_{HGV}$) this term receives a negative value for the measurements in 2012. Within the measurements in 2013, the implementation of the interaction term does not change the emission factors for both passenger cars (PC) and trucks (HGV). So the interaction term is negligible. Comparing the measured NO_x emission factors with those from the model calculation using the Handbook Emission Factors (HBEFA 3.1) there is an underestimation by the model observable. Especially concerning the heavy goods vehicles and based on this specific driving situation (Highway 100 km/h). The measured heavy metal loads in the dust are low due to the very smooth driving behavior in the tunnel.

Motivation

Given the persistently high particulate pollution in parts of Austria, politicians are called to take action. 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 PM_{10} non-exhaust emission factors. Therefor measurement campaigns in the Plabutsch road tunnel in the year 2012 and 2013 were performed and in addition NO_x and Heavy Metal emission factors were determined. The performed measurements have to be seen in addition to the emission factors published in literature. They represent a specific driving condition (Highway 100 km/h) and an unkown rate of pollution on the road during the measurements in Plabutschtunnel.

Fundamental consideration

Tunnel measurements have advantages for the determination of emission factors. In addition to the generally high emission rate there is an increase in the concentration of pollutants over the driven distance within the tunnel. So the emitted pollutants are transported in the tunnel due to the thrust of the vehicles or using a longitudinal mechanical ventilation to the exit portal. However, there is a different driving pattern in tunnels compared to city traffic or free country routes. In general, the driving is characterized by a uniform velocity profile with rare braking and acceleration. The traffic situation is markedly different from those observed on rural roads, especially in urban areas. In addition, it can be assumed that the road is less soiled in the tunnel compared to outdoor conditions, which affects the PM_{10} non-exhaust emission factors. It follows that the values determined in tunnel measurements are usually smaller than those on other road areas. That is why the results can only partially be transferred to other streettypes.

Measurement Setup

For the determination of emission factors in 2012 and 2013 two-week measurement campaigns in Plabutschtunnel in Graz were carried out. 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 slightly 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 is rarely used. For analysis only periods without mechanical ventilation were taken into account. Speed limit is set to 100 km/h for passenger cars and 80 km/h for heavy good vehicles. Section control within the tunnel is enforced. The built-in tunnel longitudinal flow measuring devices or the measurement of CO_2 allow to determine the dilution. To get by the measured NO_x concentrations the quality of the measurement results are evaluated. The measurement was carried out in the east tunnel (direction Linz). In 2012 the measuring section covered the area between the breakdown bay in the middle of the tunnel and the final breakdown bay just before the exit portal and includes 3384 m. 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. (see Figure 1). Because of the roof profile the weighted average gradient for the shorter measuring distance in the year 2012 is 0.58 % and for the long test section in 2013 0.21 %. The measuring container used (MP1 and MP2) had to be positioned, due to traffic safety and technical considerations at the beginning oft he breakdown bay (PB). Comparative measurements in 2011 have shown that the position oft he measurement equipment within the breakdown bay has only little effect on the results. 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. 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 discontinuous with a low temporal resolution. Filter sampling 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.

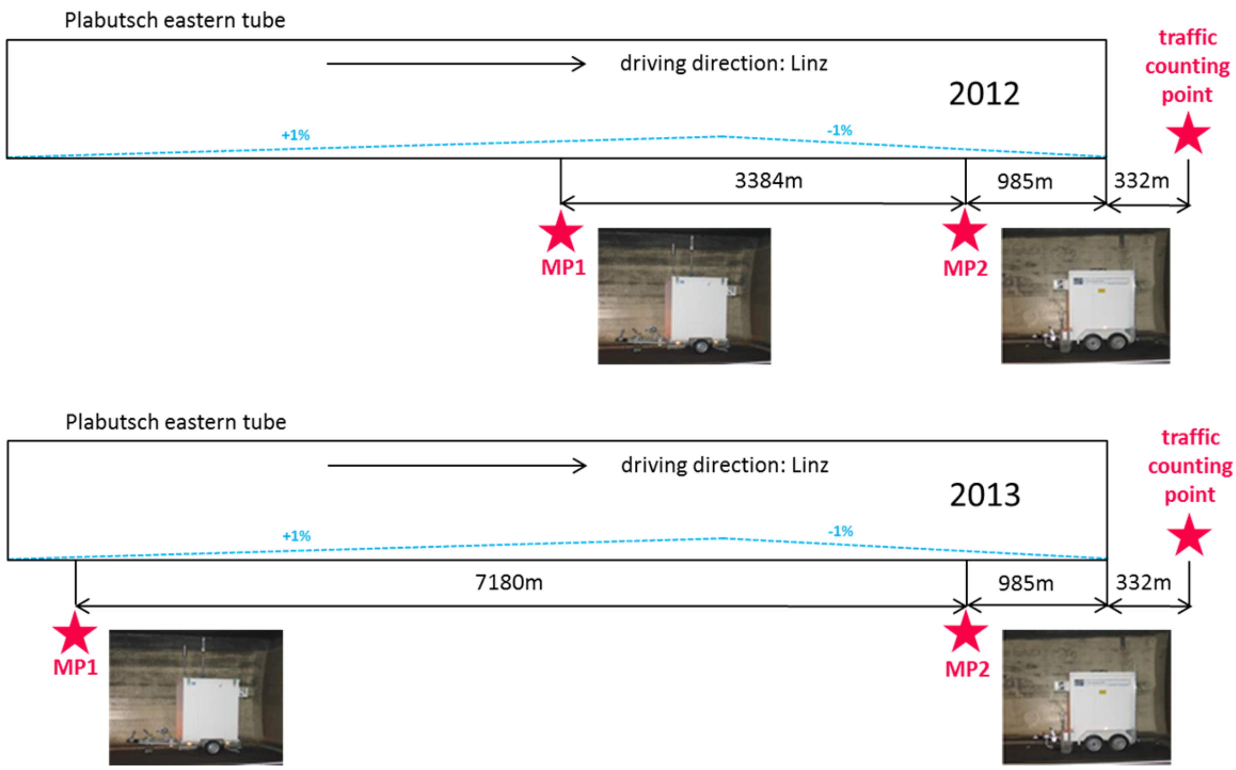

Figure 1: Overview scheme of the measurement setup.

Results

All measurement data (air quality measurement, traffic counting and air velocity) have a resolution of one minute, but for calculation the usage of a moving ten minutes average was proved to be best. As a result, short-term peak values are averaged out, but the dynamics of the values is always preserved. However, in return, the values must be temporally shiftet to compare the correct value pairs.

NO_x emission factors

The NO_x concentration in the tunnel is only dependent on the number of vehicles and the type of vehicle. So this pollutant is very well suited to correct the time offset and to validate the model system. Within this validation the NOx emission factors were calculated using a multiple linear regression (see Table 1).

Table 1: Measurement based NO_x emission factors for passenger cars (PC) and heavy goods vehicles (HGV) in Plabutschtunnel during the measurement campain 2012 and 2013, including the 95 % confidence interval, compared to HBEFA 3.1 and NEMO.

year	type of vehicle	NO_x emission factor [g/km]		
		measurement	HBEFA 3.1	NEMO
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 NO_x 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.

PM_{10} emission factors

For the evaluation of the PM_{10} emission factors only those data sets which have been used to calculate the NO_x emission factors were considered. If there are measured values missing at one of the two measurement sites the data set was excluded. This means the available number of data sets is decreasing. The procedure for the calculation of the PM_{10} emission factors is identical to the NO_x emission factors. Table 2 shows the results for PM_{10}. The measured values are compared with the model results (HBEFA 3.1, NEMO). Important is the fact that the measured PM_{10} emission factors involve PM_{10} total whereas the emission factors calculated by the model exclusively represent PM_{10} exhaust. That is why it is assumed that the emission factors from the emission models are significantly lower than those from the measurement.

Table 2: Measurement based PM_{10} emission factors for passenger cars (PC) and heavy goods vehicles (HGV) in Plabutschtunnel during the measurement campain 2012 and 2013, including the 95 % confidence interval, compared to HBEFA 3.1 and NEMO.

year	type of vehicle	PM_{10} emission factor [g/km]		
		measurement 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

As the PM measurement does not allow any distinction between exhaust and non-exhaust PM, a second information concerning one of these two shares 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. Since NEMO represents the current database and also the road gradient may be considered accurate, this model is used to calculate the exhaust emissions. In the table below the emission factors for PM_{10} non-exhaust are explicitly shown. For the purposes of updating of uncertainties, the 95% confidence interval of the total emission factor was transferred unmodified to PM non-exhaust.

Table 3: Measurement based PM_{10} non-exhaust emission factors for passenger cars (PC) and heavy goods vehicles (HGV) in Plabutschtunnel during the measurement campain 2012 and 2013, including the 95 % confidence interval.

year	type of vehivle	PM_{10} emission factor [g/km]		
		measurement exhaust + non-exhaust	NEMO exhaust	PM_{10} non-exhaust

year	type of vehivle	PM_{10} emission factor [g/km]		
		measurement exhaust + non-exhaust	NEMO exhaust	PM_{10} non-exhaust
2012	PC	0.0219 ± 0.0016	0.015	0.0069 ± 0.0016
	HGV	0.0954 ± 0.0086	0.051	0.0444 ± 0.0086
2013	PC	0.0157 ± 0.0002	0.014	0.0017 ± 0.0002
	HGV	0.0741 ± 0.0007	0.055	0.0191 ± 0.0007

One reason for the low PM_{10} non-exhaust emission factors could be the high longitudinal velocity inside the tunnel and the high volume of traffic. As a result, the particles do not have time to settle on the road again before the next vehicle raises them up again. To take this consideration into account, the formula fort he multiple regression is extended with an interaction term of the form [number of cars (PC) × number of heavy goods vehicle (HGV)]. Table 4 shows the results including the interaction term

Table 4: Measurement based PM_{10} emission factors for passenger cars (PC), heavy goods vehicles (HGV) and interaction term (PC × HGV) in Plabutschtunnel during the measurement campaign 2012 and 2013, including the 95 % confidence interval, compared to HBEFA 3.1 and NEMO.

year	type of vehicle	PM_{10} emission factor [g/km]		
		measurment 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 ± 0.0002	0.006	0.014
	HGV	0.0738 ± 0.0014	0.024	0.055
	PC × HGV	+0.0002 ± 0.0001		

The listed emission factors are total PM_{10}, but it can be assumed that the emission factor for the interaction term is priority PM_{10} non-exhaust. Reduction effects on the PM_{10} exhaust emissions can occur with very heavy traffic, but is due to the prevailing traffic numbers negligible. It can be assumed that the interaction term primarily reflects the effect of reduced deposition and resuspension.

Comparing the results for passenger cars (PC) and heavy goods vehicles (HGV) with and without interaction term (Table 3 and Table 4) it can be seen that the interction term has little impact on the measurements in 2013. The emission factors for passenger cars and heavy goods vehicles are nearly equal and the value of the interaction term is very small. The reason could be found primarily due to the distribution of the data sets. The data during the measurement campain in 2012 show a pronounced bipolar distribution while during the measurement campain in 2013 significantly more data sets with low traffic numbers are included in the calculation (see Figure 2). It can be assumed that the interaction term only leads to a significant change in the results when the surveyed data sets have a significant share of high quantities of emissions attributable to high traffic numbers. Are records dominated by data points with low or medium traffic which causes low emission levels, the effect of reduced resuspension with heavy traffic can not be observed.

The saturation point of the curve is 35 vehicles per minute. This means that from 35 vehicles per minute the calculated emission rate using this model decreases with increasing traffic, provided that the average heavy-traffic-share is 17.5%, as during the measurement campaign. The average number of vehicles per minute was, during the two-week measurement in the year 2012, 15 vehicles per minute and only three values over 35 vehicles per minute were registered.

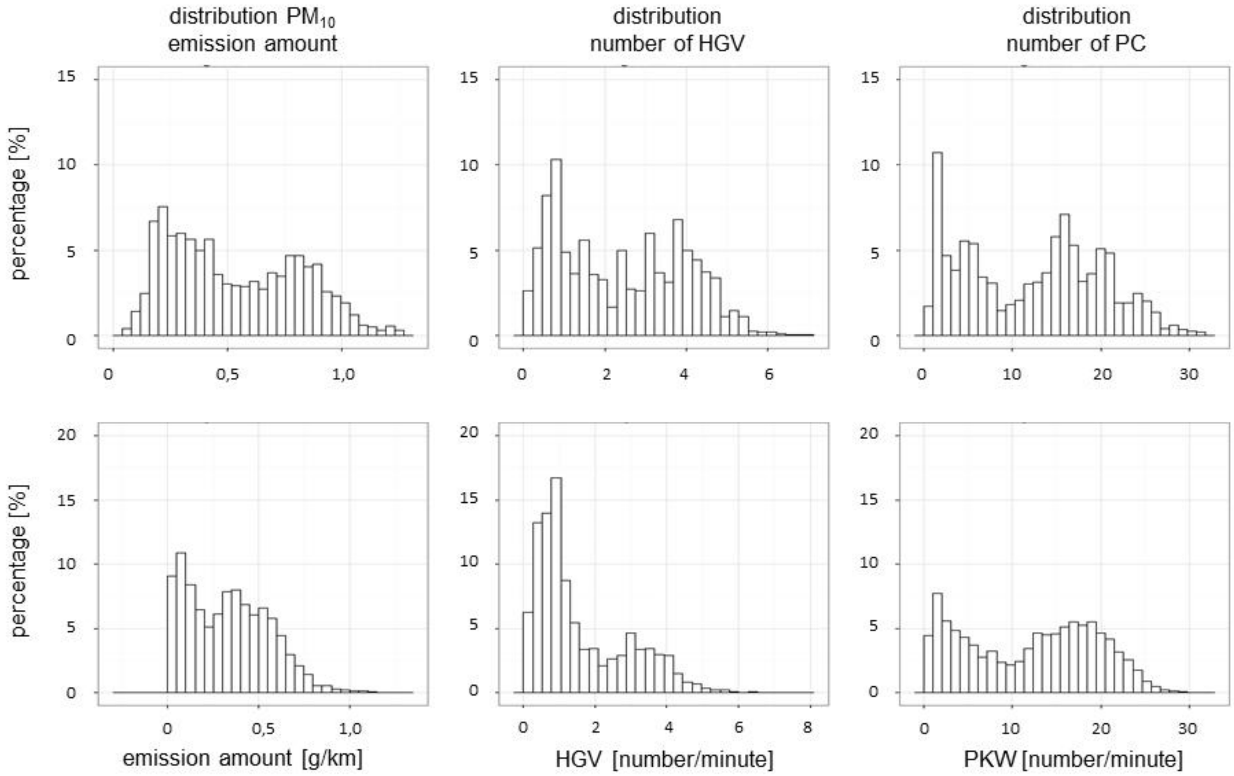

Figure 2: Classified distribution of PM_{10} emission amount and the number of heavy goods vehicles (HGV) and passenger cars (PC) over the entire measurement period, measurement period 2012 on the top and measurement period 2013 at the bottom, Plabutschtunnel.

Comparing the results of the models (with and without interaction term) the model with interaction term reproduce the measured concentrations slightly better. In particular, emission levels for low traffic numbers (up to 10 vehicles per minute) and high traffic numbers (from 32 vehicles per minute) are better represented (see Figure 3). However, it must be assumed that the value oft he interaction term particularly matched to the prevailing measurement conditions. It can be assumed that this term is highly dependent on the traffic numbers and the longitudinal velocity because the interaction term reflects the reduced deposition opportunity and related resuspension. This means the value oft he interaction term determined within thi special measurement setup could hardly be transferred to shorter and less traveled tunnel systems or outdoor routes.

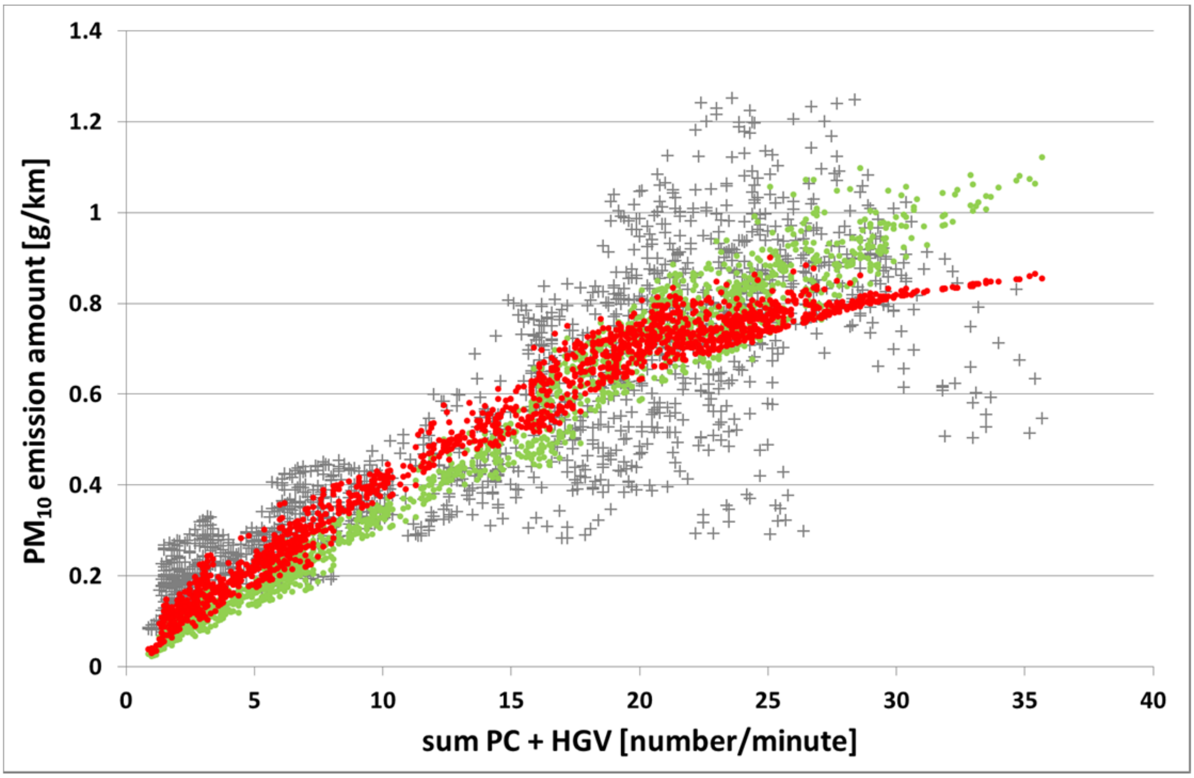

Figure 3: Comparison of the measured emission amounts (black crosses) with the model calculation with interaction term (red dots) and without interaction term (green dots), Plabutschtunnel 2012.

Regardless of whether taking the interaction term into account or not, already the calculated emission factors for PM_{10} (exhaust and non-exhaust) are throughout lower than the PM10 emission factors for only non-exhaust content found in literature (eg. Boulter, 2005; Gehring et al., 2004; Lohmeyer et. al., 2011). These emission factors are applied to outdoor routes.

Heavy metal emission factor

In addition to the NO_x and PM_{10} emission factor investigations in the year 2013 also filter analysis for heavy metals (Sb, Cu, Cr, Pb, Ni, As, Cd, Fe, Mn, Mo) have been performed.

Essential for the assessment of the quality of the detected emission factors for heavy metals is the study methodology. Heavy metal emissions can not be detected with high resolution in time, as no such measurement devices are available. So PM_{10} is collected on a filter and then chemically analyzed. For the determination of heavy metal emissions in Plabutschtunnel at the beginning of the tunnel (PB17) and at the end of the tunnel (PB1) a Digitel instrument was used for the filter loading. The application of the filter takes place two times a day for three hours (5:00 to 8:00 or 17:00 to 20:00). This approach implies that, for a smooth measurement campaign with a 14-day period up to 28 data points are available for evaluation. Due to the small sample size, the significance of statistical analysis is limited. So at a first approximation only emission factor per vehicle can be determined. A detailed calculation to distinguish passenger cars from heavy goods vehicles is not effective with such a limited number of data points. So the below listed emission factors per vehicle implicit a heavy goods vehicle share of 17.2%. That means, for systems with less heavy goods traffic, emission levels are overestimated. Those with more heavy goods traffic leads to an underestimation of the amount of emissions. The results are given in the Table below. The filter load of arsenic and cadmium was below detection limit. All other substances were analysed and evaluated.

Table 5: Heavy metal emission factors (averaged fleet) Plabutschtunnel including the 95 % confidence interval in [mg/km], 17,2 % havey traffic share implicit.

heavy metal	heavy metal emission factor [mg/km]*
antimony (Sb)	0.0029 ± 0.0009
copper (Cu)	0.0635 ± 0.0164
chromium (Cr)	0.0056 ±0.0015
nickel (Ni)	0.0009 ± 0.0008
lead (Pb)	0.0009 ± 0.0003
iron (Fe)	0.0223 ± 0.0021
manganese (Mn)	0.000185 ± 0.000016
molybdenum (Mo)	0.000020 ± 0.000004

Comparing the results with measurements in other tunnels it is found that the calculated emission factors for heavy metals are very low [Urban et al., 2006, Ellinger et al, 2014]. This is primarily due to the difference in driving condition. The tunnel Kaisermuehlen is about 2 km long tunnel on the A22 motorway and has a daily traffic up to 100 000 vehicles per day. Due to this high traffic load at peak times congested traffic is expected, whereas in Plabutschtunnel consistently flowing traffic is observed.

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