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Challenges and solutions in determining dilution ratios and emission factors from chase measurements of passenger vehicles

Ville Leinonen et al.

Correspondence to: Ville Leinonen (ville.j.leinonen@uef.fi)

S1 Concept of the Near-Wake Dilution (NWD) model

The model is based on a concept that there is a near-wake region right behind a moving vehicle and a far-wake region further behind (Fig. S1). A similar model has previously been presented by Chang et al. (2009) for the purpose of wind tunnel experiments. However, here we modify the model slightly to be used with chase experiments. The vehicle exhaust is thought to mix with the surrounding air, i.e., to dilute, within the near-wake region. This dilution caused by the vehicle movement is thought to be in its full extent in the transition region (at the distance of x_{tr} from the tailpipe). Dilution in the far-wake region is much slower because the air parcel to be diluted is the exhaust already mixed with the surrounding area within the near-wake region, instead of the raw exhaust only.

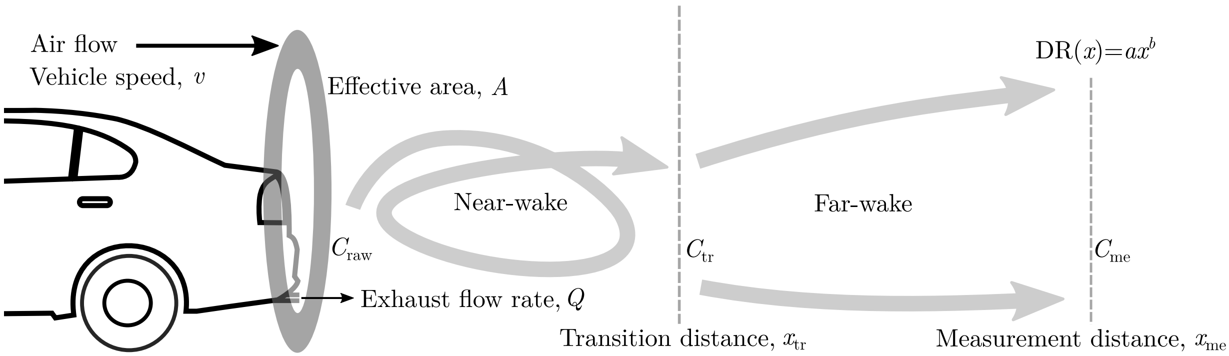

Figure S1. Schematics of the Near-Wake Dilution (NWD) model.

In the near-wake region, the eddies caused by the rear of the vehicle during driving are large and efficient to mix the exhaust with the surrounding air rapidly. The air flow is thought to pass an imaginary surface, having the effective area of A, with the speed equal to the vehicle speed (v). The volumetric flow rate of this diluting air then becomes vA, and the volumetric flow rate of the exhaust (in equal temperature to the outdoor air) is Q. The dilution ratio for a pollutant of interest is

$$\mathrm{DR} = \frac{C_{\mathrm{raw}}}{C} \tag{S1}$$

where C_{raw} is the concentration of the pollutant in the raw exhaust and C the concentration in the diluted air. Analogous to a simple flow-controlled diluter, DR at the distance of x_{tr} is

$$\mathrm{DR}(x_{\mathrm{tr}}) = \frac{vA}{Q} + \epsilon \tag{S2}$$

where ϵ is included to account any nonidealities in this concept, e.g., because DR cannot be 0 when the vehicle is stationary ($v = 0$) or because the transition region is not infinitesimally short in reality.

Many vehicle exhaust chase studies (e.g., Morawska et al. (2007)) have shown that DR typically depends on the chase distance (x in meters) with the function

$$\mathrm{DR}(x) = ax^b \tag{S3}$$

where a and b are parameters depending on vehicle category and study and are roughly the following: $a = 10...100$ and $b = 1.0...1.5$ (Keskinen and Rönkkö, 2010). Equation S3 is, however, valid only in the far-wake region (Olin, 2013), i.e., when $x > x_{\mathrm{tr}}$. Parameter b seems to not depend on v (Morawska et al., 2007), suggesting that dilution occurring in the far-wake region are driven by the dynamics of the outdoor air, such as by crosswind, rather than the vehicle speed-dependent air flow that dilutes the exhaust in the near-wake region. However, because increasing v decreases the time between releasing the exhaust from the studied vehicle and the measurement with the chase vehicle, dilution should yet be vehicle speed-dependent also in the far-wake region (lower b with higher v). Possibly higher turbulence levels with higher v induced by the moving vehicle, however, enhance the dilution rate also in the far-wake region (higher b with higher v) and thus almost cancels the effect of v out, leading to an almost vehicle speed-independent b.

Combining eqs S2 and S3, we obtain

$$\mathrm{DR}(x_{\mathrm{tr}}) = \frac{vA}{Q} + \epsilon = a x_{\mathrm{tr}}^{b} \tag{S4}$$

and the parameter a can be solved:

$$a = \frac{vA}{Q x_{\mathrm{tr}}^{b}} + \frac{\epsilon}{x_{\mathrm{tr}}^{b}}. \tag{S5}$$

Considering the measurement distance in a chase experiment, x_{m}, we further obtain (using eqs S3 and S5)

$$\mathrm{DR}(x_{\mathrm{me}}) = a x_{\mathrm{me}}^{b} = \frac{vA x_{\mathrm{me}}^{b}}{Q x_{\mathrm{tr}}^{b}} + \frac{\epsilon x_{\mathrm{me}}^{b}}{x_{\mathrm{tr}}^{b}}. \tag{S6}$$

The absolute values for parameters A, x_{me}, x_{tr}, b, and ϵ remains unknown. Nevertheless, when chasing a specific vehicle with a constant x_{me}, we can assume that all these parameters are constant. A is thought to depend on the rear shape of the vehicle, as well as is the case of x_{tr} but v may also affect x_{tr} slightly due to altered shapes of the eddies behind the vehicle. Because dilution in the far-wake region is assumed to not depend on v, the value of b presumably depends mainly on the dynamics in the outdoor air but maybe on the rear shape as well. Additionally, although the temperature of the raw exhaust is assumed to not affect the dilution dynamics, since using mass flow rates rather than volumetric flow rates in calculations typically cancels temperature out, it may still have an effect on the dilution dynamics depending on whether cooling and simultaneous expansion occurs in the near-wake or far-wake region. These uncertainties involved in this model can presumably be also accounted by the inclusion of parameter ϵ in eq S2.

Equation S6 can be further arranged to

$$\mathrm{DR}(x_{\mathrm{me}}) = \frac{v}{Q}\frac{A x_{\mathrm{me}}^{b}}{x_{\mathrm{tr}}^{b}} + \frac{\epsilon x_{\mathrm{me}}^{b}}{x_{\mathrm{tr}}^{b}} = \frac{v}{Q}\kappa + \gamma \tag{S7}$$

where the number of free parameters has been reduced from five to two (κ and γ). Using information on the measured concentration, C_{me}, and on C_{raw}, e.g., from $\mathrm{CO_2}$ measurements and its known concentration in the raw exhaust when the engine is combusting fuel, $\mathrm{DR}(x_{\mathrm{me}})$ and further the parameters κ and γ can be obtained. This can be done by plotting the obtained $\mathrm{DR}(x_{\mathrm{me}})$ data as a function of v/Q (recorded via OBD). When the dilution dynamics satisfies the theory behind this model, the data points are scattered so that linear behavior is seen. Thus, linear regression can be performed on the data points originated from the times when the engine was combusting fuel and the rest of the data points (from the times when the engine was in a motoring state) are outliers.

Whereas the study by Chang et al. (2009) uses the multiplication of the real height and width of a vehicle as the imaginary surface which the diluting air passes through, we think consider it a free parameter here instead. That is because the rear surface of a vehicle is actually the surface that does not pass any flow through but the areas around it do; therefore, A may be connected more to the perimeter of the rear rather than its surface area. In addition, the placing of the exhaust pipe or pipes on the rear of the vehicle can also affect dilution mechanics. E.g., in a case of double exhaust pipes on the both sides of the rear of a vehicle can lead to stronger dilution in reality, resulting in higher value for A when it is fitted with available data. Because the chase settings for every studied vehicle in this study are similar, we can consider κ being mostly dependent on the rear shape of a vehicle. Since γ, the parameter involving nonidealities in the NWD model, seems to be clearly higher with the gasoline vehicles of this study compared to the diesel vehicles, we consider it being mostly dependent on the used fuel in this study.

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