Characterization of Dispersion and Ultrafine-particle Emission Factors Based on Near-roadway Monitoring Part I: Light Duty Vehicles

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ABSTRACT

This paper presents near roadway light-duty vehicle (LDV) dispersion and ultrafine-particle (UFP) emission factors (EFs) as a function of vehicle flow rate, speed and mode of operation (free flow and congestion) using 300 5-min measurements of carbon dioxide (CO₂), UFPs, meteorology and traffic conditions near a LDV only roadway. Measurements were made between 2014 and 2018 on 20 days for 2 to 3 hours per day. Near roadway LDV dispersion was estimated using a vehicle emission model (MOVES) for CO₂ EFs, measured CO₂ concentrations and vehicle flow rate. EFs for UFPs were estimated based on the calculated CO₂ dispersion. This eliminated the need to rely on models to estimate dispersion. Results indicate that the near roadway LDV dispersion is a two-stage process. When there was a small number of vehicles (< 10,000 veh h⁻¹), the vehicle induced dispersion was not continuous (unsteady-state conditions). Under unsteady-state conditions, the rate of LDV dispersion near the roadway increased from 2 to 6 m² s⁻¹ as the number of vehicles increased. For larger vehicle flow rates (> 10,000 veh h⁻¹), the dispersion was continuous (steady-state continuous mixing). Under steady-state condition, the rate of dispersion was near 6 m² s⁻¹ and did not increase with additional vehicles. Dispersion models failed to respond to unsteady-state conditions and predicted constant dispersion. The UFP EFs varied from 0.5×10^{13} to 1.5×10^{13} pt km⁻¹ veh⁻¹ for LDV (3x). The increase in UFP EFs was related to increase in vehicle flow rate and speed. The outcome of this study provides important EFs for urban planner to quantify air quality near roadway due to UFPs.

Keywords: Air quality monitoring; Ultrafine particle; Dispersion; Light-duty vehicle emission; Free flow and congestion.

INTRODUCTION

Vehicle emissions are one of the main sources of urban air pollution and exposure to vehicle emissions have been associated with negative health effects. One of the main pollutants that comes from vehicles is ultrafine particles (UFPs) and they occur in large numbers close to roadways (Zhu *et al.*, 2002a; Zhang *et al.*, 2005; Wang *et al.*, 2010; Zhai *et al.*, 2015; Krecl *et al.*, 2017; Xiang *et al.*, 2018; Xiang *et al.*, 2019). UFPs are defined as particles with diameters less than 100 nm. Because of their small size, they can penetrate deep into the human body causing negative impacts on health including cardiovascular and respiratory mortality (Pope III and Dockery, 2006; Adar and Kaufman, 2007; Brook *et al.*, 2010), cancer (Pope III *et al.*, 2002), adverse birth and developmental outcomes (Kumar *et al.*, 2018), and brain diseases (Chen *et al.*, 2017). Thus, vehicle UFP emissions represent a public health concern since millions of people

live near roadways and are potentially exposed to elevated levels of ultrafine particles (Rowangould, 2013).

Current assessment of near roadway air quality mainly relies on results from dispersion models. Generally, dispersion models consider the roadway as a line source where turbulence induced by moving vehicles contribute to mixing of the vehicle exhaust. There are two dispersion models that have been widely used, California Line Source Dispersion Model (CALINE4) (Benson, 1992) and AMS/EPA Regulatory Model (AERMOD) (Cimorelli *et al.*, 2005). Both models assume that the vehicle emissions and turbulence are uniform across the road. Both models are steady-state and are usually used for long term air quality assessment (one hour or more). CALINE4 is a Gaussian dispersion model that develops a mixing cell concept that is defined as a uniform mixing region over the roadway and extends 3 m from the roadway edge. AERMOD is an atmospheric dispersion model developed by the American Meteorology Society and EPA for application to most types of pollutant sources. It is also a Gaussian dispersion model. Besides the basic information inputs in CALINE4, AERMOD require more sophisticated data input including sensible heat flux, friction velocity, convective velocity, Monin-Obukhov length, Bowen ratio, and albedo. AERMOD treats the line source as an area (or volume) source

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instead of a mixing cell. Both models simulate the dispersion process using meteorology input and do not fully considering the impact from variations in vehicle flow rate, speed and mode of operation. Studies have shown that in the near roadway environment, motion of vehicles can generate significant turbulence, and this vehicle-induced turbulence (VIT) is a function of vehicle flow rate (Kalthoff *et al.*, 2005; Gordon *et al.*, 2012). Thus, information related to variations of dispersion near roadway due to vehicle flow rate and mode of operation (free flow and congestion) is needed.

To develop strategies to mitigate human exposure, vehicle emission of UFPs from individual vehicles (emission factors) need to be investigated. UFPs number emission standard has been established in Europe since 2014 (6.0×10^{11} pt km⁻¹ veh⁻¹, Euro 6c) (Marotta *et al.*, 2015), however, it is still an unregulated pollutant in National Ambient Air Quality Standards (NAAQS) of the United States (NAAQS, 2013). To develop a standard for UFPs a comprehensive emission inventory is needed. Near roadway field measurements of UFP concentrations have been made by a number of investigators worldwide (Zhu *et al.*, 2002a, b; Morawska *et al.*, 2005; Zhang *et al.*, 2005; Birmili *et al.*, 2009; Nickel *et al.*, 2013; Krecl *et al.*, 2017). They determined that UFP from vehicles occur in large numbers and vehicle mode of operation is a critical factor in producing vehicle emissions. However, none of the previous near roadway studies have provided emission factors as a function of vehicle flow rate, speed and vehicle mode of operation.

In this study, 5-min averaged concentrations of CO₂ and UFP were measured near an LDV-only roadway (Lake Shore Drive) in Chicago IL for 2 to 3 hours on 20 days between 2014 and 2018. Variations in traffic conditions (in terms of flow rate and speed) were determined using a video camera. CO₂ emission factors (EFs) were modeled from

MOVES for different vehicle mode of operation (free flow and congestion). Dispersion near the roadway for LDVs was calculated using these parameters and then compared to dispersion model results.

METHODS

Monitoring Site

Field measurements were conducted near Lake Shore Drive (LSD) that is an 8-lane roadway (4 lanes in each direction) restricted to light duty vehicles (LDVs). Information from the Illinois Department of Transportation (IDOT, 2016) provides the annual average daily vehicles flow rate of 160,000 veh day⁻¹. Fig. 1 shows the sampling site with sampling locations and local land use identified. In this study, sampling was conducted only when the wind direction was within 45° of normal to the roadway. Also, only data collected under both directions free flow or both directions congestion conditions were used for data analysis. Average ambient background concentrations for each sampling day were used in data analysis. For easterly wind flow, the near roadway sampling (site A) was located on the west side of the roadway and the ambient background concentrations were measured 100 m upwind. The sampling site was considered ideal because the roadway is restricted to LDV with no grade and no barriers that disturb the air flow. The surrounding terrain is level in both the east and west directions and covered by sand and urban grasses. No significant urban buildings are within 1 km radius, the surface roughness was near 0.01 m ($z_0 = 0.01$ m) (Arya, 1999).

In this study, a short averaging time (5-min) was required to record the rapid changes in vehicle mode of operation. Each 5-min time period is considered a separate sampling period. A 5-min sampling period has been considered as an

Fig. 1. Map of sampling sites near Lake Shore Drive (LSD). Red cross represents background sampling locations.

ideal sampling time since it is a manageable time frame for simultaneous measurement and has been applied by previous near roadway studies (Jamriska and Morawska, 2001; Morawska *et al.*, 2005; Xiang *et al.*, 2019). Chemical reactions were not accounted for in this study since researchers have determined that differences in total particle number due to gas and particle reactions can be neglected for short term sampling times (Zhang and Wexler, 2002, 2004; Zhang *et al.*, 2004; Kurniawan and Schmidt-Ott, 2006; Ntziachristos *et al.*, 2007).

At the near roadway sampling location (site A), concentrations of carbon dioxide (CO₂) and ultrafine particles (UFPs) were measured simultaneously with meteorological conditions including wind speed and direction, temperature, and relative humidity. These parameters were also measured at the background location at the beginning and the end of each sampling day.

Total UFPs number concentrations were measured by a condensation particle counter (CPC) (TSI 8525) with measurable size range: 20–1000 nm. Daily zero check of the CPC was performed. CO₂ concentration (0 to 5000 ppm with resolution of 1 ppm) was measured by a hand-held CO₂ analyzer (E-inst AQ-Expert). Wind speed and direction, temperature and relative humidity were measured with a hand-held weather instrument (Kestrel 4500). Traffic information was recorded on an overpass that allowed all lanes of traffic information to be recorded using a video camera.

Estimation of Near Roadway LDV Dispersion

To characterize near roadway dispersion from LDVs, a tracer gas with a well-known emission factor (EF) needs to be available. In previous studies, CO and NO_x were most commonly used because of their well-documented EFs (Imhof *et al.*, 2005; Zhang *et al.*, 2005; Jones and Harrison, 2006; Wang *et al.*, 2010; Nickel *et al.*, 2013). Recently, the U.S. EPA has released a new version of the vehicle emission model, “MOVES” (U.S. EPA, 2014). MOVES is a vehicle emission model that estimates vehicle EFs based on driving cycles for various vehicle types. It defines driving cycles based on vehicle power load and speed (Frey *et al.*, 2008). Once vehicle operating modes are determined, pollutant emission rates can be derived from MOVES. In this study, CO₂ is chosen as the tracer gas because: (1) as is a non-reactive gas, the homogeneous mixing of CO₂ and particles has been verified by recent roadway studies. (Kurniawan and Schmidt-Ott, 2006; Ntziachristos *et al.*, 2007; Rönkkö *et al.*, 2017; Hietikko *et al.*, 2018), (2) MOVES can predict CO₂ EFs as a function of vehicle mode of operation better than other pollutants (e.g., CO, NO_x) (Liu and Frey, 2015), and (3) concentrations of CO₂ near roadway are well above background levels (Xiang *et al.*, 2016). Thus, in this study near roadway LDV dispersion has been estimated with EFs of CO₂, vehicle flow rates and CO₂ concentration as shown in Eq. (1).

$$D_{LDV} = \frac{EF_{CO_2,LDV} \times N_{LDV}}{C_{CO_2} - C_{CO_2,BG}} \quad (1)$$

In Eq. (1), D_{LDV} is near roadway LDV dispersion (m² s⁻¹).

$EF_{CO_2,LDV}$ the LDV emission factor for CO₂ (g m⁻¹ veh⁻¹) modeled by MOVES. N_{LDV} is the LDV flow rate (veh s⁻¹). C_{CO_2} and $C_{CO_2,BG}$ are CO₂ concentrations measured at the near roadway and background locations, respectively (g m⁻³). The differences between near roadway and background concentrations provides the pollutant concentrations contributed by vehicle emissions. The 5-min measurements have been subdivided into (1) all lane free flow and congestion driving conditions, (2) uniform vehicle flow intervals of 1,000 veh h⁻¹. This subdivision of the data allows a realistic characterization of the impact of vehicle flow rate and vehicle mode of operation on vehicle emissions ($EF \times N$), and changes in CO₂ concentrations to be related to near roadway LDV dispersion (D_{LDV}).

Due to the turbulent flow generated by the vehicle motion, the pollutant concentrations measured near roadways in short term intervals such as 5-min is highly variable even when the traffic and meteorological condition does not vary. In turbulent flow the pollutant measurements are evaluated as the sum of the ensemble mean and fluctuation components. The ensemble mean is the arithmetic average of a variable obtained from repeating an experiment many times under the same general conditions and is often used for turbulent flow conditions (Arya, 1999; Seinfeld and Pandis, 2016). The ensemble means are calculated for each vehicle flow interval (1,000 veh h⁻¹) and used to evaluate the dispersion. After calculating the dispersion, the result can be used to compare with dispersion models, like CALINE4 and AERMOD. The dispersion from CALINE4 and AERMOD were calculated based on the model input and Eq. (1).

Determination of UFP EFs for LDVs

When measurements of ultrafine particles (UFPs) and near roadway LDV dispersion (D_{LDV}) based on Eq. (1) are available, the UFP emission factors (EFs) can be determined by Eq. (2) for each 1,000 veh h⁻¹ data interval.

$$EF_{UFP,LDV} = \frac{(C_{UFP} - C_{UFP,BG}) \times D_{LDV}}{N_{LDV}} \quad (2)$$

In Eq. (2), $EF_{UFP,LDV}$ is the LDV UFP emission factor (pt m⁻¹ veh⁻¹). C_{UFP} and $C_{UFP,BG}$ are UFP concentrations measured at near roadway and background locations, respectively (pt m⁻³). Difference between C_{UFP} and $C_{UFP,BG}$ is considered as UFP contributed by vehicles. Because UFP and CO₂ were simultaneously measured, D_{LDV} from Eq. (1) was used in Eq. (2).

RESULTS AND DISCUSSION

Overview of Meteorological Condition

In this study, the average temperature was 20 (± 2)°C for free flow and 26 (± 1)°C for congestion; the average relative humidity was 71 (± 12)% for free flow and 63 (± 4)% for congestion. Atmospheric stability class were neutral or stable (class D) for most of the sampling days. On the average, free flow showed higher wind speed (1.8 ± 0.7 m s⁻¹) than congestion (1.4 ± 0.8 m s⁻¹).

Vehicle Flow Rate and Speed

Fig. 2(a) presents the vehicle speed-flow relationship recorded near LSD for southbound and northbound lanes that compare to typical traffic patterns on many roadways (Mannering and Washburn, 2012). The flow rate in each direction has a maximum capacity at a speed equal to 60 km h^{-1} . Both sides vehicle flow rate reached a maximum

capacity at a speed near 60 km h^{-1} and decreases for higher and lower speeds. The speed-flow curve was fitted using Greenshields model (Mannering and Washburn, 2012). The upper part of the speed-flow curves represents traffic with a large spacing ($1/\text{vehicle density}$) that allows vehicles to operate in free flow conditions. In free flow conditions, vehicle flow rate increases when vehicle speed decreases.

Fig. 2. Relationship between (a) 5-min vehicle flow rate and speed, and (b) 5-min vehicle flow rate and density near Lake Shore Drive (LSD) under free flow and congestion driving conditions.

The driving condition is considered congested on the lower part of the curves where vehicles are hindered by other vehicles due to small spacing between vehicles. In congestion conditions, vehicles usually show frequent stop-and-go driving patterns and higher vehicle speeds lead to higher vehicle flow rate. The large variations in speed and flow indicates that there was a significant variation in vehicle mode of operation. These variations were able to be observed due to the short sampling time (5-min).

In Fig. 2(b), the relationship between total vehicle flow rate and density is provided. For each 5-min sample, total vehicle flow rate and density are equal to the sum of LDVs in southbound and northbound. The range of the total vehicle flow rate is between 500 and 14,000 veh h⁻¹. For free flow conditions, vehicle density increased from 5 to 200 veh km⁻¹ as vehicle flow rate increased from 500 to 13,500 veh h⁻¹. The increase in vehicle flow rate results in a decrease in the distance between each vehicle. For congestion conditions, vehicle density rapidly increased from 400 to 600 veh km⁻¹ when vehicle flow rate decreased from 13,500 to 9,500 veh h⁻¹. This produced a decrease in distance between each vehicle and resulted in an increase in vehicle density. The average speed of vehicles for free flow was 96 km h⁻¹ and 26 km h⁻¹ for congestion. For free flow conditions vehicle speed varied from 60 to 130 km h⁻¹. While for congestion, vehicles speed had a range from 15 to 40 km h⁻¹.

Analysis of CO₂ EF for LDVs

Fig. 3 presents the CO₂ LDV EFs modeled by MOVES as

a function of vehicle flow rate and mode of operation (free flow and congestion). The LDV EFs for each 1,000 vehicles interval are modeled using the 5-min measured meteorology and vehicle speed as input for MOVES with default setting (age distribution and average vehicle driving cycle). These CO₂ EFs are comparable to other studies (Barth and Boriboonsomsin, 2008; Liu *et al.*, 2013; Liu and Frey, 2015) that report constant CO₂ EFs (250 g km⁻¹ veh⁻¹) for vehicle speeds above 60 km h⁻¹ that increases rapidly to 450 g km⁻¹ veh⁻¹ when vehicle speed decreases to 10 km h⁻¹. In this study, as the vehicle flow rate increased from 500 to 13,500 veh h⁻¹ LDV CO₂ EFs were near 200 g km⁻¹ veh⁻¹. For congestion conditions, LDV CO₂ EFs increased from 250 to 400 g km⁻¹ veh⁻¹ when the total vehicle flow rate decreased from 14,000 to 9,000 veh h⁻¹ (speed from 40 to 15 km h⁻¹).

CO₂ Concentrations near Roadway

Fig. 4 provides the variation in ensemble means of measured CO₂ concentrations (background subtracted) near LSD. For free flow conditions, the CO₂ concentrations increased from 0.014 to 0.14 g m⁻³ when vehicle flow rate increased from 500 to 13500 veh h⁻¹. The best fit line indicates high linear correlation ($R^2 = 0.98$). This indicates that variations in vehicle flow rate are a critical indicator of changes in CO₂ concentration under free flow conditions. For congestion conditions, despite the vehicle flow rate increase of 40% from 9500 to 13500 veh h⁻¹, the CO₂ concentration was constant near 0.18 g m⁻³. This is due to the fact that CO₂ EF is decreasing as vehicle flow rate is increasing for congestion

Fig. 3. Variation of average of CO₂ emission factors with total vehicle flow rate as a function of vehicle mode of operation (free flow and congestion). LDV emission factors were modeled using Motor Vehicle Emission Simulator (MOVES) for each 5-min measurement, which requires vehicle speed for both directions, temperature and relative humidity. Bars indicate one standard deviation.

Fig. 4. Ensemble means of 5-min measured CO_2 concentration (*background subtracted*) variation with total vehicle flow rate for different driving conditions near LSD. Ensemble means are calculated as arithmetic average for each interval. The 5-min data were divided into 1,000 veh h^{-1} interval. Bars indicate one standard deviation.

conditions. The total CO_2 emissions ($\text{EF}_{\text{fleet}} \times N$) remains relatively constant. The substantially higher CO_2 concentrations under congestion conditions indicates the need for congestion mitigation.

Variation in Near Roadway Dispersion with Variation in LDV Flow Rate

To calculate near roadway LDV dispersion (D_{LDV}) as a function of LDV flow rates, Eq. (1) was used for each 1,000 veh h^{-1} interval. The calculations are based on the CO_2 EFs from Fig. 3 and the ensemble mean CO_2 concentrations from Fig. 4. Fig. 5 shows the variation of calculated D_{LDV} as a function of vehicle flow rates and vehicle mode of operation (free flow and congestion). To better represent the dynamics of D_{LDV} , data in free flow was fitted to a logarithmic profile ($R^2 = 0.89$). For free flow conditions, when vehicle flow rates increased from 500 to 10,000 veh h^{-1} , D increased from $2 \text{ m}^2 \text{ s}^{-1}$ and became relatively constant near $6 \text{ m}^2 \text{ s}^{-1}$. The D_{LDV} increased as spacing between vehicles decreased, for low vehicle flow rates (less than 10,000 veh h^{-1} or density less than 100 veh km^{-1}), the vehicle-induced turbulence (VIT) was not continuous due to the large vehicle spacing (unsteady-state condition). For vehicle flow rates larger than 10,000 veh h^{-1} (or vehicle density more than 100 veh km^{-1}), the vehicles produce a training or drifting effect that restricts an increase in VIT (steady state condition) (Kanda *et al.*, 2006; Kim *et al.*, 2016). For congestion conditions, D_{LDV} was nearly constant with the value close to $6 \text{ m}^2 \text{ s}^{-1}$.

When comparing dispersion models (CALINE4 and

AERMOD) calculated results to results from this study, good agreement was found for high vehicle flow rate and density (more than 10,000 veh h^{-1} or 100 veh km^{-1}). For low vehicle flow rate and density (less than 10,000 veh h^{-1} or 100 veh km^{-1}), the D_{LDV} from this study increased as the vehicle flow rate increased. This is reasonable considering that the impact of vehicles on turbulent mixing is increasing (Kalthoff *et al.*, 2005; Alonso-Estébanez *et al.*, 2012; Gordon *et al.*, 2012). However, CALINE4 and AERMOD failed to response to this variability and predicted higher D_{LDV} values (50% to 300% higher). This failure can produce inaccurate predictions of near roadway pollution.

Determination of UFP EFs for LDVs

Variations in the near roadway ensemble mean UFP measured concentrations (*background subtracted*) as a function of vehicle flow rate and mode of operation are shown in Fig. 6. The figure provides the best-fit line obtained by linear least-squares regression. In Fig. 6, for free flow conditions, the UFP concentrations increased from 500 to 11,000 pt cm^{-3} when the average vehicle flow rate increased from 500 to 13,500 veh h^{-1} with a correlation coefficient (R^2) of 0.95. For congestion conditions, there was an increase from 4,500 to 6,500 pt cm^{-3} when the flow increased from 9,500 to 13,500 veh h^{-1} . The overall results indicate that there is an increase in UFP concentrations with an increase in vehicle flow rate for both free flow and congestion conditions.

As discussed in the method section, Eq. (2) was used to calculate fleet EFs of UFPs. Vehicle fleet flow rate, D_{LDV} in

Fig. 5. Variation of near roadway LDV dispersion (D_{LDV}) with total vehicle flow rate and vehicle mode of operation near LSD. The D_{LDV} for each interval is determined using Eq. (1) and ensemble means of CO_2 (in Fig. 4). The data were divided into 1,000 $veh\ h^{-1}$ interval. Bars indicate one standard deviation.

Fig. 6. Ensemble means of 5-min measured UFP concentration (*background subtracted*) variation with total vehicle flow rate for different driving conditions near LSD. Ensemble means for each interval are calculated as arithmetic average for each interval. The 5-min data were divided into 1,000 $veh\ h^{-1}$ interval. Bars indicate one standard deviation.

Fig. 5 and UFP concentrations in Fig. 6 were used as input to Eq. (2). The data were grouped by vehicle mode of operation and 1,000 veh h⁻¹. Fig. 7 provides the calculated UFP EFs from the application of Eq. (2) for LDVs as a function of vehicle flow rate and mode of operation (free flow and congestion). For free flow conditions, UFP EFs varied from 0.5×10^{13} to 1.5×10^{13} pt km⁻¹ veh⁻¹ with vehicle flow rate varies from 500 to 13,500 veh h⁻¹ (vehicle density increased from 5 to 200 veh km⁻¹). For congestion conditions, UFP EFs in this study were near 1×10^{13} pt km⁻¹ veh⁻¹ when the flow rate decreased from 14,000 to 10,000 veh h⁻¹ (vehicle density increased from 400 to 600 veh km⁻¹).

Conventionally, EFs are considered as a function of vehicle speed (Liu and Frey, 2015). Fig. 7 shows variations of UFP EFs with variations in vehicle speed for different vehicle mode of operation. For free flow, the UFP EFs increased 3 times when vehicle speed decreased from 120 to 60 km h⁻¹. For congestion conditions, when the vehicle speed decreased from 40 to 10 km h⁻¹, the UFP EFs were relatively constant at 1×10^{13} pt km⁻¹ veh⁻¹. These significant variations in UFP EFs should be considered by vehicle emission models (e.g., MOVES).

Fig. 8 compares the UFP EFs for LDVs calculated in this study with other near roadway studies. UFP EFs from this study were well within the range of the values reported from other studies. Since there is no literature reporting UFP EFs as a function of vehicle speed, only average value can be used for comparison. Extensive reviews of EFs for UFPs has been reported by researchers (Keogh *et al.*, 2010; Kumar *et al.*, 2011) that show average UFP EFs of LDVs range from

10^{13} to 10^{14} pt km⁻¹ veh⁻¹. This is consistent with the results in this study. When compared with other near roadway studies, the results are within an order of magnitude. More information about the results and other near roadway studies is provided in Table 1.

In general, LDV EFs are higher in free flow (LDV speed > 60 km h⁻¹) than in congestion conditions. For free flow conditions, LDV EFs reported by other studies ranged from 1.5×10^{13} to 21×10^{13} pt km⁻¹ veh⁻¹ with average value of 7×10^{13} pt km⁻¹ veh⁻¹. For congestion, LDV EFs from other studies varied from 1×10^{13} to 8×10^{13} pt km⁻¹ veh⁻¹ with an average value of 3×10^{13} pt km⁻¹ veh⁻¹. The differences between the studies can be explained by differences in vehicle mode of operation (e.g., vehicle speed), road geometry (e.g., distance of sampling location from roadway), lack of standardization of measuring instruments (e.g., limit of size range) and different fuel content (e.g., Sulphur) (Morawska *et al.*, 2008; Keogh and Sonntag, 2011; Jensen *et al.*, 2019) (See Table 1).

CONCLUSIONS

Driving conditions are determined to be an important indicator of UFPs emissions from LDVs. In this study, the UFP emission factors (EFs) of LDV are close to literature reported values under different driving conditions. By using short term measurements (5-min), significant variations (three times) were found in UFP EFs as a function of vehicle flow rate and speed under free flow driving condition. For free flow, UFP EFs increase from 0.5×10^{13} to 1.5×10^{13} pt km⁻¹ veh⁻¹

Fig. 7. Variation of UFP LDV emission factors as a function of total vehicle flow rate and vehicle speed under different driving conditions (free flow and congestion) near LSD. Bars indicate one standard deviation.

Fig. 8. Comparison of this study and literature reported average UFP EFs for free flow and congestion conditions. Average UFP EFs are identified with uncertainties shown in parenthesis (unit: 10^{13} pt km $^{-1}$ veh $^{-1}$). Bars indicate one standard deviation.

Table 1. Detail information reported in literatures and this study.

Reference	Location	Size range (nm)	Road type	Vehicle flow rate (veh day $^{-1}$)	Vehicle mode of operation	Vehicle speed (km h $^{-1}$)
Morawska <i>et al.</i> (2005)	Brisbane, Australia	15–700	Street canyon	n.a	free flow	100
Imhof <i>et al.</i> (2005)	Zurich, Switzerland	> 7	Street canyon	HDV% = 6	congestion	< 60
Jones and Harrison (2006) ^c	London, UK	11–450	Urban freeway	n.a	congestion	< 50
Birmili <i>et al.</i> (2009)	Berlin, Germany	10–500	Urban freeway	180,000	free flow	75–90
Wang <i>et al.</i> (2010)	Copenhagen, Denmark	10–700	Rural freeway	HDV% = 6	free flow	110
Nickel <i>et al.</i> (2013) ^f	Meckenheim, Germany	14–750	Rural freeway	55,600	free flow	120
Zhai <i>et al.</i> (2015)	Chicago, US	20–1000	Rural freeway	79,500	free flow	65–100
Krecl <i>et al.</i> (2017)	Stockholm, Sweden	> 28	Street canyon	HDV% = 18	congestion	40–60
This study	Chicago, US	20–1000	Rural freeway	160,000	free flow	< 50
				HDV% = 0	congestion	60–130
						15–40

as the vehicle flow rate increase from 500 to 13,500 veh h $^{-1}$ and vehicle speed decrease from 120 to 60 km h $^{-1}$. For congestion, the variations of UFP EFs are small compared to free flow. The results indicate that changes in vehicle speed is a critical factor for LDVs UFP EFs under free flow but not for congestion.

Variation in near roadway LDV dispersion (D_{LDV}) near roadway is a two-part process. At low vehicle flow rate, D_{LDV} increases with vehicle flow rate (from 2 to 6 m 2 s $^{-1}$).

For vehicle flow rates larger than 10,000 veh h $^{-1}$, D_{LDV} reaches a steady-state and with constant value (6 m 2 s $^{-1}$). Current dispersion models (CALINE and AERMOD) fail to response to variations in D_{LDV} at low vehicle flow rate. This also highlights the need to parameterize the D_{LDV} as a function of vehicle flow rate and density in order to quantify the effect of dispersion contributed by vehicles. However, such work is limited and requires more investigation in the near roadway environments.

ACKNOWLEDGMENTS

We would like to thank all participants in the field measurement, in particular Liuyang Sun, Xuexuan Peng for collecting field samples.

DISCLAIMER

Reference to any companies or specific commercial products does not constitute endorsement.

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Received for review, August 9, 2019

Revised, October 16, 2019

Accepted, October 19, 2019