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DETERMINANTS OF IN-CABIN EXPOSURE TO VEHICLE-INDUCED EMISSIONS

by
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AN ABSTRACT OF THE DISSERTATION OF

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Vehicular exhaust is a major air pollution source in urban areas and contributes a large portion of carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$) present in outdoor air that can flow into enclosed micro-environments. Occupants of vehicles are at highest risk of exposure to CO and $PM_{2.5}$due to their proximity to the exhaust of other vehicles. Attempts at interpreting the high levels of traffic emissions inside the vehicle attributed the problem to a large array of factors including ventilation setting, weather conditions, roadway type, vehicle characteristics and self pollution. However, several determinants remained scarcely, superficially or not yet studied such as out-vehicle sample intake location, indoor to outdoor difference in temperature, pressure and humidity levels and self pollution potential. Also, multivariate regression models reported in the literature on in-vehicle exposure to CO could explain at best 69% of CO variability inside a car cabin.

Hence, the current work aims at improving the understanding of in-cabin exposure to CO and $PM_{2.5}$, and self pollution potential inside vehicles. For this purpose, field testing was conducted using six different vehicles and involving the monitoring of in- and out-vehicle CO and $PM_{2.5}$ concentrations and 25 different potential determinants including air quality, meteorological, temporal, vehicle and traffic related variables. Monitoring data from a total of 119 mobile tests, 120 fume leakage tests, and 36 stationary tests were coupled with mathematical and regression modeling analysis to estimate in-cabin fume leakage rates inside self polluting vehicles and develop models of in-cabin air pollutant concentrations.

Air pollution levels were unexpectedly higher in new vehicles compared to old vehicles, with in-cabin air quality most correlated to that of out-vehicle air near the front windshield. Self-pollution was observed at variable rates in three of the six tested vehicles. Significant correlations were identified between indoor to outdoor pressure difference as well as $PM_{2.5}$ and CO In/Out (IO) ratios under air recirculation and window half opened ventilation modes whereas temperature and humidity difference affected CO IO ratios only under the air recirculation ventilation mode.

CO self pollution rates could not be accurately estimated in the cabins of old vehicles (1999 and 1997 cars), whereas the self pollution rates inside the 2011 model vehicle were highest when air conditioning on fresh air intake (AC FA) was used (1625-

5175 mg/h), followed by the ventilation modes one window half opened (W1/2O) (250-1100 mg/h) and air conditioning on air recirculation (AC Rec) (33-55 mg/h). On another hand, $PM_{2.5}$ self pollution was lower in the cabin of the 2011 model vehicle compared to the cabin of older vehicles. As such, for AC Rec, the self pollution rates were in the range 0.2 to 3.38 mg/h for the 2011 vehicle, compared to 3.35-10.05 and 3.6-8.4 mg/h for for the 1999 and 1997 vehicles, respectively. Similarly, for AC FA, the range was 12.7 to 32.3 mg/h for the 2011 vehicle compared to 18.6 to 35.5 mg/h and 22.6 to 39.88 mg/h for the 1999 and 1997 vehicles. Similar rates were obtained with W1/2O and ranged from 9.5 to 57.52 mg/h for the 2011 vehicle, 11.6 to 35.5 mg/h for the 1999 vehicle and 11.75 to 45.5 mg/h for the 1997 vehicle.

Best models of CO and $PM_{2.5}$ concentrations could explain 72 and 90% of the measured variability in CO and $PM_{2.5}$ concentrations, respectively, whereas models of CO and $PM_{2.5}$ in- to out- concentration ratios (IO ratios) could explain 80 and 79% of IO ratio variation, respectively. However, after allowing for interaction terms with a factor representing the presence or absence of self pollution, the predictive power of the CO concentration model decreased to 64% whereas that of the CO IO ratio model increased to 88%. Dissimilarly, the inclusion of interaction negligibly affected $PM_{2.5}$ concentration and IO ratio models indicating that there are additional parameters affecting $PM_{2.5}$ self pollution rates which were not measured in the current work.

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ABBREVIATIONS

ACH	Air Change per Hour
AUB	American University of Beirut
CARB	California Air Resources Board
CO	Carbon Monoxide
COHb	Carboxyhemoglobin
CO_2	Carbon Dioxide
EPA	Environmental Protection Agency
ft^2	foot square
GBA	Greater Beirut Area
g/m^3	gram per meter cube
hr	hour
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IO	Indoor to Outdoor
km/hr	kilometer per hour
L/s	Liter per second
m	meter
min	minute
m^2	meter square
m^3	meter cube
NAAQS	National Ambient Air Quality Standards
NDIR	Non-dispersive Infrared

NIOSH	National Institute of Occupational Safety and Health
OSHA	Office of Safety and Health Association
PM	Particulate Matter
ppb	part per billion
ppm	part per million
SHAPE	Simulation of Human Activity and Pollutant Exposure
SF_6	Sulfur Hexafluoride
TSP	Total Suspended Particulate
TVOC	Total Volatile Organic Compound
UK	United Kingdom
US	United States
USA	United States of America
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
WHO	World Health Organization
%	percent

To my son JC

CHAPTER I

INTRODUCTION

1.1 Introduction

The last two decades have witnessed a growing concern about in-vehicle air quality with emphasis on the car passenger microenvironment where greater levels of exposure to traffic related pollution have been recorded among all transport modes. Consequently, the exposure inside passenger cars, even for relatively short durations, may constitute the major fraction of people's daily exposure particularly in urban congested areas. The significance of such a problem is exacerbated by growing trends in car ownership worldwide and increased travelled distances by car which translates into longer periods of time spent in cars. Per-capita car ownership is relatively high in developed countries where the motor car became an 'obsession' (Chapman, 2007). While car ownership is lower in developing countries, a latent growth rate is foreseen for future years primarily in urban areas as a result of population growth, change in demographics, and increase in per capita income. Using India as an example, the population of the city of Mumbai grew at less than 3% per annum during 1991-2001 whereas the vehicle fleet, of which 50% are private cars, have grown at over 7% per annum (Kumar and Rao, 2006). Another study indicates that the average growth rate in vehicle ownership between the years 1960 and 2002 generally exceeded the average growth rate in per capita income in the developing world (Dargay *et al*., 2007).

Attempts at interpreting the high levels of traffic emissions inside the vehicle related the problem to a large array of factors including ventilation setting, weather conditions, roadway type, vehicle speed and self pollution. As such, while early

investigations reported no significant impact of the ventilation mode on CO exposure (Chan *et al.*, 1991), later findings were invariably different whereby reported observations were related to the ventilation mode (Chan *et al*., 2002a; Abi-Esber *et al*., 2007a; Qi *et al*., 2008). In addition, wind speed appeared to influence in-vehicle pollution levels with lower in-vehicle CO and $PM_{2.5}$ concentrations measured at high wind speeds (Zagury *et al*., 2000; Gomez Perales *et al*., 2004; 2007). Roadway type, which is a surrogate measure of traffic volume and vehicle speed was found to play an important role with the highest levels being measured during urban driving at traffic peak hours, and the lowest levels recorded during rural driving and in non-peak traffic hours (Chan and Liu, 2001; Chan *et al*., 2002b; Duci *et al*., 2003; Kaur *et al*., 2005). Higher vehicle speed is expected to decrease in-vehicle exposure as a result of increased air change rates (Ott *et al*., 2007).

Fuel type and consumption pattern are other potential determinants of in-vehicle exposure to air pollution. Indeed, depending on their composition, different types of fuels have distinct emission levels (Karavalakis *et al.*, 2010). Also, fuel demand is closely related to vehicle mass because almost all external forces on the vehicle are directly or indirectly influenced by its mass (Burgess and Choi, 2003), suggesting that different vehicle sizes have different fuel consumption rates thus generating distinct emission levels. On another hand, vehicle age and make are other potential determinants of in-vehicle CO exposure. Body cracks associated with older models favor in-vehicle pollutants' penetration. Furthermore, design parameters specific to individual vehicle types and makes (e.g., vehicle size, ventilation air intake height, air change rate) are likely to affect pollutant intrusion mechanisms into the cabin of a vehicle (El-Fadel and Abi-Esber, 2009).

Self pollution, or the intrusion of a vehicle's own engine fumes into the passenger's compartment, has also been reported to contribute to exposure inside various types of vehicles (Ireson *et al*., 2004; Behrentz *et al*., 2004; Abi-Esber and El-Fadel, 2008; Adar *et al.* 2008). Possible sources of such an intrusion were examined on school buses and comprised (1) exhaust return and entry to the vehicle via cracks, windows, and other openings in the floor, rear, or sides of the vehicle, and/or (2) engine fume leakage prior to exiting the tailpipe, from the crankcase across the firewall or from the exhaust system underneath the vehicle. To date, there are no reported studies exploring the mechanisms of engine fume entry points into the passenger cabin of a car, which is by far, the most popular transport mode.

Other potential determinants of in-vehicle exposure to traffic pollution which however were not addressed in the literature comprise out-vehicle sample intake location and indoor to outdoor difference in temperature, pressure and humidity levels. Although previous studies calculated vehicle In/Out (IO) ratios using in- and out-vehicle pollutant concentrations (Qi *et al*., 2008; Knibbs *et al*., 2010; Fruin *et al*., 2011; Hudda *et al*., 2011; Xu and Zhu, 2013; Bigazzi and Figliozzi, 2013; Tartakovsky *et al*., 2013), only a few reported the location of the out-vehicle sample intake point (Knibbs *et al.*, 2010; Bigazzi and Figliozzi, 2013; Tartakovsky *et al*., 2013) with the latter being inconsistent across studies. Substantial differences in pollutant concentrations exist at times between the four corners of a moving vehicle due to the proximity of certain locations to the tailpipe of the test car or to that of the preceding vehicle. Such differences affect the IO ratio calculations which can be low when the outdoor sample is taken from a high concentration area and high when taken from less polluted areas.

Therefore, it is of interest to target the location of out-vehicle sample intake point to the one that affects most in-vehicle air quality.

On the other hand, temperature and pressure gradients have been reported to affect pollutant infiltration factors in buildings. In a study examining particle deposition and resuspension rates, Thatcher and Layton (1995) minimized particle infiltration rates by choosing times of minimum in to out pressure and temperature differences because when unbalanced conditions exist between indoor and outdoor environments, airflow is induced through cracks and openings. The airflow rate (in m^3/s), which is governed by the power law, is the product of an airflow coefficient 'C' (in $m^3/s.Pa$) and the pressure difference (in Pa) raised to a dimensionless flow exponent 'n' (Roulet, 2012). The pressure difference across the crack and/or opening is in the order of 1 to 10 Pa for typical residences (Hunt, 1980; Jeng *et al*., 2003). On the other hand, some pressure differences across openings can be attributed to temperature differences (ASHRAE, 1993) which are also reported to affect particle infiltration through thermophoresis (Brockmann, 2011; Grau-Bové and Strlič, 2013). In the case of a moving vehicle, IO pressure differentials may reach 5000 Pa and temperature differentials are higher when the air conditioning is turned on, thus similar influences are expected but have not been quantified (Qi *et al.* 2008). As for humidity, there are no reported studies assessing its influence on pollutant infiltration in indoor environments. However, given the relationship between the magnitude of humidity differential and that of indoor to outdoor air exchange whereby high air exchange promptly brings indoor humidity to the same level encountered outside, a correlation between humidity differential and pollutant infiltration and/or buildup inside a cabin is expected and is worth assessing as well.

In terms of statistical modelling, scarce efforts targeted multiple regression models correlating exposure to several concomitantly measured explanatory factors (Ott *et al*., 1994; Flachsbart, 1999b). Based on a set of 88 trips testing for the influence of nine possible predictors, Ott *et al*. (1994) could best predict (multiple $R^2 = 0.68$; adjusted $R^2 = 0.67$) average CO exposure on a highway by a regression model including a seasonal trend (cosine function of the day of the year) and a traffic volume (proportion of time stopped) term. Later, Flachsbart (1999b) conducted a similar analytical study along a comparable highway setting. The developed models relied on a set of 80 trips and tested for 15 different variables. Consistently with findings from the previous study, the models showed that cabin exposure to CO was affected mainly by CO concentration on a previous link, travel time and average vehicle speed (multiple $R^2 = 0.70$; adjusted $R^2 = 0.69$) which constitute indirect measures of traffic volume, in addition to a seasonal term expressed by wind direction and speed. While the reported models targeted several explanatory variables, a large number of other important variables were not considered such as ventilation mode, car brand and model, possibility of self pollution, exhaust flow rate and temperature and roadway type. Also, a single, gaseous indicator is addressed leaving uncertainty as to whether particulate exposure inside a car is governed by the same variables.

Hence, the current work considers 119 mobile tests, 120 fume leakage tests, 36 stationary tests and 25 different explanatory variables in an attempt to improve the understanding of in-cabin exposure to CO and $PM_{2.5}$ and self pollution. For this purpose, field testing is implemented using six different vehicles and involved the monitoring of in- and out-vehicle CO and $PM_{2.5}$ concentrations and 25 different potential determinants including air quality, meteorological, temporal, vehicle and

traffic related variables. Mathematical and regression modeling are then implemented to compute in-cabin fume leakage rates inside self polluting cars and develop models of in-cabin air pollutant concentrations.

1.2 Scope of work

The work comprised the following tasks:

- Literature review
- Testing of in- and out-cabin exposure to CO and $PM_{2.5}$ and potential determinants during stationary and mobile on-the-road field experiments
- Testing of fume leakage inside test cars
- Mathematical simulation of in-vehicle pollutant concentrations and fume leakage rates
- Multivariate regression analysis of in-cabin pollutant concentrations

1.3 Originality and significance of the proposed research

Studies of $PM_{2.5}$ and CO exposure in the urban transport micro-environment studies have increased over the last decade. However, they selectively addressed a limited number of influencing parameters which leaves a large amount of air pollutant concentration variation inside vehicles unexplained. As a result, the current work provides a comprehensive experimental evaluation of a large number of concomitantly measured influencing parameters including those that were scarcely or not yet explored such as out-vehicle sample intake location and indoor to outdoor difference in temperature, pressure and humidity levels. In addition, the research constitutes a first attempt at investigating the self pollution potential in passenger cars of different makes

and models and assessing the mechanisms of intrusion of engine fumes into car cabins. As compared to older studies of multivariate regression of in-cabin exposure to air pollution, this study targeted two air quality indicators of distinct nature and used a database which encompassed a larger number of trips and test cars in addition to potential determinants that were not previously examined such as ventilation mode, car brand and model, possibility of self pollution, exhaust flow rate and temperature and roadway type.

Evidently, the potential significance of the proposed research program spreads across several beneficiary stakeholders including the end-user (civil and scientific community, retailers), manufacturing industries, and end-user/consumer advocates (relevant governmental departments/units, consumer protection services, etc.). While the majority of the latter stakeholders will benefit from the increased awareness and understanding of the project findings, the car manufacturing and regulatory groups should be targeted to bring about change aiming at eliminating or minimizing cabin exposure.

1.4 Thesis organization

Following this introductory chapter, chapter 2 addresses general issues related to traffic related air pollution exposure inside a car cabin. After discussing the relevance of CO and $PM_{2.5}$ as indicators of automotive emissions associated with a large array of health and environmental concerns, individual determinants of car cabin exposure to CO and $PM_{2.5}$ are discussed and a summary of the literature work spanning around them is presented. Studies targeting the modeling of air pollution exposure inside a car cabin are also visited.

Chapter 3 describes the materials and methods employed in the field testing and the mathematical and regression modeling of in-vehicle air pollution concentrations. The testing program and trajectory, the specifications of the various equipment used and the general experimental procedure were presented along with the details of the data analysis methods. The analytical and statistical modeling packages used are also described.

Chapter 4 constitutes the results and discussion section. After presenting and discussing findings from the field testing campaign in terms of air pollution exposure and indoor to out air exchange levels, the results of the mathematical and statistical modeling activities are provided and discussed.

Chapter 5 summarizes the overall results of the research, states the limitations that faced the study and outlines ways of improving it.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Adverse health outcomes in the form of increased morbidity and premature mortality or reduction of life expectancy have been associated with exposure to air pollution resulting in serious socio-economic losses (El-Fadel and Massoud, 2000; Neidell, 2004; Parker *et al*., 2008). In the context of urban areas, the exacerbation of air pollution is strongly associated with traffic-induced emissions. These emissions have been observed to penetrate various indoor environments including commuting passenger cars, where the concentration of many traffic-induced pollutants reportedly exceeded permissible exposure limits including CO (Abi-Esber *et al*., 2007a) and PM (Fondelli *et al*., 2008).

2.2 Indicators of automotive emissions

Among the diversity of pollutants that were previously examined in the in-vehicle micro-environment, CO and PM are useful indicators of automotive emissions associated with a large array of health and environmental concerns (Twigg, 2007). Indeed, CO was the first indicator evaluated in passenger compartments. It is the most abundant (Georgoulis *et al*., 2002), most chemically stable (Chan *et al*., 1999), and most commonly used marker of automotive emissions (Chan *et al*., 2002b; Lodovici *et al*., 2003).

PM is another pollutant originating from mobile sources in significant quantities (Han and Naeher, 2005) and linked, with its respirable fraction (PM_{10} and

less), to a myriad of health outcomes ranging from cardiopulmonary diseases to cancer. Despite modern treatment of vehicle exhaust using catalytic converters or diesel particle filters, the only detected decrease was in mass of particulate pollutants rather than in total particle number emissions (Geller *et al.*, 2006). Furthermore, the major fraction of PM generated by vehicle exhaust is formed by fine and toxic particles (Chan *et al*., 2002c) raising the importance of monitoring PM inside vehicles for the protection of commuters.

On the other hand, and contrary to the long-held view that air recirculation protects a vehicle's cabin from outdoor air pollutant ingression, Chan and Chung (2003) and Abi-Esber *et al.* (2007a) reported the occurrence of CO buildup inside car cabins when air recirculation was employed, attributing their observation to a likely source of CO inside the vehicle. These findings are in contradiction to those made earlier by Chan *et al.* (2002c), whereby air-conditioned vehicles were recommended as a substitute for non-air-conditioned vehicles as they recorded lower levels of PM exposure. Likewise, Chan *et al*. (2002a) found that while the adoption of an air-conditioning system was an effective way to minimize PM exposure, it significantly increased CO levels in taxis. Given the contradictory behavior of these two pollutants in response to the ventilation mode, the proposed experimental program will involve the analysis of CO and $PM_{2.5}$, both indicators of self pollution, as a function of various determinants. Guidelines and standards for CO and $PM_{2.5}$ exposure are outlined in Table 2.

Table 2.1. Standards and guidelines for CO and $PM_{2.5}$ exposure

Indicator	*Type of Standard/ Guideline*	*Source*	*Details*	*Standard/Guideline*	
				Concentration (ppm for CO, $\mu g/m^3$ for $PM_{2.5}$)	*Averaging Period*
CO	Ambient air quality (AAQ)	USEPA, 2011[a]	National AAQ Standards (NAAQS)	35	1-hr
				9	8-hr
	Air quality guideline (AQG)	WHO, 2006[b]	AAQ guideline	87	15-min
				52	30-min
				26	1-hr
				9	8-hr
	Indoor air quality (IAQ)	CARB, 2004[c]	IAQ guideline	20	1-hr
		ASHRAE, 1989[d]	Recommended level for indoor air pollution	9	8-hr
$PM_{2.5}$	AAQ	USEPA, 2006[a]	NAAQS	15	1-year
				35	24-hr
	AQG	WHO, 2006[b]	Ambient and indoor air quality guideline	10	1-year
				25	24-hr

a United States Environmental Protection Agency (USEPA) National Ambient Air Quality Standards, 40 *CFR* Part 50
b World Health Organization (WHO): Carbon Monoxide, 2nd ed., Geneva: WHO, 1999
c California Air Resources Board (CARB): Indoor air pollution in California, 2004
d American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE): ANSI/ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality, Atlanta, 1989

2.3 Determinants of in-vehicle air pollution

A multitude of determinants combine interactively to determine the trend of in-vehicle exposure, and include among others roadway type, vehicle speed, traffic density, ventilation mode, weather conditions, vehicle brand, etc. Previous studies selectively investigated variable assortments of determinants and reached scattered but important conclusions regarding their influence as outlined below.

2.3.1 Outdoor concentration

Outdoor air characterization involves either out-vehicle or ambient monitoring. Out-vehicle concentrations are those measured in the air that immediately surrounds the vehicle microenvironment, whereas ambient/fixed-site concentrations are those measured at fixed-site air quality monitoring stations in the general area. Out-vehicle and ambient concentrations are seldom similar because of the ubiquitous presence of local motor vehicle traffic emissions that cannot be captured directly by fixed monitoring stations. Relationships between exposure inside the vehicle compartment and both types of outdoor concentrations have been examined extensively.

2.3.1.1 Out-vehicle concentration

In-vehicle pollutant concentrations are expected to be closely related to the out-vehicle level because vehicle compartment air originates from the air that is adjacent to the vehicle and that penetrates into it through ventilation air inlets (windows, vents), door seams and body cracks. Chan *et al*. (2002b) reported that in-vehicle CO concentrations in major commuting corridors of Hong Kong, China, were greatly influenced by the out-vehicle concentration for a standardized ventilation mode (windows and vents closed, air conditioning (AC) on recirculation mode). However, the fluctuation of the in-vehicle level was found to be far less than that of the out-vehicle level as a result of the time lag between the two levels.

Similarly, Chan and Chung (2003) examined indoor-outdoor air quality relationships for various pollutants (CO, NO, NO_2) under different ventilation modes and driving environments of Hong Kong, China. CO levels measured on highways exhibited the highest correlation coefficients between in-vehicle and out-vehicle

concentrations among the tested indicators indicating that CO was more prone to penetration into the vehicle than other gases. Indoor and outdoor positive correlations were particularly observable for ventilation modes involving high air exchange (windows fully opened, air conditioning with fresh air intake) whereby CO level fluctuation in outdoor air was accompanied by a similar rapid response of in-vehicle air.

A comparable rapid response of in-vehicle CO level to the outdoor were identified by Abi-Esber *et al*. (2007a) in a commercial-residential area of Beirut, Lebanon, particularly for ventilation modes involving significant indoor-outdoor air exchange. Indeed, moderate to good correlations were established between in-vehicle and car-exterior CO levels with R^2 values of more than 0.322, 0.367, 0.541 for the cases "window ½-opened, vents closed", "windows opened, vents closed" and "windows closed, AC on fresh air intake, respectively. In contrast, a weak correlation was evident for the case of tightly closed cabin with air recirculation (R^2 less than 0.024).

2.3.1.2 Ambient concentrations

Several studies have invariably questioned the suitability of utilizing fixed site monitoring data for short term exposure assessment at the street micro-level. In general, concentrations are expected to be lower at the fixed site stations because of their distance from traffic and their sampling height above the commuters breathing zone. Flachsbart (1999a) reported that 14 of 16 in-vehicle exposure studies performed in the US between 1965 and 1992 simultaneously measured both ambient and passenger cabin concentrations. The mean CO concentrations inside vehicles always exceeded the mean ambient CO concentrations measured at fixed-site monitors, with a ratio ranging from 2 to 5. Similarly, Adams *et al.* (2001a) reported that mean personal exposure to $PM_{2.5}$ in

road transport modes (car, bus, underground tube) was approximately double that at an urban background fixed site monitor.

Riediker *et al.* (2003) determined exposure to CO and $PM_{2.5}$ in highway patrol vehicles, at an ambient, and a roadside location in a suburban area of southern United States. Unlike other studies, in-vehicle $PM_{2.5}$ was 24% lower than ambient and roadside levels, probably due to depositions associated with the recirculating air conditioning. However, levels of CO were highest in the cars compared to roadside and ambient levels due to potential in-vehicle engine emissions, and roadside levels were higher than ambient levels. Duci *et al*. (2003) reported after comparison of ambient to in-vehicle CO level data that there is evidence that fixed-site stations cannot assess human exposure accurately whereby CO concentrations in every tested mode of transport were higher than those recorded at the monitoring station.

Kaur *et al.* (2005) also reported that background and curbside monitoring stations were not representative of the personal exposure of individuals to $PM_{2.5}$ and CO at and around a street canyon intersection. Likewise, Abi-Esber *et al*. (2007a) identified weak positive correlations between 1-min averaged in-vehicle CO levels and 1-min averaged ambient CO levels suggesting that ambient fixed-site recordings are weak predictors of in-vehicle CO levels. More recently, Fondelli *et al.* (2008) reported that the $PM_{2.5}$ levels were above the urban ambient levels on average by 32 $\mu g/m^3$ and 20 $\mu g/m^3$ in buses and taxis, respectively. Similarly, Huang *et al*. (2012) reported that $PM_{2.5}$ and CO concentrations in commuting modes were significantly higher than those measured at fixed monitoring sites especially during heavy traffic times. Nevertheless, the correlation between in-vehicle and fixed site pollutant concentrations was higher for

$PM_{2.5}$ compared to CO, which was attributed to in-vehicle self pollution in the case of CO.

2.3.2 Roadway/landuse type, traffic density and vehicle speed

The type of commuting route has a direct relationship with in-vehicle air pollution exposure. Indeed, a roadway location and functional type are surrogate measures of several factors such as traffic volume and speed which are interrelated and are themselves affected by roadway capacity. They affect total vehicular emissions and corresponding rates.

2.3.2.1 Roadway/landuse type

In urban commercial or mixed commercial/residential areas, high traffic volumes are normal occurrence. Vehicles are required to stop/go at road intersections resulting in congestion and higher emissions along the route. The street canyon effect resulting from high-rise buildings contributes to the accumulation of emissions at street level which leads to higher out-vehicle pollutant concentration and subsequently higher in-vehicle exposure. In contrast, routes between urban and rural areas are surrounded by open spaces with no to minimal tunnels and buildings. Hence, less CO accumulates along the road vicinity and lower in-vehicle CO levels are reported.

Chan and Liu (2001) measured CO exposure in three popular transport modes of Hong Kong along three types of commuting routes namely urban-urban, urban-suburban and urban-rural. Vehicles traversing between urban and suburban areas had higher in-vehicle CO levels among all three commuting routes given the presence of tunnels. The average in-vehicle CO exposure level of a commuter in a tunnel micro-environment was reported to be 2-3 times greater than along urban and suburban roads

depending on the length of the tunnel. Chan *et al*. (2002b) measured CO levels inside experimental vehicles traversing major commuting corridors of Honk Kong and reported the lowest in-vehicle CO levels in rural areas, while the highest concentrations were recorded in urban commercial and urban mixed commercial/residential areas. Similarly, among seven standard urban routes of Athens, Greece, Duci *et al*. (2003) identified the highest CO levels on the most heavily traveled routes. Invariably, the differences between measured levels were attributed to traffic density and roadway configuration.

2.3.2.2 Traffic density

In-vehicle pollutant concentration are commonly reported to increase with increasing traffic density as a result of increased vehicle-induced emissions and hence out-vehicle levels. Ott *et al.* (1994) reported that among several parameters affecting in-vehicle exposure along an urban arterial highway of California, the fraction of time stopped, which is a measure of traffic volume, was one of the best predictors of in-vehicle CO concentrations. Similarly, Flachsbart (1999b) reported that in-vehicle exposure to CO on three links of a Honolulu highway was affected by travel time and average vehicle speed, which constitute indirect measures of traffic flow. Lighter traffic flow lowered passenger cabin exposures.

Chan and Liu (2001) reported that high traffic volume in commercial districts as a result of long busy routes and intersection traffic jams increased in-vehicle CO exposure. Vehicular exhaust, combined with the street canyon effect usually exhibited at the street level, led to higher out-vehicle CO concentration and subsequently higher in-vehicle CO level. Chan *et al.* (2002a) reported high in-vehicle CO and $PM_{2.5}$ levels in

Guangzhou (China), attributing these observations to the large traffic volume, the slow driving speeds and the frequent acceleration, deceleration and idling.

2.3.2.3 Vehicle speed

Driving at low speed or in stop and go traffic with frequent idling increases commuter exposure for several reasons. First, the ventilation of the passenger compartment uses the pressure difference between the scuttle and the ventilation exits, which is proportional to the square of the vehicle's speed (Hucho, 1998). It is thus expected that slower speeds would lower vehicle air change rate and increase pollutant buildup inside the vehicle cabin. Furthermore, heavy traffic and slow speed result in higher exhaust emissions and lower inter-vehicle distance thus increasing exhaust penetration into the vehicle.

Flachsbart *et al.* (1987) reported that along commuter routes in Washington DC, in-vehicle CO exposures fell by 35% when test vehicle speeds increased from 10 to 60 miles per hour (mph) (16 to 97 kilometer per hour (km/h)). In a similar study in Riyadh, Saudi Arabia (Koushki *et al*., 1992), in-vehicle CO exposures fell by 36% when vehicle speeds increased from 8.7 to 34.2 mph (14 to 55 km/h). Clifford *et al*. (1997) reported a comparable impact of vehicle speed on average external CO levels measured outside an experimental van traveling in Nottingham, United Kingdom. An increase of 5 mph (8 km/h) resulted in a reduction of 4.3 ppm in CO external level. The latter reduction would obviously be translated in a similar response of in-vehicle air given the close relationship between internal and external measurements as stressed in the study.

2.3.3 Ventilation mode

The envelope of a vehicle normally acts as a shield against the contaminated outdoor air in urban areas (Fletcher and Saunders, 1994); however, the degree of protection depends on several factors. The most important of which is the body condition that determines the leakage inlet flow and the used ventilation setting. Depending on the status of windows, air vents and air conditioning settings, the time constant/air change rate of the vehicle can vary considerably. Different values of vehicle air change rates were reported as a function of ventilation setting (Table 2.2).

Table 2.2. Ranges of vehicle air change rates reported in the literature for variable ventilation modes

Ventilation Mode	*Source*	*Range of ACH[i] Values (h^{-1})*	*Vehicle volume (m^3)*	*Vehicle Speed (mph)*
W1/2O, VC[a]	Ott *et al*., 1992	120	NR	20
	Park *et al*., 1998	13.3-13.7[e]	2.41	0
	Park *et al*., 1998	20[f]	3.24	0
	Park *et al*., 1998	120[f]	3.24	20
	Ott *et al*., 2007	28.9-30.8[g]	2.20	20
WC, AC Rec[b]	Engelmann *et al*., 1992	1.96-3.23[h]	NR	0
	Park *et al*., 1998	1.8-3.7[a]	2.41	0
	Ott *et al*., 2007	0.92	2.60	0
	Ott *et al*., 2007	1.6-2.4	2.60	20
WC, VC[c]	Fletcher and Saunders, 1994	0.8-8	2.42	0
	Fletcher and Saunders, 1994	14-43	3.51	35 to 70
	Ott *et al*., 1994	1.4	NR	0
	Ott *et al*., 1994	13	NR	20
	Spengler *et al*., 1994 (Cited by Park *et al*., 1998)	10	NR	NR
	Park *et al*., 1998	1.3-2.3[e]	2.41	0
	Park *et al*., 1998	1[f]	3.24	0
	Park *et al*., 1998	10[f]	3.24	20
	Ott *et al*., 2007	1.9	2.20	20
WC, AC FA[d]	Hayes, 1989	36	NR	NR

	(Cited by Chan *et al*., 1991)			
	Park *et al*., 1998	36.2-47.5[e]	2.83	0

[a] W1/2O, VC: window ½-opened, vents closed
[b] WC, AC Rec: windows closed, AC on recirculation mode
[c] WC, VC: windows closed, vents closed
[d] WC, AC FA: windows closed, AC on fresh air intake
[e] As measured using the tracer gas method
[f] As used in a modeling effort using the same software to simulate air bag deployment inside a vehicle
[g] One window opened 1.2 cm
[h] Range is reported for five different vehicles of unknown volumes
[i] ACH: air change rate

Chan *et al*. (1991) examined the effect of three different ventilation modes (windows and vents closed with air conditioning on; windows closed, vent fan on with air conditioning off; and front windows ½-opened, vent fan on with air conditioning off) on in-vehicle CO level in Raleigh, NC, and found a minor in-vehicle concentration difference (1 ppm) between the various tested conditions. While the conclusion was that the ventilation mode had no significant impact on in-vehicle CO exposure, findings made by subsequent studies were different.

Chan and Chung (2003) examined the simultaneous impact of ventilation mode and driving environment on pollutant penetration into the vehicle. In-vehicle to out-vehicle concentration ratios varied drastically from one ventilation mode to the other and for different roadway types. While natural ventilation gave the lowest in-to-out vehicle ratio in countryside commutes, air-recirculation mode was suggested for trips in polluted congested areas. CO was the only exception to the latter conclusion reportedly as a result of a likely source of CO inside the vehicle, which induced CO buildup when AC was set on air recirculation.

Greaves (2006) conducted $PM_{2.5}$ measurements inside a car driven along an urban route of Sydney, Australia with different combinations of vent positions (open or closed) and air conditioning (on or off). The vent position was found to be the most critical parameter with the average particulate concentration being well below harmful

levels when the vents are closed even in heavily congested traffic. In contrast, Abi-Esber *et al*. (2007a) measured the highest mean in-vehicle CO exposure in a typical heavily traveled commercial-residential urban area of Beirut, Lebanon with the "windows closed, vents closed" and "windows closed, AC on recirculation" ventilation settings. The exposure was less significant (2 to 3 times lower) for other ventilation modes ("windows closed, vents opened"; "one window opened, vents closed"; "one window opened, vents opened"; "one window half opened, vents closed"; "all windows opened, vents closed"; "windows closed, AC on fresh air intake"). Furthermore, the pattern of variation of indoor CO concentrations differed between the various ventilation modes. For the cases "windows closed, vents closed" and "windows closed, AC on recirculation", in-vehicle CO concentration continuously increased over the testing period to reach near steady state within 40 to 45 minutes as a result of the tight closure and the absence of dilution. In other ventilation modes, CO exhibited a fluctuating pattern suggesting an adequate exchange and dilution with the outdoor air.

The influence of air conditioning with and without fresh air intake on in-vehicle exposure to ultrafine particles (UFP, <300 nm) was examined by Qi *et al.* (2008) inside two cars of different makes (Saab 2003, and Toyota Camry 2007) one of which (Camry) had its cabin filter included in the recirculation loop of the air conditioning system. The findings indicate that unless the recirculation mode is employed, a cabin air filter is relatively inefficient. Also, the presence of the filter within the recirculation loop reduced significantly UFP exposure to low and safe levels.

2.3.4 Weather conditions

Motor vehicle emissions are usually the highest during the first few minutes of vehicle operation because combustion efficiency improves as engine temperature rises. Indeed, the magnitude of the engine start-up emissions is a function of initial engine temperature with highest emissions being experienced when ambient temperature is lowest, i.e. in winter season. Even after the vehicle has been running for several minutes and its engine has reached sufficiently high temperature, the stabilized emission rates will slightly fluctuate depending on various parameters including weather conditions such as ambient temperature and humidity, with higher emissions experienced during lower temperature and higher humidity (USEPA, 1998; CARB, 2001). Higher emissions are invariably translated into greater out-vehicle pollutant levels, and subsequently increase in-vehicle exposure. Wind speed and direction determine the magnitude and pattern of pollutant dispersion in the micro-environment immediately outside a vehicle influencing the in-vehicle micro-environment. Atmospheric pressure, presence of rainfall and depth of inversion layer are other weather parameters with potential influence on in-vehicle CO levels.

Clifford *et al*. (1997) monitored CO concentrations inside and outside an experimental van (concentration of the external air as it entered the heater and then the inside of the van) in Nottingham UK and examined the relationship between average daily external CO levels and precipitation and wind speed data obtained from a meteorological station approximately 5 miles to the south of the city. Precipitation appeared to have had little effect, while increased wind speed caused a fall in concentration and greater spread with data skewness at few extreme points. Flachsbart (1999b) correlated passenger exposure in Hawai to wind direction. Northerly winds,

which were prevalent during most of the study period, reduced cabin exposures by dispersing emissions on westbound lanes of the study site where exposures were measured. In contrast, southerly winds increased exposures by sending emissions from eastbound vehicles to the westbound lanes of the study site. A strong relationship with wind speed was also reported by Adams *et al*. (2001b) and Gomez Perales *et al*. (2004) with the former reporting that wind speed explained 20% of the variation in London's in-vehicle $PM_{2.5}$ concentrations, and the latter observing a decrease of up to 18% in CO concentrations when wind speed increased by 1 m/s. Gomez Perales *et al.* (2007) also observed a strong association between wind speed and $PM_{2.5}$, CO, and benzene concentrations in buses.

Abi-Esber *et al*. (2007a) examined the possibility of in-vehicle levels being influenced by wind speed data collected at a fixed monitoring station located near the study trajectory in a commercial-residential area of Beirut, Lebanon. Regression analysis of 1-min-average in-vehicle to car-exterior CO level ratio against 1-min-average wind speed for a number of field testing trips showed no correlation between the two variables, possibly as a result of the difference between wind speed data measured at the fixed monitoring station and actual wind speed at the street micro-level, where the closed packing of buildings influences wind flow patterns.

2.3.5 Vehicle characteristics

Vehicle age, type and make are potential determinants of in-vehicle exposure. Body cracks associated with older models favor in-vehicle pollutants penetration and increase the probability of occurrence of a self polluting effect. Furthermore, design parameters specific to individual vehicle types and makes e.g. vehicle size, vehicle and

ventilation air intake height, vehicle air change rate, air conditioning filtration system, etc. are other potential determinants of cabin exposure. While the influences of vehicle type were frequently examined, those of vehicle make were not.

Several studies reported that in-vehicle exposure varied by mode of travel / vehicle type. Chan and Liu (2001) conducted a study comparing CO exposure in selected popular commuting modes of Honk Kong including taxis, minibuses and buses. The concentration levels increased in the order: bus, minibus, and taxi. The concentration difference was attributed to the vehicle height, which directly affects breathing height. The latter is defined as the height from the road surface to the respiratory level inside the vehicle and it is about 0.9, 1.2 and 1.5 m for taxi, minibus and lower deck bus commuters, respectively. Since vehicle exhaust is generated near the road surface and the pollutant levels are higher at lower vehicle height, passengers are then exposed to highest CO levels inside taxis. Another potential explanation was the vehicle size which differed for the three tested commuting modes. The larger the vehicle size, the lower is the CO level. The lowest CO level was measured inside the bus compartment because concentrations are diluted in a larger volume. In contrast, taxis exhibited the highest CO levels because their size is smallest.

Chan *et al*. (2002a) examined commuter exposure to CO in air-conditioned and non-air-conditioned public transportation modes of Guangzhou, China. The highest average CO level was obtained in an air-conditioned taxi. In non-air-conditioned taxis, air-conditioned bus and non-air-conditioned bus, the average CO level was 1.5 to 3.5 times lower. The high CO levels in taxis and concentration difference between a taxi and a bus inferred that the in-taxi CO levels were more frequently contaminated by the presence of internal sources associated with the leakage from the taxi itself (poorly-

maintained engines or exhaust systems in fairly old taxis - > 6 years - with high mileage). The effect of vehicle height was outweighed by the effect of self-contamination.

Dependence of CO levels on transport mode was also tested by Duci *et al*. (2003) who sampled simultaneously private cars, buses and trolley modes in Athens, Greece. The results showed significantly higher mean CO levels in the private car than those in the bus and trolley due to differences in vertical gradients of CO levels along the road (related to vehicle height). Kaur *et al*. (2005) also investigated commuters' $PM_{2.5}$ and CO exposure along two different routes of Central London, UK, via five different transport modes (walking, cycling, bus, car and taxi). Consistent with previous findings, air pollution was highest in cars and taxis compared to other transport modes.

Recently, Huang *et al.* (2012) measured commuters' exposure to $PM_{2.5}$ and CO inside closed and air conditioned taxis and buses driven along two heavily traveled routes of Bejing, China. $PM_{2.5}$ concentrations were significantly lower when commuting by taxi as compared to bus, whereas CO concentrations were higher in taxis. The high $PM_{2.5}$ concentrations in buses were attributed to the frequent opening and closing of bus doors. The opposite finding regarding CO was attributed to probable in-taxi sources of CO such as leakages from engine and exhausts systems as well as to the smaller size of a taxi cabin compared to that of a bus.

2.3.6 Self Pollution inside Vehicles

An equally important, however less investigated determinant of in-vehicle exposure, is the self pollution potential, or the ingression of a vehicle's own engine fumes into the passenger's compartment. Possible sources of such an ingression were

suggested to be (1) exhaust return and entry to the vehicle via cracks, windows, and other openings in the floor, rear, or sides of the vehicle, and/or (2) engine fume leakage prior to exiting the tailpipe, from crankcase across the firewall or from the exhaust system underneath the vehicle. Literature findings on self pollution potential are discussed below (El-Fadel and Abi-Esber, 2009).

2.3.6.1 Mathematical Representation

The vehicle compartment air is expected to originate from the ambient air that is adjacent to the vehicle and that penetrates into it through ventilation air inlets (windows, vents), door seams, and body cracks. A mass balance approach (Equation 1) can be used to understand the relationship between the time series of concentrations outside the vehicle to the time series of concentrations measured inside the vehicle (Ott *et al.*, 1994).

$$\tau \frac{dC_{veh}(t)}{dt} + C_{veh}(t) = C_{ext}(t); \qquad \tau = \frac{1}{ACH} = \frac{1}{\varphi/V} \qquad \text{(Eq. 2.1)}$$

Where τ = time constant of the vehicle, h

C_{veh} = in-vehicle polluant concentration, mg/m^3

C_{ext} = out-vehicle pollutant concentration, mg/m^3

t = time, h

ACH = air exchange rate, h^{-1}

φ = volume of air flow into and out of the vehicle, m^3/h

V = interior volume of the vehicle, m^3

$$AVE_{ext}(T) - AVE_{veh}(T) = \frac{\tau}{T} C_{veh}(T) \qquad \text{(Eq. 2.2)}$$

Where	T	=	trip averaging time, s
	AVEveh(T)	=	average concentration inside the vehicle, mg/m^3
	AVEext(T)	=	average concentration outside the vehicle, mg/m^3

This relationship shows that, under the initial condition of $C_{veh}(0) = 0$, the average pollutant concentration inside the vehicle will be less than its average concentration outside and will differ by an amount τ/T times the concentration measured inside the vehicle at time T. For $T>>\tau$, the two averages will essentially coincide, because the right-hand side of Equation 2 will approach zero and the interior and exterior averages will be identical. Inconsistently, ratios of in-vehicle to out-vehicle concentrations greater than unity were reported in the literature. Such an occurrence is likely related to the existence of a pollution source inside the vehicle, i.e. the occurrence of a self pollution condition.

2.3.6.2 Field Measurements

Studies on the assessment of in-vehicle exposure in passenger cars reported that concentrations of several indicators tend to be higher inside the vehicle cabin compared to adjacent roadside air concentrations. Chan *et al*. (1991) measured in-vehicle volatile organic compounds (VOC) levels 6 folds the average of those recorded at fixed sites, attributing the high levels to in-vehicle VOC generation from car materials, faulty exhaust systems, or engine and carburetor evaporative emissions. In-vehicle to out-vehicle ratios of 1.1 were obtained for CO and most VOCs and were

attributed to emission losses from running engines and tailpipe exhausts rather than on car exterior concentrations. Consistently, several researchers (Weisel *et al*., 1992; Dor *et al*., 1995; Lawryk *et al*., 1995; Som *et al*., 2007) found that VOC levels were higher inside a moving vehicle than in the surrounding ambient air, suggesting in-vehicle sources of contaminants.

Chan *et al*. (2002b) reported median ratios greater than 1 for in-vehicle to out-vehicle CO concentrations in urban residential, rural, industrial areas and along highways of Hong Kong, and suggested the internal engine compartment as a possible additional source of CO emissions inside the vehicle. Likewise, Chan and Chung (2003) reported ratios of up to 1.8 in urban areas, 8 in tunnels, and 10 in the countryside, depending on the used ventilation mode, and suggested the possibility of a likely source of CO inside the vehicle. Similarly, Abi-Esber *et al*. (2007a) identified ratios of 1.2, 1.5 and 2.1 for the ventilation modes "windows opened, vents closed", "windows closed, AC on fresh air intake" and "window ½-opened, vents closed", respectively suggesting a high probability of occurrence of a self-polluting condition whereby in-vehicle air is contaminated by an indoor source, e.g. engine emissions leakage or exhaust fume return and ingression into the cabin. Similar observations regarding CO were also made by Riediker *et al.* (2003) and Huang *et al.* (2012).

Fondelli *et al.* (2008) observed $PM_{2.5}$ concentrations in buses and taxis in excess of the urban concentrations attributing the observation to several sources among which the exhaust of the tested vehicles themselves. Likewise, Asmi *et al.* (2009) measured in-vehicle and background concentrations of fine particles inside buses and trams and observed daily average ratios varying in the range 0.8-4.3 and 1.0-2.9 for the number and mass concentrations, respectively. The daily average ratio of < 2.5 μm

black carbon to the background varied between 2.4 and 11.4. The temporal variation of concentrations in comparison with the background suggested that the elevated levels in buses are due to traffic emissions, with a fraction of the pollutants probably coming from the vehicles themselves.

2.3.6.3 Studies Demonstrating the Occurrence of Self pollution

Behrentz *et al*. (2004), Ireson *et al*. (2004), Abi-Esber and El-Fadel (2008) and Adar *et al*. (2008) demonstrated the occurrence of self pollution in school buses and a passenger car. The former developed and applied a tracer gas method to determine the amount of a bus's own exhaust penetrating into the cabin in a study of six in-use school buses (model year 1975 to 2002) over a range of routes, roadway types, fuels, and emission control technologies. A tracer gas, SF_6, was metered into the bus's exhaust system with concomitant monitoring of the SF_6 concentration inside the bus using a handheld continuous gas chromatograph (GC). The authors reported that under certain wind conditions (i.e., wind from the rear) when the bus was stopped and idling, significant amounts of the bus's own exhaust reached the front of the bus. Self-pollution, the percentage of a bus's own exhaust that can be found inside its cabin, was a function of the bus type and age, and a strong function of window position with higher levels when windows were closed. Up to 0.3% of the air inside the cabin was found to originate from the bus's own exhaust in older buses, approximately 10 times the percentage observed for newer buses, and 25% of the black carbon concentration variance was attributed to the buses' self-pollution.

Ireson *et al.* (2004) measured the rate of self pollution of a single 1995 school bus using an iridium tracer method whereby the compound [tris (norbornadiene)

iridium(III) acetylacetonate] was added to the bus's diesel fuel and measured in the bus cabin by collection on a filter and analysis using a neutron activation method. The proportion of $PM_{2.5}$ intruding from a school bus's own exhaust into its cabin was 0.22 $\mu g/m^3$ out of an average of 72 $\mu g/m^3$. Air samples were also collected in a gasoline powered leader vehicle with open windows passing approximately five minutes in front of the study bus to establish background ambient concentrations. Concentrations of $PM_{2.5}$ inside the leader vehicle were 30 to 40% higher than those measured in the bus cabin possibly as a result of the opening of all its windows. Consistent with findings by Behrentz *et al.* (2004), average rates of the bus cabin self pollution were higher with closed windows compared to open windows. Possible routes of exhaust entry to the bus cabin were suggested to be the bus door and windows (when open), the window and door seals or other leaks in the rear of the bus.

Abi-Esber and El-Fadel (2008) used a mass balance modeling approach with field measurements of out-vehicle concentration and trip-specific movement record as boundary conditions to simulate in-vehicle CO concentration profiles under various ventilation modes. The vehicle was a 1999 gasoline powered car put in circulation in 2000 and the tests were conducted in 2005. For each ventilation mode, two types (I and II) of simulations were performed to match observed field profiles and define equivalent in-vehicle emission rates. Type I simulations examined three scenarios for each ventilation mode with variable ACH, starting with typical ACH values for stopped and moving vehicles and then varying them based on lowest and highest values reported in the literature for each simulated ventilation mode. These simulations were intended to test whether simulated levels can match actual readings without accounting for an in-vehicle ingression source. In Type II simulations, in-vehicle CO emission rates were

introduced to the simulations to represent the equivalent of the internal ingression source. Despite varying ACH over a wide range, simulated CO levels underestimated experimentally measured CO levels by factors of 47 to 88%. When an in-vehicle CO emission rate was added to account for the internal ingression source representing the self-polluting condition, simulated profiles matched better recorded profiles with equivalent emission rates of 250 to 1,250 mg/h depending on the ventilation mode. A similar mass balance modeling approach was also applied by Adar *et al.* (2008) to estimate self pollution in 53 diesel school buses in Washington (with a mean body year of 1995 in Tahoma, and 2001 in Seattle). The overall average $PM_{2.5}$ contribution from self pollution was found to be 7 $\mu g/m^3$ out of a total in-bus level of 20.9 $\mu g/m^3$, and ranged from a minimum of 5.8 out of 20.6 $\mu g/m^3$ in the newer bus fleet of Seattle to a maximum of 8.5 out of 21.4 $\mu g/m^3$ in the older bus fleet of Tahoma.

2.4 Modeling of in-vehicle pollutant concentrations

While field measurements are necessary in assessing indoor air quality in buildings and all types of micro-environments, they are often constrained by either economic or technical limitations. Therefore, mathematical modeling is relied upon to improve the understanding of chemical and physical processes that affect the fate and transport of indoor air pollutants and predict their spatial and temporal distributions with corresponding human exposures under different conditions (El-Hougeiri and El Fadel, 2004).

There are four general categories of indoor air pollutant models: source emission models, transport models, statistical models, and population exposure models. Models that predict emissions from indoor pollutant sources are generally developed

from controlled emission and transport studies in environmental test chambers. They are commonly grouped into four types representing the various pollutant source (combustion, material, activity, and external). Transport models are used to characterize the movement of air pollutants through defined indoor spaces. These models provide an estimate of the ambient pollutant concentration in a given micro-environment under a variety of user-specified scenarios. Statistical models allow the expansion of results of field studies to a larger population in the same type of micro-environments as were originally studied. They use empirical data regarding the distribution of pollutant concentrations, indoor space volumes, airflow patterns, and other user-specified input data to derive estimates of the distribution of pollutant concentrations on a larger scale. Population exposure models estimate both indoor and outdoor exposure, and can be used to estimate exposure of a population in diverse settings. They incorporate input data on air pollutant concentration and route of exposure experienced by the subject, time-activity patterns of the subject during the exposure period, health or demographic characteristics of the subject that would affect the dose received.

Various models have been developed or used to simulate pollutant concentration inside commuting vehicles. The majority of these models are statistical and population exposure models as shown in Table 2.3.

Table 2.3. Selected in-vehicle CO exposure modeling studies

Reference	*Study Description*
Ott *et al*., 1988	Measured personal CO exposures in various micro-environments of Denver including transportation vehicles, and a Monte Carlo simulation method were used to validate an existing USEPA model, known as Simulation of Human Activity and Pollutant Exposure (SHAPE). Data obtained from the first day of all the paired days of Denver study were used to generate SHAPE-predicted personal CO exposure frequency distributions for the second day, which were then compared with the actual data. The study compared favorably the CO exposure frequency distribution observed in Denver field study by the direct approach and the CO frequency distribution predicted by the indirect approach

	using Denver activity pattern and micro-environmental data in the SHAPE model.
Ott *et al*., 1994	A field study for CO level measurements was conducted on a major suburban arterial highway, El Camino Real, to help develop a realistic and accurate "submodel" of the SHAPE program for the automobile micro-environment. The model, consisting of only a single measure of traffic volume (surrounding vehicle count) and a seasonal trend component had substantial predictive power (R^2=0.68).
Liu *et al*., 1994	A Monte Carlo simulation was implemented to estimate 1- and 8-hr CO exposure levels for the population. The study used data gathered during a survey on commuting patterns and a series of CO measurements in selected micro-environments of Taipei that are affected by vehicular emissions including commuting vehicles. By computer simulations, this study showed that commuters on motorcycles and public buses were exposed to the highest CO exposure levels among all commuters on roads in Taipei. The study also demonstrated that the Monte Carlo simulation method could better estimate CO exposure levels for the public. It was reported that roadside fixed monitoring stations underestimated the general population's 1-hr CO exposure levels.
Park *et al*., 1998	The USEPA Indoor air Quality Model (IAQ model Risk Beta version 1.0.0.5, USEPA 1991) was used to estimate several contaminants from in-vehicle sources including CO emitted by airbag deployment. Large (3.24 m^3) and small (2 m^3) volume vehicles with various air change rates were used for the simulation. The results showed that while the peak CO concentration appeared to vary more with the volume of an automobile than with the change in ACH, the average CO level seemed to be more sensitive to the change in ACH for a small automobile than for a large automobile.
Flachsbart, 1999	Statistical models of passenger exposure to CO inside a motor vehicle as it traveled a coastal highway in Honolulu were presented. The study site was divided into three links. Based on data for 80 trips, the three most powerful models (adjusted R^2=0.69) were nonlinear combinations of four variables: the average CO concentration inside the cabin for the second link; wind speed and direction; and either the travel time, vehicle speed or CO emission factor for the third link. Two factors of third-link CO exposure varied seasonally: relatively lighter traffic flows and stronger winds lowered cabin exposures during the late fall, while heavier traffic flows and calmer winds elevated cabin exposures during winter and spring. This study confirmed the importance of seasonal effects on cabin exposure, as observed previously by the study of Ott *et al*. in 1994.

CHAPTER III

MATERIALS AND METHODS

3.1 Introduction

The scope of work of the proposed research was achieved through a series of sequential interrelated activities starting with the selection and design of the equipment and measurement methods, followed by the implementation of the experimental program and concluded with data analysis and analytical and regression modelling. Below is a description of the methodology.

3.2 Equipment selection and measurement methods

The instruments-supplies were determined based on the literature review and on the knowledge acquired from previous experience (Abi-Esber *et al.* 2007a; 2007b; Abi-Esber and El-Fadel 2007; 2008; El-Fadel and Abi-Esber, 2009; Abi-Esber and El-Fadel, 2012). Figure 3.1 illustrates the experimental setup. Pilot tests were conducted to validate and refine the experimental design prior to implementing the field tests. All equipments were synchronized to the clock of the laptop used for system control and data acquisition. A discussion of the measurement methods follows.

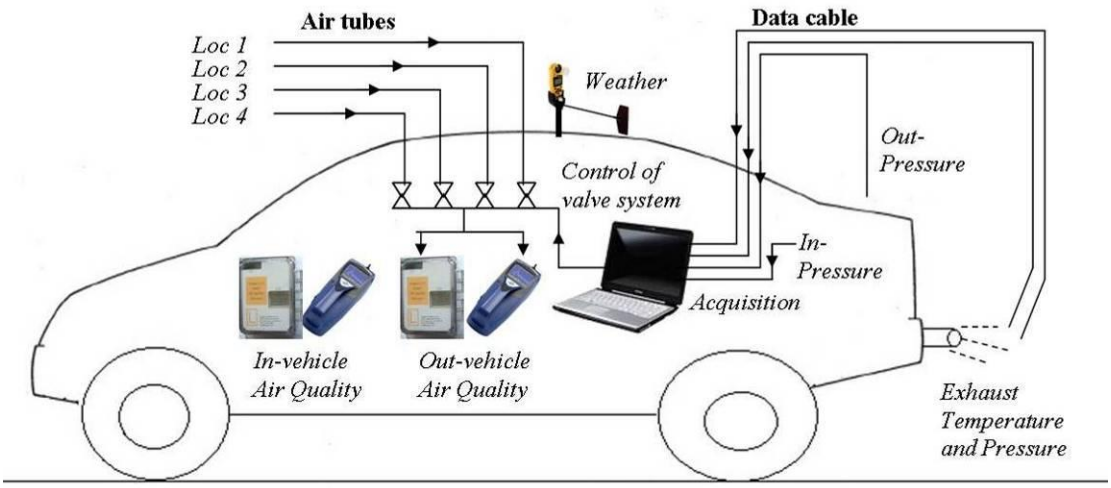


Fig. 3.1. Experimental setup

CO analyzer (Langan L76n) $PM_{2.5}$ analyzer (DustTrak II) High level CO analyzer (Sincro)

Fig. 3.2. Air quality analyzers

Four different locations in the vicinity of the vehicle were tested to identify the out-vehicle location(s) which influence(s) most in-vehicle air quality; the(se) locations would evidently constitute the best location(s) to sample in similar studies. For this reason, a system of four valves and relays (Figure 3.3) was used to alternately switch the sample intake point every one minute to one of four locations, namely rear right, rear left, front right and front left (Figure 3.4). The system is controlled by a Labview program through a data acquisition card. Plastic tubing and airtight push-in fittings and T connectors are used for sample transport and distribution.

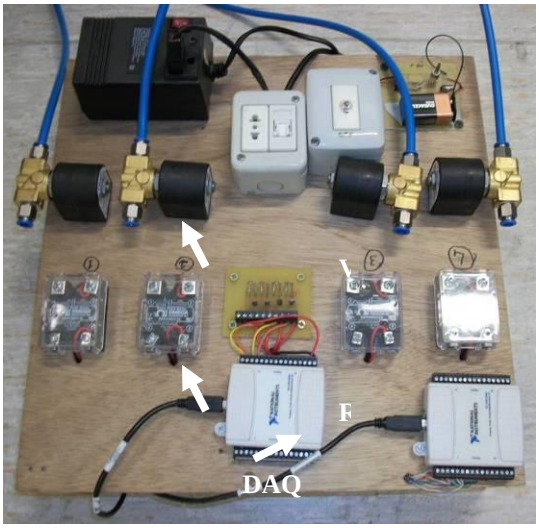


Fig. 3.3. Valve system used for out-vehicle sampling

Front right Rear left

Fig. 3.4. Sample locations of out-vehicle air intake points

3.2.1 Weather parameters

Weather parameters, including temperature, humidity and wind direction and speed are recorded every one minute using a portable weather tracker (Figure 3.5) which is installed on the roof of the car. The unit has a precision pivot and a lightweight vane extension with an incorporated level, which ensures that the unit is installed vertically. The digital compass is calibrated at every battery replacement to further improve the accuracy of wind direction readings. The response time is 1 minute for

relative humidity and 1 second for the rest of the parameters. The measurement range and accuracy are 0-100% and ±3% for relative humidity, 0.4-60 m/s and ±3% for wind speed, -45 to 125°C and ±1°C for temperature and 360 and ±5 degrees for wind direction.

Fig. 3.5. Kestrel 4500 weather tracker

3.2.2 Pressure

Analog output piezoresistive pressure sensors are used to measure the in- and out-vehicle absolute pressures (Figure 3.6). Power is supplied through a 5-volt regulator. The output analog signals are acquired on a data acquisition card with a maximum permissible input voltage of ±10 V. As the sensitivity of the analog output signal is 7 mV/psi, the pressure signals are amplified to a factor of thirty nine using a differential amplifier prior to acquisition. The range and accuracy of the output signal are 0 to 30 psi (0 to 165 mV) and ±1.5 mV/psi, respectively. An offset calibration is applied to one of two pressure sensors so that they respond similarly at the same location.

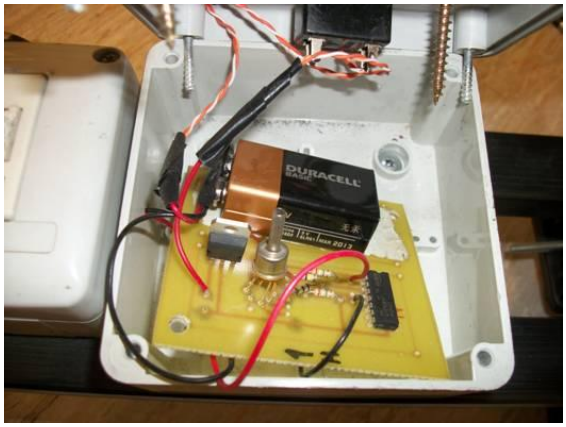


Fig. 3.6. Board used for pressure sensing

3.2.3 Exhaust flow rate

The differential pressure of exhaust fumes is measured using a pitot tube and differential pressure transducer installation (Figure 3.7). The calibrated range is 0 to 6 in H_2O recoverable in the form of a 4 to 20 mA analog output signal. A 470 Ω resistor is used to transform the output to a 1.88-9.40 volt signal acquired on a computer through a data acquisition card. Then, the differential pressure reading is coupled to a temperature reading to compute the exhaust flow rate:

$$Q = \left(\frac{\Delta P \times K^2 \times D^4 \times P \times 16590}{S_s \times (T + 460)} \right)^{1/2} \qquad \text{(Eq. 4.1)}$$

Where Q = flow rate, cubic foot per minute

ΔP = differential pressure, inch H_2O

K = flow coefficient (0.517 for an Omega FPT-6110 pitot tube)

D = inside diameter of line size, inch

P = static line pressure 14.695 psia

S_s = specific gravity at 15°C, assumed to be equal to 0.997

T = temperature of exhaust, °F

Pitot tube Pressure transmitter

Fig. 3.7. Setup used for the measurement of exhaust flow

3.2.4 Exhaust temperature

A resistance temperature detector (RTD, also known as resistance thermometer) is used to sense the exhaust temperature. Signal conditioning is then applied using a transmitter providing a 4-20 mA current loop linearized signal proportional with the temperature characteristic provided from the RTD connected to its input. The transmitter, which has a nominal range of 0-400°C was calibrated in the range 30-255°C using an Omega CL1000 hot point dry block probe calibrator. The transmitter was powered through a 24 V DC power supply and the 4-20 mA output was read out as voltage using a 560 Ω resistor. The relationship between temperature (T, °C) and voltage (V, Volts) was found to be:

$$V = 0.0336T + 0.8216 \Rightarrow T = (V - 0.8216)/0.0336 \qquad \text{(Eq. 4.2)}$$

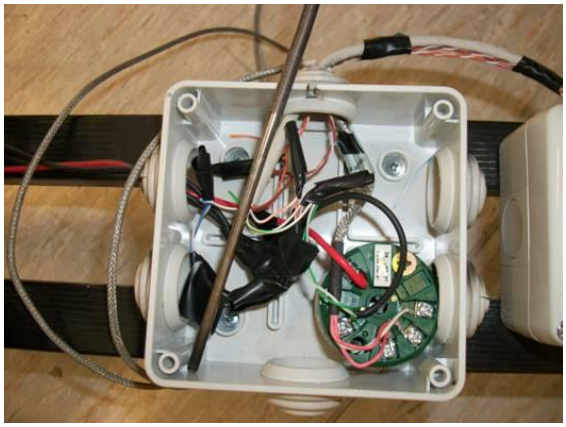


Fig. 3.8. RTD and transmitter used for the measurement of exhaust temperature

The correlation coefficient between temperature signal values calculated using the latter equation and those actually measured was found to be 0.9969 (Figure 3.9).

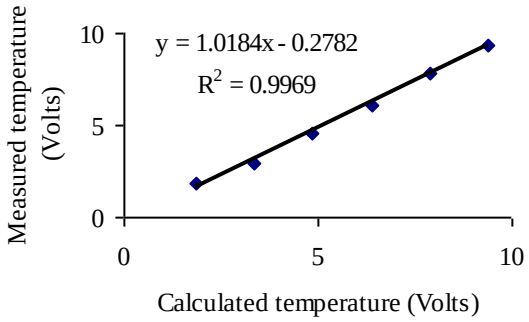


Fig. 3.9. Plot of the analog values of measured (y axis) versus calculated (x axis) temperature

3.2.5 Other equipments and supplies

Vehicle speed is recorded by a GPS-based speed meter that logs speed and location (longitude, latitude) every 100 milliseconds at an accuracy of ±0.1 km/h (Figure 3.10). Power is supplied in the vehicle through portable DC batteries and through a DC/AC inverter whenever needed. Engine fume leakage prior to exiting the tailpipe is examined using a customized exhaust extraction system (Figure 3.11). The

system collects the exhaust into a customized and well-fitted hose that is connected to the tailpipe through sealed fittings releasing away downwind from the test location.

Fig. 3.10. Speed meter

Fig. 3.11. Exhaust extraction system

3.3 Experimental program

In-vehicle exposure was assessed using cars from six different makes under three popular ventilation modes: window ½-opened (W1/2O); windows closed, air conditioning (AC) system on fresh air intake (AC FA); and windows closed, AC on recirculation (AC Rec). Car designs are selected to represent a diversity of vehicle makes and ages (Table 4.1). As test durations reportedly varied from 10 minutes to 1

hour (Adams *et al*., 2001b; Qi *et al*., 2008; Huang *et al*., 2012), a test duration of 30 to 45 minutes was used. Weather data (temperature, humidity, wind speed and direction) are collected on-board using a portable weather tracker. Three major types of tests (fume leakage, stationary and mobile) are conducted as outlined in Figure 3.12 and further discussed in the following sub sections. Figure 3.12 shows the outcomes from each category of tests and how they fill the gaps of each other. As such, while mobile tests can assess in-vehicle exposure and its relationship to several explanatory variables, the possibility of the presence of non-captured out-vehicle pollution limits their ability to determine the magnitude of self-pollution. Non-captured out-vehicle pollution refers to exhaust fumes surrounding the test vehicle and finding their way into its cabin all while not being captured by out-vehicle sampling i.e. not occurring near the intake of the sampling tubes. The latter possibility is examined by conducting stationary tests in the absence of surrounding vehicles. Similarly, while stationary tests can assess total self-pollution due to both fume leakage through firewall and exhaust return, fume leakage tests are capable of distinguishing between the two potential sources of self-pollution by implementing exhaust extraction and thus eliminating the possibility of exhaust return. It is essential to note finally that it is unlikely to have exhaust return and entry to the cabin when a car is moving. However, during mobile tests in stop and go traffic, the car's stopping intervals are substantial at times potentially leading to self pollution by exhaust return due to two possible mechanisms: 1) wind blowing from behind, or 2) high pressure at the level of the air exits of the cabin (located usually in the rear shell of the vehicle) transforming the latter to air entry points.

A total of 264 tests were planned as described in the experimental program shown in Figure 3.13.

Table 3.1. Test vehicles

Vehicle	*Model year*	*Mileage (km)*	*Engine*	*Passenger volume (ft^3)*	*Cargo volume (ft^3)*	*Exterior length (inch)*	*Exterior width (inch)*	*Exterior height (inch)*
Chevrolet Aveo	2011	8 000	1.6 L, 108 HP	91	12.4	169.7	67.3	59.3
Kia Cerato	2011	29 000	2.0 L, 156 HP	97	14.7	178.3	69.9	57.5
Toyota Yaris	2010	30 000	1.5 L, 106 HP	84	9.3	150.6	66.7	60
Toyota Celica	2001	140 000	1.8L, 140 HP	78	16.9	170.5	68.3	51.4
Kia Delta	1999	65 000	1.5 L, 87 HP	-	-	164	65.6	57.1
Honda Civic	1997	289 000	1.6 L, 106 HP	90	11.9	175.2	67.1	54.7

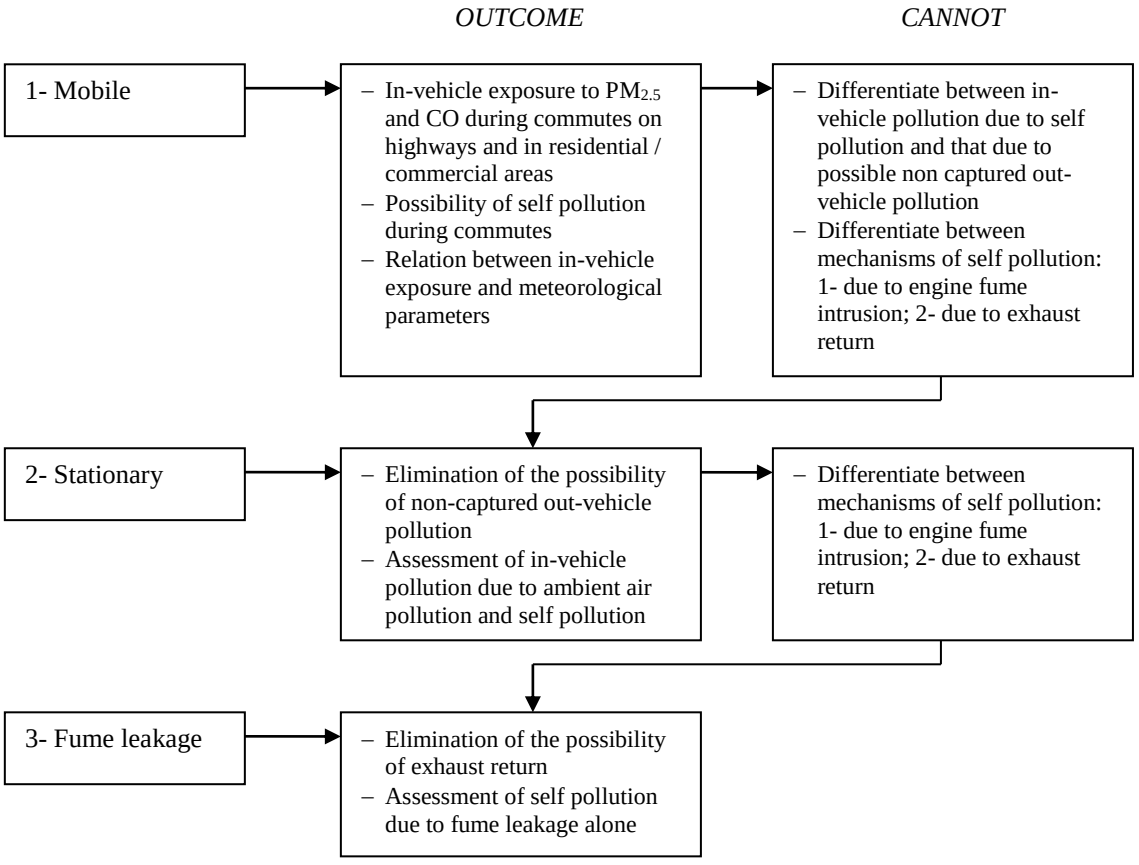


Fig. 3.12. Properties of test types

INPUT: *Test parameters*	*Type & # of tests*				***OUTPUT:*** *Analysis of the influence of*												
	Fume leakage	*Stationary*	*Mobile*	*Purpose of the tests*	*Out-vehicle level*	*Ventilation mode*	*Vehicle speed*	*Exhaust emissions*	*Exhaust temperature*	*Weather*	*Traffic count*	*Stopping intervals*	*Tunnels*	*Initial level*	*Vehicle make*	*Vehicle age*	*Self pollution*
VM: W1/2O, VC; TL: AUB garage; VS: 0; 5 cars; Duplicate tests	10			Estimate fume leakage in a stationary vehicle with exhaust gas extraction under three different ventilation modes and for six different cars	✓	✓		✓	✓	✓				✓	✓	✓	✓
VM: WC, AC FA; TL AUB garage; VS: 0; 5 cars; Duplicate tests	10				✓	✓		✓	✓	✓				✓	✓	✓	✓
VM: WC, AC Rec; TL: AUB garage; VS: 0; 5 cars; Duplicate tests	10				✓	✓		✓	✓	✓				✓	✓	✓	✓
VM: W1/2O, VC; TL: chassis dynamometer; VS: 40, 60, 80; 5 cars; Duplicate tests	30			Estimate fume leakage in chassis dynamometer tests simulating movement at various speeds with exhaust gas extraction, under three different ventilation modes and for six different cars	✓	✓	✓	✓	✓	✓				✓	✓	✓	✓
VM: WC, AC FA; TL chassis dynamometer; VS: 40, 60, 80; 5 cars; Duplicate tests	30				✓	✓	✓	✓	✓	✓				✓	✓	✓	✓
VM: WC, AC Rec; TL chassis dynamometer; VS: 40, 60, 80; 5 cars; Duplicate tests	30				✓	✓	✓	✓	✓	✓				✓	✓	✓	✓
VM: W1/2O, VC; TL: AUB campus; VS: 0; 6 cars; Duplicate tests		12		Estimate in-vehicle exposure in a stationary vehicle without exhaust gas extraction under three different ventilation modes and for six different cars	✓	✓		✓	✓	✓				✓	✓	✓	✓
VM: WC, AC FA; TL: AUB campus; VS: 0; 6 cars; Duplicate tests		12			✓	✓		✓	✓	✓				✓	✓	✓	✓
VM: WC, AC Rec; TL: AUB campus; VS: 0; 6 cars; Duplicate tests		12			✓	✓		✓	✓	✓				✓	✓	✓	✓
VM: W1/2O, VC; TL: Hamra, highway; VS: 40, 60, 80; 6 cars; Duplicate tests			36	Estimate in-vehicle exposure in a vehicle moving at 40, 60 and 80 km/hr without exhaust gas extraction, under three ventilation modes and for six different cars	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
VM: WC, AC FA; TL: Hamra, highway; VS: 40, 60, 80; 6 cars; Duplicate tests			36		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
VM: WC, AC Rec; TL: Hamra, highway; VS: 40, 60, 80; 6 cars; Duplicate tests			36		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Total number of tests	**264**				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Fig. 3.13. Experimental program

(VM: ventilation mode; TL: test location; VS: vehicle speed; WD: wind direction)

3.3.1 Testing for fume leakage

Engine fume leakage prior to exiting the tailpipe was examined using a customized exhaust extraction system (Figure 3.11). The tests took place in a controlled room (for tests simulating idle mode) or on a chassis dynamometer (for tests simulating car movement) with no background sources of CO and $PM_{2.5}$. Chassis dynamometer testing was conducted to simulate vehicle movement at respective speeds of 40, 60 and 80 km/h. The exhaust gas was collected into a customized and well-fitted hose that is connected to the tailpipe through a sealed system that releases away downwind from the test location. CO and $PM_{2.5}$ concentrations were measured concomitantly inside and in the immediate vicinity of the vehicle. In the event of CO and $PM_{2.5}$ detection inside the cabin, the contamination was attributed to engine fume leakage prior to reaching the tailpipe.

3.3.2 Stationary testing of in-vehicle exposure

In this category of tests, the car was parked at AUB campus in front of the Green Field. Exhaust fumes were allowed to flow freely from the car tailpipe to its surrounding area. Idle tests were conducted whereby CO and $PM_{2.5}$ concentrations were measured inside the cabin as well as in the outdoor air in the immediate vicinity of the car at four different locations. These tests allow the assessment of potential 'total' self pollution which comprises fume leakage and exhaust return. The tests were repeated for three ventilation modes and six car makes.

3.3.3 Mobile testing of in-vehicle exposure

In this category of tests, exhaust fumes were allowed to flow freely from the car tailpipe to its surrounding area. CO and $PM_{2.5}$ concentrations were measured inside the cabin as well as in the outdoor air in the immediate vicinity of the car at four different locations. Concomitant collection of wind, temperature, humidity and pressure were implemented. The tests were conducted in two different areas, a residential commercial area of Ras Beirut (Figure 3.14) and the highway from Beirut to Jyeh (Figure 3.15) which constitute typical areas where dense city and highway commutes, respectively, can be tested. The highway encompasses a variety of landuses including commercial, residential, industrial and open areas with very few residences/shops. A vehicle speed of maximum 40 km/hour was maintained in the Ras Beirut area, whereas speeds of 60 and 80 km/hour were tested during highway driving. Vehicle speed and location were monitored in real time during all trips.

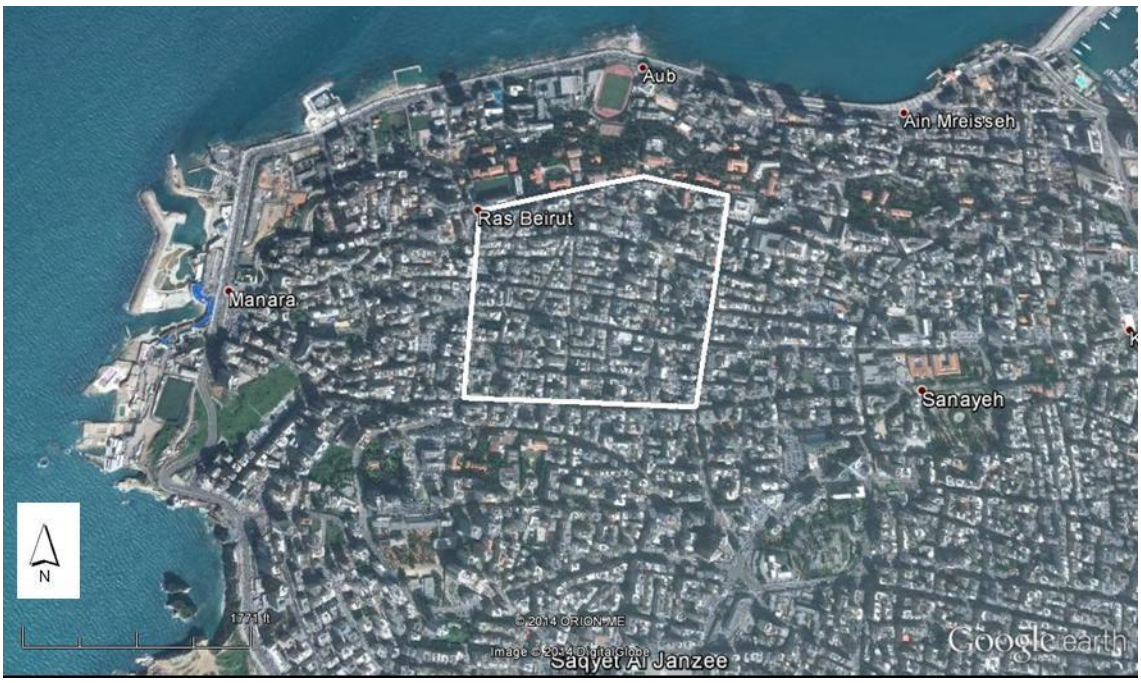


Fig. 3.14. Testing trajectory in Ras Beirut area (white line)

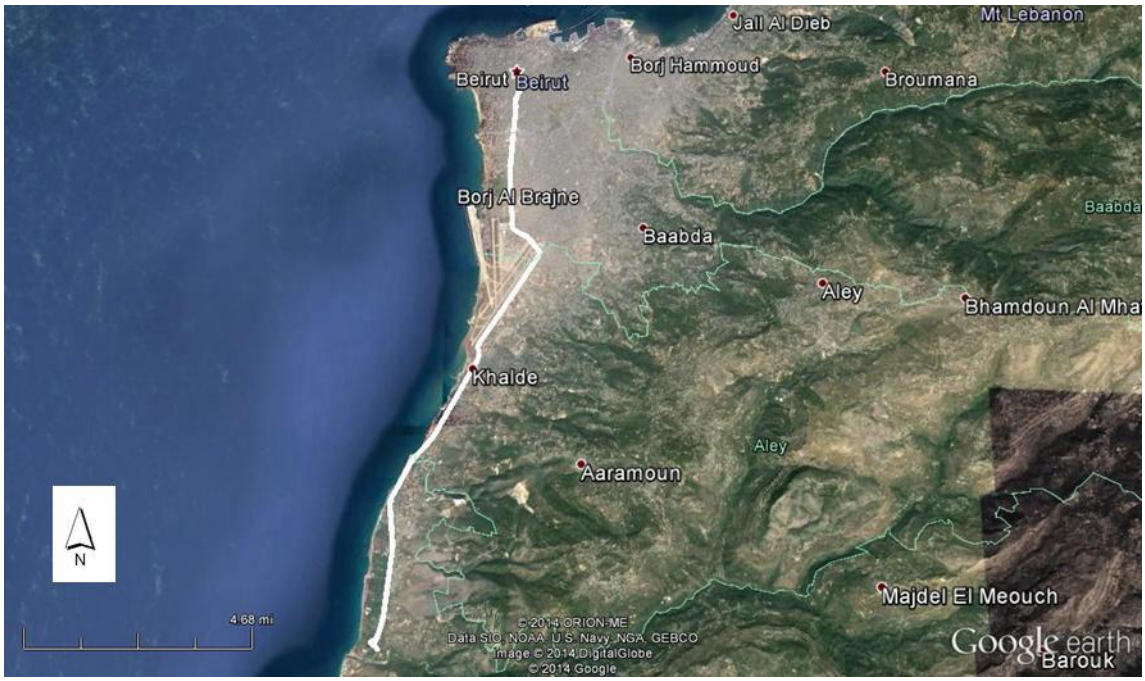


Fig. 3.15. Testing trajectory on the Beirut-Jyeh highway (white line)

3.4 Data analysis

The data analysis methods are described by subdividing them into the methods used in the five major activities conducted under the current project, namely the analysis of the experimental findings, the assessment of the influence of out-vehicle sample intake location and weather gradients, the mathematical simulation of in-vehicle concentrations and cabin fume leakage rates, and the multivariate regression modeling of in-vehicle concentrations and cabin fume leakage rates.

3.4.1 Experimental results

Trip average in- and out-vehicle $PM_{2.5}$ and CO concentrations were calculated for each mobile trip by averaging the 1-min $PM_{2.5}$ and CO measurements. A general average in-vehicle air pollutant level was calculated afterwards for each ventilation

mode and car, and was compared to the 24- and 8- hour World Health Organization (WHO) permissible exposure guidelines for $PM_{2.5}$ and CO (25 $\mu g/m^3$ and 9 ppm respectively) (WHO, 2005). Also, one-way ANOVA and linear regression analysis were used to assess the statistical significance of the influence of ventilation mode and car age on in-cabin exposure.

In addition, trip average IO ratios were used to establish the relationship between average concentration measured inside the vehicle and that measured in its vicinity. They were calculated using 1-minute IO ratios corresponding sequentially to the four tested out-vehicle locations and a single in-vehicle location which is the passenger's breathing zone. To eliminate the possibility of non-captured out-vehicle pollution during mobile tests, IO ratios were computed during idling tests in the absence of surrounding traffic. Furthermore, IO ratios were computed during chassis dynamometer tests at various speeds with exhaust gas extraction to identify potential self-pollution occurrence in the event of IO ratios greater than unity. Although on-road conditions in terms of aerosol size distribution and those encountered in stationary and fume leakage tests may be distinct, the associated change in instrument precision constitutes a factor that affects in- and out-vehicle measurements almost equally and therefore has a less significant impact on the ratio between the two. As a result, it was assumed that IO ratios measured using the same instrument can be reasonably compared independently of the measurement location.

3.4.2 Influence of out-vehicle sample intake location and pressure gradients

The influence of the out-vehicle sample intake location was assessed by conducting linear regression analysis of log-transformed in- against out-vehicle

concentrations after grouping the data based on the location of out-vehicle sample intake point. The software SPSS 16 was used to conduct regression analysis based on the least squares method. The square of the Pearson correlation coefficient (R^2) was computed and analyzed for significance using the associated ANOVA table. A regression approach was also used to assess the correlation between log transformed IO ratios and each of pressure, temperature and humidity differences between the indoor and the outdoor after grouping the data based on the used ventilation mode. For this purpose, linear and polynomial models were tested after running a check of meteorological parameters' inter-correlations. In evaluating the results of the regression analysis, candidate models satisfying three major conditions were selected: (1) the F-statistics for total regression had a probability p-value < 0.05; (2) the Student's t statistic for each independent variable coefficient had a probability p-value < 0.05; some insignificant coefficients were allowed at times only if the resulting model had higher predictive power than other models and the sign of the coefficient could be explained by scientific reasoning; (3) the model satisfies conditions (1) and (2) and has highest predictive power among the derived models.

3.4.3 Mathematical modeling

3.4.3.1. Objective

The USEPA RISK version 1.9.25 model was used to simulate in-cabin CO and $PM_{2.5}$ concentration profiles inside self polluting cars by using the measured out-vehicle concentrations and field-recorded vehicle speeds (impacting directly vehicle air change rates) and fitting the required pollutant in-cabin emission rates to match the average simulated in-cabin concentration with that observed.

3.4.3.2. Modeling concept

RISK is the third in a series of IAQ models developed by the Indoor Environment Management Branch of US EPA's National Risk Management Research Laboratory after INDOOR and EXPOSURE models. RISK allows the calculation of pollutant concentrations based on source emission rates, room-to-room air movement, air exchange with the outdoors, and indoor sink behavior. Each room is considered to be well mixed. A mass balance for each room gives:

$$V_i dC_i / dt = C_{iIN}Q_{iIN} - C_{iOUT}Q_{iOUT} + S_i - R_i \qquad \text{(Eq. 4.3)}$$

Where V_i = the volume of the room, m^3

C_i = the pollutant concentration in the room, mg/m^3

C_{iIN} = the concentration entering the room, mg/m^3

Q_{iIN} = the air flow into the room, m^3/hr

C_{iOUT} = the concentration leaving the room, mg/m^3

Q_{iOUT} = the air flow leaving the room, m^3/hr

S_i = the source term, mg/hr

R_i = the removal term, mg/hr

The subscript i refers to room i for a room in a set of multiple rooms, i = 1,2,.. N where N is the number of rooms. The removal term, R_i, includes pollutant removal by air cleaners and sinks.

From the well mixed assumption, C_{OUT} equals C_i. The previous equation can be rewritten as:

$$V_i dC_i / dt = C_{iIN}Q_{iIN} - C_i \; Q_{iOUT} + S_i - R_i \qquad \text{(Eq. 4.4)}$$

This is one of a set of similar equations that must be solved simultaneously in a multiple room model. RISK uses a fast discrete time step algorithm to solve the series of equations. The method is stable for all time steps and is accurate for sufficiently small time steps. The size of the time step depends on how rapidly concentrations are changing. In general, a time step of 1 minute is small enough when concentrations are changing rapidly, and time steps of several minutes to hours are adequate when concentrations are near steady state. The time step must be small enough to capture the changing behavior of the ventilation system, the sources, the sinks, and the individual activity patterns.

3.4.3.3. Model assumptions

The model is based on two assumptions, namely the perfect mixing and the mass conservations assumptions. The assumption of perfect mixing means that the concentration leaving the room through all exits is the same as the concentration in the room. The assumption of mass conservation means that the amount of air entering a room must equal the amount of air leaving the room. This assumption also means that the amount of outdoor air entering the building as a whole must equal the amount of air leaving the building to the outdoor.

3.4.3.4. Model scenarios and major inputs

A total of 115 scenarios comprising three self polluting test cars, two roadways, and three ventilation modes were simulated (Table 3.2). The models involved two different indicators with distinct behavior and properties as indicated in the following sections which outline the major input data.

Table 3.2. Scenarios

Scenario #	*Car*	*Ventilation*	*General speed*	*Roadway*	*Indicator*	*Test date and time*
1.1	CA2011	AC Rec	40	Hamra-Bliss	CO	22-02-2012 @ 12:36
2.1	CA2011	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	14-02-2012 @ 10:22
2.2	CA2011	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	12-02-2012 @ 8:59
2.3	CA2011	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	22-02-2012 @ 12:36
3.1	CA2011	AC Rec	60	Beirut-Jyeh	CO	21-02-2012 @ 10:25
3.2	CA2011	AC Rec	60	Beirut-Jyeh	CO	22-02-2012 @ 11:51
4.1	CA2011	AC Rec	60	Beirut-Jyeh	$PM_{2.5}$	21-02-2012 @ 10:25
4.2	CA2011	AC Rec	60	Beirut-Jyeh	$PM_{2.5}$	22-02-2012 @ 11:51
5.1	CA2011	AC Rec	80	Beirut-Jyeh	CO	21-02-2012 @ 9:40
6.1	CA2011	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	14-02-2012 @ 11:07
6.2	CA2011	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	12-02-2012 @ 10:29
6.3	CA2011	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	21-02-2012 @ 9:40
7.1	CA2011	AC FA	40	Hamra-Bliss	$PM_{2.5}$	14-02-2012 @ 9:26
8.1	CA2011	AC FA	40	Hamra-Bliss	CO	22-02-2012 @ 8:51
8.2	CA2011	AC FA	40	Hamra-Bliss	$PM_{2.5}$	22-02-2012 @ 8:51
9.1	CA2011	AC Rec	60	Beirut-Jyeh	CO	21-02-2012 @ 8:55
9.2	CA2011	AC FA	60	Beirut-Jyeh	CO	22-02-2012 @ 9:36
10.1	CA2011	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	21-02-2012 @ 8:55
10.2	CA2011	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	22-02-2012 @ 9:36
11.1	CA2011	AC FA	80	Beirut-Jyeh	CO	21-02-2012 @ 11:10
12.1	CA2011	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	14-02-2012 @ 12:37
12.2	CA2011	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	21-02-2012 @ 11:10
13.1	CA2011	W1/2O	40	Hamra-Bliss	CO	21-02-2012 @ 12:40
14.1	CA2011	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	14-02-2012 @ 8:41
14.2	CA2011	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	12-02-2012 @ 8:14
14.3	CA2011	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	21-02-2012 @ 12:40
15.1	CA2011	W1/2O	60	Beirut-Jyeh	CO	22-02-2012 @ 10:21
15.2	CA2011	W1/2O	60	Beirut-Jyeh	CO	22-02-2012 @ 11:06
16.1	CA2011	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	12-02-2012 @ 11:59
16.2	CA2011	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	22-02-2012 @ 10:21
16.3	CA2011	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	22-02-2012 @ 11:06
17.1	CA2011	W1/2O	80	Beirut-Jyeh	CO	21-02-2012 @ 11:55
18.1	CA2011	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	14-02-2012 @ 11:52
18.2	CA2011	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	12-02-2012 @ 11:14

Scenario #	*Car*	*Ventilation*	*General speed*	*Roadway*	*Indicator*	*Test date and time*
18.3	CA2011	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	21-02-2012 @ 11:55
19.1	KD1999	AC Rec	40	Hamra-Bliss	CO	03-11-2012 @ 8:43
19.2	KD1999	AC Rec	40	Hamra-Bliss	CO	07-11-2012 @ 12:09
19.3	KD1999	AC Rec	40	Hamra-Bliss	CO	28-11-2012 @ 8:29
19.4	KD1999	AC Rec	40	Hamra-Bliss	CO	28-11-2012 @ 10:44
20.1	KD1999	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	03-11-2012 @ 8:43
20.2	KD1999	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	07-11-2012 @ 12:09
20.3	KD1999	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	28-11-2012 @ 8:29
20.4	KD1999	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	28-11-2012 @ 10:44
21.1	KD1999	AC Rec	60	Beirut-Jyeh	CO	03-11-2012 @ 9:28
21.2	KD1999	AC Rec	60	Beirut-Jyeh	CO	07-11-2012 @ 11:24
21.3	KD1999	AC Rec	60	Beirut-Jyeh	CO	28-11-2012 @ 9:14
22.1	KD1999	AC Rec	60	Beirut-Jyeh	$PM_{2.5}$	03-11-2012 @ 9:28
22.2	KD1999	AC Rec	60	Beirut-Jyeh	$PM_{2.5}$	07-11-2012 @ 11:24
22.3	KD1999	AC Rec	60	Beirut-Jyeh	$PM_{2.5}$	28-11-2012 @ 9:14
23.1	KD1999	AC Rec	80	Beirut-Jyeh	CO	03-11-2013 @ 10:13
23.2	KD1999	AC Rec	80	Beirut-Jyeh	CO	07-11-2013 @ 10:39
23.3	KD1999	AC Rec	80	Beirut-Jyeh	CO	28-11-2013 @ 9:59
24.1	KD1999	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	03-11-2013 @ 10:13
24.2	KD1999	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	07-11-2013 @ 10:39
24.3	KD1999	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	28-11-2013 @ 9:59
25.1	KD1999	AC FA	40	Hamra-Bliss	CO	03-11-2013 @ 12:28
25.2	KD1999	AC FA	40	Hamra-Bliss	CO	05-11-2013 @ 13:39
26.1	KD1999	AC FA	40	Hamra-Bliss	$PM_{2.5}$	03-11-2013 @ 12:28
26.2	KD1999	AC FA	40	Hamra-Bliss	$PM_{2.5}$	05-11-2013 @ 13:39
27.1	KD1999	AC FA	60	Beirut-Jyeh	CO	03-11-2013 @ 11:43
27.2	KD1999	AC FA	60	Beirut-Jyeh	CO	05-11-2013 @ 12:54
28.1	KD1999	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	03-11-2013 @ 11:43
28.2	KD1999	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	05-11-2013 @ 12:54
29.1	KD1999	AC FA	80	Beirut-Jyeh	CO	03-11-2013 @ 10:58
29.2	KD1999	AC FA	80	Beirut-Jyeh	CO	05-11-2013 @ 12:09
30.1	KD1999	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	03-11-2013 @ 10:58
30.2	KD1999	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	05-11-2013 @ 12:09
31.1	KD1999	W1/2O	40	Hamra-Bliss	CO	05-11-2013 @ 09:54
31.2	KD1999	W1/2O	40	Hamra-Bliss	CO	07-11-2012 @ 08:24

Scenario #	*Car*	*Ventilation*	*General speed*	*Roadway*	*Indicator*	*Test date and time*
32.1	KD1999	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	05-11-2013 @ 09:54
32.2	KD1999	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	07-11-2012 @ 08:24
33.1	KD1999	W1/2O	60	Beirut-Jyeh	CO	05-11-2013 @ 10:39
33.2	KD1999	W1/2O	60	Beirut-Jyeh	CO	07-11-2012 @ 09:09
34.1	KD1999	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	05-11-2013 @ 10:39
34.2	KD1999	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	07-11-2012 @ 09:09
35.1	KD1999	W1/2O	80	Beirut-Jyeh	CO	05-11-2013 @ 11:24
35.2	KD1999	W1/2O	80	Beirut-Jyeh	CO	07-11-2012 @ 09:54
36.1	KD1999	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	05-11-2013 @ 11:24
36.2	KD1999	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	07-11-2012 @ 09:54
37.1	HC1997	Rec	40	Hamra-Bliss	CO	22-03-2012 @ 12:30
37.2	HC1997	Rec	40	Hamra-Bliss	CO	24-03-2012 @ 08:42
38.1	HC1997	Rec	40	Hamra-Bliss	$PM_{2.5}$	22-03-2012 @ 12:30
38.2	HC1997	Rec	40	Hamra-Bliss	$PM_{2.5}$	24-03-2012 @ 08:42
39.1	HC1997	Rec	60	Beirut-Jyeh	CO	22-03-2012 @ 09:42
39.2	HC1997	Rec	60	Beirut-Jyeh	CO	24-03-2012 @ 09:27
40.1	HC1997	Rec	60	Beirut-Jyeh	$PM_{2.5}$	22-03-2012 @ 09:42
40.2	HC1997	Rec	60	Beirut-Jyeh	$PM_{2.5}$	24-03-2012 @ 09:27
41.2	HC1997	Rec	80	Beirut-Jyeh	CO	22-03-2012 @ 10:27
41.2	HC1997	Rec	80	Beirut-Jyeh	CO	24-03-2012 @ 10:12
42.1	HC1997	Rec	80	Beirut-Jyeh	$PM_{2.5}$	22-03-2012 @ 10:27
42.2	HC1997	Rec	80	Beirut-Jyeh	$PM_{2.5}$	24-03-2012 @ 10:12
43.1	HC1997	AC FA	40	Hamra-Bliss	CO	23-03-2012 @ 08:49
43.2	HC1997	AC FA	40	Hamra-Bliss	CO	24-03-2012 @ 11:57
44.1	HC1997	AC FA	40	Hamra-Bliss	$PM_{2.5}$	23-03-2012 @ 08:49
44.2	HC1997	AC FA	40	Hamra-Bliss	$PM_{2.5}$	24-03-2012 @ 11:57
45.1	HC1997	AC FA	60	Beirut-Jyeh	CO	23-03-2012 @ 09:34
45.2	HC1997	AC FA	60	Beirut-Jyeh	CO	24-03-2012 @ 11:12
46.1	HC1997	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	23-03-2012 @ 09:34
46.2	HC1997	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	24-03-2012 @ 11:12
47.1	HC1997	AC FA	80	Beirut-Jyeh	CO	23-03-2012 @ 10:19
47.2	HC1997	AC FA	80	Beirut-Jyeh	CO	24-03-2012 @ 10:42
48.1	HC1997	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	23-03-2012 @ 10:19
48.2	HC1997	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	24-03-2012 @ 10:42
49.1	HC1997	W1/2O	40	Hamra-Bliss	CO	22-03-2012 @ 08:57

Scenario #	*Car*	*Ventilation*	*General speed*	*Roadway*	*Indicator*	*Test date and time*
49.2	HC1997	W1/2O	40	Hamra-Bliss	CO	23-03-2012 @ 12:27
50.1	HC1997	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	22-03-2012 @ 08:57
50.2	HC1997	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	23-03-2012 @ 12:27
51.1	HC1997	W1/2O	60	Beirut-Jyeh	CO	22-03-2012 @ 11:57
51.2	HC1997	W1/2O	60	Beirut-Jyeh	CO	23-03-2012 @ 11:49
52.1	HC1997	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	22-03-2012 @ 11:57
52.2	HC1997	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	23-03-2012 @ 11:49
53.1	HC1997	W1/2O	80	Beirut-Jyeh	CO	23-03-2012 @ 10:19
53.2	HC1997	W1/2O	80	Beirut-Jyeh	CO	24-03-2012 @ 10:42
54.1	HC1997	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	23-03-2012 @ 10:19
54.2	HC1997	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	24-03-2012 @ 10:42

Except for the ventilation mode W1/2O, where vehicle air change rates of 120 (Park *et al*., 1998), 180 and 240 h-1 were assumed for general vehicle speeds of 40, 60 and 80 km/h, regression models of air change rate as a function of vehicle speed were used to simulate the minute to minute varying air change rate during mobile trips. The models are reported by Hudda *et al.* (2012) for recirculation (Eq. 4.5) and fresh air intake (Eq. 4.6) ventilation modes.

$$\ln(\mathrm{AER}) = 2.79 + (0.019 \times \mathrm{speed}) + [0.015 \times \mathrm{age} + 3.3 \times 10^{-3} \mathrm{age}^2]$$

$$+ [-0.023 \times \mathrm{vol} - 6.6 \times 10^{-5} \mathrm{vol}^2] + \mathrm{ManufAdjustment} \qquad \text{(Eq. 4.5)}$$

Where AER = the air change rate, h^{-1}

speed = the vehicle speed, miles/h; if the speed is zero, a -0.51 factor should be added to the model

age = the age of the car, years

volume = the volume of the passenger cabin, ft^3

ManufAdjustment = the manufacturer adjustment, -0.71 for German vehicles, -0.39 for Japenese vehicles and 0 otherwise

$$\ln(\mathrm{AER}) = 4.2 + [(1.88 \times \mathrm{FanStrength}) + (-0.92 \times \mathrm{FanStrength}^2)] + (0.0048 \times \mathrm{speed}) + (-0.0073 \times \mathrm{vol}) \quad \text{(Eq. 4.6)}$$

Where FanStrength = the fraction of maximum setting, considered to be 0.5 for settings of '2' or 'medium',

And the coefficients for FanStrength and FanStrength^2 should be 0.40 and 0.13, respectively, at zero speed, and the speed term should be -0.32 at zero speed. The adequacy of the models in the context was tested by favorably comparing simulated air change rate values to those reported in the literature using similar vehicle speeds (Fletcher and Saunders; 1994; Park *et al*., 1998; Ott *et al*., 2007).

Other model inputs include the trip specific minute-to-minute variations in out-vehicle pollutant concentrations profiles, the characteristics of the HVAC mode and the pollutant properties. The air conditioner was considered to have a supply flow rate of 3600 liters per minute at the medium fan setting (Qi *et al*., 2008) and to be equipped with a pleated filter with a $PM_{2.5}$ removal efficiency of 30% (which is typical inside passenger cars). The return and exhaust flow rates for recirculation and fresh air intake modes, respectively, were considered to be equal to the supply flow rate. As for the pollutants, the respective CO and $PM_{2.5}$ densities are 0.939 and 1.7 (Pitz *et al*., 2008), diffusivities 0.07488 and 0.000000046296 m^2/hour (Marrero and Mason 1972; Kulkarni *et al*., 2011) and penetration factors 1 and 0.47 (model defaults). The deposition velocity of $PM_{2.5}$ is assumed to be 1.56 m/hour (it is reported to be in the range 1.32 to 1.80

m/hour for the particle size range 2 to 3 μm and lower velocities for sizes less than 1 μm (Thatcher and Layton, 1995)).

3.4.3.5. Model outputs

RISK provides a wide range of graphical and tabular output of the results of the calculations. In the present work, the in-cabin CO and $PM_{2.5}$ concentration profiles were simulated, and in-cabin self pollution rates were generated by comparing and matching measured concentrations to those simulated. The average, maximum and minimum concentrations were also compared and percent difference between measured and simulated data were computed.

3.4.4 Multiple regression modeling

3.4.4.1. Objective

SPSS 16.0 and R Studio were used to conduct univariate and multivariate analysis to identify, among 25 different potential influencing variables, the parameters which affect in-cabin exposure to CO and $PM_{2.5}$ and to develop models of exposure to CO and $PM_{2.5}$ inside a car cabin.

3.4.4.2. Variables

Table 3.3 outlines the independent variables used in the regression analysis. The presence of rainfall on previous day was determined based on daily rainfall data acquired from Beirut International Airport and was assigned '1' and '0' values for rainy and clear previous days, respectively. Time of day was set to '0' when trip was conducted before noon and to '1' for after noon trips. Variables X_{16} and X_{17} were set to

'1' whenever a peak traffic time was encountered during a test. Local peak times were recorded during the trips whereas general peak times were considered to comprise morning and evening rush hours (8 to 10 am and 4 to 6 pm) and the hour following schools' closure (2 to 3 pm). Digital codes were used to refer to the ventilation mode (1: W1/2O; 2: AC FA; 3: AC Rec), the test car (1: KC2011; 2: CA2011; 3: TY2010; 4: TC2001; 5: KD1999; 6: HC1997) and the Wind direction (NE: 360 and 0-91º; ES: 91-180 º; SW: 181-270 º; WN: 270 to 359 º). The Julian Day was considered to be a continuous variable in view of the large number of possible values and was included as a sinusoidal function of the form sin(2*pi*JulianDay/365)+cos(2*pi*JulianDay/365) to account for seasonality. The presence of self pollution was set to 1 for cars where fume leakage occurred during self pollution testing.

Table 3.3. Predictor variables

Code	*Description*	*Code*	*Description*
Air quality variables			
X_1	COout (ppm)	X_3	Initial COin (ppm)
X_2	PMout (μg/m^3)	X_4	Initial PMin (μg/m^3)
Meteorological variables			
X_5	Presence of rainfall on previous day	X_{10}	Pressure IO ratio
X_6	Ambient temperature (ºC)	X_{11}	Humidity IO ratio
X_7	Ambient pressure (KPa)	X_{12}	Wind speed (m/s)
X_8	Ambient relative humidity (%)	X_{13}	Wind direction (degrees)
X_9	Temperature IO ratio		
Temporal variables			
X_{14}	Time of day	X_{16}	Time corresponds to a local peak traffic time
X_{15}	Julian day	X_{17}	Time corresponds to a general peak traffic time
Car related variables			
X_{18}	Ventilation mode	X_{21}	Exhaust temperature (ºC)
X_{19}	Car	X_{22}	Exhaust flow rate (Lpm)
X_{20}	Presence of self pollution		
Traffic variables			
X_{23}	Vehicle speed (km/hour)	X_{25}	*Roadway*
X_{24}	Fraction of trip with stopped car (%)		

On another hand, a bivariate correlation analysis was run to test for collinearity between pairs of continuous variables. Statistically significant relationships are outlined in Table 3.4 in decreasing order of predictive power. Important correlations were observed between vehicle speed and fraction of trip with stopped vehicle (multiple R^2 = 0.852), ambient temperature and pressure (multiple R^2 = 0.754), vehicle speed and exhaust temperature (multiple R^2 = 0.488), exhaust temperature and fraction of trip with stopped vehicle (multiple R^2 = 0.397) and temperature and humidity differentials (multiple R^2 = 0.202). The latter collinearity may affect multiple correlation analysis by decreasing the number of significant predictors in a highly significant model.

Table 3.4. Collinearity between independent variables

Parameters	*Sample size*	*Equation*	*Multiple R^2*	*p-value*
Vehicle speed and fraction of trip with stopped vehicle	112	X_{23}=-0.133X_{24}+1.946	0.852	0.000
Ambient temperature and pressure	97	X_6=-11.386X_7+24.017	0.754	0.000
Vehicle speed and exhaust temperature	110	X_{23}=-2.469X_{21}+1.942	0.488	0.000
Exhaust temperature and fraction of trip with stopped vehicle	110	X_{21}=0.320X_{24}+0.582	0.397	0.000
Temperature differential and humidity differential	118	X_9=0.656X_{11}-0.153	0.202	0.000
Ambient temperature and wind direction	118	X_6=-0.06X_{13}+1.411	0.130	0.000
Temperature differential and pressure differential	97	X_9=-0.335X_{10}+1.507	0.120	0.001
Ambient pressure and relative humidity	97	X_7=-0.024X_8+2.038	0.092	0.003
Ambient relative humidity and wind speed	117	X_8=0.185X_{12}+1.632	0.092	0.001
Ambient pressure and wind direction	98	X_7=0.004X_{13}+1.988	0.081	0.005
Vehicle speed and exhaust flow rate	107	X_{23}=0.320X_{22}+0.582	0.072	0.005
Ambient temperature and relative humidity	118	X_6=0.217X_8+0.908	0.057	0.009
Exhaust flow rate and fraction of trip with stopped vehicle	107	X_{22}=0.320X_{24}+0.582	0.052	0.018

3.4.4.3. Methodology

The regression analysis was conducted using the software packages SPSS 16.0 and R Studio. Independent samples' t-test with grouping variable selection was used to test the influence of categorical variables by comparing the means of the grouped data. The test starts with a Levene's test of variances and returns a Sig (2-tailed) value which is the double of the test's p-value. Whenever the categorical variable generated more than two groups, one way anova with post hoc multiple comparison tests (Tamhane in the case of unequal variances and Bonferroni in the case of equal variances) was applied to test its influence. As for the influence of continuous variables, univariate analysis and a color coded correlation matrix showing variable intercorrelations was developed based on the Spearman correlation coefficient.

Multivariate regression analysis was conducted using the software R Studio using a stepwise variable selection. The stepwise regression method tests all possible sequences of variable additions and combinations. Categorical variables were added as factors. The selection of the best model was done based on the Akaike information criterion (AIC).

The AIC (Equations 4.7 and 4.8) is generally used for the identification of an optimum model in a class of competing models and was derived by Akaike (1977). The AIC has been used in various fields of statistics, engineering, hydrology and numerical analyses (Mutua, 1994) as it has a clear interpretation in model fitting. The first term on the right hand side of Equation 3 is a measure of the lack-of-fit of the chosen model, while the second term measures the increased unreliability of the chosen model due to the increased number of model parameters. The best approximating model is the one which achieves the minimum AIC in the class of the competing models.

$$AIC = -2l + 2k \qquad \text{(Eq. 4.7)}$$

$$l = -2\sum_{i=1}^{n} \log\left\{ g(x_i \mid {}_k\hat{\theta}) \right\} + 2k \qquad \text{(Eq. 4.5)}$$

Where l = log (maximized likelihood for model)

k = number of fitted parameters

g = probability density function of the fitted model

x_i = vector of observations

k = estimated parameter of the fitted model

The possibility that the existence of self pollution affected the relationship between the studied predictors and in-cabin CO and $PM_{2.5}$ concentration was assessed by adding to the model interaction terms between all continuous predictors and the variable related to the presence or absence of self pollution. The latter models were referred to in the Results and Discussion section as ‘Interaction models’ whereas those which do not take such interaction into account were called ‘No interaction models’.

A cross validation exercise was then implemented in R Studio to evaluate the predictive accuracy of the derived best interactiom and no interaction models. For this purpose, the data were randomly assigned to four different folds. Then, each fold was removed, in turn, while the remaining data was used to re-fit the regression model and to predict at the deleted observations.

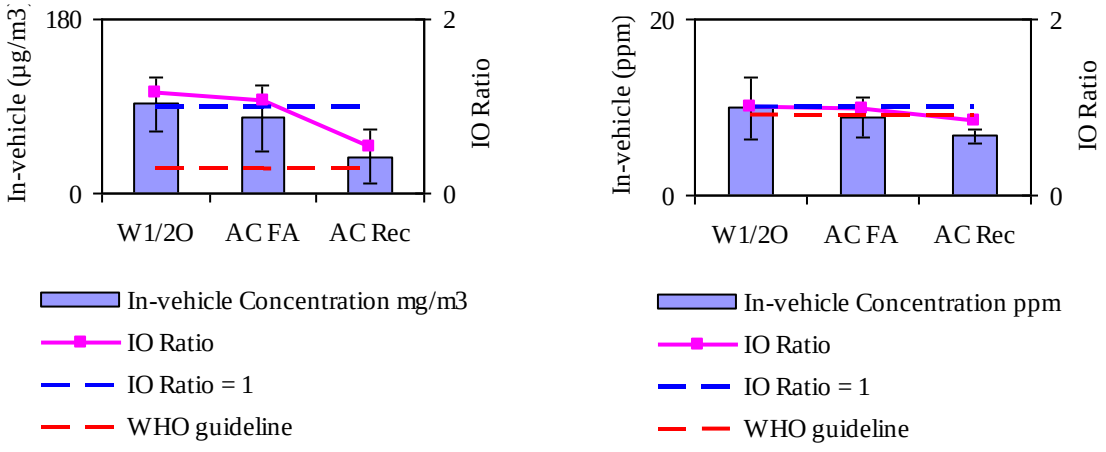
CHAPTER IV

RESULTS AND DISCUSSION

4.1 Experimental results

4.1.1 Influence of ventilation mode

Average in-vehicle concentrations during mobile tests exceeded the WHO permissible exposure guideline with all tested ventilation modes in the case of $PM_{2.5}$ (Figure 4.1-a), and with a W1/2O only in the case of CO (Figure 4.1-b). $PM_{2.5}$ and CO in-vehicle concentrations were 93±28 $\mu g/m^3$, 79±34 $\mu g/m^3$ and 38±28 $\mu g/m^3$ and 9.9±3.6 ppm, 8.8±2.3 ppm and 6.7±0.8 ppm for the ventilation modes W1/2O, AC FA and AC Rec, respectively. A one-way ANOVA test using ventilation mode as the grouping factor ascertained the significant influence of ventilation mode on in-cabin exposure with the modes W1/2O, AC FA and AC Rec presenting a decreasing order of exposure levels. The overall average $PM_{2.5}$ concentration was 71±37 $\mu g/m^3$ for all ventilation modes and test cars, thus lower than the concentrations measured in Jakarta, Indonesia, and higher than the concentrations measured in California, USA, London, UK, Raleigh NC, USA and Bejing, China (Table 4.1). Similarly, the overall average CO concentration was 8.5±2.7 ppm for all ventilation modes and test cars, thus lower than the average concentrations measured in Athens, Greece, Beirut, Lebanon and Jakarta, Indonesia, and higher than the concentrations measured in Paris, France, Milano, Italy, Helsinki, Finland and Bejing, China (Table 4.2). The frequency distributions of the in-vehicle CO and $PM_{2.5}$ concentrations (Fig. 4.2) indicate that the data are right skewed and require data transformation before applying any regression analysis.

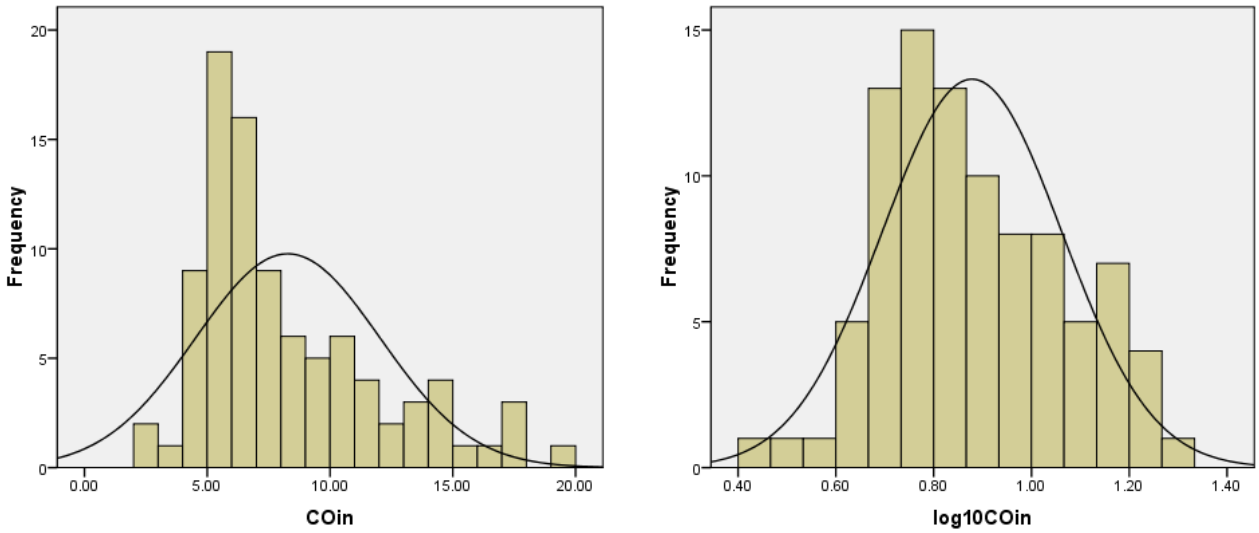


a- Average $PM_{2.5}$ concentration (µg/m^3) and IO ratio

b- Average CO concentration (ppm) and IO ratio

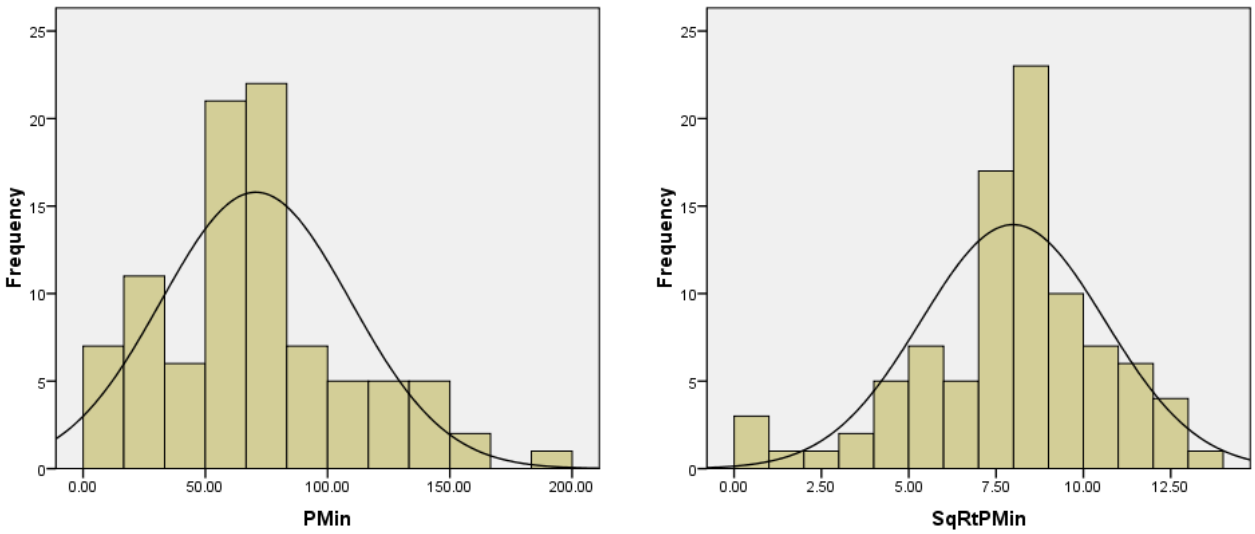
Fig. 4.1. Influence of ventilation mode on in-vehicle exposure during mobile tests

W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation; IO ratio: In/Out ratio; WHO: World Health Organization



a- In-vehicle CO concentration (ppm)

b- Log-transformed in-vehicle CO concentration



c- In-vehicle PM2.5 concentration (μg/m3)

d- Square root of PM2.5 concentration

Fig. 4.2. Frequency distribution of pollutant concentration data

In order to control for the cross-influence of out-vehicle concentration, average in to out vehicle concentration ratios (IO ratio) were calculated for each ventilation mode. A pattern similar to that of concentration variation was obtained for both pollutants (Figure 4.1). $PM_{2.5}$ IO ratios were higher than unity for the ventilation modes W1/2O and AC FA suggesting the possibility of non-captured out-vehicle pollution which refers to exhaust fumes surrounding the test vehicle and finding their way into its cabin all while not occurring near the intake of the sampling tubes. Another possibility is the potential occurrence of self-pollution. Unlike the case of $PM_{2.5}$, average CO IO ratios during mobile tests were less than or equal to 1 for all tested ventilation modes. The latter indicates the absence of non-captured out-vehicle pollution and/or self pollution or possibly the occurrence of the latter at rates which could be diluted by the cabin air exchange rate particularly that CO is a gaseous pollutant and is exchanged between the inside and the outside of the vehicle more easily than $PM_{2.5}$. Indeed, CO has a penetration factor of 1 (NRC, 2002) whereas that of $PM_{2.5}$ may vary from 0.4 to 1

depending on the indoor to outdoor pressure difference (Jeng *et al*., 2003). The possibilities of non-captured out-vehicle pollution or self pollution are assessed later through stationary and fume leakage tests. On another note, the current CO IO ratios were lower than those obtained in a testing campaign conducted earlier on the Kia Delta 1999 (Abi-Esber *et al*., 2007a) probably due to better cabin tightness at the time being (year 2005). In fact, through the years, tightness reportedly decreases whereas the air change rate of a vehicle increases (Knibbs *et al*., 2009; Fruin *et al*., 2011; Hudda *et al*., 2011). The profiles in Figure 4.3 further validate the latter assumption as larger accumulation of CO_2 was observed inside 2011 model cars compared to late 1990s cars during three successive 45 min trips using the ventilation mode windows closed, AC on recirculation, and with two people breathing inside the car, ascertaining that newer cars are associated with better air tightness. The 1999 Kia Delta and the 1997 Honda Civic had remarkably high air exchange rates particularly at speeds of 60 and 80 km/h which prevented almost completely any CO_2 accumulation inside the vehicle and brought cabin CO_2 concentrations to starting ambient levels. Another factor which has contributed to the lower Kia Delta 1999 CO IO ratios in the current work is the much higher average out-vehicle concentration. Indeed, the car's average exhaust CO concentration is 11.93% by volume in 2012 compared to 1.53% by volume in 2005. While the latter emissions did not reach the passenger cabin as demonstrated below, they affected considerably the out-vehicle concentration which was computed as the average from four locations one of which was adjacent to the exhaust pipe, lowering thus the car's CO IO ratio.

Table 4.1. Comparative Assessment of $PM_{2.5}$ Concentrations Inside Car Cabins

Study	*Location*	*Level ($\mu g/m^3$)*	*Type of reading*	*Type of vehicle*	*Method of measurement*	*Ventilation mode*
Rodes *et al*., 1998	Sacramento CA	10.8	Mean	Passenger cars	Gravimetrically	Windows closed, medium fan speed, vents open or closed
Rodes *et al*., 1998	Los Angeles CA	43	Mean	Passenger cars	Gravimetrically	Windows closed, medium fan speed, vents open or closed
Adams *et al*., 2001a	London, UK	35.7	Mean	Passenger cars	Gravimetrically	Open windows
Levy *et al*., 2002	Boston MA	100	Median	Passenger cars	Portable TSI DustTrak calibrated to tapered element oscillating microbalance	Open windows
Riediker *et al*, 2003	Raleigh NC	23	Mean	Patrol trooper	Gravimetrically and with a DataRam nephelometer	AC on recirculation
Boogaard *et al*., 2009	Netherlands	48.9	Mean	Passenger cars	Portable TSI DustTrak, no calibration	Windows closed, AC off, fan on
Huang *et al*., 2012	Bejing, China	31.6	Mean	Taxis	Portable LD-6S spectrometer calibrated gravimetrically	Windows closed, AC on
Both *et al*., 2013	Jakarta, Indonesia	87	Median	Passenger cars	Portable TSI DustTrak calibrated to beta attenuation monitor	With and without AC
This study	Beirut, Lebanon	71	Mean	Passenger cars	Portable TSI DustTrak, no calibration	Window half opened, AC on recirculation, AC on fresh air

Table 4.2. Comparative Assessment of CO Concentrations Inside Car Cabins

Study	*Location*	*Level (ppm)*	*Type of reading*	*Type of vehicle*	*Ventilation mode*
Zagury *et al.*, 2000	Paris, France	3.8	Mean	Taxis	Not controlled
Duci *et al.*, 2003	Athens, Greece	21.4	Mean	Passenger cars	Not controlled
Bruinen de Bruin *et al.*, 2004	Milan, Italy	5.7	Mean	Cars/Taxis	
Kaur *et al.*, 2005a	London, UK	1.2	Mean	Cars/Taxis	Not controlled
Scotto di Marco *et al.*, 2005	Helsinki, Finland	2.8	Mean	Passenger cars	Not controlled
Abi-Esber *et al.*, 2007	Beirut, Lebanon	20	Mean	Passenger car	Window half opened, AC on recirculation, AC on fresh air , etc.
Saksena *et al.*, 2007	Hanoi, Vietnam	18.5	Mean	Passenger cars	Windows opened, Windows closed and AC on
Huang *et al.*, 2012	Bejing, China	5.2	Mean	Taxis	Windows closed, AC on
Wu *et al.*, 2013	Bejing, China	3.4	Mean	Taxis	Windows closed and AC on; windows opened
Both *et al.*, 2013	Jakarta, Indonesia	22	Mean	Passenger cars	With and without AC
This study	Beirut, Lebanon	8.5	Mean	Passenger cars	Window half opened, AC on recirculation, AC on fresh air

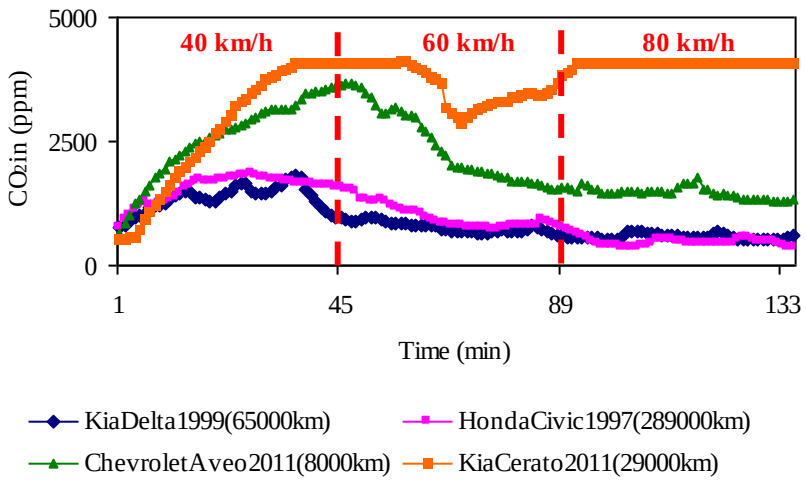


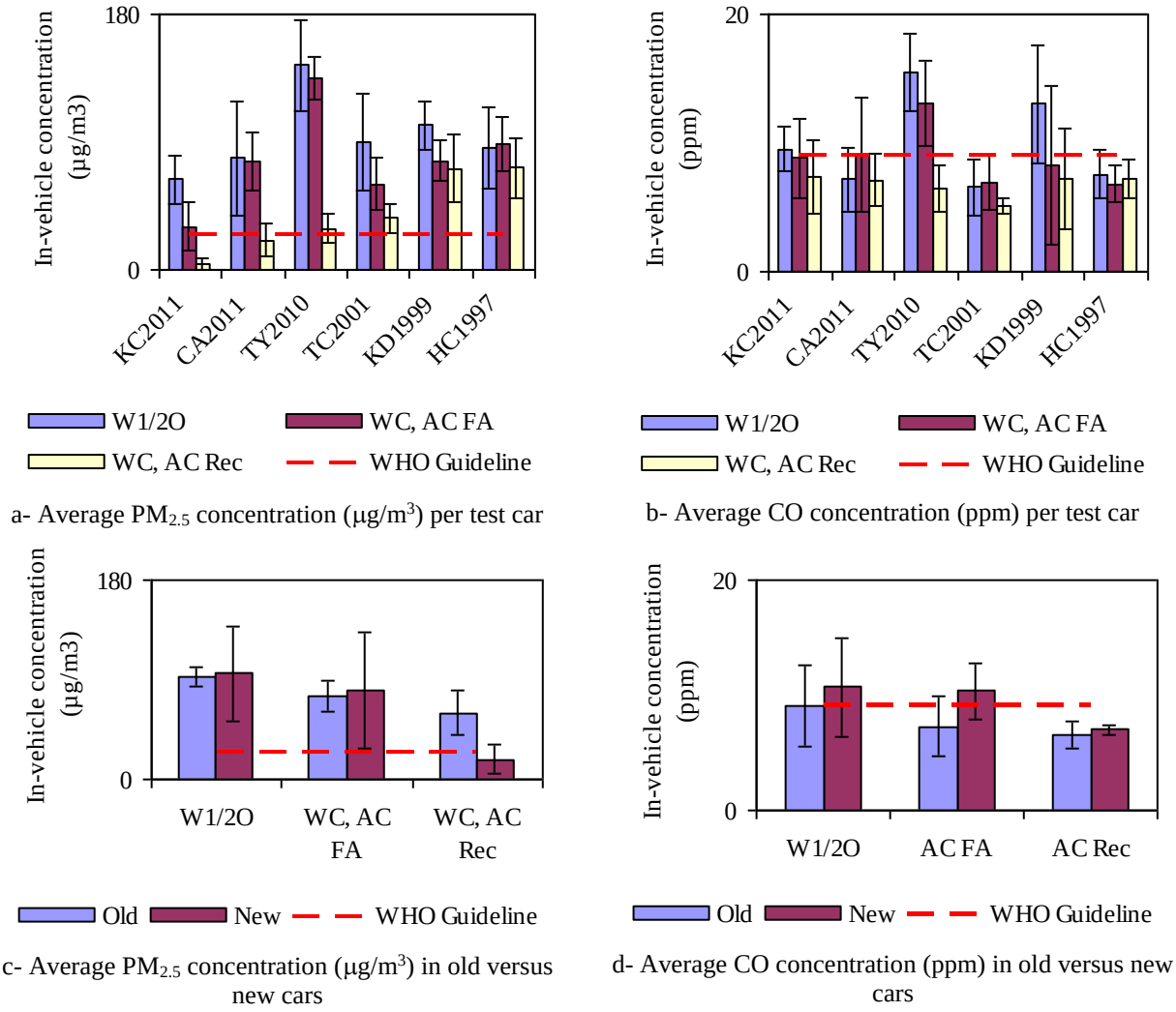
Fig. 4.3. Profiles of CO_2 variation inside the cabin of new versus old cars
Mileage is indicated between parentheses

4.1.2 Influence of vehicle age

Figures 4.4-a and 4.4-b depict average in-vehicle $PM_{2.5}$ and CO concentrations for each test car and ventilation mode during mobile tests. Except for $PM_{2.5}$ concentrations when using the ventilation mode AC Rec, no particular trend for in-vehicle exposure could be discerned for cars of variable age, possibly due to other factors with an influence which outweighs that of car age such as out-vehicle concentrations, meteorological parameters and self-pollution. Regression analysis of in-cabin CO and $PM_{2.5}$ concentrations against car age consistently returned insignificant correlations for all ventilation modes except for $PM_{2.5}$ exposure with the ventilation mode set on air recirculation ($R^2 = 0.70$; p-value = 0.000). In the latter case, in-vehicle exposure to $PM_{2.5}$ increased with increasing vehicle age due probably to the higher efficiency of AC particle filtration systems in new cars which are made of an electrostatically charged mat (special paper or nonwoven microfiber fleece) capable of attracting and capturing dust, pollen, soot and mold spores (Daly, 2006; Schnubel, 2009). As the adequate performance of the latter filters depends on its replacement schedule which is often neglected in the study area although being part of the routine vehicle maintenance requirements, the filter of a new car is likely to perform better than that of an older car.

Figures 4.4-c and 4.4-d depict a comparison of air pollutant concentrations in old cars and those in new cars during mobile tests. A surprising observation was that except for in-vehicle $PM_{2.5}$ concentrations under air recirculation mode, average pollutant concentrations were higher in new cars compared to old cars for all other ventilation modes, which is possibly related to the enhanced air tightness and absence of cracks and leaks in new vehicle cabins compared to old ones and the consequent slower

exfiltration of pollutants either entering the cabin during the test or being generated inside the cabin. On the other hand, new and enhanced particle filtration systems located within recirculation loops in new cars are responsible for the lower $PM_{2.5}$ concentrations in new cars compared to old ones.



a- Average $PM_{2.5}$ concentration ($\mu g/m^3$) per test car

b- Average CO concentration (ppm) per test car

c- Average $PM_{2.5}$ concentration ($\mu g/m^3$) in old versus new cars

d- Average CO concentration (ppm) in old versus new cars

Fig. 4.4. Influence of car age on in-vehicle exposure during mobile tests

KC: Kia Cerato; CA: Chevrolet Aveo; TY: Toyota Yaris; TC: Toyota Celica; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation; WHO: World Health Organization

4.1.3 IO ratios and self pollution occurrence

The average IO ratios for the three types of measurements, namely mobile, stationary and fume leakage are depicted in Figures 4.5 and 4.6 for $PM_{2.5}$ and CO, respectively. Fume leakage tests could not be conducted on the Toyota Celica 2001 due to lack of availability. While the AC Rec mode minimized $PM_{2.5}$ exposure during mobile on-road tests with IO ratios <1, the remaining modes were pervious to $PM_{2.5}$ and encountered IO ratios >1 for all cars except the Kia Cerato 2011 and Kia Delta 1999 (only IO ratios greater than 1.2 were considered to be higher than unity to account for potential experimental errors). In the case of CO, only the cabin of the Toyota Yaris 2010 encountered IO ratios >1 during mobile tests. Possible reasons for the occurrence of IO ratios >1 include the presence of roadway $PM_{2.5}$ pollution that could not be captured by out-vehicle sampling during mobile testing, or the possibility of occurrence of a self-pollution condition inside car cabins, which are examined in stationary and fume leakage tests.

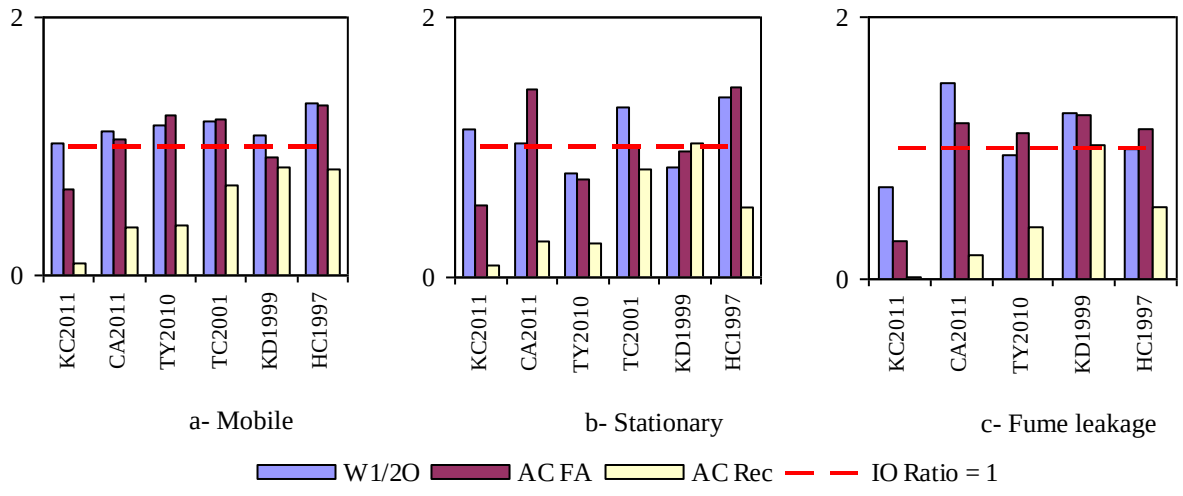


Fig. 4.5. Average $PM_{2.5}$ IO ratios in mobile, stationary and fume leakage tests

KC: Kia Cerato; CA: Chevrolet Aveo; TY: Toyota Yaris; TC: Toyota Celica; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation; IO ratio: In/Out ratio

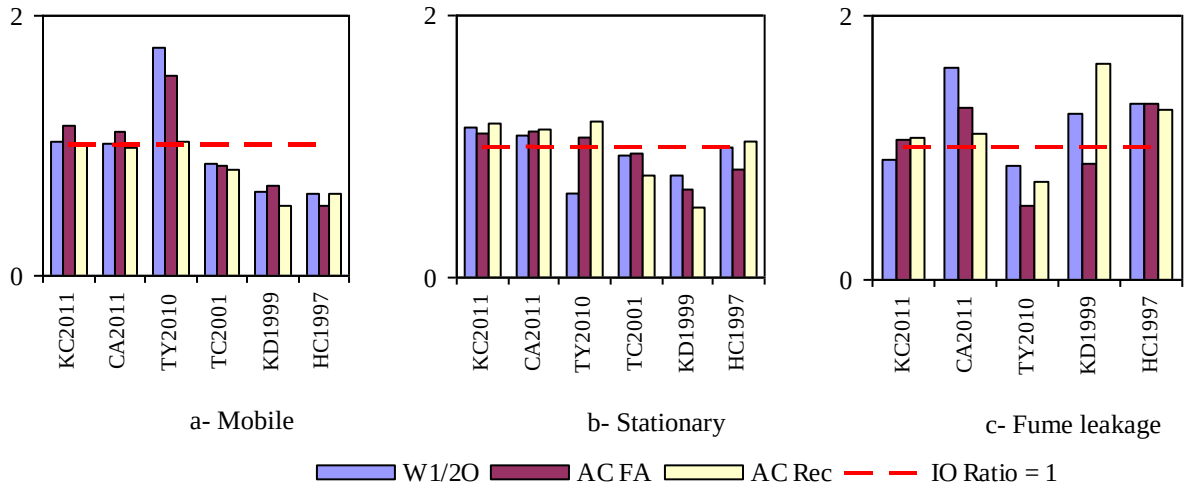


Fig. 4.6. Average CO IO ratios in mobile, stationary and fume leakage tests

KC: Kia Cerato; CA: Chevrolet Aveo; TY: Toyota Yaris; TC: Toyota Celica; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation; IO ratio: In/Out ratio

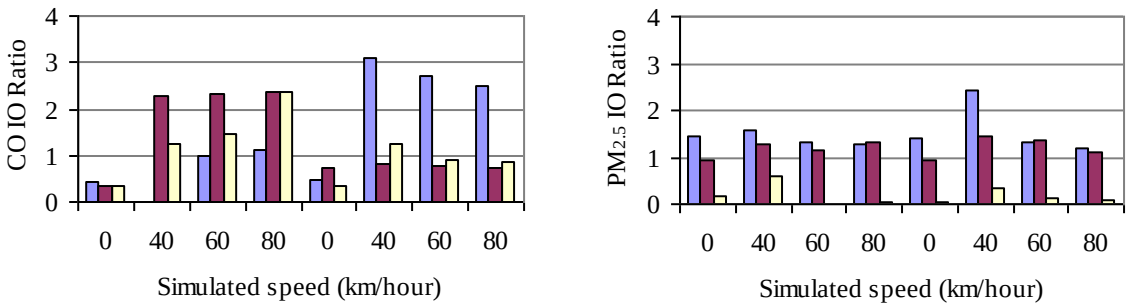
In stationary idle tests, $PM_{2.5}$ IO ratios >1 were encountered in the cabins of the Toyota Celica 2001 and Honda Civic 1997 for W1/2O tests and in the cabins of the Chevrolet Aveo 2011 and Honda Civic 1997 for AC FA tests. The latter ascertains that some pollution accumulated inside the vehicle during on-road tests was not due to nearby vehicles and was due to the test car itself, through fume ingression from the engine compartment or exhaust re-entry to the cabin. For the Toyota Celica 2001 and Honda Civic 1997, the $PM_{2.5}$ IO ratios encountered during stationary tests with the W1/2O mode were even higher than those encountered in mobile tests (1.3 and 1.4, respectively, during stationary tests compared to 1.2 and 1.3, respectively, during mobile tests). The latter can be attributed to the higher exchange rate of a moving vehicle compared to a stationary vehicle, which dilutes faster in-cabin air pollution. Similar results were recorded with the AC FA mode with $PM_{2.5}$ IO ratios of 1.4 and 1.5 in the cabins of the Chevrolet Aveo 2011 and Honda Civic 1997, respectively, compared to ratios of 1.1 and 1.3 during mobile tests. In the case of CO, IO ratios >1

were not recorded during stationary tests indicating either the absence of self pollution, or its occurrence at low rates which could be diluted by the cabin air exchange rate.

In fume leakage tests simulating car movement, $PM_{2.5}$ IO ratios >1 were encountered in the cabin of the Chevrolet Aveo 2011 and Kia Delta 1999 for W1/2O and AC FA tests. In the case of the Chevrolet Aveo 2011, the $PM_{2.5}$ IO ratios were 1.5 and 1.2 for W1/2O and AC FA tests, respectively, compared to an IO ratio of 1.1 during mobile tests for both ventilation modes. For the Kia Delta 1999, the $PM_{2.5}$ IO ratios were 1.3 for W1/2O and AC FA tests, compared to IO ratios of 1.1 and 0.9, respectively, in mobile tests. Given the absence of nearby traffic and exhaust control, the identification of IO ratios >1 suggests the occurrence of fume leakage from the engine compartment to the passenger cabin. The extent of fume leakage was generally higher for Chevrolet Aveo 2011 and Kia Delta 1999 in chassis dynamometer tests than in stationary tests as a result of the burning of fuel when simulating movement. It is also higher in fume leakage tests compared to mobile tests due to the higher air exchange rate in the case of mobile tests. It is likely that fume leakage occurred when using air recirculation as well; however the presence of the AC filtration system in the recirculation loop helped in minimizing the buildup of $PM_{2.5}$ inside the passenger cabin. Consistent results regarding fume leakage were obtained for CO with CO IO ratios of 1.6, 1.3 and 1.1 for W1/2O, AC FA and AC Rec tests, respectively, in the cabin of the Chevrolet Aveo 2011, compared to lower ratios in stationary and mobile tests. Similarly, in the cabin of the Kia Delta 1999, the CO IO ratios were 1.3, 0.9 and 1.6 for W1/2O, AC FA and AC Rec tests, respectively. The CO IO ratio was also high in the cabin of the Honda Civic 1997 with a value of 1.3 for all three ventilation modes. Therefore, findings regarding CO self-pollution are generally consistent with those of

$PM_{2.5}$ self-pollution which provides evidence that fume leakage was occurring at variable levels in the cabins of three (Chevrolet Aveo 2011, Kia Delta 1999, Honda Civic 1997) out of the six tested vehicles. Despite its contribution to measured in-vehicle pollution levels, this self-pollution could not be observed at times in mobile and stationary tests due to higher air exchange rate in the former case and to the low fuel combustion under idle conditions.

Figure 4.6 shows the individual IO ratios obtained in the fume leakage tests for the three test cars where self pollution was observed. The exceptionally high CO leakage rates obtained in the last three tests on the Chevrolet Aveo 2011 with the W1/2O mode sound odd in view of the findings from previous tests conducted on the same car at similar speeds, and could be the result of an outside contamination which was not captured by out-vehicle sampling. Otherwise, there is a great variability in fume leakage rates across cars and ventilation modes with no particular car or mode consistently presenting the highest leakage rates. Several factors come at play in the determination of the IO ratio and rate of ingression of fumes into a vehicle cabin among which the distinct meteorological conditions and combustion temperatures across tests even if the same car and ventilation mode are used.



a- Chevrolet Aveo 2011

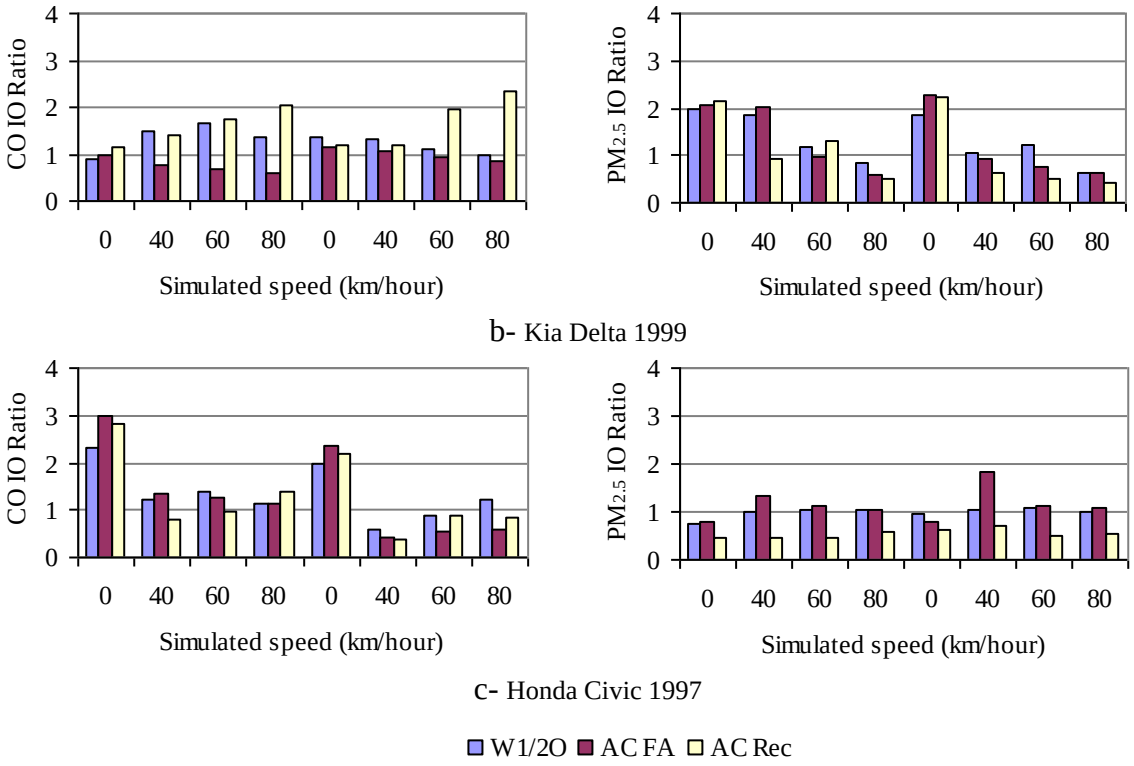


Fig. 4.7. IO ratios of CO and PM2.5 concentrations during fume leakage tests in cars where fume leakage occurs

4.2 Influence of out-vehicle sample intake location

A regression analysis was implemented to test whether the differences between the concentrations measured at the four corners of a car are statistically significant. For this purpose, out- vehicle concentrations were grouped based on the location of out-vehicle sample intake point, and one way anova with Levene's test and post hoc multiple comparisons were applied to test the influence of out-vehicle sample intake location on out-vehicle pollutant concentration. Findings from the Levene's test indicated unequal variances in the case of CO, and Tamhane test results indicated that the sample intake location had a significant influence on CO concentration with locations 3, 1, 4 and 2 respectively exhibiting decreasing out-vehicle CO concentration levels (Table 4.3). Dissimilarly, in the case of $PM_{2.5}$, the Levene's test indicated equal variances whereas

out-vehicle sample location had no influence on out-vehicle $PM_{2.5}$ concentration (Table 4.4).

Table 4.5 outlines the location where highest correlation between log transformed in- and out- vehicle CO and $PM_{2.5}$ concentrations were identified for a specific ventilation mode. The results indicate that locations 2 and 4 which represent the front area of the car near the windshield are correlated most with in-vehicle air quality with out-vehicle concentration explaining 44 to 83% of in-vehicle pollutant concentration depending on the used ventilation mode. Further work is needed to assess the relationship between the current findings and the design characteristics of the test cars and their associated aerodynamics.

Table 4.3. Influence of sample intake location on out-vehicle CO concentration

(I) LocationCO	(J) LocationCO	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	2.62820*	.93637	.034	.1248	5.1316
	3	-.63390	1.20440	.996	-3.8332	2.5654
	4	2.27382	.95766	.109	-.2834	4.8310
2	1	-2.62820*	.93637	.034	-5.1316	-.1248
	3	-3.26210*	.85130	.001	-5.5368	-.9874
	4	-.35437	.43732	.961	-1.5164	.8077
3	1	.63390	1.20440	.996	-2.5654	3.8332
	2	3.26210*	.85130	.001	.9874	5.5368
	4	2.90773*	.87467	.007	.5738	5.2417
4	1	-2.27382	.95766	.109	-4.8310	.2834
	2	.35437	.43732	.961	-.8077	1.5164
	3	-2.90773*	.87467	.007	-5.2417	-.5738

Table 4.4. Influence of sample intake location on out-vehicle $PM_{2.5}$ concentration

(I) LocationPM	(J) LocationPM	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	-1.86946	3.94071	.998	-12.3261	8.5872
	3	-.86116	3.83570	1.000	-11.0392	9.3169
	4	.96671	3.85489	1.000	-9.2622	11.1956
2	1	1.86946	3.94071	.998	-8.5872	12.3261
	3	1.00830	3.89485	1.000	-9.3269	11.3435
	4	2.83617	3.91376	.978	-7.5491	13.2214
3	1	.86116	3.83570	1.000	-9.3169	11.0392
	2	-1.00830	3.89485	1.000	-11.3435	9.3269
	4	1.82787	3.80801	.998	-8.2766	11.9324
4	1	-.96671	3.85489	1.000	-11.1956	9.2622
	2	-2.83617	3.91376	.978	-13.2214	7.5491
	3	-1.82787	3.80801	.998	-11.9324	8.2766

Table 4.5. Locations with highest correlation between log-transformed in- and out-vehicle concentrations

Indicator	*Ventilation mode*[a/]	*Best location*	*Regression analysis results at best location*	
			R^2	*p-value*
$PM_{2.5}$	W1/2O	Location 4	0.8272	0.000
	AC FA	Location 4	0.7625	0.000
	AC Rec	Location 3	0.4024	0.000
CO	W1/2O	Location 2	0.4449	0.000
	AC FA	Location 2	0.4356	0.000
	AC Rec	Location 4	0.4884	0.000

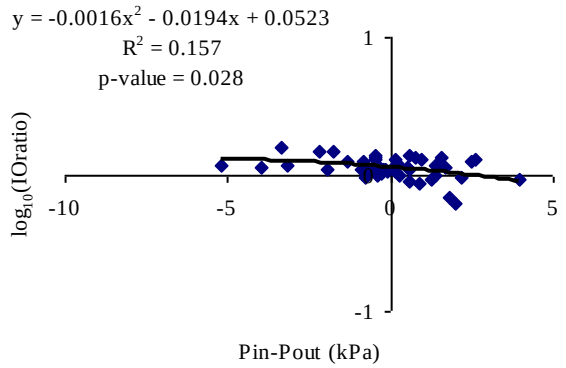
a/ *W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation*

4.3 Influence of meteorological gradients

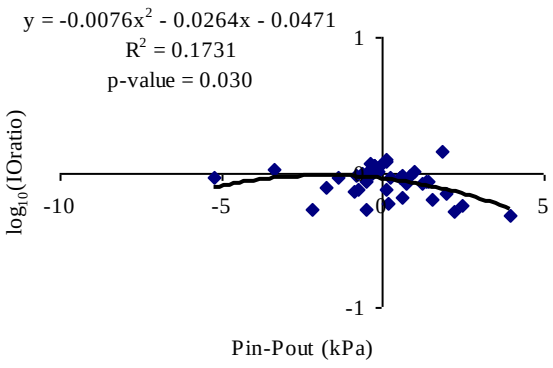
Findings regarding inter-correlations between temperature, humidity and pressure and associated differentials indicated that temperature and humidity

differentials were negatively correlated with an R^2 value of 20.2%. All other parameters exhibited weak and/or insignificant inter-correlations ascertaining that the effect of temperature and humidity differentials are independent of pressure differentials. Meteorological parameters with significant influence on pollutant IO ratios are depicted in Figure 4.8. Models with highest predictive powers were quadratic in the case of pressure difference and cubic in the case of temperature and humidity difference. Note that for the ventilation mode AC FA, meteorological parameters did not affect much examined indicators probably because the IO ratio was controlled by the constant volume of fresh air intake through the fan of the AC system which dominated all other potential determinants.

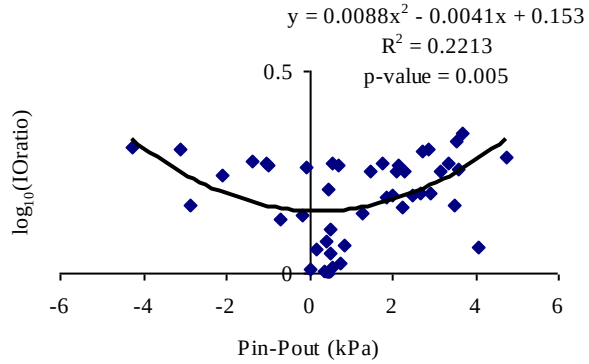
In contrast, for the ventilation mode W1/2O, the difference in pressure between the inside and the outside of the car (P_{in}-P_{out}) explained 15.7 and 17.3% of variations in $PM_{2.5}$ and CO IO ratio, respectively, despite the equally large fresh air intake. In fact, in the case of a moving vehicle with a half opened window, the IO ratio is controlled by vehicle speed which in turn controls the pressure difference between any two points inside and/or outside the vehicle (Hucho, 1998), thus the influence of pressure difference on pollutant IO ratios. Regarding temperature and humidity difference (T_{in}-T_{out} and RH_{out}-RH_{in}), no significant influence was observed for the W1/2O ventilation mode.



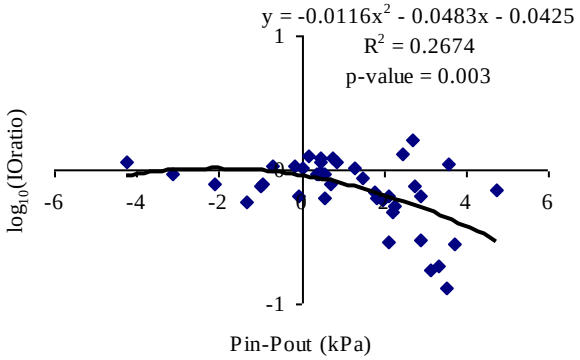
a- W1/2O, $PM_{2.5}$, Pressure difference



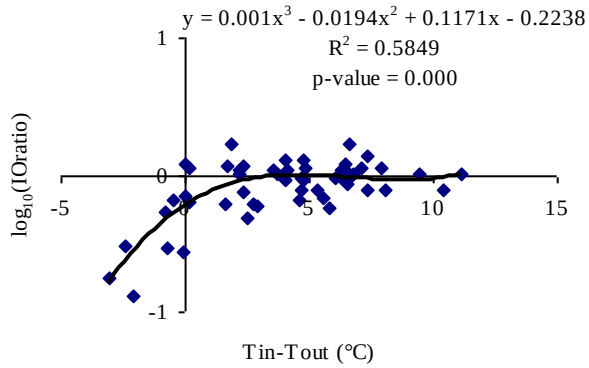
b- W1/2O, CO, Pressure difference



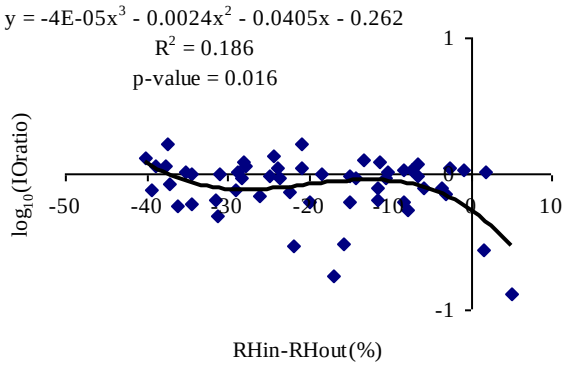
c- Rec, $PM_{2.5}$, Pressure difference



d- Rec, CO, Pressure difference



e- Rec, CO, Temperature difference



f- Rec, CO, Humidity difference

Fig. 4.8. Regression analysis of log transformed indoor to outdoor concentration ratios (IO ratio) against meteorological gradients

W1/2O: one window half opened;
AC FA: air conditioning on fresh air intake;
AC Rec: air conditioning on recirculation;
IO ratio: In/Out ratio

For the AC Rec mode, the pressure difference explained 22.1 and 26.7% of variations in $PM_{2.5}$ and CO IO ratio, respectively (p-value <0.05). The increase in the influence of pressure gradient compared to the W1/2O mode could be attributed to the closure of car vents and windows limiting fresh air intake to unconventional entry points such as body cracks, seams in doors and windows and possibly air exits in the rear part of the vehicle. The latter was also found to be influenced by temperature and humidity difference explaining 58.5 and 18.6%, respectively, of CO IO ratio variation (p-value <0.05). However, for $PM_{2.5}$, there was no significant influence of temperature and humidity on IO ratio variation.

Regarding the shape and direction of the relationships, the curves in Figures 4.8-a, 4.8-b and 4.8-d have negative leading coefficients indicating decreasing IO ratios with increasing 'P_{in}-P_{out}' values, which mean that the in-cabin $PM_{2.5}$ and CO concentration decreased with increasing outflow of pollutant-laden cabin air to the outside. The curve is asymptotic to zero for negative 'P_{in}-P_{out}' values as in the latter cases, inflow of outside air was high bringing quickly in-cabin concentrations to the same levels encountered outside the vehicle (IO ratio =1 and log IO ratio =0). The relationship was different for $PM_{2.5}$ when air recirculation is used (Figure 4.8-c) due to the presence of air filtration in the recirculation loop, which induces lower than 1 IO ratios irrespective of the sign of 'P_{in}-P_{out}'. The leading coefficient is positive which means that IO ratio increased at both curve ends where pressure differential is high. Indeed, the higher the pressure differential, the higher the air exchange of the vehicle which in the presence of filtration, constitutes a drawback to keeping clean in-cabin air thus the increase in in-vehicle concentrations and in IO ratios. The influence of temperature differential (Figure 4.8-e) was different from that of pressure differential

(Figure 4.8-d) whereby the IO ratio decreased for increasing negative 'T_{in}-T_{out}' values (which is equivalent to increasing T_{out} values). The latter is likely due to lower CO fume leakage rates and consequently low in-vehicle concentrations and IO ratios when ambient temperatures are warm. As for the influence of humidity differential on CO IO ratio, the results indicate a relationship which is opposite to that between the IO ratio and temperature differential, which is reasonable given the negative inter-correlation between temperature and humidity differentials.

4.4 Mathematical modeling of pollutant concentrations and self pollution rates

Findings from the mathematical simulation of CO and $PM_{2.5}$ concentrations are depicted in Tables 4.6 to 4.11 which outline, for each individual car and pollutant, the in-cabin emission rate needed to match average simulated and measured concentrations along with the % difference between measured and simulated average, maximum and minimum concentrations.

Table 4.6. Comparison of measured and simulated CO concentrations for Chevrolet Aveo 2011

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration (ppm)*	*Maximum Concentration (ppm)*	*Minimum Concentration (ppm)*
1.1	AC Rec	37	Observed: 10.8 Simulated:10.7 %Difference: 0.3	Observed: 11.6 Simulated:11.8 %Difference: -1.8	Observed: 10.0 Simulated: 9.6 %Difference: 4.5
3.1	AC Rec	33	Observed: 5.9 Simulated: 5.9 %Difference: -0.4	Observed: 6.7 Simulated: 6.8 %Difference: -1.1	Observed: 4.8 Simulated: 4.3 %Difference: 10.9
3.2	AC Rec	55	Observed: 6.1 Simulated: 6.1 %Difference: -0.5	Observed: 10.7 Simulated: 8.3 %Difference: 22.1	Observed: 3.3 Simulated: 3.1 %Difference: 7.5
5.1	AC Rec	37.2	Observed: 4.9 Simulated: 4.9 %Difference: 0.2	Observed: 6.4 Simulated: 6.0 %Difference: 6.9	Observed: 3.4 Simulated: 3.1 %Difference: 9.3
7.1	AC FA	5175	Observed: 16.9 Simulated: 16.9 %Difference: 0.1	Observed: 103.7 Simulated: 28.5 %Difference: 72.5	Observed: 4.1 Simulated: 12.1 %Difference: -194.9
9.1	AC FA	2200	Observed: 7.7 Simulated: 7.7 %Difference: -0.2	Observed: 17.1 Simulated: 10.9 %Difference: 36.1	Observed: 3.9 Simulated: 6.2 %Difference: -58.7
9.2	AC FA	2225	Observed: 7.7 Simulated: 7.7 %Difference: 0.0	Observed: 16.5 Simulated: 10.7 %Difference: 35.4	Observed: 4.0 Simulated: 6.1 %Difference: -52.7
11.1	AC FA	1625	Observed: 5.5 Simulated: 5.4 %Difference: 0.2	Observed: 7.7 Simulated: 6.4 %Difference: 17.5	Observed: 3.5 Simulated: 4.7 %Difference: -33.4
13.1	W1/2O	375	Observed: 11.2 Simulated: 11.2 %Difference: -0.1	Observed: 28.5 Simulated: 33.3 %Difference: -16.7	Observed: 7.8 Simulated: 4.7 %Difference: 39.5
15.1	W1/2O	400	Observed: 5.2 Simulated: 5.2 %Difference: 0.2	Observed: 7.8 Simulated: 7.5 %Difference: 3.5	Observed: 3.6 Simulated: 3.7 %Difference: -2.3
15.2	W1/2O	250	Observed: 5.1 Simulated: 5.1 %Difference: 0.0	Observed: 9.8 Simulated: 10.1 %Difference: -2.9	Observed: 3.2 Simulated: 3.1 %Difference: 3.6
17.1	W1/2O	1100	Observed: 6.5 Simulated: 6.6 %Difference: -0.3	Observed: 14.5 Simulated: 11.6 %Difference: 19.9	Observed: 3.6 Simulated: 4.1 %Difference: -12.6

VM: Ventilation mode; CA: Chevrolet Aveo; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation

Table 4.7. Comparison of measured and simulated CO concentrations for Kia Delta 1999

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration (ppm)*	*Maximum Concentration (ppm)*	*Minimum Concentration (ppm)*
19.1	AC Rec	0	Observed: 8.6 Simulated: 15.2 %Difference: -75.6	Observed: 13.1 Simulated: 19.4 %Difference: -47.9	Observed: 4.0 Simulated: 3.7 %Difference: 6.3
19.2	AC Rec	85	Observed: 14.4 Simulated: 14.4 %Difference: -0.0	Observed: 36.2 Simulated: 17.3 %Difference: 52.2	Observed: 8.1 Simulated: 8.9 %Difference: -10.0
19.3	AC Rec	0	Observed: 9.4 Simulated: 20.7 %Difference: -119.4	Observed: 12.7 Simulated: 33.3 %Difference: -161.8	Observed: 5.1 Simulated: 4.6 %Difference: 10.0
19.4	AC Rec	5.5	Observed: 11.9 Simulated: 11.9 %Difference: 1.8	Observed: 20.7 Simulated: 12.4 %Difference: 40.0	Observed: 4.9 Simulated: 7.6 %Difference: -55.8
21.1	AC Rec	0	Observed: 5.4 Simulated: 19.0 %Difference: -252.3	Observed: 10.7 Simulated: 25.5 %Difference: -138.1	Observed: 2.8 Simulated: 4.7 %Difference: -67.3
21.2	AC Rec	12	Observed: 5.9 Simulated: 5.9 %Difference: -0.2	Observed: 22.1 Simulated: 10.4 %Difference: 52.9	Observed: 2.2 Simulated: 4.2 %Difference: -90.9
21.3	AC Rec	0	Observed: 6.4 Simulated: 27.2 %Difference: -325.8	Observed: 11.1 Simulated: 42.2 %Difference: -280.0	Observed: 3.2 Simulated: 9.8 %Difference: -206.0
23.1	AC Rec	0	Observed: 3.5 Simulated: 8.1 %Difference: -135.0	Observed: 4.6 Simulated: 10.7 %Difference: -133.0	Observed: 4.6 Simulated: 10.7 %Difference: -89.3
23.2	AC Rec	0	Observed: 5.2 Simulated: 7.0 %Difference: -35.1	Observed: 9.9 Simulated: 8.6 %Difference: 13.3	Observed: 2.6 Simulated: 5.8 %Difference: -122.7
23.3	AC Rec	0	Observed: 5.3 Simulated: 11.4 %Difference: -114.5	Observed: 11.9 Simulated: 14.3 %Difference: -20.5	Observed: 3.2 Simulated: 5.5 %Difference: -72.3
25.1	AC FA	2850	Observed: 11.2 Simulated: 11.2 %Difference: -0.1	Observed: 44.0 Simulated: 16.5 %Difference: 62.5	Observed: 4.3 Simulated: 6.4 %Difference: -48.2
25.2	AC FA	6000	Observed: 19.3 Simulated: 19.4 %Difference: -0.4	Observed: 96.8 Simulated: 29.1 %Difference: 69.9	Observed: 2.0 Simulated: 14.1 %Difference: -606.5
27.1	AC FA	425	Observed: 4.0 Simulated: 4.0 %Difference: -0.3	Observed: 10.2 Simulated: 16.1 %Difference: -57.4	Observed: 1.6 Simulated: 1.8 %Difference: -14.8
27.2	AC FA	1750	Observed: 7.3 Simulated: 7.3 %Difference: -0.5	Observed: 18.0 Simulated: 12.2 %Difference: 32.1	Observed: 3.0 Simulated: 5.3 %Difference: -76.2
29.1	AC FA	0	Observed: 2.9	Observed: 6.0	Observed: 1.5

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration (ppm)*	*Maximum Concentration (ppm)*	*Minimum Concentration (ppm)*
			Simulated: 2.8 %Difference: 3.0	Simulated: 6.3 %Difference: -4.5	Simulated: 0.6 %Difference: 63.2
29.2	AC FA	575	Observed: 4.8 Simulated: 4.7 %Difference: 1.5	Observed: 11.1 Simulated: 14.8 %Difference: -33.4	Observed: 2.7 Simulated: 2.5 %Difference: 7.1
31.1	W1/2O	0	Observed: 14.6 Simulated: 32.4 %Difference: -121.6	Observed: 29.2 Simulated: 115.0 %Difference: -293.8	Observed: 4.2 Simulated: 4.5 %Difference: -7.7
31.2	W1/2O	0	Observed: 14.0 Simulated: 18.5 %Difference: -32.0	Observed: 25.9 Simulated: 89.3 %Difference: -244.8	Observed: 4.1 Simulated: 5.9 %Difference: -42.6
33.1	W1/2O	0	Observed: 17.4 Simulated: 28.6 %Difference: -64.1	Observed: 32.6 Simulated: 96.5 %Difference: -196.0	Observed: 7.8 Simulated: 3.7 %Difference: 52.4
33.2	W1/2O	0	Observed: 17.4 Simulated: 26.8 %Difference: -53.6	Observed: 24.9 Simulated: 119.0 %Difference: -377.5	Observed: 11.6 Simulated: 4.2 %Difference: 63.6
35.1	W1/2O	0	Observed: 6.7 Simulated: 7.3 %Difference: -9.2	Observed: 18.0 Simulated: 16.0 %Difference: 11.4	Observed: 3.3 Simulated: 1.9 %Difference: 41.2
35.2	W1/2O	0	Observed: 8.0 Simulated: 8.6 %Difference: -8.3	Observed: 16.6 Simulated: 24.2 %Difference: -45.8	Observed: 3.5 Simulated: 2.4 %Difference: 32.0

VM: Ventilation mode; CA: Chevrolet Aveo; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation

Table 4.8. Comparison of measured and simulated CO concentrations for Honda Civic 1997

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration (ppm)*	*Maximum Concentration (ppm)*	*Minimum Concentration (ppm)*
37.1	AC Rec	23	Observed: 10.2 Simulated: 10.2 %Difference: 0.2	Observed: 14.0 Simulated: 11.4 %Difference: 18.6	Observed: 6.9 Simulated: 7.9 %Difference: -14.7
37.2	AC Rec	23	Observed: 6.1 Simulated: 6.1 %Difference: 0.1	Observed: 8.3 Simulated: 9.2 %Difference: -10.4	Observed: 2.7 Simulated: 2.4 %Difference: 9.9
39.1	AC Rec	0	Observed: 6.6 Simulated: 7.3 %Difference: -11.0	Observed: 9.5 Simulated: 8.6 %Difference: 9.3	Observed: 3.8 Simulated: 5.0 %Difference: -30.3
39.2	AC Rec	6	Observed: 7.6 Simulated: 7.6 %Difference: 0.0	Observed: 11.8 Simulated: 9.3 %Difference: 21.4	Observed: 5.1 Simulated: 4.5 %Difference: 11.2
41.1	AC Rec	0	Observed: 6.6 Simulated: 7.3 %Difference: -10.5	Observed: 8.0 Simulated: 9.7 %Difference: -21.2	Observed: 4.2 Simulated: 3.8 %Difference: 8.5
41.2	AC Rec	0	Observed: 6.4 Simulated: 6.7 %Difference: -4.8	Observed: 7.3 Simulated: 8.1 %Difference: -11.1	Observed: 5.5 Simulated: 5.1 %Difference: 7.1
43.1	AC FA	1950	Observed: 8.9 Simulated: 8.9 %Difference: 0.1	Observed: 38.8 Simulated: 15.1 %Difference: 61.1	Observed: 2.9 Simulated: 5.5 %Difference: -88.5
43.2	AC FA	1250	Observed: 7.7 Simulated: 7.7 %Difference: -0.3	Observed: 14.2 Simulated: 11.1 %Difference: 21.8	Observed: 3.3 Simulated: 5.6 %Difference: -70.7
45.1	AC FA	1050	Observed: 6.7 Simulated: 6.7 %Difference: 0.2	Observed: 17.0 Simulated: 8.9 %Difference: 47.4	Observed: 2.8 Simulated: 4.7 %Difference: -67.2
45.2	AC FA	150	Observed: 7.0 Simulated: 7.1 %Difference: -0.2	Observed: 24.8 Simulated: 11.7 %Difference: 53.0	Observed: 2.5 Simulated: 4.5 %Difference: -80.8
47.1	AC FA	0	Observed: 4.9 Simulated: 5.3 %Difference: -6.8	Observed: 11.4 Simulated: 9.7 %Difference: 14.5	Observed: 2.4 Simulated: 2.5 %Difference: -4.8
47.2	AC FA	0	Observed: 5.6 Simulated: 5.6 %Difference: 0.2	Observed: 13.5 Simulated: 9.6 %Difference: 28.9	Observed: 3.5 Simulated: 3.4 %Difference: 3.5
49.1	W1/2O	0	Observed: 10.3 Simulated: 15.0 %Difference: -46.0	Observed: 20.4 Simulated: 67.8 %Difference: -232.5	Observed: 3.2 Simulated: 4.6 %Difference: -43.3
49.2	W1/2O	0	Observed: 7.4 Simulated: 9.3 %Difference: -25.2	Observed: 16.8 Simulated: 20.4 %Difference: -21.1	Observed: 4.5 Simulated: 3.0 %Difference: 33.2
51.1	W1/2O	0	Observed: 9.0	Observed: 34.2	Observed: 3.4

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration (ppm)*	*Maximum Concentration (ppm)*	*Minimum Concentration (ppm)*
			Simulated: 9.9 %Difference: -9.7	Simulated: 19.0 %Difference: 44.6	Simulated: 5.1 %Difference: -51.1
51.2	W1/2O	0	Observed: 9.0 Simulated: 9.9 %Difference: -9.7	Observed: 33.7 Simulated: 16.1 %Difference: 52.1	Observed: 2.9 Simulated: 4.4 %Difference: -50.0
53.1	W1/2O	0	Observed: 5.3 Simulated: 8.2 %Difference: -55.6	Observed: 10.4 Simulated: 19.7 %Difference: -89.6	Observed: 2.9 Simulated: 4.5 %Difference: -54.9
53.2	W1/2O	0	Observed: 6.1 Simulated: 10.1 %Difference: -66.8	Observed: 14.6 Simulated: 17.5 %Difference: -19.6	Observed: 2.2 Simulated: 4.4 %Difference: -97.7

VM: Ventilation mode; CA: Chevrolet Aveo; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation

Table 4.9. Comparison of measured and simulated $PM_{2.5}$ concentrations for Chevrolet Aveo 2011

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration ($\mu g/m^3$)*	*Maximum Concentration ($\mu g/m^3$)*	*Minimum Concentration ($\mu g/m^3$)*
2.1	AC Rec	0.85	Observed: 17.0 Simulated:17.0 %Difference: -0.2	Observed: 68.0 Simulated:42.2 %Difference: 38.0	Observed: 9.0 Simulated: 13.9 %Difference: -54.6
2.2	AC Rec	0.2	Observed: 10.2 Simulated:10.2 %Difference: 0.2	Observed: 69.0 Simulated: 70.0 %Difference: -1.1	Observed: 3.0 Simulated: 3.4 %Difference: -14.3
2.3	AC Rec	0.51	Observed: 11.0 Simulated:11.2 %Difference: -2.2	Observed: 25.0 Simulated: 26.8 %Difference: -7.1	Observed: 6.0 Simulated: 8.1 %Difference: -35.7
4.1	AC Rec	1.02	Observed: 15.1 Simulated: 15.1 %Difference: 0.1	Observed: 59.0 Simulated: 16.3 %Difference: 72.4	Observed: 7.0 Simulated: 13.6 %Difference: -93.9
4.2	AC Rec	1.625	Observed: 24.4 Simulated: 24.5 %Difference: -0.2	Observed: 59.0 Simulated: 29.4 %Difference: 50.2	Observed: 13.0 Simulated: 22.3 %Difference: -71.8
6.1	AC Rec	3.375	Observed: 46.7 Simulated: 46.6 %Difference: 0.2	Observed: 88.0 Simulated: 49.7 %Difference: 43.5	Observed: 24.0 Simulated: 26.0 %Difference: -8.4
6.2	AC Rec	1.25	Observed: 18.1 Simulated: 18.1 %Difference: 0.2	Observed: 34.0 Simulated: 19.4 %Difference: 43.0	Observed: 11.0 Simulated: 17.6 %Difference: -60.1
6.3	AC Rec	1.635	Observed: 24.3 Simulated: 24.3 %Difference: 0.1	Observed: 39.0 Simulated: 28.0 %Difference: 28.3	Observed: 12.0 Simulated: 23.1 %Difference: -92.7
8.1	AC FA	27.03	Observed: 92.4 Simulated: 92.4 %Difference: 0.0	Observed: 143.0 Simulated: 104.4 %Difference: 27.0	Observed: 76.0 Simulated: 85.4 %Difference: -12.3
8.2	AC FA	26.35	Observed: 84.3 Simulated: 84.2 %Difference: 0.1	Observed: 224.0 Simulated: 105.5 %Difference: 52.9	Observed: 45.0 Simulated: 72.6 %Difference: -61.3
10.1	AC FA	22.85	Observed: 69.7 Simulated: 69.6 %Difference: 0.0	Observed: 175.0 Simulated: 86.5 %Difference: 50.6	Observed: 28.0 Simulated: 59.2 %Difference: -111.4
10.2	AC FA	27.85	Observed: 77.9 Simulated: 77.8 %Difference: 0.1	Observed: 173.0 Simulated: 89.8 %Difference: 48.1	Observed: 27.0 Simulated: 70.2 %Difference: -160.0
12.1	AC FA	32.3	Observed: 96.1 Simulated: 96.1 %Difference: -0.0	Observed: 142.0 Simulated: 103.8 %Difference: 26.9	Observed: 63.0 Simulated: 87.2 %Difference: -38.3
12.2	AC FA	12.7	Observed: 38.9 Simulated: 40.0 %Difference: -0.1	Observed: 71.0 Simulated: 46.8 %Difference: 34.1	Observed: 14.0 Simulated: 33.5 %Difference: -139.4
14.1	W1/2O	21.9	Observed: 120.3	Observed: 150.0	Observed: 101.0

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration ($\mu g/m^3$)*	*Maximum Concentration ($\mu g/m^3$)*	*Minimum Concentration ($\mu g/m^3$)*
			Simulated: 120.3 %Difference: 0.0	Simulated: 145.3 %Difference: 3.1	Simulated: 109.7 %Difference: -8.6
14.2	W1/2O	9.58	Observed: 49.9 Simulated: 49.8 %Difference: 0.2	Observed: 149.0 Simulated: 101.9 %Difference: 31.6	Observed: 26.0 Simulated: 36.64 %Difference: -40.9
14.3	W1/2O	21.8	Observed: 117.1 Simulated: 117.2 %Difference: -0.1	Observed: 973.0 Simulated: 299.1 %Difference: 69.3	Observed: 40.0 Simulated: 88.3 %Difference: -120.7
16.1	W1/2O	9.5	Observed: 36.1 Simulated: 36.2 %Difference: -0.2	Observed: 73.0 Simulated: 66.1 %Difference: 9.5	Observed: 17.0 Simulated: 5.2 %Difference: 69.5
16.2	W1/2O	19.1	Observed: 79.6 Simulated: 79.6 %Difference: -0.0	Observed: 302.0 Simulated: 223.6 %Difference: 26.0	Observed: 38.0 Simulated: 60.1 %Difference: -58.1
16.3	W1/2O	14	Observed: 61.6 Simulated: 61.4 %Difference: 0.2	Observed: 132.0 Simulated: 134.9 %Difference: -2.2	Observed: 34.0 Simulated: 46.8 %Difference: -37.8
18.1	W1/2O	57.525	Observed: 144.7 Simulated: 144.6 %Difference: 0.0	Observed: 267.0 Simulated: 176.5 %Difference: 33.9	Observed: 94.0 Simulated: 124.7 %Difference: -32.7
18.2	W1/2O	13.85	Observed: 36.4 Simulated: 36.4 %Difference: -0.1	Observed: 87.0 Simulated: 45.7 %Difference: 47.5	Observed: 20.0 Simulated: 31.9 %Difference: -59.3
18.3	W1/2O	20.1	Observed: 61.1 Simulated: 61.1 %Difference: -0.1	Observed: 242.0 Simulated: 141.9 %Difference: 41.4	Observed: 21.0 Simulated: 44.5 %Difference: -111.8

VM: Ventilation mode; CA: Chevrolet Aveo; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation

Table 4.10. Comparison of measured and simulated $PM_{2.5}$ concentrations for Kia Delta 1999

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration (ppm)*	*Maximum Concentration (ppm)*	*Minimum Concentration (ppm)*
20.1	AC Rec	3.35	Observed: 66.6 Simulated: 66.6 %Difference: -0.0	Observed: 185.0 Simulated: 117.2 %Difference: 36.6	Observed: 32.0 Simulated: 59.9 %Difference: -87.1
20.2	AC Rec	4.37	Observed: 46.9 Simulated: 46.9 %Difference: 0.0	Observed: 80.0 Simulated: 50.5 %Difference: 36.9	Observed: 33.0 Simulated: 39.8 %Difference: -20.7
20.3	AC Rec	4.16	Observed: 56.7 Simulated: 56.6 %Difference: 0.1	Observed: 95.0 Simulated: 58.2 %Difference: 38.7	Observed: 42.0 Simulated: 49.7 %Difference: -18.3
20.4	AC Rec	4.3	Observed: 59.5 Simulated: 59.3 %Difference: 87.8	Observed: 212.0 Simulated: 44.7 %Difference: 78.9	Observed: 30.0 Simulated: 1.6 %Difference: 94.6
22.1	AC Rec	5.3	Observed: 68.6 Simulated: 68.6 %Difference: 0.1	Observed: 164.0 Simulated: 75.4 %Difference: 54.1	Observed: 36.0 Simulated: 43.2 %Difference: -20.1
22.2	AC Rec	10.05	Observed: 124.0 Simulated: 124.0 %Difference: 0.0	Observed: 872.0 Simulated: 149.7 %Difference: 82.8	Observed: 42.0 Simulated: 68.8 %Difference: -63.7
22.3	AC Rec	5.3	Observed: 67.0 Simulated: 67.1 %Difference: -0.1	Observed: 97.0 Simulated: 72.4 %Difference: 25.3	Observed: 45.0 Simulated: 44.1 %Difference: 2.1
24.1	AC Rec	4.65	Observed: 60.7 Simulated: 60.6 %Difference: 0.2	Observed: 119.0 Simulated: 64.7 %Difference: 45.6	Observed: 46.0 Simulated: 52.8 %Difference: -14.8
24.2	AC Rec	4.575	Observed: 62.7 Simulated: 62.6 %Difference: 0.1	Observed: 156.0 Simulated: 101.3 %Difference: 35.1	Observed: 37.0 Simulated: 57.8 %Difference: -56.2
24.3	AC Rec	7.03	Observed: 85.8 Simulated: 85.7 %Difference: 0.2	Observed: 197.0 Simulated: 94.3 %Difference: 52.1	Observed: 53.0 Simulated: 60.3 %Difference: -13.8
26.1	AC FA	23.55	Observed: 76.6 Simulated: 76.6 %Difference: -0.0	Observed: 566.0 Simulated: 150.1 %Difference: 73.5	Observed: 34.0 Simulated: 66.7 %Difference: -96.1
26.2	AC FA	20.6	Observed: 69.6 Simulated: 69.6 %Difference: -0.0	Observed: 152.0 Simulated: 98.8 %Difference: 35.0	Observed: 50.0 Simulated: 62.9 %Difference: -25.8
28.1	AC FA	20.75	Observed: 64.4 Simulated: 64.5 %Difference: -0.1	Observed: 182.0 Simulated: 75.8 %Difference: 58.3	Observed: 42.0 Simulated: 60.0 %Difference: -42.9
28.2	AC FA	35.5	Observed: 105.4 Simulated: 105.2 %Difference: 0.2	Observed: 291.0 Simulated: 130.9 %Difference: 55.0	Observed: 47.0 Simulated: 93.8 %Difference: -99.6
30.1	AC FA	18.6	Observed: 62.2	Observed: 114.0	Observed: 40.0

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration (ppm)*	*Maximum Concentration (ppm)*	*Minimum Concentration (ppm)*
			Simulated: 62.3 %Difference: -0.1	Simulated: 76.5 %Difference: 32.9	Simulated: 55.0 %Difference: -37.4
30.2	AC FA	26.8	Observed: 82.4 Simulated: 82.5 %Difference: -0.2	Observed: 141.0 Simulated: 107.1 %Difference: 24.0	Observed: 49.0 Simulated: 73.0 %Difference: -49.0
32.1	W1/2O	11.6	Observed: 79.3 Simulated: 79.2 %Difference: 0.2	Observed: 130.0 Simulated: 108.8 %Difference: 16.3	Observed: 47.0 Simulated: 61.6 %Difference: -31.0
32.2	W1/2O	16.1	Observed: 85.5 Simulated: 85.5 %Difference: -0.0	Observed: 132.0 Simulated: 104.8 %Difference: 20.6	Observed: 57.0 Simulated: 75.0 %Difference: -31.5
34.1	W1/2O	21.6	Observed: 94.1 Simulated: 94.3 %Difference: -0.1	Observed: 331.0 Simulated: 168.7 %Difference: 49.0	Observed: 47.0 Simulated: 75.2 %Difference: -60.0
34.2	W1/2O	35.5	Observed: 118.2 Simulated: 118.3 %Difference: -0.1	Observed: 646.0 Simulated: 186.8 %Difference: 71.1	Observed: 46.0 Simulated: 99.8 %Difference: -116.9
36.1	W1/2O	18.5	Observed: 62.6 Simulated: 62.4 %Difference: 0.2	Observed: 93.0 Simulated: 77.5 %Difference: 16.7	Observed: 44.0 Simulated: 53.9 %Difference: -22.5
36.2	W1/2O	28.5	Observed: 75.8 Simulated: 75.8 %Difference: 0.1	Observed: 166.0 Simulated: 98.4 %Difference: 40.7	Observed: 47.0 Simulated: 66.9 %Difference: -42.4

VM: Ventilation mode; CA: Chevrolet Aveo; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation

Table 4.11. Comparison of measured and simulated $PM_{2.5}$ concentrations for Honda Civic 1997

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration (ppm)*	*Maximum Concentration (ppm)*	*Minimum Concentration (ppm)*
38.1	AC Rec	3.6	Observed: 52.2 Simulated: 52.1 %Difference: 0.0	Observed: 98.0 Simulated: 68.2 %Difference: 30.4	Observed: 36.0 Simulated: 38.3 %Difference: -6.4
38.2	AC Rec	4.65	Observed: 65.0 Simulated: 65.0 %Difference: 0.1	Observed: 104.0 Simulated: 67.8 %Difference: 34.8	Observed: 47.0 Simulated: 62.1 %Difference: -32.1
40.1	AC Rec	4.575	Observed: 63.6 Simulated: 63.9 %Difference: -0.3	Observed: 125.0 Simulated: 73.0 %Difference: 41.6	Observed: 44.0 Simulated: 61.4 %Difference: -39.5
40.1	AC Rec	8.4	Observed: 111.5 Simulated: 111.7 %Difference: -0.1	Observed: 414.0 Simulated: 132.1 %Difference: 68.1	Observed: 53.0 Simulated: 82.6 %Difference: -55.8
42.1	AC Rec	4.6	Observed: 59.7 Simulated: 59.6 %Difference: 0.2	Observed: 81.0 Simulated: 62.5 %Difference: 22.9	Observed: 46.0 Simulated: 42.2 %Difference: 8.2
42.2	AC Rec	6.18	Observed: 79.2 Simulated: 79.2 %Difference: 0.0	Observed: 104.0 Simulated: 84.3 %Difference: 19.0	Observed: 65.0 Simulated: 62.7 %Difference: 3.6
44.1	AC FA	27	Observed: 81.6 Simulated: 81.7 %Difference: -0.2	Observed: 125.0 Simulated: 96.0 %Difference: 23.2	Observed: 51.0 Simulated: 73.2 %Difference: -43.4
44.2	AC FA	30.4	Observed: 93.4 Simulated: 93.5 %Difference: -0.1	Observed: 185.0 Simulated: 111.2 %Difference: 39.9	Observed: 70.0 Simulated: 86.6 %Difference: -23.7
46.1	AC FA	27.25	Observed: 77.1 Simulated: 77.2 %Difference: -0.1	Observed: 189.0 Simulated: 101.3 %Difference: 46.4	Observed: 45.0 Simulated: 71.0 %Difference: -57.8
46.2	AC FA	39.875	Observed: 112.0 Simulated: 112.0 %Difference: 0.0	Observed: 366.0 Simulated: 137.9 %Difference: 62.3	Observed: 61.0 Simulated: 99.4 %Difference: -63.0
48.1	AC FA	22.6	Observed: 62.6 Simulated: 62.6 %Difference: 0.0	Observed: 131.0 Simulated: 69.3 %Difference: 47.1	Observed: 44.0 Simulated: 59.9 %Difference: -36.0
48.2	AC FA	37.85	Observed: 105.7 Simulated: 105.7 %Difference: 0.0	Observed: 178.0 Simulated: 117.0 %Difference: 34.6	Observed: 74.0 Simulated: 99.4 %Difference: -34.3
50.1	W1/2O	26.55	Observed: 131.1 Simulated: 131.1 %Difference: -0.0	Observed: 390.0 Simulated: 71.9 %Difference: 81.6	Observed: 71.0 Simulated: 69.1 %Difference: 2.7
50.2	W1/2O	11.75	Observed: 65.3 Simulated: 65.4 %Difference: -0.0	Observed: 139.0 Simulated: 107.0 %Difference: 22.9	Observed: 45.0 Simulated: 50.7 %Difference: -12.6
52.1	W1/2O	45.5	Observed: 136.7	Observed: 801.0	Observed: 64.0

Scenario #	*VM*	*Emission rate (mg/hr)*	*Average Concentration (ppm)*	*Maximum Concentration (ppm)*	*Minimum Concentration (ppm)*
			Simulated: 136.8 %Difference: -0.1	Simulated: 220.0 %Difference: 72.5	Simulated: 116.0 %Difference: -80.8
52.2	W1/2O	31.5	Observed: 99.8 Simulated: 99.7 %Difference: 0.0	Observed: 519.0 Simulated: 149.0 %Difference: 71.3	Observed: 40.0 Simulated: 80.2 %Difference: -100.4
54.1	W1/2O	44	Observed: 101.9 Simulated: 101.6 %Difference: 0.3	Observed: 289.0 Simulated: 113.9 %Difference: 60.6	Observed: 72.0 Simulated: 95.7 %Difference: -32.9
54.2	W1/2O	32.75	Observed: 77.9 Simulated: 77.7 %Difference: 0.2	Observed: 213.0 Simulated: 94.9 %Difference: 55.5	Observed: 45.0 Simulated: 68.3 %Difference: -51.7

VM: Ventilation mode; CA: Chevrolet Aveo; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation

Except for cases where simulated concentrations were higher than those observed and therefore the fitting of an in-cabin emission rate was not possible, the % difference between average simulated and measured concentrations ranged from -2.2 to 0.3%. The % difference in maximum CO concentration when AC Rec was used was generally lower for CA2011 and HC1997 (-21.2 to 22.1) compared to KD1999 (-280 to 52.9) due to exceptionally high outdoor concentration in the latter case. In fact, although not reaching the car cabin as demonstrated through stationary testing, high exhaust emissions from KD1999 at out-vehicle sampling location 3 (rear right as a observed by a seated driver) yielded high out-vehicle CO concentration which increased simulated in-cabin CO concentration leading to an overestimation of the actual levels encountered inside the vehicle. Consistently, the % difference in minimum CO concentration when AC Rec was used was generally lower for CA2011 and HC1997 (-30.3 to 11.2) compared to KD1999 (-206 to 10) for the same reason.

For scenarios involving AC FA inside the CA2011 and the HC1997 cabins, the maximum and minimum CO concentrations were respectively underestimated and

overestimated (except for scenario 47.2 where the minimum was slightly overestimated) indicating that the simulated range was tighter than the actual one. The latter could be due to air change rate underestimation in both cars. As for KD1999, both maximum and minimum were overestimated at times by -57.4 and -606.5% respectively, and underestimated in other scenarios by 69.9 and 63.2% respectively, indicating that the ACH was probably overestimated in the case of KD1999 using air recirculation which inadequately increased the sensitivity of in-cabin air to outdoor fluctuations and yielded concentration rises and drops which are faster than reality. For scenarios involving W1/2O, the range of variation of the % difference between simulated maximum and minimum concentrations were smaller for the CA2011 (-16.7 to 19.9% for maximum and -12.6 to 39.5 for minimum) compared to the KD1999 (-377.5 to 11.4% for maximum and -42.6 to 63.6% for minimum) and HC1997 (-232.5 to 52.1% for maximum and -97.7 to 33.2% for minimum). In fact, the vehicle air changer rate is high when using W1/2O (120 to 240 h^{-1}) which promptly brings in-cabin CO concentration to the levels encountered in the air coming from outside, with the latter being overestimated in older cars due to out-vehicle sampling near the exhaust pipe.

Regarding $PM_{2.5}$ simulations, the maximum concentrations when using AC Rec were generally underestimated suggesting that $PM_{2.5}$ cleaning efficiency through the AC filter could be lower than the assumed value (30% for pleated filter). Other possible reasons include the underestimation of cabin ACH value, or the generation of $PM_{2.5}$ by the cabin passengers through movement and resuspension which could not be accounted for in the mathematical modeling. In contrast, the minimum concentration was generally overestimated ascertaining that the AC filtration efficiency was not overestimated particularly that the filter was within the recirculation loop for all test

cars. It is likely that the overestimation of minimum concentrations is due to ACH underestimation. Similarly, maximum and minimum concentrations were respectively underestimated and overestimated when using the AC FA mode, which is consistent with the findings from CO concentration simulations, indicating that the ACH of the AC FA mode was equally underestimated. For scenarios involving W1/2O, the simulated maximum $PM_{2.5}$ concentration was lower than the actual one for all scenarios pertaining to the KD1999 and the HC1997, indicating either the underestimation of ACH, or the existence of intermittent in-cabin emission sources that could not be accounted for in the mathematical modeling such as resuspension of settled dust. As for the minimum $PM_{2.5}$ concentration, the simulated concentrations were generally higher than the actual ones ascertaining that the ACH was generally underestimated. It is important to note finally that the respective under- and over- estimation of the extrema could be related to the underestimation of $PM_{2.5}$ penetration factor into (and out) of a vehicle cabin.

On another hand, the CO and $PM_{2.5}$ self pollution rates used to match average measured and simulated concentrations for all scenarios are illustrated in Figures 4.9 and 4.10, respectively, which also indicate the general vehicle speed during each scenario. The figures show that self pollution rates were highly variable across cars and vehicle speeds. Regarding CO self pollution, self pollution rates could not be accurately estimated in the cabins of old cars (KD1999 and HC1997) in view of the exceptionally high out-vehicle pollutant concentrations which yielded simulated in-cabin concentrations higher than measured concentrations preventing the possibility of fitting of a self pollution rate. As for the CA2011, the self pollution rates were highest when AC FA was used (1625-5175 mg/h), followed by W1/2O (250-1100 mg/h) and by AC Rec (33-55 mg/h).

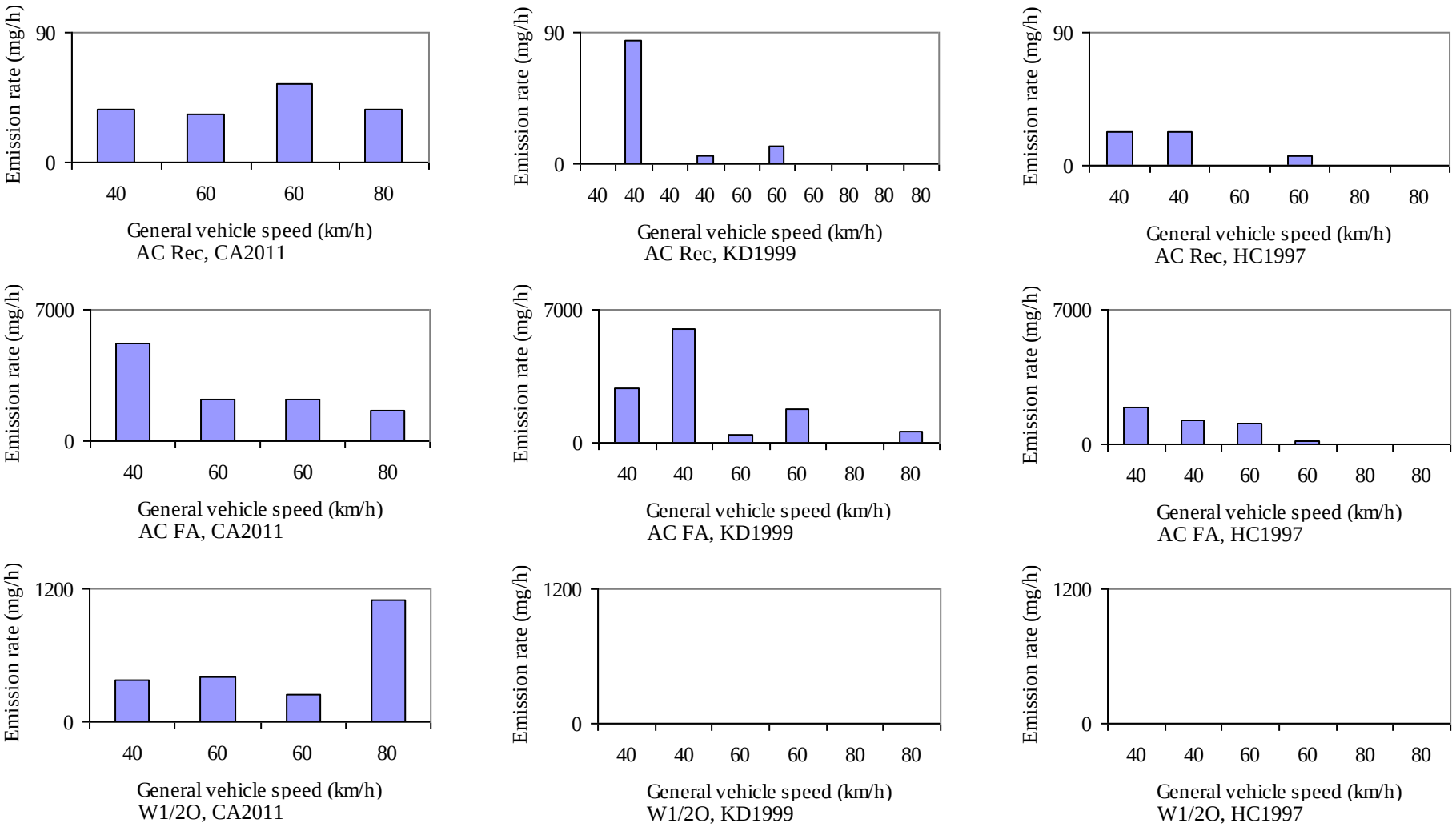


Fig. 4.9. CO self pollution rates

(*W1/2O: one window half opened; AC FA: air conditioning on fresh air intake;AC Rec: air conditioning on recirculation*)

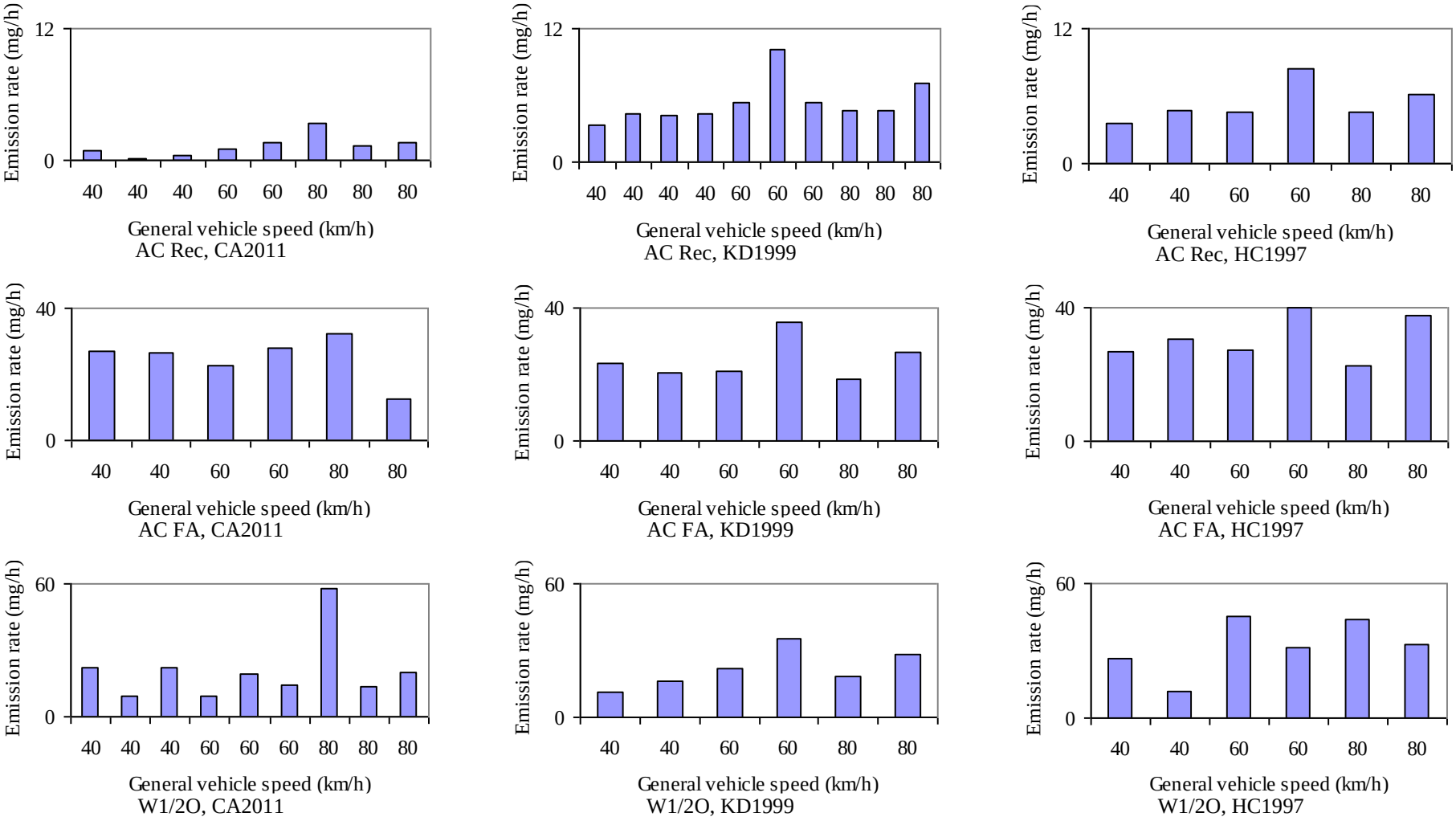


Fig. 4.10. $PM_{2.5}$ self pollution rates

(*W1/2O: one window half opened; AC FA: air conditioning on fresh air intake;AC Rec: air conditioning on recirculation*)

As for $PM_{2.5}$ self pollution, which was less affected by out-vehicle sampling location as all test cars ran on gasoline, self pollution rates were fitted for all scenarios and were lower in the cabin of the CA2011 compared to the cabin of the older cars. As such, for AC Rec, the self pollution rates were in the range 0.2 to 3.375 mg/h for CA2011 compared to 3.35-10.05 and 3.6-8.4 mg/h for KD1999 and HC1997, respectively. Similarly, for AC FA, the range was 12.7 to 32.3 mg/h for CA2011 compared to 18.6 to 35.5 mg/h and 22.6 to 39.875 mg/h for KD1999 and HC1997. Similar rates were obtained with W1/2O and ranged from 9.5 to 57.525 mg/h for CA2011, 11.6 to 35.5 mg/h for KD1999 and 11.75 to 45.5 mg/h for HC1997.

4.4.1 Sensitivity analysis

A sensitivity analysis was conducted to test for the influence of uncertainties in input air change rate, filtration efficiency, penetration factor and decay rate on model outputs particularly with respect to estimated self pollution rates (Table 4.12). For this purpose, scenarios pertaining to the self polluting car (CA2011) and covering a variety of test conditions were used (scenarios 3.2 and 4.2 for a vehicle speed of 60 km/hour using recirculation mode; scenarios 7.1 and 8.2 for a vehicle speed of 40 km/hour using fresh air intake; scenarios 17.1 and 18.3 for a vehicle speed of 80 km/hour). Findings for $PM_{2.5}$ when using AC Rec indicate that the used values for all four input parameters yielded conservative estimates of self pollution rates. Regarding $PM_{2.5}$ when using AC FA, paramters either had no influence or yielded a conservative estimate except for penetration factor which if increased from 0.47 to 1 would slightly decrease (by 17.7%) the estimated self pollution rate. Finally, in the case of $PM_{2.5}$ with W1/2O, and CO with

all ventilation modes, all input parameters were either conservative or had no influence on the estimated self pollution rates.

Table 4.12. Parametric sensitivity analysis

	Pollutant	*PM2.5*								*CO*				
Ventilation mode	*Varied input*	*ACH (h^{-1})*	*FE (%)*	*PF*	*DR (m/h)*	*Simulated PM_{in} ($\mu g/m^3$)* [a/]	*ζ_{PM}*	*Simulated ER(PM) ($\mu g/m^3$)*	*$\zeta_{ER(PM)}$*	*ACH (h^{-1})*	*Simulated CO_{in} (ppm)*	*ζ_{CO}*	*Simulated ER(CO) (ppm)*	*$\zeta_{ER(CO)}$*
Rec	ACH	2.14	30	0.47	1.56	4.2		1.625		2.14	3.7		55	
		1.07	30	0.47	1.56	3		1.66		1.07	3.3		54	
		4.28	30	0.47	1.56	6.4	0.524	1.55	-0.046	4.28	4.2	0.135	56	0.018
	FE	2.14	30	0.47	1.56	4.2		1.625						
		2.14	10	0.47	1.56	10.3		0.55						
		2.14	50	0.47	1.56	2.4	-0.643	2.7	0.992					
	PF	2.14	30	0.47	1.56	4.2		1.625						
		2.14	30	0.24	1.56	2.9		1.725						
		2.14	30	1	1.56	7.2	0.633	1.385	-0.131					
	DR	2.14	30	0.47	1.56	4.2		1.625						
		2.14	30	0.47	1.32	4.3		1.61						
		2.14	30	0.47	1.8	4.2	0	1.64	0.06					
FA	ACH	62.4	30	0.47	1.56	12.7		26.35		62.4	10.4		5175	
		31.2	30	0.47	1.56	8.2		22.55		31.2	2.8		4650	
		124.7	30	0.47	1.56	17.6	0.386	33.8	0.283	124.7	6.4	-0.385	6000	0.157
	FE	62.4	30	0.47	1.56	12.7		26.35						
		62.4	10	0.47	1.56	12.7		26.35						
		62.4	50	0.47	1.56	12.7	0	26.35	0					
	PF	62.4	30	0.47	1.56	12.7		26.35						
		62.4	30	0.24	1.56	6.5		28.6						
		62.4	30	1	1.56	26.9	0.992	21.1	-0.177					
	DR	62.4	30	0.47	1.56	12.7		26.35						
		62.4	30	0.47	1.32	12.7		26.3						
		62.4	30	0.47	1.8	12.6	-0.051	26.4	0.012					
W1/2O	ACH	240		0.47	1.56	28.5		20.1		240	5		1100	
		120		0.47	1.56	28.0		10.3		120	5		550	
		480		0.47	1.56	28.7	0.007	40	0.990	480	5	0	2200	1
	PF	240		0.47	1.56	28.5		20.1						
		240		0.24	1.56	14.6		28.75						
		240		1	1.56	60.7	1.002	0.3	-0.874					
	DR	240		0.47	1.56	28.5		20.1						
		240		0.47	1.32	28.5		20.1						
		240		0.47	1.8	28.5	0	20.1	0					

[a/] Assuming that there is no in-cabin emission rate

4.5 Regression modeling of concentrations and self pollution rates

4.5.1 Influence of categorical variables

Findings regarding the influence of categorical variables on cabin exposure to CO and $PM_{2.5}$ are depicted in Tables 4.13 and 4.14, respectively. The presence of rainfall on previous day (X_5) significantly affected pollutant concentrations with lower values following a rainy day. While the latter is expected for $PM_{2.5}$ in view of ambient particle settlement on rain droplets, a similar result was observed for CO probably due to a decrease in the number of trips conducted on the day before particularly during non peak times which lowers ambient CO concentrations. Regarding the time of the day (X_{14}), pollutant concentrations were higher for pm sampling hours compared to am sampling hours due to higher traffic emissions' buildup times in the former case; however the influence was significant for CO only, indicating that $PM_{2.5}$ concentrations were less affected by traffic emissions throughout a day. The latter is likely to be due to the banning of diesel fueled passenger cars in the study area. Local and general peak times (X_{16} and X_{17}, respectively) only affected CO concentrations ascertaining that in-vehicle $PM_{2.5}$ concentrations are less influenced by traffic volume than CO concentrations. The relationship was stronger for local peak times (p-value = 0.005) compared to general peak times (p-value = 0.043) indicating the importance of local street level conditions in the determination of in-vehicle exposure. As for ventilation mode (X_{18}), a significant difference between pollutant concentrations was encountered between 'one window ½ opened' and 'AC on recirculation' and between 'AC on fresh air intake' and 'AC on recirculation' due to distinct air exchange rate conditions. However, no significant difference was observed between 'one window ½ opened' and 'AC on fresh air intake' due to the intense air exchange conditions for both ventilation

settings. The test car had a significant influence on CO and $PM_{2.5}$ exposure with distinct mean in-vehicle pollutant concentrations with different cars. The Toyota Celica 2001 and Kia Cerato 2011 recorded exceptionally low CO and $PM_{2.5}$ concentrations, respectively. The presence of self pollution did not have a significant influence on in-vehicle concentrations possibly due to its inclusion as a categorical variable rather than an actual rate which fails to represent the actual extent of self pollution.

Table 4.13. Influence of categorical variables on cabin exposure to CO

Predictor	*Predictor value*	*Sample size*	*Mean*[a/]	*Equal variances*	*t*	*p-value*[b/]
Presence of rainfall on previous day	Yes	31	6.8	No	4.441	0.000
	No	83	9.6			
Time of day	am	69	7.8	Yes	-2.847	0.003
	pm	50	9.8			
Time corresponds to a local peak traffic time	Peak	37	10.1	Yes	-2.664	0.005
	Non Peak	82	8.1			
Time corresponds to a general peak traffic time	Peak	30	9.7	Yes	-1.734	0.043
	Non Peak	89	8.3			
Ventilation mode	W1/2O (1)	39	10.3	No	-	1&3: 0.001
	AC FA (2)	37	8.9			
	AC Rec (3)	43	7.1			
Car	KC 2011 (1)	18	8.6	No	-	1&4: 0.05 3&4: 0.001 3&6: 0.007
	CA 2011 (2)	24	8.8			
	TY 2010 (3)	19	11.8			
	TC 2001 (4)	18	6.2			
	KD 1999 (5)	22	9.3			
	HC 1997 (6)	18	7.2			
Presence of self pollution	Yes	64	8.5	Yes	-0.580	0.282
	No	55	8.9			
Roadway	Res/Comm	29	10.3	Yes	-3.624	0.000
	Highway	63	7.4			

a/ mean of the dependent variable
b/ for one way anova, only p-values <0.05 are listed

Table 4.14. Influence of categorical variables on cabin exposure to $PM_{2.5}$ ($\mu g/m^3$)

Predictor	*Predictor value*	Sample size	Mean[a/]	Equal variances		*p-value*[b/]
Presence of rainfall on previous day	Yes	31	54.7	No	3.305	0.000
	No	82	78.3			
Time of day	am	69	64.1	No	-1.501	0.069
	pm	49	76.2			
Time corresponds to a local peak traffic time	Peak	37	69.6	Yes	-0.086	0.466
	Non Peak	81	68.9			
Time corresponds to a general peak traffic time	Peak	29	70.0	Yes	-0.127	0.450
	Non Peak	89	68.9			
Ventilation mode	W1/2O (1)	39	92.8	Yes	-	1&3: 0.000 2&3: 0.000
	AC FA (2)	36	77.9			
	AC Rec (3)	43	40.3			
Car	KC 2011 (1)	18	32.5	No	-	1&3: 0.001 1&5: 0.000 1&6: 0.000 2&6: 0.043
	CA 2011 (2)	24	56.4			
	TY 2010 (3)	18	102.7			
	TC 2001 (4)	18	62.2			
	KD 1999 (5)	22	76.1			
	HC 1997 (6)	18	87.5			
Presence of self pollution	Yes	64	71.9	No	0.780	0.219
	No	54	65.8			
Roadway	Res/Comm	28	70.6	Yes	0.126	0.450
	Highway	63	71.7			

a/ mean of the dependent variable
b/ for one way anova, only p-values <0.05 are listed

4.5.2 Influence of continuous variables

Findings regarding the pairwise correlations between cabin exposure to CO and $PM_{2.5}$ and the various predictor variables and the intercorrelations between all continuous parameters including are respectively outlined in Table 4.15 and in Figure 4.11. The table only shows models with p-value > 0.05 for each indicator. Variables are sorted in the table from most to least influential. No correlation was found between X_7 (Log_{10} of ambient pressure) and X_{13} (Log_{10} of wind direction) and any of the two air pollution indicators. Significant correlations were observed between in-vehicle pollutant concentrations and out-vehicle and initial pollutant concentrations and were remarkably

high in the case of $PM_{2.5}$ whereby initial and out-vehicle $PM_{2.5}$ respectively explained 54.9 and 52.4% of in-vehicle concentrations compared to 37.4 and 20.7% in the case of CO. Statistically significant weak correlations were observed between in-vehicle and out-vehicle concentrations of different pollutants (multiple $R^2 = 0.112$ and 0.136) indicating that some of the variability in CO and $PM_{2.5}$ is attributable to a same emission source. In terms of meteorological parameters, statistically significant correlations were observed between Julian day and CO and $PM_{2.5}$ concentrations (multiple $R^2 = 0.149$ and 0.092), ambient temperature and in-vehicle $PM_{2.5}$ concentration (multiple $R^2 = 0.105$), ambient relative humidity and in-vehicle CO concentration (multiple $R^2 = 0.108$), and wind speed and in-vehicle CO concentration (multiple $R^2 = 0.127$), indicating that pollutant concentrations are affected by seasonality. Exhaust temperature (multiple $R^2 = 0.119$) and flow rate (multiple $R^2 = 0.038$) of the test cars had a statistically significant influence on in-vehicle CO concentrations indicating that some of the CO accumulated inside the test cars potentially came from their own exhaust fumes. Another possible reason is the fact that exhaust temperature and flow rate are surrogate measures of vehicle speed which is significantly related to in-vehicle CO concentrations (multiple $R^2 = 0.098$). Finally, the fraction of trip with stopped car had a statistically significant influence on in-vehicle CO concentration explaining 10.4% of CO variability.

On another hand, the color coded matrix indicated moderate to high correlations ($|r| > 0.5$) between Julian day and each of out-vehicle pressure, relative humidity and temperature with positive correlation in the case of pressure and negative correlation for the other two parameters which is due to the seasonality of meteorological conditions in the study area. The correlations were also moderate between in-vehicle CO concentration and each of vehicle speed and fraction of trip with stopped vehicle with negative correlation in

the former case and positive in the latter case. In fact, in-vehicle CO concentration decreased with increasing vehicle speed (and decreasing stopping intervals) which suggests the possibility of lower background CO concentrations on highways compared to commercial / residential areas. Dissimilarly, correlations with vehicle speed were low for $PM_{2.5}$ suggesting insignificant influence of roadway type on background $PM_{2.5}$ concentrations. Moderate correlations between out-vehicle CO concentration and each of in- and out-vehicle $PM_{2.5}$ concentration indicate that some of the variability in CO and $PM_{2.5}$ is attributable to a same emission source which is road traffic emissions. This is further indicated by the sample time series plots of CO against $PM_{2.5}$ concentration variations inside versus outside of a car cabin provided in Fig. 4.12 which show concomitant fluctuations of both indicators in a same direction and during the same minute at both in- and out- vehicle locations. Exhaust flow rate, exhaust temperature and vehicle speed are positively correlated since high speed commutes are evidently associated with higher fuel combustion rates which translate into high exhaust temperature and flow rate. For the same reason, fraction of trip with stopped vehicle which decreases with increasing vehicle speed is negatively correlated with exhaust temperature and flow rate. Initial and out-vehicle $PM_{2.5}$ concentration increased with increasing out-vehicle ambient pressures due to the absence of rainfall during high atmospheric pressure conditions. In- and out-vehicle temperatures increased with decreasing humidity ratio which indicates that out-vehicle humidity level was higher during warm season (summer, spring) commutes. Low to moderate ($0.3< \left| r \right| <0.7$) positive correlations were encountered between average in-vehicle and initial pollutant concentrations due to the influence of starting pollution levels on in-vehicle pollutant concentrations.

Low correlations ($0.3< \left| r \right| <0.5$) were encountered between all pollutant concentrations and Julian Day indicating that pollutant concentrations exhibited some

degree of seasonality except for in-vehicle CO concentration which seems to be affected by other different factors, possibly minute to minute emissions inside or adjacent to the car. Higher out-vehicle humidity levels and in-vehicle temperatures were associated with higher wind speed levels ascertaining that higher ambient humidity levels were encountered during the warm season. In fact, the summer / spring season in the study area is characterized by higher wind speeds and temperatures than the winter season. Similar to out-vehicle CO concentration, in-vehicle CO was positively correlated with in- and out-vehicle $PM_{2.5}$ concentrations due to a common emission source; the correlation is obviously higher for out-vehicle compared to in-vehicle concentration as only a proportion of the out-vehicle pollution ends up inside the vehicle depending on the test conditions. Higher out-vehicle and initial CO concentrations, and out-vehicle and subsequently in-vehicle $PM_{2.5}$ levels were encountered for warmer out-vehicle temperatures indicating that higher CO and $PM_{2.5}$ pollution levels were encountered during the warm season. An indirect low positive relationship is also observed between out-vehicle temperature (and temperature ratio) and exhaust flow rate due to the direct relationship between exhaust temperature and flow rate and the natural positive correlation between ambient temperatures and exhaust temperature. In-vehicle pressure (and pressure ratio) increased with increasing stopping intervals and decreasing vehicle speeds indicating pressure build up inside the cabin in the latter circumstances. Lower in- and out- vehicle pollutant concentrations were measured for high wind speeds indicating that the latter exerted a dilution effect on both out- and subsequently in-vehicle CO levels. Also, in-vehicle CO concentrations decreased with increasing exhaust temperature and flow rate which is the case during highway commutes which are characterized by lower out-vehicle CO concentrations. The latter is equally shown by the low negative correlation between out-vehicle CO concentration and vehicle speed. Humidity and temperature levels were negatively correlated inside the vehicle indicating

that the ventilation modes resulting in higher in-cabin temperature levels (window half opened and AC on fresh air intake) were associated with lower humidity levels than the ventilation mode involving recirculation which fostered increased humidity levels. Another interesting low and negative relationship was encountered between out-vehicle pressure and exhaust flow rate suggesting that lower out-vehicle pressure facilitated exhaust flow to the outside of the tailpipe.

Table 4.15. Univariate models of log10CO and SqRt $PM_{2.5}$

Predictor	*Sample size*	*Equation*	*Multiple R^2*	*Adjusted R^2*	*p-value*
CO					
Log_{10} (Initial COin)	119	$Y=0.427X_3+0.555$	0.374	0.368	0.000
Log_{10} (COout)	104	$Y=0.398X_1+0.506$	0.207	0.200	0.000
Log_{10} (Exhaust temperature)[a/]	116	$Y=-2.342X_{21}^2+9.025X_{21}-7.711$; AIC=177.616	0.184	0.169	0.000
	116	$Y=-0.478X_{21}+1.884$; AIC=175.9	0.119	0.111	0.000
Julian Day	119	$Y= 0.801-0.010\sin(2\pi X_{15}/365)+0.187\cos(2\pi X_{15}/365)$	0.149	0.129	0.000
SqRt (PMout)	119	$Y=0.042X_2+0.546$	0.136	0.129	0.000
Log_{10} (Vehicle speed) [a/]	112	$Y=-0.333\ X_{23}^2+0.756X_{23}-0.561$; AIC=177.685	0.133	0.117	0.000
	112	$Y=-0.153X_{23}+1.127$; AIC= 175.741	0.098	0.090	0.001
Log_{10} (Wind speed)	118	$Y=-0.455X_{12}+1.097$	0.127	0.120	0.000
Log_{10} (Ambient relative humidity)	118	$Y=-0.689X_8+2.078$	0.108	0.101	0.000
SqRt (Fraction of trip with stopped car)	112	$Y=0.023X_{24}+0.821$	0.104	0.095	0.001
SqRt (Initial PMin)	118	$Y=0.469X_4+0.785$	0.061	0.052	0.007
Log_{10} (Exhaust flow rate)	113	$Y=-0.120X_{22}+1.252$	0.038	0.030	0.038
$PM_{2.5}$					
SqRt (Initial PMin)	118	$Z=21.018X_4+2.812$	0.549	0.546	0.000
SqRt (PMout)	118	$Z=1.220X_2-2.381$	0.524	0.519	0.000
Log_{10} (Ambient temperature)	117	$Z=-80.746X_6^2+222.402X_6-144.003$	0.156	0.141	0.000
	117	$Z=-6.309X_6+11.07$	0.105	0.097	0.000
Log_{10} (COout)	103	$Z=4.061X_1+4.103$	0.112	0.104	0.001
Julian Day	118	$Z=9.617-1.221\sin(2\pi X_{15}/365) - 2.257\cos(2\pi X_{15}/365)$	0.092	0.071	0.016

a/ for variables X_{21} amd X_{23}, quadratic models exhibited high R^2 values with significant model coefficients and were therefore listed in the table with their corresponding AIC values

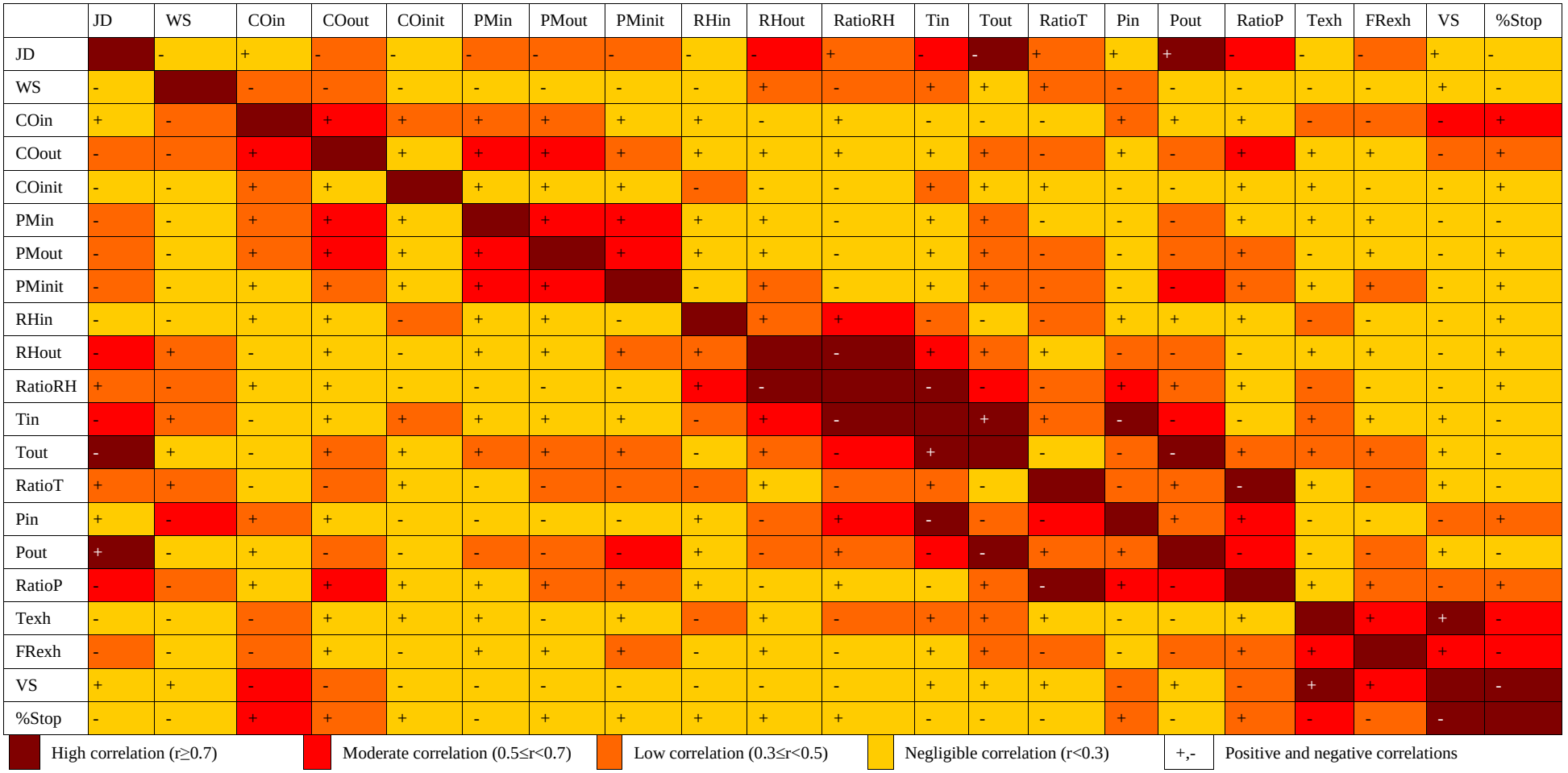


Fig. 4.11. Correlation matrix

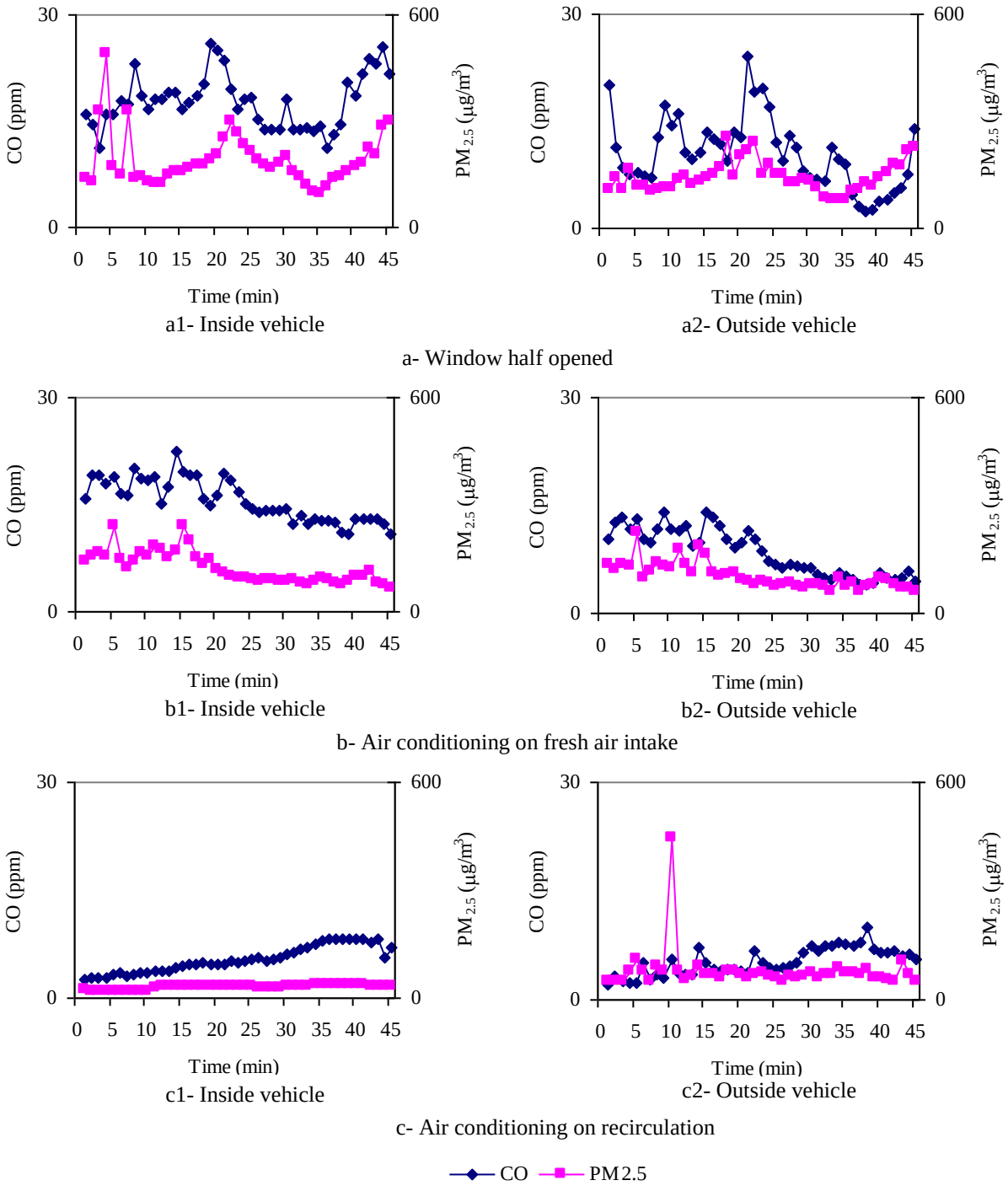


Fig. 4.12. Sample CO versus $PM_{2.5}$ time series measurements inside versus outside of the cabin of the Toyota Yaris 2010

4.5.3 Multivariate regression analysis of concentrations

Findings from multivariate analysis of cabin exposure are provided in Table 4.16 and 4.17 for models of in-cabin pollutant concentrations which do not take into account interaction with self pollution terms, and in Tables 4.18 and 4.19 for models considering such interaction. The provided models were selected based on the lowest AIC and were polished afterwards by excluding all coefficients with insignificant predictors (except for parameters included as factors if any of their categories exhibited a significant influence). All model intercepts are highly significant with p-value of less than 0.0001.

Table 4.16 shows that the best no interaction model of CO concentration could explain 72% of CO concentration variation (Multiple R-squared: 0.7733; Adjusted R-squared: 0.7229). The model indicates that for every 10 ppm increase in CO_{out} concentrations, the CO_{in} concentrations increased by 10 %. Moreover, when initial CO_{in} concentrations were 10 ppm higher, the in-vehicle CO concentrations were on average 6 % higher. These positive correlations indicate the strong relationship between CO accumulated inside the cabin and background levels and the out-vehicle concentrations. Increases in exhaust temperatures were found to result in higher in-vehicle CO concentrations. A 1 ^{o}C increase in Texh yielded a 0.5 % increase in in-vehicle CO concentration. This could be either due to 1) higher background CO levels and engine temperatures during warmer days or to 2) increased self-pollution levels inside a cabin when exhaust temperature is high. A 1 $\mu g/m^3$ increase in PMout was found to lead to a 2% increase in in-vehicle CO concentration. Variations in in-vehicle concentrations were found to be seasonal in nature. In-vehicle CO exposure was found to decrease from the beginning of January to reach a minimum by the end of March. Exposure increased from end of March until end of September, where it reaches its maximum before starting to decrease again between October and December. A rainfall event the previous day resulted in 13% drop in in-vehicle CO concentration.

Afternoon commutes on average were associated with 6% higher in-vehicle CO concentrations than before noon trips. Different cars exhibited different exposure levels, particularly for the two cars (TY2010) and (KD1999) which had on average lower in-vehicle CO concentration as compared to the rest. South-westerly and north-westerly winds tended to increase in-vehicle CO concentrations by 12% and 8% respectively as compared to north easterly winds. This variability is likely due to the concentration of traffic emissions on the urban coastline with north easterly winds flushing emissions away towards the sea and westerly winds trapping the pollution inland. Finally, in-vehicle concentrations were 10% lower on a highway compared to a commercial residential area.

Assuming constant levels of initial COin, COout, Texh and PMout, lowest in-vehicle CO concentration would be recorded end of March on a morning highway drive with north easterly winds and following a rainy day. In contrast, highest in-vehicle CO concentrations would be recorded while commuting in late September in a commercial/residential area during the afternoon of a day with south westerly winds and following a clear period with no rainfall.

Table 4.16. CO concentration (ppm), No interaction Model

Parameters	*Estimate*	*Std. Error*	*t value*	*Pr(>|t|)*	*Sig* [a/]
(Intercept)	0.771	0.196	3.929	0.000	***
Initial COin (ppm)	0.006	0.002	2.949	0.004	**
COout (ppm)	0.010	0.002	4.689	0.000	***
Texh (ºC)	0.005	0.002	2.008	0.048	*
SquareTexh	0.000	0.000	-2.085	0.041	*
PMout ($\mu g/m^3$)	0.002	0.001	3.640	0.001	***
as.factor(Presence.of.rainfall.on.previous.dayCoded)1	-0.139	0.047	-2.937	0.004	**
as.factor(TimeofDayCoded)1	0.064	0.025	2.568	0.012	*
as.factor(CarCoded)2	-0.002	0.078	-0.028	0.977	
as.factor(CarCoded)3	-0.573	0.257	-2.232	0.029	*
as.factor(CarCoded)4	0.143	0.128	1.118	0.267	
as.factor(CarCoded)5	-0.885	0.337	-2.627	0.011	*
as.factor(CarCoded)6	0.022	0.109	0.199	0.843	
sin(2 * pi * JulianDay/365)	-0.530	0.245	-2.158	0.034	*
as.factor(WDcoded2)SW	0.117	0.043	2.730	0.008	**
as.factor(WDcoded2)WN	0.076	0.031	2.476	0.016	*
as.factor(Roadway)1	-0.107	0.037	-2.869	0.005	**
a/ Significance: 0.000:'***'; 0.001: '**'; 0.01: '*'; 0.05: '-'; 0.1: ' '					

*Note: Sample size: 92; Residual standard error: 0.09505 on 72 degrees of freedom; Multiple R-squared: 0.7733; Adjusted R-squared: 0.7229; F-statistic: 15.35 on 16 and 72 DF, p-value: < 2.2e-16; AIC: -149.1963

On another hand, the best model of $PM_{2.5}$ concentration included initial and out-vehicle $PM_{2.5}$ concentrations, test car, Julian day and wind direction in addition to other parameters which were not influential in the case of CO, namely wind speed, fraction of trip with stopped vehicle, commuting during a peak hour, and ventilation mode. The model was able to predict up to 90% of concentration variation (Multiple R-squared: 0.9140; Adjusted R-squared: 0.8964). Given the model structure, the linear relationship is established between the predictors and the square root of $PM_{2.5}$. As such, the rate of change of $PM_{2.5}$ is not constant across a unit change in the predictors.

The rate of change in the in-vehicle $PM_{2.5}$ concentration per 1 ppm increase in the initial $PM_{2.5}$ concentration or in the PM_{out} concentrations increased by 0.00013 and 0.008/ppm respectively. Traveling under conditions where south-westerly or northwesterly winds were dominant increased the measured $PM_{2.5}$ concentrations by 25% and 38%, respectively, compared to north easterly winds. Unlike the case for CO, in-vehicle $PM_{2.5}$ concentrations reached their maximum and minimum levels by the end of March and September, respectively. Car type also proved to be a significant factor affecting measured in-vehicle PM2.5 concentrations. On average, the KD1999 and the TY2010 had significantly higher PM2.5 concentrations as compared to the KC2011, while the CA2011, TC2001, and the HC1997 had lower in-vehicle concentrations. These differences are possibly due to distinct $PM_{2.5}$ penetration factors across car shells at a time when CO penetration is constant and equal to 1. On another hand, the increase in ambient wind speed increased in-vehicle $PM_{2.5}$ concentration. The rate at which the increase occurred increased by 0.53 per 1 m/sec. The increase is possibly due to increased particle penetration across cracks. Moreover, as the fraction of trip with stopped vehicle increased the in-vehicle $PM_{2.5}$ concentrations decreased. This reflects the fact that in-vehicle $PM_{2.5}$ levels were found to be slightly higher on highways as compared to residential/commercial areas, where stopping was more frequent. The occurrence of a general peak hour increased in-vehicle concentration by 33% as compared to non-peak hours. Ventilation mode involving recirculation decreased $PM_{2.5}$ exposure inside a car by 63% as compared to the cars with windows half open. When the AC was on fresh air, the concentrations dropped by 11% only. This is largely a result of having the filters of all cars located within the recirculation loop

Assuming constant initial PMin, PMout, wind speed and fraction of trip with stopped vehicle, lowest in-vehicle $PM_{2.5}$ concentration would be recorded end of September during a non-peak hour of a day with north easterly winds all while the ventilation mode is set to air conditioning on with recirculation. In contrast, highest in-vehicle $PM_{2.5}$ concentration would be recorded end of March during a peak hour of a day with north westerly winds all while the ventilation mode is set to window half opened.

Table 4.17. $PM_{2.5}$ concentration ($\mu g/m^3$), No interaction Model

Parameter	*Estimate*	*Std. Error*	*t value*	*Pr(>|t|)*	*Sig* [a/]
(Intercept)	-4.330	1.252	-3.457	0.001	***
Initial PMin ($\mu g/m^3$)	0.008	0.002	3.604	0.001	***
PMout ($\mu g/m^3$)	0.063	0.005	13.145	0.000	***
AirportWind Speed (m/s)	0.517	0.136	3.798	0.000	***
Fraction Stopped (%)	-0.020	0.005	-4.381	0.000	***
as.factor(General.Peak.vs.non.peakCoded)1	0.576	0.226	2.546	0.013	*
as.factor(VMCoded)2	-0.275	0.213	-1.291	0.201	
as.factor(VMCoded)3	-2.782	0.219	-12.712	0.000	***
as.factor(CarCoded)2	-1.858	0.599	-3.100	0.003	**
as.factor(CarCoded)3	11.062	1.790	6.179	0.000	***
as.factor(CarCoded)4	-3.393	0.957	-3.547	0.001	***
as.factor(CarCoded)5	14.648	2.357	6.214	0.000	***
as.factor(CarCoded)6	-2.587	0.920	-2.811	0.006	**
sin(2 * pi * JulianDay/365)	9.792	1.806	5.423	0.000	***
as.factor(WDcoded2)SW	0.456	0.329	1.387	0.170	
as.factor(WDcoded2)WN	0.640	0.233	2.745	0.008	**
a/ Significance: 0.000:'***'; 0.001: '**'; 0.01: '*'; 0.05: '-'; 0.1: ' '					

*Note: Sample size: 118; Residual standard error: 0.7609 on 73 degrees of freedom; Multiple R-squared: 0.914; Adjusted R-squared: 0.8964; F-statistic: 51.75 on 15 and 73 DF; p-value: < 2.2e-16; AIC: 220.2905

Including interaction terms between self pollution and all continuous variables and polishing the best model by eliminating parameters with insignificant coefficients

decreased the predictive power of the in-vehicle CO concentration model from 72% to 64% (Multiple R-squared: 0.6696; Adjusted R-squared: 0.6366). The model is simpler however than the no interaction model since it includes 6 instead of 11 explanatory variables namely initial COin, PMout, presence of rainfall on previous day, wind direction, roadway and an interaction term between self pollution and the square of exhaust temperature. Holding all other parameters constant, and similar to the case with no interaction, a 1-unit increase in each of initial COin and PMout concentrations increased in-vehicle CO concentration by 1 ppm whereas the presence of rainfall on previous day decreased in-vehicle CO concentration by 0.8 ppm. North easterly winds were accompanied by 1.3 and 1.1 ppm lower in-vehicle concentration levels compared to south westerly and north westerly winds. Also, concentrations on highways were 0.8 ppm lower than those in residential commercial areas whereas the presence of self pollution yielded on average at least 1 ppm increase in in-vehicle CO concentration for each 1 $(^oC)^2$ increase in the square of exhaust temperature ascertaining the influence of self pollution on the latter parameter.

Table 4.18. CO concentration (ppm), Interaction Model

Parameter	*Estimate*	*Std. Error*	*t value*	*Pr(>|t|)*	*Sig* [a/]
(Intercept)	0.656	0.065	10.076	0.000	***
Initial COin (ppm)	0.010	0.002	5.138	0.000	***
PMout ($\mu g/m^3$)	0.003	0.001	5.708	0.000	***
as.factor(Presence.of.rainfall.on.previous.dayCoded)1	-0.116	0.030	-3.881	0.000	***
as.factor(WDcoded2)SW	0.100	0.040	2.510	0.014	*
as.factor(WDcoded2)WN	0.046	0.028	1.604	0.113	
as.factor(Roadway)1	-0.085	0.035	-2.462	0.016	*
self0:SquareTexh ($(^oC)^2$)	0.000	0.000	0.906	0.367	
self1:SquareTexh ($(^oC)^2$)	0.000	0.000	-2.507	0.014	*
a/ Significance: 0.000:'***'; 0.001: '**'; 0.01: '*'; 0.05: '-'; 0.1: ' '					

*Note: Sample size: 92; Residual standard error: 0.1089 on 80 degrees of freedom; Multiple R-squared: 0.6696, Adjusted R-squared: 0.6366; F-statistic: 20.27 on 8 and 80 DF; p-value: < 2.2e-16; AIC:-131.6694

The consideration of interaction with self pollution in the $PM_{2.5}$ concentration model did not significantly change the model's predictive power (Multiple R-squared: 0.9203; Adjusted R-squared: 0.9039). However, the influence of Julian day became significant through its cosine rather than sine term suggesting a peak in-vehicle $PM_{2.5}$ concentration by the end of June and a minimum concentration by the end of December. The latter finding is consistent with the inferences of the parameter intercorrelation matrix (Fig. 4.11) which indicated high $PM_{2.5}$ concentration inside and outside the vehicle at times of high out-vehicle temperatures. Also, self pollution was shown to affect the relationship between in-vehicle $PM_{2.5}$ concentration and each of wind speed and Julian day through decreased concentration levels at higher wind speeds for self polluting cars which is likely due to the increased air change rate and associated venting out of in-vehicle pollution. The existence of self pollution equally interfered with the seasonality of in-vehicle $PM_{2.5}$ concentration by shifting the direction of the concentration variation trend inside self polluting cars and causing a peak and a minimum by the end of December and June, respectively. The latter finding seems to be random and has no underlying physical explanation.

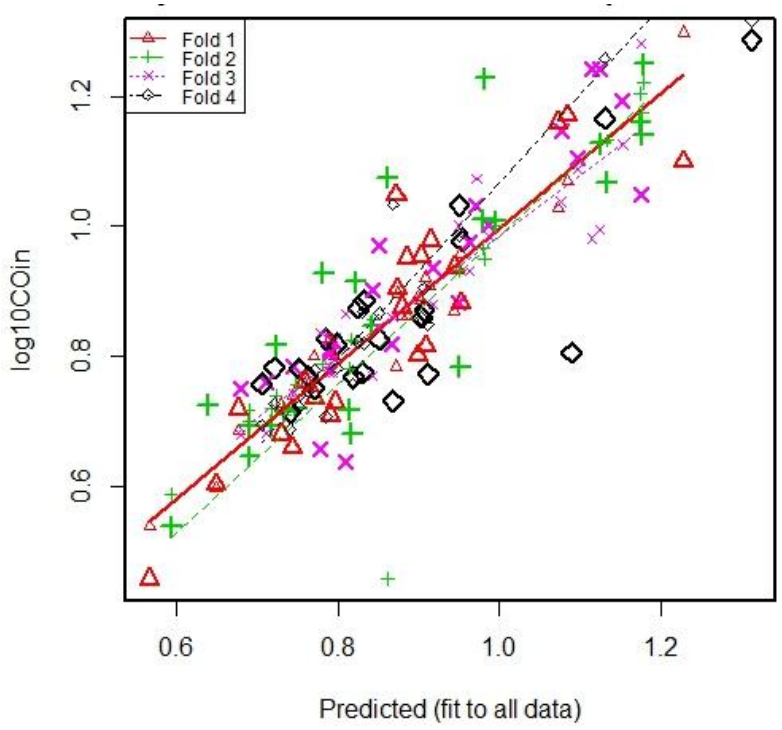
Table 4.19. $PM_{2.5}$ concentration ($\mu g/m^3$), Interaction Model

Parameter	*Estimate*	*Std. Error*	*t value*	*Pr(>|t|)*	*Sig* [a/]
(Intercept)	38.237	11.063	3.456	0.001	***
Initial PMin ($\mu g/m^3$)	0.006	0.002	2.555	0.013	*
PMout ($\mu g/m^3$)	0.057	0.005	11.820	< 2e-16	***
AirportWind Speed (m/s)	1.112	0.239	4.659	0.000	***
Fraction Stopped (%)	-0.019	0.004	-4.338	0.000	***
as.factor(General.Peak.vs.non.peakCoded)1	0.708	0.207	3.428	0.001	**
as.factor(VMCoded)2	-0.224	0.205	-1.094	0.278	
as.factor(VMCoded)3	-2.589	0.219	-11.795	< 2e-16	***
as.factor(CarCoded)2	-41.756	10.903	-3.830	0.000	***
as.factor(CarCoded)3	3.628	0.857	4.235	0.000	***
as.factor(CarCoded)4	-38.747	12.050	-3.216	0.002	**
as.factor(CarCoded)5	-40.659	10.873	-3.739	0.000	***
as.factor(CarCoded)6	-35.401	10.938	-3.236	0.002	**
cos(2 * pi * JulianDay/365)	-45.198	13.622	-3.318	0.001	**
Airport Wind Speed (m/s):self1	-0.733	0.314	-2.333	0.022	*
cos(2 * pi * JulianDay/365):self1	55.468	13.481	4.115	0.000	***
a/ Significance: 0.000:'***'; 0.001: '**'; 0.01: '*'; 0.05: '-'; 0.1: ' '					

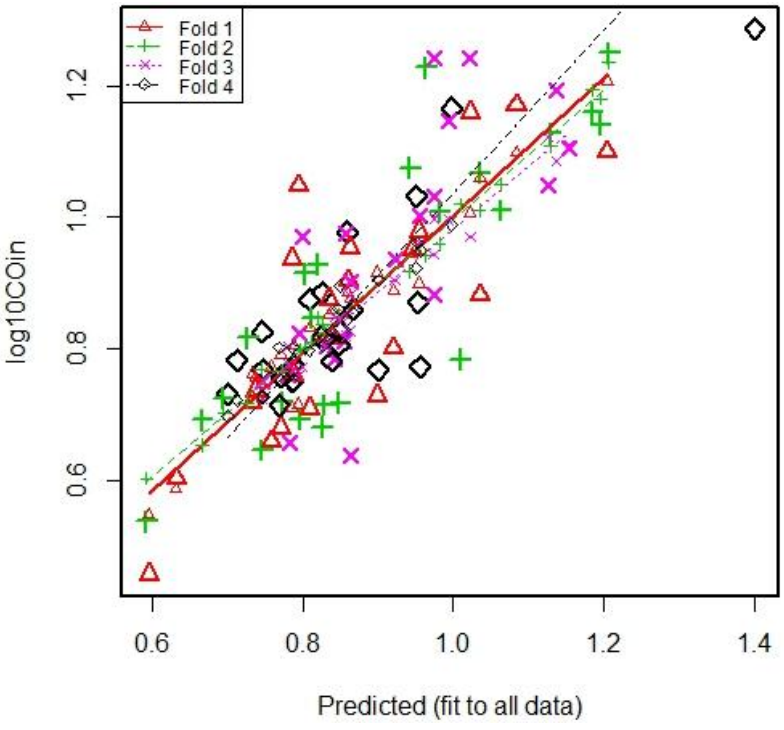
*Note: Sample size: 118; Residual standard error: 0.7326 on 73 degrees of freedom; Multiple R-squared: 0.9203, Adjusted R-squared: 0.9039; F-statistic: 56.21 on 15 and 73 DF; p-value: < 2.2e-16; AIC: 213.5419

4.5.5 Cross validation of multivariate regression models

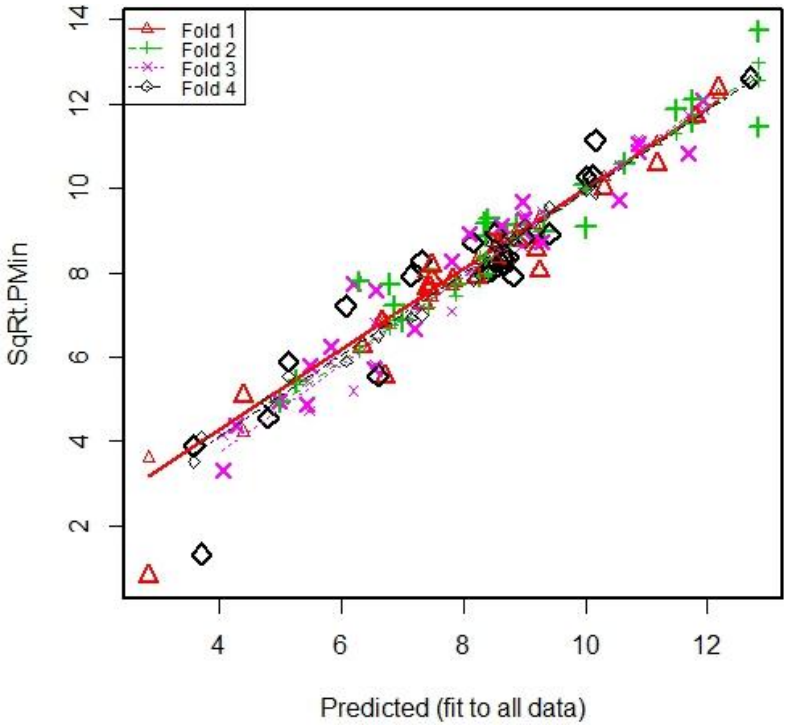
Findings from the four-fold cross validation exercise are depicted in Fig. 4.13.



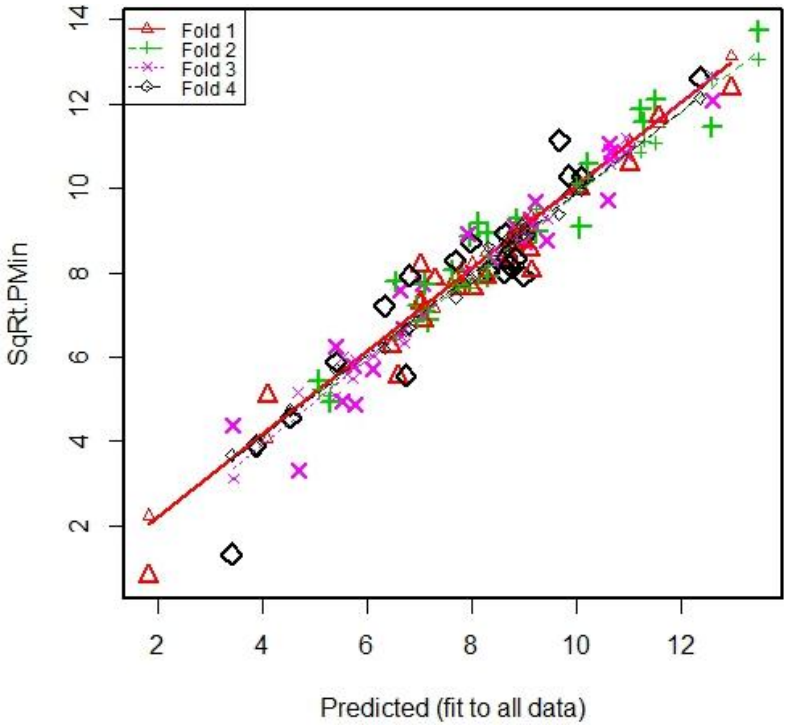
a- CO model, no interaction



b- CO model, with interaction



c- PM2.5 model, no interaction



d- PM2.5 model, with interaction

Fig. 4.13. Cross validation of best multivariate regression models

4.5.5 Multivariate regression analysis of IO ratios

The use of IO ratios instead of absolute concentration values as dependent variables with exclusion of in- and out-vehicle concentration terms from explanatory variables was tested; the resulting models are provided in Tables 4.20 and 4.21 for no interaction models, and in Tables 4.22 and 4.23 for interaction models. Compared to models of absolute values, the best **no interaction** IO model had better predictive power in the case of CO (80% for IO ratio compared to 72% for absolute in-vehicle concentration) and lower predictive power in the case of $PM_{2.5}$ (79% for IO ratio compared to 90% for absolute in-vehicle concentration). Similarly, the best **interaction** IO model had better predictive power in the case of CO (88% for IO ratio compared to 64% for absolute in-vehicle concentration) and lower predictive power in the case of $PM_{2.5}$ (78% for IO ratio compared to 90% for absolute in-vehicle concentration). Hence, it can be concluded that the studied parameters contribute better to the understanding of the transport of CO into a vehicle cabin rather than that of $PM_{2.5}$. Also, it can be noted that the inclusion of interaction with self pollution significantly improved model's predictive power in the case of CO whereas it had a negligible influence in the case of $PM_{2.5}$ which indicates that $PM_{2.5}$ self pollution is governed by parameters other than those measured in the current work.

Table 4.20. No interaction model of IO ratio of CO concentration (ppm)

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*	*Sig* [a/]
(Intercept)	3.490	0.512	6.811	0.000	***
as.factor(Presence.of.rainfall.on.previous.dayCoded)1	-0.226	0.071	-3.170	0.002	**
as.factor(TimeofDayCoded)1	0.185	0.042	4.379	0.000	***
as.factor(General.Peak.vs.non.peakCoded)1	-0.109	0.052	-2.080	0.041	*
as.factor(CarCoded)2	0.656	0.137	4.777	0.000	***
as.factor(CarCoded)3	-2.115	0.469	-4.513	0.000	***
as.factor(CarCoded)4	1.433	0.279	5.143	0.000	***
as.factor(CarCoded)5	-3.212	0.538	-5.967	0.000	***

as.factor(CarCoded)6	0.952	0.258	3.692	0.000	***
sin(2 * pi * JulianDay/365)	-2.731	0.477	-5.730	0.000	***
as.factor(WDcoded2)SW	0.149	0.072	2.072	0.042	*
as.factor(WDcoded2)WN	0.169	0.051	3.318	0.001	**
ToutC	-0.069	0.018	-3.933	0.000	***
a/ Significance: 0.000:'***'; 0.001: '**'; 0.01: '*'; 0.05: '-'; 0.1: ' '					

*Note: Sample size: 92; Residual standard error: 0.1614 on 76 degrees of freedom; Multiple R-squared: 0.8293; Adjusted R-squared: 0.8024; F-statistic: 30.78 on 12 and 76 DF; p-value: < 2.2e-16; AIC: -58.0893

Table 4.21. No interaction model of IO ratio of PM2.5 concentration (μg/m3)

	Estimate	Std. Error	t value	Pr(>|t|)	*Sig* [a/]
(Intercept)	-0.65867	0.299812	-2.197	0.031032	*
FractionStopped	-0.00289	0.000855	-3.383	0.001128	**
as.factor(VMCoded)2	-0.03058	0.041679	-0.734	0.465292	
as.factor(VMCoded)3	-0.584	0.042345	-13.791	< 2e-16	***
as.factor(CarCoded)2	0.553807	0.108426	5.108	2.30E-06	***
as.factor(CarCoded)3	0.28749	0.082704	3.476	0.000839	***
as.factor(CarCoded)4	1.856331	0.322495	5.756	1.67E-07	***
as.factor(CarCoded)5	0.814845	0.101499	8.028	8.98E-12	***
as.factor(CarCoded)6	1.69922	0.263619	6.446	9.13E-09	***
cos(2 * pi * JulianDay/365)	1.705589	0.364494	4.679	1.21E-05	***
as.factor(WDcoded2)SW	0.163293	0.06209	2.63	0.010308	*
as.factor(WDcoded2)WN	0.128584	0.046434	2.769	0.007038	**
a/ Significance: 0.000:'***'; 0.001: '**'; 0.01: '*'; 0.05: '-'; 0.1: ' '					

*Note: Sample size: 118; Residual standard error: 0.1527 on 77 degrees of freedom; Multiple R-squared: 0.8151; Adjusted R-squared: 0.7887; F-statistic: 30.86 on 11 and 77 DF; p-value: < 2.2e-16; AIC: -68.8262

Table 4.22. Interaction model of IO ratio of CO concentration (ppm)

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*	*Sig* [a/]
(Intercept)	5.294	0.718	7.375	0.000	***
TexhC	0.018	0.003	5.703	0.000	***
SquareTexh	0.000	0.000	-5.274	0.000	***
Rhout	0.009	0.003	2.935	0.004	**
FractionStopped	0.006	0.001	4.754	0.000	***

FRexhLpm	0.000	0.000	2.584	0.012	*
as.factor(Presence.of.rainfall.on.previous.dayCoded)1	-0.280	0.058	-4.844	0.000	***
as.factor(General.Peak.vs.non.peakCoded)1	-0.105	0.039	-2.702	0.009	**
as.factor(CarCoded)2	-5.150	0.712	-7.230	0.000	***
as.factor(CarCoded)3	-10.500	1.245	-8.438	0.000	***
as.factor(CarCoded)4	4.818	0.573	8.416	0.000	***
as.factor(CarCoded)5	-7.119	0.719	-9.902	0.000	***
as.factor(CarCoded)6	-5.687	0.751	-7.575	0.000	***
sin(2 * pi * JulianDay/365)	-10.920	1.234	-8.852	0.000	***
as.factor(WDcoded2)SW	0.193	0.063	3.072	0.003	**
as.factor(WDcoded2)WN	0.083	0.042	1.973	0.052	.
sin(2 * pi * JulianDay/365):self1	10.030	1.275	7.869	0.000	***
a/ Significance: 0.000:'***'; 0.001: '**'; 0.01: '*'; 0.05: '-'; 0.1: ' '					

*Note: Sample size: 92; Residual standard error: 0.1258 on 72 degrees of freedom; Multiple R-squared: 0.9018; Adjusted R-squared: 0.88; F-statistic: 41.32 on 16 and 72 DF; p-value: < 2.2e-16; AIC: -99.27496

Table 4.23. Interaction model of IO ratio of PM2.5 concentration (μg/m3)

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*	*Sig* [a/]
(Intercept)	5.363	1.955	2.743	0.008	**
AirportWindspeedm.s	0.080	0.033	2.406	0.019	*
as.factor(VMCoded)2	-0.028	0.042	-0.662	0.510	
as.factor(VMCoded)3	-0.515	0.046	-11.098	< 2e-16	***
as.factor(CarCoded)2	-5.856	2.048	-2.859	0.005	**
as.factor(CarCoded)3	0.736	0.151	4.877	0.000	***
as.factor(CarCoded)4	-4.784	2.115	-2.262	0.027	*
as.factor(CarCoded)5	-5.620	2.051	-2.740	0.008	**
as.factor(CarCoded)6	-4.688	2.035	-2.304	0.024	*
cos(2 * pi * JulianDay/365)	-5.862	2.414	-2.428	0.018	*
as.factor(WDcoded2)SW	0.251	0.069	3.652	0.000	***
as.factor(WDcoded2)WN	0.137	0.048	2.874	0.005	**
cos(2 * pi * JulianDay/365):self1	7.741	2.468	3.137	0.002	**
a/ Significance: 0.000:'***'; 0.001: '**'; 0.01: '*'; 0.05: '-'; 0.1: ' '					

*Note: Sample size: 118; Residual standard error: 0.1548 on 76 degrees of freedom; Multiple R-squared: 0.8126; Adjusted R-squared: 0.783; F-statistic: 27.45 on 12 and 76 DF; p-value: < 2.2e-16; AIC: -65.59471

CHAPTER V

SUMMARY AND CONCLUSIONS

Field assessment of in-vehicle exposure to $PM_{2.5}$ and CO was conducted in an urban congested area and along a highway during winter/spring season using six cars of different makes and ages under varied ventilation conditions with the objective of examining the influence of self pollution, out-vehicle sample intake location and weather gradients on in-vehicle concentrations. Average in-vehicle concentrations exceeded the WHO permissible exposure guidelines for all tested ventilation modes for $PM_{2.5}$ and when using a half opened window for CO. It is essential to note however the limitations of the comparison of $PM_{2.5}$ concentrations with the WHO guidelines in view of the potential error associated with the measurement method which has not yet been validated inside or adjacent to commuting microenvironments.

Three of the tested cars exhibited consistent cases of fume intrusion from the engine compartment to the car cabin indicating a high likelihood of occurrence of self pollution in passenger cars irrespective of their age. The latter self-pollution could not be observed at times in mobile and stationary tests due to the high air exchange rate in the former case and to the low fuel combustion in the latter case. The use of air recirculation with particle filtration within the recirculation loop kept the $PM_{2.5}$IO ratios below one, with decreasing filtration efficiency as car age increased. The front area of a car near the windshield correlated most with in-vehicle air quality indicating that out-vehicle sampling in similar studies should be withdrawn from this location. Finally, differences in pressure between the inside and the outside of the vehicle were found to influence air pollutant IO ratios significantly with higher correlations in the case of AC

Rec (22.1 and 26.7% of $PM_{2.5}$ and CO IO ratio variations, respectively) compared to W1/2O (15.7 and 17.3% of $PM_{2.5}$ and CO IO ratio variations, respectively). Temperature and humidity difference also affected CO IO ratios explaining 58.5 and 18.6% of their variation.

Mathematical simulation of in-vehicle CO and PM2.5 concentrations using measured outdoor concentrations and minute to minute variations in vehicle air change rates was undertaken to fit the self pollution rates required to match the average measured pollutant concentration to that simulated. While CO self pollution rates could not be accurately estimated in the cabins of old cars (1999 and 1997 cars), the self pollution rates inside the 2011 model car were highest when AC FA was used (1625-5175 mg/h), followed by W1/2O (250-1100 mg/h) and by AC Rec (33-55 mg/h). On another hand, $PM_{2.5}$ self pollution was lower in the cabin of the 2011 model car compared to the cabin of the older cars. As such, for AC Rec, the self pollution rates were in the range 0.2 to 3.375 mg/h for the 2011 car, compared to 3.35-10.05 and 3.6-8.4 mg/h for for the 1999 and 1997 cars, respectively. Similarly, for AC FA, the range was 12.7 to 32.3 mg/h for the 2011 car compared to 18.6 to 35.5 mg/h and 22.6 to 39.875 mg/h for the 1999 and 1997 cars. Similar rates were obtained with W1/2O and ranged from 9.5 to 57.525 mg/h for the 2011 car, 11.6 to 35.5 mg/h for the 1999 car and 11.75 to 45.5 mg/h for the 1997 car.

Best models of CO and $PM_{2.5}$ concentrations could explain 72 and 90% of the measured variability in CO and $PM_{2.5}$ concentrations, respectively, whereas models of CO and $PM_{2.5}$ IO ratios could explain 80 and 79% of IO ratio variation, respectively. However, after allowing for self pollution interaction, the predictive power of the CO concentration model decreased to 64% whereas that of the CO IO ratio model increased

to 88%. Dissimilarly, the inclusion of interaction negligibly affected $PM_{2.5}$ concentration and IO ratio models. The best CO concentration model (adjusted R^2 = 0.72) included initial and out-vehicle CO and $PM_{2.5}$ concentrations, exhaust temperature, presence of rainfall on previous day, time of day, test car, Julian day, wind direction and roadway type whereas the best CO IO ratio model (adjusted R^2 = 0.88) included exhaust temperature and flow rate, out-vehicle relative humidity, fractin of trip with stopped vehicle, presence of rainfall on previous day, presence of a general peak hour, test car, wind direction, Julian day and an interaction term between Julian day and spresence of self pollution. Assuming constant values for other influencing paramters, it was concluded from the best CO concentration model that the lowest in-vehicle CO concentration would be recorded end of March on a morning highway drive with north easterly winds and following a rainy day. In contrast, highest in-vehicle CO concentrations would be recorded while commuting in late September in a commercial/residential area during the afternoon of a day with south westerly winds and following a clear period with no rainfall.

On another hand, the best $PM_{2.5}$ concentration model (adjusted R^2 = 0.90) included intial and out-vehicle $PM_{2.5}$ concentrations, wind speed, fraction of trip with stopped vehicle, the presence of a general peak hour, ventilatin mode, test car, Julian day, and interaction terms between each of wind speed and Julian day and the presence of self pollution. The best $PM_{2.5}$ concentration IO ratio model (adjusted R^2 = 0.79) included the fraction of trip with stopped vehicle, ventilation mode, test car, Julian day and wind direction. Assuming constant values for other influencing paramters, it was concluded from the best $PM_{2.5}$ concentration model that the lowest in-vehicle $PM_{2.5}$ concentration would be recorded end of September during a non-peak hour of a day with north easterly winds all while the ventilation mode is set to air conditioning on with

recirculation. In contrast, highest in-vehicle $PM_{2.5}$ concentration would be recorded end of March during a peak hour of a day with north westerly winds all while the ventilation mode is set to window half opened.

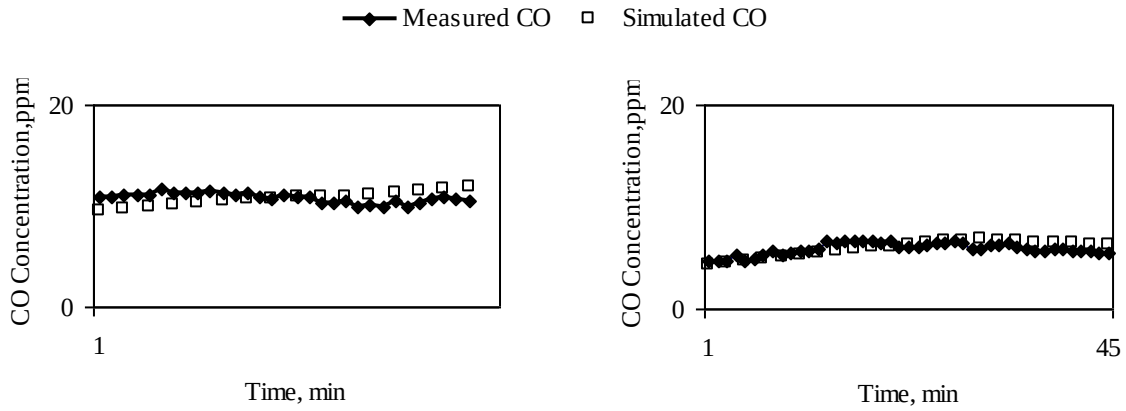
Future work should concentrate on the testing of a larger and statistically representative number of vehicles is desirable for wide generalization and validation, all while withdrawing he out-vehicle sample from the front area of the car solely, particularly if old cars were included in the sample.

APPENDIX 1

MEASURED VERSUS SIMULATED AIR POLLUTANT CONCENTRATION PROFILES

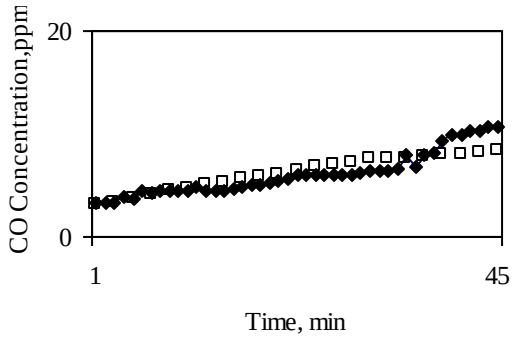
CO concentration profiles for Chevrolet Aveo 2011

Scenario number and simulated in-cabin pollution emission rate are indicated below each graph

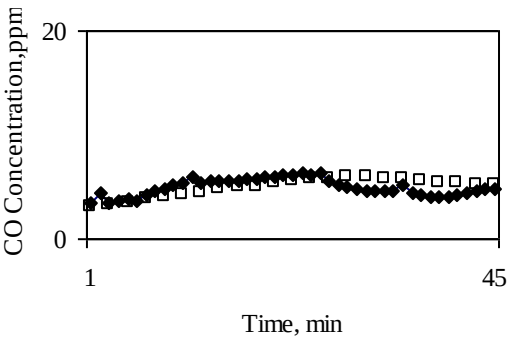


Scenario 1.1, 37 mg/hour

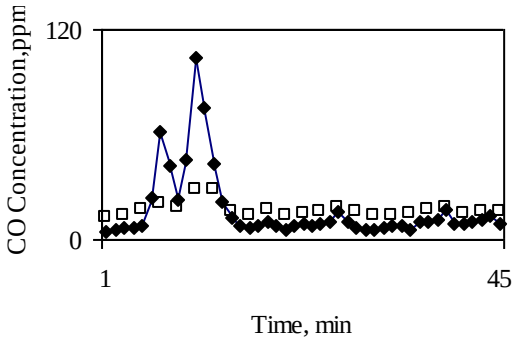
Scenario 3.1, 33 mg/hour



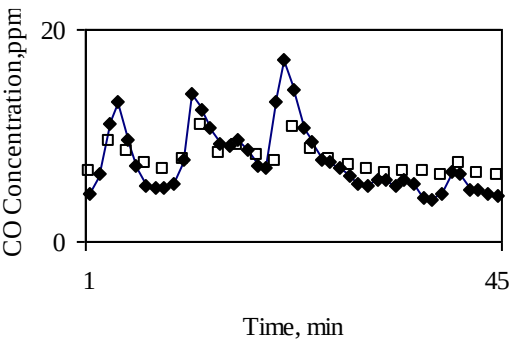
Scenario 3.2, 55 mg/hour



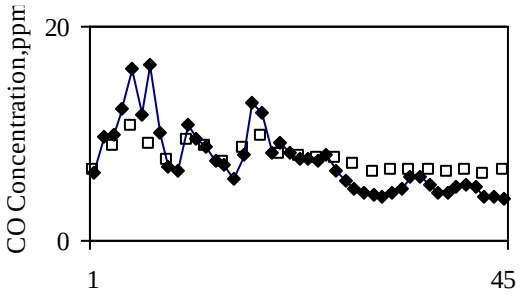
Scenario 5.1, 37.2 mg/hour



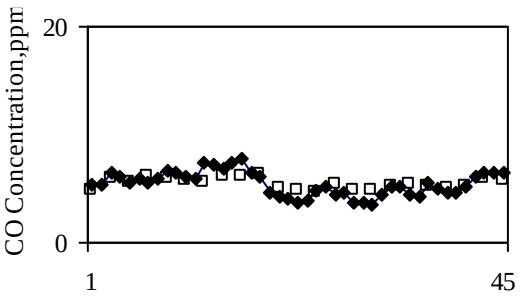
Scenario 7.1, 5175 mg/hour



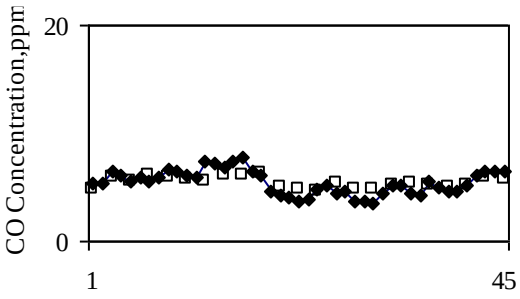
Scenario 9.1, 2200 mg/hour



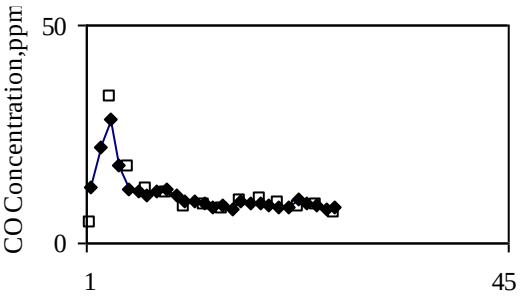
Scenario 9.2, 2225 mg/hour



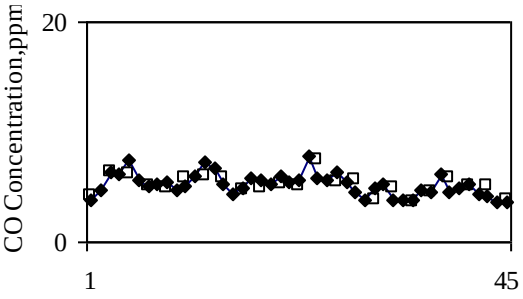
Scenario 9.2, 1625 mg/hour



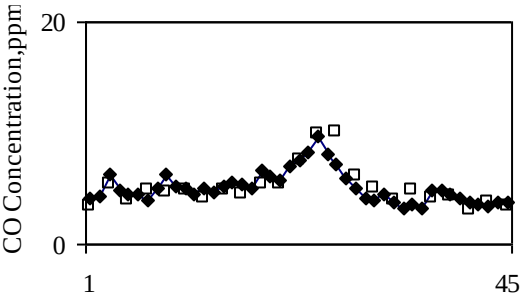
Scenario 11.1, 1625 mg/hour



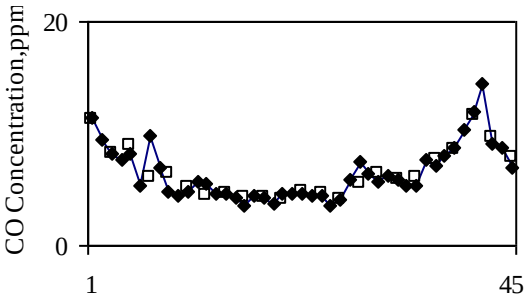
Scenario 13.1, 1625 mg/hour



Scenario 15.1, 400 mg/hour



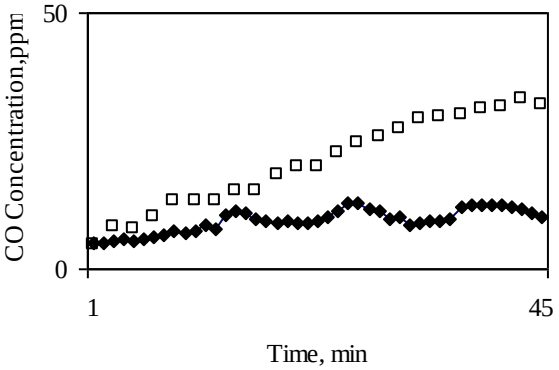
Scenario 15.2, 250 mg/hour



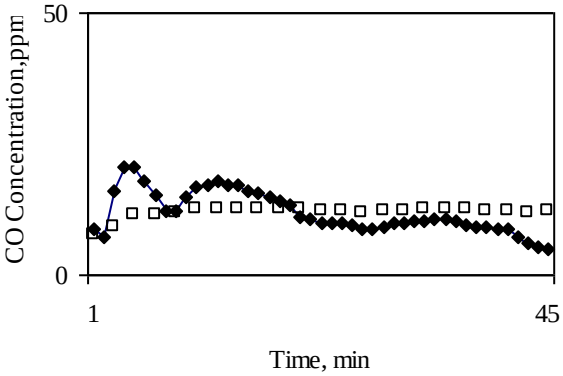
Scenario 17.1, 1100 mg/hour

CO concentration profiles for Kia Delta 1999

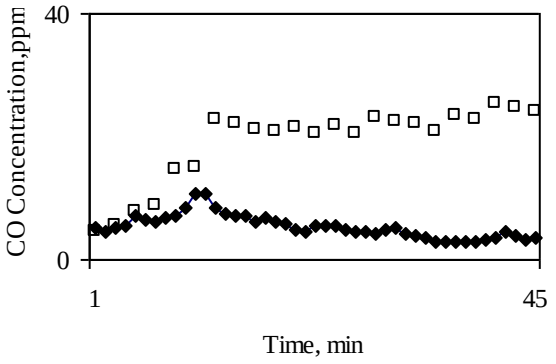
Scenario number and simulated in-cabin pollution emission rate are indicated below each graph



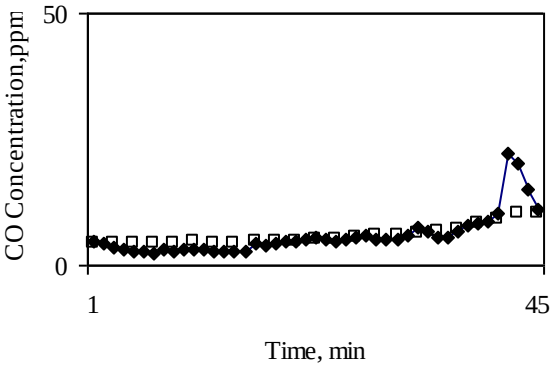
Scenario 19.3, 0 mg/hour



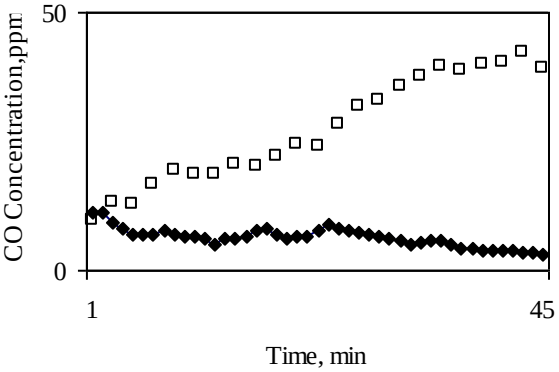
Scenario 19.4, 5.5 mg/hour



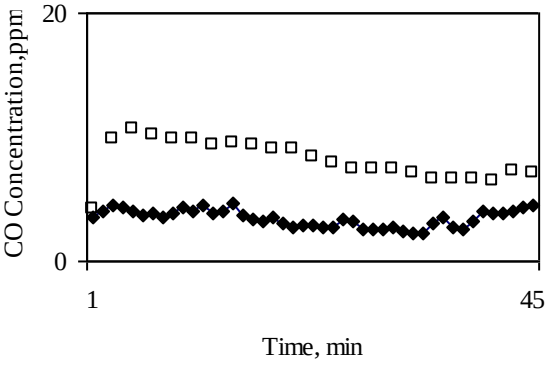
Scenario 21.1, 0 mg/hour



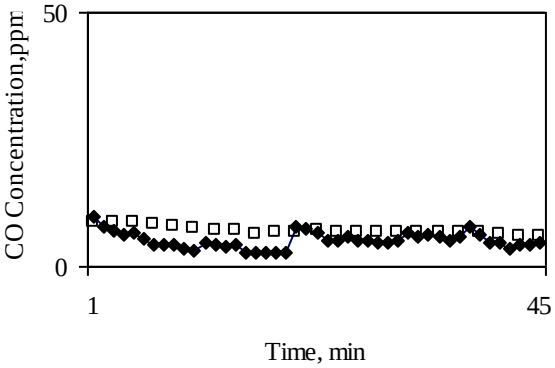
Scenario 21.2, 12 mg/hour



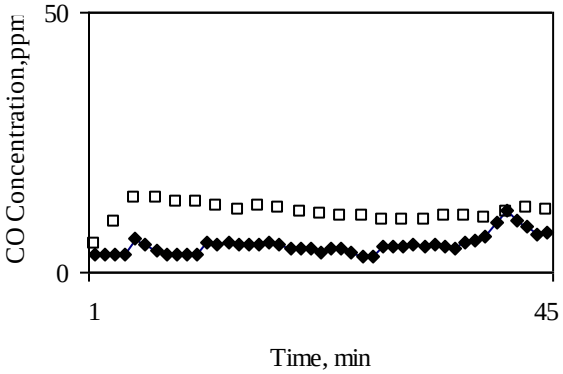
Scenario 21.3, 0 mg/hour



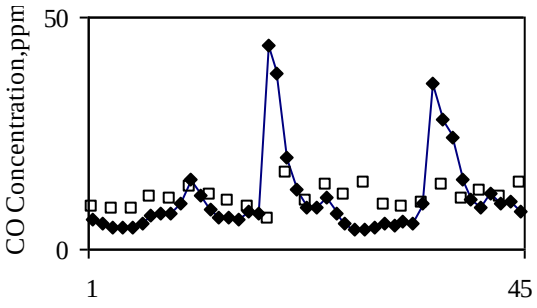
Scenario 23.1, 0 mg/hour



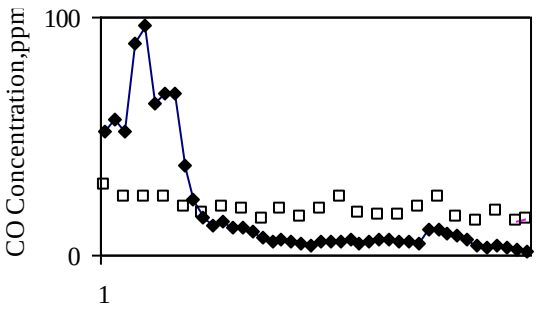
Scenario 23.2, 0 mg/hour



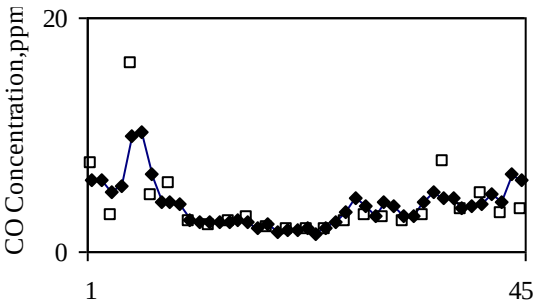
Scenario 23.3, 0 mg/hour



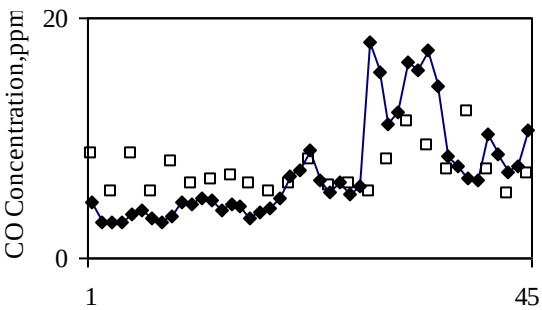
Scenario 25.1, 2850 mg/hour



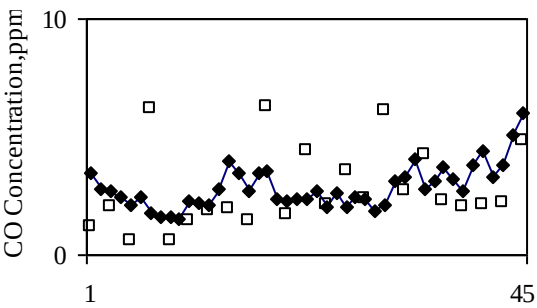
Scenario 25.2, 6000 mg/hour



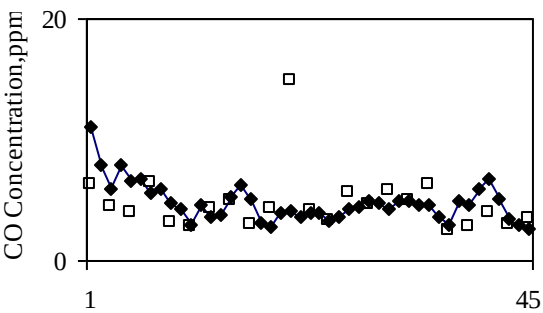
Scenario 27.1, 425 mg/hour



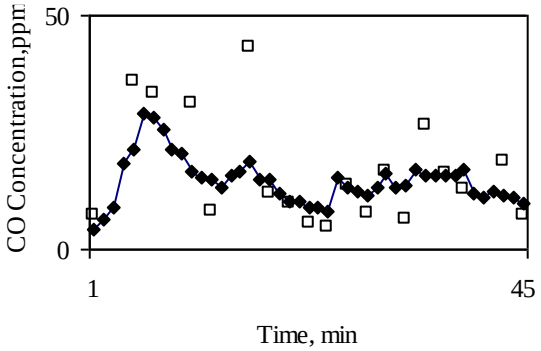
Scenario 27.2, 1750 mg/hour



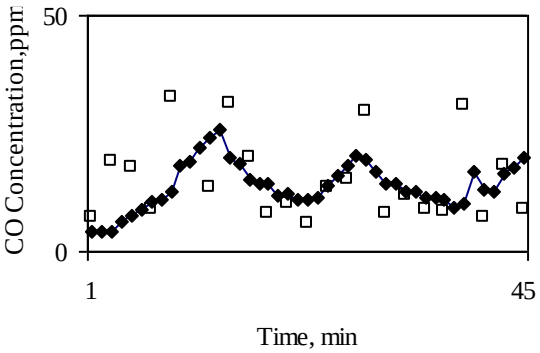
Scenario 29.1, 0 mg/hour



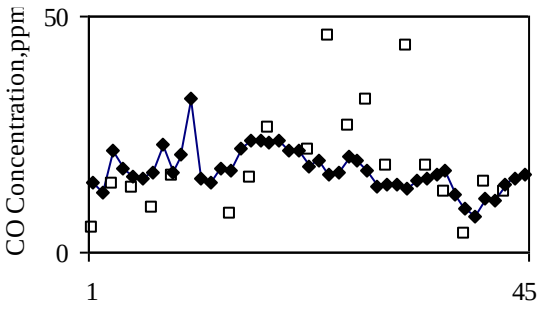
Scenario 29.2, 575 mg/hour



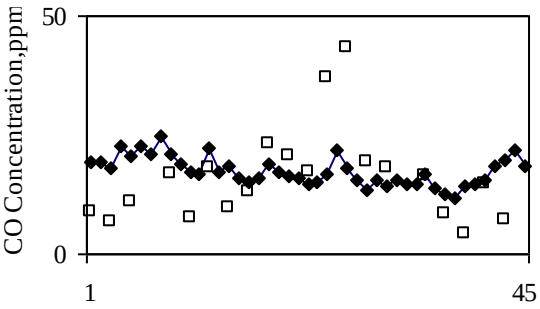
Scenario 31.1, 0 mg/hour



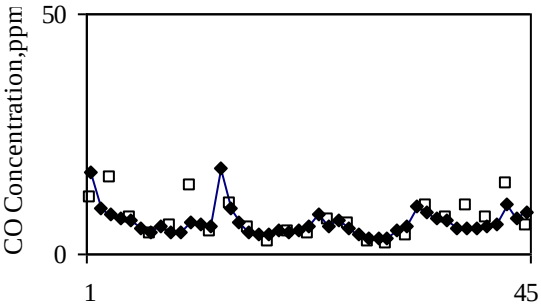
Scenario 31.2, 0 mg/hour



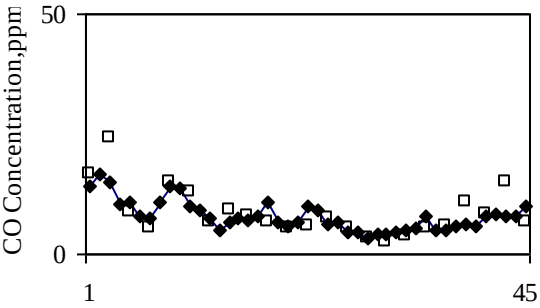
Scenario 33.1, 0 mg/hour



Scenario 33.2, 0 mg/hour



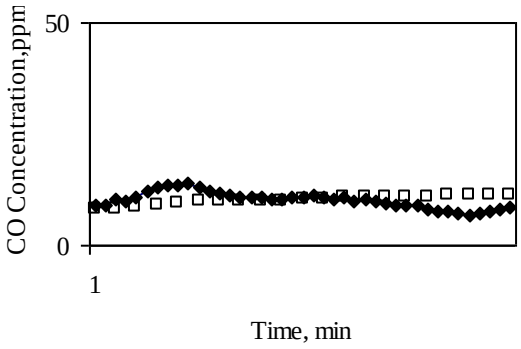
Scenario 35.1, 0 mg/hour



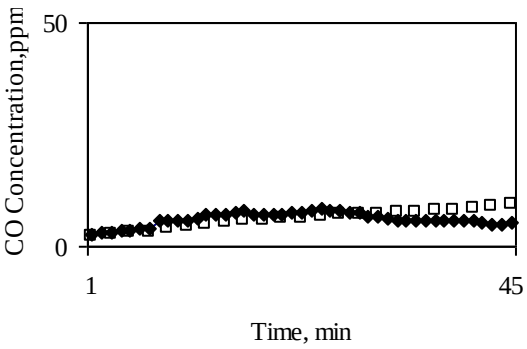
Scenario 35.2, 0 mg/hour

CO concentration profiles for Honda Civic 1997

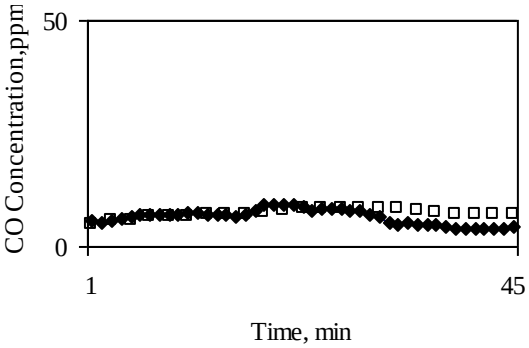
Scenario number and simulated in-cabin pollution emission rate are indicated below each graph



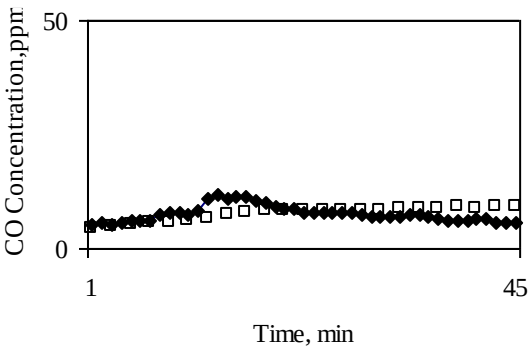
Scenario 37.1, 23 mg/hour



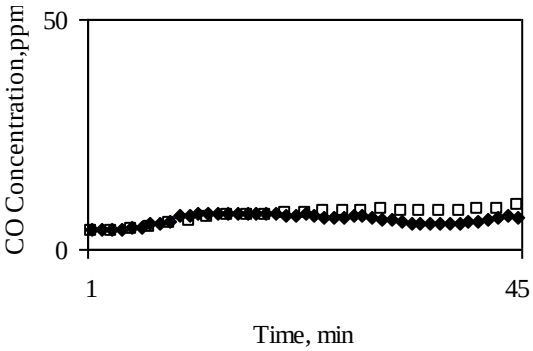
Scenario 37.2, 23 mg/hour



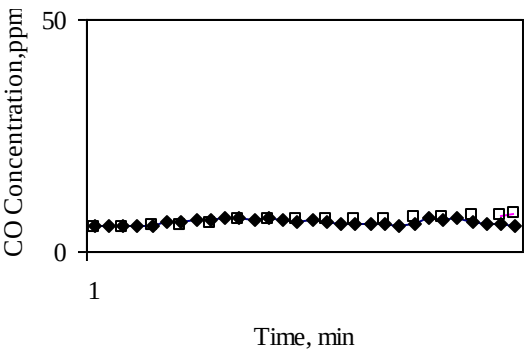
Scenario 38.1, 0 mg/hour



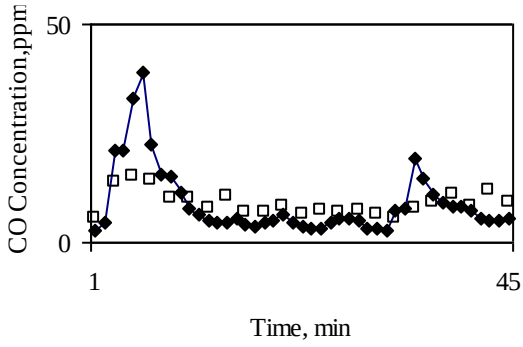
Scenario 38.2, 6 mg/hour



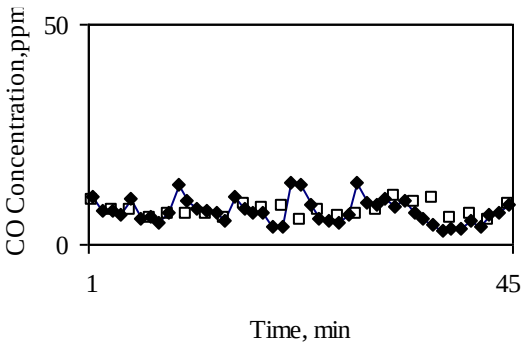
Scenario 39.1, 0 mg/hour



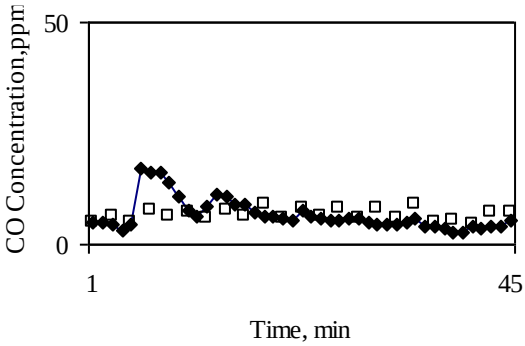
Scenario 39.2, 0 mg/hour



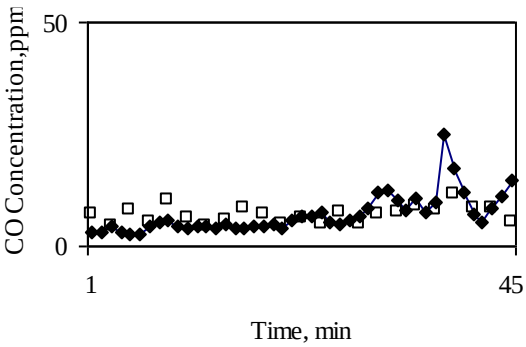
Scenario 41.1, 1950 mg/hour



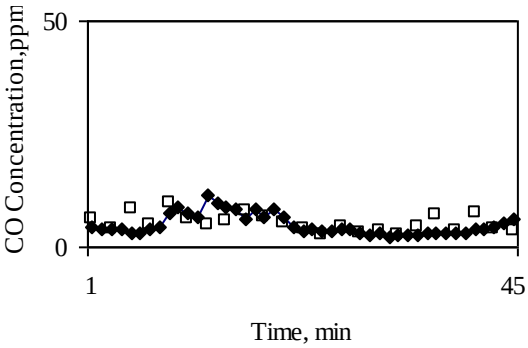
Scenario 41.2, 1250 mg/hour



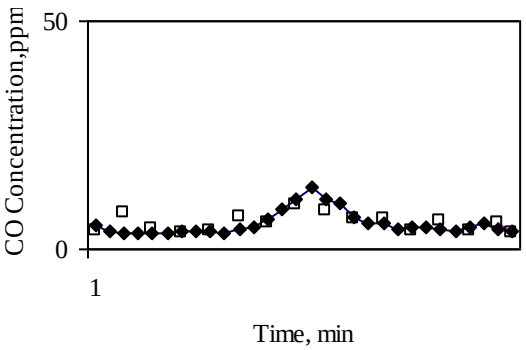
Scenario 43.1, 1050 mg/hour



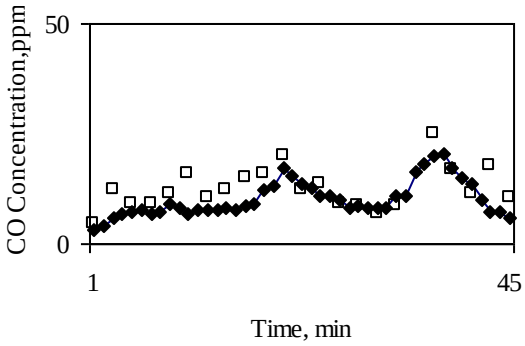
Scenario 43.2, 150 mg/hour



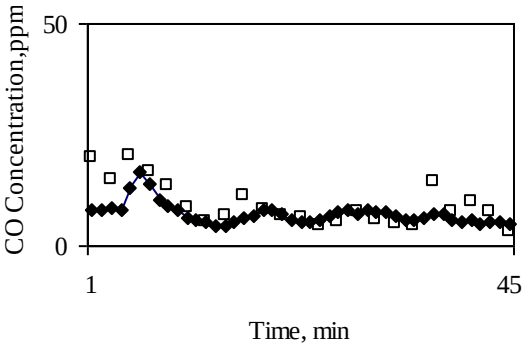
Scenario 45.1, 0 mg/hour



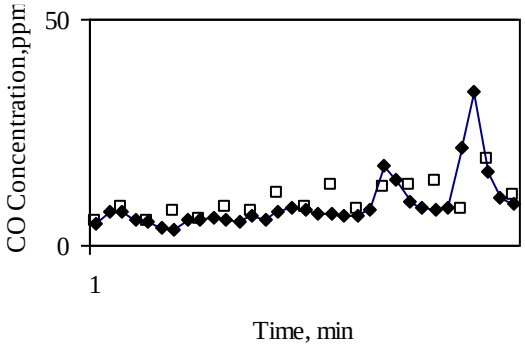
Scenario 45.2, 0 mg/hour



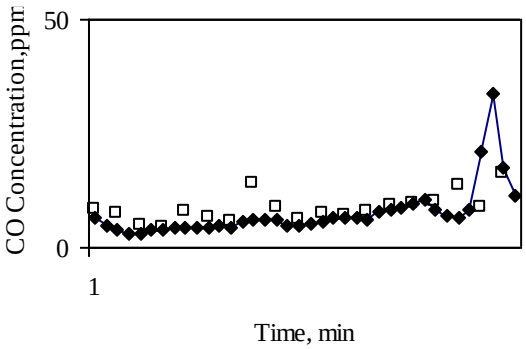
Scenario 47.1, 0 mg/hour



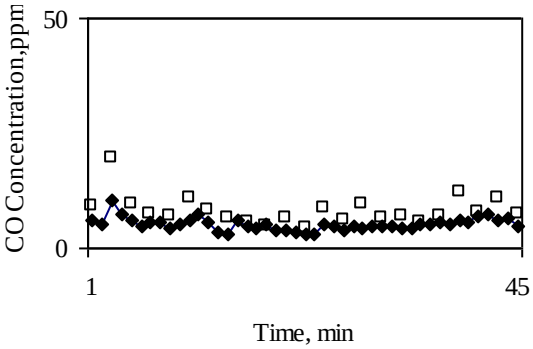
Scenario 47.2, 0 mg/hour



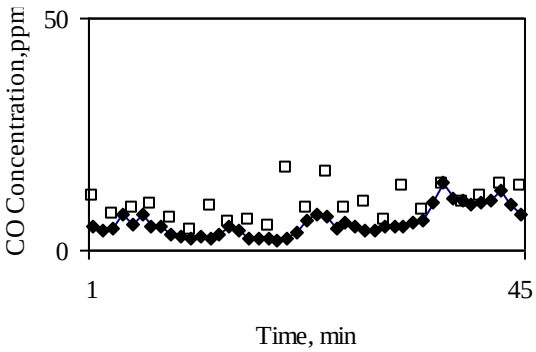
Scenario 49.1, 0 mg/hour



Scenario 49.2, 0 mg/hour



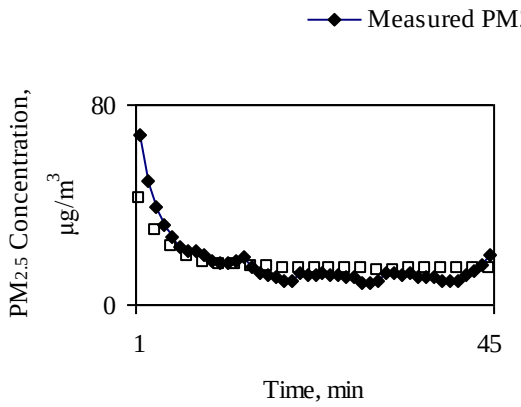
Scenario 51.1, 0 mg/hour



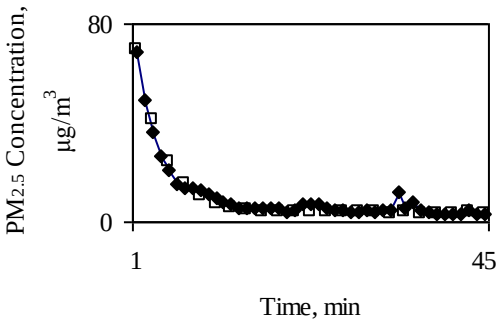
Scenario 51.2, 0 mg/hour

$PM_{2.5}$ concentration profiles for Chevrolet Aveo 2011

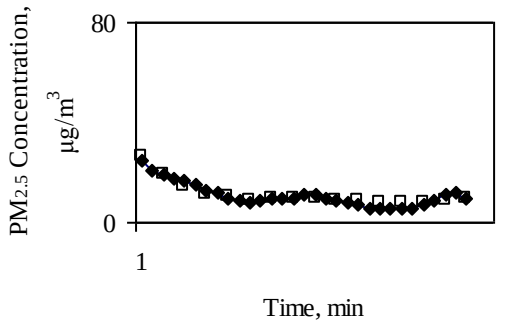
Scenario number and simulated in-cabin pollution emission rate are indicated below each graph



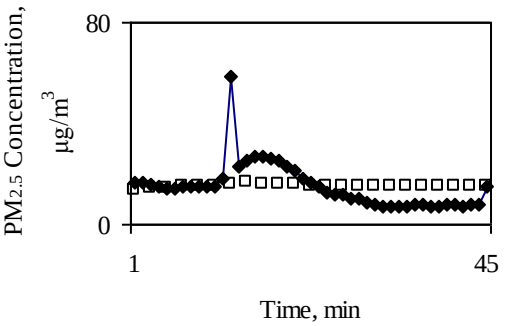
Scenario 2.1, 0.85 mg/hour



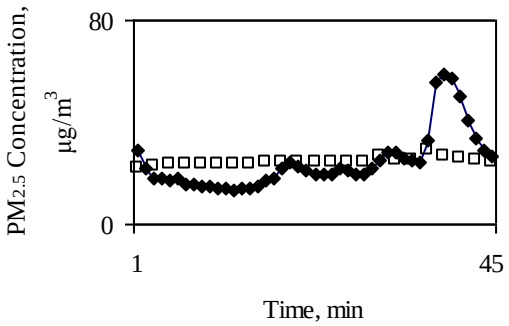
Scenario 2.2, 0.2 mg/hour



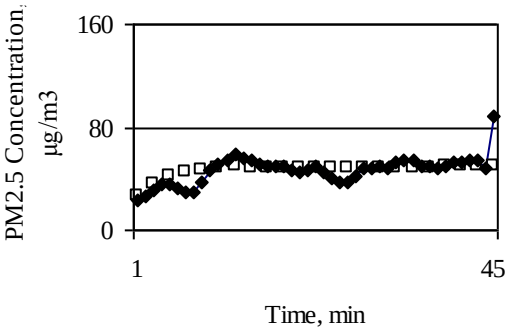
Scenario 2.3, 0.51 mg/hour



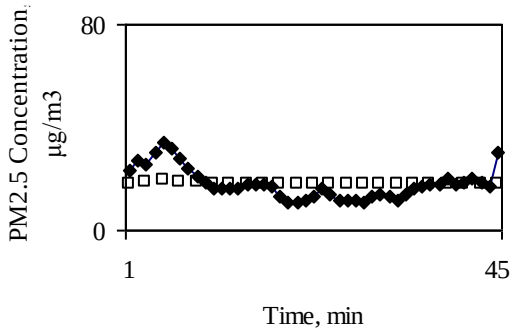
Scenario 4.1, 1.02 mg/hour



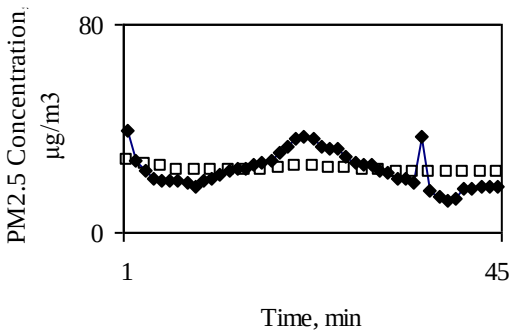
Scenario 4.2, 1.625 mg/hour



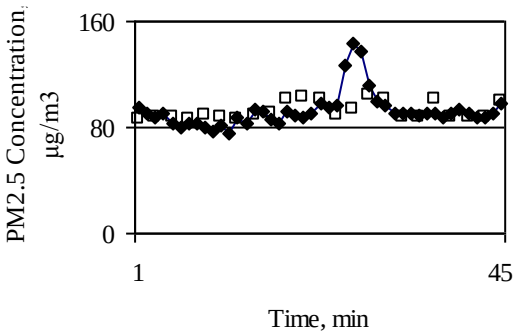
Scenario 6.1, 3.375 mg/hour



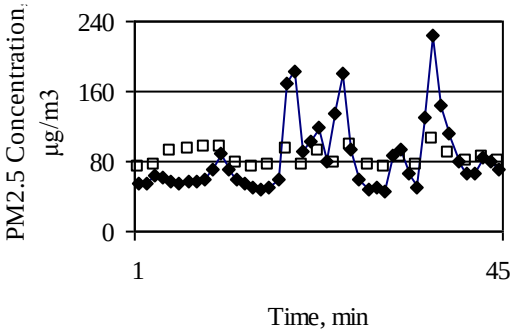
Scenario 6.2, 1.25 mg/hour



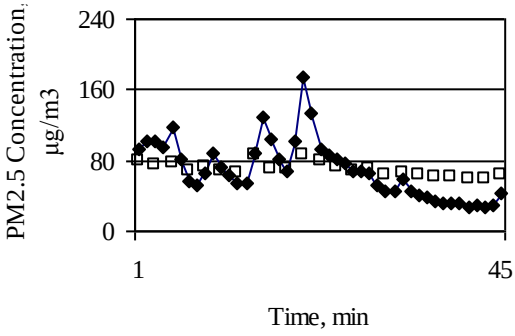
Scenario 6.3, 1.635 mg/hour



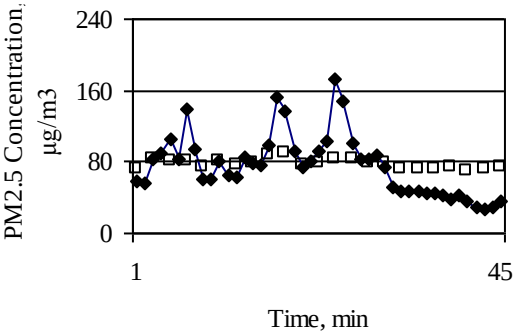
Scenario 8.1, 27.03 mg/hour



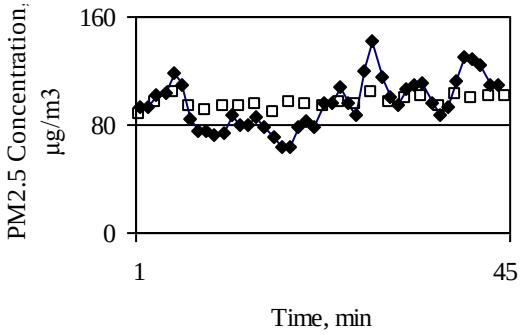
Scenario 8.2, 26.35 mg/hour



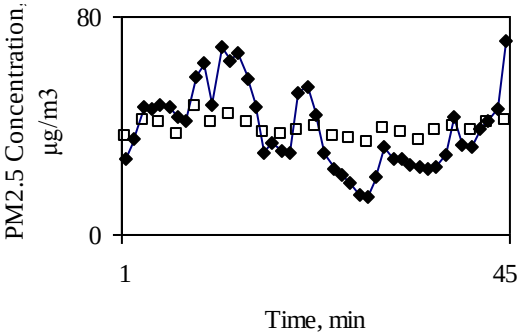
Scenario 10.1, 22.85 mg/hour



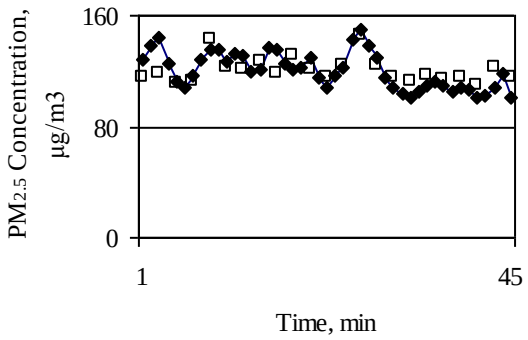
Scenario 10.2, 27.85 mg/hour



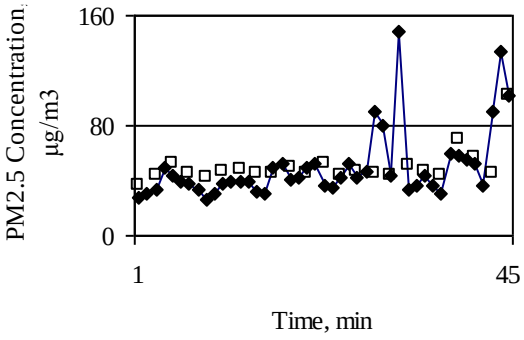
Scenario 12.1, 32.3 mg/hour



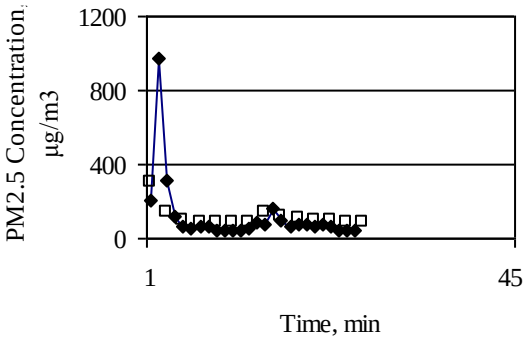
Scenario 12.2, 12.7 mg/hour



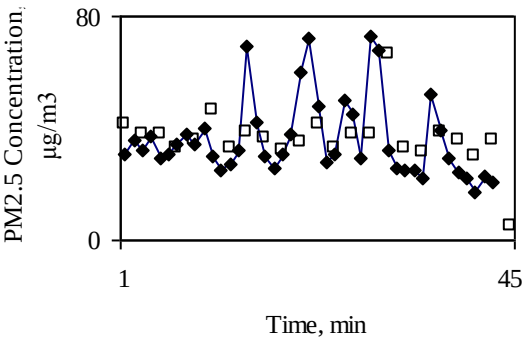
Scenario 14.1, 21.9 mg/hour



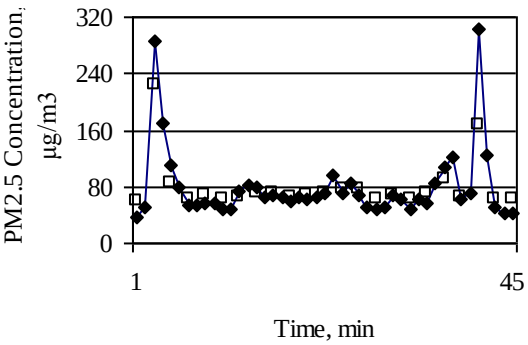
Scenario 14.2, 9.58 mg/hour



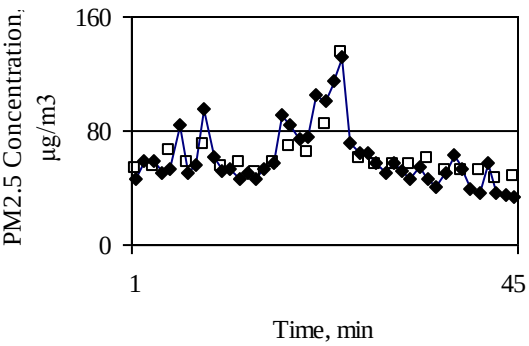
Scenario 14.3, 21.8 mg/hour



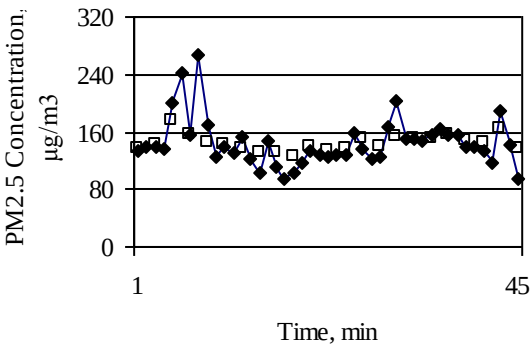
Scenario 16.1, 9.5 mg/hour



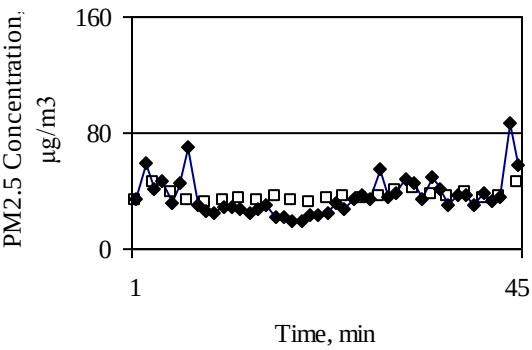
Scenario 16.2, 19.1 mg/hour



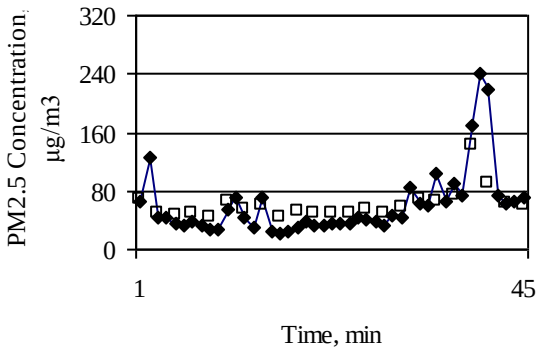
Scenario 16.3, 14 mg/hour



Scenario 18.1, 57.525 mg/hour

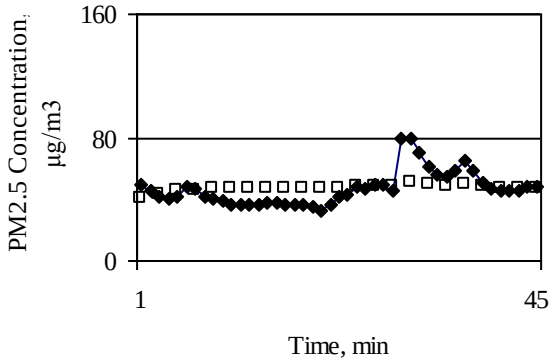


Scenario 18.2, 13.85 mg/hour

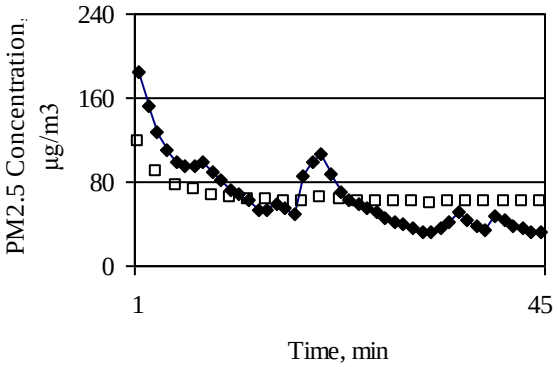


Scenario 18.3, 20.1 mg/hour

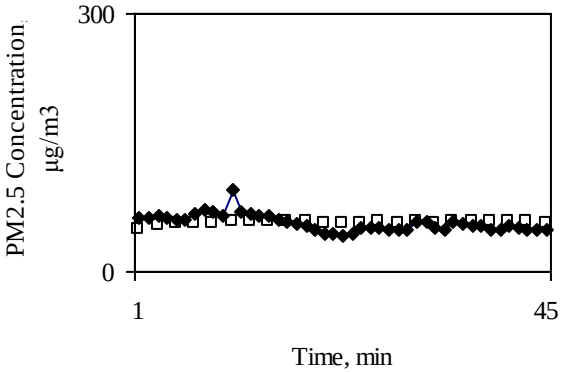
<u>$PM_{2.5}$ concentration profiles for Kia Delta 1999</u>
Scenario number and simulated in-cabin pollution emission rate are indicated below each graph



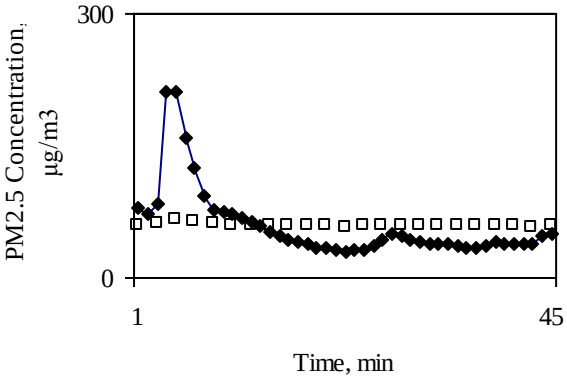
Scenario 20.1, 3.35 mg/hour



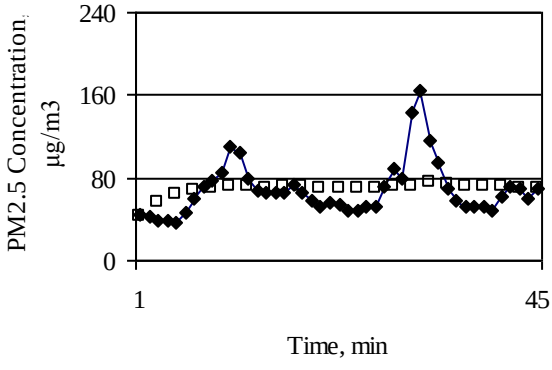
Scenario 20.2, 4.37 mg/hour



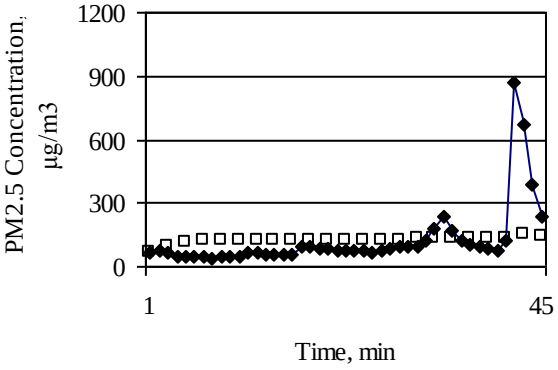
Scenario 20.3, 4.16 mg/hour



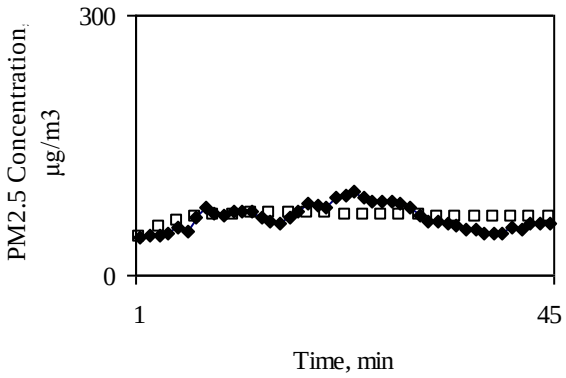
Scenario 20.3, 4.3 mg/hour



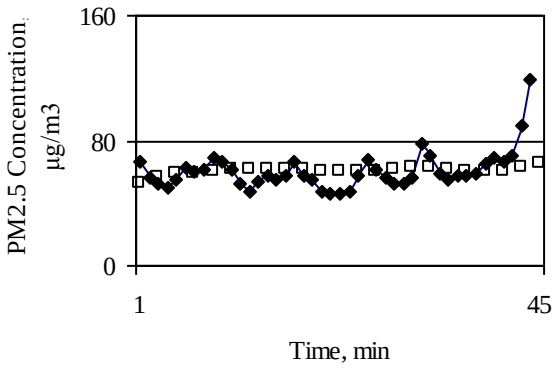
Scenario 22.1, 5.3 mg/hour



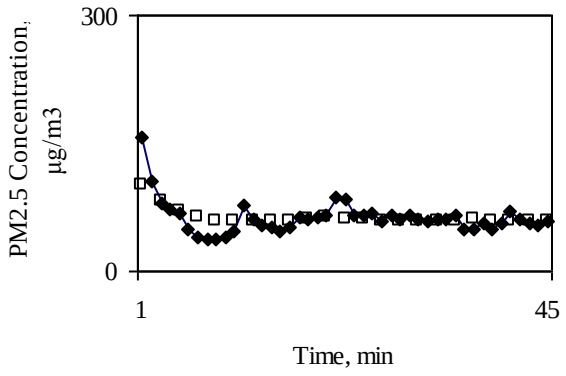
Scenario 22.2, 10.05 mg/hour



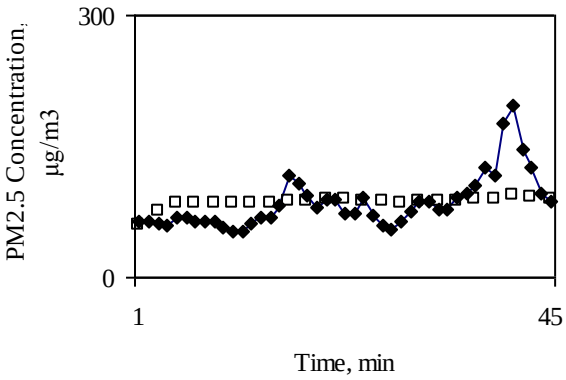
Scenario 22.3, 5.3 mg/hour



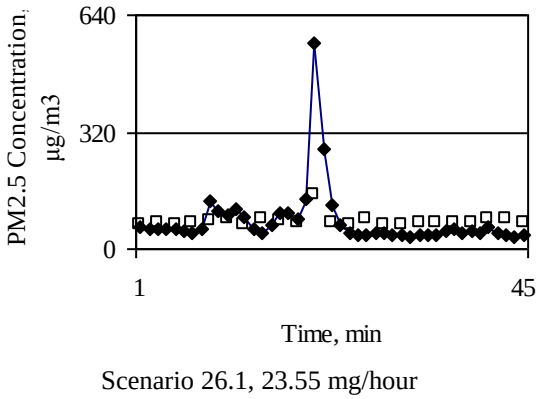
Scenario 24.1, 4.65 mg/hour



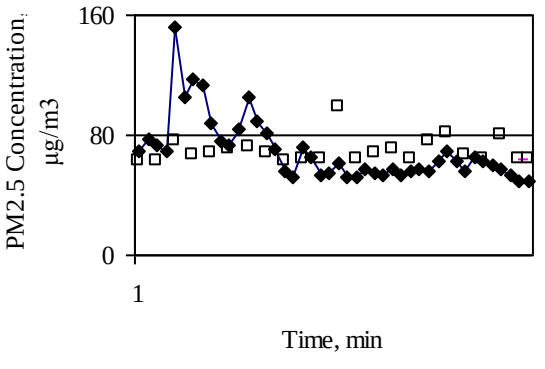
Scenario 24.2, 4.575 mg/hour



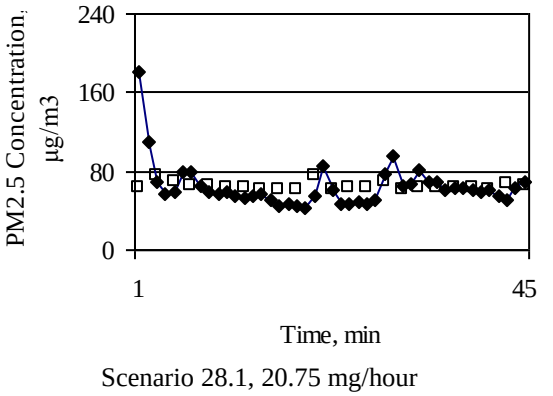
Scenario 24.3, 7.03 mg/hour



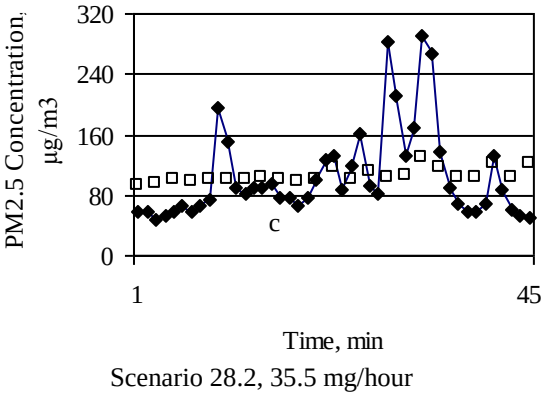
Scenario 26.1, 23.55 mg/hour



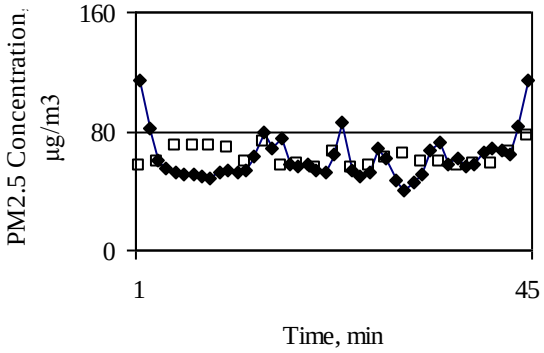
Scenario 26.2, 20.6 mg/hour



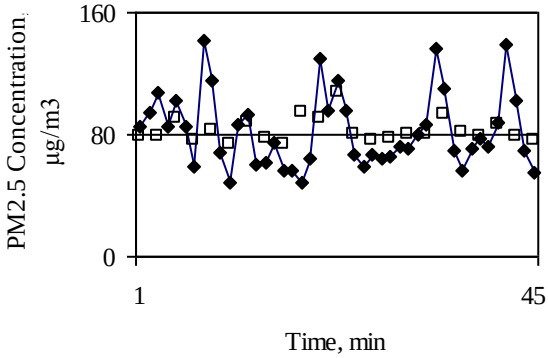
Scenario 28.1, 20.75 mg/hour



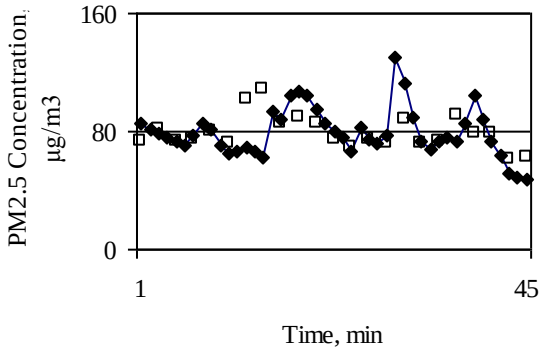
Scenario 28.2, 35.5 mg/hour



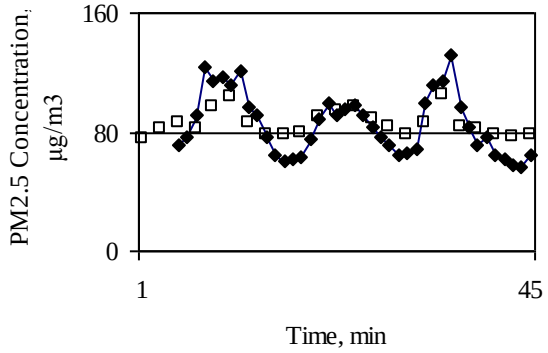
Scenario 30.1, 18.6 mg/hour



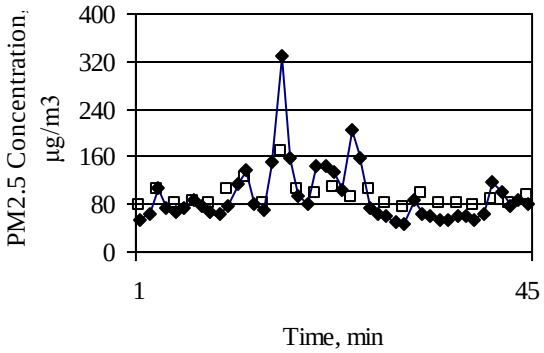
Scenario 30.2, 26.8 mg/hour



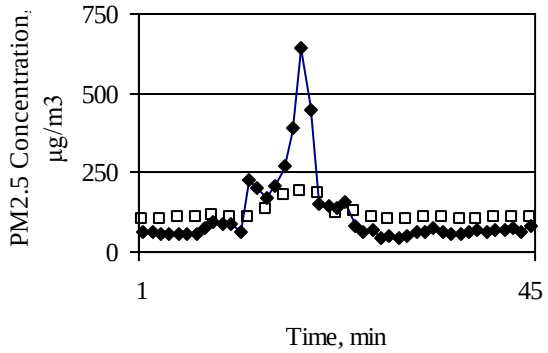
Scenario 32.1, 11.6 mg/hour



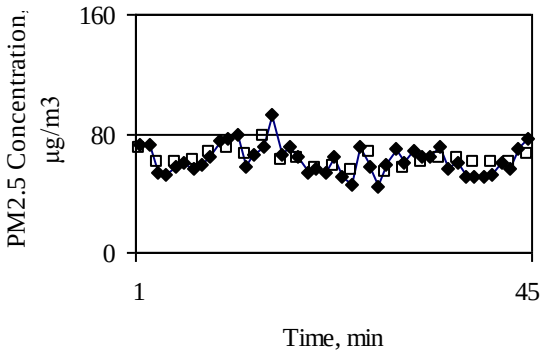
Scenario 32.2, 16.1 mg/hour



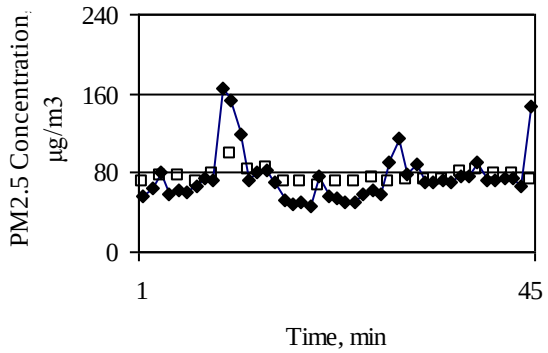
Scenario 34.1, 21.6 mg/hour



Scenario 34.2, 35.5 mg/hour



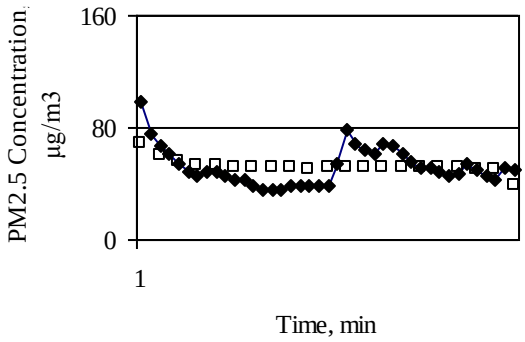
Scenario 36.1, 18.5 mg/hour



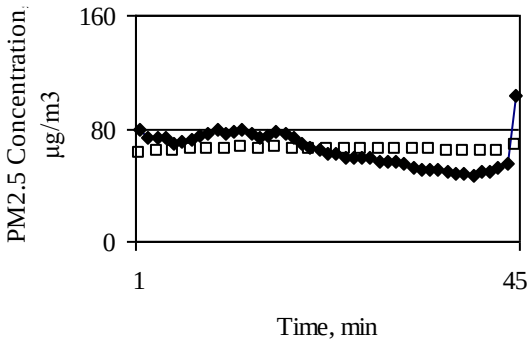
Scenario 36.2, 28.5 mg/hour

PM$_{2.5}$ concentration profiles for Honda Civic 1997

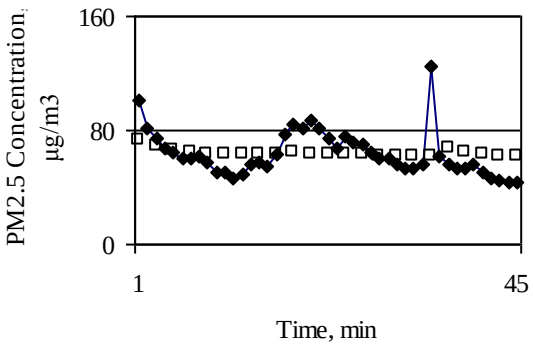
Scenario number and simulated in-cabin pollution emission rate are indicated below each graph



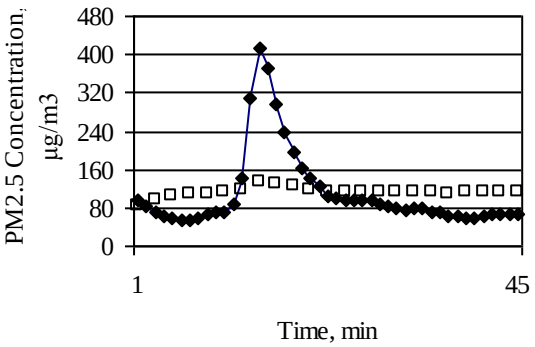
Scenario 38.1, 3.6 mg/hour



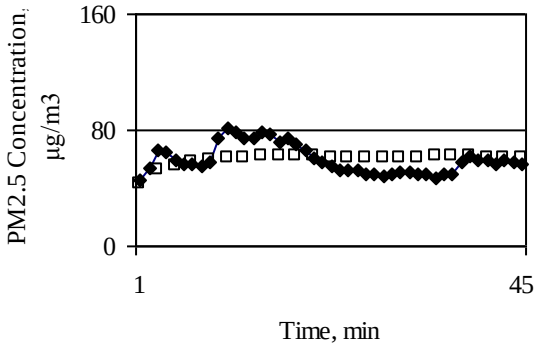
Scenario 38.2, 4.65 mg/hour



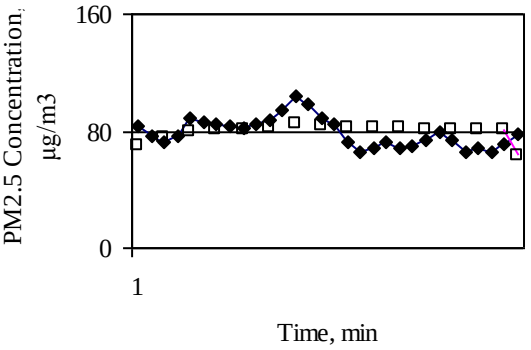
Scenario 40.1, 4.575 mg/hour



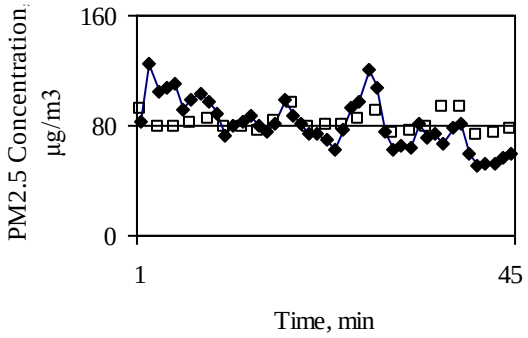
Scenario 40.2, 8.4 mg/hour



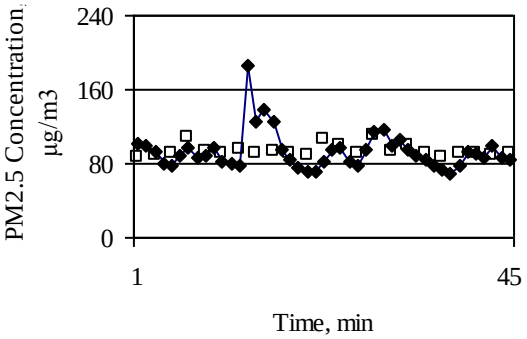
Scenario 42.1, 4.6 mg/hour



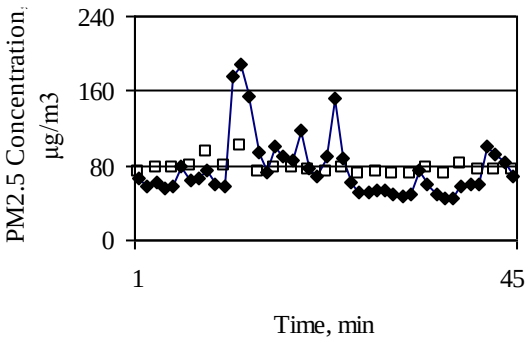
Scenario 42.1, 6.18 mg/hour



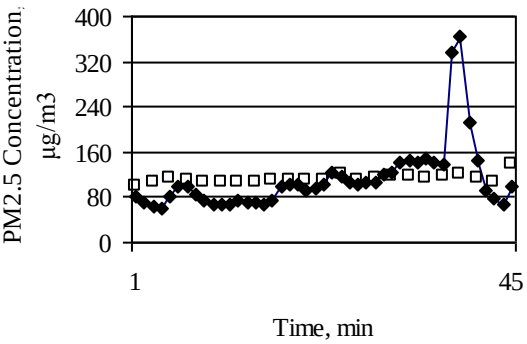
Scenario 44.1, 27 mg/hour



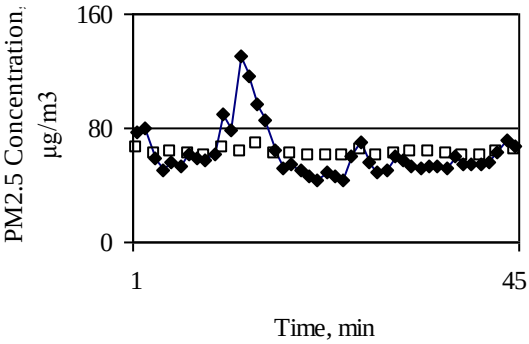
Scenario 44.2, 30.4 mg/hour



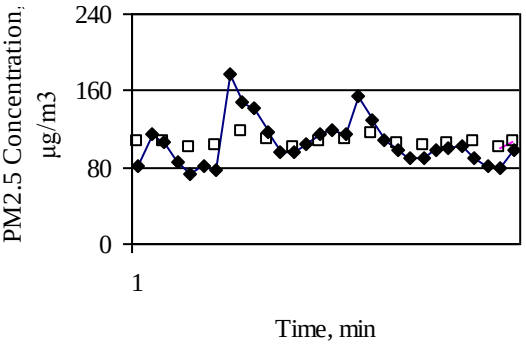
Scenario 46.1, 27.25 mg/hour



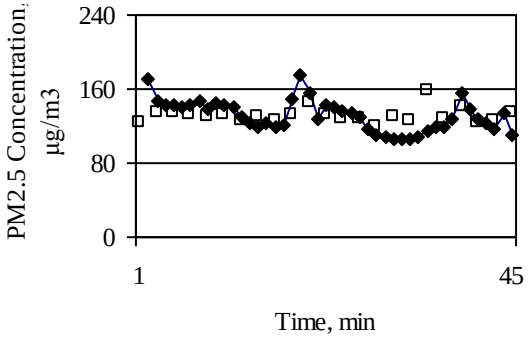
Scenario 46.2, 39.875 mg/hour



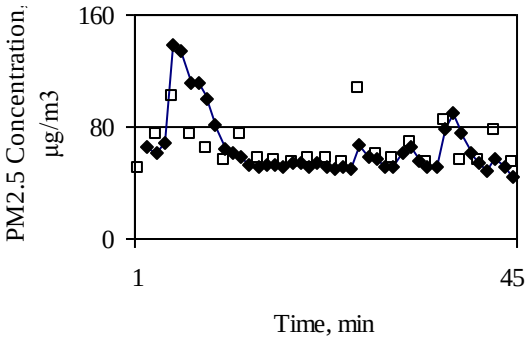
Scenario 48.1, 22.6 mg/hour



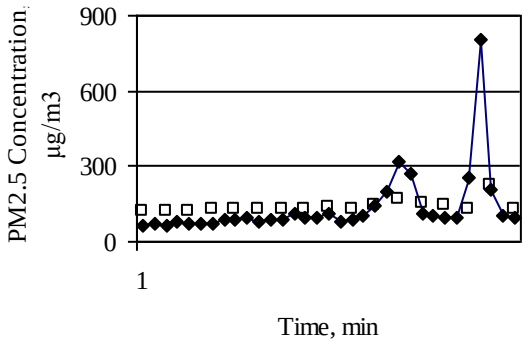
Scenario 48.2, 37.85 mg/hour



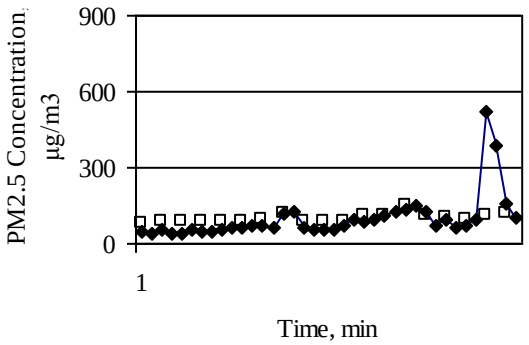
Scenario 50.1, 26.55 mg/hour



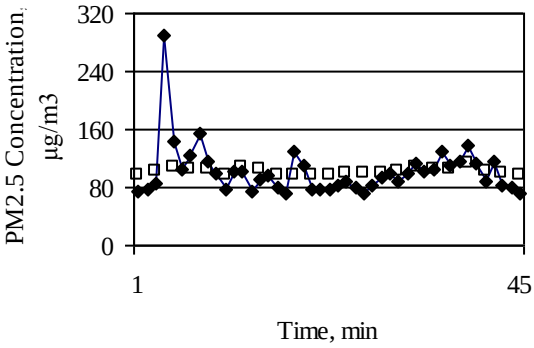
Scenario 50.2, 11.75 mg/hour



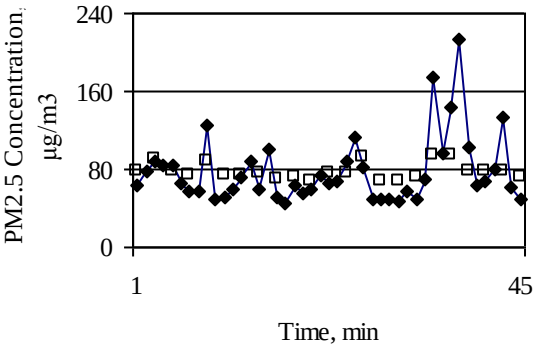
Scenario 52.1, 45.5 mg/hour



Scenario 52.2, 31.5 mg/hour



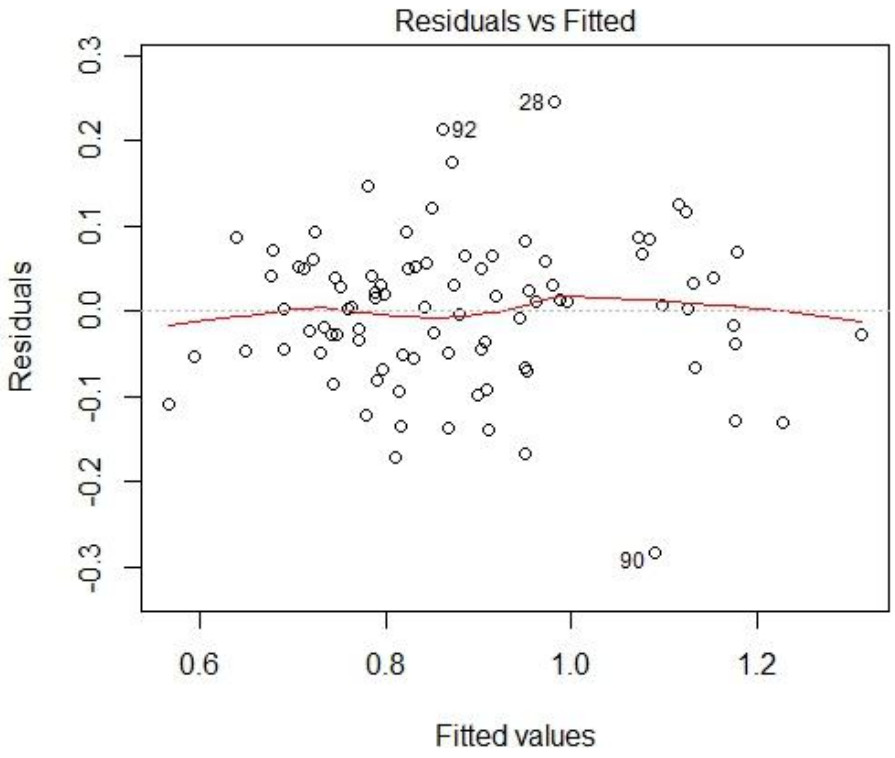
Scenario 54.1, 44 mg/hour



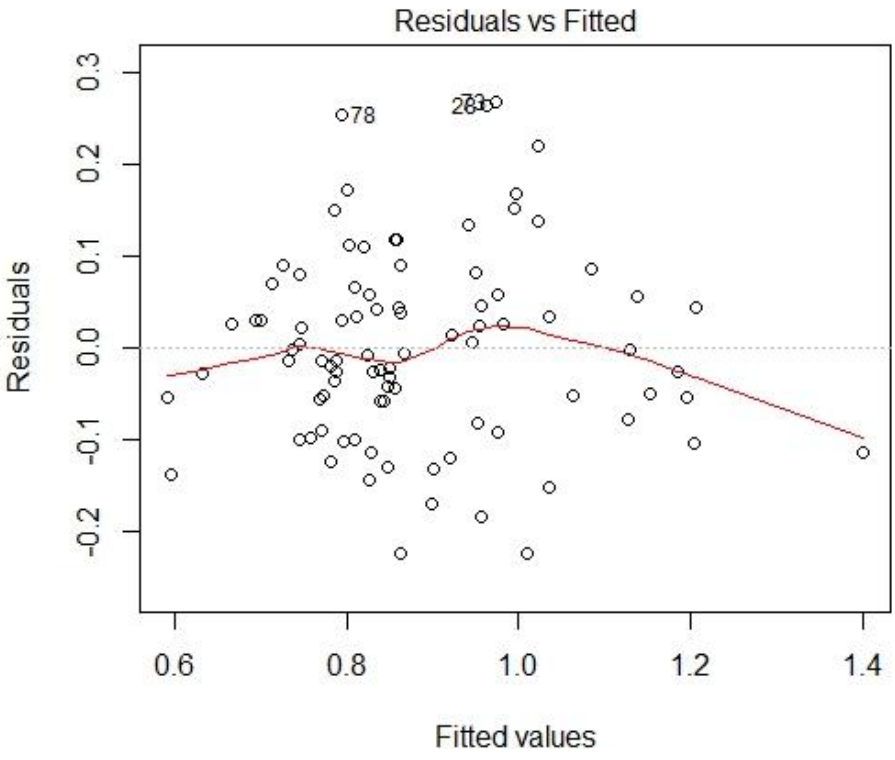
Scenario 54.2, 32.75 mg/hour

APPENDIX 2

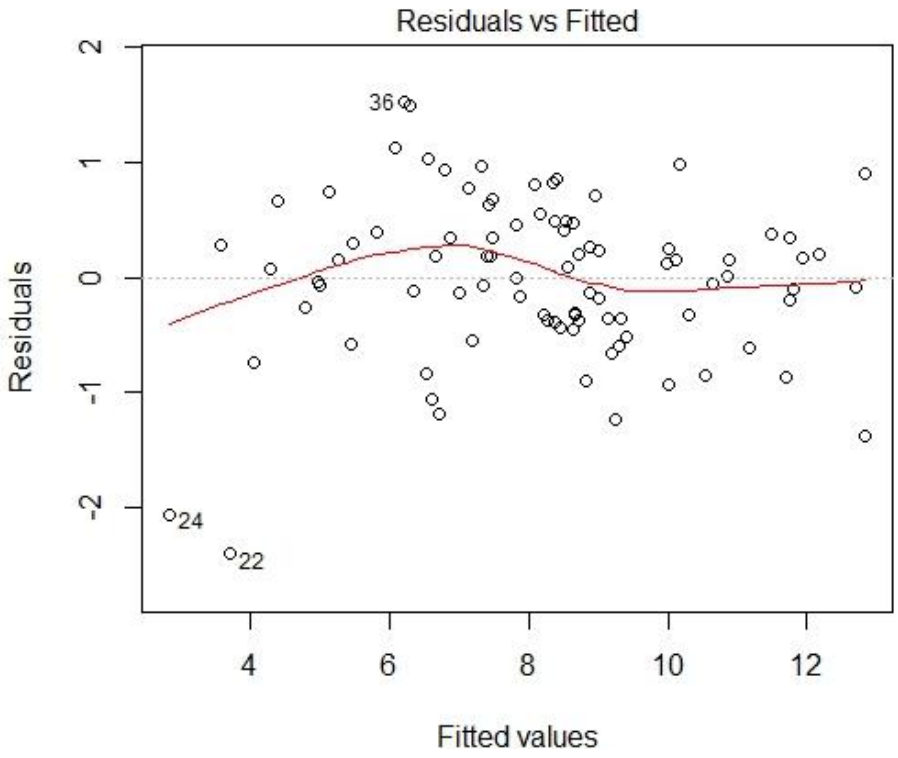
RESIDUALS OF POLLUTANT REGRESSION MODELS



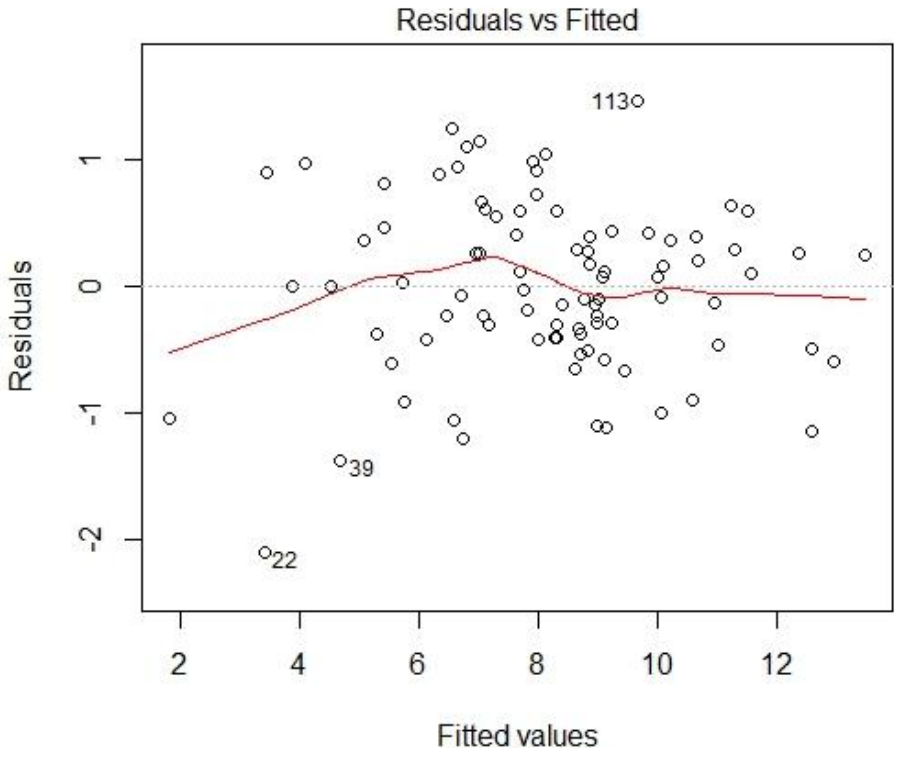
a- CO model, no interaction



b- CO model, with interaction



c- $PM_{2.5}$ model, no interaction



d- $PM_{2.5}$ model, with interaction

APPENDIX 3

In-vehicle Exposure to Carbon Monoxide Emissions from Vehicular Exhaust: A Critical Review

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ABSTRACT: Vehicle-induced emissions constitute a major source of air pollutants, particularly in urban areas, where heavy traffic is common occurrence. Contaminated air can flow into enclosed micro-environments including vehicle compartments. Among various exhaust emissions, carbon monoxide (CO) was the first indicator examined in passenger compartments. This paper presents a critical review of worldwide research work conducted to characterize CO exposure inside vehicles. Measurement methodologies for field testing are presented alongside impacts of various factors on in-vehicle CO exposure including outdoor CO levels, roadway type, ventilation mode, weather conditions and vehicle characteristics. Results of in-vehicle CO exposure measurements in various cities are compared. Modeling efforts to characterize in-vehicle CO exposure and relate it to potential explanatory factors are also discussed. Based on the review findings, limitations and future needs are defined.

KEYWORDS: In-vehicle exposure, Carbon monoxide, Air quality monitoring

Introduction

During the last three decades, there has been increasing concern within the scientific community over the impacts of indoor air quality (IAQ) on health.[48] Because people spend a significant amount of time indoors, studies were conducted to assess population exposure to pollutants in various types of micro-environments. In this context, elevated levels of traffic-related pollutants have been observed inside and near commuting micro-environments such as automobiles, buses, bicycles, trains, ferries, trams, airplanes, sidewalks, parking garages and lots, etc.,[13,14,19,28,29,55,61,67,74] with private passenger cars having one of the highest levels as a result of the low body position and the low intake point of the ventilation system leading to a close contact with the exhaust of other vehicles. The poor air quality inside vehicles explains the complaints of nauseas and motion sickness after prolonged commuting trips.[18] As such, vehicle-induced emissions during commuting periods appear to contribute significantly to total human exposure.[13,63]

Various pollutants present in exhaust fumes have been measured inside vehicles, including carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), aldehydes, and particulate matter (PM). Of these, CO was the first indicator evaluated in passenger compartments and is the most commonly used marker of automotive exhaust emissions.[16,26,56,73,74] In addition to its various potential health repercussions even on healthy people, CO was found to be the leading cause of accidental poisoning deaths with fifteen hundred people dying annually due to accidental CO exposure, and an additional 10,000 seeking medical attention.[58] Unnaturally produced CO, which accounts for the majority of CO in the troposphere, is emitted as a by-product of incomplete combustion of carbonaceous fuels (e.g. gasoline, diesel, natural gas). The latter are the primary source of energy in the transportation sector which accounts for nearly 90 to 95% of CO emissions from anthropogenic sources in developed and developing countries, respectively,[35,78] with expectations of a further increase in global traffic-related CO emissions.[78] As a result, CO exposure assessment in indoor spaces including commuting vehicles has received increased interest from the scientific community.

CO standards and guidelines

Air quality standards and guidelines are usually set to protect public health and welfare and therefore include a margin of safety to protect high-risk groups of the general public including the elderly, pregnant women, fetuses, young infants, and those suffering from anemia or certain other blood, cardiovascular, or respiratory diseases. People thought to be at greatest risk from exposure to CO levels are those with ischemic heart disease who have stable exercise-induced angina pectoris (cardiac chest pain).[72,75] Table 1 summarizes various existing CO standards and guidelines for acceptable ambient and indoor air quality.

Methodologies of CO monitoring in ambient and indoor air

Because CO is one of the major indicators in IAQ investigations,[56,54,69] particularly when the main activity source is transport related,[74] investigations into CO exposure levels and potential health outcomes require accurate, precise, and representative CO measurements.[72] The basic technologies suited for micro-environmental CO monitoring are summarized in Table 2. Being very specific to CO monitoring, nondispersive infrared (NDIR) spectrometry appears to be the current preferred technology offering several advantages including non-sensitivity to flow rate, no-need for wet chemicals, reasonable independence of ambient air temperature changes, sensitivity over wide concentration ranges, and short response time.[11,70,72] Electrochemical detection, which has shown over the past decade increased versatility for field sampling,[57,72] can be very specific for CO monitoring at low cell response time and in the absence of interfering compounds such as acetylene, ammonia, and hydrogen sulfide. Calibrations for NDIR and electrochemical instruments are accomplished from gas mixtures of known concentration. Colorimetric tubes are sometimes proposed as a cost-saving alternative. This technology, which relies on factory calibration, usually falls short of giving quantitative results, and its use is limited to providing qualitative indications only.[59]

Available CO measurement methods rely on integrated, grab or continuous sampling. Integrated or time-weighted sampling involves the integrated observation of CO levels using absorbents or the collection of a sample in a container or bag at constant flow rate for later analysis in the laboratory.[8,72] The use of this method allows the monitoring of CO exposure (in ppm-minutes or any equivalent unit) over long periods of time and is therefore significantly useful in personal exposure assessment studies.[36,72] However, this method is not capable of reflecting real time variations in CO exposure that may occur during the testing period. Grab sampling is similar to integrated sampling in that it consists of drawing the sample inside a container, syringe or flexible bag, and analyzing its content later in the laboratory. However, this method allows the monitoring of the average CO concentration (in ppm or any equivalent unit) rather than exposure as experienced during the whole sampling period. Unlike the two pre-described sampling methods, continuous CO monitoring using electronic CO analyzers is the only method that is capable of reflecting temporal variations of CO level.[13,70]

In-vehicle CO exposure has been assessed using various methods and technologies. Table 3 shows that the electrochemical sensing method is increasingly being relied upon in field testing for personal exposure monitoring, probably because of its highly improved resolution and specificity, and reduced size and power requirements. In

addition, there is a clear indication of a penchant towards continuous rather than grab or integrated sampling given the need for real time CO level monitoring to interpret temporal variation patterns as a function of potential influencing factors. In some cases, grab sampling and analysis with NDIR spectrometry (gas filter correlation) was used to validate the response of the continuous electrochemical sensing method to rapid CO concentration fluctuations.

Recent advances in the design of electrochemical sensors consisted of the replacement of the liquid electrolyte with a solid polymer electrolyte (SPE), providing a more rapid response.[6,24] Nafion® (containing tetrafluoroethylene, side-chains of perfluorinated vinyl ethers with terminal sulfonic acid functionalities) is the most widely used SPE because it is highly stable in aqueous solution under a wide range of acid-base and redox environments.[24] A major limitation of Nafion® is its sensitivity to humidity.[52] Solids prepared by sol-gel chemistry (products of which include silica, vanadia, alumina, titania) are useful alternatives for Nafion® and are insensitive to humidity in cases where CO is the analyte.[24] With regards to NDIR technology, several manufacturers have miniaturized it for portable and hand held operation (e.g. Engelhard, Horiba, Fuji Electric Systems, etc.). However, a major limitation remains the relatively high cost of the latter technology.

Determinants of CO exposure inside vehicles

The identification of high trip-to-trip and within-trip variability of CO exposure in various studies is an indication of the existence of various parameters affecting CO infiltration to and dissipation from vehicle compartments. Indeed, compared to other micro-environments, vehicles have a more complex structure whereby a multitude of factors (outdoor CO concentration, roadway type, ventilation mode, weather condition, vehicle characteristics, etc.) combine interactively to determine the trend of in-vehicle CO level variations and to raise or lower CO exposure inside the vehicle micro-environment. Impacts of individual factors on in-vehicle CO exposure were comprehensively examined throughout related literature studies and presented below. Whenever available, results from the most recent studies are provided.

Outdoor CO concentration

Outdoor air characterization involves either out-vehicle or ambient CO monitoring. Out-vehicle concentrations are those measured in the air that immediately surrounds the vehicle microenvironment, whereas ambient/fixed-site concentrations are those measured at fixed-site air quality monitoring stations in the general area. Out-vehicle and ambient concentrations are seldom similar because of the ubiquitous presence of local motor vehicle traffic emissions that cannot be captured directly by fixed monitoring stations.[74] Relationships between carbon monoxide exposure inside the vehicle compartment and both types of outdoor concentrations have been examined extensively.

Out-vehicle CO concentration

In-vehicle CO concentrations were commonly reported to be closely related to the out-vehicle level.[12,16,18] In fact, vehicle compartment air originates from the air that is adjacent to the vehicle and that penetrates into it through ventilation air inlets (windows, vents), door seams and body cracks. Ott *et al.* (1994)[63] used a mass balance approach

(Equation 1) to examine the relationship between the time series of concentrations outside the vehicle to the time series of concentrations measured inside the vehicle.

$$\tau \frac{dCO_{veh}(t)}{dt} + CO_{veh}(t) = CO_{ext}(t); \quad \tau = \frac{1}{ACH} = \frac{1}{\varphi / V} \qquad (1)$$

Where τ = *time constant of the vehicle, s*
CO_{veh} = *in-vehicle CO concentration, mg/m^3*
CO_{ext} = *out-vehicle CO concentration, mg/m^3*
t = *time, s*
ACH = *air exchange rate, s^{-1}*
φ = *volume of air flow into and out of the vehicle, m^3/h*
V = *interior volume of the vehicle, m^3*

Equation 1 can be integrated and divided by the trip averaging time T (Equation 2) to obtain the average CO concentration inside the vehicle over any averaging time (Equation 3).

$$\frac{\tau}{T} CO_{veh}(T) + \frac{1}{T}\int_0^T CO_{veh}(t)dt = \frac{1}{T}\int_0^T CO_{ext}(t)dt \qquad (2)$$

Since $AVE_{veh}(T) = \frac{1}{T}\int_0^T CO_{veh}(T)dt$

And $AVE_{ext}(T) = \frac{1}{T}\int_0^T CO_{ext(}T)dt$

$$AVE_{ext}(T) - AVE_{veh}(T) = \frac{\tau}{T} CO_{veh}(T) \qquad (3)$$

Where T = *trip averaging time, s*
$AVE_{veh}(T)$ = *average CO concentration inside the vehicle, mg/m^3*
$AVE_{ext}(T)$ = *average CO concentration outside the vehicle, mg/m^3*

This relationship shows that, under the initial conditions of $CO_{veh}(0) = 0$, the average concentration inside the vehicle will be less than the average concentration outside and will differ by an amount τ/T times the concentration measured inside the vehicle at time T. For $T>>\tau$, the two averages will essentially coincide, because the right-hand side of Equation 3 will approach zero (provided that $CO_{veh}(T)$ does not increase too greatly with time) and the interior and exterior averages will be identical, except for the case when CO is being emitted by an indoor source or when CO emissions from an immediate undiluted vehicle exhaust contaminates the vehicle micro-environment directly.

Chan *et al.* (1991)[12] measured interior and exterior CO concentrations simultaneously in Raleigh, North Carolina and identified, in two different cars driven in the same region, similar in-vehicle CO concentrations indicating that pollutant concentrations inside vehicles were more strongly influenced by out-vehicle concentrations that entered into the passenger compartment rather than the vehicle make/model. Chan *et al*. (2002b)[16] reported comparable results in major commuting corridors of Honk Kong, China, whereby in-vehicle CO concentrations were greatly

influenced by the out-vehicle concentration for a standardized ventilation mode (windows and vents closed, air conditioning (AC) on recirculation mode). However, the fluctuation of the in-vehicle level was found to be far less than that of the out-vehicle level as a result of the time lag between the two levels. Similar findings were made earlier by Petersen and Sabersky (1975)[66] in Los Angelos, California (CA), by Colwill and Hickman (1980)[22] in London, England, and by Koushki *et al.* (1992)[50] in Riyadh, Saudi Arabia.

Similarly, Chan and Chung (2003)[18] examined indoor-outdoor air quality relationships for various pollutants (CO, NO, NO_2) under different ventilation modes and driving environments of Hong Kong, China. CO levels measured on highways exhibited the highest correlation coefficients between in-vehicle and out-vehicle concentrations among the tested indicators indicating that CO was more prone to penetration into the vehicle than other gases. Indoor and outdoor correlations were particularly observable for ventilation modes involving high air exchange (windows fully opened, air conditioning with fresh air intake) whereby CO level fluctuation in outdoor air was accompanied by a similar rapid response of in-vehicle air. A comparable rapid response of in-vehicle CO level to the outdoor were identified by Abi Esber *et al*. (2007)[1] in a commercial-residential area of Beirut, Lebanon, particularly for ventilation modes involving thorough indoor-outdoor air exchange. Indeed, moderate to good correlations were established between in-vehicle and car-exterior CO levels with multiple R^2 values of more than 0.322, 0.367, 0.541 for the cases "window ½-opened, vents closed", "windows opened, vents closed" and "windows closed, AC on fresh air intake, respectively. In contrast, a weak correlation was evident for the case of tightly closed cabin with air recirculation (multiple R^2.less than 0.024).

The trend of CO level variation inside vehicles was therefore consistently found throughout numerous studies to be closely related to the out-vehicle trend with more gradual variations. However, the identification of in-vehicle to out-vehicle CO level ratios that are greater than 1 introduced the possibility of having either an immediate external CO source that is not being detected by the out-vehicle sampling line or an internal self-contamination effect caused by in-vehicle sources such as engine vapor or vehicular exhaust intrusion across the fire wall, from underneath the vehicle, or from the draft area behind the vehicle. While Petersen and Allen (1982),[65] Koushki *et al*. (1992)[50] and Clifford *et al.* (1997)[21] reported in-vehicle to out-vehicle ratios lower than 1 (0.92, 0.84 and 0.7) in Los Angeles, California, Riyadh, Saudi Arabia and Nottingham, United Kingdom, respectively, Chan *et al.* (1991)[12] reported a median ratio of approximately 1.1 in Raleigh, NC. The latter was attributed to the different heights of inlets between the exterior sampling lines (placed in the middle of the car roof), and the ports of the vehicle's intake mechanism (front hood and side windows) that receive greater contamination (engine running loss emissions and tailpipe exhausts from other vehicles which have a more direct impact on in-vehicle concentrations than the measured car exterior concentrations). Likewise, Van Wijnen *et al.* (1995)[73] identified higher CO concentrations inside rather than outside vehicles driven along busy routes of Amsterdam, the Netherlands, and explained that it is the effect of vehicle exhaust of preceding car entering into the vehicle compartment through the ventilation system. Chan *et al*. (2002b)[16] also reported median ratios greater than 1 in urban residential, rural, industrial areas and along highways of Hong Kong, and suggested the internal engine compartment as a possible additional source of CO emissions inside the vehicle. Chan and Chung (2003)[18] reported ratios of up to 1.8 in urban areas, 8 in tunnels and 10

in countryside depending on the used ventilation mode. The relatively high in-vehicle to out-vehicle CO ratio compared to other pollutants suggested the possibility of a likely source of CO inside the vehicle. Abi Esber *et al*. (2007)[1] identified ratios of 1.2, 1.5 and 2.1 for the ventilation modes "windows opened, vents closed", "windows closed, AC on fresh air intake" and "window ½-opened, vents closed", respectively suggesting a high probability of occurrence of a self-polluting condition whereby in-vehicle air is contaminated by an indoor source, e.g. engine emissions or exhaust fume return and ingression into the cabin.

Ambient CO concentrations

Several studies have invariably questioned the suitability of utilizing fixed site monitoring data for short term exposure assessment at the street micro-level.[3,23,33,45,62,66] In general, concentrations are expected to be lower at the fixed site stations because of their distance from the traffic and their sampling height above the commuters breathing zone.

In Raleigh, NC, Chan *et al*. (1991)[12] observed that median CO concentrations reached 11 ppm inside test vehicles whereas median levels at fixed-site monitors were only 2.8 ppm. Likewise, Liu *et al*. (1994)[55] measured a mean in-vehicle CO level of 11 ppm against a mean fixed-site CO level of 8.3 ppm in Taipei, Taiwan. The representativeness of roadside fixed stations in estimating target group exposures (students, adult workers, roadside business workers, bus drivers) was evaluated through Monte Carlo simulations. It was found that the measurements from fixed roadside stations underestimated the short-term CO exposure levels (l hour (hr)) of all groups because of the dispersion effect through which CO concentrations become lower at roadside stations, which are normally located several meters away from the side lanes of traffic roads and above the commuter's breathing zones (1-1.5 m) where the actual exposure occurs. Flachsbart (1999a)[35] reported that 14 of 16 in-vehicle exposure studies performed in the US between 1965 and 1992 simultaneously measured both ambient and passenger cabin concentrations. Regardless of the study, the mean CO concentrations inside vehicles always exceeded the mean ambient CO concentrations measured at fixed-site monitors, with a ratio ranging from 2 to 5 regardless of when the study was conducted. The ratio exceeded 5 for two studies carried out during the early 1980s. Flachsbart (1999b)[36] presented a statistical analysis of passenger exposure to CO inside a motor vehicle as it traveled a coastal highway in Honolulu, Hawaii and identified factors that affect cabin exposure and their interrelations. Among these, ambient CO concentration had a modest explanatory power to predict cabin exposure (R^2=0.25) relative to other factors such as average vehicle speed and in-vehicle CO concentration on previous links. Zagury *et al*. (2000)[79] reported a mean in-vehicle (taxi) CO level of 3.8 against an ambient level of 1 ppm on average in Paris, France. More recently, Duci *et al*. (2003)[27] found after comparison of ambient to in-vehicle CO level data that there is evidence that fixed-site stations cannot assess human exposure accurately whereby CO concentrations in every tested mode of transport were higher than those recorded at the monitoring station. Similar to other studies, the unrepresentativeness of roadside fixed stations data in estimating CO exposure was attributed to dispersion effects. Likewise, Abi Esber *et al*. (2007)[1] identified weak correlations (multiple R^2 = 0.002 to 0.214) between 1-min average in-vehicle CO levels and 1-min average ambient CO levels suggesting that ambient fixed-site recordings are weak predictors of in-vehicle CO levels.

Roadway/landuse type, traffic density and vehicle speed

The type of commuting route has a direct relationship with the in-vehicle CO level.[14] Indeed, a roadway location and functional type are surrogate measures of several factors such as traffic volume and speed which are interrelated and are themselves affected by a roadway's capacity. They affect total vehicular emissions and corresponding rates.

Roadway/landuse type

Early studies on in-vehicle exposure to vehicle-induced emissions reported that commuting routes affect CO exposure significantly.[7,12,23,32,73] Recently, Chan and Liu (2001)[14] measured CO exposure in three popular transport modes of Honk Kong along three types of commuting routes namely urban-urban, urban-suburban and urban-rural. Vehicles traversing between urban and suburban areas had higher in-vehicle CO levels among all three commuting routes given the presence of tunnels. Chan *et al*. (2002b)[16] measured CO levels inside experimental vehicles traversing major commuting corridors of Honk Kong and reported the lowest in-vehicle CO levels in rural areas, while the highest concentrations were recorded in urban commercial and urban mixed commercial/residential areas. Similarly, among seven standard urban routes of Athens, Greece, Duci *et al*. (2003)[27] identified the highest CO levels on the most heavily traveled routes.

Invariably, the differences between measured levels were attributed to traffic density and roadway configuration. For instance, CO levels are often far greater in tunnels than in open roads due to the absence of adequate ventilation and dispersion. The average in-vehicle CO exposure level of a commuter in a tunnel micro-environment was reported to be 2-3 times greater than along urban and suburban roads depending on the length of the tunnel, and the inherent traffic volume and ventilation rate.[14] In urban commercial or mixed commercial/residential areas, high traffic volumes are normal occurrence. Vehicles are required to stop at road intersections resulting in congestion along the route. The street canyon effect resulting from high-rise buildings contributes to the accumulation of emissions at street level which leads to higher out-vehicle CO concentration and subsequently higher in-vehicle CO.[12,27] In contrast, routes between urban and rural areas are surrounded by open spaces with no to minimal tunnels and buildings. Hence, less CO accumulates along the road vicinity and lower in-vehicle CO levels are measured.[14]

Traffic density

In-vehicle CO level was commonly reported to increase with increasing traffic density as a result of increased emissions and hence out-vehicle levels. Ott *et al.* (1994)[63] examined nine covariates (ambient CO at two fixed stations, atmospheric stability, seasonal trend function, time of day, average surrounding vehicle count, trip duration, time stopped at lights, and instrument type) to explain the variability of in-vehicle mean CO exposures observed during trips along an urban arterial highway of California, El Camino Real. Among the various examined covariates, the fraction of time stopped, which is a measure of traffic volume, was one of the best predictors of in-vehicle CO concentrations.

Flachsbart (1999b)[36] also presented statistical models of passenger exposure to depict the relationship between in-vehicle exposure to CO on three links of a Honolulu highway and various factors that could affect it. The models showed that cabin exposure

was affected by travel time and average vehicle speed which constitute indirect measures of traffic flow. Lighter traffic flow lowered passenger cabin exposures.

Other studies identified concomitant increases in in-vehicle CO level and traffic volume. Peterson and Allen (1982) found that the CO level is highest in stop and go traffic.[65] Chan and Liu (2001)[14] reported that high traffic volume in commercial districts as a result of long busy routes and intersection traffic jams increased in-vehicle CO exposure. Vehicular exhaust, combined with the street canyon effect usually exhibited at the street level, led to higher out-vehicle CO concentration and subsequently higher in-vehicle CO level. Chan *et al.* (2002a)[15] reported higher in-vehicle CO levels in Guangzhou, China as a result of the rapid increase in traffic volume over the last decade. In Guangzhou, the slow driving speeds and frequent acceleration, deceleration and idling greatly affect in-vehicle air quality.[80]

Vehicle speed

Driving at low speed or in stop and go traffic with frequent idling increases commuter exposure for several reasons. First, the ventilation of the passenger compartment uses the pressure difference between the scuttle and the ventilation exits which is proportional to the square of the vehicle's speed.[47] It is thus expected that slower speeds would lower vehicle air change rate and increase pollutant buildup inside the vehicle cabin. Furthermore, heavy traffic and slow speed result in higher exhaust emissions and lower inter-vehicle distance thus increasing exhaust penetration into the vehicle.

Flachsbart *et al.* (1987)[32] reported that along commuter routes in Washington DC, in-vehicle CO exposures fell by 35% when test vehicle speeds increased from 10 to 60 miles per hour (mph) (16 to 97 kilometer per hour (km/h)). In a similar study in Riyadh, Saudi Arabia (Koushki *et al*., 1992),[50] in-vehicle CO exposures fell by 36% when vehicle speeds increased from 8.7 to 34.2 mph (14 to 55 km/h). Clifford *et al*. (1997)[21] reported a comparable impact of vehicle speed on average external CO levels measured outside an experimental van traveling in Nottingham, United Kingdom. An increase of 5 mph (8 km/h) resulted in a reduction of 4.3 ppm in CO external level. The latter reduction would obviously be translated in a similar response of in-vehicle air given the close relationship between internal and external measurements as stressed in the study. Flachsbart's (1999b) statistical models relating passenger CO exposure to various potential influencing factors support the latter results whereby vehicle speed predicted CO cabin exposure CO fairly well (multiple $R^2 = 0.507$) (Equations 4 to 6).[36]

$$AVE_{veh} = 229.06/(VS)^{1.123} \quad (4)$$

$$AVE_{veh} = 1.4(T)^{1.123} \quad (5)$$

$$VS = 1.55/(T/60) \quad (6)$$

Where AVE_{veh} = *average CO concentration inside test vehicle, ppm*

T = *travel time, min*

VS = *test vehicle's average speed, mph*

1.55 = *length of the link, miles*

Ventilation mode

Ventilation mode is the most studied operational characteristic as a potential determinant of in-vehicle CO level. The envelope of a vehicle normally acts as a shield against the contaminated outdoor air in urban areas;[37] however, the degree of protection depends on several factors the most important of which is the body condition that determines the leakage inlet flow and the used ventilation setting. Depending on the status of windows, air vents and air conditioning settings, the time constant/air change rate of the vehicle can vary considerably. Different values of vehicle air change rates were reported as a function of ventilation setting (Table 4).

Chan *et al*. (1991)[12] examined the effect of three different ventilation modes (windows and vents closed with air conditioning on; windows closed, vent fan on with air conditioning off; and front windows ½-opened, vent fan on with air conditioning off) on in-vehicle CO level in Raleigh, NC, and found a very slight in-vehicle concentration difference (1 ppm) between the various tested conditions. While the conclusion was that the ventilation mode had no significant impact on in-vehicle CO exposure, findings made by subsequent studies were invariably different.

Chan and Liu (2001)[14] compared in-vehicle CO levels in various air-conditioned and non-air-conditioned popular transport modes in Honk Kong, China. While for both ventilation modes, the in-vehicle CO level was governed by the out-vehicle CO, a dampening effect was observed in the case of air-conditioned vehicles. The rapidly changing out-vehicle CO level caused a greater fluctuation of in-vehicle level in non-air-conditioned vehicles than in air-conditioned vehicles as a result of the higher air exchange rate.

In a similar field survey in Guangzhou, China,[15] in-vehicle CO levels were greatly influenced by the ventilation condition. While air-conditioning was found to be an effective way to minimize particulate exposure, the CO level in an air-conditioned taxi was significantly higher than that in a non-air-conditioned taxi. The low air exchange rate resulting from the frequent closure of fresh air vents, combined with the presence of an internal source (leakage from the vehicle itself) increased the accumulation of CO level in the air-conditioned taxi. In contrast, no significant difference was discerned in average CO level between an air-conditioned and a non-air-conditioned bus because of the large compartment volume of a bus which can result in less noticeable build-up within the time frame of the test.

Chan and Chung (2003)[18] examined the simultaneous impact of ventilation mode and driving environment on pollutant penetration into the vehicle. In-vehicle to out-vehicle concentration ratios varied drastically from ventilation mode to the other and in different environments. While natural ventilation gave the lowest in-to-out vehicle ratio in countryside commutes, air-recirculation mode was suggested for trips in polluted congested areas. CO was the only exception to the latter conclusion as a result of a likely source of CO inside the vehicle which induced CO buildup when AC was set on air recirculation.

In-vehicle CO concentration profiles were monitored by Abi Esber *et al*. (2007)[1] under several ventilation modes in a typical heavily traveled commercial-residential urban area of Beirut, Lebanon. The highest mean CO exposure was experienced for the "windows closed, vents closed" and "windows closed, AC on recirculation" ventilation settings. The exposure was less significant (2 to 3 times lower) for other ventilation modes ("windows closed, vents opened"; "one window opened, vents closed"; "one window opened, vents opened"; "one window half opened, vents closed"; "all windows

opened, vents closed"; "windows closed, AC on fresh air intake"). Furthermore, the pattern of variation of indoor CO concentrations differed between the various ventilation modes. For the cases "windows closed, vents closed" and "windows closed, AC on recirculation", in-vehicle CO concentration continuously increased over the testing period to reach near steady state within 40 to 45 minutes as a result of the tight closure and the absence of dilution. In contrast, CO levels for the other ventilation modes exhibited a fluctuating pattern suggesting an adequate exchange and dilution with the outdoor air.

In order to determine the effectiveness of ventilation in flushing out in-vehicle pollutants, a number of researchers performed investigations of carbon dioxide (CO_2) exposure inside vehicles' cabin. Although not considered toxic, CO_2 is a useful indicator of the effectiveness of air exchange inside indoor micro-environments and may cause suffocation when the concentration is high enough to displace oxygen. In this context, Cheng *et al*. (2006) measured CO_2 levels inside the cabins of commercial trucks passing across the border between Canada and the US and found them to be below the recommended value most of the time probably as a result of the frequent opening of windows.[20] In contrast, Li *et al.* (2006) examined the concentrations of various pollutants inside air-conditioned passenger cars of the Bejing Ground Railway Transit System, and reported them to be acceptable except for CO_2 advocating thus the need for improving the ventilation inside passenger cars.[53] Chan (2003) monitored CO_2 inside air-conditioned and non air-conditioned buses in Hong Kong and reported that the exposure level to CO_2 inside an air-conditioned vehicle is strongly dependent on the number of passengers and reached at some instances ten times the concentration prevailing outside the vehicle when the air-conditioned bus was full, thus exceeding acceptable air quality guidelines. It was also found that CO_2 levels for a non-air-conditioned bus remained low due to better air exchange between in- and out-vehicle environments.[17] Coupled to the previously described findings from CO monitoring inside air-conditioned and non air-conditioned vehicles, results of CO_2 exposure monitoring indicate that there is a general consensus that the use of air conditioning may impede cabin air exchange fostering the accumulation of pollutants inside a vehicle.

Weather conditions

Motor vehicle emissions are usually the highest during the first few minutes of vehicle operation because emissions combustion efficiency improves as engine temperature rises. Indeed, the magnitude of the engine start-up emissions is a function of initial engine temperature with highest emissions being experienced when ambient temperature is lowest, i.e. in winter season. Even after the vehicle has been running for several minutes and its engine has reached sufficiently high temperature, the stabilized emission rates will slightly fluctuate depending on various parameters including weather conditions such as ambient temperature and humidity,[71] with higher emissions experienced during lower temperature and higher humidity.[9] Higher emissions is invariably translated into greater ambient CO levels, and subsequently increases CO cabin exposure. Wind speed and direction determine the magnitude and pattern of CO dispersion in the micro-environment immediately outside a vehicle influencing thus the in-vehicle micro-environment. Atmospheric pressure, presence of rainfall and depth of inversion layer are other weather parameters with potential influence on in-vehicle CO levels.

In an attempt to explain the variability of in-vehicle mean CO exposure on an arterial highway in California, Ott *et al*. (1994)[63] examined its relationship to nine covariates (the details of the study are summarized in section VI) and found that a seasonal trend term (Equation 8) and a measure of traffic volume (the proportion of the time stopped) were the best predictors (multiple R^2 = 0.68) of average in-vehicle CO exposure (Equation 7). In effect, they observed that in-vehicle CO concentrations were higher during winter than during summer, due possibly to the long warm-up time required in cold conditions and the greater frequency of ground-based inversions in winter.

$$Y = 4.2625 + 0.365X_4 + 1.5478 \ln X_8 \quad (7)$$

$$X_4 = \cos(2\pi d / 365.25) \quad (8)$$

Where Y = *logarithm of mean CO exposure*
X_4 = *seasonal trend function*
X_8 = *proportion of trip that the vehicle was stopped*
d = *day number with d=1 on January 1 and d=365.25 on December 31*

A comparable seasonal impact on ambient CO concentration was reported more recently by Duci *et al*. (2003)[27] who found that the difference between summer and winter mean ambient CO level is significant, with winter levels being higher.

In Hawai where temperatures were seldom cold enough in winter to increase CO emissions from motor vehicles and passenger cabin exposures, Flachsbart (1999b)[36] correlated passenger exposure to atmospheric pressure (Equation 9) and wind speed (Equation 10). Wind direction was also found to be an important factor, with northerly winds, which were prevalent during most of the study period, reducing cabin exposures by dispersing emissions on westbound lanes of the study site where exposures were measured. In contrast, southerly winds increased exposures by sending emissions from eastbound vehicles to the westbound lanes of the study site. Exposure models for wind direction, ambient temperature, depth of inversion layer and presence of rainfall on the study site could not be developed.

$$AVE_{veh} = -10.82 + 0.493(AP) - 0.00197(AP)^2 \quad (9)$$

$$AVE_{veh} = 22.81 - 0.75(WS) \quad (10)$$

Where AP = *atmospheric pressure at sea level at Honolulu International Airport, mbar*
WS = *hourly wind speed at Honolulu International Airport, mph*

Clifford *et al*. (1997)[21] monitored CO concentrations inside and outside an experimental van (concentration of the external air as it entered the heater and that inside the van) in Nottingham UK and examined relationships between average daily external CO levels and precipitation and wind speed data obtained from a meteorological station approximately 5 miles to the south of the city. Precipitation appeared to have little effect while increased wind speed caused a fall in concentration and greater spread with data skewness at few extreme points. A similar weak

relationship between CO exposure and wind speed was identified previously by Cortese and Spengler (1976), Petersen and Allen (1982) and Dor *et al*. (1995).[23,26,65]

Zagury *et al*. (2000)[79] measured taxi drivers exposure to various pollutants in Paris, France. At higher wind, lower CO concentrations were recorded (2.8 and 4.2 ppm, respectively). A strong relationship with wind speed (r^2= 0.52) was also reported by Gomez Perales *et al*. (2004)[39] for buses and minibuses. CO concentrations decreased by 12% and 18% in the respective transport modes when wind speed increased by 1 m/s.

Abi Esber *et al*. (2007)[1] examined the possibility of in-vehicle levels being influenced by wind speed data collected at a fixed monitoring station located near the study trajectory in a commercial-residential area of Beirut, Lebanon. Regression analysis of 1-min-average in-vehicle to car-exterior CO level ratio against 1-min-average wind speed for a number of field testing trips showed no correlation between the two variables, possibly as a result of the difference between wind speed data measured at the fixed monitoring station and actual wind speed at the street micro-level where the closed packing of buildings influences wind flow patterns.

Vehicle characteristics

Vehicle age, type and make are potential determinants of in-vehicle CO exposure. Body cracks associated with older models favor in-vehicle pollutants penetration and increase the probability of occurrence of a self polluting effect. Furthermore, design parameters specific to individual vehicle types and makes e.g. vehicle size, vehicle and ventilation air intake height, vehicle air change rate, etc. are other potential determinants of cabin CO exposure.[14] While the influences of vehicle type were frequently examined, those of vehicle make were not.

Chan *et al*. (1991)[12] measured CO concentrations inside two sedans of different ages (a 1987 Mercury Sable four-door sedan with 26,856 miles and a 1983 Mercury Marquis four-door sedan with 62,856 miles), driven together under similar ventilation conditions, and exposed to similar roadway concentrations of CO each time. No significant differences between the two vehicles were discerned.

Several studies reported that in-vehicle CO exposure varied by mode of travel / vehicle type. Chan *et al*. (1999)[13] conducted a comprehensive survey from November 1995 to July 1996 in Hong Kong to assess the effect of traffic-induced emissions inside different commuting micro-environments on commuter exposure. The results indicate that commuter exposures in decreasing order of measured pollutant level for respective commuting microenvironments are: the private car, the group consisting of a light bus, bus, tram, MTR (Mass Transit Railway) and train, and finally the ferry.

Chan and Liu (2001)[14] conducted a similar study that compares CO exposure in selected popular commuting modes of Honk Kong including taxis, minibuses and buses. The concentration levels increased in the same order: bus, minibus and taxi. The concentration difference was attributed to the vehicle height which directly affects breathing height. The latter is defined as the height from the road surface to the respiratory level inside the vehicle and it is about 0.9, 1.2 and 1.5 m for taxi, minibus and lower deck bus commuters, respectively. Since vehicle exhaust is generated near the road surface and the pollutant levels are higher at lower vehicle height, passengers are then exposed to highest CO levels inside taxis. Another potential explanation was the vehicle size which differed for the three tested commuting modes. The larger the vehicle size, the lower is the CO level. Lowest CO level was measured inside the bus

compartment because concentrations are diluted in a larger volume. In contrast, taxis exhibited the highest CO levels because their size is smallest.

Chan *et al*. (2002a)[15] examined commuter exposure to CO in air-conditioned and non-air-conditioned public transportation modes of Guangzhou, China. The highest average CO level was obtained in an air-conditioned taxi. In non-air-conditioned taxis, air-conditioned bus and non-air-conditioned bus, the average CO level was 1.5 to 3.5 times lower. The high CO levels in taxis and concentration difference between a taxi and a bus inferred that the in-taxi CO levels were more frequently contaminated by the presence of internal sources associated with the leakage from the taxi itself (poorly-maintained engines or exhaust systems in fairly old taxis - > 6 years - with high mileage). The effect of vehicle height was outweighed by the effect of self-contamination.

Dependence of CO levels to transport mode used was also tested by Duci *et al*. (2003)[27] who sampled simultaneously private cars, buses and trolley modes in Athens, Greece. The results showed significantly higher mean CO levels in the private car than those in the bus and trolley due to differences in the vertical gradients of CO levels along the road (related to vehicle height).

Worldwide in-vehicle CO concentrations

The trend towards reducing global traffic-related emissions will potentially contribute to reducing in-vehicle CO exposure. Indeed, in 1995, over 85% of all new, gasoline-powered vehicles had either a three-way or oxidation-only catalytic converter.[35] However, future progress in reducing global emissions from mobile sources is threatened by accelerating growth rates of urban areas and motor vehicle ownership and use, both of which exceed the global rate of population growth due mainly to latent demand in developing countries or countries in transition. [35,78] In addition, the decline in public transport usage, inadequate urban transport regulations and legislation, and weak or fragmented urban transportation institutions are aggravating the problem in developing countries.[78]

Comparison of in-vehicle CO exposure findings between various countries helps to pinpoint the regions of the world where commuters are at greater risk from cabin CO exposure. Furthermore, the comparison of old and recent data in the same country permits the identification of control or management measures, and the evaluation of national emission reduction strategies. Note at the onset that comparisons are usually constrained by differences in sampling methods, date, time and duration, traffic profile, and meteorological conditions and can thus provide only a global view of observations.[42]

International comparisons of in-vehicle CO exposure

A number of studies have examined CO exposure inside vehicles driven on various types of roadways worldwide. Results of CO measurements inside vehicles in urban areas are presented in Tables 5 and 6. The data reflect a general view of CO levels inside vehicles for various ventilation modes. In studies where mean CO levels were reported for individual ventilation conditions [14,16] an average value was computed.

The comparison of the results confirms that in-vehicle CO levels are higher in automobiles than in other larger closed transit modes. Levels are generally lower than the 1-hour IAQ guideline set by CARB (20 ppm) and AAQ guideline set by WHO (26

ppm), with the exception of Mexico City where remarkably high CO levels exceeding CARB and WHO 1-hour guidelines were recorded in all types of vehicles in 1991 and in minibuses in 2002, and Athens where levels recorded in 2003 inside automobiles exceeded only the CARB guideline. The level recorded in 2005 at Beirut inside an automobile (20 ppm) was at the CARB 1-hour guideline but relatively high if compared to levels recorded in other international urban areas.

While minimal risk seems to be associated with short term trips of less than 1 hour, levels recorded inside automobiles driven in Paris (1991-1992), Athens (1998-1999), Hong Kong (1995-1996), Taipei (1989-1991) and Beirut (2005) exceeded the 8-hour CO exposure guidelines (WHO; ASHRAE: 9 ppm). This was also the case for other transport modes driven in Mexico (1991; 2002), and Athens (1998-1999). Higher potential exposure risk is generally associated with longer trip durations.

Evolution of in-vehicle CO exposure

A long term downward trend in commuter CO exposure levels can be discerned due to tighter automobile CO emission standards coupled with a replacement of old vehicles with newer models, particularly in developed countries.[35] Figure 1 illustrates the latter trend. Mean CO concentrations fell from 37 ppm in 1965, as reported by Haagen-Smit (1966)[41] in a study in Los Angeles, California, to 3 ppm in 1992 in a study by Lawryk *et al*. (1995)[51] in suburbs of New York City implying a reduction of 92% over a 27-year period. Similarly Ott *et al*. (1994)[63] measured in-vehicle CO concentrations on 88 standardized trips over a one-year period in 1980-81 on a suburban highway near San Jose, California and reported a mean CO concentration of 9.8 ppm. In 1991-1992, a survey of the same highway with a similar methodology reported that the mean in-vehicle CO concentration had dropped to 4.6 ppm implying a reduction of 46.9% over an 11-year period.[35] A more recent study in California by Rodes *at al.* (1998) indicated further reduction in in-vehicle CO exposure with an average level of 3.6 mg/m^3 (3.1 ppm) in Sacramento and Los Angelos.[68]

Similarly, in the United Kingdom, in-vehicle CO levels declined from 1976 to 1995 due to the decrease in CO produced per kilometer traveled, coupled with the decision by the Economic Commission for Europe to adopt CO emission standards for old motor vehicles that required the use of three-way catalytic converters.[35] In 1974, the average CO levels inside 11 automobiles driven in London ranged from 12 to 60 ppm.[22] The study conducted in 1995 reported an average CO exposure of 3 to 22 ppm in Nottingham.[21] The exposure dropped further in 2003 to a level of 1.3 ppm in passenger cars driven across London.[49]

In contrast, in Hong Kong, results of in-vehicle CO levels in buses and minibuses in 1995-1996[13] were not significantly different from those reported by a later study conducted in 1999[14] inside the same micro-environments with the most recent data unexpectedly higher for minibuses than the older data. This result could be attributed to seasonal differences since data of 1999 were recorded during the winter (January to April) and those of 1995-1996 during the winter/early summer (November to July), or to the vehicle size. In fact, CO levels measured inside automobiles decreased between the years 1995-1996[13] and 1998-1999[16]. While Chan *et al*. (1999)[14] measured an average CO level of 10.1 ppm, the level measured by Chan *et al*. (2002b)[16] was 1.9 ppm.

There also has been a substantial decrease in CO exposure inside various types of transport modes in Mexico based on results from three studies conducted 12 years apart.

In 2002 and 2003, Gomez-Perales *et al*. (2004; 2007)[39,40] measured CO levels inside minibuses, buses and metros that are lower than levels measured in the same micro-environments and on the same routes of Mexico City in 1991[30] (Figure 2). This can be partially attributed to measures adopted by the government to reduce CO emissions including improvement of fuel quality, the introduction of catalytic converters, and a program of inspection and maintenance.[39]

Modeling of in-vehicle CO exposure

Field measurements constitute the most trustworthy method of assessing in-vehicle exposure to vehicular emissions and hence have been intensely relied upon for this purpose. However, the high cost associated with implementing field monitoring programs creates a need for alternate complementary assessment tools such as mathematical modeling to improve the understanding of vehicle-induced emissions and to simulate concentration profiles with corresponding human exposures under varied conditions. In this context, various models have been developed or used to simulate pollutant concentrations inside commuting vehicles (Table 7), with mass balance and statistical models being the most common.

Mass balance models generally use the box mass balance concept (Equation 11). For non-reactive pollutants ($k \approx 0$), no air filtration ($f = 0$) and internal sources ($S = 0$), and complete mixing, the formulation of the model becomes similar to the model reported by Ott *et al*., 1994[63] (see Equation 1).

$$dM = (1 - f)\varphi CO_{ext}\,dt - \varphi CO_{veh}\,dt - kM dt + S dt \qquad (11)$$

Where M = *mass of indoor contaminant, mg*
f = *fraction of the contaminant filtered in the entering air*
k = *rate of decay, settling and removal,* h^{-1}
S = *internal source emission, mg/h*

Heinsohn *et al*. (1993)[44] predicted in-vehicle CO concentrations with fresh air intake as external CO source using a three-dimensional sequential box model (SBM) and was able to demonstrate the validity of the well-mixed assumption for a vehicle circulating in a queue and with CO-laden outdoor air intake as the only CO source. Likewise, Park *et al*. (1998)[64] used a mass balance model developed by the USEPA to estimate in-vehicle CO concentrations following air bag deployment and noted the large variation in air change rates experienced by vehicles moving in "stop and go" traffic. Indeed, the air exchange rate of such a vehicle is dependent upon many parameters including window conditions (open or closed), vehicle speed, outside wind speed (when windows are open), the mechanical ventilation system of the automobile, and the temperature difference between the inside and outside of an automobile (specially when windows are closed without mechanical ventilation). Abi Esber *et al*. (2007)[1] also used a mass balance model developed by USEPA to simulate in-vehicle carbon monoxide (CO) concentration profiles based on car-exterior levels and trip-specific movement record. Coupling of field monitoring efforts and mathematical simulations allowed the determination of sources contributing to in-vehicle exposure and the demonstration of occurrence of CO ingression into the vehicle compartment from the engine combustion and/or exhaust return of the test vehicle.

On the other hand, statistical models of exposure to motor vehicle emissions enable the identification of factors that contribute to individual exposure levels and of interrelations between these factors. While univariate models of cabin exposure predict cabin exposure based on one single variable, the more powerful multivariate models are based either on linear or non-linear combinations of several variables describing potential influencing factors to determine cabin exposure. While statistical models are powerful in the domain of results interpretation, their empirical nature limits their applicability in case studies where other settings and conditions are encountered. Major developed multivariate statistical models are outlined in Table 8. The latter models, developed to describe in-vehicle exposure on highways, relied on a full range of observations extending over long periods of time increasing thus their generality and applicability to other similar settings. Indeed, based on a set of 88 trips testing for the influence of nine possible predictors, Ott *et al*. (1994)[63] could best predict (R^2 = 0.68) average CO exposure by a regression model including a seasonal trend term (cosine function of the day of the year) and traffic volume (proportion of time stopped) terms. The model was described later by Flachsbart (1999b)[36] to be powerful and elegant as it could explain in-vehicle CO exposure in function of two variables only. The inclusion of ambient CO concentration in the model could slightly improve its power. The insights of the latter study inspired Flachsbart (1999b)[36] to conduct a similar analytical study along a comparable highway setting. The developed models relied on a set of 80 trips and tested for 15 different variables. Consistently with findings from the previous study, the models showed that cabin exposure was affected mainly by travel time and average vehicle speed (R^2 = 0.69) which constitute indirect measures of traffic volume, in addition to a seasonal term expressed by wind direction and speed. Such exposure models can be used both to improve the understanding of factors affecting CO exposure and to make predictions of average exposure based on easily measurable variables.

Conclusions, limitations and research needs

Traffic-related exposure assessment studies are important because they provide the scientific basis for pollution control actions and assist in setting priorities in taking environmental control measures.[37] In recent years, an increasing number of in-vehicle CO exposure studies have been reported. Monitoring technologies varied from NDIR spectrometry to electrochemical sensing with the latter being capable of providing real time tracking of CO concentration evolution with highly improved resolution and specificity, and reduced size and power requirements. Examination of relationships of in-vehicle CO exposure to various potential influencing factors showed positive correlations with out-vehicle CO levels, traffic density, and ambient humidity and negative correlations with vehicle speed, wind speed, ambient temperature, and vehicle size. Ambient CO measurements at fixed roadside stations were found to underestimate in-vehicle CO exposure because of the dispersion effect along roadside stations generally situated several meters away from traffic roads and above the commuter's breathing zones.

High CO levels exceeding international indoor CO exposure guidelines were measured inside vehicles driven in numerous cities worldwide. Implementation of motor vehicle emission standards and inspection and maintenance programs, coupled with the growing use of advanced catalytic converters, cleaner burning fuels and personal computers for telecommuting and teleshopping are all expected to reduce the

CO exposure of urban commuters. However, the downward trend is threatened by accelerating growth rates of urban areas and motor vehicle ownership and use, and sometimes weak and fragmented regulatory frameworks, particularly in developing countries. Undoubtedly, this adds the in-vehicle CO exposure to the list of environmental priorities to be continuously monitored and managed and explains the increasing interest in in-vehicle CO exposure studies in recent decades.

Though the number of in-vehicle CO exposure studies is steadily increasing, inherent field testing strategies suffer from various uncertainties and limitations. For instance, differences among measuring methodologies, lack of strict quality assurance and control, and lack of precise description of testing conditions (seasonal and meteorological characteristics, landuse, ventilation, trip duration, trip start and end time) often make it difficult to generalize findings or compare between studies. Furthermore, there are uncertainties associated with the accuracy of the data collected by the increasingly used continuous electrochemical methods due to their affordibility. Indeed, the time lag between the change in CO concentration inside a moving vehicle and an electrochemical sensor reaching its final steady-state reading raises a concern about whether this methodology can yield accurate results when the tested CO concentration is rapidly fluctuating, as is likely the case for in-vehicle CO level monitoring under variable traffic conditions. Another constraint is the positive interference with various gases including hydrogen gas which is present in the exhaled breath of some persons as a result of metabolism of certain foods.

In addition to actual field measurements, mathematical modeling was sometimes used either to simulate in-vehicle CO concentration profiles or to improve the understanding of vehicle-induced emissions. Mass balance models could elucidate various issues related to the origin, fate and transport kinetics of CO accumulated inside a vehicle compartment. Statistical models were able to determine in-vehicle CO exposure as a function of one or more influencing factors and at variable explanatory powers, with the most powerful ones being multivariate models relating cabin exposure to various predictor variables.

Future research needs should emphasize primarily the use of standard protocols to ensure accurate and defensible results and to enable inter-comparisons between various studies developed either in different countries, or in the same country but at different time scales. Reference measurement methods and standard trip durations are advised. Studies that re-examine in-vehicle CO exposure in a particular region where it was previously examined should make sure to use consistent methodologies to facilitate comparisons and to document the effect of emission control programs on commuter exposure. In addition, individual in-vehicle CO exposure studies should cover various pollutants, roadways, seasons, ventilation modes, to flush out case specific results.

Analytically, evaluation of CO monitoring with electrochemical sensors is called for to determine their sensitivity, stability, and selectivity and to establish equivalency to high-performance NDIR spectrometry methods. Furthermore, the relatively low CO levels measured inside vehicles creates the need to account for the concern of positive interference when employing electrochemical devices.

In the domain of mathematical modeling of cabin exposure, possibilities of prediction of in-vehicle CO levels based on routinely measured parameters such as wind speed, ambient temperature, traffic flow, ambient CO level, etc. have to be stressed in order to build powerful assessment tools capable at replacing traditional costly field monitoring programs.

Tables

TABLE 1. CO standards and guidelines as established by international agencies

Type of Standard/ Guideline	*Source*	*Details*	*Standard/Guideline*	
			Concentration (ppm)	*Averaging Period*
Ambient air quality (AAQ)	USEPA, 2000[72]	National AAQ Standards (NAAQS)	35	1-hr
			9	8-hr
	WHO, 1999[75]	AAQ guideline	87	15-min
			52	30-min
			26	1-hr
			9	8-hr
Indoor air quality (IAQ)	CARB, 2004[10]	IAQ guideline	20	1-hr
	Health Canada, 2004[43]	Residential acceptable short term exposure range	≤11	8-hr
			≤25	1-hr
	ASHRAE, 1989[5]	Recommended level for indoor air pollution	9	8-hr
	OSHA, 2002[60]	Permissible exposure limit	50	8-hr
	ACGIH, 1994[2]	Time weighted average	25	8-hr

TABLE 2. Instrumentation for CO monitoring inside micro-environments[59,77]

Technology	*Guidance*	*Typical Vendors*	*Comments*
Electrochemical Sample air is passed through a cell wherein oxidation of CO produces a signal that is proportional to concentration	Woebkenberg and McCammon (1995) Range: 1-100 ppmv Accuracy: ±5% Precision: ±5% MDL[a/]: <1 ppmv	Capteur, Draeger, Safety, Figaro, Gas Tech, KD, Interscan, Metrosonics MSA, Neotronics, Sensidyne	Can be very specific for CO; portable units available. Specificity in industrial settings is achieved by inlet scrubber of uncertain efficiency for some chemicals
Nondispersive Infrared (NDIR) Spectrometry Absorption of infrared radiation by CO in a sample cell is compared to that of a reference (CO-free) absorption cell	ASTM D 3162[b/] Woebkenberg and McCammon (1995) Range: 1-100 ppmv Accuracy: ±5% Precision: ±5% MDL: <1 ppmv	Engelhard, Monitor Labs, Thermo Environmental	Very specific for CO; based on USEPA reference method; portable units are available (Engelhard)
Colorimetric Tube Sample gases are drawn through a chemically treated sorbent bed that changes color in the presence of CO; length of color stain is correlated with concentration	ASTM D 4599 Range: 5-100,000 ppmv Accuracy: ±25% Precision: NA MDL: NA	Draeger Safety, Sensidyne	Requires external air pump (may be hand-powered). Disposable system (single use) that relies on factory calibration. May be of lower resolution than other technologies. Not generally recommended for monitoring public exposure to CO

[a/]MDL: Method detection limit

[b/]ASTM: American Society for Testing and Materials

TABLE 3. Summary of CO monitoring methodologies encountered in various studies

Source	*Sampling method*	*Operating principle*	*Other details related to measurement methodology*
Abi Esber *et al*, 2007[1]	Continuous/ Grab	Electrochemical	A GEM^{TM}2000 portable monitor gas analyzer by CES Landtec was used. An electrochemical CO gas pod (0 to 500 ppm) with a response time of less than 60 seconds was connected to the instrument to measure CO levels. Readings were stored in the instrument at 1-min intervals (Resolution: 1 ppm).
Di Marco *et al*., 2005[25]	Continuous	Electrochemical	Langan Model T15 high resolution electrochemical sensors with a data logger were used. Readings were collected at 1-min intervals.
Gomez Perales *et al*., 2004[39]	Continuous	Electrochemical	Langan Model T15 sensors equipped with a DataBear® data logger were used. CO monitors were programmed to measure 1-min averages.
Chan and Chung, 2003[18]	Continuous	Electrochemical	A portable IAQCALC carbon oxides sampler was used. Data were taken every three minutes to reduce the response time.
Duci *et al*., 2003[27]	Continuous	Electrochemical	The Solomat MPM4100 Environmental Monitoring System CO portable monitor equipped with the amperometric two-electrode sensor 1212GS (0-500 ppm) was used. Instantaneous readings were stored every 15 s by the data log system and average 1-min data were calculated (Accuracy: 2 ppm; Resolution: 0.1 ppm).
Lodovici *et al*., 2003[56]	Continuous	NDIR	NA
Prasad *et al*., 2003[67]	Continuous	Electrochemical	A portable electrochemical cell based OLDHAM, TX12 monitor was used.
Chan *et al*., 2002a[15]	Continuous	Electrochemical	Portable CO monitors (Interscan Co., Model 148) were used. It is a real time electrochemical-sensing voltammetric device. The data were displayed and recorded by a portable data logger (Metrosonics, Model dl-714). The data were logged every 30 seconds.
Chan *et al*., 2002b[16]	Continuous/ Grab	Electrochemical/ NDIR	An electrochemical voltammetric sensing Interscan 4148 portable continuous CO monitor (0-50 ppm) was used. Readings were recorded every 15 s by a Metrosonics dl-714 portable data logger and the output was programmed to give half-minute averaged intervals. In some trips, Tedlar sampling bags were used to collect air samples to supplement the portable CO monitor. The bags were transported to the laboratory for analysis within 2 h and the samples were measured by a thermo electron (model 48) CO ambient analyzer.
Chau *et al*., 2002[19]	NA	Electrochemical	An electrochemical sensor model PM 7400 (Metrosonic, NY, USA) was used (Accuracy: ± 5%; Resolution: 1 ppm).
Georgoulis *et al*., 2002[38]	Continuous	Electrochemical	A Langan Model T15 high resolution electrochemical sensor with a data logger was used to collect 1-min interval readings.
Chan and Liu, 2001[14]	Continuous	Electrochemical	An electrochemical voltammetric sensing Interscan 4148 portable continuous CO monitor

Source	*Sampling method*	*Operating principle*	*Other details related to measurement methodology*
			(0-50 ppm) was used. Readings were recorded every 15 s by a Metrosonics dl-714 portable data logger and the output was programmed to give half-minute averaged intervals.
Zagury *et al*., 2000[79]	Continuous/ Grab	Electrochemical/ NDIR	A PAC II CO (Draeger industry) portable monitor with an electrochemical detection cell (0–500 ppm) was used. Readings were made every 3 s, and the data collection system was linked to a sensor programmed to calculate the average of these readings at 1 min intervals. This method of measurement has been validated inside cars and compared favourably with sampling by Tedlar bags and analysis by NDIR spectrometry.
Chan *et al*., 1999[13]	Continuous/ Grab	Electrochemical/ NDIR	An electrochemical volumetric sensing portable CO monitor Model 4148, Interscan Co was used. Data were recorded by a portable data logger Metrosonics dl-714 programmed to store 15 s average values. Samples collected in Tedlar bags were analyzed using a gas filter correlation CO Analyzer Model 48, Thermo Environmental Instruments Inc.
Clifford *et al*., 1997[21]	Continuous	Electrochemical	Two CO sensors manufactured by Crowcon Instruments (Abingdon, U.K.) were used. The data from the sensors were logged at 10 s intervals using a Grant Instruments (Cambridge) 12 bit "Squirrel" logger.
Flachsbart, 1999b[36]	Integrated	Electrochemical	General Electric (Model 15ECS3CO3) CO detectors with a response time of less than 1 min were used (0-500 ppm). The detector is attached by a cable to an integrator which displays the result as ppm-minutes of CO exposure (Accuracy: ± 2 ppm at zero concentration, ± 10% from 0 to 500 ppm).
Rodes *et al*., 1998[68]	Continuous	Electrochemical	Draeger electrochemical monitors were used.
Liu *et al*., 1994[55]	Grab	NDIR	Tedlar bag samples were analyzed by a NDIR-based CO analyzer by Horiba Inc., APMA Model 350E.
Ott *et al*., 1994[63]	Continuous	Electrochemical	General Electric Model 15ECS3CO3 CO detector was used. Data were recorded on a portable Esterline-Angus strip chart recorder, and were later digitized at intervals spaced only 12 s apart.
Chan *et al*., 1991[12]	Continuous	Electrochemical	Interscan Model 4146 CO monitors made of electrochemical cells were used. The electrical signals of these samplers were continuously transmitted to Rustrak Ranger data loggers

TABLE 4. Vehicle air change rates for various ventilation modes and moving speeds[a/]

Ventilation Mode	*Source*	*Range of ACH Values in h^{-1}*		*Vehicle Speed in case of moving vehicle mph (km/h)*
		Stationary Car	*Moving Car*	
Windows Closed, Vents Closed	Ott *et al*., 1994[63]	1.4	13.1	20 mph (32 km/h)
	Spengler e*t al*., 1994 (Cited by Park *et al*., 1998[64])	-	10	20 mph (32 km/h)
	Fletcher and Saunders, 1994[37]	0.8-8	-	-
	Fletcher and Saunders, 1994[37]	-	14-43	35 to 70 mph (55 to 108 km/h)
	Clifford *et al*., 1997[21]	-	6	Low speed
	Park *et al*., 1998[64]	1-3	-	-
Windows Closed, Vents Opened	Fletcher and Saunders, 1994[37]	0.8-10.5	-	-
Window ½-Opened, Vents Closed	Park *et al*., 1998[64]	13.3-26.1	-	-
	Park *et al*., 1998[64]	-	120	20 mph (32 km/h)
	Abi Esber *et al*., 2007[1]	20	120	19 mph (30 km/h)
Windows Closed, AC on Recirculation	Park *et al*., 1998[64]	1.8-3.7	-	-
	Abi Esber *et al*., 2007[1]	2	10	19 mph (30 km/h)
Windows Closed, AC on Fresh Air Intake	Park *et al*., 1998[64]	36.2-47.5	-	-
	Hayes, 1989 (Cited by Chan *et al*., 1991[12])	-	36	-
	Abi Esber *et al*., 2007[1]	36	36	19 mph (30 km/h)

[a/]Car features (make, model and volume) and wind speed data were also reported by Park *et al*., 1998[64] and Fletcher and Saunders, 1994,[37] being potential influencing factors

TABLE 5. Studies of CO exposure inside automobiles/experimental vans

Location	*Study*	*Testing year*	*Level (ppm)*	*Averaging time (min)*
San Jose, USA	Ott *et al*., 1993*	1991-1992	4.6	-
Sacramento, USA	Rodes *et al*., 1998[68]	September to October 1997	0-3[c/]	120
Los Angelos, USA	Rodes *et al*., 1998[68]	September to October 1997	3-6[c/]	120
Mexico City, Mexico	Fernandez-Bremauntz & Ashmore, 1995a[31]	Winter 1991	55.2-57[c/]	35-63
Paris, France	Dor *et al*., 1995[26]	1991-1992	12[a/]	82-106
Paris, France	Zagury *et al*., 2000[79]	Winter 1997	3.8[a/]	480
Athens, Greece	Duci *et al*., 2003[27]	Summer 1998/ November 1998 to February 1999	21.4[a/]	30
Amsterdam, The Netherlands	Van Wijnen *et al*., 1995[73]	-	4[a/]	60
London, UK	Kaur *et al*., 2005[49]	Spring 2003	1.3[a/]	60
Hong Kong, China	Chan *et al*., 1999[13]	November 1995 to July 1996	10.1[a/]	11-90
Hong Kong, China	Chan *et al*., 2002b[16]**	November 1998 to January 1999	1.9[a/]	15-20
Taipei, Taïwan	Liu *et al*., 1994[55]	December 1989 to February 1991	11[a/]	30-60
Beirut, Lebanon	Abi Esber *et al*., 2007[1]	May to August 2005	20[a/]	45

[a/]Mean [b/]Median [c/]Range
*Cited by Flachsbart, 1999a.[35] The study was conducted on an urban highway near San Jose, California

TABLE 6. Studies of CO exposure inside closed transit modes other than automobiles and experimental vans

Location	*Study*	*Testing year*	*Vehicle Type*	*Level (ppm)*	*Averaging time (min)*
Mexico City, Mexico	Fernandez-Bremauntz & Ashmore, 1995b[31]	Winter 1991	Minibus Bus Metro	32-63[b/] 26-38[b/] 17-25[b/]	38-99
Mexico City, Mexico	Gomez-Perales *et al*., 2004[39]	May to June 2002	Minibus Bus Metro	8-24[b/] 7-20[b/] 4-11[b/]	39-88
Hong Kong, China	Chan *et al*., 1999[13]	November 1995 to July 1996	Light bus Bus Tram Train MTR* Ferry	1.3-3.9[b/]/2.4[a/] 0.9-4.6[b/]/1.9[a/] 2[a/] 1[a/] 1.5[a/] 0.6[a/]	14-38 20-41 45 42 22-30 16
Hong Kong, China	Chan & Liu, 2001[14]	January to April 1999	Minibus Bus	2.9[a/] 1.9[a/]	120
Guangzhou, China	Chan *et al*., 2002a[15]	May to December 2001	Bus Subway	8.6[a/] 3.1[a/]	150
Paris, France	Dor *et al*., 1995[26]	1991-1992	Bus Subway	4[a/] 2[a/]	-
Athens, Greece	Duci *et al*., 2003[27]	Summer 1998/ November 1998 to February 1999	Bus Trolley Subway	10.4[a/] 9.6[a/] 4[a/]	30

[a/]Mean [b/]Range
*Mass Transit Railway

TABLE 7. Summary of in-vehicle CO exposure modeling studies

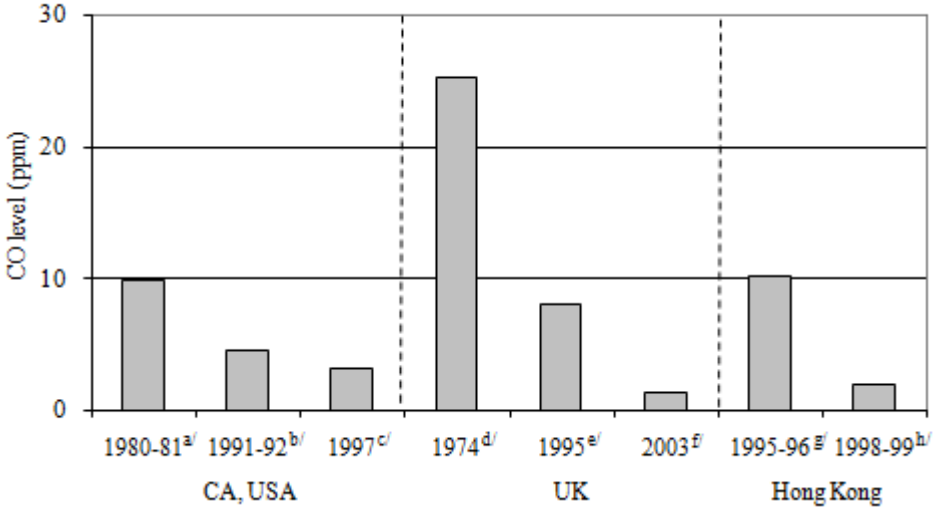
Reference	*Study Description*
Chan *et al*., 1991[12]	Matrices of in-vehicle and fixed site measurements of CO, VOCs and ozone showed a high correlation between VOCs (r = 0.62-0.96) and a moderate correlation (r = 0.37-0.46) between measured in-vehicle CO and VOCs concentrations. The extrapolation of CO commuter exposure models to study commuters' VOC exposures was not advised. Linear regression models were developed to predict in-vehicle VOC levels based on fixed site VOC measurements, roadway characteristics and an error term. The models had consistent slope estimates, moderate error terms, and were found to account for about 50-63% of the variation in in-vehicle VOC measurements.
Heinsohn *et al*., 1993[44]	A three-dimensional SBM was proposed to predict the time-varying contaminant (smoke, CO) concentrations at arbitrary points inside the passenger compartment of a 1989 4-door mid-sized sedan for two situations: (1) different combinations of passengers who smoke cigarettes, (2) CO entering the automobile's fresh air intake while cars are in a queue. Inputs to the model include the dimensions of the compartment, the flow rate of and contaminant concentration in air entering and leaving the compartment through ventilation air inlets and outlets, and doors' and windows' leaks, location and emission rate of contaminant sources within the compartment. The SBM can accommodate time variations in any or all of these parameters. The compartment (1.92 m^3) was divided into 24 individual smaller volume boxes defined by a set of coordinates and the contaminant concentration in each box was calculated using the conservation of mass. Data generated by the SBM show that the concentrations were not uniform within the compartment in the case of smoking passengers. In contrast, in case of CO ingression through makeup air only, the compartment behaves like a single, well-mixed box model with uniform and quick internal mixing mechanisms.

Reference	*Study Description*
Ott *et al*., 1994[63]	Field CO measurements were conducted on a major suburban arterial highway, El Camino Real, California, to develop a realistic and accurate submodel of the SHAPE (Simulation of Human Activities and Pollutant Exposures) program for the automobile micro-environment. The model, consisting of only a single measure of traffic volume (surrounding vehicle count) and a seasonal trend component had good predictive power (R^2=0.68). In contrast, ambient CO levels, although partially correlated with average exposures, contributed comparatively little predictive power to the model. The model can be used to better understand factors affecting CO exposures on highways and to make predictions about changes in emissions and traffic variables.
Liu *et al*., 1994[55]	Consisted of a survey of commuting patterns in Taipei, Taiwan including random samples of primary school students and adult workers with CO measurements in vehicles and near roadways. A Monte Carlo simulation was then implemented to estimate 1- and 8-hr CO exposure levels. Commuters on motorcycles and public buses experienced the highest CO levels among all commuters. The Monte Carlo simulations were shown to estimate better CO exposure levels than roadside fixed monitoring stations.
Park *et al*., 1998[64]	The USEPA Indoor air Quality Model (Risk model, 1991) was used to estimate concentrations of several contaminants (PCE, formaldehyde, RSP) emitted by in-vehicle sources, including CO emitted by airbag deployment. Large (3.24 m^3) and small (2 m^3) volume vehicles with various air change rates were used in the simulation. The results showed that while the peak CO concentration appeared to vary more with the volume of an automobile than with the change in ACH, the average CO level seemed to be more sensitive to the change in ACH for a small car than for a large one.
Flachsbart, 1999b[36]	Statistical models were presented to simulate in-vehicle CO exposure along a coastal highway in Honolulu. The study site was divided into three links. The models predicted the average CO concentration inside the vehicle's passenger cabin on the third link as a function of several variables: the average CO concentrations inside the cabin on previous links; traffic, temporal and meteorological variables; motor vehicle CO factors; and ambient CO concentrations. Based on data from 80 trips, the three most powerful models (adjusted R^2=0.69) were nonlinear combinations of four variables: the average CO concentration inside the cabin for the second link; wind speed and direction; and either the travel time, vehicle speed or CO emission factor for the third link. Several nonlinear models were based on data for 62 trips for which ambient CO concentrations were available. For this database, the most practical models (adjusted R^2=0.67) combined three variables: the ambient CO concentration; the second link travel time; and either the travel time, vehicle speed or CO emission factor for the third link. Two factors of third-link CO exposure varied seasonally: relatively lighter traffic flows and stronger winds lowered cabin exposures during the late fall, while heavier traffic flows and calmer winds increased cabin exposures during winter and spring. The importance of seasonal effects on cabin exposure was confirmed.
Abi Esber *et al.*, 2007[1]	The USEPA RISK Model version 1.9.25 with measured car-exterior CO levels and trip-specific movement record as boundary conditions were used to simulate in-vehicle carbon monoxide (CO) concentration profiles. The simulation results were coupled with field measurements to demonstrate the occurrence of CO ingression into the vehicle compartment from the engine combustion and/or exhaust return of the test vehicle. The amount of infiltrated CO was found to be equivalent to an in-vehicle source emitting 250 to 1,250 mg/hr of CO depending on the vehicle ventilation settings.

TABLE 8. Summary of major multivariate statistical models of in-vehicle CO exposure assessment

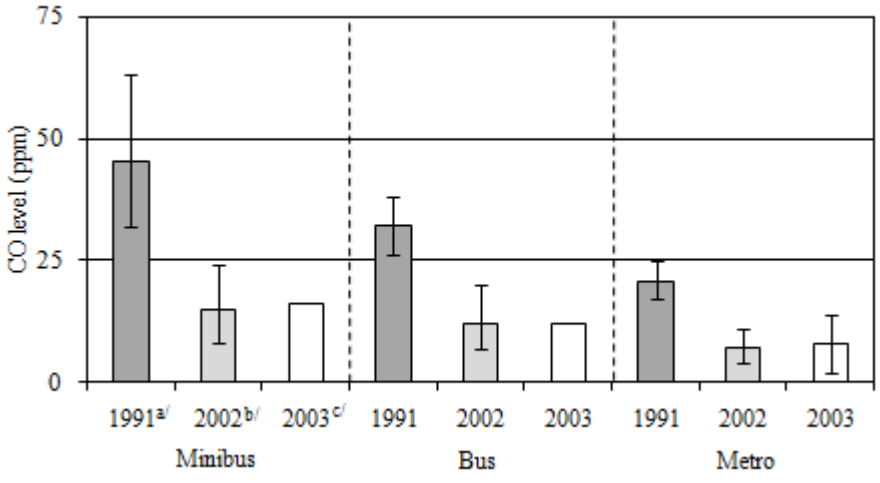
Reference	*Variables*		*Regression models*
Ott *et al*., 1994[63]	Y	Logarithm of the mean CO exposure Y= ln[AVE_{veh}(T)]	A simple but effective model included only two variables: $Y=4.2625+0.3657X_4+1.5478\ln X_8$ (multiple $R^2=0.679$; adjusted $R^2=0.672$) (12)
	X_1,X_2	Ambient concentrations at fixed monitoring stations	The equation that is optimal with respect to the adjusted R^2 criterion is:
	X_3	Atmospheric stability index	$Y=4.7614-0.2702\ln X_1+0.7141\ln X_2+0.2472X_4+0.2792\ln X_6-2.3625X_7+1.5627\ln X_8-0.774X_9$ (multiple
	X_4	Seasonal trend function	$R^2=0.781$; adjusted $R^2=0.766$) (13)
		$X_4=\cos(2\pi d/365.25)$ with d=1 on January 1 and d=365.25 on December 31	The equation that is optimal with respect to the Mallow's C_p criterion is: $Y=4.50655-0.2861\ln X_1+0.7549\ln X_2+0.2547X_4+0.2811\ln X_6-2.1680X_7+1.5204\ln X_8$ (multiple $R^2=0.784$;
	X_5	Time of day of drive	adjusted $R^2=0.766$) (14)
	X_6	Average surrounding vehicle count (SVC) at intersections	A robust regression analysis was applied to the data to improve the reliability of the results. The following relationships correspond to equations 13, 14, and 15, respectively:
	X_7	Time duration of trip	$Y=3.412+0.3272X_4+0.8947\ln X_8$ (multiple $R^2=0.560$) (15)
	X_8	Proportion of the trip that the vehicle was stopped at a traffic light	$Y=4.408-0.2605\ln X_1+0.7082\ln X_2+2446X_4+0.2626\ln X_6-2.006X_7+1.444\ln X_8-0.687X_9$ (multiple $R^2=0.750$) (16)
	X_9	Categorical variable: instrument type	$Y=4.027-0.2680\ln X_1+0.7417\ln X_2+0.2437X_4+0.2583\ln X_6-1.697X_7+1.347\ln X_8$ (multiple $R^2=0.765$) (17)
Flachsbart, 1999b[36]	CE_i	Passenger exposure on link i (ppm)	Based on data from 80 trips, the three most powerful models (adjusted $R^2=0.69$) were nonlinear combinations of four variables:
	i	Link number, varying from 1 to 3	$\log CE_3 = 0.534+0.292(\log CE_2)+0.700(\log TT_3)+0.104(WD_3)-0.356(\log WS_3)$ (18)
	TF3	Traffic flow on link 3 (veh/15 min)	$\log CE_3 = 1.913+0.292(\log CE_2)-0.700(\log VS_3)+0.104(WD_3)-0.356(\log WS_3)$ (19)
	TTi	Test vehicle's travel time on link i (min)	$\log CE_3 = -0.157+0.295(\log CE_2)+0.696(\log EF_3)+0.112(WD_3)-0.365(\log WS_3)$ (20)
	VS3	test vehicle's average speed on link 3 based on TT3 (mph)	with $VS_3=1.55/(TT_3/60)$, where 1.55 is the length of link 3.
	ET_i	Time when test vehicle enters link i	Based on data for 62 trips for which ambient CO concentrations were available, the most practical
	AT_3	Ambient temperature at HIA while vehicle on link 3 (°F)	models (adjusted $R^2=0.67$) combined three variables: $\log CE_3 = 0.428+0.425(\log TT_2)+0.593(\log TT_3)+0.432(\log AC_3)$ (21)
	WD_3	Wind direction at HIA while test vehicle on link 3; if	$\log CE_3 = 1.597+0.425(\log TT_2)-0.593(\log VS_3)+0.432(\log AC_3)$ (22)
		ψ=an azimuth from north, then $WD_3=0$ for $0°<\psi<80°$	$\log CE_3 = -0.158+0.437(\log TT_2)+0.585(\log EF_3)+0.437(\log AC_3)$ (23)
		and $280°<\psi<360°$ and $WD_3=1$ for $80°\leq\psi\leq280°$	From a set of four meteorological variables potentially affecting ambient CO concentration, wind speed
	WS_3	Hourly wind speed at HIA while test vehicle on link 3 (mph)	had the most predictive power (multiple $R^2=0.31$) $AC_3 = 2.82-0.33(WS_3)+0.012(WS_3)^2$ (24)
	EF_3	Mobile 4.1 exhaust CO emission factor while test vehicle on link 3 (g/veh-mi)	It has been shown also that wind speed variation was related to that of ambient temperature and wind direction:
	AC_3	Hourly ambient CO concentration recorded at Leahi Hospital while test vehicle on link 3 (ppm)	$WS_3 = 6.9\times10^{-9}(AT_3)^{4.908}$ (25) $WS_3 = 8.30+3.47(WD_3)$ (26)

Figures



a/Ott *et al*., 1994[63]
b/Flachsbart, 1999a[35]
c/Rodes *et al*., 1998[68]
d/Colwill and Hickmann, 1980[22]
e/Clifford *et al*., 1997[21]
f/Kaur et al., 2005[49]
g/Chan *et al*., 1999[13]
h/Chan *et al*., 2002b[16]

FIGURE 1. Evolution of mean CO exposure inside automobiles in various developed countries



a/Fernandez-Bremauntz and Ashmore, 1995a[31]
b/Gomez-Perales *et al*., 2004[39]
c/Gomez-Perales *et al.*, 2007[40]

FIGURE 2. Evolution of mean and range of CO exposure inside various types of transport modes in Mexico City

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APPENDIX 4

Indoor to outdoor air quality associations with self-pollution implications inside passenger car cabins

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ABSTRACT: In this study, in-vehicle and out-vehicle concentrations of fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) are measured to assess commuter's exposure in a commercial residential area and on a highway, under three popular ventilation modes namely, one window half opened, air conditioning on fresh air intake, and air conditioning on recirculation and examine its relationship to scarcely studied parameters including self pollution, out-vehicle sample intake location and meteorological gradients. Self pollution is the intrusion of a vehicle's own engine fumes into the passenger's compartment. For this purpose, six car makes with different ages were instrumented to concomitantly monitor in- and out-vehicle $PM_{2.5}$ and CO concentrations as well as meteorological parameters. Air pollution levels were unexpectedly higher in new cars compared to old cars, with in-cabin air quality most correlated to that of out-vehicle air near the front windshield. Self-pollution was observed at variable rates in three of the six tested cars. Significant correlations were identified between indoor to outdoor pressure difference and $PM_{2.5}$ and CO In/Out (IO) ratios under air recirculation and window half opened ventilation modes whereas temperature and humidity difference affected CO IO ratios only under the air recirculation ventilation mode.

KEYWORDS: In-vehicle exposure, automotive emissions, self-pollution, meteorological gradient

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Introduction

Vehicular exhaust is a major source of air pollution and contributes significantly to roadway, ambient and indoor air quality in urban areas. Outdoor air can flow into indoor micro-environments with passenger cars reportedly associated with the highest levels of exposure among commuting vehicles because of the low body position and the low intake point of the ventilation system that result in a close contact with the exhaust of other vehicles (Kaur *et al*., 2007; El-Fadel and Abi-Esber, 2009; Knibbs *et al*., 2011). Hence, despite the relatively short period of time spent in cars, exposure levels are of concern given the immediate proximity to motor vehicles plus, in urban areas, high ambient concentrations (Adams *et al*., 2001a). Compared to other micro-environments, in-vehicle exposure is more complex to understand because it is affected by several interactive determinants including ventilation setting, roadway type, vehicle characteristics and self pollution.

Self-pollution, or the intrusion of a vehicle's own engine fumes into the passenger's compartment, has been reported to contribute to exposure inside various types of vehicles. Besides demonstrating the occurrence of CO self pollution inside a passenger car using field testing and mass balance simulations, Abi-Esber and El-Fadel (2008) reported that ratios of in-vehicle to out-vehicle concentrations greater than unity were invariably attributed in the literature to the occurrence of a self-polluting condition and the likely existence of a pollution source inside the vehicle. Indeed, Chan *et al.*(1991), Weisel *et al.* (1992), Dor *et al.* (1995) and Lawryk *et al.*(1995) found that VOC levels were higher inside a moving vehicle than in surrounding ambient air, suggesting in-vehicle sources including engine vapor intrusion across the fire wall, from underneath the vehicle, or from the draft area behind the vehicle. More recently, Chan *et al.* (2002) reported median ratios greater than 1 for in-vehicle to out-vehicle CO

concentrations in urban residential, rural, industrial areas and along highways of Hong Kong, and suggested the internal engine compartment as a possible additional source of CO emissions inside the vehicle. Likewise, Chan and Chung (2003) reported ratios of up to 1.8 in urban areas, 8 in tunnels and 10 in countryside depending on the used ventilation mode and suggested the possibility of a likely source of CO inside the vehicle. Behrentz *et al.* (2004) measured self-pollution in school buses using a tracer gas technique and found that up to 0.3% of the air inside the cabin was from the bus' own exhaust in older buses, approximately 10 times the percentage observed for newer buses, and that 25% of the variation in black carbon concentration was attributed to self-pollution within the buses. Fondelli *et al.* (2008) observed $PM_{2.5}$ concentrations in buses and taxis in excess of the urban concentrations attributing the observation to several sources among which the exhaust of the tested vehicles themselves. Likewise, Asmi *et al.* (2009) measured in-vehicle and background concentrations of fine particles inside buses and trams and observed daily average ratios varying in the range 0.8-4.3 and 1.0-2.9 for the number and mass concentrations, respectively, suggesting that the elevated levels in buses are due to traffic emissions, with a fraction of the pollutants probably coming from the vehicles themselves. However, to date, there are no reported studies exploring the mechanisms of self-pollution by $PM_{2.5}$ in the passenger cabin of a car, which is by far the most popular transport mode.

Other potential determinants of in-vehicle exposure to traffic pollution which were not addressed in the literature comprise out-vehicle sample intake location and indoor to outdoor difference in temperature, pressure and humidity levels. Although previous studies calculated vehicle In/Out (IO) ratios using in- and out-vehicle pollutant concentrations (Qi *et al*., 2008; Knibbs *et al*., 2010; Fruin *et al*., 2011; Hudda *et al*., 2011; Xu and Zhu, 2013; Bigazzi and Figliozzi, 2013; Tartakovsky *et al*., 2013), only a few reported the location of the out-vehicle sample intake point (Knibbs *et al.*, 2010; Bigazzi and Figliozzi, 2013; Tartakovsky *et al*., 2013) with the latter being inconsistent across studies. Substantial differences in pollutant concentrations exist at times between the four corners of a moving vehicle due to the proximity of certain locations to the tailpipe of the test car or to that of the preceding vehicle. Such differences affect the IO ratio calculations which can be low when the outdoor sample is taken from a high concentration area and high when taken from less polluted areas. Therefore, it is of interest to target the location of out-vehicle sample intake point to the one that affects most in-vehicle air quality.

On the other hand, temperature and pressure gradients have been reported to affect pollutant infiltration factors in buildings. In a study examining particle deposition and resuspension rates, Thatcher and Layton (1995) minimized particle infiltration rates by choosing times of minimum in to out pressure and temperature differences because when unbalanced conditions exist between indoor and outdoor environments, airflow is induced through cracks and openings. The airflow rate (in m^3/s), which is governed by the power law, is the product of an airflow coefficient 'C' (in $m^3/s.Pa$) and the pressure difference (in Pa) raised to a dimensionless flow exponent 'n' (Roulet, 2012). The pressure difference across the crack and/or opening is in the order of 1 to 10 Pa for typical residences (Hunt, 1980; Jeng *et al*., 2003). On the other hand, some pressure differences across openings can be attributed to temperature differences (ASHRAE, 1993) which are also reported to affect particle infiltration through thermophoresis (Brockmann, 2011; Grau-Bové and Strlič, 2013). In the case of a moving vehicle, IO pressure differentials may reach 5000 Pa and temperature differentials are higher when

the air conditioning is turned on, thus similar influences are expected but have not been quantified (Qi *et al.* 2008). As for humidity, there are no reported studies assessing its influence on pollutant infiltration in indoor environments. However, given the relationship between the magnitude of humidity differential and that of indoor to outdoor air exchange whereby high air exchange promptly brings indoor humidity to the same level encountered outside, a correlation between humidity differential and pollutant infiltration and/or buildup inside a cabin is expected and is worth assessing as well.

Hence in this study, the above described information gaps were addressed by measuring in-vehicle exposure to $PM_{2.5}$ and CO while driving in a commercial/residential urban area and on a highway during winter and spring seasons under three popular ventilation modes while considering the influence of car age, self-pollution and out-vehicle sample intake location. Also, polynomial models correlating vehicle IO ratios to indoor and outdoor differences in pressure, temperature and humidity are developed.

Materials and methods

Study area

Trips were conducted during the period November 2011 to November 2012 between 8:30 a.m. and 1:00 p.m. along two different trajectories to represent a variety of possible testing speeds. Trajectory 1 is a 2,333 m-circuit in a commercial/residential area of Hamra-Bliss Area, Beirut, Lebanon (Fig. 1b) experiencing congested stop and go traffic at speeds of up to 40 km/h. Trajectory 2 is a 70 km double carriage highway on the Beirut-Jyeh highway in Lebanon (Fig.1c) experiencing slow moving traffic in its Northern part (average speed of 60 km/h) and faster traffic (average speed of 80 km/h) in the remaining Southern part. Based on earlier surveys by the American University of Beirut (2009) and the Ministry of Public Works (2006) and assuming an annual growth rate of 2%, average traffic counts were estimated at 1071, 2397 and 1073 vehicles per hour on the three respective trajectories with a vehicle fleet composed mostly of passenger cars (80%), taxis (3%), heavy duty vehicles (12%), and 2/3-wheelers (5%) (MoE/URC/GEF, 2012).

Monitoring program

In-vehicle exposure is assessed using gasoline powered cars of six different makes selected to represent a diversity of vehicle designs and ages (Table 1) under three ventilation modes: 1) driver window ½-opened, air conditioning (AC) off, vents closed (W1/2O); 2) windows closed, AC on fresh air intake (AC FA), fan setting ‘medium’ or ‘2’; and 3) windows closed, AC on recirculation (AC Rec), fan setting ‘medium’ or ‘2’. The tested ventilation modes are commonly used to ensure comfort inside a car cabin because opening all windows generates noise with a strong air flow and is not appropriate during rainy days. In the cold season and in the absence of rain or snow, one of the windows is often rolled down half way while air conditioning is used in the warm season on recirculation or fresh air intake modes with windows closed. The test cars were either rented (Kia Cerato 2011, Chevrolet Aveo 2011, Toyota Yaris 2010) or borrowed (Toyota Celica 2001, Kia Delta 1999, Honda Civic 1997) and had four doors and windows except the Toyota Celica 2001 which had only two. The maintenance logs of the borrowed vehicles show that AC filter replacement did not take place on any of

them since their purchase. The same is expected for the rented vehicles as AC filter replacement is not part of the routine vehicle maintenance requirements in the study area. Three types of tests (fume leakage, stationary, and mobile) were conducted (Table 2) totalling 264 tests at a duration of 30 to 45 minutes each test.

In fume leakage tests, engine fume leakage prior to exiting the tailpipe is examined by extracting tailpipe fumes using a customized exhaust extraction system. The exhaust fumes are collected into a well-fitted hose that is connected to the tailpipe through a sealed system that releases 15 m away downwind from the test location. Tests simulating idle mode were conducted at a controlled garage located on campus of AUB whereas those simulating engine combustion during car movement were conducted on a chassis dynamometer with both locations free from background $PM_{2.5}$ and CO sources. Chassis dynamometer testing is used to simulate engine combustion during vehicle movement at speeds of 40, 60 and 80 km/h. It cannot however simulate wind and associated vibration which constitutes a limitation to the current work. The engine was running during these tests at average speeds of 800, 1500, 1600 and 2150 rounds / minute for speeds of 0, 40, 60 and 80 km/h, respectively. The exhaust pipes of the vehicles were inspected prior to field testing to ensure the absence of cracks or holes and to avoid the possibility of fume leakage to the immediate surroundings of the vehicle. $PM_{2.5}$ and CO concentrations are measured concomitantly inside and in the immediate vicinity of the vehicle. In the event of $PM_{2.5}$ or CO detection inside the cabin, the contamination would be attributed to engine fume leakage prior to reaching the tailpipe.

In stationary tests, the cars are parked at AUB campus in front of a playground, which constitutes a relatively open area where the influence of nearby cars and roadway emissions are precluded. Exhaust fumes are allowed to flow freely from the car tailpipe to its surrounding area. Idle tests were conducted whereby $PM_{2.5}$ and CO concentrations are measured inside the cabin as well as in the outdoor air in the immediate vicinity of the car.

In mobile tests, the cars are driven with a driver and a passenger at average speeds of 40 km/h on Trajectory 1 and 60 or 80 km/h on Trajectory 2, which are typical driving speeds in commercial/residential areas and on highways, respectively. Exhaust fumes are allowed to flow freely from the car tailpipe to its surrounding area. $PM_{2.5}$ and CO concentrations were measured inside the cabin as well as in the outdoor air in the immediate vicinity of the car. During all tests, vehicle occupants refrained from smoking to preclude non-traffic sources of $PM_{2.5}$ and CO inside the vehicle.

Fig. 2 outlines the outcomes from each category of tests all while showing how they fill the gaps of each other. As such, while mobile tests can assess in-vehicle exposure and its relationship to several explanatory variables, the possibility of the presence of non-captured out-vehicle pollution limits their ability to determine the magnitude of self-pollution. Non-captured out-vehicle pollution refers to exhaust fumes surrounding the test vehicle and finding their way into its cabin all while not being captured by out-vehicle sampling i.e. not occurring near the intake of the sampling tubes. The latter possibility is examined by conducting stationary tests in the absence of surrounding vehicles. Similarly, while stationary tests can assess total self-pollution due to both fume leakage through firewall and exhaust return, fume leakage tests are capable of distinguishing between the two potential sources of self-pollution by implementing exhaust extraction and thus eliminating the possibility of exhaust return. It is essential to note finally that it is unlikely to have exhaust return and entry to the cabin when a car is

moving. However, during mobile tests in stop and go traffic, the car's stopping intervals are substantial at times potentially leading to self pollution by exhaust return due to two possible mechanisms: 1) wind blowing from behind, or 2) high pressure at the level of the air exits of the cabin (located usually in the rear shell of the vehicle) transforming the latter to air entry points.

Vehicle instrumentation

Air quality indicators

Two new portable DustTrak analyzers (model 8532) by TSI Inc. were used for in- and out-vehicle $PM_{2.5}$ monitoring with a log interval of 1 minute. The setup is illustrated in Figs. 3a and 3b. The analyzers rely on the optical backscatter technology with a measurement range of 0.001-150 mg/m^3 and an accuracy of ±0.1% of reading or 0.001 mg/m^3, whichever is greater. They are factory-calibrated to the respirable fraction of the International Organization for Standardization (ISO) 12103-1, A1 Arizona test dust, which is representative of a wide variety of ambient aerosols (Kim *et al*., 2004). A zero calibration was applied prior to every use. Size-selective impactors were attached to the inlets of the analyzers to pre-condition the size range of the particles entering the instrument to $PM_{2.5}$. The impactors were cleaned and oiled at the end of each sampling day which helps maintain the flow within 5% of factory's setpoint (3 L/min) in order to achieve the correct particle cutpoint (2.5 μm). The precision of the analyzer was determined experimentally to be ±4% at a roadside location (R^2 = 0.99) and ±20% at a university campus location (R^2 = 0.97) using sixty 1-minute collocated measurements. The latter was accounted for in the current work by considering indoor to outdoor ratios higher or equal to 1.2 as an indication of indoor concentrations higher than those outdoor. Conflicting results regarding the accuracy of DustTrak analyzers in comparison with gravitational methods of measurement have been reported with Kim *et al.* (2004), Wallace *et al*. (2011) and Both *et al.* (2013) indicating that $PM_{2.5}$ concentrations measured by a DustTrak and reference or equivalent reference method of measurement being generally similar to each other (with an underestimation factor of 0.97, a bias and a precision of 10 and 6%, and a correlation coefficient R^2 = 0.96, respectively), whereas earlier findings by Chang *et al*. (2001) and Levy *et al*. (2002) indicate that the analyzer overestimated $PM_{2.5}$ exposure by factors of 2 and 2.8, respectively. The calibrations were conducted on the roof of an ambient air quality monitoring station usually located away from roads (Chang *et al.*, 2001), at an unknown location (Levy *et al*., 2002), at an apprentice welding school and a power plant overhaul site (Kim *et al.*, 2004), inside and outside households (Wallace *et al*., 2011) and at a residential site 20 m away from a roadway and one floor above ground level (Both *et al*., 2013). None of the latter studies was conducted inside or adjacent to commuting micro-environments where aerosol particle characteristics and distribution may potentially exhibit different analyzer performance. As a result, further validation of the DustTrak analyzers is warranted and ongoing. At this stage, they have invariably been relied upon in previous studies of commuter exposure to traffic related $PM_{2.5}$ emissions (Dennekamp *et al*., 2002; Levy *et al*., 2002; Boogard *et al*., 2009; Both *et al*., 2013) which facilitates comparative assessments and partial validation.

Two new portable Langan CO analyzers (model L76n) by Langan Products Inc. were used for in- and out-vehicle CO monitoring with a log interval of 1 minute. The analyzers rely on the electrochemical technology with a measurement range of 1 to 200 ppm, a resolution of 0.1 ppm and a response time ($t_{90\%}$) of 40 seconds (determined

experimentally). Calibration with zero and span gas (50 ppm) was undertaken at the beginning of each testing round (every two weeks). The accuracy of the analyzer was tested in the range 0-3 ppm against a reference non-dispersive infrared spectrometry method revealing satisfactory instrument performance ($R^2 = 0.93$) (Chang *et al*., 2001). Similar to the DustTrak analyzers, Langan analyzers are invariably relied upon in previous studies of commuter exposure to traffic related CO emissions (Bruinen de Bruin *et al*., 2004; Gomez-Perales *et al*., 2004; Kaur *et al*., 2005a; 2005b; Scotto di Marco *et al*., 2005; Huang *et al*. 2012; Wu *et al*., 2013). In-vehicle carbon dioxide (CO_2) monitoring was also conducted using a Telaire 7001 unit which relies on the infrared analysis technology with a measurement range of 0 to 10000 ppm, a resolution of ±1 ppm and an accuracy of 50 ppm or ±5% of the reading, whichever is greater. The Telaire unit was calibrated to a default ambient CO_2 level of 500 ppm at the beginning of each testing round.

Out-vehicle sampling was conducted at four locations surrounding the test vehicle to capture its boundary conditions of air quality. For this purpose, a system of four valves and relays is used to alternately switch the sample intake point every one minute to one of four locations, namely rear left of the car as observed by a seated driver (location 1), front left (location 2), rear right (location 3) and front right (location 4) (Fig. 3c). The latter were selected among a multitude of locations around the vehicle being representative of four probable sources of out-vehicle air entering the cabin. The front locations are near the grill air intake of the AC system whereas the rear locations are close to the air exit points of the car cabin which may turn into air entry points when they exhibit high pressure levels in the case of an idling car. In addition, one of the rear locations (rear right) is near the exhaust pipe and represents a boundary condition of out-vehicle concentrations. Polyethylene tubing and airtight push-in fittings are used for out-vehicle sample transport and distribution. The tubes are 1.5 m long with an inner diameter of 5.7 mm. The sampling flow rate inside the tubes were 6 L/min, as the DustTrak analyzers were run at their default flow rate of 3 L/min, and the CO sensor was exposed to the out-vehicle sample using Sensidyne Gil-Air-5 pumps calibrated to a flow rate of 3 L/min. Given the small aerodynamic diameter of the measured particles, the inlet efficiency can reasonably be assumed to be 100% (Brockmann, 2011) suggesting no particle losses at the tubes' inlets. Similarly, no losses due to gravitational deposition along the tubes' walls are expected as the sampling velocity across the line (~14 km/hour) is significantly higher than the deposition velocities of $PM_{2.5}$ particles (in the range 1.32 to 1.80 m/hour for the particle size range 2 to 3 μm and lower velocities for sizes less than 1 μm (Thatcher and Layton, 1995)). Finally, losses due to electrostatic deposition could not be estimated given the absence of information regarding the charge of the measured particles. They are however expected to be minimal as the sampling velocity was high enough to ensure efficient particle entrainment and line transmission (Brockmann, 2011).

Meteorological indicators

Real time on-board monitoring of in- and out-vehicle pressure, temperature and humidity was also undertaken. Pressure was measured using analog output piezoresistive pressure sensors (Omega PX72-030AV). The range and accuracy of the output signal are 0 to 30 psi (0 to 165 mV) and ±1.5 mV/psi, respectively. In-vehicle temperature and humidity are logged every minute by the Langan analyzer. Out-vehicle temperature and humidity are logged every minute by an on-board portable weather

tracker (Kestrel 4500) installed on the roof of the car. The response time is one minute for relative humidity and one second for temperature. The measurement range and accuracy are 0-100% and ±3% for relative humidity and -45 to 125°C and ±1°C for temperature.

Indoor to outdoor pressure, temperature and humidity differences were measured simultaneously during mobile and stationary tests to examine their influence on pollutant penetration inside the vehicle under fluctuating out-vehicle concentrations. However, only out-vehicle meteorological data were measured during chassis dynamometer tests because they were conducted in a room with exhaust gas extraction and stable out-vehicle concentrations. As a result, in-vehicle concentration fluctuations were attributed to fume leakage inside the cabin with the latter being affected by out-vehicle meteorological conditions only.

Data analysis

Trip average in- and out-vehicle $PM_{2.5}$ and CO concentrations were calculated for each mobile trip by averaging the 1-min $PM_{2.5}$ and CO measurements. A general average in-vehicle air pollutant level was calculated afterwards for each ventilation mode and car, and was compared to the 24- and 8- hour World Health Organization (WHO) permissible exposure guidelines for $PM_{2.5}$ and CO (25 $\mu g/m^3$ and 9 ppm respectively) (WHO, 2005). Also, one-way ANOVA and linear regression analysis were used to assess the statistical significance of the influence of ventilation mode and car age on in-cabin exposure.

In addition, trip average IO ratios were used to establish the relationship between average concentration measured inside the vehicle and that measured in its vicinity. They were calculated using 1-minute IO ratios corresponding sequentially to the four tested out-vehicle locations and a single in-vehicle location which is the passenger's breathing zone. To eliminate the possibility of non-captured out-vehicle pollution during mobile tests, IO ratios were computed during idling tests in the absence of surrounding traffic. Furthermore, IO ratios were computed during chassis dynamometer tests at various speeds with exhaust gas extraction to identify potential self-pollution occurrence in the event of IO ratios greater than unity. Although on-road conditions in terms of aerosol size distribution and those encountered in stationary and fume leakage tests may be distinct, the associated change in instrument precision constitutes a factor that affects in- and out-vehicle measurements almost equally and therefore has a less significant impact on the ratio between the two. As a result, it was assumed that IO ratios measured using the same instrument can be reasonably compared independently of the measurement location.

The influence of the out-vehicle sample intake location was assessed by conducting linear regression analysis of log-transformed in- against out-vehicle concentrations after grouping the data based on the location of out-vehicle sample intake point. The software SPSS 16 was used to conduct regression analysis based on the least squares method. The square of the Pearson correlation coefficient (R^2) was computed and analyzed for significance using the associated ANOVA table. A regression approach was also used to assess the correlation between log transformed IO ratios and each of pressure, temperature and humidity differences between indoor and outdoor after grouping the data based on the used ventilation mode. For this purpose, linear and polynomial models were tested after running a check of meteorological parameters' inter-correlations. In evaluating the results of the regression analysis,

candidate models satisfying three major conditions were selected: (1) the F-statistics for total regression had a probability p-value < 0.05; (2) the Student's t statistic for each independent variable coefficient had a probability p-value < 0.05; some insignificant coefficients were allowed at times only if the resulting model had higher predictive power than other models and the sign of the coefficient could be explained by scientific reasoning; (3) the model satisfies conditions (1) and (2) and has highest predictive power among the derived models.

Results and Discussion

Influence of ventilation mode

Average in-vehicle concentrations during mobile tests exceeded the WHO permissible exposure guideline with all tested ventilation modes in the case of $PM_{2.5}$ (Fig.4a), and with a W1/2O only in the case of CO (Fig.4b). $PM_{2.5}$ and CO in-vehicle concentrations were 93±28 $\mu g/m^3$, 79±34 $\mu g/m^3$ and 38±28 $\mu g/m^3$ and 9.9±3.6 ppm, 8.8±2.3 ppm and 6.7±0.8 ppm for the ventilation modes W1/2O, AC FA and AC Rec, respectively. A one-way ANOVA test using ventilation mode as the grouping factor ascertained the significant influence of ventilation mode on in-cabin exposure with the modes W1/2O, AC FA and AC Rec presenting a decreasing order of exposure levels. The overall average $PM_{2.5}$ concentration was 71±37 $\mu g/m^3$ for all ventilation modes and test cars, thus lower than the concentrations measured in Jakarta, Indonesia, and higher than the concentrations measured in California, USA, London, UK, Raleigh NC, USA and Bejing, China (Table 3). Similarly, the overall average CO concentration was 8.5±2.7 ppm for all ventilation modes and test cars, thus lower than the average concentrations measured in Athens, Greece, Beirut, Lebanon and Jakarta, Indonesia, and higher than the concentrations measured in Paris, France, Milano, Italy, Helsinki, Finland and Bejing, China (Table 4).

In order to control for the cross-influence of out-vehicle concentration, average in to out vehicle concentration ratios (IO ratio) were calculated for each ventilation mode. A pattern similar to that of concentration variation was obtained for both pollutants (Fig. 4). $PM_{2.5}$ IO ratios were higher than unity for the ventilation modes W1/2O and AC FA suggesting the possibility of non-captured out-vehicle pollution which refers to exhaust fumes surrounding the test vehicle and finding their way into its cabin all while not occurring near the intake of the sampling tubes. Another possibility is the potential occurrence of self-pollution. Unlike the case of $PM_{2.5}$, average CO IO ratios during mobile tests were less than or equal to 1 for all tested ventilation modes. The latter indicates the absence of non-captured out-vehicle pollution and/or self pollution or possibly the occurrence of the latter at rates which could be diluted by the cabin air exchange rate particularly that CO is a gaseous pollutant and is exchanged between the inside and the outside of the vehicle more easily than $PM_{2.5}$. Indeed, CO has a penetration factor of 1 (NRC, 2002) whereas that of $PM_{2.5}$ may vary from 0.4 to 1 depending on the indoor to outdoor pressure difference (Jeng *et al*., 2003). The possibilities of non-captured out-vehicle pollution or self pollution are assessed later through stationary and fume leakage tests. On another note, the current CO IO ratios were lower than those obtained in a testing campaign conducted earlier on the Kia Delta 1999 (Abi-Esber *et al*., 2007) probably due to better cabin tightness at the time being (year 2005). In fact, through the years, tightness reportedly decreases whereas the air change rate of a vehicle increases (Knibbs *et al*., 2009; Fruin *et al*., 2011; Hudda *et al*.,

2011). The profiles in Fig. 5 further validate the latter assumption as larger accumulation of CO_2 was observed inside 2011 model cars compared to late 1990s cars during three successive 45 min trips using the ventilation mode windows closed, AC on recirculation, and with two people breathing inside the car, ascertaining that newer cars are associated with better air tightness. The 1999 Kia Delta and the 1997 Honda Civic had remarkably high air exchange rates particularly at speeds of 60 and 80 km/h which prevented almost completely any CO_2 accumulation inside the vehicle and brought cabin CO_2 concentrations to starting ambient levels. Another factor which has contributed to the lower Kia Delta 1999 CO IO ratios in the current work is the much higher average out-vehicle concentration. Indeed, the car's average exhaust CO concentration is 11.93% by volume in 2012 compared to 1.53% by volume in 2005. While the latter emissions did not reach the passenger cabin as demonstrated below, they affected considerably the out-vehicle concentration which was computed as the average from four locations one of which was adjacent to the exhaust pipe, lowering thus the car's CO IO ratio.

Influence of vehicle age

Figs 6a and 6b depict average in-vehicle $PM_{2.5}$ and CO concentrations for each test car and ventilation mode during mobile tests. Except for $PM_{2.5}$ concentrations when using the ventilation mode AC Rec, no particular trend for in-vehicle exposure could be discerned for cars of variable age, possibly due to other factors with an influence which outweighs that of car age such as out-vehicle concentrations, meteorological parameters and self-pollution. Regression analysis of in-cabin CO and $PM_{2.5}$ concentrations against car age consistently returned insignificant correlations for all ventilation modes except for $PM_{2.5}$ exposure with the ventilation mode set on air recirculation ($R^2 = 0.70$; p-value = 0.000). In the latter case, in-vehicle exposure to $PM_{2.5}$ increased with increasing vehicle age due probably to the higher efficiency of AC particle filtration systems in new cars which are made of an electrostatically charged mat (special paper or nonwoven microfiber fleece) capable of attracting and capturing dust, pollen, soot and mold spores (Daly, 2006; Schnubel, 2009). As the adequate performance of the latter filters depends on its replacement schedule which is often neglected in the study area although being part of the routine vehicle maintenance requirements, the filter of a new car is likely to perform better than that of an older car.

Figs 6c and 6d depict a comparison of air pollutant concentrations in old cars and those in new cars during mobile tests. A surprising observation was that except for in-vehicle $PM_{2.5}$ concentrations under air recirculation mode, average pollutant concentrations were higher in new cars compared to old cars for all other ventilation modes, which is possibly related to the enhanced air tightness and absence of cracks and leaks in new vehicle cabins compared to old ones and the consequent slower exfiltration of pollutants either entering the cabin during the test or being generated inside the cabin. On the other hand, new and enhanced particle filtration systems located within recirculation loops in new cars are responsible for the lower $PM_{2.5}$ concentrations in new cars compared to old ones.

IO Ratios and self-pollution occurrence

The average IO ratios for the three types of measurements, namely mobile, stationary and fume leakage are depicted in Figs 7 and 8 for $PM_{2.5}$ and CO, respectively. Fume leakage tests could not be conducted on the Toyota Celica 2001 due to lack of

availability. While the AC Rec mode minimized $PM_{2.5}$ exposure during mobile on-road tests with IO ratios <1, the remaining modes were pervious to $PM_{2.5}$ and encountered IO ratios >1 for all cars except the Kia Cerato 2011 and Kia Delta 1999 (only IO ratios greater than 1.2 were considered to be higher than unity to account for potential experimental errors). In the case of CO, only the cabin of the Toyota Yaris 2010 encountered IO ratios >1 during mobile tests. Possible reasons for the occurrence of IO ratios >1 include the presence of roadway $PM_{2.5}$ pollution that could not be captured by out-vehicle sampling during mobile testing, or the possibility of occurrence of a self-pollution condition inside car cabins, which are examined in stationary and fume leakage tests.

In stationary idle tests, $PM_{2.5}$ IO ratios >1 were encountered in the cabins of the Toyota Celica 2001 and Honda Civic 1997 for W1/2O tests and in the cabins of the Chevrolet Aveo 2011 and Honda Civic 1997 for AC FA tests. The latter ascertains that some pollution accumulated inside the vehicle during on-road tests was not due to nearby vehicles and was due to the test car itself, through fume ingression from the engine compartment or exhaust re-entry to the cabin. For the Toyota Celica 2001 and Honda Civic 1997, the $PM_{2.5}$ IO ratios encountered during stationary tests with the W1/2O mode were even higher than those encountered in mobile tests (1.3 and 1.4, respectively, during stationary tests compared to 1.2 and 1.3, respectively, during mobile tests). The latter can be attributed to the higher exchange rate of a moving vehicle compared to a stationary vehicle, which dilutes faster in-cabin air pollution. Similar results were recorded with the AC FA mode with $PM_{2.5}$ IO ratios of 1.4 and 1.5 in the cabins of the Chevrolet Aveo 2011 and Honda Civic 1997, respectively, compared to ratios of 1.1 and 1.3 during mobile tests. In the case of CO, IO ratios >1 were not recorded during stationary tests indicating either the absence of self pollution, or its occurrence at low rates which could be diluted by the cabin air exchange rate.

In fume leakage tests simulating car movement, $PM_{2.5}$ IO ratios >1 were encountered in the cabin of the Chevrolet Aveo 2011 and Kia Delta 1999 for W1/2O and AC FA tests. In the case of the Chevrolet Aveo 2011, the $PM_{2.5}$ IO ratios were 1.5 and 1.2 for W1/2O and AC FA tests, respectively, compared to an IO ratio of 1.1 during mobile tests for both ventilation modes. For the Kia Delta 1999, the $PM_{2.5}$ IO ratios were 1.3 for W1/2O and AC FA tests, compared to IO ratios of 1.1 and 0.9, respectively, in mobile tests. Given the absence of nearby traffic and exhaust control, the identification of IO ratios >1 suggests the occurrence of fume leakage from the engine compartment to the passenger cabin. The extent of fume leakage was generally higher for Chevrolet Aveo 2011 and Kia Delta 1999 in chassis dynamometer tests than in stationary tests as a result of the burning of fuel when simulating movement. It is also higher in fume leakage tests compared to mobile tests due to the higher air exchange rate in the case of mobile tests. It is likely that fume leakage occurred when using air recirculation as well; however the presence of the AC filtration system in the recirculation loop helped in minimizing the buildup of $PM_{2.5}$ inside the passenger cabin. Consistent results regarding fume leakage were obtained for CO with CO IO ratios of 1.6, 1.3 and 1.1 for W1/2O, AC FA and AC Rec tests, respectively, in the cabin of the Chevrolet Aveo 2011, compared to lower ratios in stationary and mobile tests. Similarly, in the cabin of the Kia Delta 1999, the CO IO ratios were 1.3, 0.9 and 1.6 for W1/2O, AC FA and AC Rec tests, respectively. The CO IO ratio was also high in the cabin of the Honda Civic 1997 with a value of 1.3 for all three ventilation modes. Therefore, findings regarding CO self-pollution are generally consistent with those of

$PM_{2.5}$ self-pollution which provides evidence that fume leakage was occurring at variable levels in the cabins of three (Chevrolet Aveo 2011, Kia Delta 1999, Honda Civic 1997) out of the six tested vehicles. Despite its contribution to measured in-vehicle pollution levels, this self-pollution could not be observed at times in mobile and stationary tests due to higher air exchange rate in the former case and to the low fuel combustion under idle conditions.

Fig 9 shows the individual IO ratios obtained in the fume leakage tests for the three test cars where self pollution was observed. The exceptionally high CO leakage rates obtained in the last three tests on the Chevrolet Aveo 2011 with the W1/2O mode sound odd indeed in view of the findings from previous tests conducted on the same car at similar speeds, and could be the result of an outside contamination which was not captured by out-vehicle sampling. Otherwise, there is a great variability in fume leakage rates across cars and ventilation modes with no particular car or mode consistently presenting the highest leakage rates. Several factors come at play in the determination of the IO ratio and rate of ingression of fumes into a vehicle cabin among which the distinct meteorological conditions and combustion temperatures across tests even if the same car and ventilation mode are used. Work is currently on-going to develop multiple regression models attempting to explain the IO variability across tests by correlating it to its potential determinants.

Influence of out-vehicle sample intake location

Table 5 outlines the location where highest correlation between log transformed in- and out- vehicle CO and $PM_{2.5}$ concentrations were identified for a specific ventilation mode. The results indicate that locations 2 and 4 which represent the front area of the car near the windshield are correlated most with in-vehicle air quality with out-vehicle concentration explaining 44 to 83% of in-vehicle pollutant concentration depending on the used ventilation mode. Further work is needed to assess the relationship between the current findings and the design characteristics of the test cars and their associated aerodynamics.

Influence of meteorological gradients

Findings regarding inter-correlations between temperature, humidity and pressure and associated differentials are outlined in Table 6. The temperature and humidity differentials were negatively correlated with an R^2 value of 18.6%. All other parameters exhibited weak and/or insignificant inter-correlations ascertaining that the effect of temperature and humidity differentials are independent of pressure differentials. Meteorological parameters with significant influence on pollutant IO ratios are depicted in Fig. 10. Models with highest predictive powers were quadratic in the case of pressure difference and cubic in the case of temperature and humidity difference. Note that for the ventilation mode AC FA, meteorological parameters did not affect much examined indicators probably because the IO ratio was controlled by the constant volume of fresh air intake through the fan of the AC system which dominated all other potential determinants.

In contrast, for the ventilation mode W1/2O, the difference in pressure between the inside and the outside of the car (P_{in}-P_{out}) explained 15.7 and 17.3% of variations in $PM_{2.5}$ and CO IO ratio, respectively, despite the equally large fresh air intake. In fact, in the case of a moving vehicle with a half opened window, the IO ratio is controlled by vehicle speed which in turn controls the pressure difference between any two points

inside and/or outside the vehicle (Hucho, 1998), thus the influence of pressure difference on pollutant IO ratios. Regarding temperature and humidity difference (T_{in}-T_{out} and RH_{out}-RH_{in}), no significant influence was observed for the W1/2O ventilation mode.

For the AC Rec mode, the pressure difference explained 22.1 and 26.7% of variations in $PM_{2.5}$ and CO IO ratio, respectively (p-value <0.05). The increase in the influence of pressure gradient compared to the W1/2O mode could be attributed to the closure of car vents and windows limiting fresh air intake to unconventional entry points such as body cracks, seams in doors and windows and possibly air exits in the rear part of the vehicle. The latter was also found to be influenced by temperature and humidity difference explaining 58.5 and 18.6%, respectively, of CO IO ratio variation (p-value <0.05). However, for $PM_{2.5}$, there was no significant influence of temperature and humidity on IO ratio variation.

Regarding the shape and direction of the relationships, the curves in Figs. 10a, 10b and 10d have negative leading coefficients indicating decreasing IO ratios with increasing 'P_{in}-P_{out}' values, which mean that the in-cabin $PM_{2.5}$and CO concentration decreased with increasing outflow of pollutant-laden cabin air to the outside. The curve is asymptotic to zero for negative 'P_{in}-P_{out}' values as in the latter cases, inflow of outside air was high bringing quickly in-cabin concentrations to the same levels encountered outside the vehicle (IO ratio =1 and log IO ratio =0). The relationship was different for $PM_{2.5}$ when air recirculation is used (Fig. 10c) due to the presence of air filtration in the recirculation loop, which induces lower than 1 IO ratios irrespective of the sign of 'P_{in}-P_{out}'. The leading coefficient is positive which means that IO ratio increased at both curve ends where pressure differential is high. Indeed, the higher the pressure differential, the higher the air exchange of the vehicle which in the presence of filtration, constitutes a drawback to keeping clean in-cabin air thus the increase in in-vehicle concentrations and in IO ratios. The influence of temperature differential (Fig. 10e) was different from that of pressure differential (Fig. 10d) whereby the IO ratio decreased for increasing negative 'T_{in}-T_{out}' values (which is equivalent to increasing T_{out} values). The latter is likely due to lower CO fume leakage rates and consequently low in-vehicle concentrations and IO ratios when ambient temperatures are warm. As for the influence of humidity differential on CO IO ratio, the results indicate a relationship which is opposite to that between the IO ratio and temperature differential, which is reasonable given the negative inter-correlation between temperature and humidity differentials (see Table 6).

Conclusions

Field assessment of in-vehicle exposure to $PM_{2.5}$ and CO was conducted in an urban congested area and along a highway during winter/spring season using six cars of different makes and ages under varied ventilation conditions with the objective of examining the influence of self pollution, out-vehicle sample intake location and weather gradients on in-vehicle concentrations. Average in-vehicle concentrations exceeded the WHO permissible exposure guidelines for all tested ventilation modes for $PM_{2.5}$ and when using a half opened window for CO. It is essential to note however the limitations of the comparison of PM $_{2.5}$ concentrations with the WHO guidelines in view of the potential error associated with the measurement method which has not yet been validated inside or adjacent to commuting microenvironments.

Three of the tested cars exhibited consistent cases of fume intrusion from the engine compartment to the car cabin indicating a high likelihood of occurrence of self pollution in passenger cars irrespective of their age. The latter self-pollution could not be observed at times in mobile and stationary tests due to the high air exchange rate in the former case and to the low fuel combustion in the latter case. Testing of a larger and statistically representative number of vehicles is desirable for wide generalization and validation. The use of air recirculation with particle filtration within the recirculation loop kept the $PM_{2.5}$IO ratios below one, with decreasing filtration efficiency as car age increased. The front area of a car near the windshield correlated most with in-vehicle air quality indicating that out-vehicle sampling in similar studies should be withdrawn from this location. Finally, differences in pressure between the inside and the outside of the vehicle were found to influence air pollutant IO ratios significantly with higher correlations in the case of AC Rec (22.1 and 26.7% of $PM_{2.5}$ and CO IO ratio variations, respectively) compared to W1/2O (15.7 and 17.3% of $PM_{2.5}$ and CO IO ratio variations, respectively). Temperature and humidity difference also affected CO IO ratios explaining 58.5 and 18.6% of their variation.

Tables

Table 1. Test Vehicles

Vehicle	*Model year*	*Mileage (km)*	*Engine*	*Passenger volume (ft^3)*	*Exterior length (inch)*	*Exterior width (inch)*	*Exterior height (inch)*
Chevrolet Aveo(CA)	2011	8,000	1.6 L, 108 HP	91	169.7	67.3	59.3
Kia Cerato (KC)	2011	29,000	2.0 L, 156 HP	97	178.3	69.9	57.5
Toyota Yaris(TY)	2010	30,000	1.5 L, 106 HP	84	150.6	66.7	60
Toyota Celica (TC)	2001	140,000	1.8L, 140 HP	78	170.5	68.3	51.4
Kia Delta (KD)	1999	65 000	1.5 L, 87 HP	-	164	65.6	57.1
Honda Civic (HC)	1997	289,000	1.6 L, 106 HP	90	175.2	67.1	54.7

Table 2. Experimental Program

	Type and number of tests			
***INPUT:** Test parameters[a/]*	*Fume leakage*	*Stationary*	*Mobile*	*Purpose of the tests*
VM: W1/2O; TL: AUB garage; VS: 0; 5 cars; Duplicate tests	10			Estimate fume leakage in a stationary vehicle with exhaust gas extraction under three ventilation modes and for five different cars
VM: AC FA; TL: AUB garage; VS: 0; 5 cars; Duplicate tests	10			
VM: AC Rec; TL: AUB garage; VS: 0; 5 cars; Duplicate tests	10			
VM: W1/2O; TL: chassis dynamometer; VS: 40, 60, 80; 5 cars; Duplicate tests	30			Estimate fume leakage in chassis dynamometer tests simulating movement at speeds of 40, 60 and 80 km/hr, with exhaust gas extraction, under three ventilation modes for five different cars
VM: AC FA; TL: chassis dynamometer; VS: 40, 60, 80; 5 cars; Duplicate tests	30			
VM: AC Rec; TL: chassis dynamometer; VS: 40, 60, 80; 5 cars; Duplicate tests	30			

VM: W1/2O; TL: AUB campus; VS: 0; 6 cars; Duplicate tests	12		Estimate in-vehicle exposure in a stationary vehicle away from traffic-induced emissions, without exhaust gas extraction under three ventilation modes for six different cars
VM: AC FA; TL: AUB campus; VS: 0; 6 cars; Duplicate tests	12		
VM: AC Rec; TL: AUB campus; VS: 0; 6 cars; Duplicate tests	12		
VM: W1/2O; TL: Hamra, highway; VS: 40, 60, 80; 6 cars; Duplicate tests		36	Estimate in-vehicle exposure in a vehicle moving at 40 km/hr in a residential-commercial zone, and 60 and 80 km/hr on a highway, without exhaust gas extraction, under three ventilation modes for six different cars
VM: AC FA; TL: Hamra, highway; VS: 40, 60, 80; 6 cars; Duplicate tests		36	
VM: AC Rec; TL: Hamra, highway; VS: 40, 60, 80; 6 cars; Duplicate tests		36	
Total number of tests	**264**		
Test duration, min	**30-45**		Test durations reportedly vary from 10 minutes to 1 hour (Adams *et al*., 2001b; Qi *et al*., 2008; Huang *et al*., 2012)

[a/] VM: ventilation mode; W1/2O: one window ½-opened and vents closed; AC FA: vents closed and air conditioning on fresh air intake; AC Rec: vents closed and AC on recirculation; TL: test location; VS: vehicle speed; WD: wind direction)

Table 3. Comparative Assessment of $PM_{2.5}$ Concentrations Inside Car Cabins

Study	*Location*	*Level ($\mu g/m^3$)*	*Type of reading*	*Type of vehicle*	*Method of measurement*	*Ventilation mode*
Rodes *et al*., 1998	Sacramento CA	10.8	Mean	Passenger cars	Gravimetrically	Windows closed, medium fan speed, vents open or closed
Rodes *et al*., 1998	Los Angeles CA	43	Mean	Passenger cars	Gravimetrically	Windows closed, medium fan speed, vents open or closed
Adams *et al*., 2001a	London, UK	35.7	Mean	Passenger cars	Gravimetrically	Open windows
Levy *et al*., 2002	Boston MA	100	Median	Passenger cars	Portable TSI DustTrak calibrated to tapered element oscillating microbalance	Open windows
Riediker *et al*, 2003	Raleigh NC	23	Mean	Patrol trooper	Gravimetrically and with a DataRam nephelometer	AC on recirculation
Boogaard *et al*., 2009	Netherlands	48.9	Mean	Passenger cars	Portable TSI DustTrak, no calibration	Windows closed, AC off, fan on
Huang *et al*., 2012	Bejing, China	31.6	Mean	Taxis	Portable LD-6S spectrometer calibrated gravimetrically	Windows closed, AC on
Both *et al*., 2013	Jakarta, Indonesia	87	Median	Passenger cars	Portable TSI DustTrak calibrated to beta attenuation monitor	With and without AC
This study	Beirut, Lebanon	71	Mean	Passenger cars	Portable TSI DustTrak, no	Window half opened, AC on

				calibration	recirculation, AC on fresh air

Table 4. Comparative Assessment of CO Concentrations Inside Car Cabins

Study	*Location*	*Level (ppm)*	*Type of reading*	*Type of vehicle*	*Ventilation mode*
Zagury *et al*., 2000	Paris, France	3.8	Mean	Taxis	Not controlled
Duci *et al*., 2003	Athens, Greece	21.4	Mean	Passenger cars	Not controlled
Bruinen de Bruin *et al*., 2004	Milan, Italy	5.7	Mean	Cars/Taxis	
Kaur *et al*., 2005a	London, UK	1.2	Mean	Cars/Taxis	Not controlled
Scotto di Marco *et al*., 2005	Helsinki, Finland	2.8	Mean	Passenger cars	Not controlled
Abi-Esber *et al*., 2007	Beirut, Lebanon	20	Mean	Passenger car	Window half opened, AC on recirculation, AC on fresh air , etc.
Saksena *et al*., 2007	Hanoi, Vietnam	18.5	Mean	Passenger cars	Windows opened, Windows closed and AC on
Huang *et al*., 2012	Bejing, China	5.2	Mean	Taxis	Windows closed, AC on
Wu *et al*., 2013	Bejing, China	3.4	Mean	Taxis	Windows closed and AC on; windows opened
Both *et al*., 2013	Jakarta, Indonesia	22	Mean	Passenger cars	With and without AC
This study	Beirut, Lebanon	8.5	Mean	Passenger cars	Window half opened, AC on recirculation, AC on fresh air

Table 5. Locations with highest correlation between log-transformed in- and out-vehicle concentrations

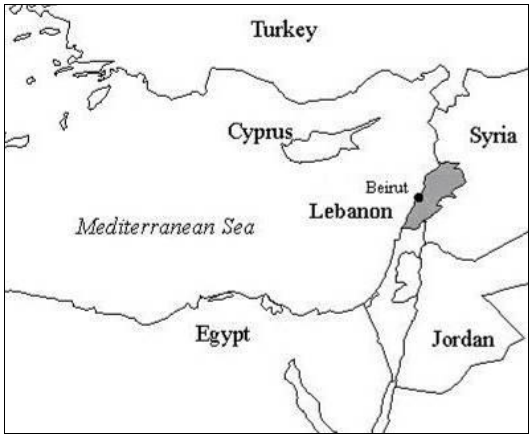
Indicator	*Ventilation mode*[a/]	*Best location*	*Regression analysis results at best location*	
			R^2	*p-value*
$PM_{2.5}$	W1/2O	Location 4	0.8272	0.000
	AC FA	Location 4	0.7625	0.000
	AC Rec	Location 3	0.4024	0.000
CO	W1/2O	Location 2	0.4449	0.000
	AC FA	Location 2	0.4356	0.000
	AC Rec	Location 4	0.4884	0.000

a/ *W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation*

Table 6. Relationship between meteorological parameters

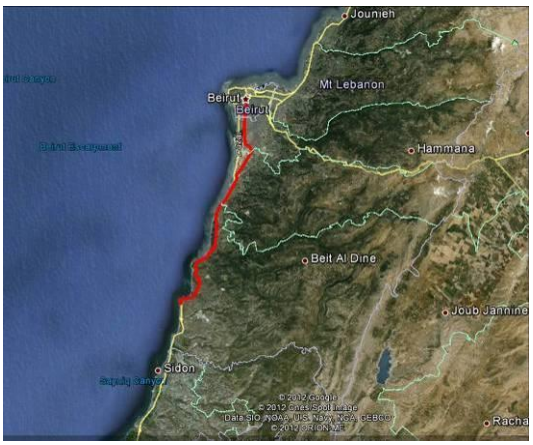
Parameters (y and x)	*Equation*	R^2	*p-value*
Temperature and humidity	y =0.02x+17.88	0.003	0.460
Temperature and pressure	y =0.81x-5.22	0.065	0.354
Humidity and pressure	y =-5.55x+222.16	0.021	0.036
Temperature and humidity differentials	y =-0.10x+3.3	0.186	0.000
Temperature and pressure differentials	y =-0.01x+4.56	0.002	0.614
Humidity and pressure differentials	y = -0.07x-16.19	0.004	0.460

Figures



a- Location of Lebanon in the Middle East

b- Trajectory 1 in Beirut area (red line)



c- Trajectory 2 on the Beirut-Jyeh highway (red line)

Fig. 1. Location of field testing trajectories

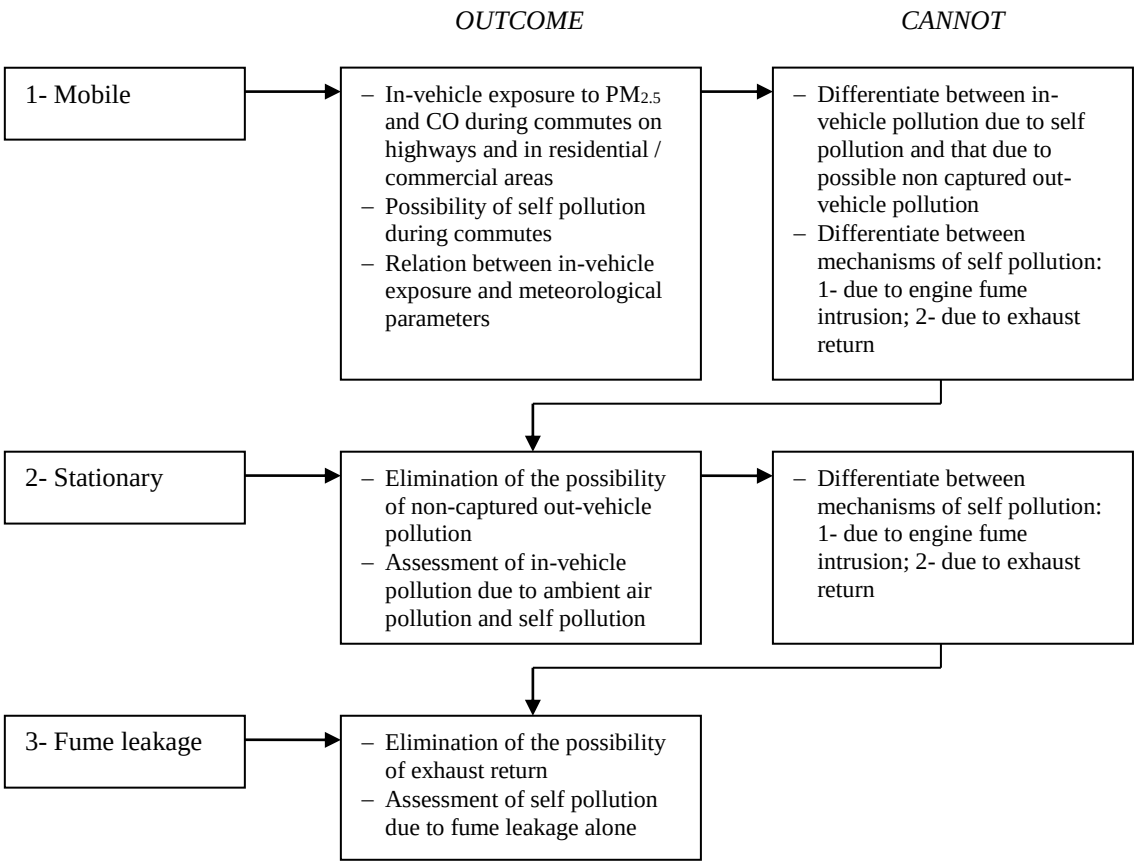
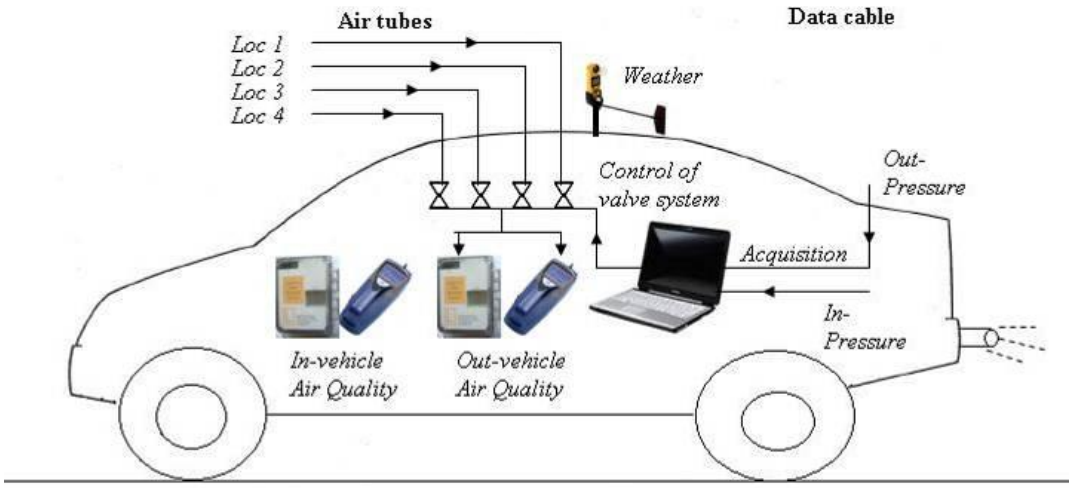
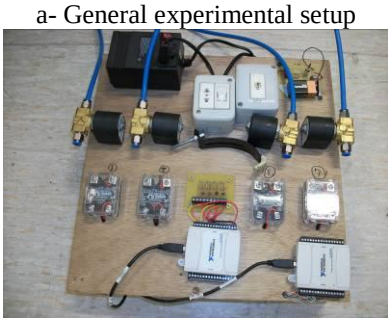


Fig. 2. Properties of testing categories



a- General experimental setup

Analyzers and laptop used for data acquisition



Valve system used for changing out-vehicle sample intake location

Board used for sensing of absolute pressure

b- Experimental setup components

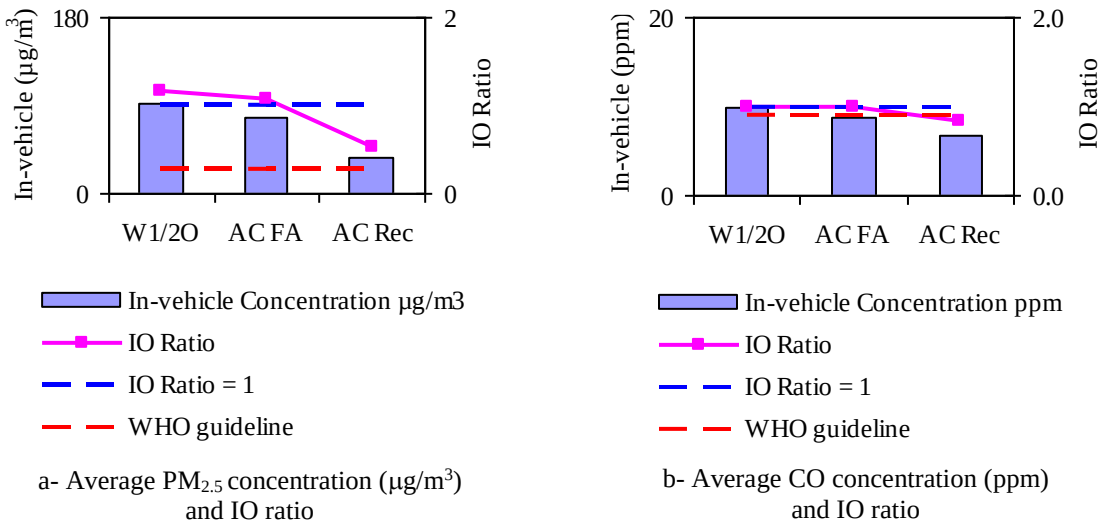
Location 1 (Rear left)

Location 3 (Rear right)

Location 4 (Front right)

c- Sample out-vehicle air intake locations

Fig. 3. Vehicle instrumentation



a- Average $PM_{2.5}$ concentration (µg/m^3) and IO ratio

b- Average CO concentration (ppm) and IO ratio

Fig.4. Influence of ventilation mode on in-vehicle exposure during mobile tests
W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation; IO ratio: In/Out ratio; WHO: World Health Organization

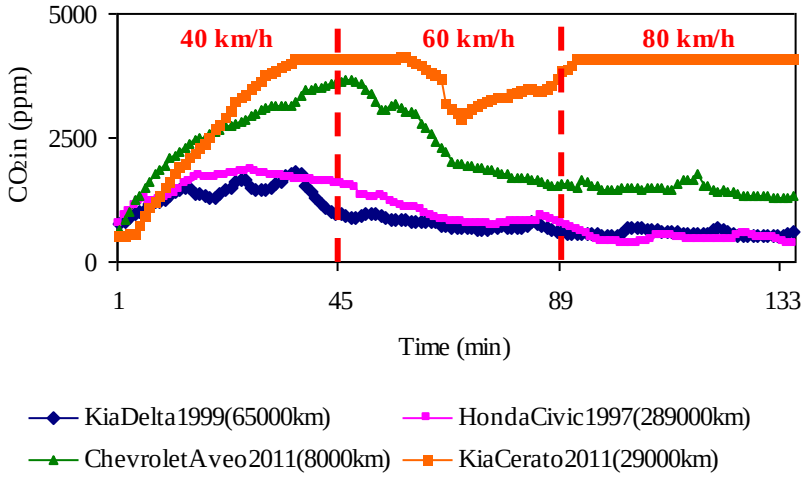
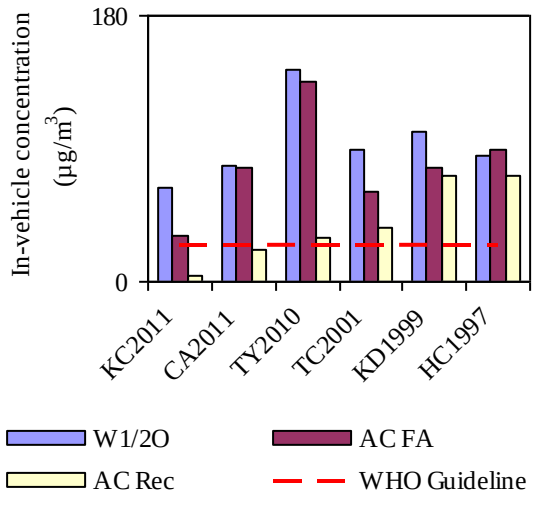
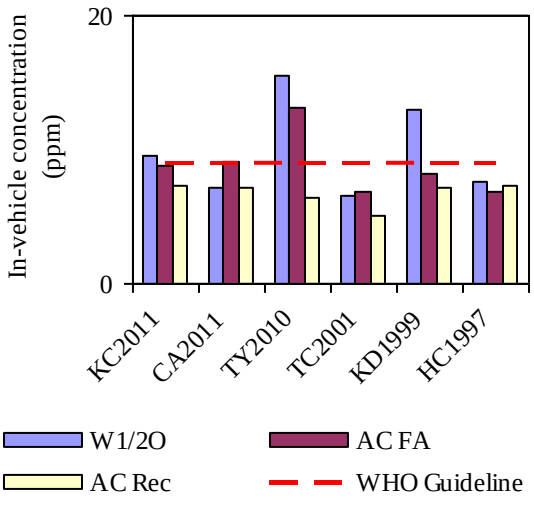


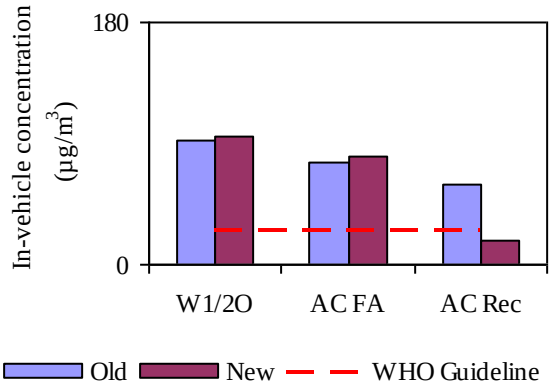
Fig. 5. Profiles of CO_2 variation inside the cabin of new versus old cars (mileage is indicated between parentheses)



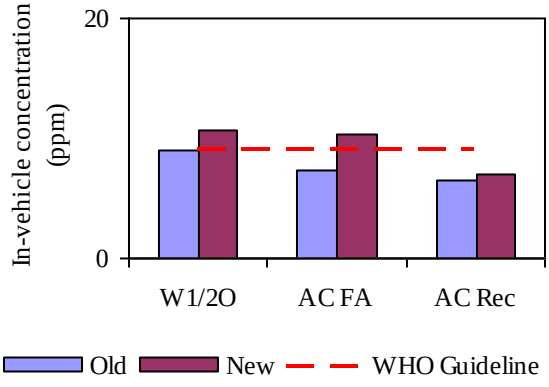
a- Average $PM_{2.5}$ concentration (µg/m^3) per test car



b- Average CO concentration (ppm) per test car



c- Average $PM_{2.5}$ concentration (µg/m^3) in old versus new cars



d- Average CO concentration (ppm) in old versus new cars

Fig.6. Influence of car age on in-vehicle exposure during mobile tests

KC: Kia Cerato; CA: Chevrolet Aveo; TY: Toyota Yaris; TC: Toyota Celica; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation; WHO: World Health Organization

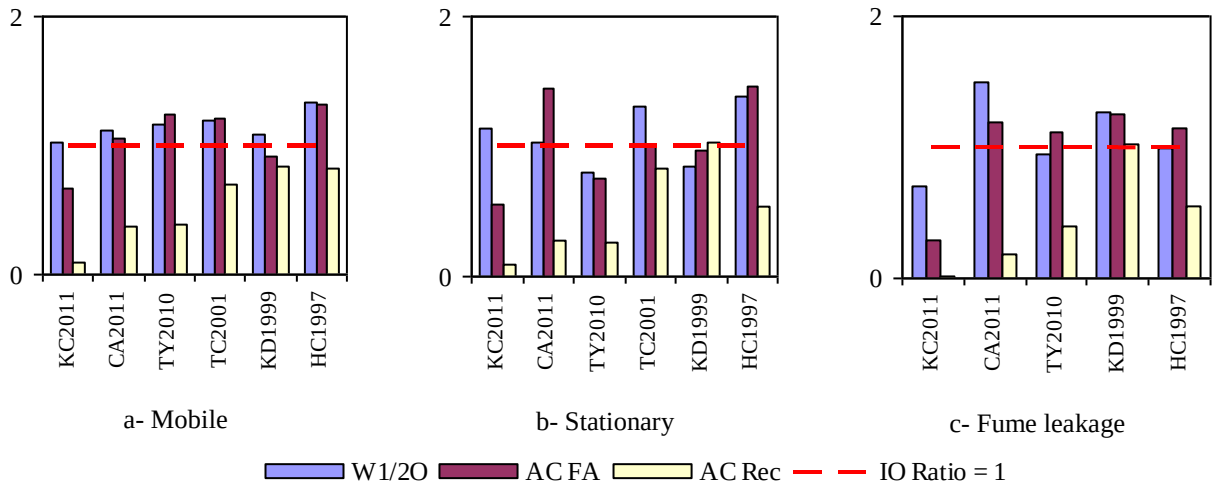


Fig. 7. Average $PM_{2.5}$ IO ratios in mobile, stationary and fume leakage tests
KC: Kia Cerato; CA: Chevrolet Aveo; TY: Toyota Yaris; TC: Toyota Celica; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation; IO ratio: In/Out ratio

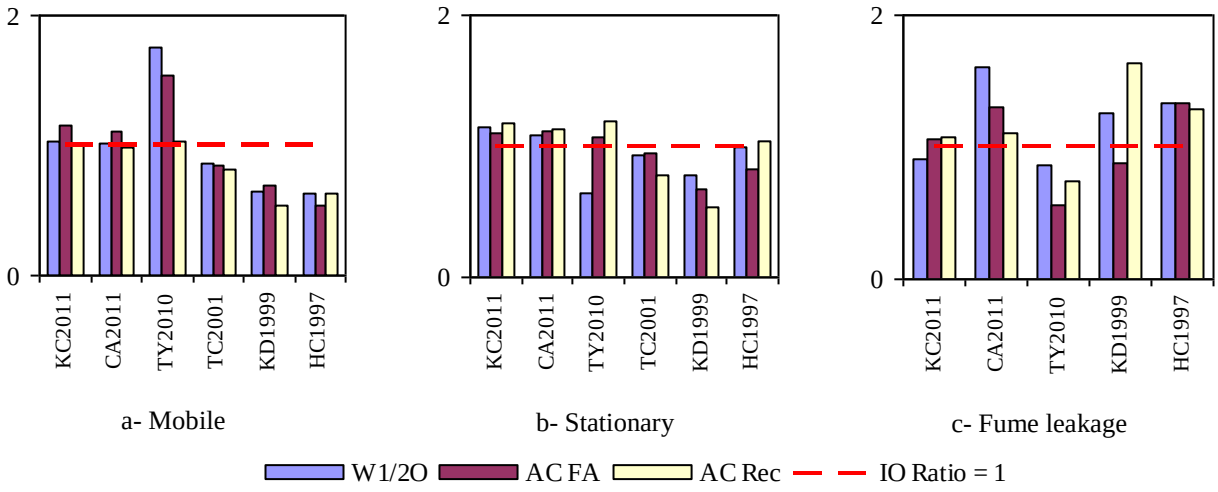


Fig.8. Average CO IO ratios in mobile, stationary and fume leakage tests
(KC: Kia Cerato; CA: Chevrolet Aveo; TY: Toyota Yaris; TC: Toyota Celica; KD: Kia Delta; HC: Honda Civic; W1/2O: one window half opened; AC FA: air conditioning on fresh air intake; AC Rec: air conditioning on recirculation; IO ratio: In/Out ratio)

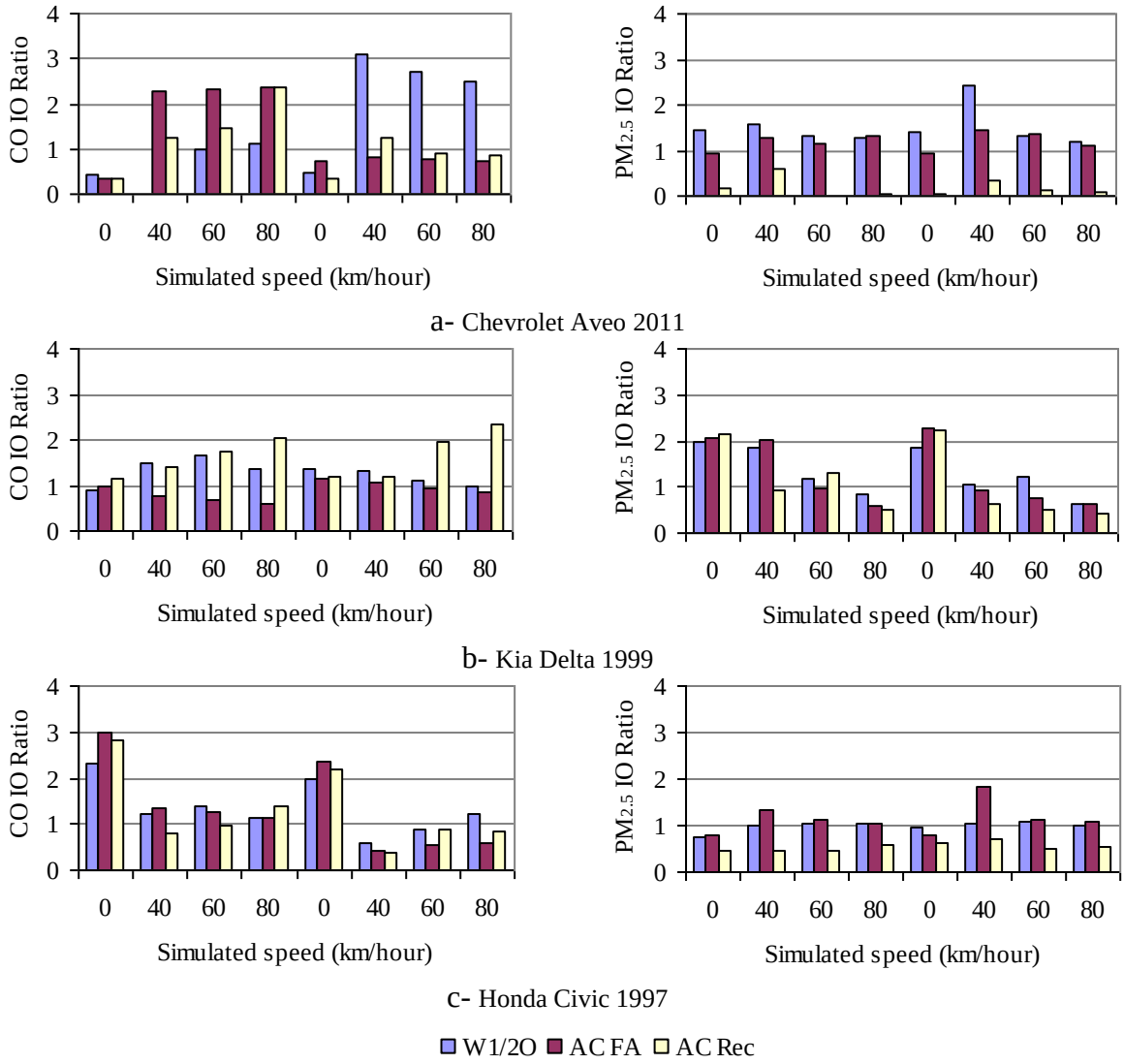


Fig. 9. IO ratios of CO and $PM_{2.5}$ concentrations during fume leakage tests in cars where fume leakage is observed

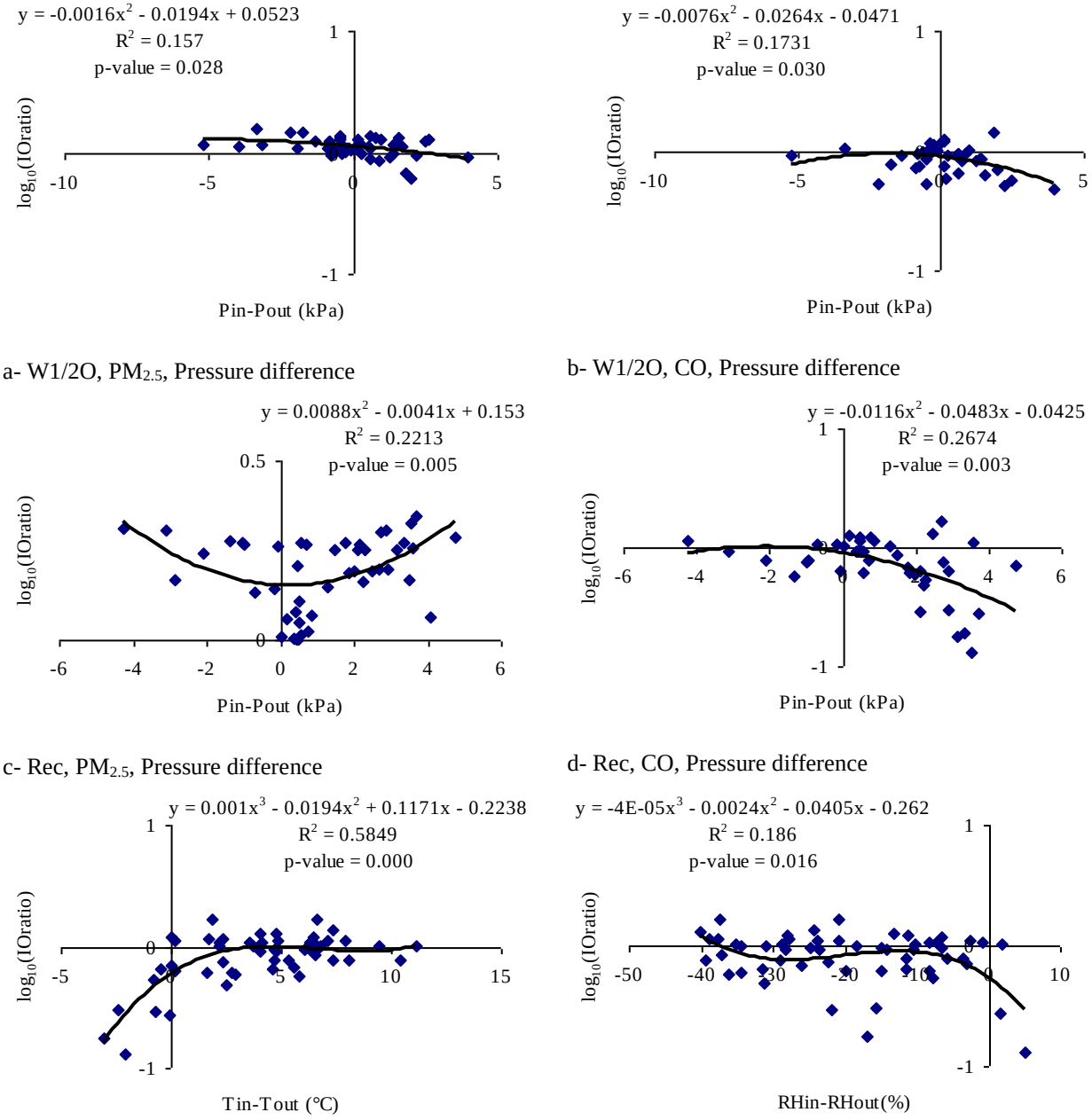


Fig. 10. Regression analysis of log transformed indoor to outdoor concentration ratios (IO ratio) against meteorological gradients
W1/2O: one window half opened;
AC FA: air conditioning on fresh air intake;
AC Rec: air conditioning on recirculation;
IO ratio: In/Out ratio

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APPENDIX 5

Correlation of in-vehicle exposure to operational and environmental determinants

Draft Paper, in review

ABSTRACT: In the context of the assessment of traffic emissions inside vehicles, scarce efforts targeted multivariate regression analysis of in-vehicle exposure and could explain at best 69% of carbon monoxide (CO) variability inside a car cabin. Further research is needed to identify the factors governing the remaining variability. The paper measures in- and out-cabin CO and fine particlulate ($PM_{2.5}$) concentrations in passenger cars with concomitant monitoring of 25 different potential determinants including those not previously addressed by multivariate regression analysis studies, namely ventilation mode, car brand and model, possibility of self pollution, exhaust flow rate and temperature and roadway type. Multivariate regression models of in-cabin CO and $PM_{2.5}$ concentrations were then developed using a stepwise selection method based on the Akaike Information Criterion. Best models of CO and $PM_{2.5}$ concentrations could explain 72 and 90% of the measured variability in CO and $PM_{2.5}$ concentrations.

KEYWORDS: multivariate regression, car cabin exposure, CO, $PM_{2.5}$

Introduction

Vehicular fuel combustion is a major source of particulate matter and carbon monoxide emissions. As a result, the car cabin represents a microenvironment where peak exposure to such pollutants is likely to occur (Hudda *et al*., 2011; Knibbs *et al*., 2011; El-Fadel and Abi-Esber, 2009) due to its proximity to the emitting source. Attempts at interpreting the high levels of traffic emissions inside vehicles related the problem to a large array of factors, including ventilation setting, weather conditions, roadway type, vehicle speed and self pollution. While the latter were investigated in scattered research studies (Koushki *et al*., 1992; Clifford *et al*., 1997; Flachsbart, 1999a, Chan and Liu, 2001; Chan *et al*., 2002a; 2002b; Chan and Chung, 2003; Duci *et al*., 2003; Riediker *et al.*, 2003; Behrentz *et al*., 2004; Ireson *et al*., 2004; Greaves, 2006; Gomez Perales *et al.* 2007; Abi-Esber and El-Fadel, 2008; Adar *et al*., 2008; Fondelli *et al.*, 2008; Qi *et al*., 2008; Asmi et al., 2009; Huang *et al*., 2012), few have attempted to develop models capable of correlating exposure to in vehicle and out vehicle predictive factors (Ott *et al*., 1994; Flachsbart, 1999b). Based on a set of 88 trips, Ott *et al*. (1994) tested the influence of nine possible predictors on average CO exposure on a highway. Their regression model included a seasonal term along with a traffic volume term. Later, Flachsbart (1999b) conducted a similar study along a comparable highway setting. The developed models relied on a set of 80 trips and tested for 15 different variables. Consistent with findings from the previous study, the models showed that cabin exposure to CO was affected mainly by CO concentrations on the previous link, travel time, and the average vehicle speed all of which constitute indirect measures of traffic volume, in addition to a seasonal term expressed by wind direction and speed. While previously models provided key insight on the model of in vehicle exposure, a large number of important variables were not considered. These factots include ventilation mode, car brand and model, possibility of self pollution, exhaust flow rate and temperature, and roadway type. Also, the developed models focused on a gaseous indicator, leaving uncertainty as to whether particulate exposure inside a car is governed by the same set of variables.

The current work considers 119 mobile tests, 120 fume leakage tests, and 25 different explanatory variables in an attempt to both improve the understanding of in-

cabin exposure to CO and $PM_{2.5}$ and quanify indoor and outdoor pollutant exchange rates. For this purpose, field testing was implemented using six different vehicles and involved the monitoring of in- and out-vehicle CO and $PM_{2.5}$ concentrations and 25 different potential determinants. Multivariate regression models of in-vehicle concentrations and indoor to outdoor air exchange were then developed. The developed models accounted for potential interactions between continuous predictor variable and for the presence or absence of self pollution. As compared to the previous studies, this study targeted two air quality indicators of distinct nature and attempted to develop more comprehensive models that account for potential determinants that were not previously examined.

Methodology

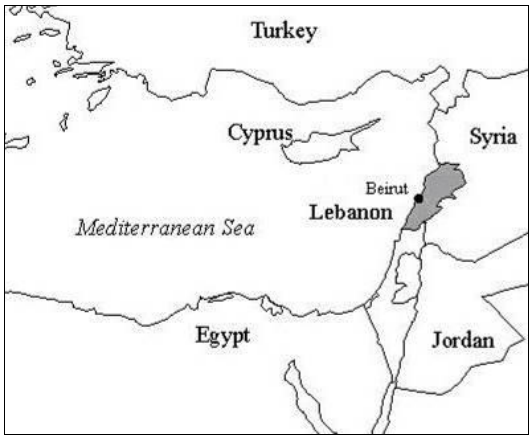
Field tests were conducted involving real time monitoring of in- and out-vehicle CO and $PM_{2.5}$ concentrations, vehicle speed, exhaust flow rate and temperature and in-and out-vehicle meteorological parameters. Corresponding ambient wind speed, wind direction and daily rainfall were also acquired. Multivariate regression analysis was then conducted to identify the main variables affecting in-vehicle concentrations.

Field Testing

Experimental program

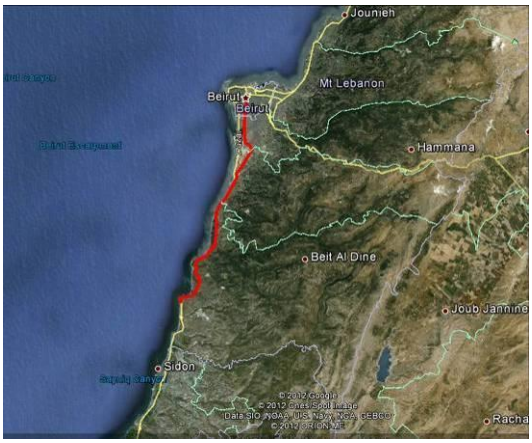
Trips were conducted during the period November 2011 to November 2012 between 8:30 a.m. and 1:30 p.m. along two different trajectories to represent a variety of possible testing speeds. Trajectory 1 is a 2,333 m-circuit in a commercial/residential area of Hamra-Bliss Area, Beirut, Lebanon (Fig. 1b) experiencing congested stop and go traffic at speeds of up to 40 km/h. Trajectory 2 is a 70 km double carriage highway on the Beirut-Jyeh highway in Lebanon (Fig.1c) experiencing slow moving traffic in its Northern part (average speed of 60 km/h) and faster traffic (average speed of 80 km/h) in the remaining Southern part. The setup is illustrated in Fig. 2. In-vehicle exposure is assessed using gasoline powered cars of six different makes (Table 1) selected to represent a diversity of vehicle designs and ages under three ventilation modes: 1) driver window ½-opened, air conditioning (AC) off, vents closed (W1/2O); 2) windows closed, AC on fresh air intake (AC FA), fan setting ‘medium’ or ‘2’; and 3) windows closed, AC on recirculation (AC Rec), fan setting ‘medium’ or ‘2’.

The cars were driven with a driver and a passenger at average speeds of 40 km/h on Trajectory 1 and 60 or 80 km/h on Trajectory 2, which are typical driving speeds in commercial/residential areas and on highways, respectively. A trip of 45 minutes was used. Exhaust fumes were allowed to flow freely from the car tailpipe to its surrounding area. $PM_{2.5}$ and CO concentrations were measured inside the cabin as well as in the outdoor air in the immediate vicinity of the car. During all tests, vehicle occupants refrained from smoking to preclude non-traffic sources of $PM_{2.5}$ and CO inside the vehicle. A total of 119 mobile trips were conducted as indicated in the experimental program (Table 2). For each set of conditions, at least duplicate tests were conducted for validation.



a- Location of Lebanon in the Middle East

b- Trajectory 1 in Beirut area (red line)

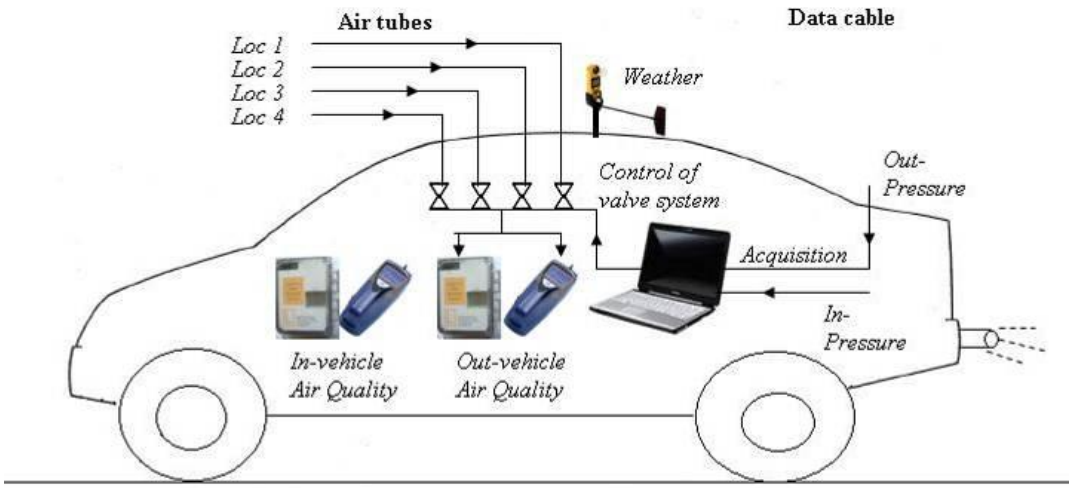


c- Trajectory 2 on the Beirut-Jyeh highway (red line)

Figure 1. Study area

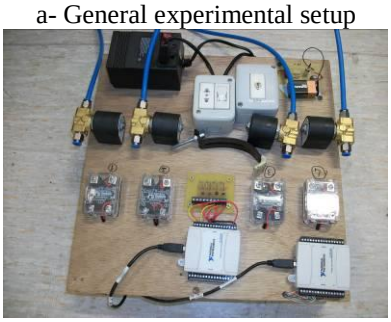
Table 1. Test Vehicles

Vehicle	*Model year*	*Mileage (km)*	*Engine*	*Passenger volume (ft^3)*
Chevrolet Aveo(CA)	2011	8,000	1.6 L, 108 HP	91
Kia Cerato (KC)	2011	29,000	2.0 L, 156 HP	97
Toyota Yaris(TY)	2010	30,000	1.5 L, 106 HP	84
Toyota Celica (TC)	2001	140,000	1.8L, 140 HP	78
Kia Delta (KD)	1999	65 000	1.5 L, 87 HP	85
Honda Civic (HC)	1997	289,000	1.6 L, 106 HP	90



a- General experimental setup

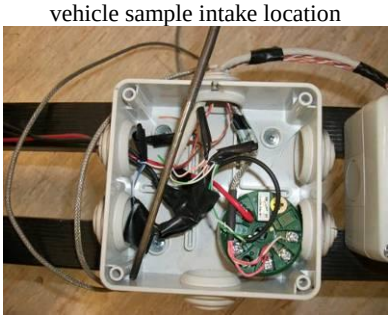
b- Analyzers and laptop used for data acquisition



c- Valve system used for changing out-vehicle sample intake location

d- Board used for sensing of absolute pressure

e- Pressure transducer



f- Resistance thermometer and transmitter for sensing temperature

g- Speedometer

Figure 2. Vehicle instrumentation

Air quality

Two new portable DustTrak analyzers (model 8532) by TSI Inc. were used for in and out-vehicle $PM_{2.5}$ monitoring with a log interval of 1 minute (Fig. 2b). The analyzers rely on the optical backscatter technology with a measurement range of 0.001-150 mg/m^3 and an accuracy of ±0.1% of reading or 0.001 mg/m^3, whichever is greater. A zero calibration was applied prior to every use. Two new portable Langan CO analyzers (model L76n) by Langan Products Inc. were used for in- and out-vehicle CO monitoring with a log interval of 1 minute (Fig. 2b). The analyzers rely on the electrochemical technology with a measurement range of 1 to 200 ppm, a resolution of 0.1 ppm and a response time ($t_{90\%}$) of 40 seconds (determined experimentally). Calibration with zero and span gas (50 ppm) was undertaken at the beginning of each testing round (every two weeks).

Table 2. Number of tests conducted in the experimental program

Ventilation mode	*W1/2O*			*AC FA*			*AC Rec*			**Total**
Trajectory	*Traj 1*	*Traj 2*		*Traj 1*	*Traj 2*		*Traj 1*	*Traj 2*		
Car Speed, km/hr	*40*	*60*	*80*	*40*	*60*	*80*	*40*	*60*	*80*	
Chevrolet Aveo 2011	3	3	3	2	2	2	3	3	3	24
Kia Cerato 2011	2	2	2	2	2	2	2	2	2	18
Toyota Yaris 2010	2	2	2	3	2	2	2	2	2	19
Toyota Celica 2001	2	2	2	2	2	2	2	2	2	18
Kia Delta 1999	2	2	2	2	2	2	4	3	3	22
Honda Civic 1997	2	2	2	2	2	2	2	2	2	18
Total	13	13	13	13	12	12	15	14	14	
	13	26		13	24		15	28		**119**
	39			37			43			

* W1/2O: one window ½-opened and vents closed; AC FA: vents closed and air conditioning on fresh air intake; AC Rec: vents closed and AC on recirculation

Out-vehicle sampling was conducted at four locations surrounding the test vehicle to capture its boundary conditions of air quality. For this purpose, a system of four valves and relays (Fig. 2c) was used to alternately switch the sample intake point every one minute to one of four locations, namely rear left of the car as observed by a seated driver (location 1), front left (location 2), rear right (location 3) and front right (location 4). The four locations were selected among a multitude of locations around the vehicle, as they are representative of four probable sources of out-vehicle air entering the cabin. The front locations are near the grill air intake of the AC system whereas the rear locations are close to the air exit points of the car cabin, which may turn into air entry points when they exhibit high pressure levels in the case of an idling car. In addition, one of the rear locations (rear right) is near the exhaust pipe and represents a boundary condition of out-vehicle concentrations. Polyethylene tubing and airtight push-in fittings were used for out-vehicle sample transport and distribution. The tubes were 1.5 m long with an inner diameter of 5.7 mm. The sampling flow rate inside the tubes were 6 L/min, as the DustTrak analyzers were run at their default flow rate of 3 L/min, and the CO sensor was exposed to the out-vehicle sample using Sensidyne Gil-Air-5 pumps calibrated to a flow rate of 3 L/min. Given the small aerodynamic diameter of the measured particles, the inlet efficiency can reasonably be assumed to be 100% (Brockmann, 2011) suggesting no particle losses at the tubes' inlets. Similarly, no losses due to gravitational deposition along the tubes' walls are expected as the sampling velocity across the line (~14 km/hour) was significantly higher than the deposition velocities of $PM_{2.5}$ particles (in the range 1.32 to 1.80 m/hour for the particle size range 2 to 3 μm and lower velocities for sizes less than 1 μm (Thatcher and Layton, 1995)). Finally, losses due to electrostatic deposition could not be estimated given the absence of information regarding the charge of the measured particles. They are however expected to be minimal as the sampling velocity was high enough to ensure efficient particle entrainment and line transmission (Brockmann, 2011).

Meteorological parameters

Real time on-board monitoring of in- and out-vehicle pressure, temperature and humidity was also undertaken. Pressure was measured using analog output piezoresistive pressure sensors (Omega PX72-030AV, Fig. 2d). The range and accuracy of the output signal are 0 to 30 psi (0 to 165 mV) and ±1.5 mV/psi, respectively. In-vehicle temperature and humidity were logged every minute by the Langan analyzer. Out-vehicle temperature and humidity were logged every minute by an on-board portable weather tracker (Kestrel 4500) installed on the roof of the car. The response time was one minute for relative humidity and one second for temperature. The measurement range and accuracy are 0-100% and ±3% for relative humidity and -45 to 125°C and ±1°C for temperature.

Exhaust flow rate

The differential pressure of exhaust fumes was measured using a pitot tube and differential pressure transducer installation (Fig. 2e). The calibrated range was 0 to 6 in H_2O recoverable in the form of a 4 to 20 mA analog output signal. A 470 Ω resistor was used to transform the output to a 1.88-9.40 volt signal acquired on a computer through a data acquisition card. Then, the differential pressure reading was coupled to a temperature reading to compute the exhaust flow rate:

$$Q = \left(\frac{\Delta P \times K^2 \times D^4 \times P \times 16590}{S_s \times (T + 460)} \right)^{1/2} \quad (1)$$

Where

Q	=	flow rate, cubic foot per minute
ΔP	=	differential pressure, inch H_2O
K	=	flow coefficient (0.517 for an Omega FPT-6110 pitot tube)
D	=	inside diameter of line size, inch
P	=	static line pressure, 14.695 psia
S_s	=	specific gravity at 15°C, assumed to be equal to 0.997
T	=	temperature of exhaust, °F

Exhaust temperature

A resistance temperature detector (RTD, also known as resistance thermometer) was used to sense the exhaust temperature. Signal conditioning was then applied using a transmitter providing a 4-20 mA current loop linearized signal proportional with the temperature characteristic provided from the RTD connected to its input. The transmitter, which has a nominal range of 0-400°C was calibrated in the range 30-255°C using an Omega CL1000 hot point dry block probe calibrator. The transmitter was powered through a 24 V DC power supply and the 4-20 mA output was read out as voltage using a 560 Ω resistor. The relationship between temperature (T, °C) and voltage (V, Volts) was found to have a correlation coefficient of 0.9969:

$$V = 0.0336T + 0.8216 \Rightarrow T = (V - 0.8216)/0.0336 \quad (2)$$

Vehicle speed

Vehicle speed was recorded by a GPS-based speed meter that logs speed and location (longitude, latitude) every 100 milliseconds at an accuracy of ±0.1 km/h (Fig. 2g).

Self pollution testing

Engine fume leakage prior to exiting the tailpipe was examined by extracting tailpipe fumes using a customized exhaust extraction system. For this purpose, 120 tests were implemented whereby exhaust fumes were collected into a well-fitted hose that was connected to the tailpipe through a sealed system that released gases 15 m away downwind from the test location. Tests simulating idle mode were conducted at a controlled garage located on campus of the American University of Beirut whereas those simulating engine combustion during car movement were conducted on a chassis dynamometer. Both locations were free from background $PM_{2.5}$ and CO sources. Chassis dynamometer testing was used to simulate engine combustion during vehicle movement at speeds of 40, 60 and 80 km/h. The exhaust pipes of the vehicles were inspected prior to field testing to ensure the absence of cracks or holes and to avoid the possibility of fume leakage to the immediate surroundings of the vehicle. $PM_{2.5}$ and CO concentrations were measured concomitantly inside and in the immediate vicinity of the vehicle. In the event concentrations of $PM_{2.5}$ or CO inside the cabin were found to be higher than those encountered outside, the contamination would be attributed to engine fume leakage prior to reaching the tailpipe. The details of the findings from the latter tests are reported elsewhere (Abi-Esber and El-Fadel; 2013). Three of the six test cars exhibited consistent cases of fume intrusion from the engine compartment to the car cabin, namely the Chevrolet Aveo 2011, the Kia Delta 1999 and the Honda Civic 1997.

Variables

A set of variables representing in-vehicle conditions and the ambient environment were measured (Table 3). The presence of rainfall on previous day was determined based on daily rainfall data acquired from Beirut International Airport and was treated as a binary variable, with ‘1’assigned for rainy days and ‘0’ for clear days. Similarly, the time of day was divided into before noon and after noon trips. Traffic time was accounted for in terms of two variables, X_{16} and X_{17} (Table 3). These were set to a value of ‘1’ when a peak traffic time was encountered. Local peak times were recorded during the trips whereas general peak times were considered to comprise morning and evening rush hours (8 to 10 am and 4 to 6 pm) and the hour following schools’ closure (2 to 3 pm). Categorical codes were used to refer to the ventilation mode (1: W1/2O; 2: AC FA; 3: AC Rec), the test car (1: KC2011; 2: CA2011; 3: TY2010; 4: TC2001; 5: KD1999; 6: HC1997), and the prevailing Wind direction (NE: 0-91º; ES: 91-180 º; SW: 181-270 º; WN: 270 to 359 º). The Julian Day was considered to be a continuous variable and was included as a sinusoidal function of the form sin(2*pi*JulianDay/365)+cos(2*pi*JulianDay/365) to account for potential seasonality. The presence of self-pollution was accounted for in terms of a binary variable, with a value of ‘1’ assigned for cars where fume leakage occurred during self-pollution testing and value of ‘0’ otherwise. Roadways were divided into highways and commercial residential roads with ‘1’ assigned to former and ‘1’ to the latter.

Table 3. Predictor variables

Code	*Description*	*Code*	*Description*
Air quality variables			
X_1	COout (ppm)	X_3	Initial COin (ppm)
X_2	PMout ($\mu g/m^3$)	X_4	Initial PMin ($\mu g/m^3$)
Meteorological variables			
X_5	Presence of rainfall on previous day	X_{10}	Pressure IO ratio
X_6	Ambient temperature (ºC)	X_{11}	Humidity IO ratio
X_7	Ambient pressure (KPa)	X_{12}	Wind speed (m/s)
X_8	Ambient relative humidity (%)	X_{13}	Wind direction (degrees)
X_9	Temperature IO ratio		
Temporal variables			
X_{14}	Time of day	X_{16}	Time corresponds to a local peak traffic time
X_{15}	Julian day	X_{17}	Time corresponds to a general peak traffic time
Car related variables			
X_{18}	Ventilation mode	X_{21}	Exhaust temperature (ºC)
X_{19}	Car	X_{22}	Exhaust flow rate (Lpm)
X_{20}	Presence of self-pollution		
Traffic variables			
X_{23}	Vehicle speed (km/hour)	X_{25}	Roadway type
X_{24}	Fraction of trip with stopped car (%)		

The response variables were transformed to ensure normality. As such, in-vehicle CO concentration values were log transformed (Log_{10}) to avoid problems caused by the right-skewness of concentration data. For the same reason, a square root (SqRt) transformation was applied to in-vehicle $PM_{2.5}$ concentrations, since zero concentrations were recorded when air recirculation was selected in a car.

Data analysis

Correlations between predictors were first examined and quantified using the spearman correlation factor. The correlation results were then used to develop a predictive multivariate regression model. A stepwise regression approach was adopted, whereby all variable combinations were tested. The selection of the best model was based on the Akaike information criterion (AIC). The AIC (Equations 2 and 3) is generally used for the identification of an optimum model in a class of competing models (Akaike, 1977). The AIC has been used in various fields of statistics, engineering, hydrology and numerical analyses (Mutua, 1994). Selected models were then 'polished', whereby all parameters with insignificant model coefficients were eliminated.

$$AIC = -2l + 2k \quad (2)$$

$$l = -2\sum_{i=1}^{n} \log\left\{ g(x_i \mid {}_k\hat{\theta}) \right\} + 2k \quad (3)$$

Where	l	=	log (maximized likelihood for model)
	k	=	number of fitted parameters
	g	=	probability density function of the fitted model
	x_i	=	vector of observations
	k	=	estimated parameter of the fitted model

Results and Discussion

Pairwise correlations

Correlations between the continuous predictor variables and the response variables were explored and are outlined in the color coded correlation matrix shown in Figure 3. The matrix indicated moderate to high correlations ($|r|>0.5$) between in-vehicle CO concentration on one end and vehicle speed and fraction of trip with stopped vehicle on the other. The correlation was negative in the former case and positive in the latter case. In fact, in-vehicle CO concentration decreased with increasing vehicle speed (and decreasing stopping intervals) which suggests the possibility of lower background CO concentrations on highways compared to commercial / residential areas. Dissimilarly, correlations with vehicle speed were low for $PM_{2.5}$ suggesting insignificant influence of roadway type on background $PM_{2.5}$ concentrations. Moderate correlations between out-vehicle CO concentration and each of in- and out-vehicle $PM_{2.5}$ concentration indicate that some of the variability in CO and $PM_{2.5}$ is attributable to a same emission source which is road traffic emissions. This is further indicated by the sample time series plots of CO against $PM_{2.5}$ concentration variations inside versus outside of a car cabin which show concomitant fluctuations of both indicators during the same minute at both in- and out- vehicle locations. Exhaust flow rate, exhaust temperature, and vehicle speed were positively correlated since high speed commutes are evidently associated with higher fuel combustion rates which translate into high exhaust temperature and flow rate. For the same reason, fraction of trip with stopped vehicle, which decreases with increasing vehicle speed, was negatively correlated with exhaust temperature and flow rate. Initial and out-vehicle $PM_{2.5}$ concentration increased with increasing out-vehicle ambient pressures due to the absence of rainfall during high atmospheric pressure conditions. In- and out-vehicle temperatures increased with decreasing humidity ratio which indicates that out-vehicle humidity levels were higher during warm season (summer, spring) commutes. Low to moderate ($0.3<|r|<0.7$) positive correlations were encountered between average in-vehicle and initial pollutant concentrations due to the influence of starting pollution levels on in-vehicle pollutant concentrations.

Low correlations ($0.3<|r|<0.5$) were encountered between all pollutant concentrations and Julian Day indicating that pollutant concentrations exhibited some degree of seasonality except for in-vehicle CO concentration which seems to be affected by other different factors, possibly minute to minute emissions inside or adjacent to the car. Higher out-vehicle humidity levels and in-vehicle temperatures were associated with higher wind speed levels ascertaining that higher ambient humidity levels were encountered during the warm season. In fact, the summer / spring season in the study area is characterized by higher wind speeds and temperatures than the winter season. Similar to out-vehicle CO concentration, in-vehicle CO was positively correlated with in- and out-vehicle $PM_{2.5}$ concentrations due to a common emission source; the correlation is obviously higher for out-vehicle compared to in-vehicle concentration as only a proportion of the out-vehicle pollution ends up inside the vehicle depending on the test conditions. Higher out-vehicle and initial CO concentrations, and out-vehicle and subsequently in-vehicle $PM_{2.5}$ levels were encountered for warmer out-vehicle temperatures indicating that higher CO and $PM_{2.5}$

pollution levels were encountered during the warm season. An indirect low positive relationship was also observed between out-vehicle temperature (and temperature ratio) and exhaust flow rate due to the direct relationship between exhaust temperature and flow rate and the natural positive correlation between ambient temperatures and exhaust temperature. In-vehicle pressure (and pressure ratio) increased with increasing stopping intervals and decreasing vehicle speeds indicating pressure build up inside the cabin in the latter circumstances. Lower in- and out- vehicle pollutant concentrations were measured for high wind speeds indicating that the latter exerted a dilution effect on both out- and subsequently in-vehicle CO levels. Also, in-vehicle CO concentrations decreased with increasing exhaust temperature and flow rate which is the case during highway commutes which are characterized by lower out-vehicle CO concentrations. The latter is equally shown by the low negative correlation between out-vehicle CO concentration and vehicle speed. Humidity and temperature levels were negatively correlated inside the vehicle indicating that the ventilation modes resulting in higher in-cabin temperature levels (window half opened and AC on fresh air intake) were associated with lower humidity levels than the ventilation mode involving recirculation which fostered increased humidity levels. Another interesting low and negative relationship was encountered between out-vehicle pressure and exhaust flow rate suggesting that lower out-vehicle pressure facilitated exhaust flow to the outside of the tailpipe.

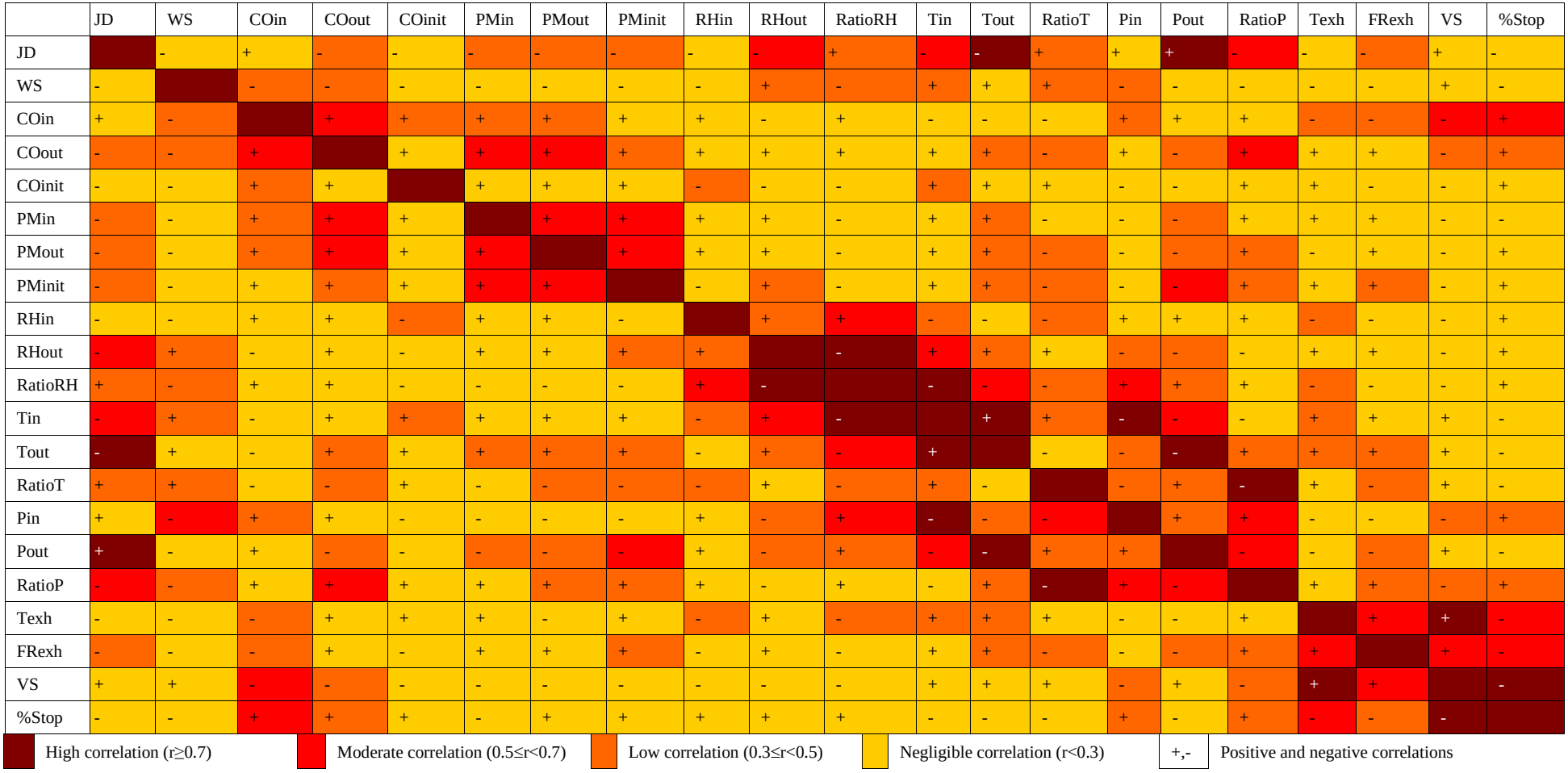


Figure 3. Correlation matrix

Multivariate regression analysis of pollutant concentrations

Findings from multivariate analysis of cabin exposure are provided in Tables 4 and 5 for models of in-cabin pollutant concentrations. The best model for predicting CO concentrations was able to explain 72% of the measured CO concentration variation (Multiple R-squared: 0.7733; Adjusted R-squared: 0.7229). The model indicates that for every 10 ppm increase in CO_{out} concentrations, the CO_{in} concentrations increased by 10 %. Moreover, when initial CO_{in} concentrations were 10 ppm higher, the in-vehicle CO concentrations were on average 6 % higher. These positive correlations indicate the strong relationship between CO accumulated inside the cabin and background levels and the out-vehicle concentrations. Increases in exhaust temperatures were found to result in higher in-vehicle CO concentrations. A 1 ^{o}C increase in Texh yielded a 0.5 % increase in in-vehicle CO concentration. This could be either due to 1) higher background CO levels and engine temperatures during warmer days or to 2) increased self-pollution levels inside a cabin when exhaust temperature is high. A 1 $\mu g/m^3$ increase in PMout was found to lead to a 2% increase in in-vehicle CO concentration. Variations in in-vehicle concentrations were found to be seasonal in nature. In-vehicle CO exposure was found to decrease from the beginning of January to reach a minimum by the end of March. Exposure increased from end of March until end of September, where it reaches its maximum before starting to decrease again between October and December. A rainfall event the previous day resulted in 13% drop in in-vehicle CO concentration. Afternoon commutes on average were associated with 6% higher in-vehicle CO concentrations than before noon trips. Different cars exhibited different exposure levels, particularly for the two cars (TY2010) and (KD1999) which had on average lower in-vehicle CO concentration as compared to the rest. South-westerly and north-westerly winds tended to increase in-vehicle CO concentrations by 12% and 8% respectively as compared to north easterly winds. This variability is likely due to the concentration of traffic emissions on the urban coastline with north easterly winds flushing emissions away towards the sea and westerly winds trapping the pollution inland. Finally, in-vehicle concentrations were 10% lower on a highway compared to a commercial residential area.

Table 4. Model for predicting log-transformed indoor CO concentrations (ppm) in a vehicle

Parameters	*Estimate*	*Std. Error*	*t value*	*Pr(>|t|)*	*Sig* [a/]
(Intercept)	0.771	0.196	3.929	0.000	***
Initial CO_{in} (ppm)	0.006	0.002	2.949	0.004	**
CO_{out} (ppm)	0.010	0.002	4.689	0.000	***
T_{exh} (ºC)	0.005	0.002	2.008	0.048	*
$Texh^2$	0.000	0.000	-2.085	0.041	*
PM_{out} ($\mu g/m^3$)	0.002	0.001	3.640	0.001	***
Presence of rainfall on previous day	-0.139	0.047	-2.937	0.004	**
Afternoon trips	0.064	0.025	2.568	0.012	*
Car type: CA2011	-0.002	0.078	-0.028	0.977	
Car type: TY2010	-0.573	0.257	-2.232	0.029	*
Car type: TC2001	0.143	0.128	1.118	0.267	
Car type: KD1999	-0.885	0.337	-2.627	0.011	*
Car type: HC1997	0.022	0.109	0.199	0.843	
sin(2 * Π * Julian Day/365)	-0.530	0.245	-2.158	0.034	*
SW winds	0.117	0.043	2.730	0.008	**
WN winds	0.076	0.031	2.476	0.016	*
Highway road	-0.107	0.037	-2.869	0.005	**
a/ Significance: 0.000:'***'; 0.001: '**'; 0.01: '*'; 0.05: '-'; 0.1: ' '					

*Note: Sample size: 92; Residual standard error: 0.09505 on 72 degrees of freedom; Multiple R-squared: 0.7733; Adjusted R-squared: 0.7229; F-statistic: 15.35 on 16 and 72 DF, p-value: < 2.2e-16; AIC: -149.1963

Similar to CO, the best model of $PM_{2.5}$ concentration (Table 5) included initial and out-vehicle $PM_{2.5}$ concentrations, test car, Julian day and wind direction in addition to other parameters which were not influential in the case of CO, namely wind speed, fraction of trip with stopped vehicle, commuting during a peak hour, and ventilation mode. The model was able to predict up to 90% of concentration variation (Multiple R-squared: 0.9140; Adjusted R-squared: 0.8964). Given the model structure, the linear relationship is established between the predictors and the square root of $PM_{2.5}$. As such, the rate of change of $PM_{2.5}$ is not constant across a unit change in the predictors.

The rate of change in the in-vehicle $PM_{2.5}$ concentration per 1 ppm increase in the initial $PM_{2.5}$ concentration or in the PM_{out} concentrations increased by 0.00013 and 0.008/ppm respectively. Traveling under conditions where south-westerly or northwesterly winds were dominant increased the measured $PM_{2.5}$ concentrations by 25% and 38%, respectively, compared to north easterly winds. Unlike the case for CO, in-vehicle $PM_{2.5}$ concentrations reached their maximum and minimum levels by the end of March and September, respectively. Car type also proved to be a significant factor affecting measured in-vehicle PM2.5 concentrations. On average, the KD1999 and the TY2010 had significantly higher PM2.5 concentrations as compared to the KC2011, while the CA2011, TC2001, and the HC1997 had lower in-vehicle concentrations.

These differences are possibly due to distinct $PM_{2.5}$ penetration factors across car shells at a time when CO penetration is constant and equal to 1. On another hand, the increase in ambient wind speed increased in-vehicle $PM_{2.5}$ concentration. The rate at which the increase occurred increased by 0.53 per 1 m/sec. The increase is possibly due to increased particle penetration across cracks. Moreover, as the fraction of trip with stopped vehicle increased the in-vehicle $PM_{2.5}$ concentrations decreased. This reflects the fact that in-vehicle $PM_{2.5}$ levels were found to be slightly higher on highways as compared to residential/commercial areas, where stopping was more frequent. The occurrence of a general peak hour increased in-vehicle concentration by 33% as compared to non-peak hours. Ventilation mode involving recirculation decreased $PM_{2.5}$ exposure inside a car by 63% as compared to the cars with windows half open. When the AC was on fresh air, the concentrations dropped by 11% only. This is largely a result of having the filters of all cars located within the recirculation loop.

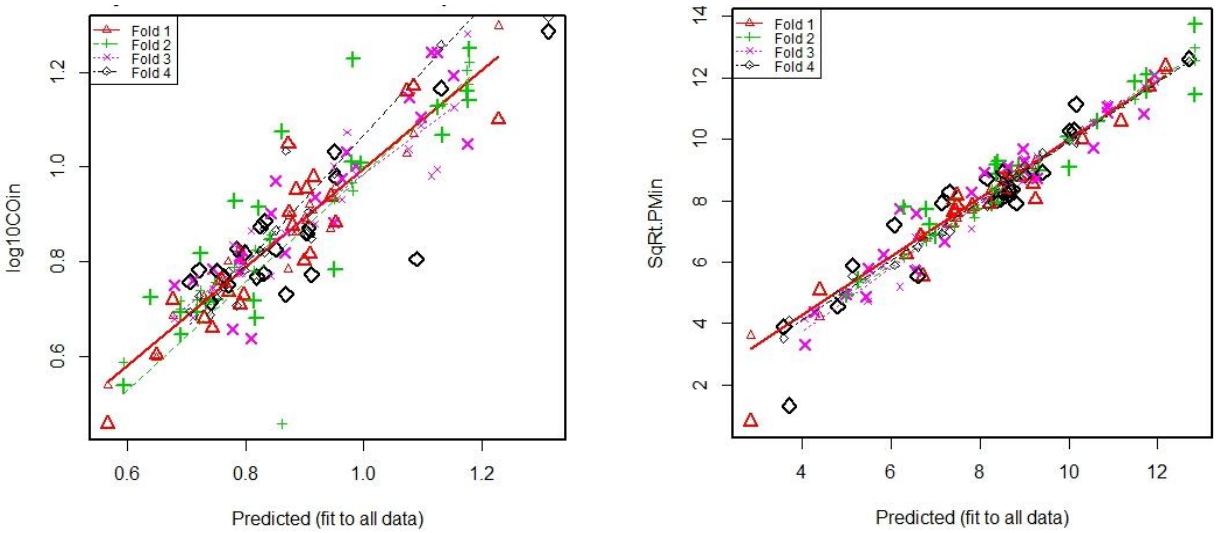
Table 5. Model for predicting log-transformed indoor $PM_{2.5}$ concentration ($\mu g/m^3$) in a vehicle

Parameter	*Estimate*	*Std. Error*	*t value*	*Pr(>|t|)*	*Sig* [a/]
(Intercept)	-4.330	1.252	-3.457	0.001	***
Initial PMin ($\mu g/m^3$)	0.008	0.002	3.604	0.001	***
PMout ($\mu g/m^3$)	0.063	0.005	13.145	0.000	***
AirportWind Speed (m/s)	0.517	0.136	3.798	0.000	***
Fraction Stopped (%)	-0.020	0.005	-4.381	0.000	***
as.factor(General.Peak.vs.non.peakCoded)1	0.576	0.226	2.546	0.013	*
AC on Fresh Air	-0.275	0.213	-1.291	0.201	
AC on Recirculation	-2.782	0.219	-12.712	0.000	***
Car type: CA2011	-1.858	0.599	-3.100	0.003	**
Car type: TY2010	11.062	1.790	6.179	0.000	***
Car type: TC2001	-3.393	0.957	-3.547	0.001	***
Car type: KD1999	14.648	2.357	6.214	0.000	***
Car type: HC1997	-2.587	0.920	-2.811	0.006	**
sin(2 * pi * JulianDay/365)	9.792	1.806	5.423	0.000	***
as.factor(WDcoded2)SW	0.456	0.329	1.387	0.170	
as.factor(WDcoded2)WN	0.640	0.233	2.745	0.008	**
a/ Significance: 0.000:'***'; 0.001: '**'; 0.01: '*'; 0.05: '-'; 0.1: ' '					

*Note: Sample size: 118; Residual standard error: 0.7609 on 73 degrees of freedom; Multiple R-squared: 0.914; Adjusted R-squared: 0.8964; F-statistic: 51.75 on 15 and 73 DF; p-value: < 2.2e-16; AIC: 220.2905

In an attempt to check against over-fitting, a cross validation exercise was implemented. For this purpose, the data were randomly assigned to four different folds. Then each fold was removed, in turn, while the remaining data was used to re-fit the regression model. The generated model was used to predict the deleted observations. A

comparison between model predictions and the actual data in the deleted fold was then conducted. Findings from the four-fold cross validation exercise are depicted in Figure 4. Results indicate that the generated models are robust and do not suffer from over-fitting.



a- CO model b- PM2.5 model

Figure 4. Cross validation of best multivariate regression models

Implications for in-vehicle exposure

The derived CO and $PM_{2.5}$ multivariate models suggest that assuming constant levels of initial COin, COout, Texh and PMout, lowest in-vehicle CO concentration would be recorded end of March on a morning highway drive with north easterly winds and following a rainy day. In contrast, highest in-vehicle CO concentrations would be recorded while commuting in late September in a commercial/residential area during the afternoon period, with south westerly winds and following a clear period with no rainfall. Similarly, assuming constant initial PMin, PMout, wind speed and fraction of trip with stopped vehicle, lowest in-vehicle $PM_{2.5}$ concentration would be recorded end of September during a non-peak hour of a day with north easterly winds all while the ventilation mode is set to air conditioning on with recirculation. In contrast, highest in-vehicle $PM_{2.5}$ concentration would be recorded end of March during a peak hour of a day with north westerly winds all while the ventilation mode is set to window half opened.

The analysis also showed that when accounting for a whole array of potential determinants of CO and $PM_{2.5}$ inside a vehicle cabin, some factors formerly believed to be important determinants of in-vehicle exposure such as vehicle speed and the presence of a local peak did not appear to have a significant influence on trip average in-vehicle pollutant concentration. This could be due to the fact that vehicle speed was related to roadway type with the inclusion of roadway type suppressing the need for specifying minute to minute variations in vehicle speed particularly that the analysis was run on trip average determinant values rather than on minute to minute trip specific variations. Also, a better substitute to the dichotomous variable related to the presence or absence

of a local peak would be traffic count data, whenever available, which would better describe local traffic conditions.

Besides initial and/or out-vehicle pollutant concentrations, other important parameters influencing CO exposure inside a vehicle include exhaust temperature, presence of rainfall on previous day, time of day, car type, Julian day, wind direction, and roadway type. Ventilation mode did not appear to play a significant role in the determination of in-vehicle CO exposure. Dissimilarly, for $PM_{2.5}$, ventilation mode was significantly influential with the ventilation mode involving recirculation presenting lower pollutant concentrations when compared to other ventilation modes. In addition, wind speed, fraction of trip with stopped vehicle and commuting during a peak hour were found to affect in-vehice exposure to $PM_{2.5}$ at a time when they were insignificant predicors in the case of CO. The latter finding indicates that distinct factors govern CO and $PM_{2.5}$ exposure inside a vehicle.

An interesting finding was the influence of various car types on in-vehicle exposure to air pollution with some of the pollution being contributed by self pollution. The latter points to the importance of the strengthening of the governmental mechanical inspection programs and their expansion to include testing for self pollution by comparing in- and out-vehicle pollutant concentrations and maintaining a related database. In the event that cars from the same manufacturer revealed common occurences of self pollution conditions, a ban on the import of the subject manufacturer would be enforced.

Finally, although pairwise correlations showed significant influences at times of meteorlogical determinants such as pressure, temperature, relative humidity and their indoor to outdoor ratios on in-vehicle CO and $PM_{2.5}$ concentrations, a single surrogate term, the Julian Day, revealed more useful to introduce in a multivariate model of in-vehicle exposure than the other meteorological determinants with consistently significant implications for both CO and $PM_{2.5}$. Different results are expected however if minute to minute estimations of cabin concentrations are sought.

Summary and Conclusion

Multivariate regression models of CO and $PM_{2.5}$ concentrations were developed using a database of 119 mobile tests, 120 fume leakage tests and 25 different predictor variables in an attempt to improve the understanding of in-cabin exposure to CO and $PM_{2.5}$ and indoor and outdoor pollutant exchange. Best models of CO and $PM_{2.5}$ concentrations could explain 72 and 90% of the measured variability in CO and $PM_{2.5}$ concentrations, respectively. In-vehicle CO concentrations were found to be affected by the initial and out-vehicle CO and $PM_{2.5}$ concentrations, exhaust temperature, presence of rainfall on previous day, time of day, car type, Julian day, wind direction, and roadway type. On another hand, the $PM_{2.5}$ concentration model indicated that the intial and out-vehicle $PM_{2.5}$ concentrations, wind speed, fraction of trip with stopped vehicle, commuting during a general peak hour, ventilation mode, test car, and Julian day were important factors affecting the in-vehicle concentrations.

The model results provide a novel way to quantify the complex roles that traffic, seasonality, vehicle characteristics, ventilation, meteorology, and ambient air quality play in dictating commuter exposure to CO and $PM_{2.5}$ when traveling on a highway or in a commercial/residential area.

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APPENDIX 6

Carbon monoxide and fine particulate matter self pollution rates inside cabins of passenger cars

Draft Paper, in review

ABSTRACT: In this study, in-vehicle and out-vehicle concentrations of fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) are measured during 64 on-road trips using three small size vehicles where self pollution was observed through chassis dynamometer testing. A mass balance modeling was then conducted to simulate the magnitude of the self pollution inside vehicles. For this purpose, measured outdoor concentrations and variations in vehicle air change were used to estimate self pollution rates and match the average measured concentrations. While CO self pollution rates could not be accurately estimated in the cabins of older models (1999 and 1997 vehicles), the self pollution rates inside the 2011 vehicle ranged from a low of 33 mg/h with AC on recirculation to a high of 5175 mg/h when the AC was set on the Fresh Air intake. On the other hand, while $PM_{2.5}$ self pollution was lower in the cabin of the 2011 model compared to the cabin of the older vehicles, a similar pattern was exhibited with the various ventitaltion modes whereby the lowest self pollution rate (0.2 mg/h) was observed with the AC on recirculation and reaching nearly 40 and 58 mg/h when the AC was on Fresh Air intake or the window was half opened (depending on vehicle age).

KEYWORDS: car cabin exposure, mathematical modeling, self pollution rate

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Introduction

Passenger exposure to vehicle-induced emissions is a common occurrence, particularly when commuting in small vehicles because of the low body position and the low intake point of the ventilation system leading to a close contact with the exhaust of other vehicles. Compared to other micro-environments, in-vehicle exposure is more complex to understand because it is affected by several interactive determinants including roadway type, ventilation setting, weather conditions, vehicle characteristics and self pollution.

Being a surrogate measure of traffic volume and speed, the roadway location and functional type affect total vehicular emissions. Highest in-vehicle CO levels were measured inside vehicles commuting in commercial-residential areas (Chan and Liu, 2001; Chan *et al*., 2002b; Duci *et al*., 2003). Indeed, such areas are characterized by low speed commutes and/or stop and go traffic with frequent idling which would increase exhaust emissions and decrease vehicle air change rate and inter-vehicle distance thus increasing the potential of exhaust penetration into the vehicle. In contrast, traveling at high speed in open areas increases cabin ventilation and hence has been associated with lower in-vehicle air exposure (Koushki *et al*., 1992; Clifford *et al*., 1997a; and Alm *et al*., 1999). Equally important, the ventilation mode and associated status of windows, air vents and air conditioning settings can affect the vehicle air change rate and in-vehicle air quality significantly. While early investigations by Chan *et al*. (1991) showed no significant impact of ventilation mode on in-vehicle CO exposure, recent findings by Abi Esber *et al*. (2007a) demonstrated the opposite for modes involving closure of windows and vents whereby highest exposure levels were recorded with or without the use of an air conditioning system. Similarly, Chan *et al*. (2002a) consistently reported that while the adoption of an air-conditioning system was an effective way to minimize PM exposure, it significantly increased CO levels in taxis. Weather conditions were also shown to play a significant role whereby a higher wind speed, lower temperature, and

higher humidity decrease car-exterior concentrations and corresponding in-vehicle levels (Ott *et al*., 1994; Alm *et al*., 1999; USEPA 1998a; Duci *et al*. 2003;Gomez-Perales *et al*. 2007). Transport mode is another commonly examined in-vehicle exposure determinant with vehicle-to-vehicle variability attributed to height from road and cabin volume. Recent studies showed that exposure increased with decreasing vehicle volume and height, with roadway and railway transport modes exhibiting highest and lowest exposure levels, respectively (Chan and Liu, 2001; Chan *et al*., 2002a; 2002c; Gomez-Perales *et al*., 2007).

Self-pollution, or the intrusion of a vehicle's own engine fumes into the passenger's compartment, has been reported to contribute to exposure inside various types of vehicles. Besides demonstrating the occurrence of CO self pollution inside a passenger car using field testing and mass balance simulations, Abi-Esber and El-Fadel (2008) reported that ratios of in-vehicle to out-vehicle concentrations greater than unity were invariably attributed in the literature to the occurrence of a self-polluting condition and the likely existence of a pollution source inside the vehicle. Indeed, Chan *et al.*(1991), Weisel *et al.* (1992), Dor *et al.* (1995) and Lawryk *et al*.(1995) found that VOC levels were higher inside a moving vehicle than in surrounding ambient air, suggesting in-vehicle sources including engine vapor intrusion across the fire wall, from underneath the vehicle, or from the draft area behind the vehicle. More recently, Chan *et al.* (2002) reported median ratios greater than 1 for in-vehicle to out-vehicle CO concentrations in urban residential, rural, industrial areas and along highways of Hong Kong, and suggested the internal engine compartment as a possible additional source of CO emissions inside the vehicle. Likewise, Chan and Chung (2003) reported ratios of up to 1.8 in urban areas, 8 in tunnels and 10 in countryside depending on the used ventilation mode and suggested the possibility of a likely source of CO inside the vehicle. Behrentz *et al.* (2004) measured self-pollution in school buses using a tracer gas technique and found that up to 0.3% of the air inside the cabin was from the bus' own exhaust in older buses, approximately 10 times the percentage observed for newer buses, and that 25% of the variation in black carbon concentration within the buses was attributed to self-pollution. Fondelli *et al.* (2008) observed $PM_{2.5}$ concentrations in buses and taxis in excess of the urban concentrations attributing the observation to several sources among which the exhaust of the tested vehicles themselves. Likewise, Asmi *et al.* (2009) measured in-vehicle and background concentrations of fine particles inside buses and trams and observed daily average ratios varying in the range 0.8-4.3 and 1.0-2.9 for the number and mass concentrations, respectively, suggesting that the elevated levels in buses are due to traffic emissions, with a fraction of the pollutants probably coming from the vehicles themselves. However, to date, there are no reported studies exploring the mechanisms of self-pollution by $PM_{2.5}$ in the passenger cabin of a car, which is by far the most popular transport mode.

In this study, commuters' exposure to carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$) inside a vehicle compartment was examined. For this purpose, pollutantmeasurements were conducted inside and outside three self polluting test cars, on two distinct roadway types and under three commonly used ventilation modes. The field monitoring efforts were coupled with mathematical simulations to relate in-vehicle to out-vehicle levels, assess in-vehicle concentrations and exposure profiles, and estimate in-cabin CO and $PM_{2.5}$ emission rates.

Methodology

Field Testing

Self pollution testing

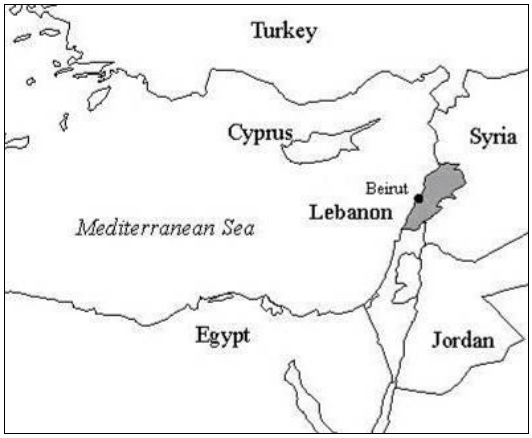
The possibility of engine fume leakage prior to exiting the tailpipe was examined inside six different test cars representing variable car designs and ages (Table 1) by extracting tailpipe fumes using a customized exhaust extraction system. The exhaust fumes were collected into a well-fitted hose that is connected to the tailpipe through a sealed system that releases 15 m away downwind from the test location. Tests simulating idle mode were conducted at a controlled garage located on campus of the American University in Beirut (AUB) whereas those simulating engine combustion during car movement were conducted on a chassis dynamometer with both locations free from background $PM_{2.5}$and CO sources. Chassis dynamometer testing was used to simulate engine combustion during vehicle movement at speeds of 40, 60 and 80 km/h. The engine was running during these tests at average speeds of 800, 1500, 1600 and 2150 rounds / minute for speeds of 0, 40, 60 and 80 km/h, respectively. The exhaust pipes of the vehicles were inspected prior to field testing to ensure the absence of cracks or holes and to avoid the possibility of fume leakage to the immediate surroundings of the vehicle. $PM_{2.5}$and CO concentrations were measured concomitantly inside and in the immediate vicinity of the vehicle. In the event of $PM_{2.5}$ or CO detection inside the cabin, the contamination would be attributed to engine fume leakage prior to reaching the tailpipe. Three of the tested cars (CA2011, KD1999 and HC1997) exhibited consistent cases of fume intrusion from the engine compartment to the car cabin and were subsequently used during mobile testing as described in the experimental program.

Table 1. Test cars

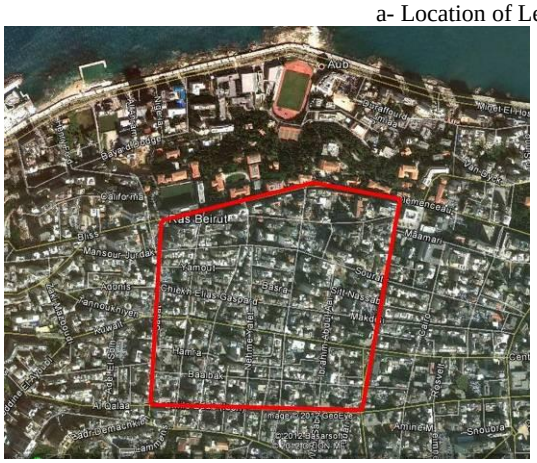
Vehicle	*Model year*	*Mileage (km)*	*Engine*	*Passenger compartment volume (ft^3)*
Chevrolet Aveo(CA)	2011	8,000	1.6 L, 108 HP	91
Kia Cerato (KC)	2011	29,000	2.0 L, 156 HP	97
Toyota Yaris(TY)	2010	30,000	1.5 L, 106 HP	84
Toyota Celica (TC)	2001	140,000	1.8L, 140 HP	78
Kia Delta (KD)	1999	65 000	1.5 L, 87 HP	-
Honda Civic (HC)	1997	289,000	1.6 L, 106 HP	90

Experimental program

Trips were conducted during the period November 2011 to November 2012 between 8:30 a.m. and 1:30 p.m. along two different trajectories to represent a variety of possible testing speeds. Trajectory 1 is a 2,333 m-circuit in a commercial/residential area of Hamra-Bliss Area, Beirut, Lebanon (Fig. 1b) experiencing congested stop and go traffic at speeds of up to 40 km/h. Trajectory 2 is a 70 km double carriage highway on the Beirut-Jyeh highway in Lebanon (Fig.1c) experiencing slow moving traffic in its Northern part (average speed of 60 km/h) and faster traffic (average speed of 80 km/h) in the remaining Southern part.



a- Location of Lebanon in the Middle East



b- Trajectory 1 in Beirut area (red line)

c- Trajectory 2 on the Beirut-Jyeh highway (red line)

Figure 1. Study area

The setup is illustrated in Fig. 2. In-vehicle exposure is assessed under three ventilation modes: 1) driver window ½-opened, air conditioning (AC) off, vents closed (W1/2O); 2) windows closed, AC on fresh air intake (AC FA), fan setting 'medium' or '2'; and 3) windows closed, AC on recirculation (AC Rec), fan setting 'medium' or '2'. The cars are driven with a driver and a passenger at average speeds of 40 km/h on Trajectory 1 and 60 or 80 km/h on Trajectory 2, which are typical driving speeds in commercial/residential areas and on highways, respectively. A trip of 45 minutes is used. Exhaust fumes are allowed to flow freely from the car tailpipe to its surrounding area. $PM_{2.5}$ and CO concentrations were measured inside the cabin as well as in the outdoor air in the immediate vicinity of the car. During all tests, vehicle occupants refrained from smoking to preclude non-traffic sources of $PM_{2.5}$ and CO inside the vehicle. 64 mobile trips were conducted as indicated in the experimental program (Table 2). For each set of conditions, at least duplicate tests were conducted for validation.

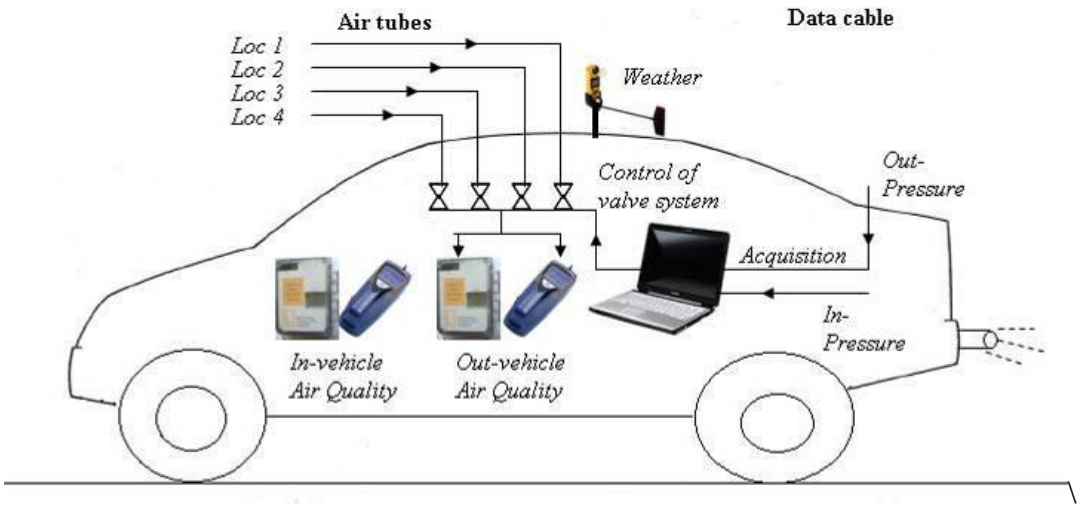


Figure 2. Experimental setup

Table 2. Number of tests conducted in the experimental program

Ventilation mode	*W1/2O*			*AC FA*			*AC Rec*			**Total**
Trajectory	*Traj 1*	*Traj 2*		*Traj 1*	*Traj 2*		*Traj 1*	*Traj 2*		
Car Speed, km/hr	*40*	*60*	*80*	*40*	*60*	*80*	*40*	*60*	*80*	
Chevrolet Aveo 2011	3	3	3	2	2	2	3	3	3	24
Kia Delta 1999	2	2	2	2	2	2	4	3	3	22
Honda Civic 1997	2	2	2	2	2	2	2	2	2	18
Total	7	7	7	6	6	6	9	8	8	
	7	14		6	12		9	16		**64**
	21			18			25			

* W1/2O: one window ½-opened and vents closed; AC FA: vents closed and air conditioning on fresh air intake; AC Rec: vents closed and AC on recirculation

Vehicle instrumentation

Two new portable DustTrak analyzers (model 8532) by TSI Inc. were used for in- and out-vehicle $PM_{2.5}$ monitoring with a log interval of 1 minute. The analyzers rely on the optical backscatter technology with a measurement range of 0.001-150 mg/m^3 and an accuracy of ±0.1% of reading or 0.001 mg/m^3, whichever is greater. They are factory-calibrated to the respirable fraction of the International Organization for Standardization (ISO) 12103-1, A1 Arizona test dust, which is representative of a wide variety of ambient aerosols (Kim *et al*., 2004). A zero calibration was applied prior to every use. Size-selective impactors were attached to the inlets of the analyzers to pre-condition the size range of the particles entering the instrument to $PM_{2.5}$. The impactors were cleaned and oiled at the end of each sampling day to help maintain the flow within 5% of factory's setpoint (3 L/min) and achieve the correct particle cutpoint (2.5 μm). The precision of the analyzer was determined experimentally to be ±4% at a roadside location (R^2 = 0.99) and ±20% at a university campus location (R^2 = 0.97) using sixty 1-minute collocated measurements. DustTrak analyzers have invariably been relied upon in previous studies of commuter exposure to traffic related $PM_{2.5}$ emissions (Dennekamp *et al*., 2002; Levy *et al*., 2002; Boogard *et al*., 2009; Both *et al*., 2013), which facilitates comparative assessments and partial validation.

Two new portable Langan CO analyzers (model L76n) by Langan Products Inc. were used for in- and out-vehicle CO monitoring with a log interval of 1 minute. The analyzers rely on the electrochemical technology with a measurement range of 1 to 200 ppm, a resolution of 0.1 ppm and a response time ($t_{90\%}$) of 40 seconds (determined experimentally). Calibration with zero and span gas (50 ppm) was undertaken at the beginning of each testing round (every two weeks). The accuracy of the analyzer was tested in the range 0-3 ppm against a reference non-dispersive infrared spectrometry method revealing satisfactory instrument performance ($R^2 = 0.93$) (Chang *et al*., 2001). Similar to the DustTrak analyzers, Langan analyzers are invariably relied upon in previous studies of commuter exposure to traffic related CO emissions (Bruinen de Bruin *et al*., 2004; Gomez-Perales *et al*., 2004; Kaur *et al*., 2005a; 2005b; Scotto di Marco *et al*., 2005; Huang *et al*. 2012; Wu *et al*., 2013).

Out-vehicle sampling was conducted at four locations surrounding the test vehicle to capture its boundary conditions of air quality. For this purpose, a system of four valves and relays is used to alternately switch the sample intake point every one minute to one of four locations, namely rear left of the car as observed by a seated driver (location 1), front left (location 2), rear right (location 3) and front right (location 4) (Fig. 3c). The latter were selected among a multitude of locations around the vehicle being representative of four probable sources of out-vehicle air entering the cabin. The front locations are near the grill air intake of the AC system whereas the rear locations are close to the air exit points of the car cabin which may turn into air entry points when they exhibit high pressure levels in the case of an idling car. In addition, one of the rear locations (rear right) is near the exhaust pipe and represents a boundary condition of out-vehicle concentrations. Polyethylene tubing and airtight push-in fittings are used for out-vehicle sample transport and distribution. The tubes are 1.5 m long with an inner diameter of 5.7 mm. The sampling flow rate inside the tubes were 6 L/min, as the DustTrak analyzers were run at their default flow rate of 3 L/min, and the CO sensor was exposed to the out-vehicle sample using Sensidyne Gil-Air-5 pumps calibrated to a flow rate of 3 L/min. Given the small aerodynamic diameter of the measured particles, the inlet efficiency can reasonably be assumed to be 100% (Brockmann, 2011) suggesting no particle losses at the tubes' inlets. Similarly, no losses due to gravitational deposition along the tubes' walls are expected as the sampling velocity across the line (~14 km/hour) is significantly higher than the deposition velocities of $PM_{2.5}$ particles (in the range 1.32 to 1.80 m/hour for the particle size range 2 to 3 μm and lower velocities for sizes less than 1 μm (Thatcher and Layton, 1995)). Finally, losses due to electrostatic deposition could not be estimated given the absence of information regarding the charge of the measured particles. They are however expected to be minimal as the sampling velocity was high enough to ensure efficient particle entrainment and line transmission (Brockmann, 2011).

Finally, vehicle speed was recorded by a GPS-based speed meter that logs speed and location (longitude, latitude) every 100 milliseconds at an accuracy of ±0.1 km/h

Mathematical modeling

The USEPA RISK version 1.9.25 model was used to simulate in-cabin CO and $PM_{2.5}$ concentration profiles inside self polluting cars by using the measured out-vehicle concentrations and field-recorded vehicle speeds (impacting directly vehicle air change

rates) and fitting the required pollutant in-cabin emission rates to match the average simulated in-cabin concentration with that observed.

Modeling concept

RISK is the third in a series of IAQ models developed by the Indoor Environment Management Branch of US EPA's National Risk Management Research Laboratory after INDOOR and EXPOSURE models. RISK allows the calculation of pollutant concentrations based on source emission rates, room-to-room air movement, air exchange with the outdoors, and indoor sink behavior. Each room is considered to be well mixed which is a reasonable assumption in the case of a small size vehicle compartment. The corresponding mass balance can be represented by Equation 1:

$$V_i dC_i / dt = C_{iIN} Q_{iIN} - C_{iOUT} Q_{iOUT} + S_i - R_i \quad (1)$$

Where V_i = the volume of the room, m^3
C_i = the pollutant concentration in the room, mg/m^3
C_{iIN} = the concentration entering the room, mg/m^3
Q_{iIN} = the air flow into the room, m^3/hr
C_{iOUT} = the concentration leaving the room, mg/m^3
Q_{iOUT} = the air flow leaving the room, m^3/hr
S_i = the source term, mg/hr
R_i = the removal term, mg/hr

The subscript i refers to room i for a room in a set of multiple rooms, i = 1,2,.. N where N is the number of rooms which is equal to 1 in the case of a vehicle. The removal term, R_i, includes pollutant removal by air cleaners and sinks. From the well mixed assumption, C_{OUT} equals C_i, and Equation (1) can be rewritten as:

$$V_i dC_i / dt = C_{iIN} Q_{iIN} - C_i \; Q_{iOUT} + S_i - R_i \quad (2)$$

The mass balance equation in the case of a vehicle compartment whereby $Q_{IN} = Q_{OUT} = \varphi = V \times ACH$ can be expressed by:

$$\tau \frac{dC_{veh}}{dt} = C_{ext}(t) - C_{veh}(t) + S - R; \qquad \tau = \frac{1}{ACH} = \frac{1}{(\varphi / V)} \quad (3)$$

Where C_{veh} = in-vehicle CO concentration, mg/m^3
C_{ext} = out-vehicle CO concentration, mg/m^3
τ = time constant of the vehicle, h
ACH = air change rate of the vehicle, h^{-1}
φ = volume of air flow into and out of the vehicle, m^3/h
V = interior volume of the vehicle, m^3

RISK uses a fast discrete time step algorithm to solve the series of equations. The method is stable for all time steps and is accurate for sufficiently small time steps. The size of the time step depends on how rapidly concentrations are changing. In general, a time step of 1 minute is small enough when concentrations are changing rapidly, and time steps of several minutes to hours are adequate when concentrations are near steady state. The time step must be small enough to capture the changing behavior of the ventilation system, the sources, the sinks, and the individual activity patterns.

Model assumptions

The model is based on two assumptions, namely the perfect mixing (which is reasonably justifiable in the case of a small vehicle compartment) and the mass conservations assumptions that are applicable to enclosed environemts of any size and shape. The assumption of perfect mixing means that the concentration leaving the room through all exits is the same as the concentration in the room. The assumption of mass conservation means that the amount of air entering a room must equal the amount of air leaving the room. This assumption also means that the amount of outdoor air entering an enclosed environment as a whole must equal the amount of air leaving it to the outdoor.

Model scenarios and major inputs

A total of 115 scenarios comprising the three self polluting test cars, two roadways, and three ventilation modes were simulated (Table 3). The models involved two different indicators with distinct behavior and properties as outlined below.

Table 3. Simulated scenarios

Scenario #	*Car*	*Ventilation*	*General speed*	*Roadway*	*Indicator*	*Test date and start time*
1.1	CA2011	AC Rec	40	Hamra-Bliss	CO	22-02-2012 @ 12:36
2.1	CA2011	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	14-02-2012 @ 10:22
2.2	CA2011	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	12-02-2012 @ 8:59
2.3	CA2011	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	22-02-2012 @ 12:36
3.1	CA2011	AC Rec	60	Beirut-Jyeh	CO	21-02-2012 @ 10:25
3.2	CA2011	AC Rec	60	Beirut-Jyeh	CO	22-02-2012 @ 11:51
4.1	CA2011	AC Rec	60	Beirut-Jyeh	$PM_{2.5}$	21-02-2012 @ 10:25
4.2	CA2011	AC Rec	60	Beirut-Jyeh	$PM_{2.5}$	22-02-2012 @ 11:51
5.1	CA2011	AC Rec	80	Beirut-Jyeh	CO	21-02-2012 @ 9:40
6.1	CA2011	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	14-02-2012 @ 11:07
6.2	CA2011	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	12-02-2012 @ 10:29
6.3	CA2011	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	21-02-2012 @ 9:40
7.1	CA2011	AC FA	40	Hamra-Bliss	$PM_{2.5}$	14-02-2012 @ 9:26
8.1	CA2011	AC FA	40	Hamra-Bliss	CO	22-02-2012 @ 8:51
8.2	CA2011	AC FA	40	Hamra-Bliss	$PM_{2.5}$	22-02-2012 @ 8:51
9.1	CA2011	AC Rec	60	Beirut-Jyeh	CO	21-02-2012 @ 8:55
9.2	CA2011	AC FA	60	Beirut-Jyeh	CO	22-02-2012 @ 9:36
10.1	CA2011	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	21-02-2012 @ 8:55
10.2	CA2011	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	22-02-2012 @ 9:36
11.1	CA2011	AC FA	80	Beirut-Jyeh	CO	21-02-2012 @ 11:10
12.1	CA2011	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	14-02-2012 @ 12:37
12.2	CA2011	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	21-02-2012 @ 11:10
13.1	CA2011	W1/2O	40	Hamra-Bliss	CO	21-02-2012 @ 12:40
14.1	CA2011	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	14-02-2012 @ 8:41
14.2	CA2011	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	12-02-2012 @ 8:14
14.3	CA2011	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	21-02-2012 @ 12:40
15.1	CA2011	W1/2O	60	Beirut-Jyeh	CO	22-02-2012 @ 10:21
15.2	CA2011	W1/2O	60	Beirut-Jyeh	CO	22-02-2012 @ 11:06
16.1	CA2011	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	12-02-2012 @ 11:59
16.2	CA2011	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	22-02-2012 @ 10:21
16.3	CA2011	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	22-02-2012 @ 11:06
17.1	CA2011	W1/2O	80	Beirut-Jyeh	CO	21-02-2012 @ 11:55
18.1	CA2011	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	14-02-2012 @ 11:52

Scenario #	*Car*	*Ventilation*	*General speed*	*Roadway*	*Indicator*	*Test date and start time*
18.2	CA2011	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	12-02-2012 @ 11:14
18.3	CA2011	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	21-02-2012 @ 11:55
19.1	KD1999	AC Rec	40	Hamra-Bliss	CO	03-11-2012 @ 8:43
19.2	KD1999	AC Rec	40	Hamra-Bliss	CO	07-11-2012 @ 12:09
19.3	KD1999	AC Rec	40	Hamra-Bliss	CO	28-11-2012 @ 8:29
19.4	KD1999	AC Rec	40	Hamra-Bliss	CO	28-11-2012 @ 10:44
20.1	KD1999	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	03-11-2012 @ 8:43
20.2	KD1999	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	07-11-2012 @ 12:09
20.3	KD1999	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	28-11-2012 @ 8:29
20.4	KD1999	AC Rec	40	Hamra-Bliss	$PM_{2.5}$	28-11-2012 @ 10:44
21.1	KD1999	AC Rec	60	Beirut-Jyeh	CO	03-11-2012 @ 9:28
21.2	KD1999	AC Rec	60	Beirut-Jyeh	CO	07-11-2012 @ 11:24
21.3	KD1999	AC Rec	60	Beirut-Jyeh	CO	28-11-2012 @ 9:14
22.1	KD1999	AC Rec	60	Beirut-Jyeh	$PM_{2.5}$	03-11-2012 @ 9:28
22.2	KD1999	AC Rec	60	Beirut-Jyeh	$PM_{2.5}$	07-11-2012 @ 11:24
22.3	KD1999	AC Rec	60	Beirut-Jyeh	$PM_{2.5}$	28-11-2012 @ 9:14
23.1	KD1999	AC Rec	80	Beirut-Jyeh	CO	03-11-2013 @ 10:13
23.2	KD1999	AC Rec	80	Beirut-Jyeh	CO	07-11-2013 @ 10:39
23.3	KD1999	AC Rec	80	Beirut-Jyeh	CO	28-11-2013 @ 9:59
24.1	KD1999	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	03-11-2013 @ 10:13
24.2	KD1999	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	07-11-2013 @ 10:39
24.3	KD1999	AC Rec	80	Beirut-Jyeh	$PM_{2.5}$	28-11-2013 @ 9:59
25.1	KD1999	AC FA	40	Hamra-Bliss	CO	03-11-2013 @ 12:28
25.2	KD1999	AC FA	40	Hamra-Bliss	CO	05-11-2013 @ 13:39
26.1	KD1999	AC FA	40	Hamra-Bliss	$PM_{2.5}$	03-11-2013 @ 12:28
26.2	KD1999	AC FA	40	Hamra-Bliss	$PM_{2.5}$	05-11-2013 @ 13:39
27.1	KD1999	AC FA	60	Beirut-Jyeh	CO	03-11-2013 @ 11:43
27.2	KD1999	AC FA	60	Beirut-Jyeh	CO	05-11-2013 @ 12:54
28.1	KD1999	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	03-11-2013 @ 11:43
28.2	KD1999	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	05-11-2013 @ 12:54
29.1	KD1999	AC FA	80	Beirut-Jyeh	CO	03-11-2013 @ 10:58
29.2	KD1999	AC FA	80	Beirut-Jyeh	CO	05-11-2013 @ 12:09
30.1	KD1999	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	03-11-2013 @ 10:58
30.2	KD1999	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	05-11-2013 @ 12:09
31.1	KD1999	W1/2O	40	Hamra-Bliss	CO	05-11-2013 @ 09:54
31.2	KD1999	W1/2O	40	Hamra-Bliss	CO	07-11-2012 @ 08:24
32.1	KD1999	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	05-11-2013 @ 09:54
32.2	KD1999	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	07-11-2012 @ 08:24
33.1	KD1999	W1/2O	60	Beirut-Jyeh	CO	05-11-2013 @ 10:39
33.2	KD1999	W1/2O	60	Beirut-Jyeh	CO	07-11-2012 @ 09:09
34.1	KD1999	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	05-11-2013 @ 10:39
34.2	KD1999	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	07-11-2012 @ 09:09
35.1	KD1999	W1/2O	80	Beirut-Jyeh	CO	05-11-2013 @ 11:24
35.2	KD1999	W1/2O	80	Beirut-Jyeh	CO	07-11-2012 @ 09:54
36.1	KD1999	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	05-11-2013 @ 11:24
36.2	KD1999	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	07-11-2012 @ 09:54
37.1	HC1997	Rec	40	Hamra-Bliss	CO	22-03-2012 @ 12:30
37.2	HC1997	Rec	40	Hamra-Bliss	CO	24-03-2012 @ 08:42
38.1	HC1997	Rec	40	Hamra-Bliss	$PM_{2.5}$	22-03-2012 @ 12:30
38.2	HC1997	Rec	40	Hamra-Bliss	$PM_{2.5}$	24-03-2012 @ 08:42
39.1	HC1997	Rec	60	Beirut-Jyeh	CO	22-03-2012 @ 09:42
39.2	HC1997	Rec	60	Beirut-Jyeh	CO	24-03-2012 @ 09:27

Scenario #	*Car*	*Ventilation*	*General speed*	*Roadway*	*Indicator*	*Test date and start time*
40.1	HC1997	Rec	60	Beirut-Jyeh	$PM_{2.5}$	22-03-2012 @ 09:42
40.2	HC1997	Rec	60	Beirut-Jyeh	$PM_{2.5}$	24-03-2012 @ 09:27
41.2	HC1997	Rec	80	Beirut-Jyeh	CO	22-03-2012 @ 10:27
41.2	HC1997	Rec	80	Beirut-Jyeh	CO	24-03-2012 @ 10:12
42.1	HC1997	Rec	80	Beirut-Jyeh	$PM_{2.5}$	22-03-2012 @ 10:27
42.2	HC1997	Rec	80	Beirut-Jyeh	$PM_{2.5}$	24-03-2012 @ 10:12
43.1	HC1997	AC FA	40	Hamra-Bliss	CO	23-03-2012 @ 08:49
43.2	HC1997	AC FA	40	Hamra-Bliss	CO	24-03-2012 @ 11:57
44.1	HC1997	AC FA	40	Hamra-Bliss	$PM_{2.5}$	23-03-2012 @ 08:49
44.2	HC1997	AC FA	40	Hamra-Bliss	$PM_{2.5}$	24-03-2012 @ 11:57
45.1	HC1997	AC FA	60	Beirut-Jyeh	CO	23-03-2012 @ 09:34
45.2	HC1997	AC FA	60	Beirut-Jyeh	CO	24-03-2012 @ 11:12
46.1	HC1997	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	23-03-2012 @ 09:34
46.2	HC1997	AC FA	60	Beirut-Jyeh	$PM_{2.5}$	24-03-2012 @ 11:12
47.1	HC1997	AC FA	80	Beirut-Jyeh	CO	23-03-2012 @ 10:19
47.2	HC1997	AC FA	80	Beirut-Jyeh	CO	24-03-2012 @ 10:42
48.1	HC1997	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	23-03-2012 @ 10:19
48.2	HC1997	AC FA	80	Beirut-Jyeh	$PM_{2.5}$	24-03-2012 @ 10:42
49.1	HC1997	W1/2O	40	Hamra-Bliss	CO	22-03-2012 @ 08:57
49.2	HC1997	W1/2O	40	Hamra-Bliss	CO	23-03-2012 @ 12:27
50.1	HC1997	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	22-03-2012 @ 08:57
50.2	HC1997	W1/2O	40	Hamra-Bliss	$PM_{2.5}$	23-03-2012 @ 12:27
51.1	HC1997	W1/2O	60	Beirut-Jyeh	CO	22-03-2012 @ 11:57
51.2	HC1997	W1/2O	60	Beirut-Jyeh	CO	23-03-2012 @ 11:49
52.1	HC1997	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	22-03-2012 @ 11:57
52.2	HC1997	W1/2O	60	Beirut-Jyeh	$PM_{2.5}$	23-03-2012 @ 11:49
53.1	HC1997	W1/2O	80	Beirut-Jyeh	CO	23-03-2012 @ 10:19
53.2	HC1997	W1/2O	80	Beirut-Jyeh	CO	24-03-2012 @ 10:42
54.1	HC1997	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	23-03-2012 @ 10:19
54.2	HC1997	W1/2O	80	Beirut-Jyeh	$PM_{2.5}$	24-03-2012 @ 10:42

Except for the ventilation mode W1/2O, where vehicle air change rates of 120 (Park *et al*., 1998), 180 and 240 h^{-1} were assumed for general vehicle speeds of 40, 60 and 80 km/h, regression models of air exchange rate as a function of vehicle speed during recirculation (Equation 3) and fresh air intake (Equation 4) ventilation modes were used to simulate the minute to minute varying air exchange rate during mobile trips (Hudda *et al.* 2012). These models were validated by favorably comparing simulated air exchange rate values to those reported in the literature using similar vehicle speeds (Fletcher and Saunders; 1994; Park *et al*., 1998; Ott *et al*., 2007).

$$\ln(\mathrm{AER}) = 2.79 + (0.019 \times \mathrm{S}) + [0.015 \times \mathrm{A} + 3.3 \times 10^{-3} \mathrm{A}^2] + [-0.023 \times \mathrm{V} - 6.6 \times 10^{-5} \mathrm{V}^2] + \mathrm{MA} \quad (4)$$

Where AER = Air exchange rate, h^{-1}

S = Speed, miles/h; if the speed is zero, a -0.51 factor should be added to the model

A = Age of the car, years

V = Volume of passenger cabin, ft^3

	MA	=	Manufacturer adjustment, -0.71 for German vehicles, -0.39 for Japenese vehicles and 0 otherwise

$$\ln(\mathrm{AER}) = 4.2 + [(1.88 \times \mathrm{FS}) + (-0.92 \times \mathrm{FS}^2)] + (0.0048 \times \mathrm{S}) + (-0.0073 \times \mathrm{V}) \quad (5)$$

Where	FS	=	Fan strength as a fraction of maximum setting, considered to be 0.5 for settings of '2' or 'medium'; coefficients for FanStrength and FanStrength^2 should be 0.40 and 0.13, respectively, at zero speed
	S	=	Speed, miles/h; if the speed is zero, the speed term should be -0.32

The adequacy of the models in the context was tested by favorably comparing simulated air change rate values to those reported in the literature using similar vehicle speeds (Fletcher and Saunders; 1994; Park *et al*., 1998; Ott *et al*., 2007).

Other model inputs include the trip specific minute-to-minute variations in out-vehicle pollutant concentrations profiles, the characteristics of the HVAC mode and the pollutant properties. The air conditioner was considered to have a supply flow rate of 3600 liters per minute (l/min) at the medium fan setting (Qi *et al*., 2008) and to be equipped with a pleated filter with a $PM_{2.5}$ removal efficiency of 30% (which is typical inside passenger cars). The return and exhaust flow rates for recirculation and fresh air intake modes, respectively, were considered to be equal to the supply flow rate. As for the pollutants, the respective CO and $PM_{2.5}$ densities are 0.939 and 1.7 (Pitz *et al*., 2008), diffusivities 7.49 x 10^{-2} and 4.63 x 10^{-8} m^2/hour (Marrero and Mason 1972; Kulkarni *et al*., 2011) and penetration factors 1 and 0.47 (model defaults). The deposition velocity of $PM_{2.5}$is reported to range between 1.32 and1.80 m/hour for the particle size range 2 to 3 μm and lower velocities for sizes less than 1 μm (Thatcher and Layton, 1995). In this study, a velocity of 1.56 m/hour was used for $PM_{2.5}$.

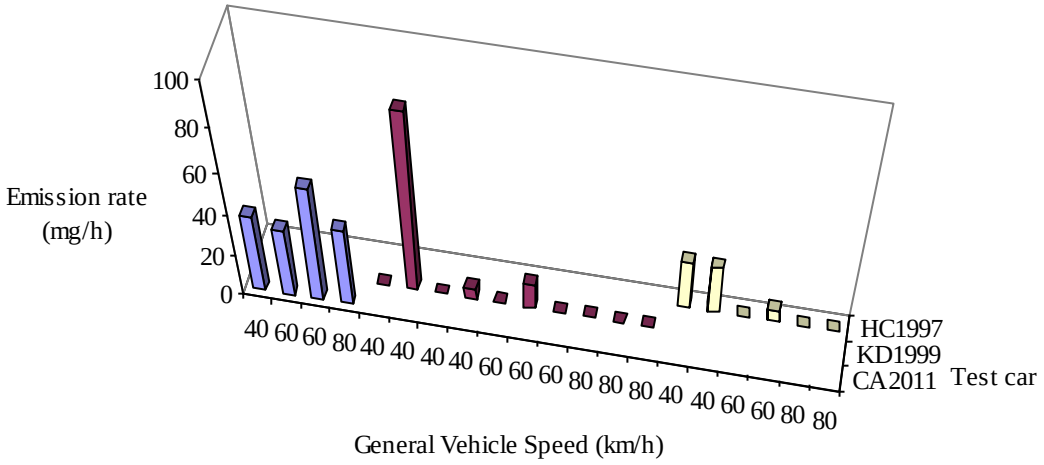
Model outputs

While, RISK can provide a wide range of graphical and tabular output, in the present work, only the in-cabin CO and $PM_{2.5}$ concentration profiles were simulated, and in-cabin self pollution rates were estimated by comparing and matching measured concentrations to those simulated. The average, maximum and minimum concentrations were also compared and percent difference between measured and simulated data were computed.

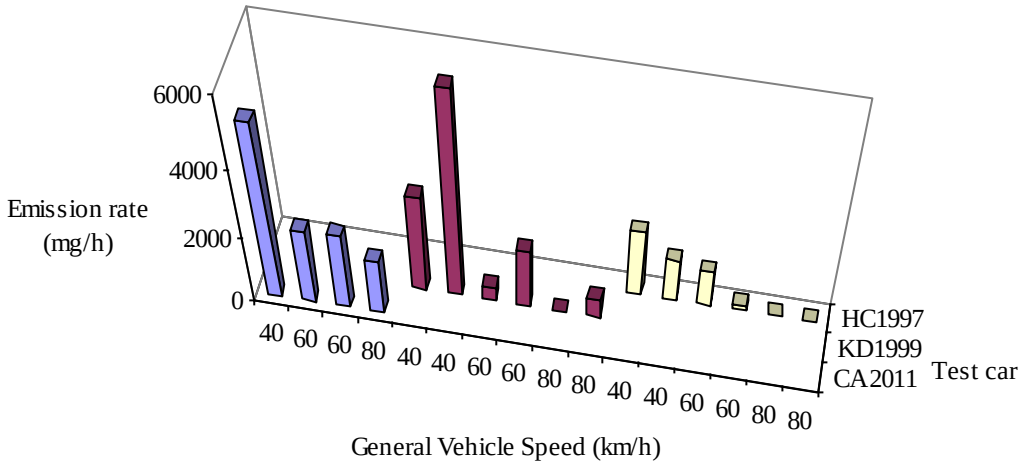
Results and Discussion

The CO and $PM_{2.5}$ self pollution rates used to match average measured and simulated concentrations for all scenarios are illustrated in Figures 3 and 4, respectively, which also indicate the general vehicle speed during each scenario. The figures show that self pollution rates were highly variable across cars and vehicle speeds. Regarding CO self pollution, self pollution rates could not be accurately estimated in the cabins of old cars (KD1999 and HC1997) in view of the exceptionally high out-vehicle pollutant concentrations which yielded simulated in-cabin concentrations higher than measured concentrations preventing the possibility of fitting of a self pollution rate. As for the CA2011, the self pollution rates were highest when AC FA was used (1625-5175 mg/h), followed by W1/2O (250-1100 mg/h) and by AC Rec (33-55 mg/h). Regarding, $PM_{2.5}$

self pollution, which was less affected by out-vehicle sampling location as all test cars ran on gasoline, self pollution rates were fitted for all scenarios and were lower in the cabin of the CA2011 compared to the cabin of the older cars. As such, for AC Rec, the self pollution rates were in the range 0.2 to 3.375 mg/h for CA2011 compared to 3.35-10.05 and 3.6-8.4 mg/h for KD1999 and HC1997, respectively. Similarly, for AC FA, the range was 12.7 to 32.3 mg/h for CA2011 compared to 18.6 to 35.5 mg/h and 22.6 to 39.875 mg/h for KD1999 and HC1997. Similar rates were obtained with W1/2O and ranged from 9.5 to 57.525 mg/h for CA2011, 11.6 to 35.5 mg/h for KD1999 and 11.75 to 45.5 mg/h for HC1997.



AC Rec



AC FA

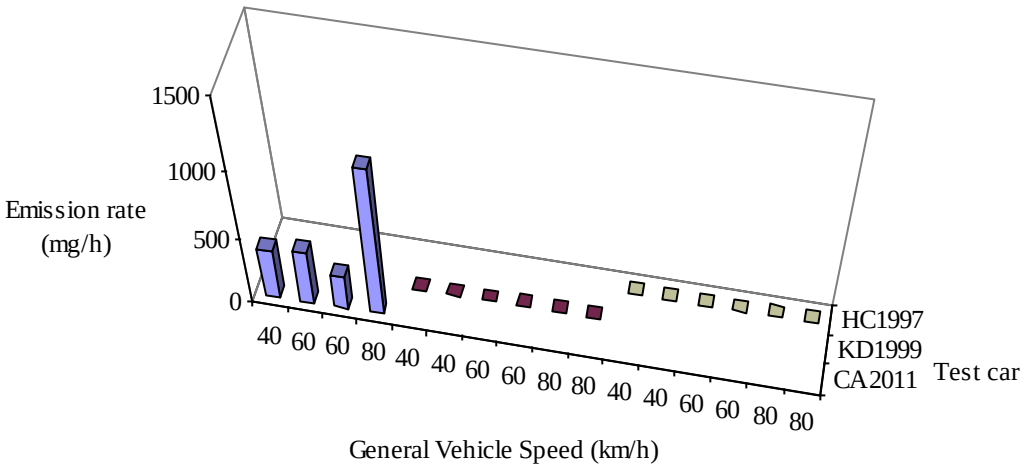
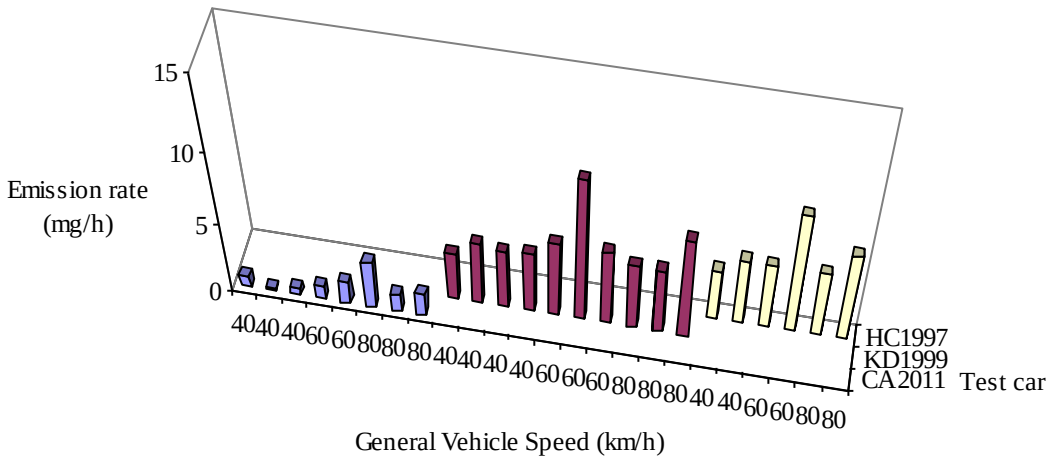
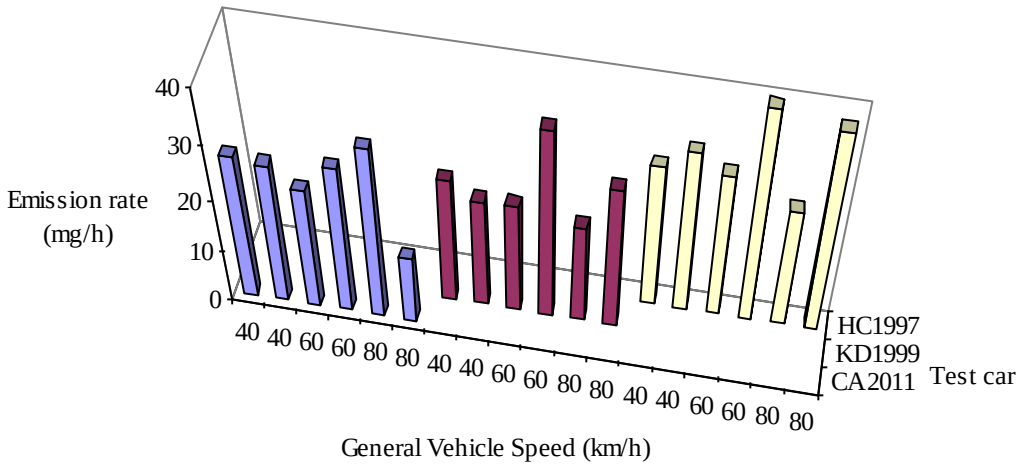


Figure 3. CO self pollution rates

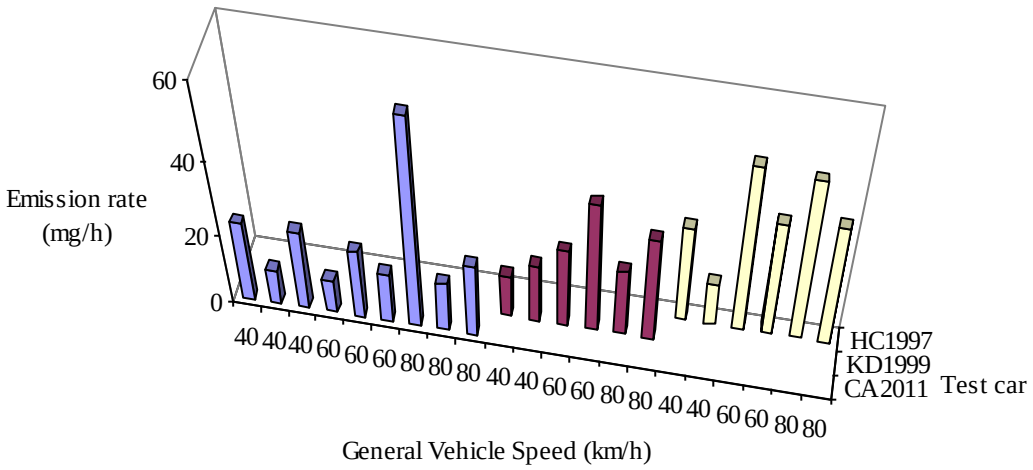
W1/2O: one window half opened; AC FA: air conditioning on fresh air intake;AC Rec: air conditioning on recirculation;



AC Rec



AC FA



W12O

Figure 3. PM2.5 self pollution rates

W1/2O: one window half opened; AC FA: air conditioning on fresh air intake;AC Rec: air conditioning on recirculation;

Table 4 outlines for each individual car, pollutant and ventilation mode, the % difference between measured and simulated average, maximum and minimum concentrations. Except for cases where simulated concentrations were higher than those observed and therefore the fitting of an in-cabin emission rate was not possible, the % difference between average simulated and measured concentrations ranged from -2.2 to 0.3%. The % difference in maximum CO concentration when AC Rec was used was generally lower for CA2011 and HC1997 (-21.2 to 22.1) compared to KD1999 (-280 to 52.9) due to exceptionally high outdoor concentration in the latter case. In fact, although not reaching the car cabin as demonstrated through stationary testing, high exhaust emissions from KD1999 at out-vehicle sampling location 3 (rear right as a observed by a seated driver) yielded high out-vehicle CO concentration which increased simulated in-cabin CO concentration leading to an overestimation of the actual levels encountered inside the vehicle. Consistently, the % difference in minimum CO concentration when AC Rec was used was generally lower for CA2011 and HC1997 (-30.3 to 11.2) compared to KD1999 (-206 to 10) for the same reason.

Table 4. Comparison of measured and simulated average, maximum and minimum concentrations

Indicator	Car	Ventilation mode	Range of %difference between measured and simulated concentration		
			Average	Maximum	Minimum
CO	CA2011	AC Rec	-0.5 – 0.3	-1.8 – 22.1	4.5 – 10.9
		AC FA	-0.2 – 0.2	17.5 – 72.5	-194.9 - -33.4
		W1/2O	-0.3 – 0.2	-16.7 – 19.9	-12.6 – 39.5
	KD1999	AC Rec	-325.8 – 1.8	-280 – 52.9	-206 – 10
		AC FA	-0.5 – 3	-57.4 – 69.9	-606.5 – 63.2
		W1/2O	-121.6 - -8.3	-377.5 – 11.4	-42.6 – 63.6
	HC1997	AC Rec	-11 – 0.2	-21.2 – 21.4	-30.3 – 11.2
		AC FA	-6.8 – 0.2	14.5 – 61.1	-88.5 - -4.8
		W1/2O	-66.8 - -9.7	-232.5 – 52.1	-97.7 – 33.2
$PM_{2.5}$	CA2011	AC Rec	-2.2 – 0.2	-7.1 – 72.4	-93.9 - -8.4
		AC FA	-0.1 – 0.1	26.9 – 52.9	-160 - -12.3
		W1/2O	-0.2 0.2	-2.2 – 69.3	-120.7 – 69.5
	KD1999	AC Rec	-0.1 – 87.8	25.3 – 82.8	-87.1 – 94.6
		AC FA	-0.2 - 0.2	24 – 73.5	-99.6 - -25.8
		W1/2O	-0.1 – 0.2	16.3 – 71.1	-116.9 - -22.5
	HC1997	AC Rec	-0.3 – 0.2	19 – 68.1	-55.8 – 8.2
		AC FA	-0.2 – 0	23.2 – 62.3	-63 - -23.7
		W1/2O	-0.1 – 0.3	22.9 – 81.6	-100.4 – 2.7

For scenarios involving AC FA inside the CA2011 and the HC1997 cabins, the maximum and minimum CO concentrations were respectively underestimated and overestimated (except for scenario 47.2 where the minimum was slightly overestimated) indicating that the simulated range was tighter than the actual one. The latter could be due to air change rate underestimation in both cars. As for KD1999, both maximum and minimum were overestimated at times by -57.4 and -606.5% respectively, and underestimated in other scenarios by 69.9 and 63.2% respectively, indicating that the ACH was probably overestimated in the case of KD1999 using air recirculation which inadequately increased the sensitivity of in-cabin air to outdoor fluctuations and yielded concentration rises and drops which are faster than reality. For scenarios involving W1/2O, the range of variation of the % difference between simulated maximum and minimum concentrations were smaller for the CA2011 (-16.7 to 19.9% for maximum

and -12.6 to 39.5 for minimum) compared to the KD1999 (-377.5 to 11.4% for maximum and -42.6 to 63.6% for minimum) and HC1997 (-232.5 to 52.1% for maximum and -97.7 to 33.2% for minimum). In fact, the vehicle air changer rate is high when using W1/2O (120 to 240 h^{-1}) which promptly brings in-cabin CO concentration to the levels encountered in the air coming from outside, with the latter being overestimated in older cars due to out-vehicle sampling near the exhaust pipe.

Regarding $PM_{2.5}$ simulations, the maximum concentrations when using AC Rec were generally underestimated suggesting that $PM_{2.5}$ cleaning efficiency through the AC filter could be lower than the assumed value (30% for pleated filter). Other possible reasons include the underestimation of cabin ACH value, or the generation of $PM_{2.5}$ by the cabin passengers through movement and resuspension which could not be accounted for in the mathematical modeling. In contrast, the minimum concentration was generally overestimated ascertaining that the AC filtration efficiency was not overestimated particularly that the filter was within the recirculation loop for all test cars. It is likely that the overestimation of minimum concentrations is due to ACH underestimation. Similarly, maximum and minimum concentrations were respectively underestimated and overestimated when using the AC FA mode, which is consistent with the findings from CO concentration simulations, indicating that the ACH of the AC FA mode was equally underestimated. For scenarios involving W1/2O, the simulated maximum $PM_{2.5}$ concentration was lower than the actual one for all scenarios pertaining to the KD1999 and the HC1997, indicating either the underestimation of ACH, or the existence of intermittent in-cabin emission sources that could not be accounted for in the mathematical modeling such as resuspension of settled dust. As for the minimum $PM_{2.5}$ concentration, the simulated concentrations were generally higher than the actual ones ascertaining that the ACH was generally underestimated. It is important to note finally that the respective under- and over- estimation of the extrema could be related to the underestimation of $PM_{2.5}$ penetration factor into (and out) of a vehicle cabin.

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