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# Field study of air change and flow rate in six automobiles

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## Abstract

For many people, a relatively large proportion of daily exposure to a multitude of pollutants may occur inside an automobile. A key determinant of exposure is the amount of outdoor air entering the cabin (i.e. air change or flow rate). We have quantified this parameter in six passenger vehicles ranging in age from 18 years to <1 year, at three vehicle speeds and under four different ventilation settings. Average infiltration into the cabin with all operable air entry pathways closed was between 1 and 33.1 air changes per hour (ACH) at a vehicle speed of 60 km/h, and between 2.6 and 47.3 ACH at 110 km/h, with these results representing the most (2005 Volkswagen Golf) and least air-tight (1989 Mazda 121) vehicles, respectively. Average infiltration into stationary vehicles parked outdoors varied between ~0 and 1.4 ACH and was moderately related to wind speed. Measurements were also performed under an air recirculation setting with low fan speed, while airflow rate measurements were conducted under two non-recirculate ventilation settings with low and high fan speeds. The windows were closed in all cases, and over 200 measurements were performed. The results can be applied to estimate pollutant exposure inside vehicles.

*Keywords*: Air change rate; Ventilation; Automobile; Vehicle; Exposure.

## Practical Implications

There is increasing recognition of the often disproportionately large contribution of in-vehicle pollutant exposures to overall measures. This has highlighted the need for accurate and representative quantification of determinant factors to facilitate exposure estimation and mitigation. The ventilation rate in a vehicle cabin is a key parameter affecting the transfer of pollutants from outdoors to the cabin interior, and vice-versa. New data regarding this variable are presented here, and the results indicate substantial variability in outdoor air infiltration into vehicles of differing age. The efficacy of simple measures to reduce outdoor air infiltration into 'leaky' vehicles to increase occupant protection would be a worthwhile avenue of further research.

## Introduction

Compared to other built environments, the automobile cabin has seemingly received less attention in terms of the quantification of key parameters affecting its air quality, particularly air changes per hour (ACH) occurring there (Gameiro da Silva, 2002), which is a key determinant of the exposure of occupants to pollutants. Klepeis et al. (2001) reported that 5.5% of a typical day is spent inside a vehicle, based on their survey of about 9400 United States residents. Given the generally short duration of most commuter trips in automobiles, there has perhaps been a tendency to direct many fundamental studies of indoor environmental quality towards the home, work or school environments. Nevertheless, many published in-vehicle studies have identified elevated levels of many unleaded and diesel fuel related pollutants, such as volatile organic compounds (Duffy and Nelson, 1997), carbon monoxide (Chan et al., 1991; Ott et al., 1994), elemental carbon (Adams et al., 2002), $PM_{2.5}$ (Rodes et al., 1998), and ultrafine particles (Zhu et al., 2007), compared to other environments and/or background levels. Recent work has estimated that 1.5 h of vehicle occupancy on a combination of Los Angeles arterial and freeway roads during a day (i.e. typical of a return commute to a workplace) can account for 33–45% of daily exposure to ultrafine particulate matter (Fruin et al., 2008), which supports similar estimates made by Zhu et al. (2007). For persons whose occupation necessitates longer periods be spent inside a vehicle (e.g. police officers, couriers, taxi, and truck drivers), the relative contribution of in-vehicle exposures to overall measures is likely to be greater, particularly if driving in heavily trafficked or congested areas. Exposure to traffic-related pollutants can have deleterious health implications, especially for more susceptible occupants, such as people older than 60 years or those who have existing health issues (Peters et al., 2004). However, other groups may also be affected, and the undesirable short-term health effects of in-vehicle $PM_{2.5}$ exposures on a sample of police officers have been described by Riediker et al. (2004). Particulate exposure inside vehicle cabins may also result in reduced driver vigilance (Wyon et al., 1995). Under low air change rate conditions, in-cabin pollutant sources, such as cigarette smoking (Ott et al.,

2008), and material emissions from new vehicles (Zhang et al., 2008) could make potentially significant contributions to vehicle occupant exposure.

The amount of outdoor air entering an automobile can be expressed in terms of ACH or a volume flow rate. Measurement of air change rates inside passenger cars (both stationary and moving), buses and trucks appear sporadically in the literature, with the earliest identified study conducted by Petersen and Sabersky (1975), who measured between 18 and ~39 ACH in a stock Chevrolet at speeds between 0 and ~97 km/h, respectively. Ott et al. (2008) have recently summarized previous work in this area, and also supplemented the limited existing data with measurements of ACH performed in four vehicles under open and closed window conditions. In addition to the work reviewed by Ott et al. (2008), Guillemin et al. (1992) estimated means between 11.62 and 14.51 ACH inside truck cabins. Kvisgaard (1995) described methods for measuring local-mean-age-of-air inside a moving vehicle at up to 100 ACH. Conceição et al. (1997) measured up to 16 ACH inside an intercity bus travelling at 80 km/h, as a means of experimentally assessing the efficacy of a contaminant removal duct. Kvisgaard and Pejtersen (1999) detailed the measurement of outdoor airflow rate in a Honda Civic hatchback under a wide range of heating ventilation and air conditioning (HVAC) system settings and vehicle speeds, using constant injection of sulphur hexafluoride ($SF_6$). Batterman et al. (2006) evaluated a perfluorocarbon tracer ventilation measurement method inside a 2000 model Subaru Legacy with windows closed, recirculation off and a low fan setting, and reported an average of 92 ACH at an average vehicle speed of 105 km/h. Using $SF_6$ decay, Rim et al. (2008) measured between 2.6 and 4.55 ACH inside school buses. Zhang et al. (2008) measured between <0.1 and 0.63 ACH in a variety of small passenger cars parked in an underground garage. As part of a larger study, we required specific measurements of ACH and flow rate in a range of common vehicles representative of those driven on Australian roads, when both stationary and travelling at speed, and under a range of ventilation settings with the windows closed.

## Methods

### Selection of Vehicles and Research Design

There were 11.2 million passenger vehicles registered in Australia in 2006, with an average age of 9.8 years, and 21% of which were manufactured before 1991 (Australian Bureau of Statistics, 2006). We sought a small group of test vehicles to represent those being driven on Australian roads. Our focus was directed toward passenger vehicles, as these represent 78% of the Australian fleet (Australian Bureau of Statistics, 2006). In addition, we wished to include vehicles having very basic HVAC systems (i.e. no air conditioning and no filtration) and those having more advanced systems (air conditioning and filtration). The final sample of vehicles is listed in Table 1. As the vehicles are referred to henceforth by the name they are marketed under in Australia, some common international variants are provided. Two similar vehicles of differing age (2000 model Subaru Liberty and 2007 model Subaru Outback) were included to examine the effect of approximately 7 years of service life on air infiltration into the cabin. Odometer readings prior to the commencement of testing are provided in Table 1. Five of the vehicles were privately owned, while the 2005 Toyota HiLux was a university-owned vehicle. Three of the vehicles were near-new, but all were well-maintained and subject to the regular maintenances recommended by the manufacturer, as indicated by their service log books.

Four ventilation conditions were assessed. In even the most basic automotive HVAC system, the number of possible combinations of fan speed, vent position and air intake position (recirculate or fresh) is large. As such, the ventilation conditions shown in Table 2 were selected to encompass a range of settings and best match the required outcomes of this study. The abbreviated names for each ventilation condition assessed reflected the air intake position (i.e. E = external and R = recirculate) and the fan speed (i.e. 1 = first fan speed position and 3 = third fan speed position, and so on). The INF condition was named as such to reflect that air entering under this setting would do so via infiltration. The inclusion of the baseline infiltration condition was intended to represent the best measure afforded to occupants of a vehicle for mitigation of outdoor air intrusion. Given that Engelmann et al. (1992) reported highly

variable differences between their test vehicles in the deliberate provision of outdoor make-up air under an air recirculation condition, we also wished to determine if this was the case in our test group. An additional recirculate ventilation condition, referred to as R4 in Table 2, was assessed in the 2005 Toyota HiLux. Measurements were conducted at nominal vehicle speeds of 0, 60 and 110 km/h. Based on a pilot study in Houston, Texas, Long et al. (2002) reported that 20% of passenger vehicles observed had one or more window (window, sunroof or convertible top) open during rain-free days characterized by an outdoor temperature range of 27.2–35°C. We did not include any open window scenarios in our selection of ventilation conditions, and instead focused our work towards the likely more predominant (in Sydney and most Australian cities, at least) closed window settings. However, automobile air change data collected under an open window setting are available elsewhere (Ott et al., 2008; Park et al., 1998; Rodes et al., 1998). A window opened by even a small amount can substantially increase the air change rate in a vehicle cabin under a given ventilation condition compared to the same condition with windows closed (Ott et al., 2008).

## Experimental Equipment and Methods

Suitable roadways were located where the test vehicles could be driven in a safe and uninterrupted manner at the desired speed for the necessary duration. Tests were conducted at times when traffic volume was low. Due to the high airflows expected under the fresh air ventilation conditions (E1 and E3), and the unsuitability of the measurement equipment for the concentration–decay method at high ACH (Gameiro da Silva, 2002; Kvisgaard, 1995), the constant injection technique using $SF_6$ as a tracer was used for these measurements. For the two remaining ventilation conditions (R1 and INF), the $SF_6$ concentration–decay approach was employed. A detailed handling of the application and theory underlying these techniques can be found in ASTM (2006). An Innova type 1412 photoacoustic field gas monitor and Innova type 1303 multipoint sampler and doser were used. All sampling and dosing tubes used were of the manufacturer recommended composition. The dosing nozzle was flushed and calibrated

Table 1. Test group characteristics.

| Automobile | Also marketed as | Model year | Chassis type | Odometer (km) | HVAC filter | Operable vents | AC | Est. volume ($m^3$) |
|---|---|---|---|---|---|---|---|---|
| Mazda 121 | Ford Festiva, Kia Pride | 1989 | Small Hatchback | 156 778 | No | No | No | 3.32 |
| Mitsubishi Magna | Mitsubishi Diamante | 1998 | Large Sedan (Saloon) | 129 241 | No | Yes | Yes | 3.72 |
| Subaru Liberty | Subaru Legacy | 2000 | Mid-Size Station Wagon (Estate Car) | 94 385 | Yes | Yes | Yes | 4.65 |
| Toyota HiLux | Toyota Tacoma | 2005 | Utility (Pick-Up)[a] | 7861 | No | Yes | Yes | 3.33 |
| Volkswagen Golf | Volkswagen Rabbit | 2005 | Large Hatchback | 7120 | Yes | Yes | Yes | 3.88 |
| Subaru Outback | Subaru Legacy Outback | 2007 | Mid-Size Station Wagon (Estate Car) | 7688 | Yes | Yes | Yes | 4.43 |

[a] This vehicle featured a 5 seat cabin (‘crew cab’), separated from the cargo tray by the rear firewall.

Table 2. Ventilation conditions assessed.

| Condition | Fan | Fan speed | Air intake | Vent state | Vent direction | AC | Temperature | Windows |
|---|---|---|---|---|---|---|---|---|
| E1 | On | Lowest | Fresh | All open | Cabin | On | Coolest | All closed |
| E3 | On | Second-highest[a] | Fresh | All open | Cabin | On | Coolest | All closed |
| R1 | On | Lowest | Recirculate | All open | Cabin | On | Coolest | All closed |
| INF | Off | n/a | Recirculate | All closed | Cabin | Off | n/a | All closed |
| R4[b] | On | Highest | Recirculate | All open | Cabin | On | Coolest | All closed |

[a] In the 2007 Subaru Outback, the fourth setting of six possible was used. In all other vehicles the third setting of four possible was used. [b] This ventilation condition was assessed in the 2005 Toyota HiLux only.

periodically according to specifications. The equipment had been calibrated by the manufacturer prior to use. Innova type 7620 software (LumaSense, Ballerup, Denmark) was used to set up and control all measurements. Some initial measurements were conducted using a Brüel & Kjær type 1302 photoacoustic gas monitor and Brüel & Kjær type 1303 multipoint sampler and doser (Brüel & Kjær, Naerum, Denmark). An empirical correction factor was determined to allow inter-comparability between results obtained with the Brüel & Kjær system and those measured with the Innova system. Foam padding was used to protect the equipment and dampen vibration, which can affect the gas monitor at certain frequencies (LumaSense, 2008a; Ott et al., 2008). The waste air from the ventilation measurement equipment was voided outside of the vehicle. The flow rate of the equipment was minimal and not likely to significantly affect air change rate, even in a stationary vehicle. Following each measurement, the vehicle cabin was flushed with outdoor air for 5–10 min to obviate any effects of background $SF_6$ on the subsequent measurement.

### Measurements in Moving Automobiles

Sulphur hexafluoride was dosed into the HVAC system inlet, located at the junction of the front windscreen and bonnet (hood). During constant injection measurements, air samples were taken from the passenger side footwell vent, the passenger side centre dashboard vent and the driver's side right dashboard vent. Tests of this nature took 15–30 min. Under the R1 and INF ventilation settings, tracer was dosed into the cabin under the E1 condition with the vehicle stationary and engine running. A single sampling point in the centre of the cabin between the front seats was used. Ott et al. (2008) used sampling points placed in the front and rear of test vehicles and reported that ACH measurements for the two locations were very similar, thus our use of a single sampling point was justified. Once the tracer concentration had stabilised (generally after about 15 min), dosing ceased and the required ventilation setting was selected. The tracer concentration at this point was typically 10–15 ppm. The vehicle was then driven to the required speed for a duration similar to that of the constant injection tests. Vehicle speed was recorded by a global positioning system (GPS). During all

tests conducted in a moving vehicle the cabin was occupied by one person of approximately 0.08 $m^3$.

During measurement exercises in moving vehicles, every effort was made to ensure that measurements were distributed evenly between travel directions on the test roadway to avoid the possibility of bias due to the predominant winds (Fletcher and Saunders, 1994). Winds observed during all tests were light, and measurements were performed during periods characterized by stable weather conditions.

### Measurements in Stationary Automobiles

All stationary measurements were conducted with the engine of the test vehicle running. Measurements of E1, E3 and R1 in stationary vehicles were performed in a covered parking garage, while stationary measurements of INF were conducted on an open outdoor car park. During these measurements, wind direction and speed outside of the vehicle were measured at a height of 2 m by a RM Young model 05103 wind monitor (R.M. Young, Traverse City, MI, USA). Air temperature outside and inside of the vehicles was measured using Vaisala HMP45A probes (Vaisala, Helsinki, Finland). The interior volume of the test vehicles was estimated by measuring the number of ACH occurring in a stationary vehicle at a determined flow rate (Fletcher and Saunders, 1994). Three volume estimates were performed in each vehicle and the average of these calculated. During all stationary measurements the vehicle cabin was unoccupied.

### Ancillary Measurements and Repeatability

For every combination of vehicle, speed and ventilation setting, three replicate measurements were conducted. Although most were successful, occasional equipment malfunction or factors which affected the ability to maintain vehicle speed, such as road works or unexpected traffic, resulted in some data being discarded. Excluding interior volume estimates, 212 successful ventilation measurements were performed.

According to the manufacturer, the repeatability of Innova 1412 measurements is ±1% under standard conditions, and the influence of

temperature and pressure is negligible (LumaSense, 2008a). The dosing calculation accuracy of the Innova 1303 is stated as ±2% (LumaSense, 2008b). Audio recordings of comments made by the investigator were performed during measurements, and assisted in creating accurate test logs and determining the suitability of data for subsequent analyses. Measurements were conducted in January, May and June, 2006, and September and December, 2007.

### Analysis Methods

Airflow rates measured using the constant injection method were output by the control software and then imported into a spreadsheet program. The time when the vehicle reached the required test speed, and the duration for which this speed was maintained were determined from the GPS and the driver————————————s audio logs. Basic descriptive statistics were calculated for airflow measurements corresponding to this period. For the majority of tests, these were based on 12–16 airflow measurements, collected over approximately 18–30 min. The mean gas concentration measured across the three sample points during tests was recorded. The deviation of the mean of each sample point from this figure was also calculated. Kvisgaard and Pejtersen (1999) suggest that if this deviation is equal to or <3% for each point, then the uncertainty in the result is ±5% or less.

For all measurements using the concentration–decay technique, the natural logarithm of $SF_6$ concentration was plotted against elapsed time in hours. After removing data points recorded during dosing, linear regression was applied to the remaining points. The number of ACH was recorded as the gradient of the regression line (ASTM, 2006). The cycle time of the equipment during these tests was faster than during constant injection measurements, due the use of one sampling point. An average of 30 data points collected over approximately 15 min were used to determine ACH. Tests conducted under higher ACH conditions took less time, while many of those conducted in stationary vehicles lasted for 1 h or more. Any measurements that failed to result in an exponential decay were not used in further analyses. Due to the relatively small number of samples for the purposes of statistical analysis, only basic descriptive statistics were calculated.

## Results and Discussion

### Vehicle Interior Volume Estimates

Table 1 gives the results of vehicle volume estimates. The estimates for the two hatchback vehicles (1989 Mazda 121 and 2005 Volkswagen Golf) at 3.32 and 3.88 $m^3$, respectively, were relatively large compared to the other test vehicles, and also the limited number of vehicle interior volume measurements reported in the literature (Fletcher and Saunders, 1994; Ott et al., 2008; Park et al., 1998). However, it should be considered that in a typical hatchback vehicle, the boot (trunk) is separated from the cabin by a removable partition. In our test hatchbacks, these partitions had to be removed to accommodate the $SF_6$ cylinder.

The relatively low estimated volume of the 2005 Toyota HiLux at 3.33 $m^3$ is due to the layout of a crew cab type utility vehicle consisting of a cabin physically separated from the cargo tray. The 4.65 $m^3$ estimated in the 2000 Subaru Liberty station wagon was 5% higher than equivalent measurement of 4.43 $m^3$ in the analogous 2007 Subaru Outback. The estimated volume of the 1998 Mitsubishi Magna sedan was 3.72 $m^3$, which is the same as the volume estimated by Ott et al. (1992) in a 1986 model Mazda 626 sedan using a tape measure. Standard deviation of volume estimates based on three replicate measurements in each vehicle ranged from 0.02 to 0.17 $m^3$, for the 2005 Volkswagen Golf and 2000 Subaru Outback, respectively, although the majority were below 0.05 $m^3$.

Based on the limited data reported, gas decay methods of assessing vehicle volume have been shown to result in estimates 4–17% higher than those obtained by manual measurement in the same vehicle (Fletcher and Saunders, 1994; Ott et al., 2008). The exclusion of hollow sections in concealed or difficult to reach parts of the interior during manual measurement is the likely cause of this (Ott et al., 2008). Our tracer gas estimate of volume in the 2000 Subaru Liberty was 13.5% higher than that estimated by Batterman et al. (2006) in the same year and model vehicle, although the estimation method employed by the authors was not stated.

### Constant Injection Measurements: E1 and E3 Ventilation Conditions in Stationary and Moving Automobiles

Descriptive statistics and linear regression models for all ventilation conditions and vehicles are provided in Table 3. The results of airflow measurements conducted under the E1 and E3 ventilation modes are presented in Figures 1 and 2, respectively. Ninety-six per cent of constant injection airflow measurements conformed to the guidelines suggested by Kvisgaard and Pejtersen (1999) for achieving better than ±5% uncertainty. Those measurements which did not meet the guideline did so by a small margin only.

When stationary, the mean measured flows under the E1 condition varied between 96 and 155 $m^3/h$. The equivalent range under the E3 mode was 225–300 $m^3/h$. In both cases, the lowest flow rate was measured in the 1989 Mazda 121 and the highest in the 2005 Volkswagen Golf. The variation in flow rates in stationary vehicles is due entirely to differences in blower fan air delivery between vehicles, as the vehicles were tested in a garage protected from wind.

At the nominal test speed of 60 km/h, the range of mean airflow values recorded under the E1 setting across the test group ranged from 147 to 245 $m^3/h$, with the former measure made in the 2007 Subaru Outback and the latter in the 1998 Mitsubishi Magna. Under the E3 setting, the lowest mean airflow of 271 $m^3/h$ was recorded in the 2005 Toyota HiLux, while the maximum mean value of 343 $m^3/h$ was measured in the 1998 Mitsubishi Magna.

Mean measurements at 110 km/h under the E1 condition ranged from 177 to 281 $m^3/h$. These measures were recorded in the 2000 Subaru Liberty and 1989 Mazda 121, respectively. Under the E3 setting the lowest mean flow of 292 $m^3/h$ was measured in the 2005 Toyota HiLux, while the highest mean flow of 399 $m^3/h$ was recorded in the 1998 Mitsubishi Magna. Under both ventilation conditions, the increase in airflow compared to other speeds was highly variable between vehicles and can be seen in Figures 1 and 2 and Table 3.

Kvisgaard and Pejtersen (1999) measured airflows in a Honda Civic hatchback under a ventilation setting equivalent to our E1 condition of ~140, ~160 and ~190 $m^3/h$, at 0, 60 and 110 km/h, respectively. They also conducted measurements in the same vehicle using a setting equivalent to our E3, which

Table 3 – Linear regression models and descriptive statistics for all test vehicles.

| Automobile | | E1 ($m^3$/h) | E3 ($m^3$/h) | R1 (ACH) | INF (ACH)[a] |
|---|---|---|---|---|---|
| 1989 Mazda 121 | Regression, ($R^2$) | y=1.78x + 93.83, (0.99) | y=1.16x + 222.50, (0.99) | y=0.45x + 3.90, (0.92) | y=0.32x + 14.12, (0.76) |
| | 0km $h^{-1}$: mean, *n*, s.d. | 96.1, 3, 0.8 | 224.9, 3, 2.1 | 0.2, 2, n/a | 1.4, 2, n/a |
| | 60 km $h^{-1}$: mean, *n*, s.d. | 189.7, 2, n/a | 284.4, 3, 3.0 | 35.6, 3, 5.2 | 33.1, 3, 6.1 |
| | 110 km $h^{-1}$: mean, *n*, s.d. | 281.3, 2, n/a | 346.4, 3, 2.7 | 47.1, 3, 3.6 | 47.3, 3, 3.7 |
| 1998 Mitsubishi Magna | Regression, ($R^2$) | y=1.16x + 156.14, (0.92) | y=1.27x + 266.20, (0.99) | y=0.21x + 1.05, (0.87) | y=0.14x - 0.52, (0.92) |
| | 0km $h^{-1}$: mean, *n*, s.d. | 148.8, 3, 3.2 | 264.4, 3, 0.4 | 3.3, 3, 0.5 | 0.1, 1, n/a |
| | 60 km $h^{-1}$: mean, *n*, s.d. | 245.2, 2, n/a | 343.5, 2, n/a | 8.2, 3, 0.6 | 7.8, 3, 0.2 |
| | 110 km $h^{-1}$: mean, *n*, s.d. | 266.9, 2, n/a | 398.8, 2, n/a | 26.2, 3, 0.3 | 14.6, 3, 1.9 |
| 2000 Subaru Liberty | Regression, ($R^2$) | y=0.41x + 130.61, (0.92) | y=0.40x + 259.32, (0.91) | y=0.06x + 0.41, (0.99) | y=0.05x + 0.42, (0.98) |
| | 0km $h^{-1}$: mean, *n*, s.d. | 132.3, 3, 1.2 | 257.7, 3, 6.6 | 0.5, 3, 0.02 | 0.3, 3, 0.1 |
| | 60 km $h^{-1}$: mean, *n*, s.d. | 151.7, 3, 1.4 | 287.0, 3, 5.0 | 4.1, 3, 0.1 | 3.6, 3, 0.2 |
| | 110 km $h^{-1}$: mean, *n*, s.d. | 176.9, 3, 9.0 | 298.6, 2, n/a | 7.3, 3, 0.5 | 6.0, 3, 0.3 |
| 2005 Toyota HiLux[b] | Regression, ($R^2$) | y=0.78x + 126.37, (0.90) | y=0.29x + 259.02, (0.93) | y=0.06x + 0.90, (0.97) | y=0.04x + 1.82, (0.99) |
| | 0km $h^{-1}$: mean, *n*, s.d. | 131.7, 3, 1.2 | 260.6, 3, 1.2 | 0.7, 3, 0.1 | 1.2, 3, 0.4 |
| | 60 km $h^{-1}$: mean, *n*, s.d. | 154.8, 2, n/a | 271.4, 2, n/a | 4.8, 3, 0.1 | 4.2, 3, 0.1 |
| | 110 km $h^{-1}$: mean, *n*, s.d. | 217.0, 3, 12.0 | 292.5, 3, 4.1 | 6.7, 3, 0.6 | 6.0, 2, n/a |
| 2005 Volkswagen Golf | Regression, ($R^2$) | y=0.63x + 149.99, (0.87) | y=0.30x + 298.05, (0.91) | y=0.03x + 0.05, (0.99) | y=0.03x - 0.95, (0.96) |
| | 0km $h^{-1}$: mean, *n*, s.d. | 155.1, 3, 0.7 | 300.0, 3, 0.3 | 0.1, 3, 0.01 | 0, 3, 0 |
| | 60 km $h^{-1}$: mean, *n*, s.d. | 174.2, 3, 8.1 | 311.8, 3, 3.6 | 1.3, 3, 0.1 | 1.0, 2, n/a |
| | 110 km $h^{-1}$: mean, *n*, s.d. | 224.4, 2, n/a | 333.1, 2, n/a | 2.7, 3, 0.1 | 2.6, 3, 0.2 |
| 2007 Subaru Outback | Regression, ($R^2$) | y=0.50x + 127.14, (0.91) | y=0.10x + 286.49, (0.90) | y=0.08x + 0.02, (0.96) | y=0.31x - 0.04, (0.98) |
| | 0km $h^{-1}$: mean, *n*, s.d. | 131.0, 3, 1.9 | 286.4, 2, n/a | 0.3, 3, 0.05 | 0.3, 3, 0.1 |
| | 60 km $h^{-1}$: mean, *n*, s.d. | 147.0, 3, 0.7 | 292.3, 3, 1.3 | 4.0, 3, 0.3 | 17.4, 3, 1.3 |
| | 110 km $h^{-1}$: mean, *n*, s.d. | 183.9, 3, 4.1 | 296.3, 1, n/a | 8.8, 3, 0.8 | 32.0, 3, 0.9 |

Variable y in regression models refers to ACH or $m^3$/h, depending on ventilation mode. Variable x refers to vehicle speed in km $h^{-1}$. [a] Linear regression equations for a given vehicle under the INF condition were based on measures made at 60 and 110 km/h. Mean wind speeds measured during infiltration tests in stationary vehicles were 9.83, 1.37, 1.09, 5.77, 3.06 and 2.49 km/h for the 1989 Mazda 121, 1998 Mitsubishi Magna, 2000 Subaru Liberty, 2005 Toyota HiLux, 2005 Volkswagen Golf and 2007 Subaru Outback, respectively. [b] The INF ventilation condition was assessed twice in this vehicle. The values given above were recorded in January 2006. Subsequent testing in September 2007 resulted in means of 4.4 ($n$ = 3, s.d. = 0.3) and 6.1 ($n$ = 3, s.d. = 0.5) ACH at 60 and 110 km/h, respectively. The equation derived from linear regression applied to these data was: $y = 0.03x + 2.35$ ($R^2 = 0.89$). An additional ventilation mode, referred to as R4 in table 2, was measured in the 2005 Toyota HiLux. Measured mean values under this setting were 1.7 ($n$ = 4, s.d. = 0.03), 5.5 ($n$ = 3, s.d. = 0.1) and 7.7 ($n$ = 3, s.d. = 0.5) ACH at 0, 60 and 110 km/h, respectively. Linear regression applied to data collected under the R4 setting gave the following equation: $y = 0.06x + 1.82$ ($R^2 = 0.99$).

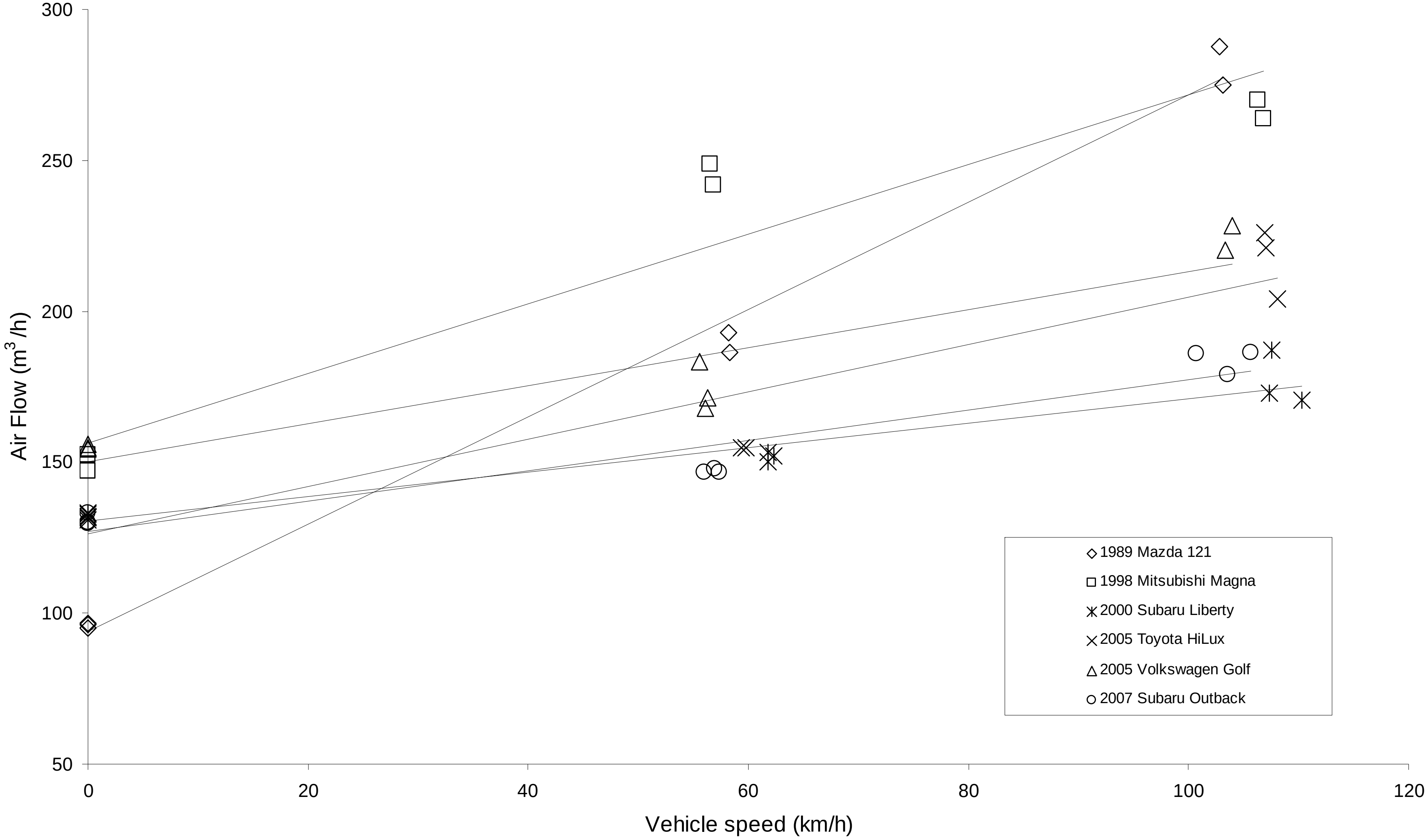


Figure 1. Vehicle speed vs. air flow rate under the E1 ventilation condition.

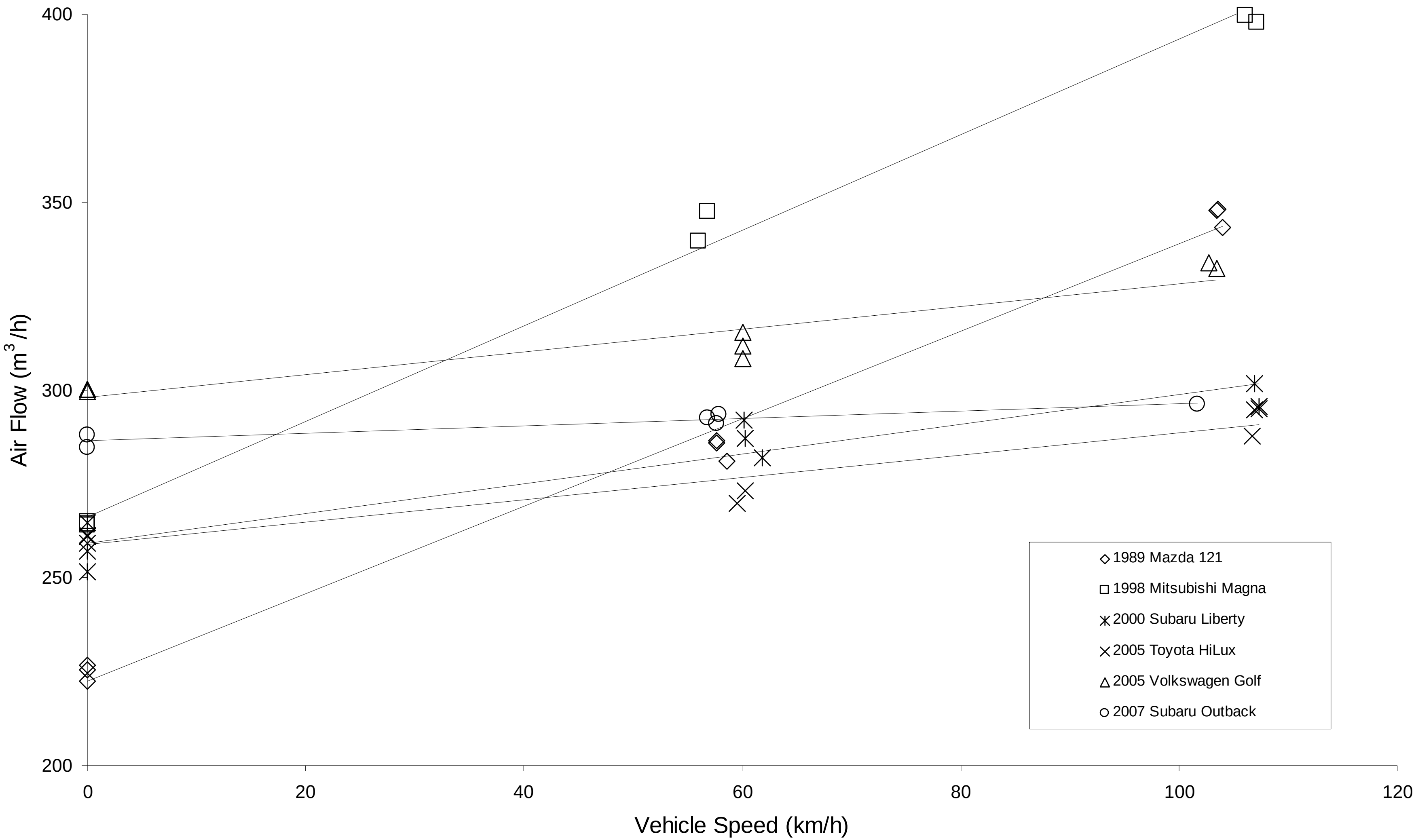


Figure 2. Vehicle speed vs. air flow rate under the E3 ventilation condition

resulted in airflows of ~260, ~300 and ~320 $m^3$/h at the vehicle speeds mentioned above. All of their reported measurements lie within the ranges we recorded under the same speed and ventilation settings.

Rodes et al. (1998) reported air change rates measured in three vehicles under a medium fan setting with recirculation switched off and closed windows. A stationary measurement was performed only in a 1997 Ford Explorer, which resulted in value of 20.7 ACH. At ~56 km/h in the same vehicle, the measured value was 35.7 ACH. Measurements were conducted in three vehicles at 89 km/h, which resulted in a range of 56–98 ACH. Although we measured outdoor airflow in differing units from Rodes et al. (1998), based on our estimates of vehicle volume, measurements made under our E1 condition compare moderately well with theirs.

Park et al. (1998) measured between 36.2 and 47.5 ACH in a stationary 1994 model Hyundai Sonata sedan with windows closed and recirculation switched off. Based on the interior volume reported by the authors, this is equivalent to a volume flow rate range of 103–135 $m^3$/h. These values lie within the range we recorded for our test vehicle group under the E1 setting when stationary.

As stated previously, Batterman et al. (2006) applied perfluorocarbon tracer techniques to measure air change rate in a 2000 model Subaru Legacy/Liberty station wagon with recirculation off, a low fan setting and windows closed at an average vehicle speed of 105 km/h. Despite the similarities between test conditions, the mean value of 177 $m^3$/h measured in our 2000 model Subaru Liberty under the E1 setting at an almost identical average speed is considerably lower than their reported mean of 92 ACH, which corresponds to a flow rate of 377 $m^3$/h using the estimated interior volume of 4.1 m3 provided by Batterman et al. (2006). However, the primary motivation for their study was to evaluate a measurement methodology, and furthermore, they stated that their results should not be taken as representative.

Values of ~30 ACH (~72 $m^3$/h) reported by Ott et al. (2008) in a 2005 Ford Taurus under a setting comparable to E1 at a range of speeds were significantly lower than those we measured. However, they noted the results obtained under

this condition were not correlated with vehicle speed, due to a vehicle dependent factor. Therefore, the variation between their results and ours is not surprising.

Our data generally confirm a linear increase in airflow with increasing vehicle speed, and the results of linear regression models fitted to data collected in all vehicles under both E1 and E3 condition are given in Table 3. The model gradients are steeper for the two oldest vehicles, and decrease significantly for the newer vehicles, which can be seen in Figures 1 and 2. For example, under the E3 condition there is only a minor increase in mean flow of 10 $m^3$/h for a speed increase of over 100 km/h in the 2007 Subaru Outback, the newest of the tested vehicles. The model gradients decreased under the E3 condition compared to the E1 condition in all but one case (1998 Mitsubishi Magna). The scope of this work was not intended to cover the mechanics underlying automobile HVAC systems; however, the interested reader is directed to the model for passive ventilation in a moving vehicle with closed windows and fan and recirculation off developed by Fletcher and Saunders (1994) and recently validated by Ott et al. (2008). When viewed in conjunction with our data, the aforementioned studies highlight the influence of an operating fan, and possibly other factors (such as inlet and outlet vent position, filter presence, and size of HVAC ducting) on reduction of natural ventilation flow that would, in some of our test vehicles, otherwise occur at speed under a fresh air intake setting.

### Concentration-decay Measurements: Infiltration in Stationary Automobiles

Figure 3 and Table 3 show the results of concentration-decay measurements performed under the INF ventilation mode with the test vehicles stationary, plotted against mean wind speed during the tracer decay period. During these tests, average wind direction measurements indicated that winds originated from the rear or front the vehicle, based on the definitions of Fletcher and Saunders (1994).

Three replicate tests made in the 2005 Volkswagen Golf of approximately one hour duration each during mean wind speeds of 2.6–3.8 km/h failed to result in a measurable decay in tracer gas concentration. Therefore, the air change rate for these conditions has been plotted as 0 per hour. Measurements made in the

remaining vehicles ranged from 0.14 to 1.8 ACH, which is generally in accord with other reported values (Fletcher and Saunders, 1994; Ott et al., 2008; Park et al., 1998; Zhang et al., 2008). For comparison, data reported by Park et al. (1998) in three unoccupied stationary vehicles under similar ventilation conditions and subject to winds that originated from the front of their test vehicles are also included in Figure 3. Although Park et al. (1998) found no statistically significant relationship between wind speed and infiltration in stationary vehicles, their data combined with ours reveals a moderate tendency of the air change rate to increase with wind speed in vehicles for which a sufficient range of wind speeds occurred during measurements (see also Fletcher and Saunders, 1994). Increasing age of vehicles and the associated weathering of door seals and other leakage pathways is likely to result in higher infiltration rates (Park et al., 1998). However, it should be considered that wind speeds during our measurements in most newer vehicles were consistently low. We did not observe any thermal effects on infiltration despite temperature differences of up to 11°C between the vehicle cabin and outdoor environments. Likewise, the presence of winds originating from the front or rear of the vehicles during our measurements did not result in different infiltration rates. These two findings support those of Fletcher and Saunders (1994), and in the case of the former, Park et al. (1998) also.

### Concentration-decay Measurements: Infiltration in Moving Automobiles

The results of measurements performed under the INF condition in moving vehicles are shown in Figure 4 and Table 3. Data collected under the INF condition while moving have been plotted separately from those collected with the vehicle stationary, as Fletcher and Saunders (1994) noted that a vehicle driven at a particular speed resulted in a higher number of ACH than would occur in a stationary vehicle subject to an equivalent wind speed. Results obtained increased linearly and ostensibly fell into four distinct categories. At 60 km/h, mean infiltration into the 2005 Volkswagen Golf was 1.0 ACH, while at 110 km/h the equivalent measure was 2.6 ACH, making it the most air-tight vehicle in the test group. Mean values measured in the 2000 Subaru Liberty were

3.6 and 6.0 ACH, at 60 and 110 km/h, respectively. Infiltration into the 2005 Toyota HiLux while moving was re-assessed 20 months after the initial test, during which time the odometer reading increased by 16,226 km. During the first set of measurements in January 2006, mean air changes at 60 and 110 km/h were 4.2 and 6.0 per hour, respectively. Measurements performed in September 2007 under the same conditions resulted in means of 4.4 and 6.1 ACH, indicating no significant changes in the air tightness of the vehicle occurred as a result of the relatively modest amount of usage it received between the two tests. Values reported by Ott et al. (2008) under a comparable ventilation setting in a 2005 Ford Taurus and 2005 Toyota Corolla have been plotted on Figure 4, and it can be seen that our measurements in the 2000 Subaru Liberty and 2005 Toyota HiLux exhibited good agreement with these. Mean infiltration into the 1998 Mitsubishi Magna at 60 km/h was 7.8 ACH, and 14.6 ACH at 110 km/h. Equivalent measurements performed in the 1989 Mazda 121 resulted in mean values of 33.1 and 47.3 ACH, which should be treated cautiously, as the ability of the gas monitoring equipment to adequately measure such high air changes is limited due to its time constant (Kvisgaard, 1995). In addition, the contribution of tracer gas from semi-enclosed sections inside the cabin where the age of air is increased may also become significant under such conditions (G. Clausen, 2008; personal communication). Nonetheless, if these factors affected our measurements, then the 'true' number of air changes in this vehicle would be higher than we recorded. Air infiltration into the 1989 Mazda 121 was one order of magnitude greater than that into the 2005 Volkswagen Golf at the speeds tested.

Results under the INF condition for the 2007 Subaru Outback are not included in Figure 4, as the HVAC system of this vehicle automatically reverted to fresh air intake when the fan was turned off. However, the measured mean values of 17.4 and 32.0 ACH at 60 and 110 km/h, as shown in Table 3, agree reasonably with those presented by Fletcher and Saunders (1994) and Ott et al. (2008) for passive ventilation with both recirculation and the fan switched off and the windows closed.

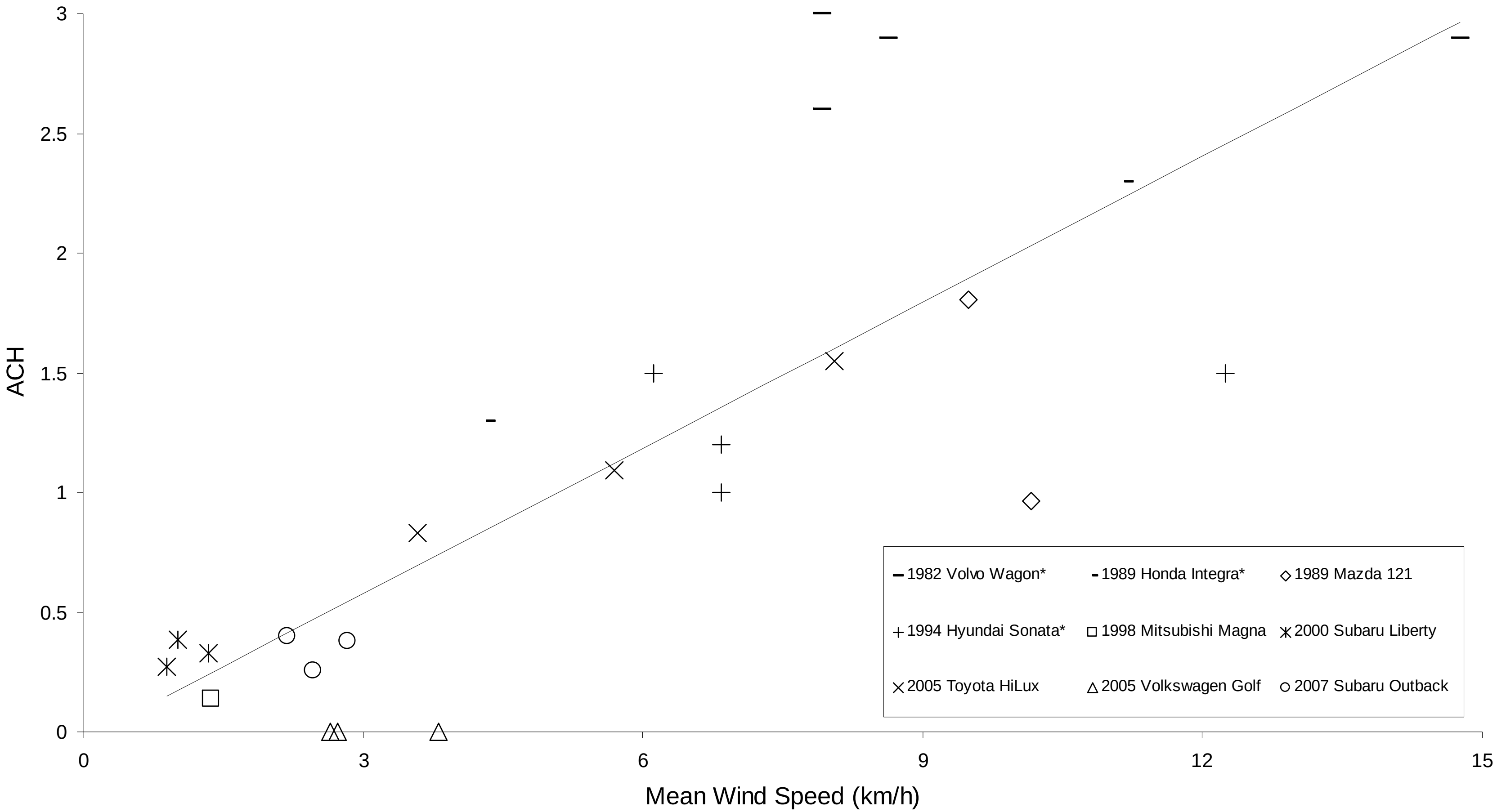


Figure 3. Mean wind speed vs. ACH in stationary vehicles under the INF ventilation condition. *Denotes results reported by Park et al. (1998). Linear regression applied to the data reported by Park et al. (1998), combined with our data, returned an equation of: y = 0.20x - 0.03 ($R^2$ = 0.64). Variable y in regression model refers to ACH, variable x refers to wind speed in km $h^{-1}$. Note that measurements reported for the 2007 Subaru Outback were obtained after its HVAC system automatically reverted to fresh air intake when the fan was switched off.

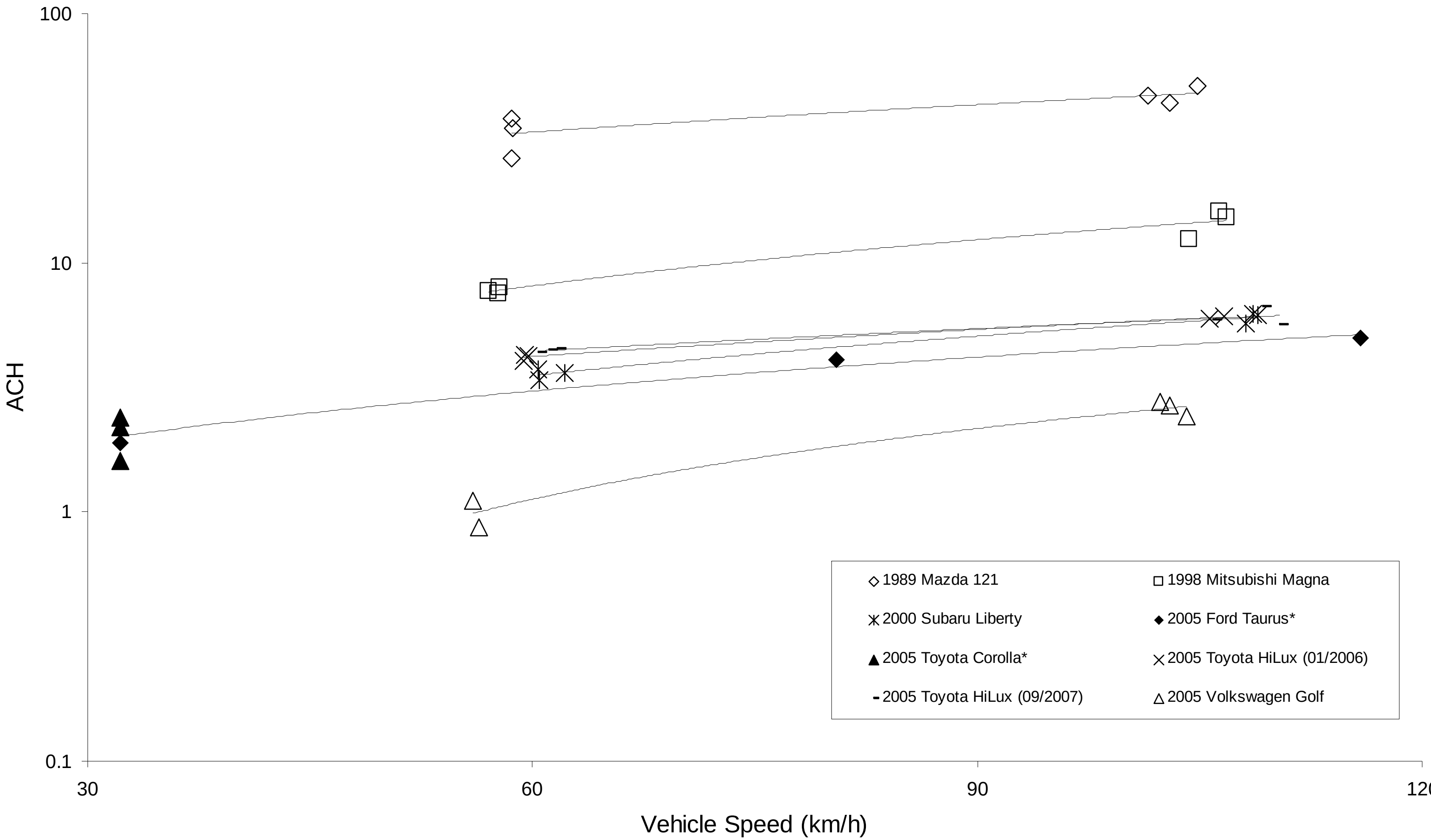


Figure 4. Vehicle speed vs. ACH in moving vehicles under the INF ventilation condition. *Denotes results reported by Ott et al. (2008). Linear regression applied to the data reported by Ott et al. (2008) for a 2005 Ford Taurus returned an equation of: $y = 0.04x + 0.81$ ($R^2 = 0.98$). Variable y in regression model refers to ACH, variable x refers to vehicle speed in km/h.

The likely primary pathway of air infiltration is the recirculation damper, which can deteriorate over time and present a less effective barrier to incoming air. Due to the test vehicles being privately owned, we were not able to dismantle their HVAC systems and physically examine the state of the damper. Window and door seals are the other likely sources of infiltration, and can also be prone to reduced effectiveness with age and wear. The factory-fitted air vents inside the cabin of the 1989 Mazda 121 were not operable and permanently set in the open position, which reduces resistance to air infiltrating through the HVAC system. There are a multitude of air infiltration pathways in automobiles. Ziskind et al. (1981) examined these in buses, taxis and police vehicles, and a similar study based on common passenger vehicles currently in use would be a worthwhile avenue of future research.

### Concentration-decay Measurements: Recirculate Setting in Stationary and Moving Vehicles

Figure 5 and Table 3 show the measured air changes in the vehicle group under a recirculation setting. With the vehicles stationary, the measured air changes were generally <1 per hour, except in the 1998 Mitsubishi Magna where a mean of 3.3 ACH occurred. Due to differing measurement locations, it is difficult to compare results obtained under the INF and R1 settings when the vehicles were stationary. While moving, the air change rate in most vehicles was very similar to the values recorded under the INF setting, as Table 3 shows. This result indicates that little, if any, outdoor air is deliberately introduced into the cabin by the operating HVAC system. However, air change at 110 km/h under the R1 mode in the 1998 Mitsubishi Magna was almost double that measured under the INF condition. It is thought that this is due to a vehicle-dependent factor that allows additional air to enter under this setting. This finding may also explain why a significantly higher air change rates were measured under the R1 setting than under the INF setting when this vehicle was stationary, despite measurements of the former being conducted in a covered parking garage and those of the latter being performed outdoors. Mean air changes measured under the R4 setting in the 2005 Toyota HiLux were approximately 1 per hour higher at all speeds than mean values recorded under the R1 setting. Increasing fan speed

and the associated change in negative pressurization in the vicinity of the recirculation damper thus appeared to moderately accentuate infiltration.

Our measurements under the R1 setting compare well with the limited number collected under similar conditions as reported in the literature. Data from Rodes et al. (1998) and Ott et al. (2008) have been plotted on Figure 5. It is interesting to note that the results of Rodes et al. (1998) for a 1991 Chevrolet Caprice and 1997 Ford Explorer and Ford Taurus are comparable to our measurements made in the 1989 Mazda 121 and 1998 Mitsubishi Magna, respectively. As the work of Rodes et al. (1998) was conducted almost 10 years before our measurements, this introduces the likelihood of vehicle air-tightness being a reflection of manufacturing and design techniques, rather than a direct indicator of damper and seal degradation. However, a combination of both factors is likely. In addition, some manufacturers may allow a certain amount outdoor air intrusion to prevent excessive $CO_2$ build-up.

The inability to implement a representative INF mode in the 2007 Subaru Outback made it difficult to compare the effect of its shortened service life on infiltration compared to the 2000 Subaru Liberty. However, using the measures recorded in the 2007 Subaru Outback under the R1 condition as a surrogate for infiltration, it can be seen from Table 3 that the mean values recorded are comparable to those made in the 2000 Liberty under the INF condition. It is not possible to make a conclusive statement based on the data collected, but it would appear that no significant decrease in air-tightness has occurred in the 2000 Subaru Liberty during seven years of service prior to this study.

Pui et al. (2008) reported that significant reductions in nanoparticle concentration inside vehicles were achieved through the use of recirculation in two vehicles fitted with filters. The vehicles tested were both recent models (2003 Saab 93 and 2007 Toyota Camry). Similar findings were previously reported by Zhu et al. (2007). Becalski and Bartlett (2006) noted that the use of a recirculate setting in a 2002 model Honda Civic sedan substantially lowered the concentration of in-cabin methanol (introduced through the application of windshield cleaning fluid) compared to non-recirculate settings. Our data support these findings, but also indicate that outdoor air intrusion under a recirculation

setting varies considerably between vehicles of differing age, and conceivably so too does the protection of the occupants from both internal and external pollutant sources.

The recirculate condition is perhaps the most relevant ventilation mode, as it represents, in most cases, increased protection from outdoor air compared to the E1 and E3 modes, while offering the occupant better thermal comfort options compared to the INF mode. Car manufacturers and traffic regulatory authorities often recommend drivers use this setting when travelling through polluted or dusty environments. Recirculation can also substantially reduce the power required to cool or heat air compared to fresh air intake of ambient air, which consequently results in improved fuel efficiency and reduced emissions (Farrington and Rugh, 2000). Therefore, mitigation of high outdoor air infiltration into vehicle cabins is relevant not only to occupant protection, but also to overall vehicle fleet emissions. In the case of an internal pollutant source, discretionary use of fresh air intake ventilation conditions or open windows is advisable.

## Conclusions

- Under fresh air intake ventilation modes and closed windows, outdoor airflow increased with increasing vehicle speed, and generally varied by 50–100 $m^3/h$ between test vehicles at a given speed.
- The amount of increase in airflow with speed was greater in older vehicles. The causes have not been investigated in this study, but changes in HVAC system design in newer vehicles are thought to be a significant influence.
- Under fresh air intake conditions and closed windows, the operation of the HVAC fan is likely to have reduced the influence of pressure gradient-driven passive ventilation into some vehicles.

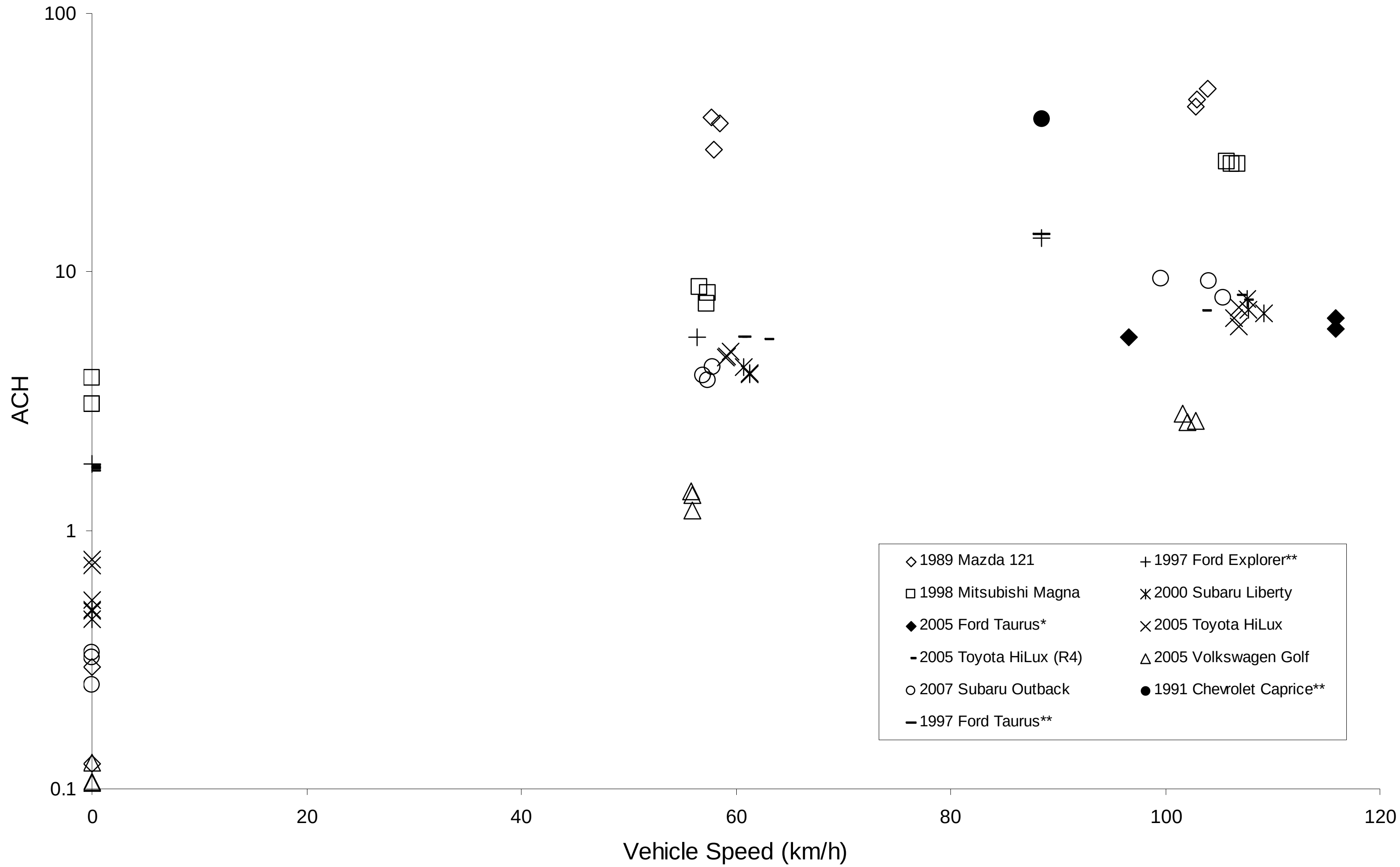


Figure 5. Vehicle speed vs. ACH under the R1 ventilation condition. *Denotes results reported by Ott et al. (2008). **Denotes results reported by Rodes et al. (1998). Linear regression applied to the data reported by Rodes et al. (1998) for a 1997 Ford Explorer returned an equation of: $y = 0.12x + 0.94$ ($R^2 = 0.88$). Variable y in regression model refers to ACH, variable x refers to vehicle speed in km/h.

- Infiltration of outdoor air with all operable leakage pathways closed under all test conditions was one order of magnitude greater in the least air tight vehicle (1989 Mazda 121) compared to the most air tight (2005 Volkswagen Golf).
- There is considerably less variation between vehicles in passive ventilation with the fresh air intake mode selected (Fletcher and Saunders, 1994; Ott et al., 2008) compared to air infiltrating with recirculate selected, as the influence of vehicle-dependent factors related to the recirculation damper, window and door seal air tightness increase under the latter setting.
- Based on limited data, we found no apparent evidence of a significant reduction in air-tightness in both the 2000 Subaru Liberty and 2005 Toyota HiLux over periods of 7 years and 20 months, respectively.
- There was little evidence to suggest any additional outdoor air is deliberately brought into the most test vehicles by the HVAC system under a recirculation setting, other than that which infiltrates naturally. However, this may not be the case for the 1998 Mitsubishi Magna, nor for all vehicles generally.
- The substantial variability in outdoor airflow and change rate between vehicles highlights the importance of accurate quantification of these parameters as a means of better estimating and understanding variations in exposure of occupants of different vehicles to a range of pollutants.
- The results of this study generally agree well with the limited number of previously published studies for similar closed window cases. We have provided substantial new data to supplement existing results, in addition to filling gaps in the knowledge of automobile cabin airflow and change rates. In conjunction with recent contributions by Ott et al. (2008), we feel the available data now better represent the vehicle fleet in many countries.
- The results presented here can be applied to estimation of pollutant concentrations in automobile cabins with closed windows, from sources both internal and external.

- Further work could include detailed assessment of the determinants of air leakage and examination of its specific pathways in automobiles. The efficacy of remedial measures to reduce leakage in less air tight vehicles, while preventing excessive occupant generated $CO_2$ accumulation, could also be assessed.

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## References

Adams, H.S., Nieuwenhuijsen, M.J., Colvile, R.N., Older, M.J. and Kendall, M. (2002) Assessment of road users' elemental carbon personal exposure levels, London, UK, Atmos. Environ., 36, 5335–5342.

ASTM (2006) Standard test method for determining air change in a single zone by means of tracer gas dilution, West Conshocken, PA, ASTM International (Standard E741-00).

Australian Bureau of Statistics (2006) Motor vehicle census, Australia http://www.ausstats.abs.gov.au/Ausstats/subscriber.nsf/0/61D1D30E79B4AF3BCA257234001C2654/$File/93090_31%20mar%202006.pdf (accessed 21 July, 2008).

Batterman, S., Jia, C., Hatzivasilis, G. and Godwin, C. (2006) Simultaneous measurement of ventilation using tracer gas techniques and VOC concentrations in homes, garages and vehicles, J. Environ. Monit., 8, 249–256.

Becalski, A. and Bartlett, K.H. (2006) Methanol exposure to car occupants from windshield washing fluid: a pilot study, Indoor Air, 16, 153–157.

Chan, C.-C., Özkaynak, H., Spengler, J.D. and Sheldon, L. (1991) Driver exposure to volatile organic compounds, CO, ozone and $NO_2$ under different driving conditions, Environ. Sci. Technol., 25, 964–972.

Conceição, E.Z.E., Silva, M.C.G. and Viegas, D.X. (1997) Air quality inside the passenger compartment of a bus, J. Expo. Anal. Environ. Epidemiol., 7, 521–534.

Duffy, B.L. and Nelson, P.F. (1997) Exposure to emissions of 1,3-butadiene and benzene in the cabins of moving motor vehicles and buses in Sydney, Australia, Atmos. Environ., 31, 3877–3885.

Engelmann, R.J., Pendergrass, W.R., White, J.R. and Hall, M.E. (1992) The effectiveness of stationary automobiles as shelters in accidental releases of toxic materials, Atmos. Environ., 26A, 3119–3125.

Farrington, R. and Rugh, J. (2000) Impact of vehicle air-conditioning on fuel economy, tailpipe emissions and electric vehicle range, Golden, CO, National Renewable Energy Laboratory publication NREL/CP-540-28960 http://www.nrel.gov/docs/fy00osti/28960.pdf (accessed 21 July,2008).

Fletcher, B. and Saunders, C.J. (1994) Air change rates in stationary and moving motor vehicles, J. Hazard. Mater., 38, 243–256.

Fruin, S., Westerdahl, D., Sax, T., Sioutas, C. and Fine, P.M. (2008) Measurements and predictors of on-road ultrafine particle concentrations and associated pollutants in Los Angeles, Atmos. Environ., 42, 207–219.

Gameiro da Silva, M.C. (2002) Measurements of comfort in vehicles, Meas. Sci. Technol., 13, R41–R60.

Guillemin, M.P., Herrera, H., Huynh, C.K., Droz, P.-O. and Vu Duc, T. (1992) Occupational exposure of truck drivers to dust and polynuclear aromatic hydrocarbons: a pilot study in Geneva, Switzerland, Int. Arch. Occup. Environ. Health, 63, 439–447.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C. and Engelmann, W.H. (2001) The national human

activity pattern survey (NHAPS): a resource for assessing exposure to environmental pollutants, J. Expo. Anal. Environ. Epidemiol., 11, 231–252.

Kvisgaard, B. (1995) Air distribution measurements in cars using tracer gas. In: Proceedings of Associazione Technica Dell' Automobile Third International Conference on Vehicle Comfort and Ergonomics, Bologna, Paper 95A1057, 443–452.

Kvisgaard, B. and Pejtersen, P. (1999) Measurement of flow in automobile ventilation systems, Innova AirTech Instruments technical document http://www.lumasense.dk/Articles.139.0.html (accessed 21 July, 2008).

Long, T., Johnson, T. and Ollison, W. (2002) Determining the frequency of open windows in motor vehicles: a pilot study using a video camera in Houston, Texas during high temperature conditions, J. Expo. Anal. Environ. Epidemiol., 12, 214–225.

LumaSense (2008a) http://www.lumasense.dk/fileadmin/Files/Product_data/1412_PD_A4_Web.pdf (accessed 21 July, 2008).

LumaSense (2008b) http://www.lumasense.dk/fileadmin/Files/Product_data/1303_PD_A4_Web.pdf (accessed 21 July, 2008).

Ott, W., Langan, L. and Switzer, P. (1992) A time series model for cigarette smoking activity patterns: model validation for carbon monoxide and respirable particles in a chamber and an automobile, J. Expo. Anal. Environ. Epidemiol., 2 (Suppl. 2), 175–200.

Ott, W., Switzer, P. and Willits, N. (1994) Carbon monoxide exposures inside an automobile traveling on an urban arterial highway, J. Air Waste Manag. Assoc., 44, 1010–1018.

Ott, W., Klepeis, N. and Switzer, P. (2008) Air change rates of motor vehicles and in-vehicle pollutant concentrations from secondhand smoke, J. Expo. Sci. Environ. Epidemiol., 18, 312–325.

Park, J.-H., Spengler, J.D., Yoon, D.-W., Dumyahn, T., Lee, K. and Ozkaynak, H. (1998) Measurement of air exchange rate of stationary vehicles and estimation of in-vehicle exposure, J. Expo. Anal. Environ. Epidemiol., 8, 65–78.

Peters, A., von Klot, S., Heier, M., Trentinaglia, I., Hörmann, A., Wichmann, E. and Löwel, H. (2004) Exposure to traffic and the onset of myocardial infarction, N. Engl. J. Med., 351, 1721–1730.

Petersen, G.A. and Sabersky, R.H. (1975) Measurements of pollutants inside an automobile, J. Air Pollut. Control Assoc., 25, 1028–1032.

Pui, D.Y.H., Qi, C., Stanley, N., Oberdörster,G. and Maynard, A. (2008) Recirculating air filtration significantly reduces exposure to airborne nanoparticles, Environ. Health Perspect., 116, 863–866.

Riediker, M., Cascio, W.E., Griggs, T.R., Herbst, M.C., Bromberg, P.A., Neas, L., Williams, R.W. and Devlin, R.B. (2004) Particulate matter exposure in cars is associated with cardiovascular effects in healthy young men, Am. J. Respir. Crit. Care Med., 169, 934–940.

Rim, D., Siegel, J., Spinhirne, J., Webb, A. and McDonald-Buller, E. (2008) Characteristics of cabin air quality in school buses in Central Texas, Atmos. Environ., 42, 6453–6464.

Rodes, C., Sheldon, L., Whitaker, D., Clayton, A., Fitzgerald, K., Flanagan, J., DiGenova, F., Hering, S. and Frazier, C. (1998) Measuring concentrations of selected air pollutants inside California vehicles, Report prepared for California EPA http://www.arb.ca.gov/research/abstracts/95-339.htm#Main (accessed 21 July, 2008).

Wyon, D.P., Wyon, I. and Norin, F. (1995) The effects of negative ionisation on subjective symptom intensity and driver vigilance in a moving vehicle, Indoor Air, 5, 179–188.

Zhang, G.-S., Li, T.-T., Luo, M., Liu, J.-F., Liu, Z.-R. and Bai, Y.-H. (2008) Air pollution in the microenvironment of parked new cars, Building Environ., 43, 315–319.

Zhu, Y., Eiguren-Fernandez, A., Hinds, W.C. and Miguel, A.H. (2007) In-cabin commuter exposure to ultrafine particles on Los Angeles freeways, Environ. Sci. Technol., 41, 2138–2145.

Ziskind, R.A., Rogozen, M.B., Carlin, T. and Drago, R. (1981) Carbon monoxide intrusion into sustained-use vehicles, Enviorn. Int., 5, 109–123.