

AUTOMOBILE HVAC SYSTEMS: AIR FLOW, LEAKAGE AND THEIR EFFECTS ON IN-VEHICLE AIR QUALITY

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ABSTRACT

We have sought to accurately quantify automobile HVAC air flow rates in four passenger vehicles, under a range of different ventilation settings and speeds. We used Sulphur Hexafluoride (SF₆) as a tracer gas, coupled with a portable doser/sampler system to quantify flow rates and leakage.

Results of this work indicate a linear increase in HVAC air flow rate with increasing vehicle speed for all vehicles. Older vehicles were much less airtight than newer vehicles, a likely reflection on improved design and reduced door seal deterioration observed in the newer vehicles. HVAC systems in newer vehicles generally delivered a smaller volume of air than older vehicles under the same ventilation settings.

The results are of particular interest to those involved with engineering and modelling in-vehicle environments and associated HVAC systems, especially in relation to pollutants. For example, subsequent air quality assessments in the same fleet of vehicles indicated that the inside/outside ratios of combustion-derived submicrometer particle concentrations were highest inside the cabins of the oldest vehicle.

KEYWORDS

Vehicle, Automobile, Air Flow, Leakage, AER

INTRODUCTION

Recently, the focus of many pollutant exposure-based studies has shifted towards assessment of environments where the total duration of exposure may be relatively short, but the pollutant concentrations encountered may be substantially greater than those found in locations where an increased proportion of time is spent. These exposures, although brief, have the capacity to induce a range of deleterious health effects in exposed persons, particularly those with existing allergies and/or respiratory conditions (e.g. Svartengren et al 2000). Based on a survey of over 9,000 people, Klepeis et al. (2001) reported that United States residents spend 5.5% of each 24 hour period 'in-transit'. Rodes et al. (1998) found that concentrations of many pollutants encountered in vehicles traversing roadways were significantly elevated relative to ambient monitoring locations. As part of our project, a pilot study was conducted in Sydney, Australia on 2 roadways of differing types (open roadway and enclosed tunnel), both characterised by an analogous volume and composition of traffic. Under the 4 different ventilation settings used in the study vehicle, mean concentrations of submicrometer particulate matter observed in the enclosed tunnel were at least one order of magnitude greater than those on the open roadway, and also two orders of magnitude above mean concentrations measured inside non-smoking houses and offices. Given this, it seems useful for a tunnel management organisation to have the ability to estimate the mean concentration of a given pollutant likely to be encountered in a vehicle cabin, based on a concurrent or recently measured concentration of the pollutant taken in a tunnel. This provides the roadway operators with the opportunity to alert motorists when an in-vehicle concentration threshold is likely to be exceeded, such that basic mitigative measures can be implemented by drivers to minimise exposure. To achieve this aim, a simple mass

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balance model can be employed, however, to ensure the best possible result, accurate quantification of vehicle HVAC performance is required.

As part of an on-going project, we have assessed air flow rates under four different ventilation settings in a fleet of four common passenger vehicles of varying chassis types. Measurements were undertaken in both stationary and moving vehicles. Although studies of a similar nature have been conducted previously, the methodology utilised in these was variable and the number of measurements made was often minimal. We have sought to comprehensively quantify these parameters in a range of vehicles, such that model accuracy and integrity can be maintained. A subsequent phase of the project involved measurement of inside/outside concentrations ratios of submicrometer particles in the study fleet during short trips, and some preliminary results of this work will also be presented.

Previous Work

Measurements of vehicular air change and/or flow rate appear in publications from over 30 years ago. Petersen and Sabersky (1975) described measurements of Air Exchange Rate (AER) undertaken in a 'stock' Chevrolet, utilising Carbon Monoxide (CO) as a tracer gas. Tests were conducted at speeds up to ~100 km/h. Their results, whilst generally consistent with later work, were based on only a handful of tests and a minimal set of ventilation settings.

Engelmann et al. (1992) measured AER in a stationary vehicle using alcohol as a tracer. They conducted tests under several different ventilation conditions, but no testing was conducted in a moving vehicle. Ott et al. (1992) and Ott et al. (1994), reported some vehicular AER values, measured using CO as a tracer, as part of a relatively large and long-term study. However, their study vehicles and ventilation protocols were quite limited.

Fletcher and Saunders (1994) conducted a study which examined AER in moving and stationary vehicles. Their work was primarily directed towards estimation of AER of a moving vehicle based on leakage characteristics determined for that vehicle whilst stationary. However, as part of the evaluation of estimates made, AER measurements were made in a moving vehicle using Sulphur Hexafluoride (SF₆) as a tracer at vehicle speeds up to ~110 km/h. The results of these tests indicated a linear increase in AER with vehicle speed. Conceição et al. (1997) also employed SF₆ as a tracer to conduct a limited number of AER measurements inside a passenger bus.

Park et al. (1998) reported values of AER for several stationary vehicles under a range of ventilation settings using CO₂ as a tracer. Rodes et al. (1998), utilised CO, and similar methodology to that employed by Ott et al. (1992), to conduct a limited number of AER assessments across three vehicles. Kvisgaard and Pejtersen (n.d.) produced a useful reference manual detailing suggested measurement protocols for determination of air flow through automotive HVAC systems. While much of this work is specific to equipment used, results of measurements taken under a range of ventilation settings and driving conditions are given. This work formed the basis of several techniques described herewith.

METHODS

Four common passenger vehicles formed the study fleet; a 1989 Mazda 121 (small hatch-back), a 1998 Mitsubishi Magna (family sedan), a 2005 Toyota HiLux Dual-Cab (utility vehicle/pick-up truck) and a 2005 VW Golf (large hatch-back). All of the vehicles except the Mazda 121 were fitted with air conditioning. The VW Golf was fitted with a factory-installed pollen filter in the HVAC system. Three ventilation modes were selected to represent typical operating scenarios in the study area, Sydney, Australia. Additionally, a closed cabin mode was also used to provide baseline leakage data. The ventilation modes were;

- 1 – Completely Closed Cabin (CCC): Fan off, all vents closed, air intake set to recirculate, all windows closed. Air conditioner off. Air entering under this scenario is referred to from here on as leakage.
- 2 - Recirculate 1 (R1): Fan set to lowest speed, all vents open and in the 'face only' position, air intake set to recirculate, air conditioner on and set to full cooling mode. All windows closed.
- 3 – External 1 (E1): Fan set to lowest speed, all vents open and in the 'face only' position, air intake set to external, air conditioner on and set to full cooling mode. All windows closed.
- 4 – External 3 (E3): Fan set to second highest speed, all vents open and in the 'face only' position, air intake set to external, air conditioner on and set to full cooling mode. All windows closed.

Tests were conducted at 0km/h (i.e. stationary vehicle with motor running), 60km/h and 110km/h. Moving vehicle tests were undertaken in locations featuring a sufficient length of reasonably straight roadway with no obstructions (traffic lights, 'roundabouts'), such that the vehicle could maintain a given speed safely and for at least 15 minutes. Another consideration was quality of road surface, as excessive vibration can affect the accuracy of the measurement equipment.

An Innova 1303 multi-point sampler/doser and 1412 photoacoustic gas monitor were used during testing, and SF₆ was used as a tracer gas. Both systems were calibrated prior to testing. The equipment and SF₆ cylinder were set up in the boot (trunk) of the vehicles, and powered using a deep-cycle absorbed glass mat battery through a pure sine-wave inverter. A laptop computer ran the necessary software (Innova type 7620). The constant emission method was used for tests involving either the E1 or E3 ventilation modes, due to the very high air flow/exchange rates present. Using a single dosing channel, tracer was dosed into the air intake located at the base of the windshield on most vehicles. To ensure a representative and precise measurement, three sampling points were used; the passenger footwell vent, a centre dashboard vent and the far right hand side dashboard vent. The results of these tests are given by the control software in units of cubic metres per hour (m³/h). The concentration-decay method was used to assess flows whilst under the R1 and leakage ventilation conditions. Tracer was dosed in the same location as the constant emission tests, and a single sample point was positioned in the centre of the vehicle cabin away from any air jets. Once the necessary settings had been implemented in the software control program, the measurements were started and the vehicle was driven at the required speed for 15-30 minutes depending on available road length. In the case of the concentration-decay tests, tracer was dosed into the HVAC system under the E1 mode with the vehicle stationary on the side of the roadway until a uniform concentration was reached, assisted by the use of a small 12 volt fan. This usually took 12-15 minutes, after which the desired ventilation setting was selected and the vehicle driven to the appropriate speed. Most of these methods were based on those described by Kvisgaard and Pejtersen (n.d.). During all tests conducted in a moving vehicle, a Global Positioning System recorded vehicle speed. Stationary measurements under the E1, E3 and R1 modes were conducted in a semi-enclosed carport. Stationary measurements under the leakage condition were made in an open carpark. Wind speed was also monitored whilst conducting these tests in a manner similar to that of Fletcher and Saunders (1994).

It should be noted that a consequence of ventilation testing in vehicles is that routing of dose lines from the inside to outside is often required. It is important to ensure that if this is the case, the exit point of the tube/cable should be sealed as well as possible using thick, waterproof tape. Also, it is prudent to void waste air from the gas monitor outside the vehicle using a short length of tubing, particularly if using the concentration-decay method. This has the potential to affect the results if the flow rate of the instrument is significant. This was assessed, and no discernable difference was observed between tests where waste air was voided inside or outside the vehicle. To convert measurements expressed in units of AER to a flow rate, and vice-versa, the internal volume of the vehicle must be known. This was assessed using the method described by Fletcher and Saunders (1994).

Each test was replicated three times, therefore a given vehicle required at least 12 tests to be conducted at each speed (i.e. 4 ventilation modes * 3 tests per mode). As tests were undertaken at three different speeds, a minimum of 36 tests were conducted in each vehicle. Over 200 tests were completed during the course of the study. Some tests had to be abandoned in the field for various reasons, such as failure to maintain speed, gas bottle problems, power supply failure and HVAC blower fan failure in one vehicle. Other tests were discarded in the analysis stage, particularly some constant emission tests where an initially low dose rate caused the software to overestimate air flow rate, and due to the long averaging period, the measurement failed to stabilise before the roadway became unsuitable and the test ended. The success rate throughout testing was ~75%. Tests were conducted in January and May of 2006.

Data analysis was relatively straightforward. Flow rate data collected during constant emission tests were averaged, and were typically based on at least 15 individual measurements. Where instability in the measurements existed or unreasonable values were reported due to operational problems, data were discarded. For concentration decay tests, dosing data were removed, thereby leaving only the decay section of the test. The natural logarithms for these data were computed and plotted, and a straight line-of-best-fit derived. The slope of the line was recorded as the AER. Most values are

based on a minimum of 9 data points. Where obvious deviation from an approximately straight line existed in the logarithm values, data were not used. However, concentration-decay tests were generally very successful.

In a subsequent phase of the study, we examined inside/outside ratios of submicrometer particulate matter in the study fleet and the effect of the four ventilation settings on these. Testing was done with a TSI 3007 condensation particle counter and a datalogger-based switching system that controlled the state of a conductive 'Y-type' valve, based on a similar experimental setup described by Rodes et al. (1998). Short trips were made through a tunnel characterised by a large volume of heavy truck traffic, and contiguous measures of particle concentration inside and outside the vehicle were made in 20 second blocks (i.e. 20 seconds sampling inside followed by 20 seconds sampling outside). Outside samples were taken from the windshield base, and inside samples were made proximate to the air vents. A dilution system was used to maintain the sample concentrations below the maximum detection threshold of the particle counter, and the data were corrected for this and clearance of sampled air through the tubing. A detailed description of the dilution system can be found in Knibbs et al. (in press). Average inside/outside ratios are yet to be computed for all trips, but some preliminary results will be presented in this paper.

RESULTS AND DISCUSSION

The relationships between speed and air flow for each vehicle and ventilation setting are given in figures 1, 2, 3 and 4; corresponding to the Mazda 121, Mitsubishi Magna, Toyota HiLux and VW Golf, respectively. All constant emission tests conformed to the precision guidelines given by Kvisgaard and Pejtersen (n.d.), whereby the average measured concentration at each sampling point should not deviate by more than 3% from the average concentration across all measured points. This ensures greater than 5% precision of a given measurement. Results of concentration decay tests have been converted to flow rates, based on the estimated volume of each vehicle. Estimated vehicle volumes are given in table 1, and are in generally good agreement with the small amount of volume data available (Ott et al. 1992, Fletcher and Saunders 1994, Park et al. 1998). The volume measurements seem similar, but it must be considered that the hatchback vehicles had their boot (trunk) partitions removed and also that the HiLux has a 4 seat cabin which is physically separated from the cargo tray by the rear firewall. Due to the measurement techniques used, results for E1 and E3 modes incorporate leakage through the inlet vent only, whilst R1 measurements incorporate leakage via all pathways.

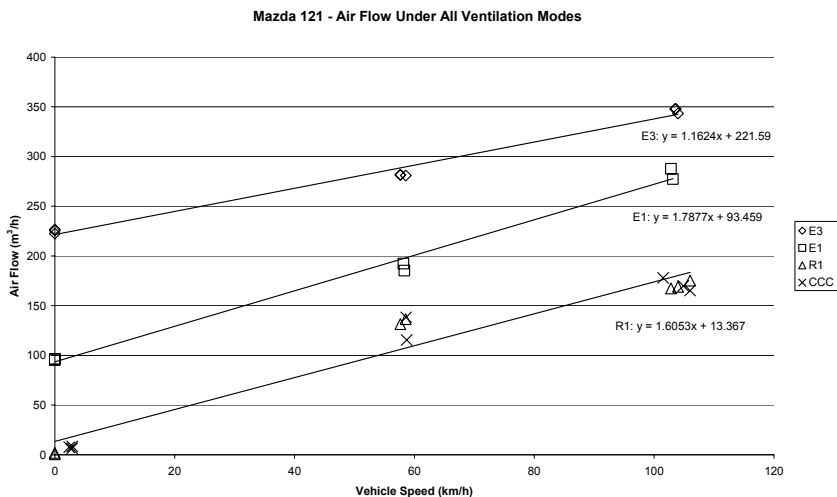


Figure 1 – Vehicle speed vs. air flow under four different ventilation settings in a 1989 Mazda 121

Table 1 – Estimated internal volumes of the study vehicles

Vehicle	Estimated Volume (m ³)
121	3.32
HiLux	3.33
Magna	3.72
Golf	3.88

The results for the 1989 Mazda 121 indicate a linear increase in air flow with increasing vehicle speed under all ventilation modes. It is clear that all air entering the vehicle under the R1 mode is leakage (i.e. the values for R1 and CCC are essentially the same), and therefore no make-up air is introduced under this mode, only that which infiltrates naturally. Of most interest is the large volume of leakage air entering the vehicle, particularly at high speed (~170m³/h at 110 km/h). Compared to the other, newer vehicles, the Mazda allows a much greater volume of outside air to enter the vehicle, even when the windows are shut, the air vents are closed, the fan is off and the intake set to recirculate. This is due to the design of the vents in the 121, which are not capable of full closure like those in most newer vehicles. Also, the door and window seals, as well as other major leakage pathways, had visibly deteriorated over the vehicles 17 year life. Park et al. (1998) suggested that changes in design and manufacturing, in addition to corrosion, vibration and impacts, are the main factors which explain the difference in air tightness between older and newer vehicles, and this is likely to be the case here also. Additionally, operational use of the small 'door' which is engaged when switching from fresh air intake to recirculate could result in a wearing of the foam seal with time, providing an additional leakage pathway.

Mitsubishi Magna - Air Flow Under All Ventilation Modes

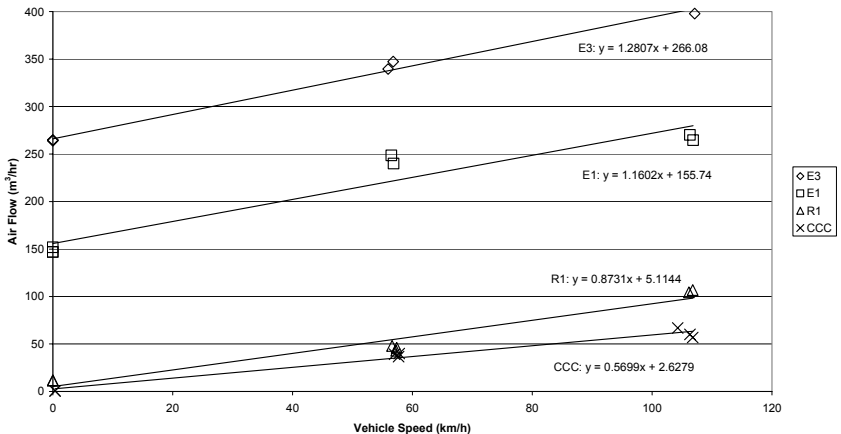


Figure 2 - Vehicle speed vs. air flow under four different ventilation settings in a 1998 Mitsubishi Magna

A generally linear increase in air flow with increasing speed was also present in the results for the 1998 Mitsubishi Magna, shown in figure 2. This vehicle had the highest measured air flow of all test vehicles, approximately 400m³/h at 110km/h under the E3 mode. Up to 60km/h, it appears that air entering the vehicle under the R1 mode is due entirely to leakage, however, at 110km/h there is a disparity of about 50m³/h between airflow under the R1 and CCC modes. It is thought that this is due to a vehicle-dependent mechanical factor, such that some make-up air is allowed to enter under the

R1 mode above a certain speed/pressure. The underlying cause of this disparity will be under investigation in future work. The Magna appeared to have a physically larger HVAC system than other study vehicles, and as such, could very likely accommodate a greater volume of air. This would explain the high values observed and also the relatively steep gradient of the E3 and E1 data compared to most other vehicles. It seems likely that newer vehicles, as a consequence of an increasing number of accessories such as airbags, have less space available for the installation of large HVAC systems and fans. The base model Magna featured none of these 'modern' accessories.

Figure 3 shows the speed vs. flow relationship for the 2005 model Toyota HiLux utility vehicle. Again, a generally linear relationship is present. Like the Mazda 121, the air entering under the R1 setting is exclusively via leakage. However, the volume of air entering the vehicle in this way is greatly reduced compared to the Mazda 121, which is 16 years older than the HiLux. This reflects the increased air tightness of the HiLux due to its much shorter operational time, and subsequent lack of significant deterioration in materials such as door and window seals. Design principles and build quality may have also improved in the period between manufacture of each vehicle. The Mitsubishi Magna lies about halfway between the HiLux and 121 in terms of air tightness, and also vehicle age.

The air flows under the E1 and E3 modes are lower than the equivalent measures made in the 121 and Magna. The gradient of the line-of-best-fit under these modes is also reduced compared to the older vehicles. The HiLux was fitted with airbags on the passenger side proximate to the blower fan, which was observed to be relatively small. As a consequence of this, the maximum flow rates are ~75% of those observed in the Magna. The comparatively small increase in flows from 0 to 110 km/h under the E3 modes implies that either the system is approaching its maximum possible air flow, or that a much greater pressure differential is required to produce the relatively high increases in air leakage observed in the older vehicles.

Toyota HiLux - Air Flow Under All Ventilation Modes

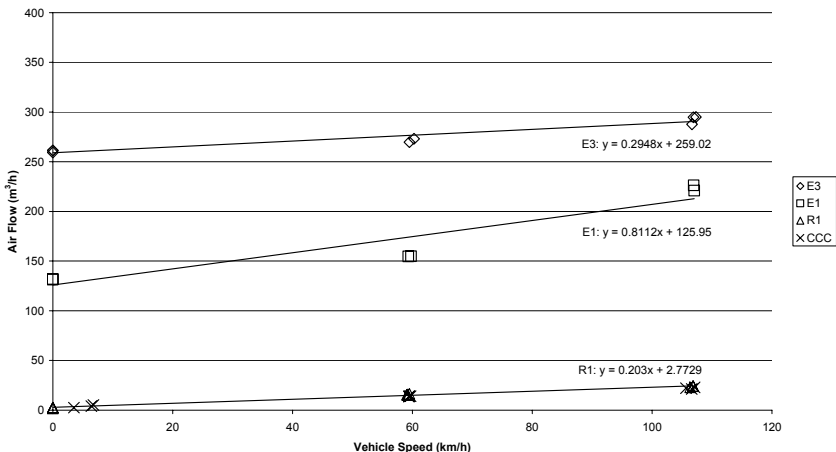


Figure 3 - Vehicle speed vs. air flow under four different ventilation settings in a 2005 Toyota HiLux dual-cab

Results for the 2005 VW Golf are shown in figure 4. All air entering under the R1 mode is due to leakage, as with the other vehicles. Of particular interest are the extremely low air flow values under the R1 and CCC modes. Even at 110 km/h, only ~10m³/h air leaks into the vehicle cabin, making the Golf the most airtight of all tested vehicles. The Golf was also the newest vehicle in the study fleet, and although built in the same year as the HiLux, its odometer reading was lower and therefore also its cumulative time on the road. All rubber seals were observed to be fully intact and in excellent condition.

Like the HiLux, air flows under the E1 and E3 modes were generally lower than in the older vehicles. A comparably slight gradient in the relationship between air flow and vehicle speed was also present under these modes. This further implies that either the HVAC system is nearing its maximum flow, or due to the geometry and positioning of the system, a larger pressure differential than that afforded by the highest vehicle speed is required to cause a gradient similar to those observed in the 121 and Magna. One factor which might explain this is the position of the air intake vents, which for both new vehicles were concealed by the upper lip of the bonnet, and consequently are not directly exposed to the air stream generated by vehicle speed. The 121 and Magna both had an older style of intake vent, which is clearly visible from outside the vehicle and is fully exposed to air streams. For all vehicles, it would appear that the blower fan provides the initial air flow (i.e. the value measured at 0 km/h), and additional increases in flow with vehicle speed are the consequence of pressure gradient driven infiltration through the HVAC system, although some leakage via seals and other common pathways could also be expected. Petersen and Sabersky (1975), when discussing air exchange in a moving vehicle up to ~100 km/h, noted their assumption that “general leakage rather than the fan is the dominant factor in determining air exchange at these speeds”. The current results tend to support this statement, and the nature of pressure differences across vehicle cabins are under scrutiny in a follow-up study. A summary table of average air flow values for the study fleet under each combination of ventilation mode and speed is given in table 2. The results presented in this paper are broadly consistent with previous studies. However, due to the multitude of potential ventilation settings in vehicles, and also a lack of detailed information in some work, a direct comparison is not generally possible.

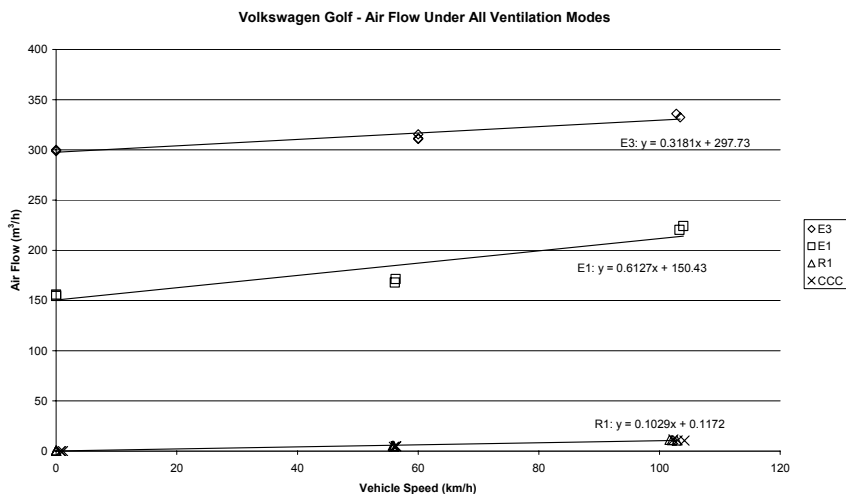


Figure 4 - Vehicle speed vs. air flow under four different ventilation settings in a 2005 VW Golf

Persons wishing to make a judicious decision regarding the use of air exchange values in either a modelling or design context are encouraged to consult the values presented here, along with the studies mentioned earlier in this paper, in order to find the most appropriate data for their needs.

Finally, the significance of air flow and leakage on in-vehicle air quality was highlighted as part of an additional study utilising the same vehicle fleet. Some preliminary data, based on several sampling exercises, have shown that the trip average inside/outside ratio of submicrometer particulate matter under the R1 mode in the VW Golf was 0.07. The equivalent measurement made in the Mazda 121 was 0.51. This emphasises the impact that leakage can have on vehicle occupant pollutant exposures, and implies that the best protection will be afforded by newer, more airtight automobiles.

CONCLUSIONS

Air flow in passenger vehicles increases with vehicle speed in a generally linear manner, driven by air pressure gradients across the vehicle cabin. How well sealed the cabin and/or HVAC system is dictates the amount of air which will enter via this mechanism. Older vehicles which have been in operation for several years are likely to have deterioration around the door, window and HVAC seals, which permits a relatively large volume of outside air to infiltrate the vehicle, even when the cabin is closed or the recirculate mode is in effect. For all study vehicles, it generally appears as though no (or very little) make-up air is introduced under the recirculate mode, and any air which enters under this setting is doing so via leakage pathways only. However, this may not be the case for all vehicles (Engelmann et al. 1992). Newer vehicles were much more airtight than older vehicles, and this is a reflection upon the reduced weathering of door seals and other leakage pathways, as well as a likely improvement in design and manufacturing processes. Newer vehicles had observably smaller HVAC components, such as blower fans, and consequently delivered a smaller volume of air than older vehicles under the same ventilation settings. The newer vehicles in the study fleet also had their air intake vents concealed by the bonnet, and this may also explain the relatively low flow rates observed. Vehicle air tightness can have a significant effect on in-vehicle air quality, and this was highlighted by results from a recent follow-up study, where the oldest vehicle in the fleet had an average inside/outside submicrometer particle concentration ratio more than five times greater than the same measure made in the newest vehicle. Further work will focus on assessment of additional ventilation modes and vehicles, and also evaluation of the nature of pressure differences across the cabin, and the effect of pressure gradients on air flow and leakage.

Table 2 – Summary table of average air flow values recorded in the study vehicles

	E1 (m ³ /h)	E3 (m ³ /h)	R1 (m ³ /h)	CCC (m ³ /h)	Wind Spd.
Mitsubishi Magna					
0 km/h	148.6	264.4	11.6	0.6	0.4 km/h
60 km/h	244.3	343.5	45.6	38.6	-
110 km/h	267.3	399.8	110.9	61.2	-
Toyota HiLux					
0 km/h	131.7	260.6	2.3	3.9	5.6 km/h
60 km/h	154.8	271.5	15.9	14.0	-
110 km/h	217.2	292.5	23.8	22.1	-
VW Golf					
0 km/h	155.1	299.5	0.4	0.0	0.9 km/h
60 km/h	169.7	312.6	5.2	4.6	-
110 km/h	222.2	334.2	11.0	11.0	-
Mazda 121					
0 km/h	96.0	224.9	1.3	7.5	2.7 km/h
60 km/h	188.8	281.4	125.2	113.6	-
110 km/h	282.5	346.4	170.5	171.0	-

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