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Air change rates in stationary and moving motor vehicles

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Abstract

The project was carried out to determine the likely infiltration rate of a gas into a stationary motor vehicle for different wind speeds and directions. Measurements were first made on five vehicles under both positive and negative pressures to determine their leakage characteristics both with the vents open and with them closed. A tracer gas method was then used to determine the air change rates in the vehicles for different wind speeds and directions. Measurements on one vehicle enabled a constant to be evaluated which enabled infiltration rates to be found for other vehicles in terms of leakage characteristics and wind conditions. Predicted values of air change rates can be used to estimate the build-up of a contaminant infiltrating into a vehicle.

In the second part of the project the scenario considered was that of a vehicle moving through a cloud of contminant. Measurements of air change rates (ACH) were made on a vehicle driven at constant speeds of between 35 and 70 mph (15 and 32 m/s). Although the variation of ACH with speed was similar to that for the stationary vehicle in an airflow, a higher ACH was found for the moving vehicle than would be predicted for the stationary vehicle, using the leakage characteristics.

1. Introduction

In the event of an accident involving a vehicle which is carrying a toxic load, the possibility exists that a toxic vapour or gas cloud could be released; that is a sudden contamination of the outdoor air could occur. A recently published report [1] on transport risk assessment made the assumption that “for toxic events the construction of cars means that the passengers are effectively out of doors”. However it is possible that any vehicle caught up in the accident may offer a greater degree of protection to

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its occupants if they remain inside it than if they were to abandon the vehicle with the objective of escaping on foot. The envelope of the vehicle could act as a shield against the contaminated outdoor air; the degree of protection afforded by the vehicle would depend on several factors. In order to make an assessment of this situation, it is necessary to know the leakage characteristics of the vehicle, the effective leakage area characterising the leakage function, and the sensitivity and dependence of air infiltration rates on the prevailing weather conditions. Experience from the measurement of passive air infiltration into buildings suggests that the major driving force would be the wind speed. Although the inside/outside temperature difference for vehicles could be high, the internal height of a vehicle will in general be small, and the 'stack effect' might be expected to be of secondary importance. Other factors which could play a part include wind direction, leakage distribution and localised airflow conditions, i.e. the effect of sheltering by other vehicles. This latter effect has not been extensively investigated even in the case of buildings [2]; however it has been reported [3] that wind shelter can change ventilation rates by up to a factor of five for houses in a closely-spaced row. Shelter effects are beyond the scope of the present investigation.

In a report [4] of experiments on the infiltration of gases and respirable particles into stationary cars in a large room where, apart from air movement produced by large fans used to mix the tracer throughout the room, the vehicles were not subjected to an external air flow, the authors conclude under "future research" that one of the "important questions to be answered before the sheltering offfered by automobiles is adequately defined" is that of the air change rate for moving vehicles. The second scenario considered therefore is that in which a vehicle is driven through an essentially stationary cloud of contaminant.

2. Leakage characteristics

In the case of building envelopes, the flow/pressure differential relationship is usually modelled by a power law of the form

$$Q = C(\Delta p)^n \tag{1}$$

where Q is the volume flow rate ($m^3\,s^{-1}$), C is a flow coefficient ($m^3\,s^{-1}$ at 1 Pa), Δp is the pressure difference (Pa) between the inside and outside of the structure, and n is the flow exponent which can, in theory, lie in the range 0.5–1.0 but which most usually lies between 0.5–0.75. The values of the parameters C and n for the structure are determined experimentally from flow/pressure measurements and describe the leakage characteristics over the range of pressure differences examined. The leakage into a building takes place in practice through numerous cracks and openings. An equivalent leakage area (ELA) is sometimes used as a measure of the total leakage area. It is calculated as the area of a sharp edged orifice, for which $n = \frac{1}{2}$, which would pass the same volume flow rate as the structure at a given pressure differential. A value of the pressure difference (Δp_{ref}) must therefore be stated when ELA data are presented. ELA can then be given by

$$\mathrm{ELA} = \frac{Q}{C_{\mathrm{d}}\left[\dfrac{2\Delta p_{\mathrm{ref}}}{\rho}\right]^{1/2}} \tag{2}$$

where C_{d} is a discharge coefficient and ρ is the density of air (kg m^{-3}). Using Q from Eq. (1) gives

$$\mathrm{ELA} = \frac{C}{C_{\mathrm{d}}}\left(\frac{\rho}{2}\right)^{1/2} \Delta p_{\mathrm{ref}}^{n-1/2}. \tag{3}$$

The same methodology can be applied to the leakage of air into motor vehicles. Note that the internal pressure can be positive or negative relative to atmospheric pressure. Whilst this may not have a large effect on measurements made in buildings, it could be significant for motor vehicles where doors may be pulled onto or pushed away from rubber seals or where there are “flapping” devices (devices which act as flap valves to facilitate the closing of doors). It has also been suggested [4] that the asymmetric geometry of some cracks with respect to the flow direction could explain the changes in leakage characteristics which occur with no change in leakage area. The value of the power $\frac{1}{2}$ in Eq. (2) is that which is used for a sharp edged orifice; it would therefore seem appropriate to choose a value of C_{d} which corresponds to this value, i.e. $C_{\mathrm{d}} = 0.6$. In reality the opening would consist of an ensemble of long thin twisting cracks (usually of considerable depth compared with their height), holes, tubes etc. The ELA is not claimed to represent reality but refers only to an assumed sharp-edged orifice. As long as the rest of the numerical model makes the same assumption about C_{d}, then there should be no problem but care must be taken when comparing models from different countries, e.g. American and Swedish models use a value of C_{d} of 1.0 whilst Canadian models use 0.6.

3. Stationary vehicles

3.1. Leakage measurements

Volume flow rate/pressure differential measurements were made on 5 vehicles which are briefly described in Table 1. Although vehicles C and D were of similar size and design, they were manufactured by different companies. The measurement technique consisted of replacing a window of the vehicle by a hardboard panel, sealed to the bodywork, with a connection to a variable speed fan. The volume flow rate into or out of the vehicle was measured using an orifice plate, for pressure differentials of up to 55 Pa which were measured on a digital micromanometer. Fig. 1 shows data for vehicle B plotted logarithmically for both pressurisation and depressurisation. Vehicles were tested with all windows fully closed both with all vents open and with them closed. Under conditions of depressurisation a vehicle’s doors would be pulled onto rubber seals making the vehicle “tighter” whilst under pressurisation the opposite

Table 1
Vehicle description

Vehicle	Description
A	Estate car; 4 doors plus rear hatch; 1.5 years old (Renault 21, Savana)
B	Small saloon car; 2 doors plus rear hatch; 3 years old (Nissan Micra)
C	Transit van (1); 2 front doors plus 1 double rear door plus 1 sliding side door; 1.5 years old (Renault Master)
D	Transit van (2); 2 front doors plus 1 double rear door plus 1 sliding side door; 3.5 years old (Ford Transit)
E	Crew bus; 2 front doors, 1 double rear door plus 2 sliding windows; 4.5 years old (Ford Transit)

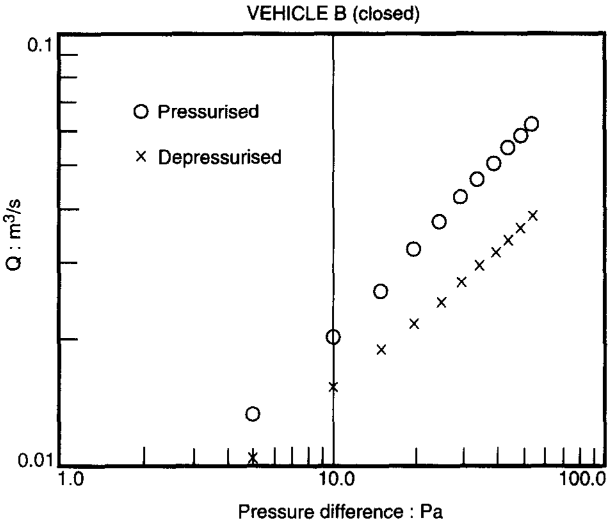

Fig. 1. Variation of leakage rate with pressure difference.

would occur. As expected the flow rate at a given pressure difference is therefore higher for pressurisation than for depressurisation although there is no evidence of the "flapping" mentioned above (which would have shown up as a change in the gradient in the flow/pressure plot). Table 2 summarises the data for all 5 vehicles and includes the ELAs evaluated at the usual reference pressure difference of 4 Pa. Values of the flow exponent, n tended to be higher for the pressurised than the depressurised vehicles but the value was fairly constant, especially for the depressurised cases. For vehicles A, B and C the vents accounted for between 30–40% of the ELA whilst for D and E the values were 11 and 18% respectively. This is reflected in the closeness in the values of the flow coefficients for D and E.

Table 2
Vehicle flow characteristics

Vehicle	Flow characteristics	Pressurised		Depressurised	
		Vents open	Vents closed	Vents open	Vents closed
A	C (m^3 s^{-1} at 1 Pa)	1.0×10^{-2}	0.64×10^{-2}	0.88×10^{-2}	0.52×10^{-2}
	n	0.61	0.67	0.56	0.58
	ELA[a] (m^2)	150×10^{-4}	104×10^{-4}	124×10^{-4}	75×10^{-4}
B	C	0.71×10^{-2}	0.46×10^{-2}	0.74×10^{-2}	0.45×10^{-2}
	n	0.62	0.65	0.54	0.53
	ELA[a]	108×10^{-4}	73×10^{-4}	101×10^{-4}	60×10^{-4}
C	C	1.9×10^{-2}	1.1×10^{-2}	1.8×10^{-2}	1.2×10^{-2}
	n	0.55	0.59	0.58	0.58
	ELA[a]	276×10^{-4}	162×10^{-4}	265×10^{-4}	169×10^{-4}
D	C	2.0×10^{-2}	1.8×10^{-2}	1.9×10^{-2}	1.8×10^{-2}
	n	0.57	0.57	0.55	0.53
	ELA[a]	285×10^{-4}	255×10^{-4}	268×10^{-4}	241×10^{-4}
E	C	1.8×10^{-2}	1.6×10^{-2}	1.8×10^{-2}	1.6×10^{-2}
	n	0.56	0.56	0.54	0.53
	ELA[a]	245×10^{-4}	221×10^{-4}	238×10^{-4}	206×10^{-4}

[a] Evaluated at 4 Pa.

3.2. *Vehicle volumes*

The internal volume of vehicles A and E were estimated using a tracer gas method. A quantity of tracer gas (SF_6, sulphur hexafluoride) was released into the vehicle and mixed throughout its interior using a small fan. Air was passed through the vehicle at a known rate and the tracer gas concentration decay with time was measured using an infra-red gas analyser. Under these conditions the air change rate remains constant and the tracer gas concentration exhibits an exponential decay with time. Hence a natural log/linear plot of concentration/time will have a negative gradient which is equal to the number of air changes per hour (ACH). As the ventilating volume flow rate is known, the internal volume of the vehicle can be calculated. Values are given in Table 3 together with values estimated from the internal dimensions of the vehicles after allowing for seats etc.

All the measurements referred to above were carried out in an under-building car park so as to minimise any wind effects.

3.3. *Air change rate measurements*

Measurements of air change rates were made on two of the vehicles, A and B, parked in the open on an exposed site. Wind speed and direction were measured

Table 3

Vehicle	External dimensions (m)			Volume (m^3)	
	Length	Height	Width	Decay method	Measured
A	4.55	1.22	1.58	3.69	3.51
B	3.56	1.22	1.52		2.42
C	5.28	2.03	1.98		13.78
D	5.27	1.95	1.90		10.09
E	4.46	1.70	1.90	8.53	7.68

continuously throughout each test at a distance of approximately 3 m from the vehicle and at a height of 1.2 m; temperatures were measured both inside and outside the vehicle. The vehicle vents were either in the fully open or fully closed positions throughout a test.

Tracer gas was mixed with the air in the vehicle and its concentration was measured as it decayed with time as a consequence of the infiltration of air into the vehicle. From the concentration/time relationship, the ACH could then be calculated.

Fig. 2 shows the data for vehicle A with the vents closed. The log of the ACH is plotted against the wind speed (V_s) in $m\,s^{-1}$. The data has been grouped for wind direction. Wind direction has been taken as being from the "front" when it was within ±45° of the forward direction of the vehicle; similarly for the "rear" cases. No discernible difference was found between the "front" and "rear" cases and the data has been plotted under one symbol. The results for the remaining two quadrants have been combined as "side"; for vehicles A and B, the sides were identical. This may not be true for vehicles where, for example, the greater part of one side is a sliding door although the results for the front and rear suggest otherwise. Although there will be some smearing of the data, due to the way in which wind direction is specified, it can be seen from Fig. 2 that the wind from the "side" induces a significantly higher air infiltration rate than when from the "front" or "rear". A linear regression applied to the log/log data shows that the number of air changes per hour varies as $V_s^{1.05}$ and $V_s^{1.21}$ respectively. Fig. 3 shows results for vehicle B presented in a similar manner. Not only can the features noted above be discerned, but the results for vehicles A and B are very close together. The ACH varies as $V_s^{1.15}$ and $V_s^{1.33}$ for the side and front/rear respectively. Fig. 4 shows the results of measurements on vehicle A with the vents open. In this case the direction of the wind relative to the car has no noticeable effect and the air change rate is, as would be expected, higher than in the "closed" case. The ACH varies as $V_s^{1.27}$. Although temperature differences between the car interior and the exterior varied by up to about 20 °C, no appreciable effect on ACH was noted.

3.4. Evaluation

As no significant effect of temperature difference was noted, the infiltration rate into a given vehicle has been taken to depend only on wind effects. The pressure difference

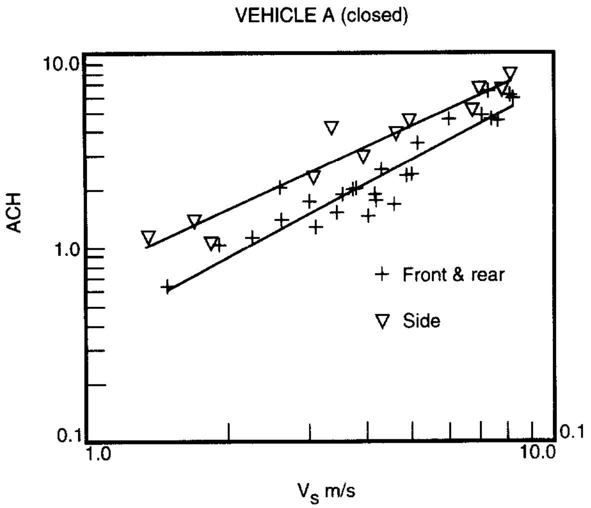

Fig. 2. Variation of ACH with wind speed.

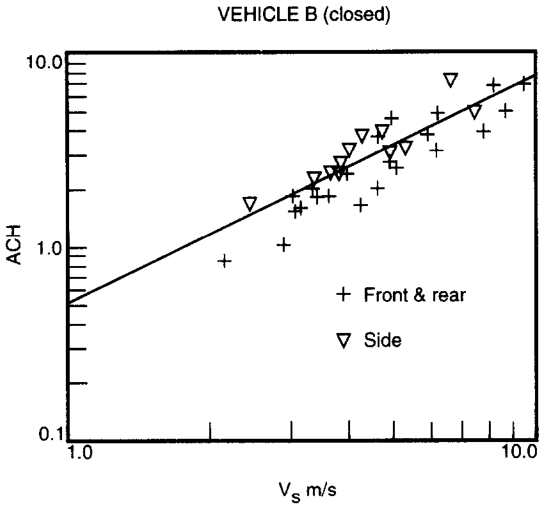

Fig. 3. Variation of ACH with wind speed.

Δp is then given by

$$\Delta p = \tfrac{1}{2}\, C_{\mathrm{p}} \rho V_{\mathrm{s}}^2$$

where C_{p} is a pressure coefficient. If the vehicle was shielded, for example by other vehicles, this could be taken into account in the choice of the pressure coefficient. Using Eq. (1) gives

$$Q = C C_{\mathrm{p}}^n \left(\frac{\rho}{2}\right)^n V_{\mathrm{s}}^{2n}.$$

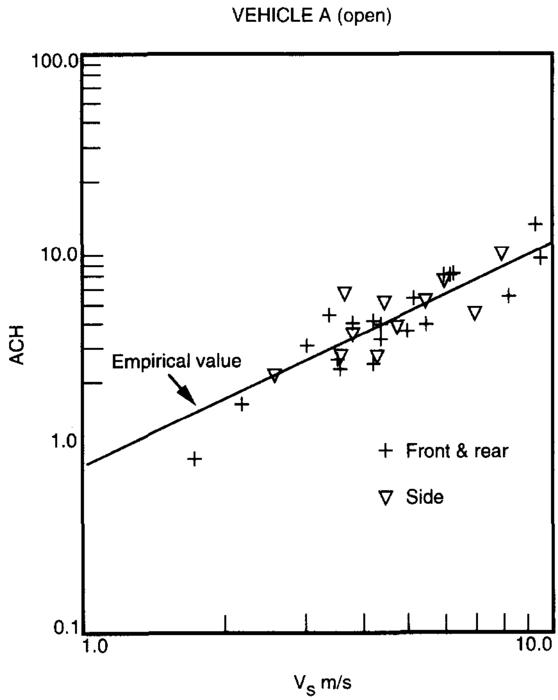

Fig. 4. Variation of ACH with wind speed.

If C_p^n is taken to be a constant, K, then:

$$Q = CK\left(\frac{\rho}{2}\right)^n V_s^{2n} \,. \tag{4}$$

The ACH is then found by multiplying Eq. (4) by [3600/volume of the vehicle]. Values of C and n are known for the five vehicles from the pressurisation/depressurisation tests (Table 2). Because during natural ventilation by the wind the inlet leakage sites will be pressurised and the outlets depressurised, the value of K was evaluated using the data obtained for vehicle A with the vents closed, taking C and n to be the means of the respective pressurisation and depressurisation values. This gave K (as a round value) as 0.1. Eq. (4) then becomes

$$Q = 0.1C\left(\frac{\rho}{2}\right)^n V_s^{2n}. \tag{5}$$

Putting the values of C and n found for vehicle A with the vents open into Eq. (5) and using the measured volume of the vehicle (Table 3), the variation of the ACH with time can be calculated; this has been added to Fig. 4 and shows a good fit with the data. (The value of the exponent of V_s is 1.18 compared with that of 1.27 from the fitted data.) Similarly using the leakage characteristics and volume of vehicle B with the vents in the closed position, the variation of the air change rate with wind speed ($V_s^{1.18}$) has been calculated and is shown on Fig. 3. Again the fit with the data is good.

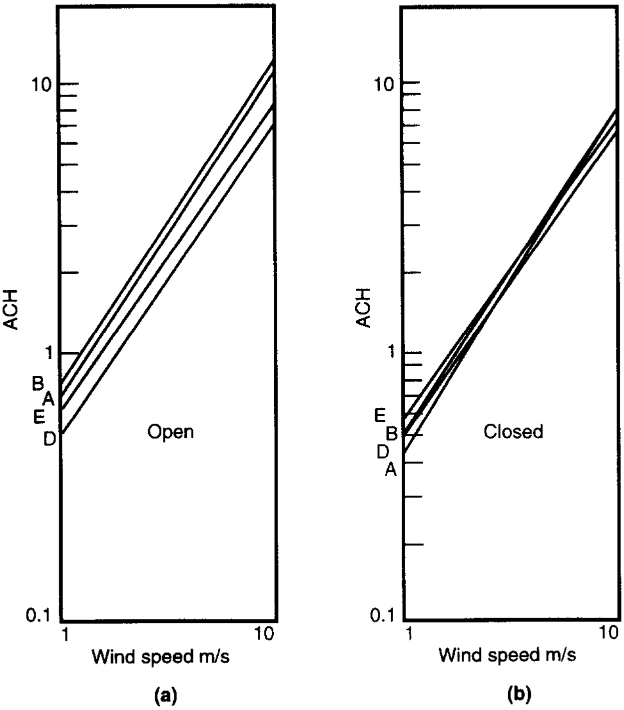

Fig. 5. Empirical ACH.

3.5. Discussion

Figs. 5(a) and (b) show the predicted variation of air changes per hour with wind speed for some of the vehicles under open and closed conditions respectively. These values have been calculated using Eq. (5) with the data from the pressurisation/depressurisation tests and the vehicles' internal volumes. As would be expected, the ACHs in the "closed" cases are lower than the "open" values. There is not a great amount of spread in the air change rates at any given wind speed; in the "closed" case they are remarkably close and the scatter on experimental results would outweigh the variation between vehicles. The significance of the air exchange rate can be seen if we consider a vehicle at rest in a gas cloud of a constant concentration c_0. The concentration (c) in the vehicle will increase exponentially with time (t in hours) according to the relationship

$$\frac{c}{c_0} = 1 - \mathrm{e}^{-\mathrm{ACH}t}.$$

Table 4 shows values of c/c_0 calculated using this equation for a range of air change rates and times.

Table 4
Variation of concentration with ACH and time

Time hours	C/C_0			
	1 ACH	2 ACH	5 ACH	10 ACH
0	0	0	0	0
0.25	0.22	0.39	0.71	0.92
0.5	0.39	0.63	0.92	0.99
0.75	0.53	0.78	0.98	1
1	0.63	0.86	0.99	1

4. Moving vehicle

4.1. Experimental method

The vehicle used in these tests was estate car which had been used in the earlier part of the investigation (vehicle A). The method used to measure the air change rate was to fill the vehicle with a tracer gas and to monitor the concentration decay as the vehicle was driven at a steady speed with all the air vents in the closed position. The tracer gas used was sulpur hexafluoride at an initial concentration of about 15 ppm. The concentration was measured by a battery operated electron-capture gas analyser which had been calibrated previously. Data from the tests, which typically lasted for about four minutes, were stored on a data logger for subsequent analysis. A relatively straight, open road was chosen for the tests, where steady speeds of between 35 mph (15.6 $\mathrm{m\,s^{-1}}$) and 70 mph (31.3 $\mathrm{m\,s^{-1}}$) could be maintained for the duration of each test. The traffic load on the road was very light. This could have been important, especially at low speeds, when the effect of other vehicles overtaking could have created large disturbances; tests under these conditions were avoided. Measurements were made at 10 s intervals at the lower speeds and 5 s intervals at the higher speeds. Tests were carried out under dry weather conditions when the mean wind speed did not exceed 4 $\mathrm{m\,s^{-1}}$ and measurements were made on passes along the road in both directions to minimise any effect of the ambient windspeed.

4.2. Results

From a log/linear plot of the concentration inside the vehicle against time, the number of air changes per hour could be calculated. No effect of the direction of the vehicle pass along the road could be detected; values were plotted together against the corresponding vehicle speed (V_{m} $\mathrm{m\,s^{-1}}$) and the results are shown in Fig. 6. From a least squares fit of the data, the ACH was found to vary with $V_{\mathrm{m}}^{1.27}$ with of the order of 40 ACH being produced by a vehicle speed of 30 $\mathrm{m\,s^{-1}}$. The standard error on the value of the exponent was 0.096.

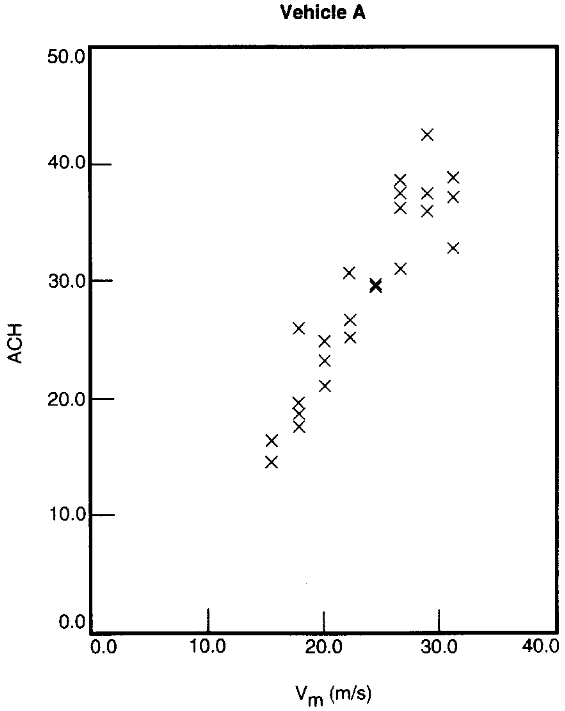

Fig. 6. Variation of ACH with vehicle speed.

The case of a vehicle moving in relatively still air is not fully physically comparable with that of a stationary vehicle in a moving air stream. There are a number of differences. With the vehicle moving (i) there is relative movement between the floor of the vehicle and the ground. The airflow in this region will in general be greater than when the vehicle is stationary; (ii) due to the engine cooling fan there may be an increased airflow around the vehicle bulkhead. Both of these factors could be expected to increase the ACH for any given relative vehicle/wind speed. Nevertheless the situations are sufficiently close to warrant a comparison of the corresponding sets of data. The results for the moving vehicle have therefore been compared with those for the same vehicle parked on an open site, with all vents closed, and exposed to a wind at an angle of between ±45° to the front or rear of the vehicle. Analysis of the data had shown the ACH to vary with $V_s^{1.21}$ where the wind speed, V_s, lay in the approximate range 1.5–9.5 $\mathrm{m\,s^{-1}}$. The value of the exponent had a standard error of 0.094. From the leakage characteristics of the vehicle, the ACH had been predicted to vary as $V^{1.25}$. These values compare very favourably with that of $V_m^{1.27}$ found above.

4.3. Analysis of data

Fig. 7 shows the data from both sets of experiments plotted together. Although the two sets of data do not overlap, there are sufficient similarities to make one suppose

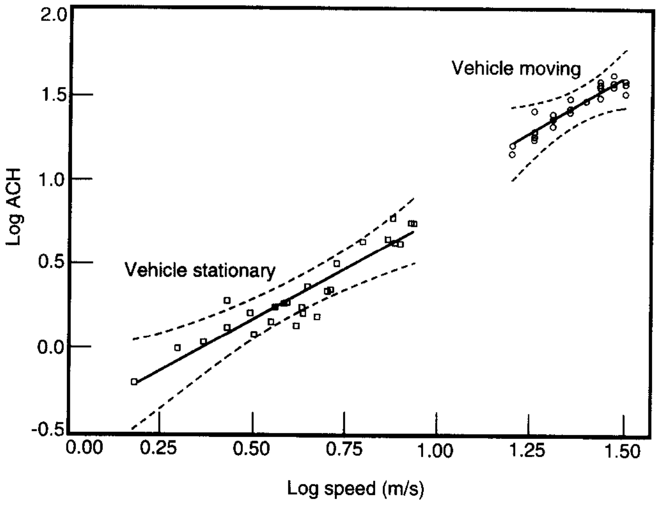

Fig. 7. Variation of ACH with relative vehicle/wind speed.

that they may belong to the same data set. Also shown are straight line fits to the log/log values of each data set taken separately, with the 95% confidence limits allowing for a 20% scatter in the data due to errors from all sources e.g. variation in wind direction, variation of wind speed during a test, reading errors etc. Most of the data lie within these limits. If we assume therefore that it can be fitted by this means we would have

$$\log(\text{ACH}) = \alpha_s + \beta_s \log V_s$$

and

$$\log(\text{ACH}) = \alpha_m + \beta_m \log V_m,$$

where α_s and α_m are constants [intercepts on the log(ACH) axis], and β_s and β_m are the exponents. A formal analysis of the data was carried out by applying the method of constrained least squares [6]. Four hypothesis were tested, viz.

H_0: (i.e. different intercepts, different slopes),
H_1: (i.e. different intercepts, same slope),
H_2: (i.e. same intercept, different slopes),
H_3: (i.e. same intercept, same slope).

and the results are shown in Table 5.

It can be seen from Table 5 that there is little increase in the residual sum of squares (RSS) as one moves from H_0 to H_1 and H_2. Although there is an increase in the RSS between H_0 and H_3, reference to tables of the F-test [7] shows that the increase is not significant at the 90% level. Of the four hypotheses H_1 is the most attractive both on physical grounds and as a predictive tool. The air change rate in a vehicle is driven by pressure differences, which will result from the difference in the relative speed between

Table 5
Residual sum of squares (RSS)

	α_s	β_s	α_m	β_m	RSS
H_0	– 0.426	1.21	– 0.295	1.27	0.264
H_1	– 0.434	1.22	– 0.226	1.22	0.265
H_2	– 0.421	1.20	– 0.421	1.36	0.226
H_3	– 0.573	1.46	– 0.573	1.46	0.349

the air and the vehicle. This would be in favour of the slopes being the same. For the reasons outlined above the air change rate could be expected to be substantially higher for the moving vehicle; this would lead to different intercepts on the ACH axis with $\alpha_m > \alpha_s$, as is the case with hypothesis H_1. From the point of view of predicting air change rates in moving vehicles, it has been shown that, for a stationary vehicle, the variation of air change rate with wind speed could be predicted from measurements of the leakage characteristics of the vehicle i.e. a flow coefficient (C) and exponent (n). In general the volume flow rate, Q, into the vehicles was given by

$$Q = 0.1C\left(\frac{\rho}{2}\right)^n V^{2n}$$

where ρ is the density of air. In this case, the air change rate for this vehicle when stationary, (ACH_s), was given by

$$ACH_s = 0.43V_s^{1.24}.$$

For the moving vehicle the air change rate (ACH_m) is approximately 40% higher i.e.

$$ACH_m = 0.6V_s^{1.24}.$$

For the purpose of assessing the vehicle's value as a shelter these formulae give conservative values.

5. Conclusions

(i) Leakage characteristics of five vehicles have been measured for both positive and negative pressures with the vehicle vents open and closed; no evidence of "flapping" was found.

(ii) Temperature difference (i.e. the stack effect) was found to have a negligible effect.

(iii) Measurement of the variation of air change rate with wind speed on one vehicle enabled a constant to be evaluated whereby the infiltration rate can be found in terms of leakage characteristics and wind conditions.

(iv) Predicted air change rates under different vent conditions and for another vehicle were good.

(v) Predicted air change rates can be used to estimate the build-up of a contaminant infiltrating into a vehicle.

(vi) Measurements of the variation of air change rate (ACH) with speed in a vehicle moving at between 15–32 m/s show that it is similar to that of a stationary vehicle due to the wind speed.

(vii) Although the variations are very similar, a higher ACH is found for the moving vehicle.

(viii) The ACH in a stationary vehicle can be predicted from the leakage characteristics of the vehicle; the ACH in the moving vehicle was about 40% higher than the value which would be predicted at the same vehicle/wind relative speed for the stationary vehicle.

Acknowledgement

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