

Particle penetration into the automotive interior

I. Influence of vehicle speed and ventilatory mode

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Penetration of particulate aeroallergens into the interiors of two, new, similar Chrysler Corporation passenger vehicles (having no evidence of intrinsic microbial contamination) was studied on a large circular test track during periods of high pollen and spore prevalence. Impactor collections were obtained at front and rear seat points and at the track center during periods with (1) windows and vents closed and air conditioning on, (2) windows closed, vents open, and no air conditioning, and (3) air conditioner off, front windows open, and vents closed. These conditions were examined sequentially during travel at 40, 50, 60, and 80 kph. Particle recoveries within the two, new, similar Chrysler Corporation passenger vehicles did not vary with the speed of travel, either overall or with regard to each of the three ventilatory modalities. In addition, collections at front and rear seat sampling points were comparable. Highest interior aeroallergen levels were recorded with WO, and yet, these levels averaged only half the concurrent outside concentrations at track center. Recoveries within the cars were well below recoveries obtained outside when windows were closed (both VO and AC modes). These findings suggest window ventilation as an overriding factor determining particle ingress into moving vehicles. Efforts to delineate additional determinants of exposure by direct sampling are feasible and would appear essential in formulating realistic strategies of avoidance. (J ALLERGY CLIN IMMUNOL 1991;87:581-5.)

The progressive growth of vehicle numbers and of distances driven (e.g., 1.43 trillion personal passenger vehicle miles driven in the United States in 1988)¹ are prominent features of contemporary life in developed countries. Because of these related trends, and the congested roadways that naturally result, time spent in motor vehicles has risen steadily for large demographic groups.

Many subjects with inhalant allergy report variations in symptom severity during and after automobile travel. Commonly, heightened distress is described

Abbreviations used

AC: Air conditioner on, vents and windows closed

VO: Air conditioner off, vents open, windows closed

WO: Air conditioner off, vents closed, windows open

RPM: Revolutions per minute

kph: Kilometers per hour

and attributed to an (assumed) increased exposure potential in moving, naturally ventilated cars. Such complaints often are remedied by window closure and use of onboard air conditioner. However, mechanical cooling units also have been indicated as sources of bioactive microbial particles and/or volatiles, which may determine symptoms in occasional vehicles.²

Effects on exposure to airborne allergens of factors such as ventilation regimen, seating position, and vehicle speed are fundamental to the development of realistic strategies for automobile travel by sensitive subjects. Since there are essentially no data describing the influx of bioaerosols in this setting, we have stud-

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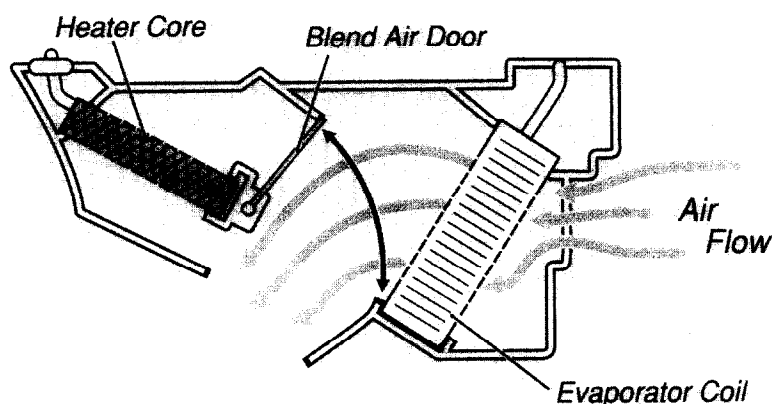


FIG. 1. "Blend-air" ventilation system demonstrating the airflow pattern during AC and VO operation when the dashboard-mounted air-temperature control lever (which moves the blend-air door) is set at "cool." As this lever is moved further toward "warm," the blend-air door opens (i.e., moves clockwise, as illustrated by the *solid arrow*), allowing more air to pass through the heater core. During "vent" and "heater" operation, no coolant flows through the evaporator coil. (Drawing modified from Chrysler Corp., 1979.)

TABLE I. Number of trials by speed, ventilatory mode, and automobile model

	Ventilatory mode		
	AC	VO	WO
Speed (kph)*			
40	9	9	9
50†	2	2	2
60	7	7	16
80	8	8	17
Model			
Omni	4	4	4
Reliant	22	22	40

*Both vehicles.

†Not used in speed comparisons.

ied several exposure determinants under precisely defined conditions.

METHODS

All studies were performed on a circular, paved test track, 426.7m (1400 feet) in diameter, at the Chelsea Proving Grounds of Chrysler Corporation. This site is in a rural, substantially agricultural area about 20 miles west-southwest of Ann Arbor, Mich. Immediately upwind of the track are open areas of scrub growth as well as oak and hickory forest. The center of the track is covered by grasses and weeds that are mowed periodically.

New (odometer reading, <1000 miles) cars were kindly provided by the Chrysler Corporation: a 4-door Dodge Omni for the initial sampling series and a 4-door Plymouth Reliant for investigations in the following year. The positions of the four air output (supply) vents on the dashboards of the two models were very similar. Both cars were equipped with identical factory-installed air conditioner evaporator/heater systems with the "blend-air reheat" principle,^{3,4} the most common system in American-made automobiles. In this arrangement, all ventilation-system air passes through the air conditioner evaporator coil and, depending on the position of the "blend-air" door that is controlled by a dashboard-mounted, air-temperature control lever, all, some, or none of this air also passes through the heater core (Fig. 1). It is notable that, during vent operation, air passes over the air conditioner evaporator coil of this system, although the compressor is off and no coolant is circulating.

Particle prevalence was measured with two aeroallergen model Rotorod samplers (Sampling Technologies, Inc., Los Altos Hills, Calif.) without rain shields, operated from the cigarette lighter of each vehicle with a 12 V to 120 V power inverter. One sampler was placed consistently on the front (right) passenger seat and one sampler on the left side of the back seat. A wooden support elevated each sampler to approximately "nose level," 32 inches (81 cm) above the seat. During each trial, a separate, continuous air sample was collected at the geometric center of the track at a height of 40 inches (1.03 m) with a portable 12 V Rotorod sampler powered by two 6 V lantern batteries. A stroboscopic tachometer was used periodically throughout the study to con-

TABLE II. Comparison of particle concentration* by location and ventilatory mode

Mode	Location		
	Front seat	Back seat	Outside (track center)
AC (N = 26)	62 (25-1531)	75 (25-226)	2301 (653-8110)
VO (N = 26)	80 (25-255)	75 (21-271)	2600 (432-15668)
WO (N = 44)	1342 (414-4355)	1455 (470-4508)	2704 (851-8610)

*Geometric mean (± 1 SD) of particles per cubic meter.

firm the rotational speed of all Rotorod sampling heads. The 12 V (outdoor) sampler operated at 2280 (± 20) RPM, and the 120 V units (in the vehicle) both ran at 2340 (± 20) RPM, all slightly less than the manufacturer's specification of 2400 RPM.

For each trial, before sampler turn-on, the vehicle was driven one "equilibration" lap around the track (i.e., approximately 1.34 km or 0.83 miles) with the proper components engaged for the defined ventilation mode to be studied. There followed either 5 or 10 minutes of driving at one of four fixed speeds with all samplers operating. Samples were collected with a defined sequence of ventilation modes: (1) air conditioner on, vents and windows closed (AC), (2) air conditioner off, vents open, and windows closed (VO), and (3) air conditioner off, vents closed, and all windows wide open (WO). Trials of these ventilatory modes were carried out at 40, 50, 60, and 80 kph in both clockwise and counterclockwise directions. The number of trials with each speed, ventilatory mode, and automobile model are listed in Table I. The two 50 kph trials were not included in speed comparisons. All trials were done between 10 AM and 4 PM on days without precipitation during the local growing season (namely, May through September).

After exposure, one rotorod of each exposed pair was mounted in a clear acrylic microscope stage adapter (Sampling Technologies, Inc.) and stained with Calberla's solution⁵ for microscopic analysis. All recognizable pollen and fungus spores (referred to as total "particles") were identified and counted at a magnification of $\times 312.5$ with a Zeiss (Carl Zeiss, Inc., Thornwood, N.Y.) light microscope. For analysis of particle size-related effects, basidiospores (all 10 μm or less in diameter) were analyzed separately from other fungus spores. With the exposed rod area, sampling-head circle of rotation, RPMs, and exposure time, particle counts were converted to particles recovered per cubic meter of air processed. Trials were deleted from the study if the sampling surface of the outdoor Rotorod presented <40 particles on its sampling surface (approximately 170 particles per cubic meter of air).

All data were log transformed before analysis to approximate more closely a normal distribution. Spearman's rank correlation was used to test the independence of concurrently determined inside-outside as well as front seat-back seat

particle levels. The Wilcoxon signed-rank test was used to make inside-outside comparisons for each ventilation mode and also for front seat-back seat comparisons. Kruskal-Wallis one-way analysis of variance or, when the grouping variable had only two categories, the Mann-Whitney U test was used to evaluate differences between ratios of particle recoveries (potentially varying with ventilation mode and vehicle speed) in the vehicle to particle recoveries outside the vehicle.

RESULTS

Particle level comparisons by vehicular speed and sampler location

With the ratios of particles recovered in the front and back seats to ratios at the center of the track as a primary variable, vehicle speed within the range studied did not appear to systematically influence bioaerosol penetration into the test vehicles. After noting the lack of speed-related differences, data from trials based on different speeds were combined for additional investigations focused on modes of ventilation.

Front seat and back seat total particle concentrations were strongly correlated during trials of each ventilation mode ($r^2 > 0.76$ for all modes), and geometric mean particle levels did not differ between front seat and back (Table II). However, the front seat was slightly more likely to yield higher recoveries in paired comparisons for AC and WO modes ($p = 0.096$ and 0.088 , respectively). Therefore, front and back seat data were analyzed separately.

Inside-outside particle level comparisons

Inside-outside particle levels were most strongly correlated during WO trials ($r^2 = 0.808$) with lower but significant positive correlations for VO ($r^2 = 0.696$) and AC trials ($r^2 = 0.534$). (Data are provided for front seat only; back seat correlations were similar.) Particle levels measured inside the vehicle were always lower than levels outside for AC

and VO trials, and for all but three of 44 (front seat) and four of 44 (back seat) WO trials.

Ventilation mode comparison

AC and VO trials were not different with respect to either front seat/outside or back seat/outside particle concentration ratios ($p = 0.46$ and 0.87 , respectively). Since particle recoveries during these ventilation modes were very similar (Table II), they were combined, designated as "window closed" trials, and compared with WO trials. Data pooled in this way demonstrated that inside-outside particle ratios were significantly lower during window closed (namely, AC and VO) trials than during WO trials ($p < 0.001$).

Particle size considerations

For a subset of the data, basidiospores (all $<10 \mu\text{m}$), total spores, and pollen (all $>15 \mu\text{m}$) recovered on Rotorods were separately analyzed with respect to effects of speed, location (front seat, back seat, or track center), and ventilatory mode on particle concentrations. Results did not differ among these particle categories or between any single category and the total particle results presented above.

DISCUSSION

Although driving in a relatively small circle at fixed speeds for 10-minute intervals differs from most "normal" automobile travel, it did allow ambient particle concentrations, always measured within a reasonable distance of the automobile, to be related to concurrent conditions inside the vehicle. The circular path travelled also effectively excluded differences in wind direction among the trials as a factor influencing particle penetration. Furthermore, the site and format of this study allowed the maintenance of predetermined, specific speeds without compromising safety. Driving conditions also differed from conditions normally encountered, since no other vehicles were present as sources of air turbulence around the test vehicles. Such disturbances undoubtedly affect airflow patterns near the automotive air intakes and also serve to entrain (and refloat) spores and pollen that are produced (or have settled) by the roadside.

The vehicle speeds studied reflected speeds commonly maintained and legally acceptable for urban and suburban driving. Over the range selected, speed of travel had no evident effect on particle penetration, although further extremes (e.g., <30 or >90 kph) might yet produce discernable differences. In theory, as vehicle speed increases, *relative* particle inertia also will increase, making pollen and spores more likely to follow the airstream *past* (and thereby avoid) automobile air intakes (e.g., intake cowls or open win-

dows). Possibly opposing this particle inertia-based effect, larger volumes of air passing through the vehicle and greater resulting turbulence at higher speeds might increase the total number of particles available for capture if eddies limited exfiltration or prevented deposition on interior surfaces. However, actual concentrations would not be expected to rise if air and entrained particles left the vehicle at essentially the same increased rate at which they entered.

Although a few older automobile models have small vents near the rear doors that allow passenger compartment air to escape, newer automobiles (including automobiles used in these tests) depend on small cracks and openings for exhaust of ventilation air. With the ventilation system on and all windows closed, the effects of speed on airflow rates is probably relatively small. Even a limited window opening might be expected to greatly increase ventilation rates.

Operating differences between the two interior samplers were carefully excluded; rotation speed and height were equal. The units also had been compared earlier⁶ with respect to both intrasampler (between rods) and intersampler differences, which were random and averaged $<15\%$. Ogden et al.⁷ described slight differences in pollen recovery by rotoslides⁷ and Rotorods⁸ between 0 and 10 mph ambient wind speeds. We have been unable to document such differences with our equipment. Although front/back seat airspeed differences might have occurred, it is unlikely that the differences would have had a noticeable effect on sampling efficiency.

Samples were not collected in the driver's seat position, since a vehicle operator, necessarily, was always present. The bluff shape of this occupant also may have caused spatial differences in particle concentrations between the two in-car sampling points. However, effects of occupants on particle distribution were not additionally addressed in this initial study. At the present time, it must be assumed that particle levels in the front seat "passenger" position best reflect levels behind the steering wheel, given the bilateral symmetry of vehicle outline and of the sources of interior ventilation. Side-to-side differences would almost certainly occur if right and left windows were opened unequally.

The efficiency of particle entry into the automobiles may have varied, depending, in part, on aerosol size. We found no evidence of differential penetration between small ($<10 \mu\text{m}$) basidiospores and large ($>14 \mu\text{m}$) pollen grains. However, as collection efficiency of the Rotorod sampler becomes quite low for small particles (i.e., about 55% at $15 \mu\text{m}$ and $<5\%$ at $5 \mu\text{m}$),⁹ exhaustive comparisons by particle diameter were not feasible.

In general, particle types recovered within the au-

tomobiles were the same as types observed on track-center samples. This observation, as well as the close association between particle levels within the automobile and levels concurrently present outside, even during AC and VO modes of operation, strongly suggests outdoor air as the main source of particles recovered in the vehicle interior. This inference was supported especially by the WO trials, which demonstrated a very strong inside-outside correlation. An alternative source of bioaerosols within vehicles is microbial contamination of air intake ducts and air conditioner surfaces.² We sought to exclude this effect by using "new" automobiles and by driving an "equilibration" lap before beginning each sampling interval. This strategy reflected our own (unpublished) data, from several dozen vehicles, suggesting that, where fungus spore output from auto air conditioners occurs, it is largely as an initial 1- to 3-minute "burst" rather than as sustained emission. The extremely low fungus-spore levels encountered in our studies during ventilation-system operation argue against a significant contribution from cooling-coil contamination.

Although lower particle levels than levels in outside air were not unexpected in the "window closed" trials (namely, AC and VO sequences), interior concentrations tended to fall well below concentrations at track center, even with WO. It is possible that particle momentum, relative to vehicle speed, restricted the entry, especially of larger particles that would have tended to follow airflow past the side windows. Based on comments by pollen-sensitive patients, however, this WO particle reduction is not generally perceived as lessening symptoms, although clinical relief during automobile air conditioner operation often is gratifying. This apparent inconsistency may simply indicate the lack of a substantive, dose-response relationship affecting symptom severity in the prevalence ranges occurring within and outside *naturally* ventilated vehicles. In addition, allergen dosing to mucous surfaces, especially the conjunctivae, may rise with the high incident airflow and jet effects that prevail during high-speed travel with WO. The same aerodynamic factors also might augment symptom severity by stimulation of upper airway "irritant" receptors that remain poorly characterized.

The similarity of particle levels in AC and VO trials may indicate comparably low bioaerosol penetration but could have reflected the sequence of ven-

tilation modes used. VO trials always followed AC trials with a one-lap equilibration interval, and it is likely that the air conditioner coils were still moist. Since VO air also passed over these coils, some particles could have been intercepted and removed by the wet surfaces. Additional investigation will be required, therefore, before firm conclusions regarding particle penetration into vehicles during "vents open with windows closed" ventilation are possible.

Caution is also necessary in generalizing these results to other passenger vehicles, since different window and/or air intake designs, as well as details of exterior shape, may influence particle penetration into automotive interiors. It is likely that results might differ when small "vent" windows in various positions are used, windows partially open, or vents only in nonair-conditioned automobiles. The complexity of factors that may promote and/or limit particle ingress into cars leaves little basis for predictive models at this point. Therefore, we are continuing the empirical evaluation of key determinants.

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