Vacuum cleaner emissions as a source of indoor exposure to airborne particles and bacteria

SUPPORTING INFORMATION

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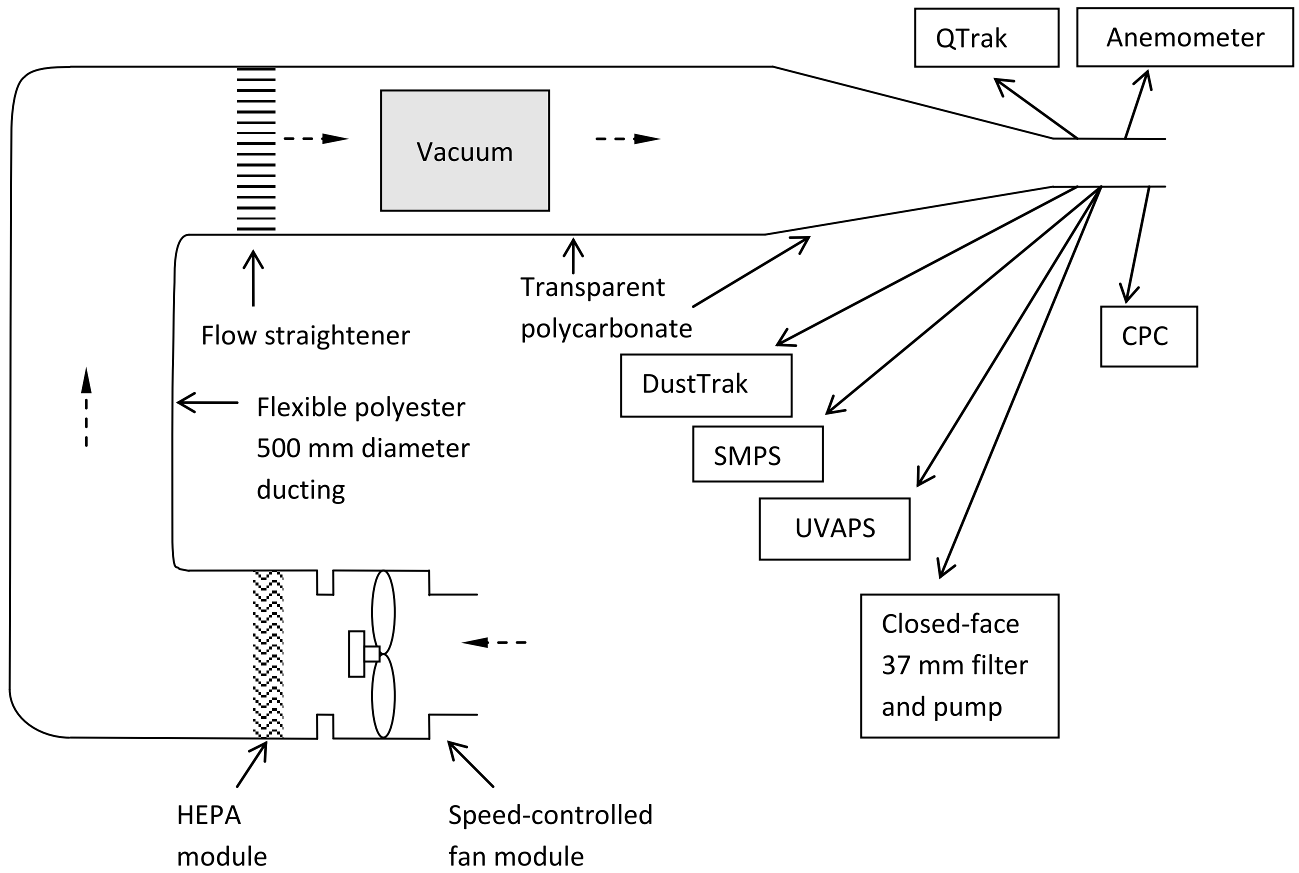

Figure S1. Experimental set-up for emission rate measurements.

Table S1. Characteristics of the 21 vacuums tested.

Vacuum #	Brand	Model	Motor Power (W)	Dust Collector[c]	Est. Dust Content (%)	Exhaust HEPA	Approx. Age (yrs)	Approx. New Price ($AUD)
1	AEG	Vampyr 7303	1400	DPB	25	N	12	300
2	Dyson	DC08	1400	PC	0	Y	8	800
3	Dyson	DC08	1400	PC	25	Y	8	800
4	Dyson	DC19	1400	PC	10	Y	4	800
5	Electrolux	Harmony Line Z3347	1600	DPB	65	Y	7	350
6	Electrolux	Z570[b]	-	PC	5	N	1	90
7	Hako	RocketVac[a]	1200	DPB	50	N	3	450
8	Hako	RocketVac XP[a]	1500	RFB	0	N	1.5	450
9	Hako	SuperVac[a]	1200	DPB	50	N	3	500
10	Hoover	Freespace TFS7182	1800	PC	25	Y	2	280
11	Hoover	Hygiene	2000	DPB	25	Y	5	500
12	iRobot	Roomba 530[b]	-	PC	5	N	2	300
13	Kambrook	Jaguar KBV30	1900	PC	5	N	3	150
14	Kambrook	Jaguar KBV50	1800	PC	50	N	1	150
15	Piranha	PetPal	1600	PC	15	N	3.5	225
16	Ryobi	VC20HD	1250	MD	0	N	0.5	75
17	Sanyo	SC53AB	1300	RFB	10	N	12	200
18	Sanyo	SC185R	1800	DPB	80	N	2	170
19	Sanyo	SCN500	1700	RFB	30	N	3	125
20	Volta	U228	1050	DPB	0	N	22	250
21	Volta	U229	1100	DPB	0	N	17	250

[a] Professional-grade model. [b] Battery-powered model. [c] DPB = Disposable Paper Bag, PC = Plastic Chamber, RFB = Reusable Fabric Bag, MD = Metal Drum.

Table S2. Spearman's rank correlation coefficients between bag dust bacteria content (bacteria g^{-1} dust) and bacteria emissions (bacteria min^{-1}) during cold and warm start measurements.

	Bag Dust Bacteria Content
Bacteria ER (Cold)	0.05
Bacteria ER (Warm)	-0.39

Table S3. Spearman's rank correlation coefficients between vacuum emissions and potential determinants during warm start tests. Numbers in bold indicate statistical significance at the 5% level (two-tailed).

	ER UFP	ER > 0.54 µm	ER $PM_{2.5}$	ER Bacteria	Mean CMD	Temp.	Price	Age
ER UFP	1							
ER > 0.54 µm	***0.79***	1						
ER $PM_{2.5}$	***0.84***	***0.90***	1					
ER Bacteria	-0.37	-0.14	-0.16	1				
Mean CMD	0.41	0.29	0.27	-0.55	1			
Temp.	0.09	-0.04	0.02	-0.01	-0.19	1		
Price	-0.31	***-0.47***	-0.39	0.31	-0.1	0.04	1	
Age	-0.27	-0.33	-0.40	0.52	***-0.58***	0.24	0.42	1

Table S4. Spearman's rank correlation coefficients between warm and cold start emission rates for each measured parameter. Numbers in bold indicate statistical significance at the 5% level (two-tailed).

	Cold/Warm Correlation
ER UFP	***0.96***
ER > 0.54 µm	***0.90***
ER $PM_{2.5}$	***0.80***
ER Bacteria	-0.06
Mean CMD	***0.49***
Temp.	0.47

Table S5. Ratio of mean emission rate with dust collector removed to dust collector in place.

Vacuum #	Brand	Model	Dust Collector[c]	ER UFP	Mean CMD	ER 0.54 - 20 µm	ER $PM_{2.5}$
1	AEG	Vampyr 7303	DPB	0.7	0.1	1.7	1.8
2	Dyson	DC08	PC	n.d.	n.d.	n.d.	n.d.
3	Dyson	DC08	PC	1.3	1.2	9.7	n.d.
4	Dyson	DC19	PC	1.1	0.6	1.5	0.6
5	Electrolux	Harmony Line Z3347	DPB	1.0	0.6	9.3	2.1
6	Electrolux	Z570[b]	PC	n.d.	n.d.	n.d.	n.d.
7	Hako	RocketVac[a]	DPB	n.d.	n.d.	n.d.	n.d.
8	Hako	RocketVac XP[a]	RFB	0.9	0.6	0.8	0.4
9	Hako	SuperVac[a]	DPB	0.4	0.7	0.5	n.d.
10	Hoover	Freespace TFS7182	PC	0.4	0.3	0.1	0.1
11	Hoover	Hygiene	DPB	n.d.	n.d.	n.d.	n.d.
12	iRobot	Roomba 530[b]	PC	n.d.	n.d.	n.d.	n.d.
13	Kambrook	Jaguar KBV30	PC	0.9	1.1	3.8	n.d.
14	Kambrook	Jaguar KBV50	PC	0.8	0.2	0.3	0.6
15	Piranha	PetPal	PC	1.8	0.5	2.1	n.d.
16	Ryobi	VC20HD	MD	0.9	1.4	1.5	1.9
17	Sanyo	SC53AB	RFB	6.4	1.0	33	12
18	Sanyo	SC185R	DPB	1.6	2.6	0.2	0.3
19	Sanyo	SCN500	RFB	2.0	0.9	3.7	1.6
20	Volta	U228	DPB	n.d.	n.d.	n.d.	n.d.
21	Volta	U229	DPB	n.d.	n.d.	n.d.	n.d.
		Median		1.0	0.7	1.6	1.1

[a] Professional-grade model. [b] Battery-powered model. [c] DPB = Disposable Paper Bag, PC = Plastic Chamber, RFB = Reusable Fabric Bag, MD = Metal Drum.

n.d. = no data

Particle sampling efficiency in the flow tunnel

The air velocity at the flow tunnel exit was set to 0.7 m s^{-1}, but varied between tests as a result of the particular vacuum being measured. It was therefore not possible to achieve isokinetic sampling, which is of relevance to larger particles rather than UFP. Accordingly, the deviation from isokinetic sampling (i.e. 100% aspiration efficiency) of particles in each of the size ranges measured by the DustTrak, UVAPS and closed-face filter was calculated.[1] The DustTrak exhibited negligible deviation from isokinetic aspiration of 2.5 µm particles during all measurements. The maximum aspiration efficiency of the UVAPS for a 20 µm particle during a single measurement was 140%, although efficiency was between approximately 97 and 103% during the large majority of measurements. The closed-face filter used for bacteria sampling collected with >90% efficiency for particles <4 µm, which decreased to 50% for 12 µm particles.

1. Hinds, W.C. *Aerosol Technology*; Wiley Interscience: New York, 1999.

Correction of TSI DustTrak data

The TSI DustTrak is a portable aerosol photometer that has consistently been shown to overestimate particle mass concentrations by a factor of 2-3 when used to measure indoor and outdoor air dominated by aerosols other than the standard test dust used for calibration by the manufacturer.[1] There was little to indicate whether the same might be true of vacuum emissions, therefore we performed a series of experiments to determine an appropriate correction factor for our measurements.

Instrumentation. A Thermo Scientific 1405-DF Tapered Element Oscillating Microbalance (TEOM) was used as the reference instrument with which to determine $PM_{2.5}$ mass concentration. Apart from being a standard method for measuring particle mass, the TEOM we employed had the additional advantage of being able to account for the presence of semi-volatile material in sampled particles. This was achieved by alternating every 6 minutes between measuring the total mass of airborne particles (base period) and any change of mass due to volatization in a filtered and cooled air flow (reference period).[2]

By default, the TEOM output a running 1 hour average $PM_{2.5}$ concentration every 6 minutes. As we required higher temporal resolution, we recorded the frequency of the element every 10 seconds. Following each switch from base to reference period and vice-versa, we excluded the first 100 seconds of data to allow stabilization of the element frequency.[4] We then used this data to calculate mass concentrations based on the change in frequency of the element and the known sample flow.[3,4] The average $PM_{2.5}$ concentration was determined by subtracting the reference period value from the prior and subsequent base period values.[2]

A TSI DustTrak was fitted with 2.5 µm inlet and set to record 10 second average $PM_{2.5}$ concentrations. It was zero-checked before and after the measurements and its time-stamp was synchronized with the TEOM. The DustTrak's data was used to calculate averages matched with those of the TEOM.

Experiments. The TEOM sampling head and support tripod were placed inside a 3 m^3 chamber. The main body of the TEOM was located immediately outside the chamber and a short length of conductive tubing was used to transport samples from the TEOM head. The DustTrak was installed in the chamber next to the TEOM head and sampled from the same height.

Three vacuums of the 21 we tested were used to assess the response of the DustTrak (#5, 13, and 15). Each test involved placing a vacuum inside the chamber and running it for approximately 15 minutes or until $PM_{2.5}$ concentrations stablized, during which the vacuum aspirated air from outside the chamber via a tube. This approach was adopted as initial tests indicated that concentrations remained low when the vacuum aspirated chamber air. Sampling continued until concentrations decayed to background levels, which took several hours. Vacuums #5 and 13 were each tested twice in this manner, while vacuum #15 was tested once.

Analysis. As we sought to determine an overall correction factor applicable to all vacuums measured in the study, we combined data from the 3 vacuums tested as part of the DustTrak calibration process. Paired average DustTrak and TEOM readings were calculated as described above. These were log-transformed to improve normality, and reduced major axis (RMA) regression was performed to determine the relationship between the instruments. This technique is more appropriate than standard ordinary least squares regression when applied to the response of air quality instruments, as it does not make the assumption of no error in the independent variable.[1] Figure S2 shows the results.

Correction factor. RMA regression fit the data reasonably well ($R^2 = 0.77$), and the line was described by the following equation that was used to correct the data:

$$\ln_{TEOM} = 0.86 \ln_{DustTrak} - 0.29 \quad (1)$$

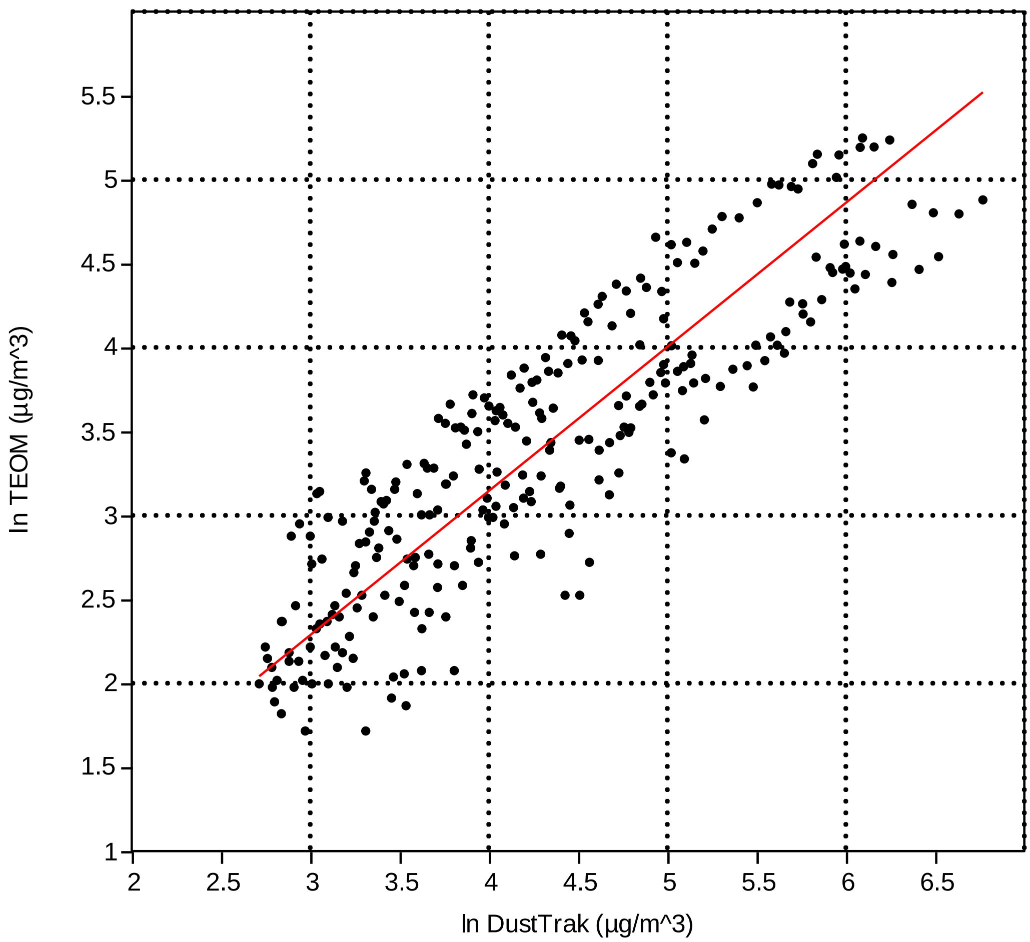

Figure S2. Reduced Major Axis regression through DustTrak and TEOM readings based on combined data from 3 vacuums. Slope: 0.85822, Int: -0.28775, $R^2 = 0.77$, $n = 264$.

Finally, it should be noted that due to the need for vacuums to aspirate ambient air during chamber tests and the subsequent effects on air exchange rate, it was not possible to achieve $PM_{2.5}$ concentrations as high as those measured during some flow tunnel tests, especially those of high emitting vacuums. While it is not ideal to extrapolate correction factors beyond the range on which they are based, in this case it represented a better option than the alternative of not correcting data at all.

1. Kingham, S.; Durand, M.; Aberkane, T.; Harrison, J.; Wilson, J.G.; Epton, M. Winter comparison of TEOM, MiniVol and DustTrak PM_{10} monitors in a woodsmoke environment. *Atmos. Environ.* **2006**, 40, 338-347.
2. Thermo Scientific. **2009**. TEOM 1405-DF Operating Guide.
3. Patashnick, H.; Rupprecht, G.; Ambs, J.L.; Meyer, M.B. Development of a reference standard for particulate matter mass in ambient air. *Aerosol Sci. Tech*. **2001**, 34, 42-45.
4. Asbach, C.; Kuhlbusch, T.A.J.; Fissan, H. Investigation on the gas particle separation efficiency of the gas particle partitioner. *Atmos Environ*. **2005**, 39, 7825-7835.