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ORIGINAL ARTICLE

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Exhaust ventilation in attached garages improves residential indoor air quality

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Abstract

Previous research has shown that indoor benzene levels in homes with attached garages are higher than homes without attached garages. Exhaust ventilation in attached garages is one possible intervention to reduce these concentrations. To evaluate the effectiveness of this intervention, a randomized crossover study was conducted in 33 Ottawa homes in winter 2014. VOCs including benzene, toluene, ethylbenzene, and xylenes, nitrogen dioxide, carbon monoxide, and air exchange rates were measured over four 48-hour periods when a garage exhaust fan was turned on or off. A blower door test conducted in each garage was used to determine the required exhaust fan flow rate to provide a depressurization of 5 Pa in each garage relative to the home. When corrected for ambient concentrations, the fan decreased geometric mean indoor benzene concentrations from 1.04 to 0.40 μg/m^3, or by 62% (P<.05). The garage exhaust fan also significantly reduced outdoor-corrected geometric mean indoor concentrations of other pollutants, including toluene (53%), ethylbenzene (47%), m,p-xylene (45%), o-xylene (43%), and carbon monoxide (23%) (P<.05) while having no impact on the home air exchange rate. This study provides evidence that mechanical exhaust ventilation in attached garages can reduce indoor concentrations of pollutants originating from within attached garages.

KEYWORDS
attached garages, BTEX, indoor air quality, infiltration, mechanical ventilation, residential intervention

1 | INTRODUCTION

Recent Canadian studies have shown that non-smoking, single-family homes with attached garages have higher indoor levels of certain air pollutants, including benzene, compared to homes without.[1–4] In these studies, homes with attached garages had indoor benzene concentrations that were 2.4–2.9 times higher than homes without attached garages, after adjusting for other factors. This is of concern given that approximately 61% of all Canadian dwellings have an attached garage[5] and that benzene is a known carcinogen.[6–8] In addition, even though few jurisdictions have developed indoor air guidelines for benzene, Health Canada (HC), the World Health Organisation (WHO), and the European Commission (EC) have all recommended that residential benzene levels be reduced as much as possible to minimize exposures.[9–11]

A 2014 unpublished Health Canada survey of products and equipment found in attached garages conducted across nine Canadian metropolitan areas found that homeowners generally use their garage to park vehicles and store material (e.g., fuels, automotive products, gas-powered equipment, and solvents). It has previously been shown that gasoline-powered vehicles and equipment, as well as some material

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stored in garages, may release pollutants during storage or when operated even briefly. These pollutants include carbon monoxide (CO), nitrogen dioxide (NO_2), and volatile organic compounds (VOCs), including the BTEX species (benzene, toluene, ethylbenzene, and xylenes).[12–16] Therefore, attached garages may contain many sources of pollutants that have the potential to cause adverse health effects in humans depending on pollutant concentrations and the duration of exposure.[10,17–19]

Transfer of air pollutants from attached garages into homes is fostered by leaks in the building envelope. This includes walls/ceilings shared by the garage and the home and/or the door leading into the garage from the home. Furthermore, air transfer is also promoted when there is a negative depressurization in the home relative to the garage. During winter, Canadian homes are often under a negative pressure with respect to their attached garage and the ambient air.[20] This negative pressure differential arises in part from the use of exhaust fans/mechanical ventilation systems in the home, which exhaust more air than they bring in and also from the "stack effect" where large indoor and outdoor temperature differences occurring in winter cause air to be drawn into the home at ground level and exhaust from the upper floors, much like a chimney.[21] A study by Graham et al.[21] found that the garage can contribute up to 16% of total indoor CO. Fugler et al.[22] also found that up to 45% of the total infiltrating air in a home originated from the garage, while others have shown that 40%–60% of the total indoor benzene can originate from the garage.[23,24] These studies have all identified that there is a significant degree of infiltration of air from attached garages into homes.

The Canadian National Building Code (NBC)[25] contains some provisions to prevent the transfer of pollutants from attached garages to the dwelling unit, and the nature of these provisions changes as a function of the type of garage and the number of vehicles parked in them. For all garage types, there must be a minimum of a conformed air barrier system installed between the garage and the dwelling; all joints of the membrane materials used in the air barrier system must be sealed and structurally supported; every door between the garage and the remainder of the dwelling should be tightly fitted and weatherstripped and should not be located in a room intended for sleeping. However, the NBC (2010) imposes no requirement for mechanical ventilation in the garage for all types of garages that can accommodate 4 cars or less.

Previous studies have outlined various strategies to reduce residential exposures to VOCs originating from attached garages, including maintaining a negative pressure in the garage with respect to the indoor living space, sealing penetrations from the living area into the garage, and implementing behavioral changes such as parking the car outside.[22,23,26–29] Although many of these strategies have been highlighted as promising interventions warranting further examinations, their efficacy has not yet been demonstrated consistently.[23,28]

This study was a multiyear project undertaken by Health Canada, in collaboration with the National Research Council of Canada. The purpose of this study was to test the effectiveness of two interventions aimed at improving indoor air quality in homes with attached garages. The first intervention was the installation and use of an exhaust fan in the garage to reduce the transfer of pollutants from the garage into the home. Fans were sized to achieve a 5 Pascal (Pa) depressurization of the garage relative to the home, as this amount of depressurization has been used in the past to protect adjacent areas during the remediation of contaminated sites (*i.e.*, asbestos),[30,31] and could realistically be obtained in the residential environment. The second intervention was the improvement of the seal between the home and the attached garage by identifying and remedying leakage areas in the connecting wall. This study reports on the results from the first intervention only. The results of the second intervention will be reported elsewhere.

Practical Implications

- This study found that operating an exhaust fan in the attached garage can significantly reduce BTEX (benzene, toluene, ethylbenzene, and xylenes) concentrations and carbon monoxide levels inside homes. Therefore, mechanical ventilation is a relatively simple and effective intervention for improving indoor air quality in homes with attached garages.

2 | METHODS

2.1 | Study design

This study employed a randomized crossover design. During January and February of 2014, three groups of 9–12 homes were monitored for two consecutive weeks. The fan was set to run for 48 hours (Monday to Wednesday) for the first half of the homes in each group and then unplugged with the intake sealed with aluminum tape for the subsequent 48 hours (Wednesday to Friday). This protocol was then repeated in reverse order the following week. The second half of the homes in each group began with the fan unplugged. During each 48-hour sampling period, air pollutants and other relevant parameters were measured in the main living area (*i.e.*, living room), garage, and outdoors.

Sampling was conducted during the winter season only when the forces (*i.e.*, stack and wind) that promote the transfer of air from attached garages into the adjoining homes are at their strongest. Air monitoring was conducted on weekdays as unpublished results of Health Canada studies conducted in homes with attached garages in Halifax demonstrated no significant differences in indoor benzene concentrations between weekends and weekdays.

Ethics approval was provided by both Health Canada and National Research Council Canada Research Ethics Boards.

2.2 | Participant recruitment

A telephone polling company randomly phoned households in Ottawa, Ontario, identifying potential participants based on the following inclusion criteria: be residents of Ottawa; be the owner-occupier of a single detached home, semi-detached home or row house/townhouse; be over 18 years; be able to complete questionnaires in English or French and physically and mentally capable of participation; be non-smoking households; have no commercial activities conducted in the home; have an attached garage with a connecting door to the home; have either an attached garage sharing only one wall, a basement garage or an integrated/built-in garage in which a fan could be installed easily; and agree to have both a fan installed in the garage and for the garage–home interface to be sealed. During the recruitment process, the survey company used a screening questionnaire to confirm participants' eligibility.

2.3 | Prior to the intervention

Once a list of eligible homes was finalized, an initial home visit was scheduled to ensure that the fan could be installed given the configuration of the garage, that the home was not located too far from Ottawa, or that the garage was not too leaky to achieve a 5 Pa pressure differential. In addition, during this visit, residents provided informed consent, and technicians administered both a baseline questionnaire and a survey of products/equipment stored in the attached garage. The home and garage volumes were measured, as well as the number air changes per hour at 50 Pa (ACH_{50}) of the home and garage.

2.3.1 | Blower door testing for fan sizing

The ACH_{50} of the home and garage was measured using an Orifice Blower Door according to the American Society for Testing and Materials' (ASTM) test method E 779-03.[32] Three different test configurations were employed: (i) home only with the main garage door open to ensure the zone in the garage was at ambient pressure; (ii) garage only with the front door of the home open to ensure the main dwelling was at ambient pressure; and (iii) home and garage combined with the house–garage interface door left open to ensure that both the home and garage were at equal pressure. The obtained airflow leakage curves were used to obtain the ACH_{50} by dividing the airflow at 50 Pa by the respective zone volumes. The airflow leakage curves were also used to extrapolate the airflow at 5 Pa in order to size the exhaust fan to be installed in the garage to ensure a 5 Pa depressurization when it was operating continuously. For a small number of the homes in the initial recruitment pool, the required fan flow rate was too large to reasonably achieve the required depressurization (n=3) and these homes were removed from the study. The results and a detailed analysis of the airtightness data will be presented in a subsequent publication dealing specifically with the sealing intervention.

2.3.2 | Exhaust fan installation

In fall 2012 and winter 2013, each participant had an exhaust fan installed in their attached garages by a qualified contractor. The fans were installed with the exhaust grille in either the exterior garage wall, in the case of a built-in or basement garage, or through the soffit when the garage had a separate or contiguous roof with the home. The typical installation time was on the order of 3–5 hours depending on the garage type and amount of material stored in the garage. The exhaust fan was plugged into an existing outlet and ran continuously when in operation. The flow rates provided by the fans ranged from 231 cubic meters per hour (m^3/h) (136 cubic feet per minute (CFM)) to a maximum of 866 m^3/h (510 CFM). For the garages requiring moderate to large flow rate (>500 m^3/h), the flow rate of the fan was kept at the factory settings. For the garages requiring small flow rates (<425 m^3/h), the factory settings of the fan was adjusted to achieve the required flow.

2.4 | Air monitoring conducted during the intervention

2.4.1 | BTEX measurements

BTEX levels were sampled using clean and evacuated stainless steel Summa™ canisters. Indoor, outdoor, and garage measurements were made at each of the residences using 6.0-L canisters deployed every 48 hours. Each canister was evacuated to an initial negative pressure of −28 to −30 inches of mercury, and over the course of the sampling period, the vacuum inside the canister was replaced air at a constant flow rate of 2 mL/min by the means of flow controllers. The flow controllers were assembled and leak tested by Environment Canada and Climate Change. Between homes the gauges were flushed for 48 hours with dry nitrogen gas to eliminate cross-contamination between samples. Samples were analyzed within 30 days using a cryogenic pre-concentration technique with a high-resolution gas chromatograph (Model 6890 or 7890, Agilent Technologies, Palo Alto, CA, USA) and a mass-selective detector (GC-MS) (Model 5973 or 5975, Agilent Technologies, Palo Alto, CA, USA). VOCs were separated on a 60-meter, 0.32-mm-internal diameter (ID) fused silica capillary column with a 1.0 μm film thickness of Agilent J&W Scientific (Palo Alto, CA, USA) DB-1. To achieve the detection limits desired, air samples were concentrated before injection into the GC-MS using an Entech Model 7100A pre-concentrator with autosampler (Entech Instruments Inc., Simi Valley, CA, USA). The Summa canister analysis methods followed the EPA Compendium Method TO-15.[33]

2.4.2 | NO_2 measurements

NO_2 was monitored for 48 hours indoors, outdoors, and in the attached garage using Ogawa passive samplers (Ogawa & Company).[34] Following exposure, badges were placed into a sealed ziploc bag in an opaque plastic container and refrigerated during storage and shipping. The NO_2 carbonate-coated filter was then analyzed using a modified Ogawa protocol. This included a reduction in the extraction volume to 1.2 mL to improve sensitivity. Each filter pad was placed in a 25-mL screw-cap Nalgene bottle, and 1.2 mL of type-1 water was added. The bottles were then capped, and the samples were sonicated for 30 minutes. The extract was then filtered through an IC MILXH, 13-mm-diameter, 0.45-mm pore size syringe filter (Fisher Scientific) into autosampler vials with filterless caps. The sample extracts were analyzed on a Thermo Fischer Scientific, Dionex ICS-1000 with an IonPac AG9-HC 4 50 mm guard, and an IonPac AS9-HC 4 250 mm analytical column.

2.4.3 | Ventilation measurements

The air exchange rates (AERs) of the home and garage were estimated using the two-zone approach of the perfluorocarbon tracer (PFT) gas method.[35] The two-zone approach of the PFT method was ideal for this study as it provided a rate of air exchange with outdoor air for both zones (the home and the garage). The PFT method uses inert PFT gases, emitted from sources at a constant, temperature-dependent rate, then captured on capillary absorptive tubes (CATs). Five colocated perfluoro-1,2-dimethylcyclohexane (oc-PDCH) sources were deployed in the main living room. Two perfluoromethylcyclohexane (PMCH) and two perfluorodimethylcyclobutane (PDCB) sources were deployed in the garage to address concerns about how well the air is mixed in the garage. For each 48-hour sampling period, one CAT was deployed in a central location in the living room. Two sources were used in the garage to address concerns about how well the air is mixed in the garage. The garage CAT was placed between the PMCH emitter and the connecting door, while the PDCB emitter was placed on the opposite wall of the garage. All emitters were collocated with a temperature logger to allow for the adjustment of their emission rates. Mass balance equations were used to calculate home and garage AERs using garage and home PFT gases measured by the garage and home CATs, emission rates, and home and garage volumes. Garage AERs were averaged to minimize any imprecision in the AER calculations due to incomplete mixing.

Detailed information regarding the QAQC methods and results for the VOC, NO_2, and ventilation measurements can be found in the supplemental material.

2.4.4 | CO, temperature, and relative humidity measurements

Carbon monoxide was monitored indoors and in the attached garage using a Langan Model T15n Enhanced CO monitor (Langan Products, Inc., San Francisco, CA, USA) and recorded at 5-minute intervals.

Indoor relative humidity and temperature were recorded every 5 minutes using a HOBO Data Logger (Onset, Cape Cod, MA, USA). In the garages, temperature was recorded every 5 minutes using the Langan Model T15n Enhanced CO monitor, while relative humidity was recorded every 5 minutes using HOBO Data Loggers. Outdoor temperature and relative humidity were downloaded from http://climate.weather.gc.ca/for the entire sampling season.

2.4.5 | Pressure differential

For each 48-hour sampling period, the pressure differential was measured directly across the garage–home connecting door with a Veris Industries Differential Air Pressure Transducer model PXULX05S (Tualatin, OR, USA).

2.4.6 | Questionnaires

During each 24-hour sampling period, participants completed a daily online questionnaire on activities (i.e., cooking, cleaning) that occurred in their home that could have affected indoor air quality. The data from these 24-hour questionnaires were then combined to cover each 48-hour sampling period. Technicians administered a one-time baseline questionnaire to participants during the study to collect information on household characteristics, including any products, gasoline-powered equipment, and cars stored in their attached garage.

2.5 | Statistical analysis

2.5.1 | Treatment of values below the detection limit

Concentrations for BTEX and NO_2 were left unadjusted, regardless of whether they fell above or below the method detection limit (MDL). Samples with concentrations higher than their corresponding MDL were interpreted as valid, and the value reported by the analytical laboratory was used. Samples with concentrations lower than their corresponding MDL were identified as below the detection limit. However, these values were retained for the statistical analysis given that imputing with commonly used methods (*i.e.*, dividing the minimum detection limit by the square root of 2) can lead to censored distributions that may result in more biased predictions.[36]

2.5.2 | Efficacy of the intervention

A linear mixed model with a variance components covariance structure was used to evaluate the efficacy of the intervention at reducing both indoor and garage concentrations of BTEX, NO_2, and CO. Fan status was included as a dichotomous indicator variable (fan off/fan on). The dependent variable was typically the natural logarithm of the 48-hour indoor and garage pollutant concentrations. However, log transformation was not feasible for the pressure differential data or indoor CO concentrations. This was due to a high percentage of negative values in the pressure differential dataset and a distribution that became more skewed with log transformation for indoor CO concentrations. Random intercepts were used in all models to account for correlations between repeated measures from each house.

With the exception of CO, all models were corrected for their corresponding outdoor concentrations. For BTEX, the corresponding outdoor concentrations were subtracted from both the indoor concentrations and the garage concentrations to create outdoor-corrected dependent variables. This approach is based on the principles outlined in the mass balance equation and allows for a more direct assessment of the fan's ability to mitigate exposures related to the presence of an attached garage. This approach assumes that the penetration fraction (P) for gas molecules can be taken to be 1, assuming complete penetration, and that deposition (k) is zero as the BTEX species are non-reactive. As NO_2 is a reactive gas, outdoor concentrations were included in the model to adjust for any confounding effects. Outdoor CO was not measured, and therefore, no outdoor adjustment was possible.

Other variables considered as potential confounders included daily questionnaire data (*i.e.*, number of cars parked in the garage, how long cars were parked in the garage, how long the garage door was open, window opening, use of gas-powered items such as snow blowers), baseline questionnaire data (*i.e.*, furnace type, presence of a gas stove, a central vacuum connection through the garage/home interface), and temperature data (ambient temperature, absolute garage–indoor temperature differential, absolute garage–outdoor temperature differential, and absolute indoor–outdoor temperature differential). No factors were determined to be confounders, but variables that were significant predictors of home/garage concentrations were included in the final models for completeness (see Table S1 for the full list of significant variables included). Garage AER was not considered as a confounder given its strong correlation with fan use.

2.5.3 | Assessment of garage leakiness as a potential mitigating factor

To assess the influence of garage leakiness on home and garage pollutant concentrations, each home was assigned to one of three categories—leaky garage, somewhat leaky garage, and tight garage. These categories were determined by dividing the distribution of garage average ACH_{50} into tertiles. In the absence of clear guidelines in the literature as to what constitutes a leaky garage, it was felt that this approach would allow us to assess a range of "leaky" conditions. Garage leakiness was then entered into a general linear model as a categorical predictor variable. Models were run using data collected during fan off conditions only and were adjusted for absolute garage–outdoor temperature differences.

All analyses were conducted in SAS EG 5.1 (SAS Institute, Cary, NC, USA). Figures were completed using Microsoft Excel 2010 (Microsoft, Redmond, Washington, USA).

3 | RESULTS AND DISCUSSION

3.1 | Recruitment and household characteristics

3.1.1 | Recruitment

Of 1125 unique telephone numbers dialed by the polling firm, 775 could not be reached after multiple attempts, 102 refused to answer the screening questionnaire, 180 homeowners were ineligible based on the inclusion criteria, and 16 numbers were not in service. Ultimately, a list of 52 eligible participants was compiled.

Following an initial home visit with each of the qualified participants, 6 decided to withdraw, 6 never returned calls by the study coordinator, and 7 were excluded by the research team for various reasons (*i.e.*, the garage was too leaky to achieve a 5 Pa pressure differential, the home was located too far from Ottawa, the configuration of the garage made the fan impossible to install, participant availability). Overall, 33 homes in the Ottawa area were eligible and participated in the study.

3.1.2 | Household characteristics

Household characteristics for all homes are presented in Table 1. Most homes were detached single-family dwellings (94%), with an attached garage sharing only one wall (61%). Many of the homes were built between 1981 and 2000 (46%), although homes were built as early as 1946 and as late as 2010. With only a few exceptions, the garage age was the same as the home age. Approximately half of the homes had an additional garage door (other than the main garage door) leading to the outside (48%). Forced air was typically used as the main type of heating system (97%), and only two homes used a natural gas stove for cooking (6%). Home volume ranged from 356 m^3 to 1369 m^3, and garage volume ranged from 35 m^3 to 189 m^3.

In general, homeowners parked their cars in their attached garage (88%), with the majority of people parking one car in their garage (60%). The median number of minutes that cars were parked in the garage during the 48-hour period was 1485 (24.75 hours), with a range between 0 and 3675 minutes (61.25 hours) (sum of all cars).

3.2 | Pollutant concentrations

Pollutant concentrations are presented in Fig. 1a and b and Supplemental Table S4. Overall, levels of BTEX species were significantly higher ($P<.05$) in the attached garage than those found in the home and outdoors. This is not unexpected, as BTEX species are typically derived from the evaporative and tailpipe emissions of the gasoline-powered vehicles and equipment that are often found in garages.[12,14] As well, BTEX levels in homes have been shown to increase after both a cold start (vehicle started at ambient temperature) and hot soak (cooling off from a hot vehicle after it is turned off).[16,37] This is consistent with other studies that have shown significantly higher concentrations in the garage compared with the homes.[23,24] As well, indoor geometric mean concentrations of BTEX species reported here during the fan off time period (see Table S3) are similar to what has been reported in several North American homes with attached garages.[1–3,23] For example, winter indoor geometric mean benzene concentrations reported elsewhere ranged from 1.5 μg/m^3 in Regina, Saskatchewan,[1] to 2.5 μg/m^3 in Quebec City, Quebec.[2] However, indoor levels reported here are lower than what has been reported for homes with attached garages in the Boston Exposure Assessment in Microenvironments (BEAM) Study[24] and the indoor air component of the Canadian Health Measures Survey.[4] These differences may be a result of seasonal differences. Outdoor levels of BTEX were low, and geometric mean concentrations were not significantly different during the fan off and fan on periods (P=.42–.96).

Indoor NO_2 concentrations were lower than both garage and outdoor concentrations, with levels highest outdoors (Fig. 1b). Higher outdoor NO_2

TABLE 1 Housing characteristics

Housing characteristic	n	%
Home type		
Detached single-family home	31	94%
Row house	2	6%
Garage type		
Integrated or built-in garage	13	39%
Attached garage sharing only one wall	20	61%
Construction year of home		
1946–1960	4	12%
1961–1980	10	30%
1981–2000	15	46%
2001 or later	4	12%
Construction year of garage		
1946–1960	3	9%
1961–1980	10	30%
1981–2000	15	46%
2001 or later	4	12%
Missing	1	3%
Flow rates of installed fans		
231 m^3/h (136 CFM)	1	3%
346 m^3/h (192 CFM)	1	3%
418 m^3/h (246 CFM)	1	3%
510 m^3/h (300 CFM)	10	30%
595 m^3/h (350 CFM)	1	3%
605 m^3/h (356 CFM)	1	3%
765 m^3/h (450 CFM)	3	9%
866 m^3/h (510 CFM)	15	45%
Additional garage door (other than the main garage door) leading to the outside		
Yes	16	48%
No	17	52%
Natural gas stove		
Yes	2	6%
No	31	94%
Natural gas clothes dryer		
Yes	3	10%
No	30	90%
Main type of heating system		
Forced air	32	97%
Baseboard heaters	1	3%
Any windows open during the 48-hour sampling period?		
Yes	24	18%
No	107	82%
Missing	1	0%
Any cars parked in the garage during the 48-h sampling period?		
Yes	115	88%
No	16	12%
Missing	0	0%
Maximum number of cars parked in the garage during the 48-h sampling period?		
0	16	12%
1	78	60%
2	33	25%
3	4	3%
	Median (min–max)	
Median number of minutes cars were parked in the garage in past 48 h (min–max)	1485 (0–3675)	
Median garage volume m^3 (min–max)	99 (35–189)	
Median home volume m^3 (min–max)	664 (356–1369)	

levels versus indoor concentrations have been reported elsewhere,[1,19,38,39] and this is expected for homes without major indoor sources such as gas stoves. In this study, only 2 homes had gas stoves (see Table 1). Indoor geometric mean concentrations found in this study (fan off=8.9 μg/m^3, fan on=9.4 μg/m^3) are similar to median concentrations reported across Canada, which ranged from 5.5 μg/m^3 [40] to 10.4 μg/m^3.[19,41]

The mean levels of CO in the home over the 48-hour averaging period were all below 2 ppm, whereas garage CO concentrations were highly variable ranging from 0 to 12 ppm, with some 48-hour concentrations in the garage exceeding Health Canada's 24-hour guideline for CO of 10 ppm.[17] These indoor CO concentrations are comparable to average levels in homes without gas stoves (0.5–5 ppm),[42] as well as to levels reported in 3 homes with attached garages during hot soak and cold start tests (0.3–2.6 ppm).[21]

Tables with the descriptive statistics for the air pollutants of interest can be found in the supplemental material (see Table S3).

3.3 | Indoor/outdoor, garage/outdoor, and garage/indoor pollutant ratios

3.3.1 | Indoor/outdoor ratios

Indoor/outdoor (I/O), garage/outdoor (G/O), and garage/indoor (G/I) pollutant ratios are presented in Table 2. Median I/O ratios for BTEX during the fan off period ranged from 2.83 (benzene) to 16.09 (m,p-xylene), suggesting the presence of indoor and/or garage sources.

Of the BTEX species, the lowest I/O ratio observed was for benzene, which is not surprising given that there are few indoor sources of benzene in homes without smokers.[2,43–54] This is consistent with what has been found in other Canadian studies, where the median I/O ratio for benzene ranged from 1.5 to 2.4.[10] For all BTEX species, the median I/O ratio decreased when the fan was operating, suggesting that the indoor source, the attached garage, was minimized through the use of a fan (Table 2).

These results are in contrast to those found for NO_2, which had median I/O ratios <1 during both fan off and fan on periods. This is not surprising given that there were very few indoor sources of NO_2 in participating homes (*i.e.*, only two homes had gas stoves). The median I/O ratios reported here of 0.39 and 0.43 during the fan off and fan on periods, respectively, were very similar to those reported in winter for homes with electric stoves in Halifax, Nova Scotia (median I/O=0.50).[19] These low I/O ratios are consistent with other studies that have estimated that only approximately 60±10% of NO_2 infiltrates from outdoors.[55–57] NO_2 may also be removed from the indoor environment through reactions with other compounds.[58]

3.3.2 | Garage/outdoor ratios

G/O ratios for BTEX species were even greater than the I/O ratios (Table 2), indicating a significant contribution from garage sources. During fan off periods, the median G/O ratios ranged from 11.4 (benzene) to 80.9 (m,p-xylene). All BTEX G/O ratios were substantially reduced through the use of fan (range: 3.0–12.9). For NO_2, the G/O

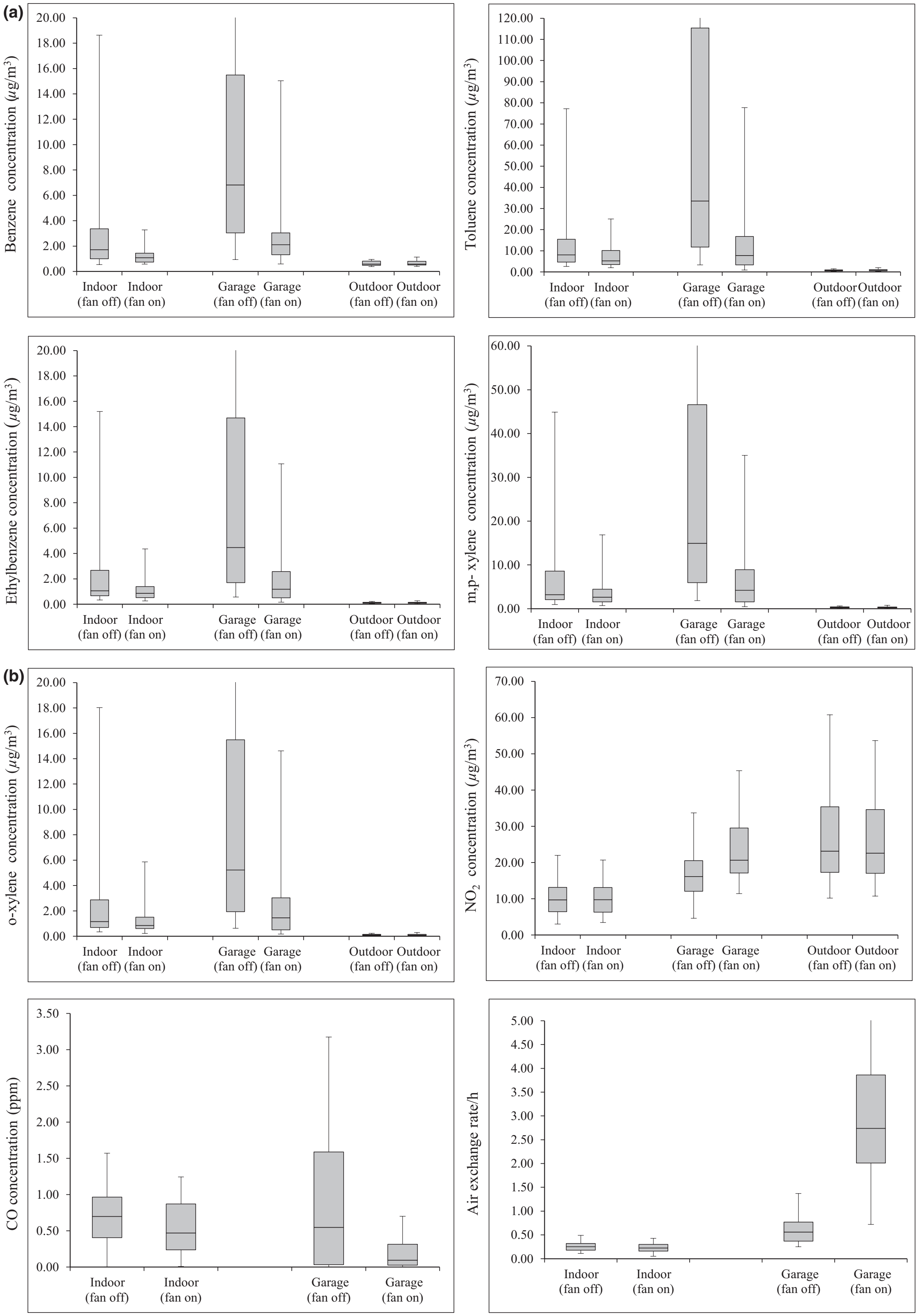

FIGURE 1 (a) Indoor, garage and outdoor concentrations of benzene (μg/m3) (top left), toluene (μg/m3) (top right), ethylbenzene (μg/m3) (bottom left) and m,p-xylene (μg/m3) (bottom right) when the fan was turned off and on. Boxplots show medians, 25–75 percentiles (box) and min-max (whiskers). (b) Indoor, garage and outdoor concentrations of o-xylene (μg/m3) (top left), NO2 (μg/m3) (top right), CO (ppm) (bottom left) and AER/h (bottom right) when the fan was turned off and on. Boxplots show medians, 25–75 percentiles (box) and min-max (whiskers).

Table 2 Indoor/outdoor(I/O), garage/outdoor (G/O), and garage/indoor (G/I) ratios

	Ratio	Fan	n	Min	p5	p10	Q1	Median	Q3	p90	p95	Max	Geometric Mean (95% CI)*
Benzene	I/O	Fan off	60	1.0	1.2	1.3	1.7	2.8	4.6	11.1	25.5	58.0	**3.2 (2.5, 4.2)**
		Fan on	60	0.8	1.0	1.1	1.3	1.6	2.3	3.1	5.3	37.4	**1.9 (1.5, 2.4)**
	G/O	Fan off	61	1.1	1.8	2.5	4.8	11.4	28.3	47.6	78.9	572.4	**11.9 (8.7, 16.4)**
		Fan on	63	1.0	1.2	1.3	1.6	3.0	4.5	7.5	17.3	27.9	**3.3 (2.4, 4.5)**
	G/I	Fan off	60	0.1	1.1	1.7	2.5	4.1	6.5	8.4	9.2	10.1	**3.6 (2.8, 4.8)**
		Fan on	60	0.1	0.7	0.8	1.1	1.6	2.6	4.8	7.2	8.2	**1.7 (1.3, 2.2)**
Toluene	I/O	Fan off	60	2.6	3.4	5.4	7.2	12.7	25.5	53.7	99.9	382.9	**14.9 (11.1, 20.1)**
		Fan on	60	1.0	1.7	2.7	4.8	9.2	13.5	24.7	35.9	46.3	**8.2 (6.0, 11.0)**
	G/O	Fan off	61	1.7	6.0	7.9	21.1	52.3	114.6	245.4	486.3	1967.6	**48.6 (32.3, 73.1)**
		Fan on	63	1.5	1.8	2.8	4.5	10.1	28.3	45.3	78.8	374.0	**11.2 (7.4, 16.8)**
	G/I	Fan off	60	0.1	0.9	1.2	2.5	3.7	5.4	7.6	8.5	9.6	**3.3 (2.4, 4.5)**
		Fan on	60	0.1	0.3	0.3	0.8	1.3	2.9	5.8	8.9	12.3	**1.4 (1.0, 1.9)**
Ethylbenzene	I/O	Fan off	60	1.9	3.1	5.0	6.6	12.0	22.0	50.9	123.3	416.8	**14.4 (10.3, 20.0)**
		Fan on	60	1.0	1.4	3.1	5.0	8.3	15.4	36.0	51.4	236.0	**8.9 (6.4, 12.4)**
	G/O	Fan off	61	1.6	3.8	7.5	17.7	63.3	101.0	272.8	444.3	3574.3	**47.7 (31.3, 72.6)**
		Fan on	63	1.4	1.6	2.5	4.2	8.7	26.4	40.4	97.0	378.0	**11.1 (7.3, 16.8)**
	G/I	Fan off	60	0.2	0.5	0.8	2.4	3.9	6.0	9.3	10.7	11.8	**3.5 (2.6, 4.7)**
		Fan on	60	0.2	0.2	0.3	0.6	1.2	2.5	5.0	8.3	15.0	**1.2 (0.9, 1.7)**
m,p-xylene	I/O	Fan off	60	2.0	3.3	5.6	7.5	16.1	31.2	88.6	283.8	680.9	**19.6 (13.4, 28.5)**
		Fan on	58	1.0	1.2	2.7	5.9	10.3	20.4	59.0	91.0	737.0	**11.2 (7.7, 16.4)**
	G/O	Fan off	61	1.8	4.7	11.6	26.0	80.9	167.3	354.3	525.6	5587.1	**66.7 (42.3, 105.2)**
		Fan on	61	0.7	1.7	2.2	5.5	12.9	42.0	87.8	120.3	307.6	**14.3 (9.1, 22.6)**
	G/I	Fan off	60	0.2	0.5	0.9	2.4	4.1	6.4	9.0	10.5	12.7	**3.6 (2.6, 4.9)**
		Fan on	60	0.1	0.2	0.3	0.6	1.3	2.6	5.9	8.3	14.8	**1.2 (0.9, 1.7)**
o-xylene	I/O	Fan off	60	2.2	3.3	4.4	7.1	14.7	29.1	80.5	211.9	649.4	**17.7 (12.3, 25.4)**
		Fan on	59	0.9	1.2	3.0	5.0	9.9	20.5	39.6	87.0	246.0	**10.2 (7.1, 14.6)**
	G/O	Fan off	61	2.0	5.1	10.8	25.3	75.8	143.1	367.3	546.3	5458.1	**60.9 (38.7, 95.8)**
		Fan on	62	1.1	1.5	2.1	5.0	10.8	34.6	65.9	92.2	334.3	**12.4 (7.9, 19.5)**
	G/I	Fan off	60	0.4	0.6	0.8	2.3	4.0	6.2	9.3	10.5	12.6	**3.6 (2.6, 4.9)**
		Fan on	60	0.1	0.2	0.3	0.6	1.2	2.7	6.0	8.1	15.9	**1.2 (0.9, 1.7)**
NO_2	I/O	Fan off	65	0.1	0.1	0.2	0.3	0.4	0.5	0.7	0.9	1.5	0.4 (0.3, 0.4)
		Fan on	64	0.1	0.2	0.2	0.3	0.4	0.5	0.7	0.8	2.2	0.4 (0.3, 0.5)
	G/O	Fan off	66	0.1	0.2	0.3	0.4	0.7	0.9	1.2	1.3	2.3	**0.6 (0.5, 0.7)**
		Fan on	65	0.5	0.5	0.6	0.8	0.9	1.1	1.4	1.5	4.8	**0.9 (0.8, 1.1)**
	G/I	Fan off	65	0.3	0.6	0.7	1.2	1.7	2.4	4.2	5.0	6.9	**1.7 (1.4, 2.0)**
		Fan on	64	0.6	0.9	1.1	1.7	2.3	3.3	4.4	5.2	11.8	**2.3 (1.9, 2.8)**

*Significant (P<.05) differences between geometric mean ratios during fan on and fan off periods presented in bold.

ratio was <1 during the fan off period and approached 1 during the fan on period, suggesting an outdoor contribution to garage concentrations during both time periods.

3.3.3 | Garage/indoor ratios

All G/I ratios in this study were >1. Batterman et al.[23] suggest that G/I ratios >1 signify garage sources. In their study, G/I ratios for aromatics exceeded 10, showing the dominance of garage sources. In our study, median G/I ratios for the BTEX species were approximately 4.0 and approximately 2.0 for NO_2. The lower G/I ratios found in this study are likely a result of increased stack and wind forces in the winter sampling season (as compared to a spring/summer sampling conducted by Batterman et al.[23]), which promote the transfer of air from the attached garage into the adjoining home.

TABLE 3 Influence of fan on indoor and garage air parameters. Adjusted geometric mean and 95% CI reported

	Indoor			Garage		
	Geometric mean (95% CI)*			Geometric mean (95% CI)*		
Parameter	Fan Off	Fan On	% Change	Fan Off	Fan On	% Change
Benzene (outdoor corrected) (μg/m^3)	**1.0 (0.7, 1.7)**	**0.40 (0.25, 0.63)**	**−62**	**5.8 (3.6, 9.3)**	**1.1 (0.7, 1.8)**	**−81**
Toluene (outdoor corrected) (μg/m^3)	**9.1 (6.3, 13.1)**	**4.3 (2.98, 6.17)**	**−53**	**30.8 (18.9, 50.4)**	**6.6 (4.0, 10.8)**	**−79**
Ethylbenzene (outdoor corrected) (μg/m^3)	**1.3 (0.9, 1.9)**	**0.7 (0.5, 1.0)**	**−47**	**4.4 (2.7, 7.4)**	**0.9 (0.5, 1.5)**	**−80**
m,p-Xylene (outdoor corrected) (μg/m^3)	**4.1 (2.7, 6.2)**	**2.3 (1.5,3.4)**	**−45**	**14.8 (8.9, 24.6)**	**3.1 (1.9, 5.2)**	**−79**
o-Xylene (outdoor corrected) (μg/m^3)	**1.4 (0.9, 2.1)**	**0.8 (0.5, 1.2)**	**−43**	**5.0 (2.9, 8.5)**	**1.0 (0.6, 1.7)**	**−81**
CO (ppm)	**0.7 (0.6, 0.9)**	**0.6 (0.4, 0.7)**	**−23**	**0.1 (0.1, 0.3)**	**0.0 (0.0, 0.1)**	**−61**
NO_2 (μg/m^3)	8.8 (7.6, 10.3)	9.3 (8.0, 10.9)	6	**14.7 (13.0, 16.6)**	**21.9 (19.3, 24.8)**	**49**
Air Exchange Rate/h	0.2 (0.2, 0.3)	0.2 (0.2, 0.3)	−9	**0.6 (0.5, 0.7)**	**3.0 (2.4, 3.6)**	**440**
Pressure Differential (pa)	–	–	–	**0.9 (−0.7, 2.4)**	**−4.1 (−5.6, −2.5)**	**−564**

*Significant (P<.05) findings presented in bold.

3.4 | Effectiveness of garage fan

3.4.1 | Effectiveness of the garage fan in reducing pollutant concentrations

A summary of the percent changes in the adjusted geometric mean concentrations can be found in Table 3. Statistically significant reductions were seen indoors during the periods when the garage fan was operating compared to when it was not. These reductions ranged from 43% to 62% for all of the outdoor-corrected BTEX species (P<.05). The reduction was even greater in the attached garage where decreases in outdoor-corrected BTEX species ranged from 79% to 81% (P<.05). For CO, levels were reduced by 23% indoors and 61% in the garage (P<.05).

The intervention did not significantly influence NO_2 concentrations in the home. However, garage concentrations of NO_2 did significantly increase (P<.05) when the fan was operational to more closely reflect outdoor concentrations. The lack of change in the indoor concentrations is likely due to the fact that indoor concentrations would have been largely influenced by outdoor concentrations under baseline conditions. This is because the majority of the leakage in a home occurs between the building envelope and the outdoor environment, and not the garage–home interface.[59] In this study of 67 homes, the garage-to-home interface only accounted for 10%–13% of the total home leakage.[59] Therefore, it is unlikely that this type of intervention will significantly reduce indoor concentrations in instances where outdoor pollutant concentrations exceed or are equal to the garage concentration.

To our knowledge, few studies have examined the effectiveness of mechanical ventilation and/or garage exhaust in reducing pollutant concentrations in the home or in the garage. Kaluza[60] reported that keeping the garage at a negative pressure relative to the house prevented CO transport into a house in Alaska. However, no studies are currently available that have examined the influence of a garage fan, or any other mitigation strategy, on BTEX species. This is despite the substantial evidence to support the fact that transport of contaminants from the garage has the potential to negatively impact indoor air quality[61] and subsequent health.[18,62–66]

3.4.2 | Influence of the fan operating on AER and the garage–indoor pressure differential

A summary of the percent changes in the adjusted geometric mean AER and mean garage–indoor pressure differentials can also be found in Table 3. Geometric mean garage AER increased by about fivefold (2.97/0.56=5.3) when the fan was operational, which is in strong agreement with the dramatic fivefold decrease observed in garage pollutant concentrations (Table 3). The home's AER, temperature, and relative humidity were not significantly impacted by fan status (Table 3, Table S3). There was also a 564% reduction in the mean indoor–garage pressure differential.

However, these numbers do not reflect the fact that some homes had a much greater depressurization than others and that some homes did not meet the intended target depressurization of 5 Pa. In fact, only 27% of homes met the targeted depressurization. We conducted stratified analyses for homes that met the depressurization target and those that did not and determined that although the intervention significantly reduced pollutant concentrations in both groups, the effect of the fan was approximately double in the homes that met the depressurization target. However, the garage AER was also increased by the same magnitude. These results suggest that the dramatic decrease in the observed garage and home pollutant concentrations was most likely due to a combination of both (i) depressurization of the garage relative to the dwelling and (ii) reduction of pollutant concentrations through dilution and exhaust.

3.5 | Influence of garage airtightness

Homes with leakier garages (higher garage ACH_{50}) did not have statistically significantly lower levels of pollutants indoors. There were

TABLE 4 Influence of garage leakiness on indoor and garage air parameters during fan off period. Adjusted geometric mean and 95% CI reported

	Indoor					Garage				
	Geometric mean (95% CI)			% Change		Geometric mean (95% CI)			% Change	
Parameter	Leaky [a]	Somewhat Leaky [b]	Tight [c]	Leaky vs Tight	Somewhat Leaky vs Tight	Leaky [a]	Somewhat Leaky [b]	Tight [c]	Leaky vs Tight	Somewhat Leaky vs Tight
Benzene (outdoor corrected) (μg/m^3)	0.6 (0.2, 1.6)	1.5 (0.5, 4.3)	2.0 (0.7, 5.6)	−72	−27	**2.0 (0.7, 5.6)**	**10.0 (3.6, 27.8)**	**15.3 (5.4, 43.1)**	**−87**	**−35**
Toluene (outdoor corrected) (μg/m^3)	5.8 (2.7, 12.4)	13.1 (5.9, 29.1)	14.9 (7.0, 31.8)	−61	−12	14.4 (5.3, 39.0)	58.7 (21.8, 157.6)	57.9 (21.3, 157.7)	−75	1
Ethylbenzene (outdoor corrected) (μg/m^3)	1.0 (0.4, 2.2)	1.6 (0.7, 3.7)	1.9 (0.8, 4.3)	−49	−17	2.2 (0.8, 6.4)	7.4 (2.6, 21.1)	9.6 (3.3, 27.8)	−77	−23
m,p-Xylene (outdoor corrected) (μg/m^3)	3.1 (1.3, 7.5)	5.3 (2.1, 13.2)	5.9 (2.5, 14.2)	−47	−11	7.5 (2.6, 21.6)	24.5 (8.7, 69.5)	31.4 (10.9, 90.2)	−76	−22
o-Xylene (outdoor corrected) (μg/m^3)	1.1 (0.5, 2.9)	1.8 (0.7, 4.6)	2.1 (0.8, 5.1)	−45	−14	2.7 (0.9, 7.9)	8.6 (3.0, 24.5)	10.7 (3.7, 31.0)	−75	−20
CO (ppm)	0.6 (0.9, 1.2)	0.4 (0.7, 0.9)	0.4 (0.7, 0.9)	24	−1	0.1 (0.0–1.3)	0.4 (0.0–3.7)	0.3 (0.0–3.1)	−57	23
NO_2 (μg/m^3)	9.1 (6.1, 13.6)	11.1 (7.4, 16.4)	8.9 (5.9, 13.3)	2	25	19.2 (13.7, 26.7)	17.1 (12.3, 23.7)	11.5 (8.3, 16.1)	66	48
AER/h	0.3 (0.2, 0.4)	0.3 (0.2, 0.4)	0.2 (0.1, 0.3)	47	53	**0.7 (0.5, 1.0)**	**0.8 (0.6, 1.1)**	**0.3 (0.3, 0.5)**	**117**	**135**
Pressure Differential (Pa)	–	–	–			2.2 (0.6, 7.3)	3.5 (1.0, 12.4)	2.0 (0.6, 7.2)	7	71

[a]Leaky garage>44.4 ACH50 (n=10 homes).
[b]Somewhat leaky garage 19.5–44.4 ACH50 (n=10 homes).
[c]Tight garage <19.5 ACH50 (n=9 homes).
*Significant (P<.05) findings presented in bold.

significant differences in the outdoor-corrected garage benzene concentrations and garage AER (Table 4). These results suggest that simply having a leakier garage may not be adequately protective against contaminant infiltration into the home. Other strategies such as mechanical ventilation are more reliable. However, the overall trends in the data do suggest lower indoor levels of pollutants in homes with leakier garages, and our lack of statistically significant findings may be a result of our relatively small sample size (n=30).

3.6 | Cost of the intervention

There were several costs associated with the implementation of this intervention. The upfront costs included the cost of the fan ($193.50 to $290.40 depending on the make/model), the cost of installation ($435), and the cost of wiring each fan with a three-prong plug ($75). The electrical cost of operating the fan continuously in winter was estimated to be approximately $4.26 to $8.05 per month depending on the fan installed. These estimates take into account the time of use pricing structure and are based on Hydro Ottawa's 2013 posted price range of 6.7–12.4 cents/kWh. There may have been additional heating demand in the house due to the enhanced ventilation in the garage as some occupants indicated that their homes were colder when the fan was operational. However, the additional heating costs were not captured in this study. All monetary amounts reported here are in Canadian dollars.

4 | LIMITATIONS AND CONCLUSIONS

This study has several limitations. This study was conducted in only one season/location, and therefore, the results of this study may differ in other seasons or regions with different climates/housing stock. We elected to conduct the study during the season when the transfer of pollutants from the garage into the home is most pronounced due to temperature differences. Furthermore, we did not have sufficient power to thoroughly examine the question of whether having a leakier garage is able to reliably reduce concentrations of garage pollutants indoors. Finally, as a crossover study, carryover effects may be of concern between treatment periods. However, as the study repeated the fan on/fan off periods twice, in opposite order, carryover is adjusted for in the study design. Also, if any carryover effects remained, they would bias the results toward the null or underestimate the effect of the intervention.

Attached garages are a well-documented predictor of elevated indoor exposure to certain air pollutants. Risk communications should continue to stress source control as a mitigation strategy, including removing paints, solvents, and other VOC sources from the garage, along with avoiding activities in the garage that emit VOCs, such as operating and storing gas-powered equipment. Many residents continue to use the garage as storage for chemicals, power equipment, and vehicles, so other mitigation options beyond source control are needed.

Mechanical ventilation has been demonstrated as a feasible, effective option for reducing the infiltration of VOCs from the garage into the home. This intervention study demonstrated that exhaust ventilation is able to dilute BTEX concentrations in the garage, as well as frequently reversing the pressure differential that can draw garage air into the house. Regardless of the mode of action (depressurization or dilution), garage exhaust fans significantly reduced indoor levels of pollutants originating from the garage. As a result, the potential health risks posed to homeowners due to infiltration of garage pollutants into the home may be mitigated through the implementation of this simple intervention.

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