Journal of Exposure Analysis and Environmental Epidemiology **(2003) 13, 31–41**

1053-4245/03/$25.00

www.nature.com/jea

Measurement of volatile organic compounds inside automobiles[†]

MARION J. FEDORUK[a] AND BRENT D. KERGER[b]

[a]*Department of Medicine, University of California, Irvine, California, USA*
[b]*Health Science Resource Integration, Inc., Tallahassee, Florida, USA*

The objective of the current study was to evaluate the types and concentrations of volatile organic compounds (VOCs) in the passenger cabin of selected sedan automobiles under static (parked, unventilated) and specified conditions of operation (i.e., driving the vehicle using air conditioning alone, vent mode alone, or driver's window half open). Data were collected on five different passenger sedan vehicles from three major automobile manufacturers. Airborne concentrations were assessed using 90-min time-weighted average (TWA) samples under U.S. Environmental Protection Agency (USEPA) Method IP-1B to assess individual VOC compounds and total VOCs (TVOCs) calibrated to toluene. Static vehicle testing demonstrated TVOC levels of approximately 400–800 $\mu g/m^3$ at warm interior vehicle temperatures (approximately 80°F), whereas TVOCs at least fivefold higher were observed under extreme heat conditions (e.g., up to 145°F). The profile of most prevalent individual VOC compounds varied considerably according to vehicle brand, age, and interior temperature tested, with predominant compounds including styrene, toluene, and 8- to 12-carbon VOCs. TVOC levels under varied operating conditions (and ventilation) were generally four- to eightfold lower (at approximately 50–160 $\mu g/m^3$) than the static vehicle measurements under warm conditions, with the lowest measured levels generally observed in the trials with the driver's window half open. These data indicate that while relatively high concentrations of certain VOCs can be measured inside static vehicles under extreme heat conditions, normal modes of operation rapidly reduce the inside-vehicle VOC concentrations even when the air conditioning is set on recirculation mode.
Journal of Exposure Analysis and Environmental Epidemiology (2003) **13,** 31–41 doi:10.1038/sj.jea.7500250

Keywords: *automobile, hydrocarbons, ventilation, volatile organic compounds.*

Introduction

Personal exposures to volatile organic compounds (VOCs) occur from a wide variety of sources and environments. There is scant information concerning vehicle VOC levels during static (nondriving) conditions and/or changes in VOC levels from static to operating conditions. Only one report that examined in-cabin VOC concentrations under static conditions (Dropkin, 1985) was located, but this study focused primarily on nitrosamine emissions, and flaws in the study design precluded the author from drawing conclusions about VOCs measured inside the new vehicles tested.

Several investigators have measured airborne VOC compounds inside the cabin of automobiles during driving in urban and other environments (Witz et al., 1986; SCAQMD et al., 1989; Chan et al., 1991a,b; Weisel et al., 1992; Lawryk et al., 1995; Jo and Choi, 1996; Jo and Park, 1999). These studies provided insights on the magnitude of exposure to selected gasoline indicator compounds (e.g., benzene, toluene, ethylbenzene, and xylenes) relating to leaking fuel or traffic emissions while driving. Lawryk et al. (1995) and Chan et al. (1991b) provided data on a wider range of (up to 24) hydrocarbon compounds measured under a variety of experimental conditions. Barrefors and Petersson (1993) examined a broader profile of in-cabin VOCs relating to tobacco smoke and vehicle emissions. These studies indicate that vehicle fuel- and exhaust-related VOCs can sometimes accumulate in the cabin of operating vehicles at levels that considerably exceed those in ambient outdoor air (e.g., two- to fourfold higher for certain compounds during an average 52-min commute; SCAQMD et al., 1989).

VOCs associated with interior sources include cabin components (e.g., sealants, carpets, vinyl, leather, plastics, foam cushions) that may retain certain VOCs during manufacturing, and/or emit these compounds over an extended period of time from off-gassing, aging-related breakdown products, heating/cooling, and so forth (USEPA, 1976a,b; Akland and Ott, 1987). Other sources of interior vehicle odors and VOC levels include intake of outdoor air contaminants from the vehicle ventilation system or open windows; tobacco smoke; spills of

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1. Abbreviations: VOC, volatile organic compound; TVOC, total volatile organic compound; USEPA, U.S. Environmental Protection Agency; AC, air conditioner; TWA, time-weighted average

2. Address all correspondence to: University of California at Irvine, Center for Occupational and Environmental Health, 19722 MacArthur Boulevard, Irvine, CA 91612, USA. Tel.: +1-949-824-8641. Fax: +1-949-824-2345. E-mail: mjf1nc@aol.com

Received 19 August 2002.

[†] This data was presented previously as a poster session at the Society of Toxicology Annual Meeting, March 18–21, 2001.

chemicals within the vehicle; use of deodorizers, cleaning, and conditioning products; as well as potential microbial VOC emissions in some instances.

The purpose of the current study is to examine the pattern and magnitude of VOC exposures in a survey of selected "new" (less than 6 months since manufacture date) and "used" (approximately 4 years since manufacture date) vehicles sold by three major auto producers in the US. We examine the influence of in-cabin temperature, operating condition (static *versus* driving), ventilation mode [air conditioner (AC) only, vent only, or vent plus open window], ambient air/traffic conditions, make (Chevrolet, Ford, or Toyota midsize vehicles), and age (new *versus* used) on airborne VOCs measured within each vehicle.

Materials and methods

Vehicles Under Study

The vehicles under study included three rental sedans less than 6 months old (two 1997 Ford Taurus and one 1997 Chevrolet Lumina) and two used sedans (1993 Toyota Camry and 1993 Ford Taurus) that were well maintained and in good operating condition. All vehicles were subjected

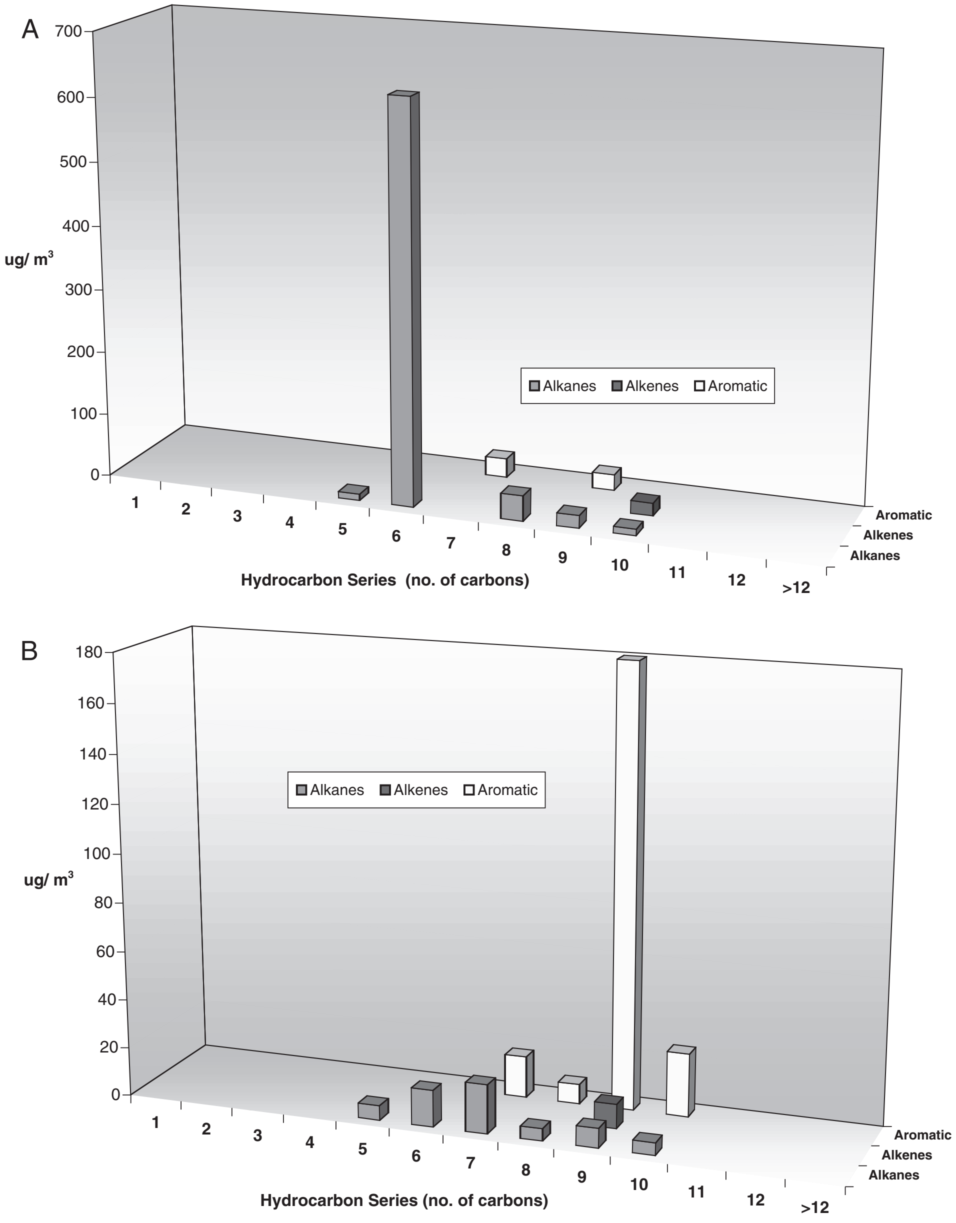

Figure 1. (A) Distribution of hydrocarbons in used 1993 Ford Taurus under high-heat (110°F), static conditions (30 min TWA). (B) Distribution of hydrocarbons in used 1993 Toyota Camry under high-heat (130°F), static conditions (30 min TWA).

Table 1. Rank order and concentration ($\mu g/m^3$) of top 10 chemicals measured inside a 1993 Toyota Camry during static and 90-min driving conditions (maximum AC on).

Moderate-heat (100°F), static conditions			Driving (90 min, maximum AC)		
Rank	Chemical	Airborne VOC concentration	Rank	Chemical	Airborne VOC concentration
1	1,2,4-Trimethylbenzene	10.9	1	Toluene	11.8
2	1,2,3-Trimethylbenzene	7.7	2	Methyl-tert-butyl ether (MTBE)	5.8
3	1-Ethyl-4-methylbenzene	6.8	3	2,2,4-Trimethylpentane	5.4
4	Toluene	6.1	4	2-Methylpentane	5
5	Hexanal	4.5	5	m,p-Xylene	3.8
6	Nonyl aldehyde	4.5	6	Pentane	3.3
7	1-Methylethylbenzene	4.2	7	2-Methylhexane	3.2
8	1-Ethyl-2-methylbenzene 5-methyl-2-methylethyl	3.6	8	3-Methylpentane	2.8
9	Cyclohexanol	3.6	9	Benzene	2.4
10	2-Butoxy ethanol	3.6	10	2,3,4-Trimethylpentane	2.3
	Subtotal	55.5		Subtotal	45.8
	TVOCs	86		TVOCs	66

to a detailed mechanical inspection to verify the absence of any fuel leaks or mechanical problems that could lead to unusual accumulations of exhaust or fuel vapors in the cabin of the vehicle.

Study Locations

Two used vehicles (1993 Ford Taurus and 1993 Toyota Camry) were tested under static and driving conditions during pilot studies conducted in the Los Angeles, CA area in June–July 1997. Three different vehicles (1997 Chevrolet Lumina, 1997 Ford Taurus, and 1993 Toyota Camry) were tested under static and driving conditions in the Foxboro, MA area including more extensive testing for effects of ventilation mode and ambient air VOCs from traffic conditions.

Measurement Devices and Sampling Protocol

Each vehicle was outfitted with a Q-Trak Indoor Air Quality Monitor (Model 8550; TSI) that was used to continuously monitor temperature and humidity within the vehicle. Average temperature and humidity values were determined for each test condition.

In-cabin sampling for airborne VOCs was conducted as a 90-min time-weighted average (TWA) air sample collected by a battery-operated personal sampling pump drawing air through a sorbent tube containing media as required under EPA Method IP-1 B (USEPA, 1990). Exceptions to the 90-min sampling time included the two high-heat static condition trials in the pilot testing of 1993 Ford and Toyota vehicles in California, where it was anticipated that air freshener odors in one of the vehicles (1993 Ford) could overload the sampling device in 90 min; in those instances, 30-min TWA samples were obtained.

The average flow rate of the battery-operated pumps was 0.2 l/min. The total air volume of each 90-min sample was between 17 and 19 l, as required for the analytical method EPA IP-1B. The sampling tubes from each vehicle were shipped on ice with chain-of-custody forms to Air Quality Sciences laboratory in Atlanta, GA.

Static in-cabin air conditions are defined for this study as having the vehicle parked outdoors in an urban area with low traffic within the surrounding one- to two-block area, with all doors and windows closed. Different times of day were selected in order to obtain results for a variety of temperatures, ranging from intense sunlight-induced heat (up to 145°F inside the cabin) to cool late evening temperatures (60–70°F). Static air sampling was conducted over a 90-min period, starting approximately 10 min after the last door-opening event. Temperature and humidity were continuously monitored to verify lack of indoor atmosphere disturbances during the sampling period.

In-cabin air conditions during driving are defined for this study as beginning upon normal entry into the vehicle, immediately starting the vehicle, and driving it in traffic for the entire 90-min sampling period under specified ventilation conditions. Three ventilation conditions were examined, each preceded by a baseline static sample. The first condition was solely running the AC in the vehicle on the highest setting and on recirculation mode, without opening any vehicle windows to vent the heat accumulated in the cabin. The second condition was solely running the fresh air vents with the fan on the highest setting, again with no windows opened. The third condition was opening the driver's side window approximately halfway, with the fresh air vents open and fan on.

Outdoor air samples were taken at selected locations to examine ambient air concentrations beside roadways with varied amounts of traffic. The same methodology was

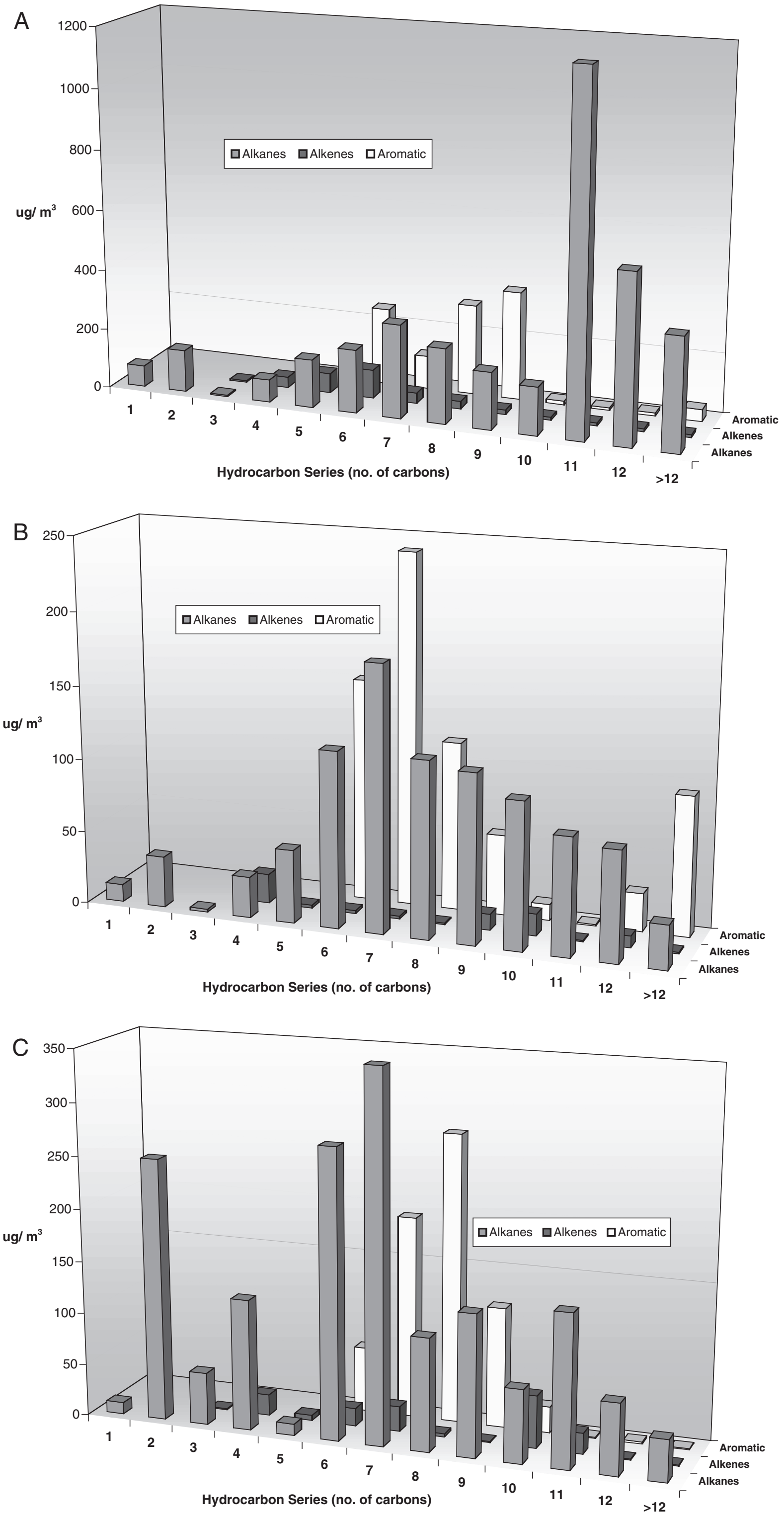

Figure 2. (A) Distribution of hydrocarbons in new 1997 Chevrolet Lumina under high-heat (145°F), static conditions (90 min TWA). (B) Distribution of hydrocarbons in new 1997 Ford Taurus under high-heat (118°F), static conditions (90 min TWA). (C) Distribution of hydrocarbons in used 1993 Toyota Camry under high-heat (145°F), static conditions (90 min TWA).

Table 2. Rank order and concentration (μg/m^3) of top 10 chemicals measured inside three vehicles during high-heat, static conditions.

New 1997 Chevrolet Lumina			New 1997 Ford Taurus			Used 1993 Toyota Camry		
Rank	Chemical	Airborne concentration	Rank	Chemical	Airborne concentration	Rank	Chemical	Airborne concentration
1	2-Methyl decane	>375	1	Toluene	>239	1	Styrene	>201
2	5-Methyl decane	>271	2	Phenol	124	2	Toluene	>191
3	Styrene	>264	3	e-Caprolactam	96	3	2-Ethyl hexanol	121
4	2-Methyl nonane	>227	4	Styrene	94	4	Heptanone	116
5	2,2,4,6,6,-Penta-methylheptane	218	5	2-Ethyl hexanoic acid	83	5	Acetic acid	103
6	Phenol	194	6	1-Methyl-2-pyrolidinone	81	6	Phenol	105
7	2-Methyl-5-propyl nonane	186	7	3-Ethyl nonane	57	7	1,2-Dichloroethane	74
8	4-Ethyl-2,2,6,6-tetra-methyl heptane	180	8	2-(2-Butoxyethoxy) ethanol	49	8	3-Ethyl nonane	63
9	2,4-Dimethyl hepatane	161	9	Nonyl aldehyde	47	9	Nonyl aldehyde	61
10	2,6-Dimethyl nonane	157	10	Hexane	41	10	Butyl acetate	59
	Subtotal	1096		Subtotal	672		Subtotal	702
	TVOCs	>5673		TVOCs	>1999		TVOCs	>2508

">" notation indicates that the measurement may understate the actual VOC concentration because the concentration exceeded the calibration range of the laboratory spike recovery testing.

used for these area samples as for those inside the study vehicles.

Analytical Methods

EPA Method IP-1 B was utilized to determine total VOCs (TVOCs) and a broad scan of individual VOC compounds (USEPA, 1990). EPA Method IP-1B utilizes gas chromatography with mass spectrophotometric (GC/MS) detection to allow measurement of a variety of halogenated hydrocarbon solvents (primarily one to four carbons) and other hydrocarbons (primarily 1–12 carbons) in the boiling point range of 80–200°C. Chemicals included in this range are primarily alkane, alkene, and lighter aromatic compounds, and their associated acid, alcohol, or aldehyde derivatives. Lower-boiling-point compounds like methane, ethane, methanol, and formaldehyde are not quantifiable by this assay. Method IP-1B specifies a thermal desorption sampling tube containing either Tenax alone, or a multiple-bed sampling tube including Tenax, carbon molecular sieves, and graphitized carbon that was utilized in the current study (Anasorb CMS/GCB1/Tenax GR; SKC, Fullerton, CA). All laboratory and field blank quality control data were within normal limits, except that certain compounds exceeded the sorbent media calibration range under static, high-heat conditions, as noted in Table 2.

Results

Pilot Study Findings

The used vehicles (1993 Ford and Toyota) under static, high-heat (110–130°F) conditions showed relatively low levels of TVOCs (<800 μg/m^3; see Figure 1A and B), with patterns dominated in one case (Toyota) by nine-carbon alkyl benzene compounds and in the other (Ford) by a deodorizer compound, 2-butoxy ethanol. Table 1 provides an overview of the VOC species detected in highest concentrations within the 1993 Toyota Camry under static, moderate-heat (100°F) conditions compared to driving in moderate highway traffic in Los Angeles with the air conditioning on recirculation mode. Although the TVOC concentrations under static and driving conditions in the 1993 Toyota were of similar magnitude (66–86 μg/m^3), the VOC profile shifted from a predominantly alkyl benzene pattern during static conditions to a predominantly alkyl pentane pattern during driving conditions.

Main Study Findings

Figure 2A–C illustrates the pattern of VOCs observed under static, high-heat (118–145°F) conditions in two newer vehicles (1997 Chevrolet and Ford) and the used 1993 Toyota. The pattern of VOCs detected within each vehicle was relatively distinct. Table 2 provides a summary of the top 10 VOCs observed at the highest airborne concentrations in each vehicle. Toluene, styrene, phenol, and various substituted alkanes were among the predominant VOC species in all three vehicles tested. The total numbers of distinct VOC compounds identified by GC/MS library matching in air samples for the static, high-heat conditions were 104 (1997 Chevrolet), 99 (1997 Ford), and 101 (1993 Toyota).

Figure 3 illustrates the four- to eightfold difference in TVOC concentrations under static, high-heat conditions (110–145°F) *versus* moderate-heat conditions (90–109°F). For the two vehicles that achieved the same, very high interior temperature of 145°F (1997 Chevrolet and 1993 Toyota), the used vehicle concentrations were less than half that of the new vehicle. The TVOC level observed

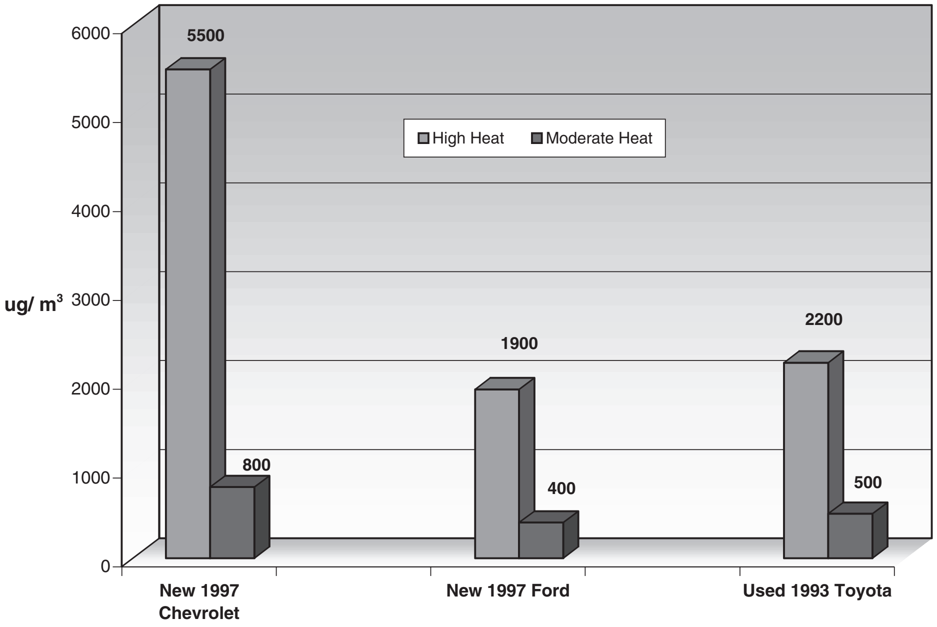

Figure 3. TVOC concentrations under static conditions inside the cabin of three vehicles under high- or moderate-heat conditions.

in the new 1997 Ford vehicle under these conditions was about one-third of the new Chevrolet levels. The Chevrolet vehicle showed relatively high concentrations of fuel hydrocarbons (e.g., heptane, octane, nonane, and decane compounds; see Table 2), which may suggest a minor fuel leak influence on the VOC pattern that was not seen in the other two vehicles with lower TVOC levels. All three vehicles showed prominent concentrations of styrene and phenol, which are presumed off-gassing products from vehicle interior components.

The change in TVOC concentrations observed for the static condition testing (high- or moderate-heat conditions) compared to driving the vehicle for 90 min in traffic with the AC operating (on recirculation mode, maximum fan speed) is shown in Figure 4. Under these conditions, a 10- to 20-fold lower air concentration of TVOCs was observed during driving conditions in the two newer vehicles tested, while the used vehicle showed about four-fold lower concentrations. The TVOC concentrations during driving conditions in Figure 4 covered a fairly narrow range (75–150 $\mu g/m^3$)

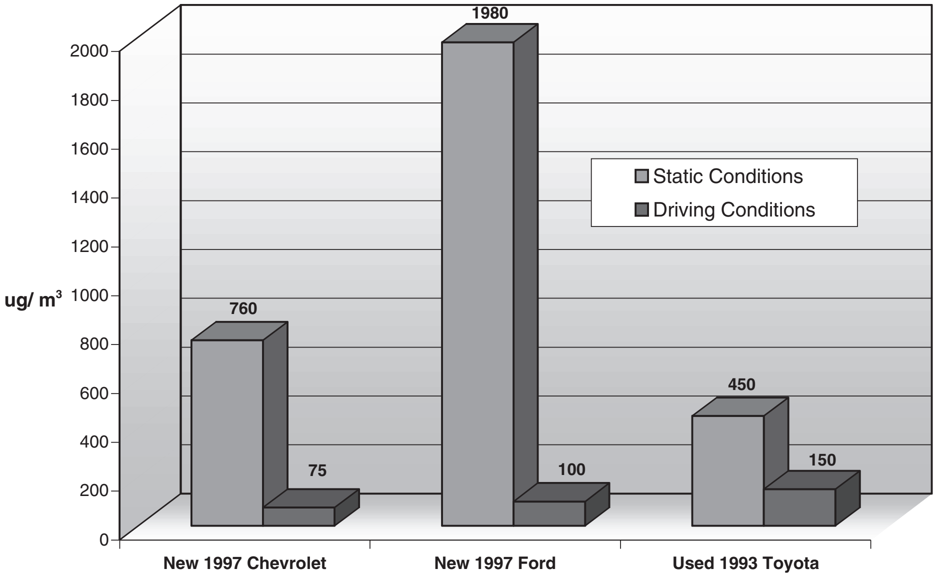

Figure 4. TVOC concentrations inside vehicles between moderate-heat, static condition and 90 min of driving (maximum AC on).

that was consistent with the driving condition data in the pilot study for the 1993 Toyota (66 μg/m^3; see Table 1).

Individual VOC data collected while driving the 1993 Toyota (Table 1) are compared to other published data in Tables 3 and 4. Table 3 provides a statistical summary of nine common hydrocarbon compounds found in gasoline that were assessed under static or driving conditions in the current study, and a comparison to measurements in other published studies that assessed up to eight of these nine VOCs. The static condition testing in the current study might be considered somewhat comparable to the idling vehicle data collected by Lawryk et al. (1995). The current study data under static, moderate-heat conditions appear to be most comparable in terms of mean values and variance across these selected compounds analyzed by Lawryk et al. The urban driving data for the 1993 Toyota in the current study appear to be generally about 4- to 10-fold lower than the other available published averages for these selected hydrocarbons (testing before 1993, generally with vehicles made before 1990). It may be important to note that the other published studies were completed before the institution of reformulated gasolines containing MTBE or other oxygenates. The urban driving data in the current study for individual and TVOCs were gathered in California in 1997, when reformulated gasolines were in regular use.

Table 4 provides a comparison of Chan et al. (1991b) with the current study of urban driving data, including the top 20 VOCs identified in the 1993 Toyota operated on Southern California area freeways. The current study data show considerably lower measured in-cabin VOC concentrations compared to the average measurements reported by Chan et al. (1991b) for urban and interstate driving, but our data were more consistent in magnitude with average values they reported for rural driving. The presence of detectable MTBE in the current study data indicates the prevalent use of reformulated gasolines that may effect a lower relative content of certain common volatile hydrocarbons like benzene, toluene, ethylbenzene, and xylenes as compared

Table 3. Comparison of selected (fuel-related) current study measurements with previously published data.

Test	Benzene	Toluene	Ethyl benzene	*m,p*-Xylene	*o*-Xylene	Hexane	3-Methyl pentane	1,2,4-Trimethyl benzene	MTBE
Current study observations: extreme heat/static conditions									
Chevrolet	14.3	78.7	32	83.2	8.4	25.7	4.8	ND	ND
Ford	1.7	239	4.7	16.2	8.8	40.7	5.8	14.3	ND
Toyota	13.9	191	10.5	37.9	22.4	4.8	ND	27.2	ND
Mean	10.0	169.6	15.7	45.8	13.2	23.7	5.3	20.8	N/A
SD	5.8	67.2	11.7	27.9	6.5	14.7	0.5	6.5	N/A
Moderate heat/static conditions									
Chevrolet	ND	38	7.5	18.5	9.9	2.6	ND	ND	ND
Ford	ND	89.5	2.7	8.4	3.9	11.2	3.1	4.3	ND
Toyota	1.9	86.8	2.5	6.6	4.7	1.7	ND	ND	2.6
Mean	1.9	71.4	4.2	11.2	6.2	5.2	3.1	4.3	2.6
SD	N/A	23.7	2.3	5.2	2.7	4.3	N/A	N/A	N/A
Moderate heat/static to 90-min driving condition									
Toyota — static	ND	6.1	1	3.2	ND	ND	ND	10.9	ND
Toyota — driving	2.4	11.8	2	3.8	1.3	1.8	2.8	ND	5.8
Lawryk et al., idling 30 min									
Mean	7.7	51	4.8	24.7	10.2	ND	1.3	N/A	N/A
SD	8.4	47.1	6.9	28.7	12.1	N/A	1.1	N/A	N/A
Driving in traffic									
High average	26.4	101.3	14.3	52.9	20.7	9.9	26	23.2	N/A
Low average	13.1	49.4	8.5	22.5	10.1	5.5	6.7	12.9	N/A
SCAQMD et al., urban driving									
High average	50.4	158	N/A	154	N/A	N/A	N/A	N/A	N/A
Low average	31.2	107	N/A	127	N/A	N/A	N/A	N/A	N/A
Chan et al.									
High average	17	45.7	11.6	39.3	14.8	N/A	N/A	N/A	N/A
Low average	9.9	33.3	5.8	20.9	7.3	N/A	N/A	N/A	N/A

ND — not detectable at 0.9 μg/m^3 based on an 18-1 sample volume.

N/A — not applicable or not measured or reported in the study.

Table 4. Comparison of top 20 VOCs during 90-min drive to other published values.

Compound	Current study	Chan et al. (ES&T)		
		Average for urban (n=34)	Average for interstate (n=35)	Average for rural (n=8)
Toluene	11.8	59.1	32.4	5.2
Methyl-tert-butyl ether (MTBE)	5.8	NM	NM	NM
2,2,4-Trimethylpentane	5.4	21.1	12	2.4
2-Methylpentane	5	23.6	14.9	3.2
m,p-Xylene	3.8	39.5	22.3	3.7
Pentane	3.3	27.9	16.4	5.2
2-Methylhexane	3.2	NM	NM	NM
3-Methylpentane	2.8	NM	NM	NM
Benzene	2.4	13.8	9.5	1.5
2,3,4-Trimethylpentane	2.3	NM	NM	NM
Heptane	2.2	5.2	3.2	0.7
Ethyl benzene	2	11.3	6.5	1.2
Isopentane	1.9	78.7	44.1	10.2
Cyclohexane	1.9	1.3	0.9	NM
Hexane	1.8	16.2	7.7	2.2
2,4-Dimethyl hexane	1.7	NM	NM	NM
3-Methyl hexane	1.6	NM	NM	NM
2-Methyl-1,3-butadiene	1.5	NM	NM	NM
2,3-Dimethyl butane	1.4	NM	NM	NM
o-Xylene	1.3	14.7	8.6	1.5

NM — not measured in the cited study.

to the Chan et al. (1991b) studies that were completed in the late 1980s when reformulated gas was not utilized.

Figure 5 shows that each of the three ventilation modes tested was capable of lowering in-cabin TVOCs to the same approximate magnitude. In-cabin TVOC measurements did not appear to correlate with interior temperature during driving. The in-cabin temperatures were lowest in the AC/Recirculation Mode testing (average 65°F, range 64.2–65.8°F), higher for the Vent/Fan Only Mode (average 81°F, range 73–84°F), and highest for the Window Open Mode (average 97.8°F, range 96.6–99.9°F).

Figure 6 provides the results of roadside area sampling on three occasions that illustrate trends in traffic-related airborne TVOC concentrations varying over approximately

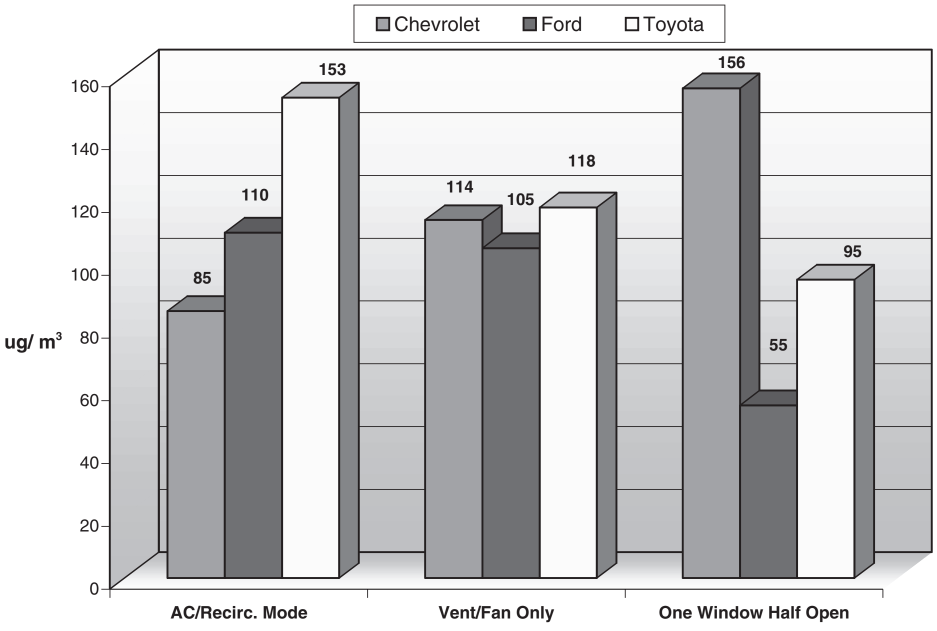

Figure 5. TVOC concentrations inside three vehicles while driving for 90 min under varied ventilation conditions.

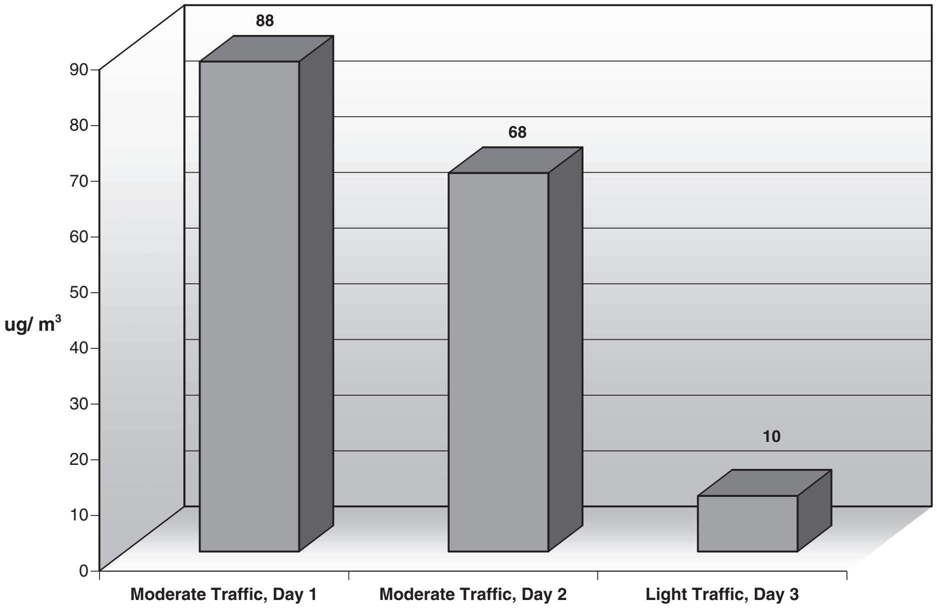

Figure 6. TVOC concentrations in outdoor air under varied traffic conditions.

an order of magnitude. The first two samples were taken during the work week when moderate traffic was transiting the area, while the third sample was taken during a weekend when much less regular traffic was present.

Discussion

The current study differs from the majority of published investigations on VOCs measured inside vehicles in that our survey was focused on characterizing the pattern and magnitude of VOCs during static and driving conditions. The majority of available studies focused primarily on quantifying selected VOC exposures during a commute (Witz et al., 1986; SCAQMD et al., 1989; Chan et al., 1991a,b; Weisel et al., 1992; Barrefors and Petersson, 1993; Lawryk et al., 1995; Jo and Choi, 1996), whereas our investigations provide insights on a somewhat broader range of accumulated VOC emissions in static vehicles, due largely to nonfuel sources of VOC emissions, e.g., styrene and phenol. The current study also provides data regarding the change in TVOC and specific VOC concentrations across vehicles of different brands, ages, and interior temperatures, and relating to changes from static conditions to varied ventilation conditions while driving.

Our pilot study of two used vehicles revealed fairly distinct VOC profiles for the two different brands tested. In one case, the VOC profile was dominated by a deodorizer compound, 2-butoxyethanol (nearly 600 μg/m^3), while the other vehicle showed predominantly C-9 alkylbenzene compounds (180 μg/ m^3) that could be related to fuel vapors or possibly solvents off-gassing from a sealant or adhesive material (see Figure 1A and B). Testing of a 1993 Toyota vehicle in the main study revealed relatively low TVOC concentrations (about 450 μg/m^3; Figure 4) in a pattern similar to the 1993 Ford (i.e., dominated by C-9 alkylbenzenes). These data suggest that minor fuel leaks or emissions from repaired items (e.g., sealants or adhesives) on 4-year-old vehicles may be a prominent source for static VOC concentrations in certain vehicles.

We also discovered a shift in the in-cabin VOC pattern between static and driving (AC on, recirculation mode) conditions in the 1993 Toyota tested in Los Angeles during moderate traffic conditions. A distinct change in VOC pattern from C-9 alkyl benzene-dominated to C-6–C-9 alkane-dominated VOCs was observed. As shown in Table 2, a homologous series of alkyl pentane compounds predominated during the driving conditions, consistent with the observations reported for auto exhaust measurements by Hampton et al. (1982). Accordingly, this shift is probably attributable to entrainment of unburned VOCs from the exhaust of other vehicles while driving in moderate traffic in Los Angeles. It further indicates that there is appreciable air turnover and exchange with outdoor air even when the ventilation is set on the AC/recirculation mode only, as suggested by other investigators who examined air exchange rates in automobiles under different conditions of operation and ventilation (Ott et al., 1992; Park et al., 1998).

TVOC concentrations inside each vehicle during static conditions were clearly dependent on interior temperature. Under static conditions, considerable differences were found in both the types and magnitude of VOCs across the three different types of vehicles tested, as well as between the same model vehicles of different ages (e.g., 4 years old *versus* less than 6 months old; see Figures 2 and 3). The TVOC level observed in the new 1997 Ford vehicle under these conditions was about a third of the new Chevrolet levels; however, this change may be due in large part to the (coincidentally) much higher average temperature achieved inside the Chevrolet (145°F) *versus* the Ford (110°F). The comparisons of our VOC concentration data with other published studies in Table 3 suggest that our measurements during static conditions are in the same range as average values reported by earlier (pre-1993) investigations of vehicles during idling or urban/interstate driving conditions.

Shifting from static to driving conditions also had a very dramatic influence on in-cabin airborne VOC concentrations in all vehicles tested during the hot summer days when this study was conducted. Figure 4 demonstrates a 4- to 20-fold change in measured TVOC concentrations between static, high-heat conditions and driving conditions with AC/recirculation mode of ventilation. Figure 5 shows that each of the three ventilation modes tested was capable of lowering in-cabin TVOCs to the same approximate magnitude, with variances being more likely due to ambient traffic conditions. These findings again suggest relatively high air turnover rates and exchange with outdoor air in all of the vehicles tested, regardless of the ventilation mode chosen. An earlier study of 140 commuter cars in the Los Angeles area showed that different ventilation conditions (open window *versus* vent *versus* AC *versus* heater) had relatively little influence (±20%) on in-cabin hydrocarbon concentrations while driving (SCAQMD et al., 1989). It seems likely that this variance is more a reflection of changes in outdoor air VOC concentrations based on the findings of our survey.

The current study was designed to examine TVOC concentration trends under a variety of test conditions and to gain insights on shifts in specific VOC compounds that may dominate the TVOC measurements. As such, this study does not provide a rigorous statistical evaluation of individual VOC concentrations, and the extent to which the data might be representative of other vehicles, other conditions, or other study designs was not examined in detail. The comparisons provided in regards to urban driving conditions in other published studies suggest that the current study data show generally lower in-cabin concentrations of gasoline-derived hydrocarbons and the presence of MTBE relating to use of reformulated gasolines in Southern California. MTBE was the second highest concentration component in the 1993 Toyota urban driving data, second only to toluene. Although our data under driving conditions are limited, they suggest that a possibly substantial influence of reformulated gasoline on the pattern and concentration of in-cabin VOCs relating to commuting exposures should be researched further.

Conclusions

Although the current study is limited in terms of the number of vehicles and different test conditions sampled, the following general conclusions can be drawn. First, interior vehicle temperature, vehicle make, age, and use of deodorizer products are important determinants of the types and magnitude of VOCs that accumulate inside new or used vehicles under static conditions. Second, driving the vehicle under any of the three ventilation conditions (AC/recirculation mode, vent mode, or vent mode+window half open) was effective in rapidly reducing the TVOC concentrations inside the cabin, achieving TWA exposure concentrations for the first 90 min of driving that were 4- to 20-fold lower than VOC concentrations measured during static, high-heat conditions. This indicates relatively high air turnover rates and exchange with outdoor air regardless of the ventilation mode chosen. And finally, our data show a shift in the pattern of individual VOCs between static and driving conditions, reflecting a greater proportion of compounds probably related to unburned fuel from other vehicles during driving conditions, and a possibly substantial influence of reformulated gasoline usage on commuter exposures.

Acknowledgments

We gratefully acknowledge Dr. Haiou Yang for her research assistance, and also the assistance of Rod Bronstein, Roxanne Agredano, and the helpful staff at Air Quality Sciences, Atlanta, GA.

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