Modeled Effects of Traffic Fleet Composition on the Toxicity of Volatile Organic Compound Emissions

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Motor vehicle emissions include many different compounds that have different levels of toxicity in humans. Volatile organic compounds (VOCs) are components of motor vehicle emissions with varying effects on human health and cancer risks. Proportional emission rates among compounds can vary substantially by vehicle and fuel type. This study addressed the question of how traffic fleet composition affects the toxicity of VOC emissions. Using inhalation unit risk estimates from the U.S. Environmental Protection Agency, VOC risk profiles were quantified for vehicle–fuel type combinations, light-duty and heavy-duty vehicle fleets, and roadway facility types (on-network and off-network). Of 14 modeled VOCs, formaldehyde, benzene, naphthalene, and 1,3-butadiene contribute most to the cumulative risk of vehicle emissions. Formaldehyde and naphthalene are mainly emitted by diesel vehicles; benzene and 1,3-butadiene are mainly emitted by gasoline vehicles. Cumulative VOC risk generated per on-network vehicle mile is four times higher for a gasoline heavy-duty vehicle and eight times higher for a diesel heavy-duty vehicle than for a gasoline light-duty vehicle. Off-network, cumulative VOC risk generated per vehicle is twice as high for gasoline heavy-duty vehicles as for diesel heavy-duty vehicles or gasoline light-duty vehicles. A case study of lane management strategies demonstrated how traffic management can change a VOC emissions risk profile and that changes in VOC emissions risk are different from changes in VOC emissions mass.

Air pollution levels in Western Europe and North America have generally declined since the late 20th century, but they are increasing in some rapidly industrializing countries, notably in Asian countries. Over the past decades, various studies have found an association between air pollution and negative health outcomes. Some of these effects are associated with development of asthma, reduced lung function, increased blood pressure (*1*), and a rise in cardiovascular morbidity (*2*) and cancer (*3–5*). Various studies have shown an association between cancer propensity and outdoor air pollution (*6–8*); however, fewer studies have found an association with cancer incidence (*9, 10*).

Volatile organic compounds (VOCs) are a group of carbon-containing compounds that evaporate readily at room temperature.

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VOCs are emitted by mobile sources and have negative effects on human health (*11*). VOCs pose hazards to human health as tropospheric ozone precursors (*12, 13*) and as contributors to cancer risk (*14*). Weichenthal et al. suggest that it is not appropriate to group all VOCs together when performing a health risk assessment because toxicity varies and not all VOCs are toxic (*2*). Tsai et al. found an increase in cardiovascular mortality in Taichung because of increases in propane, iso-butane, and benzene concentrations (*15*). Fujinaga et al. suggest that the risk of cancer from exposure to VOCs outdoors and in vehicles was high for benzene, carbon tetrachloride, and tetrachloroethene (*16*).

Polycyclic aromatic hydrocarbons (PAHs), a group of VOCs consisting of two or more aromatic rings, have the ability to bind to cellular proteins and DNA. They are metabolized enzymatically by the body and in some cases can react, causing mutations, malformations, tumors, and cancer (*17*). PAHs are mainly produced by the incomplete combustion of fossil fuels, industrial emissions, brushwood, straw, moorland heather, smoking, and soil. Liu et al. quantified incremental lifetime cancer risk associated with exposure to PAHs and found that although gasoline contributes less to the amount of emitted PAHs than does diesel, the cancer risk associated with it is higher (*18*).

The World Health Organization's International Agency for Research on Cancer lists cancer sites associated with different carcinogenic agents on the basis of information collected for more than 40 years (*19*). Each association was made on the basis of available evidence of the impact of the agent in humans. The findings suggest that there is sufficient evidence to conclude that exposure to benzene and formaldehyde is related to leukemia, exposure to benzo(a)pyrene is related to lung cancer, and exposure to 1,3-butadiene is related to cancer in hemolymphatic organs.

Many VOCs are emitted by vehicle sources (*20–24*) and are concentrated near high-traffic roadways (*1*). Traffic emissions of VOCs depend on many variables associated with each vehicle and operating conditions: vehicle type and age, engine condition, speed, fuel type, presence of emission control systems, and so on (*11, 25–27*). Previous studies have examined fuel and vehicle types from the perspective of VOC mass emission rates, near-road concentrations, and potential ozone and secondary organic aerosol formation. This study addressed the question of how traffic fleet composition affects the toxicity of motor vehicle VOC emissions—specifically, cancer risk from near-road exposure. Toxicity-weighted VOC emissions profiles can be used to identify the compounds and vehicle and fuel types that pose the highest risk for travelers, in addition to assessing the VOC risk trade-offs of traffic management strategies that affect fleet composition.

METHODOLOGY

To quantify cancer risk from inhaled VOCs emitted by mobile sources, the methodology presented in the U.S. Environmental Protection Agency's (EPA) *Risk Assessment Guidance for Superfund, Part F*, was used (*28*). Cancer risks depend on exposure time and compound toxicity. Excess lifetime cancer risk for a carcinogen receptor that was exposed via inhalation is the product of scaled exposure concentration (EC) (μg/m³) and the inhalation unit risk (IUR) $(\mu g/m^3)^{-1}$ for the VOC analyzed, x:

$$\text{risk}_x = \text{IUR}_x \times \text{EC}_x \tag{1}$$

IUR is the "upper-bound excess lifetime cancer risk estimated to result from continuous exposure to an agent at a concentration of 1 μg/m³ in air" (*28*); it is estimated as a linear extrapolation from exposures observed in studies with animals and humans. EPA provides the value for IUR only for pollutants with established carcinogenic effects. IUR values were collected from the Risk Assessment Information System (*29*).

EC is calculated for compound x as

$$\text{EC}_x = \frac{\text{CA}_x * \text{ET} * \text{EF} * \text{ED}}{\text{AT}} \tag{2}$$

where

CA_x = VOC concentration in exposure air (μg/m³),
ET = exposure time (hour/day),
EF = exposure frequency (day/year),
ED = exposure duration (years), and
AT = averaging time (lifetime in years × 365 days/year × 24 hours/day).

In this study, CA_x was considered as the incremental VOC(x) concentration above the background concentration. CA_x can be calculated from the vehicle emission rate per unit activity ($E_{x,v}$) for vehicle–fuel type v in the set of vehicle–fuel types V, the amount of vehicle activity (A_v), and a dispersion parameter (D), which is assumed to be independent of the compound or vehicle–fuel type:

$$\text{CA}_{x,v} = \sum_{v \in V} \frac{E_{x,v} A_v}{D} \tag{3}$$

We assume that D and the exposure time parameters (ET, EF, ED, and AD) are fixed and outside the scope of the study. These fixed factors are grouped into a single parameter, F, which is the same across studied VOCs. The risk of roadway exposure to compound x attributable to vehicle–fuel type v is then based on IUR, the emission rate, the amount of activity, and the fixed parameter:

$$\text{risk}_{x,v} = \text{IUR}_x E_{x,v} = \text{IUR}_x E_{x,v} A_v F \tag{4}$$

VOC emission rates for 2015 were estimated using the Motor Vehicle Emission Simulator model (MOVES), from the U.S. Environmental Protection Agency (*30*). MOVES emissions modeling features representative average-speed distributions by road type and vehicle type. Emission rates for various vehicle type combinations were modeled for benzene, methyl tertiary butyl ether, 1,3-butadiene, formaldehyde, acetaldehyde, ethylbenzene, dibenz(a,h)anthracene, benz(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)-fluoranthene, chrysene, indeno-pyrene and naphthalene. Figure 1 shows IUR values for these VOCs.

Fifty-two vehicle–fuel type combinations (13 vehicle types and four fuel types) were modeled in MOVES; however, only combinations that were more than 1% of the total vehicle miles traveled

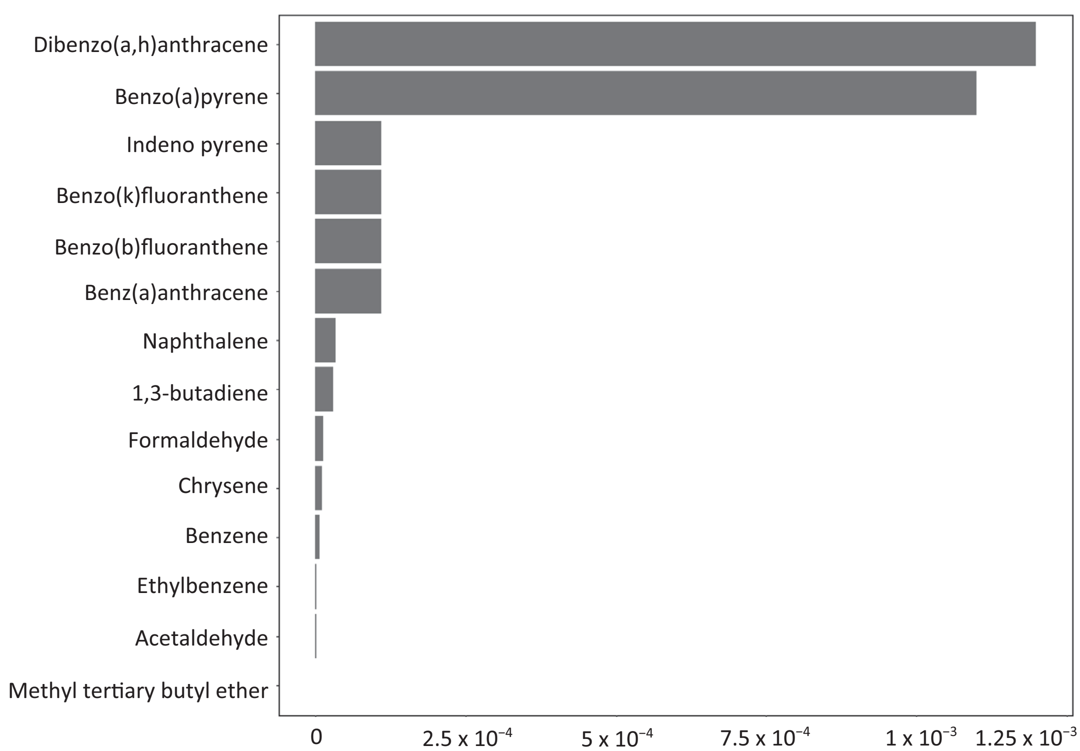

FIGURE 1 Inhalation unit risk factors for modeled VOCs.

(VMT) were included in the analysis. Two categories of facilities were modeled: on-network (urban or rural and restricted or unrestricted) and off-network. Urban and rural unrestricted roadways are arterials, collectors, and local streets; urban and rural restricted roadways are limited-access highways. Off-network facilities are locations such as parking lots, truck stops, and bus terminals (*31*). The modeled processes were running and start exhaust, evaporation permeation, evaporation fuel vapor venting, evaporation fuel leaks, crankcase start exhaust and extended idle exhaust, refueling displacement vapor loss, and refueling spillage loss. For on-network facilities, emission rates were calculated as mass per vehicle mile; for off-network locations, emission rates (primarily evaporative) were calculated as mass per vehicle per day.

Cancer risk ratios were used to cancel out the parameter F and so generalize the study by avoiding specific dispersion conditions or exposure duration. For on-network facilities, cancer risk of exposure to VOC x emitted in 1 VMT of vehicle–fuel type v ($A_v = 1$) was normalized by the risk of benzene emitted in 1 VMT by a gasoline passenger car (GPC) (Equation 5). For off-network facilities, cancer risk of exposure to VOC x per vehicle of type v in the population ($A_v = 1$) was normalized by the risk of benzene per GPCs in the population (Equation 6). Risk ratios depend on varying toxicity and emission rates. Note that F values for on-network and off-network risks would be very different, so they cannot be directly compared.

$$\text{on-network risk ratio}_{x,v} = \frac{(\text{IUR}_x E_{x,v})}{(\text{IUR}_{\text{benzene}} E_{\text{benzene,GPC}})} \quad (5)$$

$$\text{off-network risk ratio}_{x,v} = \frac{(\text{IUR}_x E_{x,v})}{(\text{IUR}_{\text{benzene}} E_{\text{benzene,GPC}})} \quad (6)$$

The risk value for benzene for GPCs was chosen as the normalization factor because it is a well-established carcinogen (*32*); with 1,3-butadiene it accounts for 68% of the cancer risk from all vehicle-related pollutants (*33*). More, GPCs cover up 45% of the national VMT.

Summing risk ratios for various VOCs (on-network or off-network) results in cumulative normalized risk (Equations 7 and 8). This value was used to compare the overall cancer risk attributable to different vehicle–fuel type combinations—although absolute cancer risk cannot be estimated without air quality modeling.

$$\text{on-network cumulative risk ratio}_v = \sum_{x_i \in x} \text{on-road risk ratio}_{x,v} \quad (7)$$

$$\text{off-network cumulative risk ratio}_v = \sum_{x_i \in x} \text{off-road risk ratio}_{x,v} \quad (8)$$

RESULTS

This section presents risk ratios for vehicle–fuel type combinations, light-duty and heavy-duty vehicle fleets, and facility types.

Vehicle activity (as VMT for on-network facilities and vehicle population for off-network) was calculated for each facility from MOVES model outputs (Figure 2). Fleet composition is characterized by passenger cars and trucks, combination long-haul trucks, light commercial trucks, and single-unit short-haul trucks.

Figure 3 shows the cumulative risk ratios for vehicle–fuel type combinations that accounted for at least 1% of total VMT. VOC risk ratios that were always below 1 across the variables were grouped into the category Others. For diesel vehicles, the risk ratios for formaldehyde and naphthalene are highest; for gasoline vehicles, the risk ratios for benzene, formaldehyde, and 1,3-butadiene are highest. The risk ratios reflect varying toxicity and emission rates. Only 1,3-butadiene, acetaldehyde, formaldehyde, naphthalene and benzo(a)pyrene are higher than 1 for any vehicle–fuel type

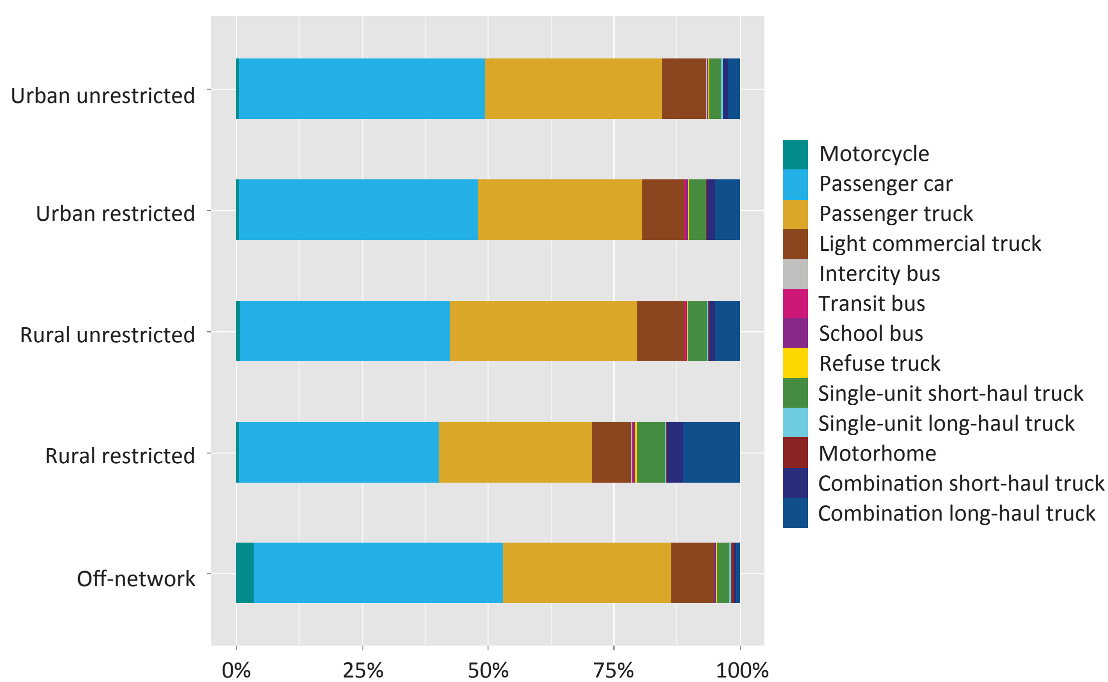

FIGURE 2 Fraction of vehicle activity by modeled vehicle types (on-network: VMT; off-network: vehicle population).

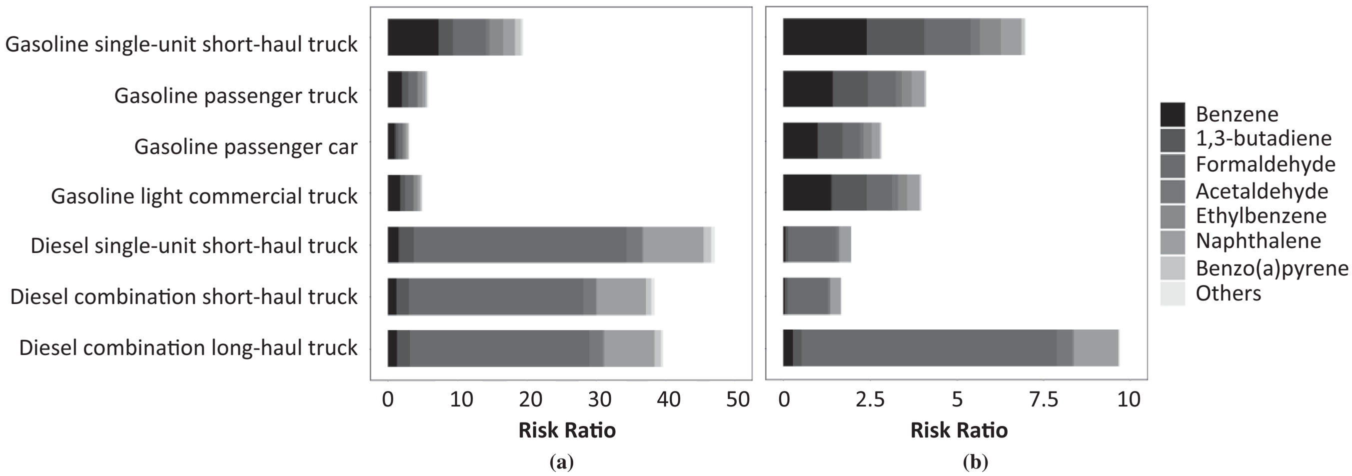

FIGURE 3 Cumulative risk ratios for (*a*) on-network and (*b*) off-network facilities by vehicle–fuel type.

(i.e., higher than the risk assigned to benzene emissioning from one GPC).

Figure 3 shows that diesel single-unit short-haul trucks have the highest on-network cumulative risk ratio (47), with the highest risk ratios for 1,3-butadiene (2.2), acetaldehyde (2.2), benzo(a)pyrene (1.1), formaldehyde (30.7), and naphthalene (8.7). In contrast, 1,3-butadiene, acetaldehyde, benzo(a)pyrene, formaldehyde, and naphthalene were 1.8%, 25.3%, 0.03%, 58.8%, and 6.4%, respectively, of urban unrestricted VOC emissions on a mass basis. Gasoline single-unit short-haul trucks have the highest risk ratios for benzene (7.3) and ethylbenzene (1.9). For gasoline passenger trucks, the risk caused by benzene from 1 VMT is twice the risk from a GPC because of mass emission rate differences. Jacobson developed a model to examine the effect on cancer in the United States from converting from gasoline to ethanol. The study also found that major human carcinogens emitted during gasoline combustion are formaldehyde, acetaldehyde, 1,3-butadiene, and benzene (*34*).

Off-network risk ratios in Figure 3 were calculated from emission rates per vehicle per day. Taking into account running, start, refueling, crankcase operation, and evaporative off-network processes, the findings suggest that risk ratios are between 0 and 7. Formaldehyde is again one of the VOCs that has a significant impact in the cumulative risk for most of the vehicle-fuel combinations; however, benzene and 1,3-butadiene contribute significantly to the cumulative cancer risk for gasoline single-unit short-haul trucks and gasoline combination short-haul trucks. Adding emissions from extended idle exhaust processes, the risk ratio for formaldehyde per diesel combination long-haul truck in the population is more than 100. For diesel combination long-haul trucks, 62% of the VOC mass is emitted during the extended idle exhaust process.

Vehicle classes include vehicle–fuel type combinations above 1% of the total VMT. The light-duty vehicle class includes GPCs, gasoline passenger trucks, and gasoline light commercial trucks. The heavy-duty vehicle class includes gasoline and diesel single-unit short-haul trucks, diesel combination short-haul trucks, and diesel combination long-haul trucks. Light-duty and heavy-duty vehicle classes were compared in terms of risk ratio to take into account that heavy-duty vehicles contribute a disproportionate share of on-network emissions compared with the vehicle population. Figure 4 shows cumulative risk ratios for these vehicle classes for

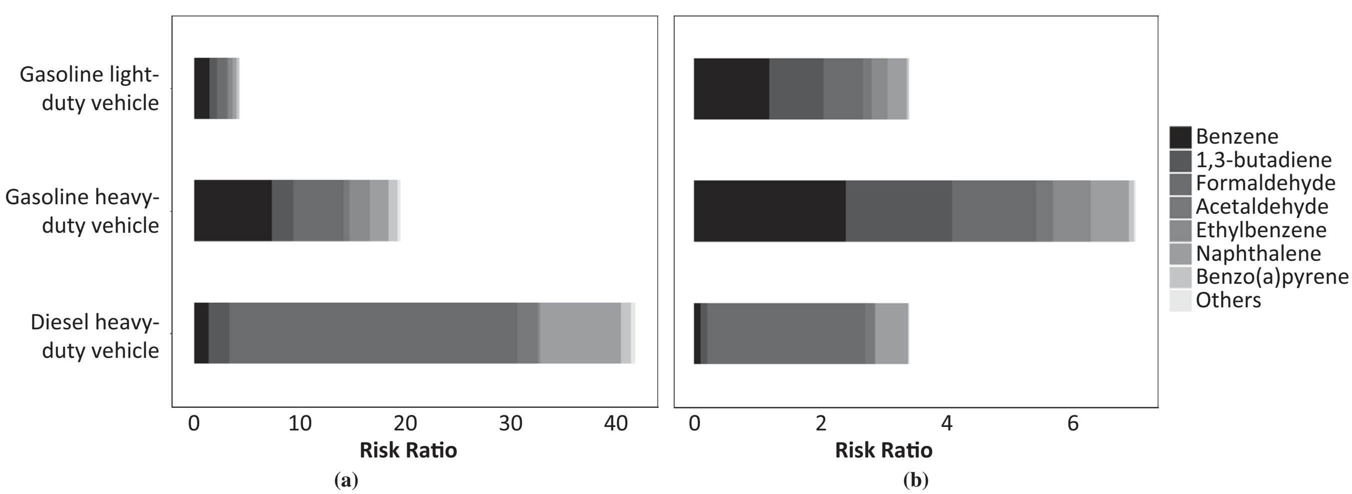

FIGURE 4 Cumulative risk ratios for (*a*) on-network and (*b*) off-network facilities by vehicle class.

on-network and off-network facilities, taking into account running, start, refueling, crankcase operation, and evaporation processes. For on-network facilities, the gasoline light-duty cumulative risk ratio (4.3) is much lower than heavy-duty cumulative risk ratios for both fuel types (41.7 for diesel and 19.5 for gasoline).

Figure 4 shows that diesel heavy-duty vehicles have the highest on-network cumulative risk ratio and the highest risk ratios for naphthalene (7.7) and formaldehyde (27.2). Across the facilities, gasoline heavy-duty vehicles have the highest risk ratios for benzene (7.3), formaldehyde (4.7), 1,3-butadiene (2.1), and ethylbenzene (1.9). In contrast to the portions of formaldehyde, and 1,3-butadiene in the cumulative risk, these compounds represent only 14.3% and 2.7% of the total mass emitted.

For off-network facilities, Figure 4 shows that gasoline heavy-duty vehicles have the highest cumulative risk ratio (6.9), with the highest risk ratios for all the VOCs excluding formaldehyde, which is almost half of the risk ratio in diesel heavy-duty vehicles. Off-network gasoline vehicle classes have the highest risk ratios for benzene; off-network diesel vehicles have high formaldehyde risk ratios. Although the portion of acetaldehyde mass emitted by gasoline heavy-duty vehicles (14.3%) is the second highest after benzene, the portion for the off-network cumulative risk ratio is low (4%) because of the IUR value.

Figure 5 shows cumulative cancer risk per unit activity from combined traffic on different facilities, aggregating the information for the various vehicle–fuel type combinations. Across facilities, the highest portion of cumulative risk among the 14 studied compounds is attributed to formaldehyde, followed by naphthalene, benzene, and 1,3-butadiene. Although benzene and naphthalene have a similar risk ratio for each facility, naphthalene on a mass basis represents only from 3% to 4% of total VOC emissions, while benzene represents more than 20%; this is the result of the high IUR for naphthalene (4.8 times the benzene IUR).

Rural restricted roadways have the highest cumulative cancer risk ratio (10.1) per VMT compared with other roadways, and the highest risk ratios for acetaldehyde (0.4), benzo(a)pyrene (0.4), formaldehyde (5.0), and naphthalene (1.5). Figure 5 shows that rural restricted facilities have a high share of combination long-haul trucks, which have high acetaldehyde and formaldehyde emission rates. From a rural, restricted emissions mass basis perspective, acetaldehyde, benzo(a)pyrene, formaldehyde, and naphthalene account for 18.7%, 0.03%, 38.8%, and 4.4%, respectively.

Urban unrestricted roadways have the highest risk ratios for 1,3-butadiene (0.9), benzene (1.8), and ethylbenzene (0.5) because of the high fraction of light-duty vehicles. Urban unrestricted roadways are also characterized by stop-and-go driving, resulting in larger VOC emission rates per mile (*35, 36*). In contrast to what is shown in Figure 5, formaldehyde, naphthalene, benzene, and 1,3-butadiene were 32.0%, 3.7%, 25.6%, and 3.0%, respectively, of urban unrestricted VOC emissions on a mass basis. Off-network cumulative risk is attributed to benzene (1.1), 1,3-butadiene (0.8), and formaldehyde risk (0.7) in similar proportions. The portion of the cumulative risk for benzene (33.2%), acetaldehyde (4.2%), ethylbenzene (7.2%), and 1,3-butadiene (23.9%) is higher than for on-network facilities, most likely because of a larger share of evaporative emissions.

On-network risk ratios were compared against risk ratios calculated from VOC emission rates and near-network concentration values from other studies. Two studies were used for comparison. One was by Fujinaga et al., who estimated total cancer risks from concentrations measured inside GPCs at on-network and off-network facilities (*16*) and one was by Schauer et al., who measured tail-

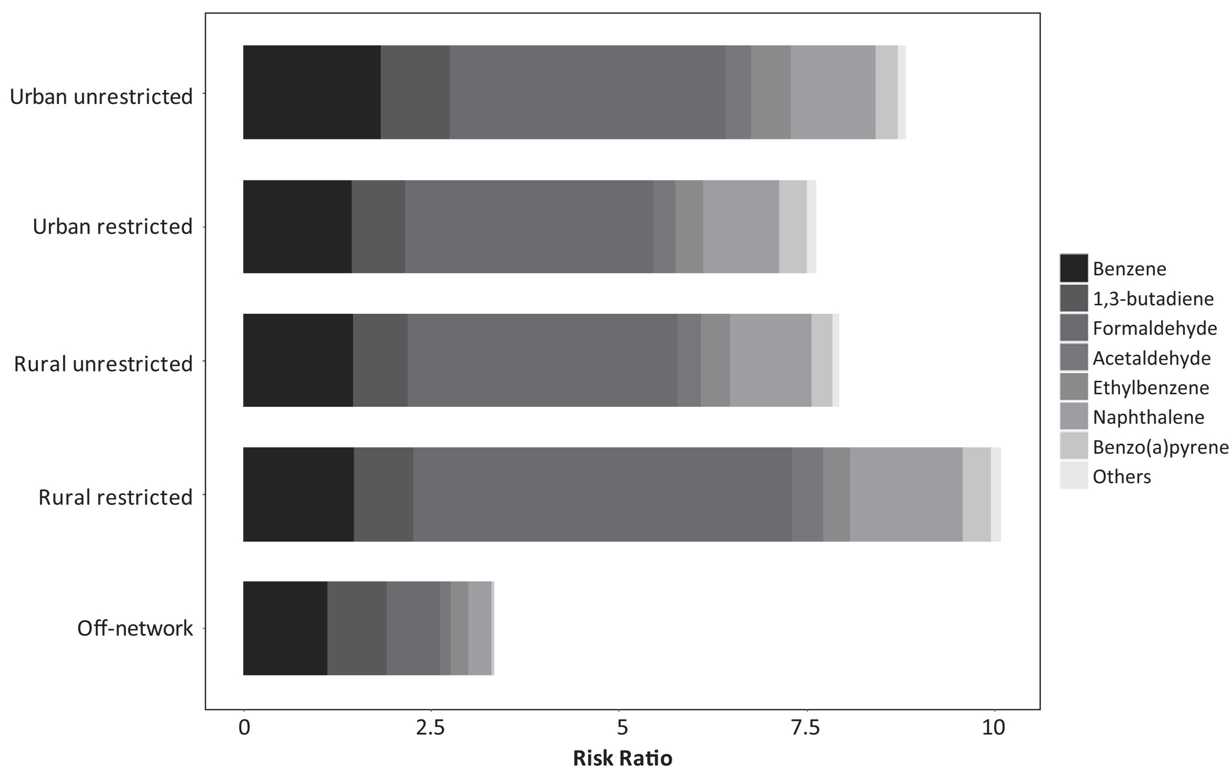

FIGURE 5 Cumulative risk ratios by facility.

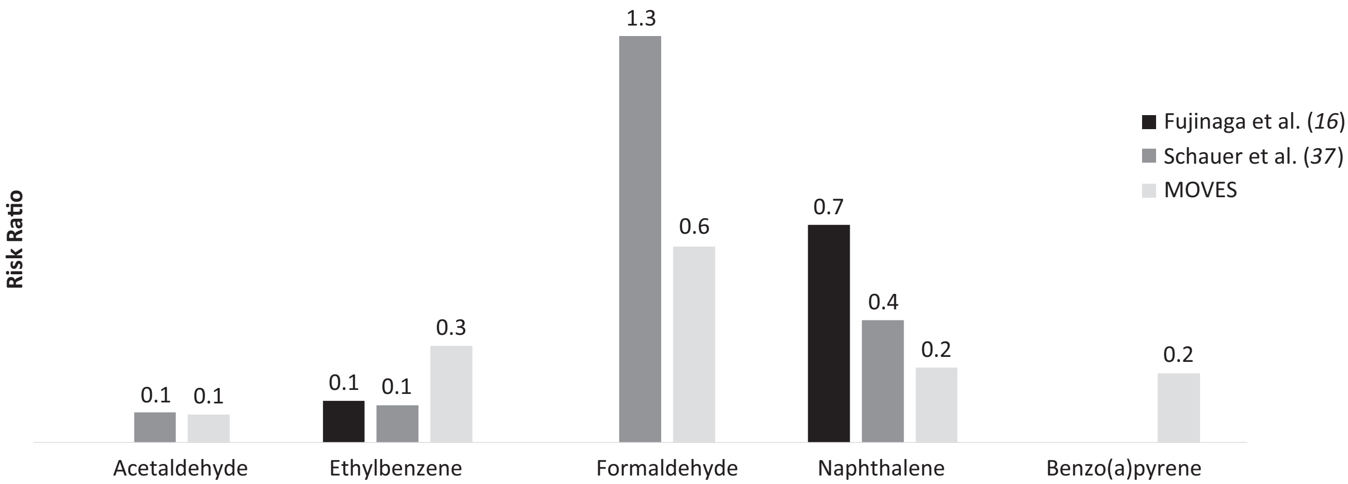

FIGURE 6 Gasoline passenger car risk ratios from various studies.

pipe emission rates of VOCs from gasoline motor vehicles (*37*). Results are summarized in Figure 6. GPC ratios for ethylbenzene and benzo(a)pyrene are higher for MOVES data than for real-world data measured in other studies. The Fujinaga et al. and Schauer et al. studies show some similarity for ethylbenzene ratios, but not for naphthalene. In the Fujinaga et al. study, data were collected at on- and off-network facilities, affecting concentration measurements because of the inclusion of evaporation processes. Comparing MOVES data against data from the Fujinaga et al. study suggests that the acetaldehyde ratios differ by less than 1%. This comparison also shows that in the Schauer et al. study, the highest risk was formaldehyde, followed by naphthalene and ethylbenzene. MOVES data show a similar distribution; risk is higher for formaldehyde, followed by ethylbenzene and naphthalene.

CASE STUDY

A case study was used to show how changes in traffic composition can influence VOC risk profiles. Vehicle class–segregated lane strategies (e.g., truck-only or bus-only lanes) and traffic management strategies, such as restrictions on heavy-duty vehicles on certain roads or during certain time periods, have been implemented in various places all over the world (Bogotá, Colombia; Beijing, China; Ahmedabad, India; Barcelona, Spain; and Santiago, Chile, to mention a few examples) in response to congestion, air pollution, and climate change. Bigazzi and Figliozzi estimated emissions effects of four managed-lane scenarios and found that vehicle class–segregated lane strategies (truck-only lanes) tend to have greater emissions reductions than general-purpose lane strategies (*38*). Emission rates were modeled using MOVES for the I-5 freeway in Portland, Oregon, for 2010, segmented into light-duty and heavy-duty vehicles. In contrast to this study, Bigazzi and Figliozzi calculated emission rates as a function of speed and congestion levels; for this reason, only truck-only lane scenarios were used for the case study (*38*).

Using data from Bigazzi and Figliozzi, incremental risk (Equation 1) was quantified during travel above background risk to compare two managed-lane strategies (which take into account elastic demand). Traffic flows in vehicles per hour (vph) for light-duty (q_{LD}) and heavy-duty (q_{HD}) vehicles in each scenario were the following:

1. Base condition: $q_{\mathrm{LD}} = 4{,}860$; $q_{\mathrm{HD}} = 540$.
2. Add a truck-only lane: $q_{\mathrm{LD}} = 5{,}056$; $q_{\mathrm{HD}} = 591$.
3. Convert one general-purpose lane to a truck-only lane: $q_{\mathrm{LD}} = 4{,}428$; $q_{\mathrm{HD}} = 591$.

Exposure concentration (Equation 2) was calculated using on-network incremental concentration and receptor exposure time ($ET * EF * ED/AD$) equal to 1 (i.e., travel time equal to the time spent in the background concentration). On-network incremental concentration (Equation 3) was estimated from the emission rates (per distance) calculated in the previous section, activity values of the traffic flows shown above, and a dispersion factor of 9.87 m^2/s (*39*) for all VOCs. Figure 7 shows results of this analysis for all 14 VOCs as the percentage of change in risk from base conditions for each strategy.

Because of a shift toward heavy-duty vehicles in the fleet, the truck-only lane strategies disproportionately increase the contribution of aldehydes and decrease the contribution of aromatics to cumulative risk. Converting the general-purpose lane to a truck-only lane results in a decrease of incremental risk for benzene (–4.1%), acetaldehyde (–3.3%), formaldehyde (–6.4%), and ethylbenzene (–7.1%) because of the reduction in volume of light-duty vehicles. Figure 8 shows the cumulative risk for the truck-only lane strategies and the base conditions.

Cumulative risk increased for both scenarios from the base conditions: adding the truck-only lane resulted in an increase of 6.7% in the cumulative risk; converting one general–purpose lane to trucks only increased cumulative risk by 0.08%. Because of the increase in heavy-duty and light-duty vehicles in the fleet for the trucks-only-lane-added scenario, risks for all VOCs were higher than in other conditions. Formaldehyde (44% to 46%) and benzene risks (18% to 19%) have the highest portions of cumulative risk across the various scenarios. Heavy-duty vehicles contribute to the cumulative risk because of risk portions for formaldehyde (63%) and naphthalene (18%) within this fleet; in terms of emitted mass, the portions for formaldehyde and naphthalene are 55% and 6%, respectively. Although for acetaldehyde the mass portion is 24%, its contribution in cumulative risk for heavy-duty vehicles in different scenarios is around 5%. Light-duty vehicles contribute to the cumulative risk because of the risk portions for benzene (32%) and formaldehyde (26%) within this fleet. Benzene and formaldehyde contribute 37%

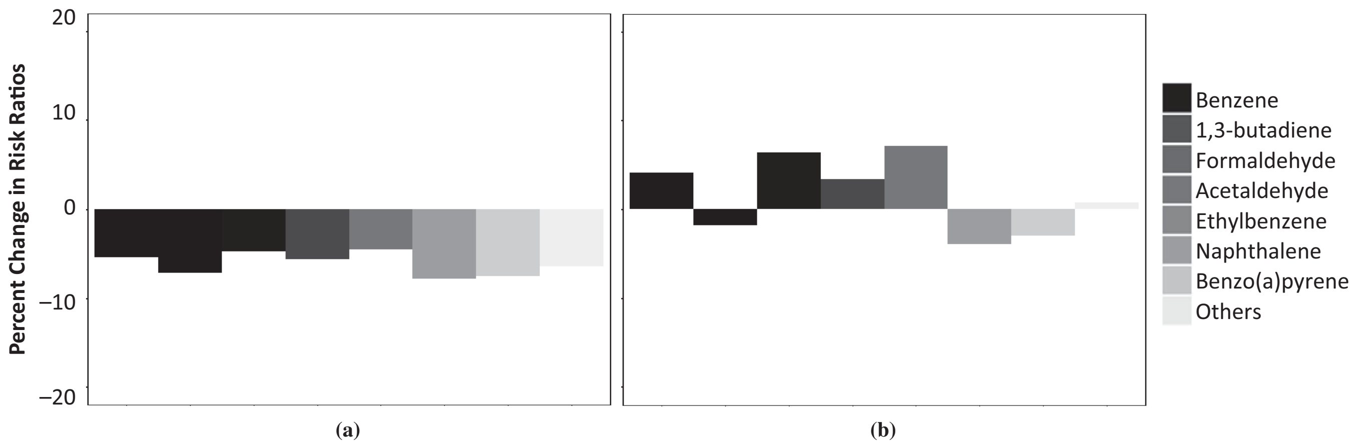

FIGURE 7 Changes in risk for two different managed-lane strategies: (*a*) truck-only lane added and (*b*) truck-only lane conversion.

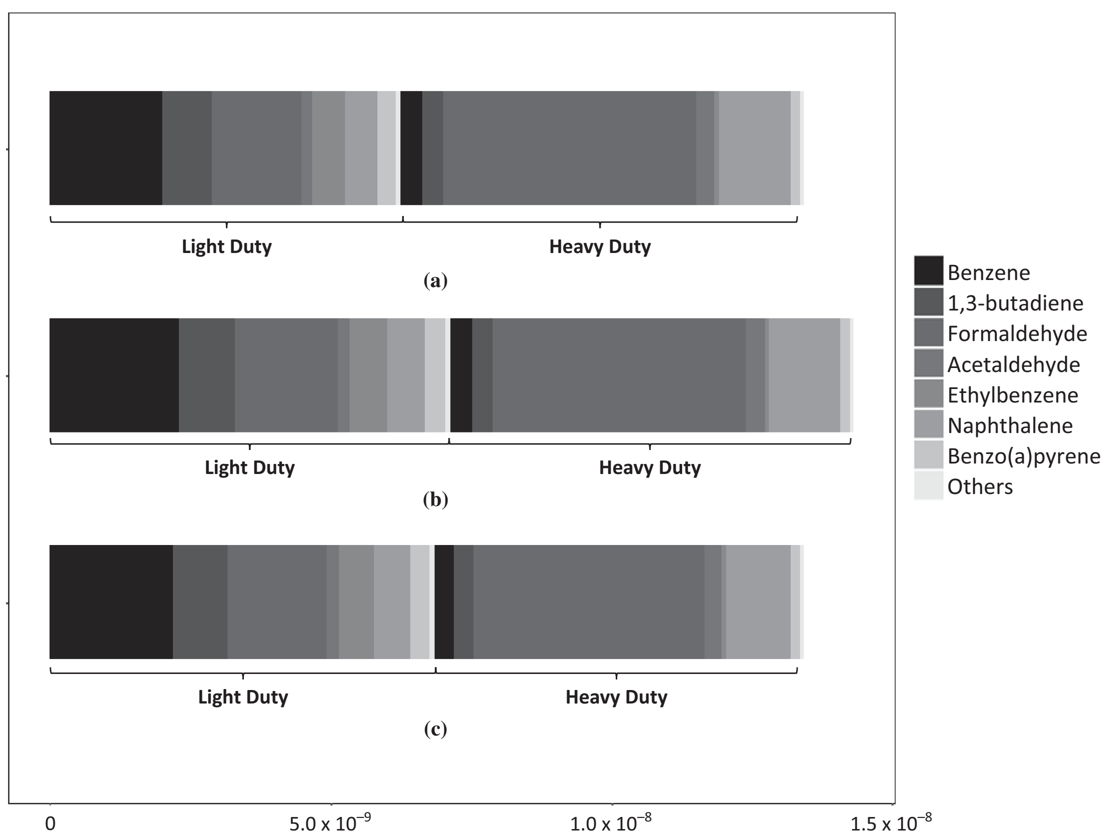

FIGURE 8 Cumulative risk for two different managed-lane strategies: (*a*) truck-only lane conversion, (*b*) truck-only lane added, and (*c*) base conditions.

and 16%, respectively, to the VOC profiles in terms of mass. Ethylbenzene has a portion of 30% on a mass basis for the VOCs emitted; in contrast, the risk associated for the different strategies is less than 10% for the cumulative risk for light-duty vehicles.

Results from the case study account only for changes in emissions and do not account for other factors, such as proximity to the truck-only lane or exposure time. Distance between the receptor and the truck-only lane is expected to have a large effect on cumulative risk because of the concentration of the VOCs. And even in scenarios with larger traffic volumes than in the base condition (higher emissions), if exposure time is reduced, the cumulative risk may be lower.

CONCLUSIONS

This research assessed how traffic composition affects the toxicity of VOC emissions. Of 14 modeled VOCs, four stand out because of their contribution to the cumulative cancer risk of vehicle emissions in relation to their toxicity and emission rates for different combinations of vehicle types: benzene, 1,3-butadiene, formaldehyde, and naphthalene. On-network, diesel heavy-duty vehicles generate the highest cumulative risk per mile because of formaldehyde and naphthalene emissions; benzene contributes more to cumulative risk for gasoline vehicles. The IUR for formaldehyde is almost two times higher than for benzene and formaldehyde emission rates for diesel vehicles are 10 times higher than benzene emission rates. Off-network, gasoline heavy-duty vehicles generate the highest cumulative risk per vehicle because of benzene and 1,3-butadiene emissions (primarily evaporative).

Cumulative VOC risk generated per vehicle mile on-network is four times higher for a gasoline heavy-duty vehicle and eight times higher for a diesel heavy-duty vehicle than for a gasoline light-duty vehicle. Off-network, cumulative VOC risk generated per vehicle is twice as high for gasoline heavy-duty vehicles as for diesel heavy-duty vehicles. It is also twice as high as for gasoline light-duty vehicles. Rural restricted roadways have the highest cumulative risk per vehicle mile because of the relatively high proportion of combination long-haul trucks. Urban unrestricted roadways have the second-highest cumulative risk per vehicle mile because of benzene and 1,3-butadiene from gasoline vehicles and high emission rates in stop-and-go conditions. A case study of lane management strategies demonstrated that traffic management can change the VOC emissions risk profile and that changes in VOC emissions risk are different from changes in VOC emissions mass.

This research assessed vehicle fleet-specific VOC emissions characteristics on a broad national scale; it did not assess the effects of speed and congestion on emission rates and subsequent risk. Post-emission dispersion and transformation are not explicitly modeled and are assumed to be the same among the modeled VOCs. This assumption is more likely to hold for on-network risk profiles than for off-network risk profiles, with likely longer time lags between emission and exposure. The methodology presented could be enhanced by addressing the effects of source-to-receptor distance on risk. Distance from the roadway is expected to have a larger impact on cumulative risk than on the relative risk studied here. Increasing distance from the roadway can affect relative risk for VOCs with different concentration–distance relationships because of the influences of background concentrations and atmospheric transformation (*40*). Another factor that will influence cumulative risk is the evolution of the vehicle fleet. A 2015 vehicle fleet was analyzed in this study; average vehicle emission rates are generally expected to decline over time because of improved exhaust controls and alternative fuels, such as electricity. The relative risks described here could also be affected if the penetration rates of new technologies vary among vehicle types. For example, if the light-duty fleet converts to electricity faster than the heavy-duty fleet, the average (per vehicle or VMT) toxicity of emissions from the light-duty fleet will decrease relative to the heavy-duty fleet.

There is both uncertainty and variability in the health effect parameters and IUR values used in this research; they were calculated on the basis of various assumptions and sometimes measured only health effects on animals. Impacts were generalized for human population in those cases on the basis of other parameters measured by the EPA. The authors recognize that there is limited precision to the IUR values; however, the factors used here were chosen on the basis of the best available evidence nowadays.

The findings of this paper can be used to map areas or corridors with high relative risk on the basis of the identified vehicle types and factors; these maps could later be used to estimate more accurate population exposure levels. This methodology would be useful in the development of a health impact assessment, which is a set of qualitative and quantitative techniques to address the potential health impacts that a project or policy may generate within a community. The methodology and findings from this paper could be used as a supplementary tool to estimate cancer risk changes caused by traffic composition for transportation projects.

Future work should consider differential transformation rates by compound and the effects of congestion levels on VOC emissions risk profiles. Estimation of various levels of exposure, to consider the impact of traffic VOCs risks for different sociodemographic groups, is indispensable in identifying vulnerable groups. This type of analysis can be replicated to consider the impact of vehicle–fuel type combination risk ratios in different professions; for example, policemen and truck drivers have a higher exposure to traffic-related VOCs that pose a potential threat to their health. Last, another group of VOCs with noncancerous effects have been found to be hazardous for human health; future work should address the question of how vehicle fleet composition and operation affect the toxicity of these compounds.

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