HEALTH RISK CHARACTERIZATION FOR TRANSPORT USERS AND WORKERS: COMMUNITY HEALTH AND CUMULATIVE RISK CONSIDERATIONS

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16. Abstract: We conducted an exposure assessment for consumers to characterize benzene (and other volatile organic compounds) exposure associated with vehicle refueling using modern sampling and analysis methodologies. The consumer exposure assessment data were extended to an occupational setting by developing worker exposure scenarios to estimate excess risk values for gasoline service station attendants and pump attendants. The risk assessment results for the consumers were then put in a holistic health context including an analysis of other individual, community, and socio-economic factors (a cumulative risk characterization). While benzene exposure during refueling was not a major cancer contributor, cancer risk was found to be a concern due to exposures to ambient air toxics. Transportation-related sources contributed to four of the five top air toxic carcinogens identified. Cancer is a major cause of death in all participant communities and half of the study participants resided in communities where challenging socio-economic conditions have potential to increase cancer mortality overall and reduce survival times for cancer patients. This cumulative risk characterization found cancer risk to be a concern in both the ambient environmental and community settings suggesting a management approach targeting both the exposure and community context.

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Executive Summary

Problem Statement

Transportation-related emissions make substantial contributions to numerous air pollutants of greatest environmental and public health concern including particulate matter (PM), carbon monoxide, ozone precursors, and volatile organic compounds (VOCs) including the Hazardous Air Pollutants or air toxics (US EPA 2014a). The potential exposures to gasoline and its constituents are well documented in the occupational setting such as refinery workers or tanker truck drivers, but modern high-quality exposure assessment data for gasoline station consumers and employees are severely lacking. The literature indicates that data for potential exposures to gasoline have not been assessed in the U.S. context for over 30 years. The results from a comprehensive exposure and risk assessment will fill this knowledge gap and ensure that current regulations and best practices are both health protective for consumers and employees at gas stations. Over this 30-year gap, both exposure and risk assessment methods have advanced, suggesting potential for an updated assessment to inform new risk management and policy approaches.

Technical Objectives

This work was designed to meet four main objectives: 1) design and implement a novel self-sampling protocol for benzene, toluene, ethylbenzene, and xylene exposures to consumers during vehicle refueling; 2) estimate cancer risk to consumers from the measured benzene exposures; 3) evaluate potential cancer risk for pump attendants in an occupational scenario building on the consumer data; and 4) develop a cumulative risk characterization for the consumers combining the cancer risk assessment findings with ambient environmental exposures to benzene and other air toxics, personal psychosocial, and community socio-economic and health data from both primary and secondary sources. The cumulative risk characterization will allow an exploration of a more comprehensive human health risk management approach beyond the specific refueling exposure that considers the broader community context.

Key Findings

Refueling Exposure and Risk

Refueling exposures averaged 5.7 ppb for benzene, 23.5 ppb for toluene, 3.9 ppb for ethylbenzene, and 16.7 ppb for xylene. Using the benzene exposure results, we developed consumer and occupational probabilistic cancer risk estimates. Cancer risk estimates were very low and below risk management limits for both consumer and occupational scenarios. These results were published in January 2021 (Patton et al. 2021).

Personal and Community Context

The study participants resided primarily in Baltimore City, Maryland, with a few residing in the neighboring areas of Baltimore, Anne Arundel, or Prince George's Counties and two residing in the Arlington or Loudoun Counties of Virginia. Based on the personal perceived stress survey instrument, stress levels were low to moderate for participants. Community health was poorest in Baltimore City and County and more favorable in the Virginia communities; however, cancer was the second most common cause of death in each community with the exception of Loudon County, Virginia, where cancer was the most common cause of death. Socio-economic conditions followed the same trend as observed in the community health data with the most challenging conditions in Baltimore City and County and greater affluence in other areas. All participant communities experience an increased risk of cancer due to ambient air toxics; on average across the participant communities, there was an excess cancer risk of 35 cases per million population over a lifetime.

Outcomes and Impacts

Potential for a New Risk Management Approach

The cumulative risk characterization suggests an integrated, cross-sectoral risk management approach. The work supports policy recommendations in two areas to reduce the community cancer risk: 1) reductions of carcinogenic air toxics sources including on-road sources; and 2) investments to improve community socio-economic conditions.

Workforce Development

The study contributed to doctoral research training for Dr. Andrew Patton in Johns Hopkins University's Department of Environmental Health and Engineering and the post-doctoral professional development for Dr. Misti Levy-Zamora (appointed in November 2021 as assistant professor at the University of Connecticut's Department of Public Health Sciences).

Acknowledgments

The authors thank all participants for their interest and contributions to the study.

Table of Contents

List of Figures

List of Tables

Background and Introduction

Transportation-related emissions make substantial contributions to numerous air pollutants of greatest environmental and public health concern including particulate matter (PM), carbon monoxide, ozone precursors, and volatile organic compounds (VOCs) including air toxics (US Environmental Protection Agency [EPA] 2020). Air pollution exposure contributes to many diseases including stroke, heart disease, lung cancer, and chronic and acute respiratory diseases and is a top risk factor for morbidity and mortality worldwide (Lim et al. 2012; WHO 2016). Within the large literature on ambient air pollution and health, research focused on populations exposed on and near roadways shows that certain exposures are elevated relative to ambient pollutant concentrations (Patton et al. 2016). These higher exposures have been associated with increased incidence and severity of outcomes such as asthma onset, pre-term and low-birth weight infants, childhood leukemia, and premature mortality (US EPA 2014a). Near-roadway research has found that there are a number of vulnerable population sub-groups at increased risk including children, older adults, people with pre-existing cardiovascular diseases, and people of low socio-economic status (US EPA 2014a).

The potential exposures to gasoline and its constituents are well documented in the occupational setting such as refinery workers or tanker truck drivers, but modern high-quality exposure assessment data for gasoline station consumers and employees are severely lacking. According to the National Association of Convenience Stores (NACS), in 2019 there were approximately 129,000 convenience store gasoline stations and mass merchandising gasoline stations in the United States, accounting for 96 percent of all commercial gasoline sold (NACS 2019). There were approximately 40 million fill ups per day at these gasoline stations as of 2012 (NACS 2013). The main form of gasoline sold is automotive gasoline, the primary fuel for internal combustion engines found in non-diesel cars, motorcycles, non-diesel trucks, and other small engines (Agency for Toxic Substances and Disease Registry [ATSDR] 1995). Gasoline is a complex, non-uniform mixture comprised of a variety of alkanes, alkenes, isoalkanes, cycloalkanes, cycloalkenes, and aromatics; many blends also contain performance-enhancing additives (International Agency for Research on Cancer [IARC] 1989). The exact ratios of these compounds vary by manufacturer and location, and even from batch to batch, depending on factors such as the source of the crude oil, the refining process used in its production, and the product specifications (ATSDR 1995; IARC 1989). Since the Clean Air Act Amendments of 1990, gasoline frequently contains ethanol in addition to petroleum products. The two most common mixtures in the United States are 10 percent ethanol/90 percent gasoline (E10) and 15 percent ethanol/85 percent gasoline (E15); approximately 95 percent of gasoline sold in the United States is E10 (Alternative Fuels Data Center 2017).

Gasoline is a known human and animal carcinogen based on the toxicity of its components (ATSDR 1995; IARC 1989). Among the constituents of gasoline, benzene has the strongest body of evidence supporting its carcinogenicity (leukemias) in occupational and non-occupational settings, and EPA, the U.S. Department of Health and Human Services, and IARC all identify benzene as a human carcinogen (ATSDR 2006; US EPA 2000; IARC 2017). Benzene content in gasoline is federally regulated, with any refineries or importers required to average less than or equal to 0.62 percent benzene by volume (US EPA 2021). Generally, gasoline in the United States is likely to contain 0.5–2.0 percent benzene by volume (Bruckner et al. 2008; US EPA 2021). Additionally, in terms of non-occupational exposures, the National Air Toxics Assessment (NATA) ambient air pollution monitoring includes benzene as a ‘national cancer risk contributor’ and provides excess cancer risk associated with that ambient benzene exposure (US EPA 2018a).

Benzene exposure has been extensively studied in both upstream (petroleum extraction and production) and downstream (refining and marketing) settings (Verma et al. 2000, 2001). However, there is little information regarding potential exposures to the gasoline station consumer, a population of millions of individuals per day in the United States. According to ATSDR, non-occupational exposures to gasoline occur as a result of customers using the gasoline pumps and inhaling any volatilized part of the gasoline mixture (ATSDR 1995). The bulk of the studies and samples associated with consumers filling their own vehicles occurred in the 1980s and 1990s and were conducted by consulting firms or industrial sources; however, there were minimal details provided on sampling methodologies and procedures (Verma et al. 2001; Page and Mehlman 1989; Northeast States for Coordinated Air Use Management 1989). Additionally, of the studies that were conducted in other countries (e.g., Singapore, Italy, England), approximately 5 percent of the mean benzene concentrations were greater than 2.5 ppm for short-duration, consumer-focused measurements—the short-term occupational exposure limit issued by the American Conference of Governmental Industrial Hygienists (Page and Mehlman 1989; Occupational Safety and Health Administration [OSHA] 2020; Periago and Prado 2005). However, studies conducted in Europe in the 2000s indicate significantly reduced exposures compared to the 1980s and 1990s (Page and Mehlman 1989; OSHA 2020; Periago and Prado 2005). In addition to consumers, there are approximately 21,000 gasoline service station attendants across the country as of 2019 who may also pump gasoline as part of their job description (Bureau of Labor Statistics 2019).

While acknowledging that it is important to evaluate specific exposures, understanding health requires a more holistic approach, considering not only chemical but also non-chemical exposures across all aspects of daily life. In environmental and occupational health, cumulative risk assessment was developed for this purpose (US EPA 1997, 2003). The research on cumulative risk has progressed over the past two decades with increasing attention to concerns for general population health resulting from exposure to chemical mixtures, such as those found at hazardous waste sites, pesticides in the food supply, or air pollutants (US EPA 1987; Food Quality Protection Act of 1996; Fox et al. 2002, 2004). In the past 10 years, research has explored an expanded cumulative risk concept that includes not only chemicals but also social, economic, and other non-chemical stressors (Chari et al. 2012; Clougherty et al. 2010; Clougherty and Kubzansky 2009; Young et al. 2012). For example, socio-economic deprivation is associated with increased exposure to air toxics (Young et al. 2012); stress may increase susceptibility to health effects of air pollution exposures (Clougherty et al. 2010); and interactions of stress and chemical exposures can increase risk or exacerbate health outcomes (Glass et al. 2009; Hicken et al. 2014). While research to understand the cumulative risk of complex exposures has progressed, gaps remain, and practical methods and applications are rare with the consequence that environmental policies may not be adequately protective of public health (Fox et al. 2017).

Problem

Protecting public health involves an understanding of multiple factors or determinants of health including exposures to biological, chemical, or physical agents in combination with other determinants including type of employment, health status, and individual behaviors among others. This need for understanding has been illustrated clearly during the COVID-19 pandemic such as in increased exposure and health risks for essential workers and people with pre-existing conditions, and mask wearing behavior. Health risk assessment practices for environmental and occupational health, however, still typically focus on a single agent or stressor and do not incorporate complex real-life exposures. In this study we piloted a cumulative risk approach that recognizes that a person or population can be exposed to multiple hazards and stressors across contexts (i.e., exposure and risk results from a combination of experiences in the home, community, workplace, and ambient environment) (Fox et al. 2018).

Approach

We conducted an exposure assessment for consumers to characterize benzene and associated VOC exposures associated with filling their gas tank using modern sampling and analysis methodologies. The exposure assessment was used to inform a consumer risk assessment scenario for gasoline station filling. The consumer exposure assessment data were extended to an occupational setting by developing worker exposure scenarios to estimate excess risk values for gasoline service station attendants and pump attendants. The risk assessment results for the consumers were put in a cumulative risk context including an analysis of community and socio-economic factors as well as self-reported stress.

Methodology

Overview

We used mixed methods combining a novel self-sampling protocol for selected chemical exposures during refueling with a self-reported survey as well as an analysis of secondary data to provide the community-level health, environment, and socio-economic context. The study was reviewed and approved by the Johns Hopkins Institutional Review Board.

Participant Chemical Exposures and Perceived Stress

We recruited community residents with vehicles in the Baltimore, Maryland, area by email and outreach on Johns Hopkins University campuses. Using a self-sampling approach as described in Patton et al. (2021) (see Figure 1 equipment photo), we measured and characterized exposures to benzene, ethylbenzene, toluene, and xylene (BTEX) under a self-pump refueling scenario. Using the sampling data, we characterized health risks to consumers. We created a model of occupational exposure and risk developed using the consumer sampling data. Cancer risk results were interpreted using standard metrics. Acceptable cancer risk for the general population is below one in a million, and the National Institute for Occupational Safety and Health (NIOSH) risk management limit for cancer risk is one in ten thousand population (NIOSH 2016).

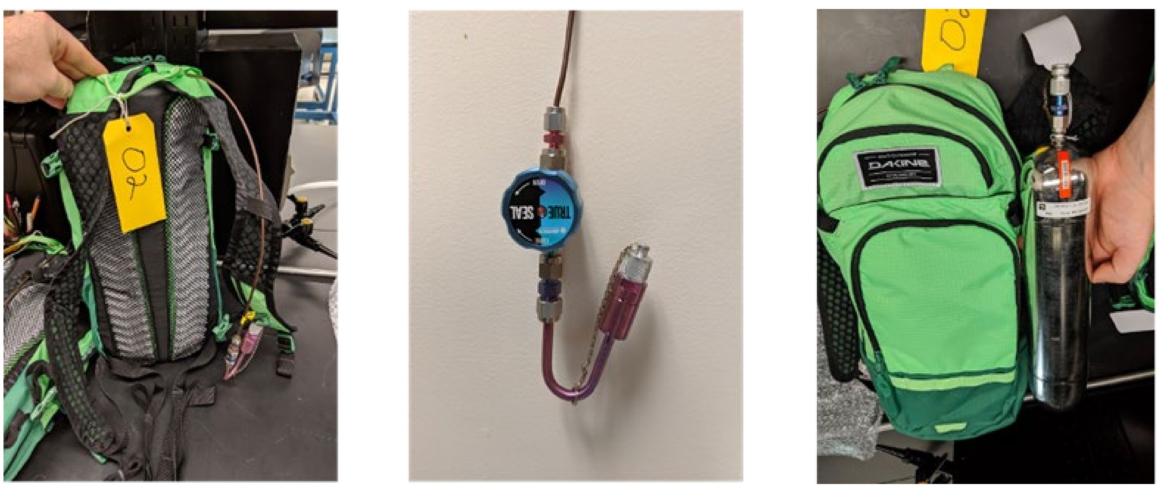

Figure 1. Self-sampling equipment.

Each participant completed a self-reported survey to assess overall personal stress using the Perceived Stress Scale (PSS) (Cohen et al. 1983; Taylor 2015). This instrument has been validated and has low respondent burden (Kopp et al. 2010). Perceived stress scores were categorized as low (score 0–5), medium (score 6–11), or high (score 12–16).

Participant demographics, BTEX, and stress data were managed using Research Electronic Data Capture (REDCap®) hosted at Johns Hopkins University (Harris et al. 2009, 2019). REDCap is a secure, web-based software platform designed to support data capture for research studies.

Community-Level Health and Socio-economic Factors

Publicly available data on community health, demographics, and environmental exposures were collected for the home communities of participants to supplement the individual-level exposure and stress data. Data sources used were the state vital statistics reports, the County Health Rankings & Roadmaps project, the U.S. Census, and NATA

(US Census 2021; County Health Rankings & Roadmaps 2021; US EPA 2018a,b; Maryland Department of Health 2019; Virginia Department of Health 2019). Census data were used to calculate the Townsend Score (TS), a metric of material deprivation, for participant census tracts as in Rice et al. (2014). The TS is developed for a specific geographic area (census tract, in this case) comprising four components, unemployment, non-car ownership, non-house ownership, and household overcrowding. A positive TS indicates deprivation, scores near zero reflect average conditions, and negative TS reflects affluence. Community-level factors are interpreted using a descriptive epidemiology approach by comparing data from participant communities to appropriate state statistics.

Cumulative Risk Characterization

Given the diverse types of data gathered, we used a qualitative approach for risk characterization (MacDonell et al. 2018). We describe the various exposures and related health effects. Multiple exposures across different health determinants (personal health and perceived stress, community exposure) contributing to specific effects indicates potential for increased risk. The approach is depicted in Figure 2, where study participants are at the center of overlapping domains of life, experiencing the health-damaging and health-promoting exposures in each domain. The final report and an individualized cumulative risk summary will be provided to participants upon request.

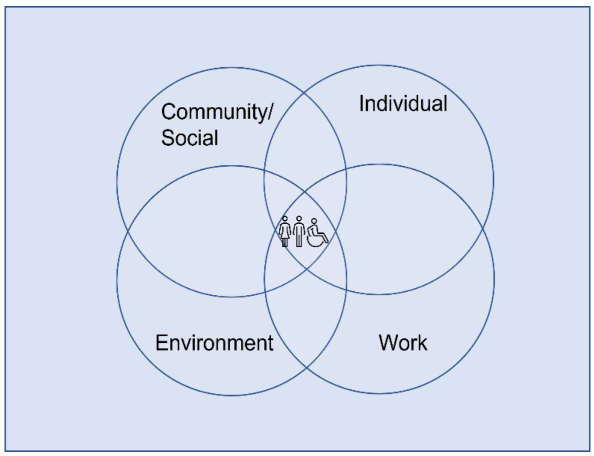

Figure 2. Illustration of the cumulative risk approach.

Results

Study Participants

From July 2019 to February 2020, 35 participants were recruited for the study (Table 1). The majority of respondents were female (69 percent) and the average age overall was 30 years. Most respondents were from Baltimore City or County (n=30, 87 percent) and a few resided in neighboring areas in Maryland or Virginia (n=4, 13 percent). Three participants were excluded from the refueling exposure assessment, due to failure of equipment or likely contamination of the sample (Patton et al. 2021). Because one participant did not provide an address, which was needed for gathering community-level data, the participant was excluded from the cumulative risk characterization.

Table 1. Participant Characteristics

Characteristic	Number (%) or Average (Range)
Number	35
Female/Male	24 (69%)/11 (31%)
Age, Average (Range)	30 (20, 58)
County of Residence	
Anne Arundel, MD	1 (2.9%)

Baltimore City, MD	26 (74%)
Baltimore, MD	4 (11%)
Prince George's, MD	1 (2.9%)
Arlington, VA	1 (2.9%)
Loudoun, VA	1 (2.9%)
Missing	1 (2.9%)
Stress Score, Average (Range)	5 (0, 11)
Low (0–5)	17 (50%)
Medium (6–11)	17 (50%)
High (12–16)	0
Townsend Score, Average (Range)	0.8 (-3, 9)
Deprived communities	18 (53%)
Average communities	3 (9%)
Affluent communities	13 (38%)
NATA Excess Cancer Risk, Average (Range)	35 (31, 38)

Refueling Exposure Assessment

Results of the refueling exposure and risk assessment were reported in Patton et al. (2021) and are briefly summarized in this report. A total of 32 samples were analyzed; exposures averaged 5.7 ppb for benzene, 23.5 ppb for toluene, 3.9 ppb for ethylbenzene, and 16.7 ppb for xylene. Using the benzene exposure results, we conducted consumer and occupational probabilistic cancer risk assessments following standard methods used by EPA and NIOSH (Daniels et al. 2020; US EPA 2014b). Cancer risk estimates were very low for both consumer and occupational scenarios. For consumers, all cancer risk estimates were below the one in a million excess risk management threshold for the general population. Cancer risk estimates for the occupational scenario approached but did not exceed the one in ten thousand NIOSH excess risk management threshold (NIOSH 2016). The cumulative risk assessment and characterization puts these results in context of other personal, community, and ambient environmental exposures.

Community Health Profiles for Participant Communities

Mortality data are one of the oldest forms of health surveillance and a foundation of community health assessments. Mortality rates describe "patterns of disease . . . so that investigation, control, and prevention measures can be applied efficiently and effectively" (Centers for Disease Control and Prevention 2012). Age-adjusted mortality rates for the most common causes of death in Maryland participant communities and for the state of Maryland are presented in Table 2. Baltimore City and County have poorer community health than the average in the state of Maryland. Baltimore City has substantially higher rates on almost all the major causes of death than in other communities and the state overall with the exception of Alzheimer's disease mortality. Baltimore County also has generally higher rates than the state for the top five most common causes of death (heart disease, cancer, stroke, accidents, and assault) but has similar or slightly lower rates for other causes. Mortality rates in Anne Arundel County are generally better than or on par with the state except for stroke and chronic lower respiratory disease. Mortality rates in Prince George's County are generally better than or on par with the state except for heart disease and stroke.

Table 2. Age-Adjusted Rates per 100,000 for the Top 10 Causes of Death in Baltimore-Area Participant Communities with Comparison to the State of Maryland

Causes of Death	Baltimore City 2017–19	Baltimore County	Anne Arundel Co. 2017–19	Prince George's Co. 2017–19	Maryland 2017–19
All Causes	1,019.8	768.8	718.7	719.5	713.0
Heart Disease	223.6	179.4	158.1	174.0	161.9
Cancers	190.8	159.9	150.5	150.4	148.6
Stroke	53.7	44.6	49.8	48.4	40.7
Accidents	58.7	43.0	37.5	31.1	36.4
Assault (Homicide)	44.4	11.2	4.7	10.1	9.9
Chronic Lower Respiratory	33.7	30.4	35.9	21.8	30.0
Diabetes Mellitus	32.8	18.1	16.7	20.1	20.1
Nephritis and Nephrosis	21.7	11.2	10.5	15.2	11.3
Influenza and Pneumonia	16.7	14.2	14.0	13.1	13.0
Alzheimer's	11.9	15.1	16.8	16.3	15.5

Mortality rates for Virginia communities and for the state are presented in Table 3. In general, community health in the participant communities of Arlington and Loudoun Counties is better than that in Virginia overall. In particular, rates for heart disease and cancer are 20–30 percent lower in Arlington and Loudoun than in the state. Even though Arlington and Loudoun Counties have better community health compared to the state, cancer is the most common cause of death in Loudoun and the second most common cause of death in Arlington.

Table 3. Age-Adjusted Rates per 100,000 for the Top 10 Causes of Death in Virginia Communities with Comparison to the State of Virginia

Causes of Death	Arlington, VA 2016	Loudoun, VA 2016	Virginia 2016
All Causes	511.6	519.3	713.0
Heart Disease	105.7	102.1	147.0
Cancers	102.2	118.1	152.4
Stroke	33.1	24.0	37.2
Accidents	17.7	25.4	40.1
Assault (Homicide)	n/a	n/a	n/a
Chronic Lower Respiratory	18.5	20.1	34.1
Diabetes Mellitus	9.7	12.7	21.3
Nephritis and Nephrosis	7.9	10.8	16.3
Influenza and Pneumonia	13.7	7.4	12.0
Alzheimer's	14.7	26.3	26.5

Table 4 summarizes data gathered from the County Health Rankings & Roadmaps, a collaborative project of the University of Wisconsin–Madison and the Robert Wood Johnson Foundation. The County Health Rankings & Roadmaps categorizes each county on a variety of health outcomes, health behaviors, socio-economic factors, and environmental factors such as air and water quality. The rankings based on health outcomes align well with the mortality data and suggest a continuum of community health in participant communities in the order presented in Table 4, with Baltimore City having the poorest outcomes and the Virginia communities having the best outcomes as indicated with the color-coding (red = low rank or poor outcomes; yellow = below average; gray = average; green = high rank or good outcomes).

Similar to the county rankings, the TS presented in Table 4, calculated at the census tract level, combines multiple characteristics to represent material deprivation. A negative score indicates an area of relative affluence; a positive score indicates an area of deprivation; and scores near zero are considered average. Respondent census tracts in Baltimore City and County have varied TSs reflecting both deprived and affluent areas; the other communities are affluent.

Table 4. County Health Rankings & Roadmaps and Townsend Scores

Indicators	Baltimore City	Baltimore County	Anne Arundel Co.	Prince George's Co.	Arlington, VA	Loudon Co., VA
Health Outcomes (County)	Lowest 25%	25–50%	Above 50%	25–50%	Above 75%	Above 75%
Other Health Factors (County)	Lowest 25%	50–75%	Above 50%	25–50%	Above 75%	Above 75%
Townsend Score (Census Tract)	Varied	Varied	Relatively Affluent	Relatively Affluent	Relatively Affluent	Relatively Affluent

Note: Color coding: red = low rank; yellow = below average; gray = average; green = high.

Ambient Air Toxics

According to NATA (US EPA 2018a), all participant communities experience an increased risk of cancer due to various air toxics. On average across the participant communities, there was an excess cancer risk of 35 cases per million population over a lifetime. This excess cancer risk is considered to be of concern in an area with a population of one million people or more (the Baltimore metropolitan area has a population of almost three million people) (US Census 2021; US EPA 2018b).

Given the high burden of disease and poorer health rankings in the Baltimore area, as described, the air toxics analysis focused on Baltimore City (Table 5). The top five air toxics contributing most to cancer risk were formaldehyde, benzene, carbon tetrachloride, acetaldehyde, and naphthalene; these five air toxics contribute about 90 percent of the total excess cancer risk. Four of these air toxics have a small to moderate attribution to on-road sources.

Table 5. Top Five Cancer Risk Contributors in Baltimore City Identified in the National Air Toxics Assessment

Cancer Risk Contributor	Excess Cancer Cases[a] (% of Total Cancer Risk)	% Attributable to On-Road Sources
Formaldehyde	19 (55%)	10%
Benzene	5 (13%)	63%
Carbon Tetrachloride	3 (9%)	0%
Acetaldehyde	2 (7%)	11%
Naphthalene	2 (5%)	59%

Note: [a] Estimated excess cases of cancer per million population over a lifetime.

Work-Related Exposures

While the majority of respondents reported being employed (29, 83 percent), most declined to identify a specific industry. More than half of the respondents reported doing office work (19, 54 percent), one reported service work (3 percent), one reported retail work (3 percent), several reported 'other' (8, 23 percent), and those reporting 'not applicable' were unemployed (5, 15 percent). Based on the data for the type of work reported (office, service, retail), we would not expect other BTEX exposures to be a concern.

Cumulative Risk Characterization

A summary of the assessment components is presented in Table 6. The cumulative risk characterization is an integrated summary looking across the components of the assessment to identify any common health effects of concern originating from multiple components. Although the quantitative assessment of exposures during refueling did not find cancer risks to be of concern, cancer is a community health issue in all participant communities (first or second most common cause of death) with cancer mortality rates highest in Baltimore City. Excess cancer risk was reported in NATA for Baltimore City. Evidence from the scientific literature suggests that residents in impoverished communities also face increased cancer mortality risk and reduced survival (Moss et al. 2020; Wang et al. 2021; Wilkes et al. 1994).

Table 6. Summary of Assessment Components

Component of Assessment	Study Findings	Health Effects
Refueling exposures (benzene)	A few ppb, short episodic exposure	No effects expected
Ambient exposure estimates	Benzene: ~5 ppb; Formaldehyde: ~19 ppb, acetaldehyde: ~2 ppb; naphthalene: ~2 ppb ; continuous exposure	Excess cancer risk
Work exposures	No benzene exposures expected	No effects expected
Perceived stress	Low–medium	No effects expected
Community health	Community health is poor in Baltimore. Cancer is the second most common cause of death in most participant communities with elevated rates in Baltimore.	Elevated cancer mortality
Community socio-economic factors	Deprived areas: 50% of participants Avg: 10% of participants Affluent: 40% of participants	For those in deprived areas: Increased overall cancer mortality risk, reduced survival for those with cancer

Conclusions and Recommendations

Conclusions

The cumulative risk characterization found cancer risk to be a concern originating from both the ambient environment and community-level health and socio-economic factors, as depicted in Figure 3 where the intersection of ambient and community domains is highlighted. Further examination of the air toxics data showed that several of the carcinogenic air toxics are in part (10 percent to 63 percent) attributable to on-road sources with formaldehyde and benzene contributing most to the total cancer risk in Baltimore communities.

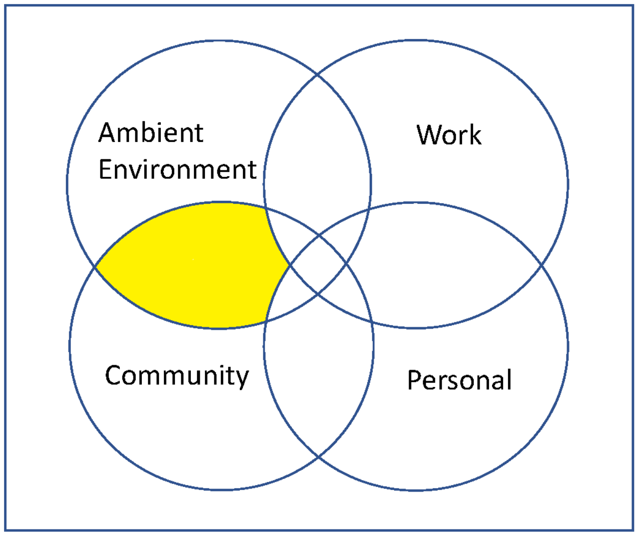

Figure 3. Study findings on cancer risk in the cumulative risk framework.

Recommendations

The findings of the cumulative risk characterization suggest additional investigation and research as well as potential changes in policy and environmental health practice.

Research

1. Further investigation is warranted for the specific on-road sources of the carcinogenic air toxics to identify the important sources and inform risk management plans.
2. Analytical research on the linkage between the air toxics exposures and cancer could be done using data from NATA and cancer incidence from the state cancer registry.

Policy and Practice

1. Include community health indicators as criteria for identifying disadvantaged communities when addressing environmental injustice as the state of California is beginning to do in its CalEnviroScreen tool (California Office of Environmental Health Hazard Assessment 2021). This tool would be a beneficial refinement to the ongoing Justice40 Initiative at the national level (Young et al. 2021).
2. EPA's NATA provides census tract-level estimates of cancer risks and metrics of non-cancer hazard related to air toxics exposures; however, there is no effort to connect those results with actual community health. The purpose of NATA is "to understand cancer risks and noncancer hazards to help EPA and others identify air toxics and source categories of greatest potential concern and to set priorities to collect additional data" on air toxics sources. Linking NATA results to an understanding of actual community health would enhance the prioritization process by identifying the highly exposed and health disadvantaged communities (a practical application building on policy recommendation one).

Outputs, Outcomes, and Impacts

Outputs: A cancer risk assessment model of refueling exposures for consumers with extension to workers is described in Patton et al. (2021).

Outcomes: The cumulative risk characterization suggests an integrated, cross-sectoral risk management approach. The work supports policy recommendations in two areas to reduce the community cancer risk: 1) reductions of the carcinogenic air toxics sources; and 2) investments to improve community socio-economic conditions.

Impacts: The refueling study provides some reassurance that, after a roughly 30-year gap in U.S.-based investigations, refueling exposures and risks are low for both consumers and pump attendants. Follow-up on the findings may identify interventions to reduce cancer risk in disadvantaged communities with a high burden of disease.

Research Outputs, Outcomes, and Impacts

Publication

The novel self-sampling protocol with cancer risk assessment models was published in the *International Journal of Environmental Research and Public Health* in January 2021:

> Patton AN, Levy-Zamora M, Fox M, and Koehler, K. (2021) Benzene Exposure and Cancer Risk from Commercial Gasoline Station Fueling Events Using a Novel Self-Sampling Protocol. *International Journal of Environmental Research and Public Health* 18: 1872. https://doi.org/10.3390/ijerph18041872

Presentations

This work has been presented by Drs. Fox and Patton:

> Patton A. Exposure and Risk in Occupational and Non-occupational Groups from Commercial Gasoline Station Filling Events. Johns Hopkins University Department of Environmental Health and Engineering Seminar, December 11, 2018, Baltimore, Maryland
>
> Fox M, Amoah J, Patton A, Koehler K, Fox M, and Zamora M. Exploring Transportation-Related Chemical Mixtures and Cumulative Risks. Transportation, Air Quality, and Health Symposium, February 2019, Austin, Texas
>
> Patton A, Koehler K, Fox M, and Zamora M. Leukemia Risk Assessment Approximation from Commercial Gasoline Station Benzene Exposures. Transportation, Air Quality, and Health Symposium, February 2019, Austin, Texas
>
> Fox M. Development of a Consumer Cumulative Risk Profile. Transportation, Air Quality, and Health Symposium, May 2021, Virtual Symposium
>
> Patton A. Benzene Exposure and Cancer Risk from Commercial Gasoline Station Fueling Events Using a Novel Self-Sampling Protocol. Transportation, Air Quality, and Health Symposium, May 2021, Virtual Symposium

Integrated Policy Approach

This work illustrates an integrated assessment approach developed from the multiple determinants of health model that underlies cumulative risk assessment in the environmental health field. The key features of the approach are:

1. To evaluate multiple exposures including chemical and non-chemical stressors across multiple domains (individual, community/social, work, ambient).
2. To consider the broader context of each individual study participant within their own community conditions including socio-economics, health, and ambient environment.

The findings of the assessment confirm that cancer is an outcome of concern in participant communities and both ambient air toxics and community socio-economic conditions can play a role in cancer development or outcomes suggesting the development of an integrated risk management policy.

Technology Transfer Outputs, Outcomes, and Impacts

Datasets: Project dataset and ancillary analysis of on-road contribution for the top five carcinogenic air toxics in Baltimore will be made available on the DataHub.

Risk assessment models: Probabilistic cancer risk assessment models (one for consumers and one for workers) were developed and described in Patton et al. (2021) following EPA and NIOSH guidance (US EPA 1987, 2005; NIOSH 2016). The publication presents the cancer risk estimating equations along with the data and parameterization used in detail to allow the models to be replicated.

Education and Workforce Development Outputs, Outcomes, and Impacts

The study contributed to doctoral research training for Dr. Andrew Patton in the Department of Environmental Health and Engineering of the Johns Hopkins Bloomberg School of Public Health. He successfully defended his dissertation in January 2021. This work also served as post-doctoral professional development for Dr. Misti Levy-Zamora then a post-doctoral fellow in the Department of Environmental Health and Engineering of the Johns Hopkins Bloomberg School of Public Health. Dr. Levy-Zamora accepted a position as assistant professor at the University of Connecticut's Department of Public Health Sciences in November 2021.

This study and other Center for Advancing Research in Transportation Emissions, Energy, and Health (CARTEEH) work has been incorporated into lecture materials for three graduate public health courses at the Johns Hopkins Bloomberg School of Public Health: Methods in Quantitative Risk Assessment (a policy course); Environmental Epidemiology; and Exposure Sciences for Health Risk Assessment. CARTEEH research serves as case examples of advancing cumulative risk assessment research and practice applications for different types of students, such as:

- For risk assessment and policy students, it introduces environmental health and transportation system concepts.
- For epidemiology students, it is an example of human health risk assessment tools in practice.
- For environmental exposure assessment students, it serves to introduce concepts of cumulative risk assessment and measurement of psychosocial stress.

References

Agency for Toxic Substances and Disease Registry. (1995) Toxicological Profile for Gasoline. Available online: https://www.atsdr.cdc.gov/toxprofiles/tp72.pdf

Alternative Fuels Data Center. (2017) Ethanol Blends. Available online: https://www.afdc.energy.gov/fuels/ethanol_blends.html

ATSDR. (2006) Toxicological Profile for Benzene. Available online: https://www.atsdr.cdc.gov/toxprofiles/tp3.pdf

Bruckner J, Anand S, and Warren, A. (2008) Toxic Effects of Solvents and Vapors. In: Klaasen C, editor. Casarett & Doull's Toxicology: The Basic Science of Poisons, Seventh. McGraw Hill. p. 981–1051.

Bureau of Labor Statistics. (2019) Industries at a Glance: Gasoline Stations: NAICS 447. Available online: https://www.bls.gov/iag/tgs/iag447.htm

California Office of Environmental Health Hazard Assessment. (2021) About CalEnviroScreen. https://oehha.ca.gov/calenviroscreen/about-calenviroscreen

Centers for Disease Control and Prevention. (2012) Introduction to Epidemiology: Core Epidemiologic Functions. https://www.cdc.gov/csels/dsepd/ss1978/lesson1/section4.html#:~:text=Section%204%3A%20Core%20Epidemiologic%20Functions,studies%2C%20evaluation%2C%20and%20linkages

Chari R, Burke TA, White RH, and Fox MA. (2012) Integrating Susceptibility into Environmental Policy: An Analysis of the National Ambient Air Quality Standard for Lead. *International Journal of Environmental Research and Public Health* 9: 1077–1096. https://doi.org/10.3390/ijerph9041077

Clougherty JE and Kubzansky LD. (2009) A Framework for Examining Social Stress and Susceptibility to Air Pollution in Respiratory Health. *Environmental Health Perspectives* 117:1351–1358. https://doi.org/10.1289/ehp.0900612

Clougherty JE, Rossi CA, Lawrence J, Long MS, Diaz EA, Lim RH, McEwen B, Koutrakis P, and Godleski JJ. (2010) Chronic Social Stress and Susceptibility to Concentrated Ambient Fine Particles in Rats. *Environmental Health Perspectives* 118(6):769–75. https://doi.org/10.1289/ehp.0901631

Cohen S, Kamarck T, and Mermelstein R. (1983) A Global Measure of Perceived Stress. *Journal of Health and Social Behavior*. 24(4):385–396.

County Health Rankings & Roadmaps. (2021) County Health Rankings & Roadmaps. https://www.countyhealthrankings.org/

Daniels R, Gilbert S, Kuppusamy S, Kuempel E, Park R, Pandalai S, Smith R, Wheeler M, Whittaker C, and Schulte P. (2020) Current Intelligence Bulletin 69: NIOSH Practices in Occupational Risk Assessment; National Institute for Occupational Safety and Health: Washington, DC, USA. https://www.cdc.gov/niosh/docs/2020-106/default.html

Food Quality Protection Act of 1996. Public Law 104-170.

Fox MA, Brewer LE, and Martin L. (2017) An Overview of Literature Topics Related to Current Concepts, Methods, Tools, and Applications for Cumulative Risk Assessment (2007–2016). *International Journal of Environmental Research and Public Health* 14(4): E389. https://doi.org/10.3390/ijerph14040389

Fox MA, Groopman J, and Burke T. (2002) Evaluating Cumulative Risk Assessment for Environmental Justice: A Community Case Study. *Environmental Health Perspectives* 110: 203–209. https://doi.org/10.1289/ehp.02110s2203

Fox MA, Spicer K, Chosewood LC, Susi P, Johns DO, and Dotson GS. (2018) Implications of Applying Cumulative Risk Assessment to the Workplace. *Environment International* 115: 230–238 https://doi.org/10.1016/j.envint.2018.03.026

Fox MA, Tran NL, Groopman JD, and Burke TA. (2004) Toxicological Resources for Cumulative Risk: An Example with Hazardous Air Pollutants. *Regulatory Toxicology and Pharmacology* 40:305–311. https://doi.org/10.1016/j.yrtph.2004.07.008

Glass TA, Bandeen-Roche K, McAtee M, Bolla K, Todd AC, and Schwartz BS. (2009) Neighborhood Psychosocial Hazards and the Association of Cumulative Lead Dose with Cognitive Function in Older Adults. *American Journal of Epidemiology*. 169(6): 683–692. https://doi.org/10.1093/aje/kwn390

Harris PA, Taylor R, Minor BL, Elliott V, Fernandez M, O'Neal L, McLeod L, Delacqua G, Delacqua F, Kirby J, Duda SN, and the REDCap Consortium. (2019) The REDCap Consortium: Building an International Community of Software Partners. *Journal of Biomedical Informatics* 95:103208. https://doi.org/10.1016/j.jbi.2019.103208

Harris PA, Taylor R, Thielke R, Payne J, Gonzalez N, and Conde JG. (2009) Research Electronic Data Capture (REDCap)—A Metadata-Driven Methodology and Workflow Process for Providing Translational Research Informatics Support. *Journal of Biomedical Informatics* 42(2):377–81. https://doi.org/10.1016/j.jbi.2008.08.010

Hicken MT, Dvonch JT, Schulz AJ, Mentz G, and Max P. (2014) Fine Particulate Matter Air Pollution and Blood Pressure: The Modifying Role of Psychosocial Stress. *Environmental Research* 133:195–203. https://doi.org/10.1016/j.envres.2014.06.001

IARC. (2017) Benzene. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans Volume 120. https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Benzene-2018

International Agency for Research on Cancer. (1989) Gasoline. Monographs, 45. https://monographs.iarc.who.int/wp-content/uploads/2018/06/mono45.pdf

Kopp MS, Thege BK, Balog P, Stauder A, Salavecz G, Rózsa S, Purebl G, and Adám S. (2010) Measures of Stress in Epidemiological Research. *Journal of Psychosomatic Research* 69(2):211–25. https://doi.org/10.1016/j.jpsychores.2009.09.006

Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, et al. (2012) A Comparative Risk Assessment of Burden of Disease and Injury Attributable to 67 Risk Factors and Risk Factor Clusters in 21 Regions, 1990–2010: A Systematic Analysis for the Global Burden of Disease Study 2010. Lancet 380:2224–2260. https://doi.org/10.1016/S0140-6736(12)61766-8

MacDonell MM, Hertzberg RC, Rice GE, Wright JM, and Teuschler LK. (2018) Characterizing Risk for Cumulative Risk Assessments. Risk Analysis, 38: 1183–1201. https://doi.org/10.1111/risa.12933

Maryland Department of Health. Maryland Vital Statistics Annual Report 2019. https://health.maryland.gov/vsa/Documents/Reports%20and%20Data/Annual%20Reports/2019Annual.pdf

Moss JL, Pinto CN, Srinivasan S, Cronin KA, and Croyle RT. (2020) Persistent Poverty and Cancer Mortality Rates: An Analysis of County-Level Poverty Designations. *Cancer Epidemiology, Biomarkers, and Prevention* 29(10):1949–1954. https://doi.org/10.1158/1055-9965.EPI-20-0007

NACS. (2019) Selling America's Fuel. Available online: https://www.convenience.org/topics/fuels/who-sells-americas-fuel

National Association of Convenience Stores. (2013) Fueling America: A Snapshot of Key Facts and Figures. Available online: http://www.nacsonline.com/yourbusiness/fuelsreports/gasprices_2013/pages/statisticsdefinitions.aspx

National Institute for Occupational Safety and Health. (2016) Current Intelligence Bulletin 68: NIOSH Chemical Carcinogen Policy. By Whittaker C, Rice F, McKernan L, Dankovic D, Lentz TJ, MacMahon K, Kuempel E, Zumwalde R, Schulte P, on behalf of the NIOSH Carcinogen and RELs Policy Update Committee. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2017-100.

Northeast States for Coordinated Air Use Management. (1989) Evaluation of the Health Effects from Exposure to Gasoline and Gasoline Vapors. https://nepis.epa.gov/Exe/ZyPDF.cgi/9101V3MD.PDF?Dockey=9101V3MD.PDF

Occupational Safety and Health Administration. (2020) OSHA Annotated Table Z-1. Available online: https://www.osha.gov/dsg/annotated-pels/tablez-1.html

Page NP, and Mehlman M. (1989) Health Effects of Gasoline Refueling Vapors and Measured Exposures at Service Stations. *Toxicology and Industrial Health*, Sage Publications. Sage CA: Thousand Oaks, CA. 5, 869–90. https://doi.org/10.1177/074823378900500521

Patton AN, Levy-Zamora M, Fox M, and Koehler K. (2021) Benzene Exposure and Cancer Risk from Commercial Gasoline Station Fueling Events Using a Novel Self-Sampling Protocol. *International Journal of Environmental Research and Public Health* 2021, 18, 1872. https://doi.org/10.3390/ijerph18041872

Patton AP, Laumbach R, Ohman-Strickland P, Black K, Alimokhtari S, Lioy PJ, and Kipen HM. (2016) Scripted Drives: A Robust Protocol for Generating Exposures to Traffic-Related Air Pollution. *Atmospheric Environment* 143:290–299. https://doi.org/10.1016/j.atmosenv.2016.08.038

Periago JF, and Prado C. (2005) Evolution of Occupational Exposure to Environmental Levels of Aromatic Hydrocarbons in Service Stations. The Annals of Occupational Hygiene, Oxford University Press. 49, 233–40. https://doi.org/10.1093/annhyg/meh083

Rice LJ, Jiang C, Wilson SM, Burwell-Naney K, Samantapudi A, and Zhang H. (2014) Use of segregation indices, Townsend Index, and air toxics data to assess lifetime cancer risk disparities in metropolitan Charleston, South Carolina, USA. *International Journal of Environmental Research and Public Health* 11(5):5510-26. doi: 10.3390/ijerph110505510

Taylor JM. (2015). Psychometric Analysis of the Ten-Item Perceived Stress Scale. Psychological Assessment, 27(1), 90–101. https://doi.org/10.1037/a0038100

US Census. https://www.census.gov/

US Environmental Protection Agency (EPA). (1997) Guidance on Cumulative Risk Assessment. Part 1: Planning and Scoping. https://www.epa.gov/sites/default/files/2015-01/documents/cumrisk2_0.pdf

US EPA. (2000) Integrated Risk Information System. Benzene. Available online: https://cfpub.epa.gov/ncea/iris2/chemicallanding.cfm?substance_nmbr=276

US EPA. (2003) Framework for Cumulative Risk Assessment. U.S. Environmental Protection Agency, Office of Research and Development, EPA/600/P-02/001F. https://www.epa.gov/sites/default/files/2014-11/documents/frmwrk_cum_risk_assmnt.pdf

US EPA. (2005) Guidelines for Carcinogen Risk Assessment. EPA/630/P-03/001F. https://www.epa.gov/sites/default/files/2013-09/documents/cancer_guidelines_final_3-25-05.pdf

US EPA. (2014a) Near Roadway Air Pollution and Health: Frequently Asked Questions. Office of Transportation and Air Quality, EPA-420-F-14-044, August 2014. https://www.epa.gov/sites/default/files/2015-11/documents/420f14044_0.pdf

US EPA. (2014b) Risk Assessment Forum White Paper: Probabilistic Risk Assessment Methods and Case Studies; EPA: Washington, DC. https://www.epa.gov/sites/default/files/2014-12/documents/raf-pra-white-paper-final.pdf

US EPA. (2018a) 2014 National Air Toxics Assessment. https://www.epa.gov/national-air-toxics-assessment/2014-national-air-toxics-assessment

US EPA. (2018b) 2014 Technical Support Document: EPA's 2014 National Air Toxics Assessment. https://www.epa.gov/national-air-toxics-assessment/2014-nata-technical-support-document

US EPA. (2020) Smog, Soot, and Other Air Pollution from Transportation. https://www.epa.gov/transportation-air-pollution-and-climate-change/smog-soot-and-local-air-pollution

US EPA. (2021) Gasoline Mobile Source Air Toxics. https://www.epa.gov/gasoline-standards/gasoline-mobile-source-air-toxics

Verma D, Johnson D, and McLean J. (2000) Benzene and Total Hydrocarbon Exposures in the Upstream Petroleum Oil and Gas Industry. AIHAJ—American Industrial Hygiene Association 61:255–63.

Verma DK, Johnson DM, Shaw ML, and des Tombe K. (2001) Benzene and Total Hydrocarbons Exposures in the Downstream Petroleum Industries. AIHAJ—American Industrial Hygiene Association 62: 176–94. https://doi.org/10.1080/15298660108984621

Virginia Department of Health. (2019) Virginia Health Statistics 2016 Annual Report. https://apps.vdh.virginia.gov/HealthStats/documents/pdf/2016_AR_ver1.01.pdf

Wang K, Law CK, Zhao J, Hui AY, Yip BH, Yeoh EK, and Chung RY. (2021) Measuring Health-Related Social Deprivation in Small Areas: Development of an Index and Examination of its Association with Cancer Mortality. *International Journal for Equity in Health* 20(1):216. https://equityhealthj.biomedcentral.com/articles/10.1186/s12939-021-01545-9

Wilkes G, Freeman H, and Prout M. (1994) Cancer and Poverty: Breaking the Cycle. *Seminars in Oncology Nursing* 10(2):79-88. PMID: 8059112. https://doi.org/10.1016/S0749-2081(05)80061-0

World Health Organization. (2016) WHO Releases Country Estimates on Air Pollution Exposure and Health Impact. September 27. https://www.who.int/news/item/27-09-2016-who-releases-country-estimates-on-air-pollution-exposure-and-health-impact

Young GS, Fox MA, Trush M, Kanarek N, Glass TA, and Curriero FC. (2012) Differential Exposure to Hazardous Air Pollution in the United States: A Multilevel Analysis of Urbanization and Neighborhood Socioeconomic Deprivation. *International Journal of Environmental Research and Public Health* 9:2204–25. https://doi.org/10.3390/ijerph9062204

Young SD, Mallory B, and McCarthy G. (2021). Interim Implementation Guidance for the Justice40 Initiative. Executive Office of the President, Office of Management and Budget. https://www.whitehouse.gov/wp-content/uploads/2021/07/M-21-28.pdf