13 October 2020

MATTHEW JAMES CAMPEN, PH.D., M.S.P.H.

REGENTS' PROFESSOR, UNIVERSITY OF NEW MEXICO

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EDUCATION

Postdoctoral Fellowship | June, 2002
Division of Pulmonary and Critical Care Medicine
Johns Hopkins University School of Medicine, Baltimore, MD
Cardiopulmonary Physiology, Christopher P. O'Donnell, Advisor
Genetic Contributions to Adverse Cardiac Sequelae Due to Sleep Apnea

Doctor of Philosophy | July, 2000
Department of Environmental Science and Engineering
University of North Carolina at Chapel Hill, School of Public Health
Environmental Health Science, W. Penn Watkinson, Advisor
Dissertation Title: Cardiopulmonary Toxicity of Particulate Matter Air Pollution-Associated Transition Metals in Rodents.

Master of Science in Public Health | December, 1997
University of North Carolina at Chapel Hill, School of Public Health
Environmental Health Science, W. Penn Watkinson, Advisor
Thesis Title: Cardiovascular and Thermoregulatory Toxicity of an Emission Source Particulate in Healthy and Compromised Rats.

Bachelor of Science | June, 1994
Virginia Polytechnic Institute and State University
Biochemistry and Psychology, Minor in *Chemistry*

PROFESSIONAL APPOINTMENTS

KL2 Program Director (2017-present)
Professor (2015-present)
Associate Professor (2009-2015)
Department of Pharmaceutical Sciences
College of Pharmacy
University of New Mexico, Albuquerque, NM

Director, Cardiovascular and Pulmonary Physiology (2007-2009)
Associate Scientist, Study Director (2004-2009)
Associate Research Scientist (2002-2004)
Toxicology Division, National Environmental Respiratory Center
Lovelace Respiratory Research Institute, Albuquerque, NM

CAA
EXHIBIT
11

ADJUNCT APPOINTMENTS

Adjunct Assistant Professor (2005-2008)
Department of Pathology, Center for Tropical Diseases
University of Texas, Medical Branch, Galveston, TX

Adjunct Assistant Professor (2002-2009)
School of Medicine & School of Pharmacy
University of New Mexico, Albuquerque, NM

HONORS AND AWARDS

Marshall Hahn Scholarship at VPI & SU, 1990
Mary O. Amdur Award for Environmental Inhalation Toxicology, Society of Toxicology Meeting, 1999 for presentation entitled: Cardiopulmonary Toxicity of Instilled Nickel, Vanadium, and Iron in Monocrotaline-Treated Rats. M J Campen, K L Dreher, D L Costa, and W P Watkinson.
Individual National Research Service Award, NHLBI, 2001 "Hemodynamic Responses to Apnea in Mouse Strains", 1F32HL068417-01
Graduate Volunteer Faculty Award, 2006, College of Pharmacy, University of New Mexico
Research Paper of the Year, 2007, Inhalation and Respiratory Specialty Section, Society of Toxicology, for Lund et al. (#31, below)
Young Investigator Award, Inhalation and Respiratory Specialty Section, Society of Toxicology, 2013
Society of Toxicology Achievement Award, 2014
UNM Regents' Professorship, 2017-2019

SOCIETY MEMBERSHIPS

American Physiological Society 1998-2009.
American Thoracic Society 2001-present.
Society of Toxicology, 2002-present.
- President / Executive Officer, Mountain West Regional Chapter, 2005-2007
- Councilor, Inhalation Specialty Section, 2007-2009
- Member, Research Funding Committee, 2008-2009
- Member, Disease Prevention Task Force, 2008-2011
- President, Founding Officer, Cardiovascular Specialty Section, 2010-2011
- Member, Publications Committee, 2012-2016; Chair, 2015-2016
- Member, Awards Committee, 2015-2017
- President / Executive Officer, Inhalation and Respiratory Specialty Section, 2017-2020

New Mexico Center for Environmental Health Sciences, 2003-2008
American Heart Association, 2005-present

PROFESSIONAL ACTIVITIES

Organized 2005 Mountain West Society of Toxicology Meeting, "Environmental Cardiology", Santa Fe, New Mexico
Member, Albuquerque Air Quality Board, 2006-2009
- Environmental Justice Subcommittee Member, 2007

Contributor, Cardiovascular Toxicology Chapter, 2009 Integrated Science Assessment

for Particulate Matter, Environmental Protection Agency
Contributor, Systemic Toxicology Chapter, 2009 Integrated Science Assessment for Carbon Monoxide, Environmental Protection Agency
Advisory Committee, Great Lakes Air Center for Integrated Environmental Research (GLACIER), EPA-funded program, 2010-2015
Clean Air Scientific Advisory Committee (CASAC) member, Oxides of Nitrogen Integrated Science Assessment review, US EPA, 2013
Expert Panelist, Workshop to Discuss Policy-Relevant Science to Inform EPA's Review of the Primary and Secondary National Ambient Air Quality Standards for the Effects of Particulate Matter, Feb. 9–11, 2015
Contributor, Cardiovascular Toxicology Chapter, 2016 Integrated Science Assessment for Particulate Matter, Environmental Protection Agency

GRANT REVIEW

Congressional Line-Item Program Review, National Center for Environmental Research, U.S. Environmental Protection Agency, 2006
Physiology Panel, Crew Health Joint NRA Review, National Aeronautics and Space Administration, 2008
NIEHS, 2009/01 EHS (T2) 1, EHS Training Grants Review Meeting, November, 2008
NIEHS, Special Emphasis Panel, 2009/05 ZES1 JAB-J (K9) 1 Pathways to Independence/Career Development, February, 2009
Physiology Panel, Postdoctoral Fellowship Review, National Aeronautics and Space Administration, 2009
Italian Ministry of Health, Young Investigator Awards, 2009
American Heart Association, Vascular Wall Biology Study Section, April 2010
NIEHS, Special Emphasis Panel, 2010 ZES1 JAB-C Virtual Consortium for Translational/ Transdisciplinary Environmental Research (ViCTER), May 2010
Italian Ministry of Health, Young Investigator Awards, 2010
NIEHS, Research Careers in Environmental Health, ZES1-LKB-J-K9, July 14, 2011
Colt Foundation, United Kingdom Young Investigator Award, September, 2011
Fondazione Cariplo, Italian Biomedicine Research Grants, October 2011
American Heart Association, Vascular Wall Biology Study Section, April 2013
NIEHS, Special Emphasis Panel, ZES1 JAB-C Virtual Consortium for Translational/ Transdisciplinary Environmental Research (ViCTER), May 2013
NIEHS P42 Superfund Research Centers, October 24-25, 2013
American Heart Association, Vascular Wall Biology Study Section, Co-Chair, April 2014
Colt Foundation, United Kingdom Young Investigator Award, October, 2014
American Heart Association Innovative Research Grant, Vascular Sciences, Oct 2014
NIH CSR, P51 Primate Center Review, ZRG1 BBBP-J 55 R, December, 2014
NIEHS, Special Emphasis Panel, K99/R00 Pathways to Independence/Career Development, April 2015
NIEHS, Child Health and the Environment Center Grant Review Committee, 2015/8 ZES1 LKB-D, May 2015
NIEHS, Outstanding New Environmental Scientist (ONES) Award Review Committee, ZES1 JAB-J, July 2015
NIH CSR, Systemic Injury of Environmental Exposures, ad hoc, Feb 18, 2016
NIEHS, IAM Career Application Review- ZES1 LWJ-J (KS) 1, July 11, 2016
NIEHS P30 Environmental Health Centers Review Committee, ad hoc, Aug 16-17, 2016
NIA SEP, ZAG1 ZIJ-8 (J1) Alzheimer's Disease and Air Pollution, Sept 8, 2016

CDC/NIOSH Study Section Review Panel, Oct 11, 2016
NIEHS P30 Environmental Health Centers Review Committee, ad hoc, Aug 29-30, 2017
NIA SEP, ZAG1 ZIJ-8 (J1) Alzheimer's Disease and Air Pollution, Sept 7, 2017
NIH CSR, Systemic Injury of Environmental Exposures (SIEE), Regular Member, 2017-2020

EDITORIAL CONTRIBUTIONS: JOURNALS

Inhalation Toxicology, 2006-2011 Editorial Board
Associate Editor, 2009-2016
Cardiovascular Toxicology, 2006-2011 Editorial Board
Associate Editor, 2009-2016
Toxicological Sciences, 2009-2018 Editorial Board
Associate Editor, 2011-2019
Interim Editor-in-Chief, 2013
Toxicology Letters, 2012-2015 Editorial Board

GRANT RESEARCH SUPPORT: CURRENT

P20GM130422-01A1 Campen (PI) 8/1/2020-7/31/2025
New Mexico Center for Metals in Biology and Medicine
This Center of Biomedical Research Excellence is established to leverage our institutional expertise in analytical chemistry for metal interactions with biology to address research questions related to toxicity, nutritional and therapeutic value, and potential drug delivery usage of metals. Emphasis on early career development for UNM assistant professors is a major aspect to the P20.
Role: Director Direct Costs: $7,800,000

R01ES014639 Campen (PI) 04/01/2008 – 03/31/2024
Enhancement of Coronary Constriction by Volatile Organic Air Toxics (NIEHS)
Investigating the vascular toxicity of common components of combustion mixtures and the impact on cardiac health.
Role: Principal Investigator Cumulative Direct Costs: $2,380,755

R01OH010828-01A0 Campen, Ottens (coPI) 4/1/2015-3/31/2019
Systemic Health Implications of Occupational Nanomaterial Exposure (NIOSH/CDC)
Examining the circulatory and cerebrovascular effects of pulmonary exposure to nanomaterials.
Role: Co-Principal Investigator Direct Costs: $1,600,000

R01ES026673 Campen (PI) 8/01/2016-7/31/2021
Inhalation of Contaminated Mine Waste Dusts as a Route for Systemic Metal Toxicity (NIEHS)
Assessing the cardiorespiratory health effects of metal-laden particulate matter originating from local abandoned mine sites in tribal lands of the southwestern United States.
Role: Principal Investigator Direct Costs: $1,625,180

KL2TR001448 Campen (PI) 04/1/17 – 3/31/25
Mentored Career Development Program: UNM Clinical and Translational Science Center
Building the capacity of our faculty to perform clinical and translational research, thereby addressing the significant health problems of New Mexico, the region, and the nation. Our short-term objective is to enhance our KL2 program by strengthening recruitment, augmenting individualized training, and improving mentoring to ensure that scholars become independently funded by the end of their K-award period.

Role: Principal Investigator

P42ES025589 Lewis J (PI) 08/15/17 – 3/31/22
UNM Metal Exposure Toxicity Assessment on Tribal Lands in the Southwest (METALS) Superfund Research Program
The goal of the UNM METALS center is elucidation of how exposures to metal mixtures from uranium mining wastes result in systemic inflammation - exacerbating DNA damage, immune dysregulation, and cardiovascular disease.
Role: Center Deputy Director/Administrative Core

R01ES029442 Kheradmand (PI) 08/01/19-07/31/21
Toxic Effects of eCigs following Transition from Conventional Cigarettes
Assessing the cardiovascular health effects of e-cigarettes as compared to conventional tobacco products.
Role: Co-investigator

Grant Research Support: Completed

1F32HL068417-01 Campen (PI) 8/14/01-6/30/02
Hemodynamic Responses to Apnea in Mouse Strains
Characterization of the sleep physiology and cardiovascular responses to hypoxia in several mouse strains.
Role: Principal Investigator Direct Costs: $31,303

R830839-010 Campen (PI) 4/21/03-4/20/07
US EPA STAR Award
Coronary Effects of Diesel Exhaust Particulate Matter
Examining effects of diesel exhaust on coronary vessel physiology and indices of risk for sudden cardiac death in a susceptible animal model.
Role: Principal Investigator Direct Costs: $500,000

4709-RFPA03-4/04-5 Campen (PI) 3/01/04-12/31/06
Health Effects Institute
Air Pollution-Induced Circulatory Redistribution: Potential Role of Venoconstriction in Particulate Matter-Associated Heart Failure
Investigating relative effects of diesel exhaust on constriction in the venous and arterial circulations.
Role: Principal Investigator Direct Costs: $160,000

CF 826442-01-1 Mauderly (PI) 4/1/98 – continuing
US EPA
National Environmental Respiratory Center
To place respiratory health risks from mixed pollutant atmospheres and sequential pollutant exposures in their appropriate context as a basis for regulatory and technological decision-making.
Role: Co-Investigator

RD831860 Kanagy (PI) 9/1/04-8/30/09
US EPA
Diesel-Induced Vascular Dysfunction: Role of Endothelin (ES-03-010)
Examining the role of endothelin in causing particulate matter-related cardiovascular effects.
Role: Co-Investigator

R83399001-0 Campen (PI) 1/1/09-12/31/10

US EPA STAR Award
Development of Environmental Health Outcome Indicators
Assaying tissues for biomarkers of exposure:health outcome indicators resulting from inhalation of complex combustion mixtures.
Role: Principal Investigator Direct Costs: $332,000

EPA #CR-83234701 Vedal (PI) 5/1/06-4/30/11
NPACT: Integrated Epidemiologic and Toxicologic Cardiovascular Studies to Identify Toxic Components of Fine Particulate Matter
Examining the atherosclerotic effects of contrasting source pollutants in both toxicological and epidemiological studies.
Role: Co-investigator

1R21OH010495 Campen (PI) 09/01/13-8/31/15
Endothelial Cells as Biosensors for Occupational Cardiovascular Risk
Utilizing endothelial cells to identify alterations in serum inflammatory potential induced by nanomaterial inhalation.
Role: Principal Investigator Direct Costs: $275,000

RD-83479601-0 Vedal (PI) 7/1/10-6/30/16
University of Washington Center for Clean Air Research (EPA)
Project 3. Cardiovascular Consequences of Immune Modification by Traffic-Related Emissions
Role: Project 3 Principal Investigator Direct Costs: $414,937

P20GM121176-01 Deretic (PI) 09/01/17-08/31/22
Autophagy, Inflammation and Metabolism (AIM) in Disease Center
The AIM Center is a cutting-edge program for examining how autophagy pathways are involved in a broad range of diseases. This program is designed to help develop new scientists in the fields of autophagy, inflammation and metabolism.
Role: Mentoring Director

R01ES023838-01 Campen (PI) 4/1/2016-3/31/2019
ViCTER Award: Vascular Consequences of Gas and Particulate Phases of Near-Roadway Pollution (NIEHS)
Role: Co-Principal Investigator Direct Costs: $750,000

CONTRACTS

UNM 3RN71 Campen (Study Director) 2/1/13-10/31/13
PGTi
Efficacy Testing of Test Article in Rodent Models of Pulmonary Arterial Hypertension
Role: Study Director Total Cost: $52,700

UNM Pending Campen (SD) 12/1/11-1/31/12
Theravance
Efficacy Testing of Novel Compounds in a Mouse Model of Pulmonary Arterial Hypertension, Phase 2
Role: Study Director Total Cost: $38,700

UNM 3RF48 Campen (SD) 7/29/11-12/31/11
Theravance
Efficacy Testing of Novel Compounds in a Mouse Model of Pulmonary Arterial Hypertension
Role: Study Director Total Cost: $33,220

UNM3RC91 Campen (SD) 4/1/2011-6/15/2011
Corridor Pharmaceuticals
Efficacy Testing of Novel Compounds and Sildenafil in Reversing MCT-Induced Pulmonary Hypertension in a Rodent Model
Role: Study Director Total Cost: $55,000

LRRI FY08-119 Campen (SD) 8/1/2008-1/31/2009
Theravance, Inc.
Efficacy Testing of a Novel Compound in Reducing Angiotensin-II Induced Hypertension in the Beagle Dog Model
Role: Study Director Total Costs: $94,000

LRRI #2550227 Campen (SD) 2/1/2007-1/31/2008
ExxonMobil Biomedical Sciences
Toxicogenomic Approaches to Evaluate the Cardiovascular Effects of Emissions from Diesel Engines Using Alternate Fuel Grades
Role: Study Director Total Costs: $150,000

LRRI FY07-28 Campen (SD) 6/1/2006-12/30/2007
Galleon Pharmaceuticals, Inc
Initial Efficacy Studies of S-Nitrosothiol-Related Compounds in Rats
Role: Study Director Total Costs: $226,000

LRRI FY05- 013 Campen (SD) 11/1/2004-3/31/2005
LabPharma, Ltd
Cardiovascular Safety Assay of Calcitonin Gene-Related Peptide by Inhalation in Dogs
Role: Study Director Total Costs: $98,450

DAMD17-00-C-0031 Campen (SD) 1/1/03-12/31/04
JAYCOR/DOD subcontract # 959288
Small Animal Test in Support of Model Development
Analyzing respiratory mechanics of rodents exposed to gases release in combustion processes for the development of a human model of emergency exposures.
Role: Study Director Total Costs: $400,000

PUBLICATIONS

Journal Articles:

1. Demakis, G.J., Harrison, D.W., and Campen, M.J. A test of Kinsbourne's selective activation model. *Internat. J. Neurosci.* 72:201-207, 1993.
2. Watkinson, W.P., Campen, M.J., Lyon, J.Y., Highfill, J.W., Wiester, M.J., and Costa, D.L. Impact of the hypothermic response in inhalation toxicology studies. *Ann. NY Acad. Sci.* 813:849-863, 1997.
3. Watkinson, W.P., Campen, M.J., and Costa, D.L. Arrhythmia induction after exposure to residual oil fly ash particles in the pulmonary hypertensive rat. *Toxicological Sciences* 41:209-216, 1998.
4. Kodavanti, U.K., Jackson, M.C., Ledbetter, A.D., Richards, J.R., Gardner, S.Y., Watkinson, W.P., Campen, M.J., and Costa, D.L. Lung injury from intratracheal and inhalation exposures to residual oil fly ash in a rat model of monocrotaline-induced pulmonary hypertension. *J. Toxicol. Environ. Health* 57:101-121, 1999.
5. Campen, M.J., Norwood, J., McGee, J., Mebane, R., Hatch, G.E., and Watkinson, W.P. Ozone-induced hypothermia and bradycardia in rats and guinea pigs exposed in whole-body or nose-only systems. *J. Thermal Biol*. 25:81-89, 2000.
6. Watkinson, W.P., Campen, M.J., Nolan, J.P., Kodavanti, U.P., Dreher, K.L., Su, W-Y, Highfill, J.W., and Costa, D.L. Thermoregulatory effects following exposure to particulate matter in healthy and cardiopulmonary-compromised rats. *J. Therm. Biol*. 25:131-137, 2000.
7. Campen, M.J., Costa, D.L., and Watkinson, W.P. Cardiac and thermoregulatory toxicity of residual oil fly ash in cardiopulmonary-compromised rats. *Inhal. Toxicol.* 12(S2):7-22, 2000.
8. Kodavanti, U.K., Schladweiler, M.C., Ledbetter, A.D., Watkinson, W.P., Campen, M.J., Winsett, D.W., Richards, J.R., Crissman, K.M., Hatch, G.E., and Costa, D.L. The spontaneously hypertensive rat as a

model of cardiovascular disease: evidence of exacerbated cardiopulmonary injury and oxidative stress from inhaled emission particulate matter. *Toxicol. Appl. Pharmacol.* 164(3):250-63, 2000.

9. Watkinson, W.P., Campen, M.J., Nolan, J.P., and Costa, D.L. Cardiac and systemic responses to inhaled pollutants in rodents: Effects of ozone and particulate matter. *Environ. Health Perspect.,*109:539–546*,* 2001.
10. Watkinson, W.P., Campen, M.J., Wichers, L.B., Nolan, J.P., Kodavanti, U.P., and Costa, D.L. Impact of toxic agents or adverse conditions on thermoregulatory function in awake rodents. *J. Therm. Biol*., 26:331–338*,* 2001.
11. Campen, M.J., Nolan, J.P., Schladweiler M.C.J., Kodavanti, U.P., Evansky, P., Costa, D.L., and Watkinson, W.P. Cardiac and thermoregulatory effects of inhaled particulate matter-associated transition metals in rats: a potential synergism between nickel and vanadium sulfate. *Toxicol. Sci.* 64:243-252, 2001.
12. Tagaito, Y., Polotsky, V.Y., Campen, M.J., Wilson, J.A., Balbir, A., Smith, P.L., Schwartz, A.R., and O'Donnell, C.P. A model of sleep-disordered breathing in the C57Bl/6J mouse. *J. Appl. Physiol.* 91:2758-2766, 2001.
13. Campen, M.J., Nolan, J.P., Schladweiler, M.C., Kodavanti, U.P., Costa, D.L., and Watkinson, W.P. Cardiac and thermoregulatory effects of instilled particulate matter-associated transition metals in healthy and cardiopulmonary-compromised rats. *J Toxicol Environ Health A* 65:1615-1631, 2002.
14. Campen, M.J., Tagaito, Y., Jenkins, T.P., Smith, P.L., Schwartz, A.R., and O'Donnell, C.P. Phenotypic differences in hemodynamic behavior across sleep wake states in various strains of inbred mice. *Physiol Genomics* 11:227-234, 2002.
15. Watkinson W.P., Campen M.J., Wichers L.B., Nolan J.P., and Costa D.L. Cardiac and thermoregulatory responses to inhaled pollutants in healthy and compromised rodents: modulation via interaction with environmental factors, *Environ Res* 92:35-47, 2003.
16. Campen M.J., McDonald J.D., Gigliotti A.P., Seilkop S.K., Reed M.D., and Benson J.M. Cardiovascular effects of inhaled diesel exhaust in spontaneously hypertensive rats. *Cardiovascular Toxicology* 3:353-61, 2003.
17. Tankersley, C.G., Campen, M., Bierman, A., Flanders, S.E., Broman, K.W., and Rabold, R. Particle Effects on Heart-Rate Regulation in Senescent Mice. *Inhalation Toxicology* 16:381 – 390, 2004.
18. Walker, D.M., Poirier, M.C., Campen, M.J., Cook, Jr., D.L., Divi, R.L., Nagashima, K., Lund, A.K., Cossey, P.Y., Hahn, F.F., and Walker, V.E. Persistence of Mitochondrial Toxicity in Hearts of Female B6C3F1 Mice Exposed *In Utero* to 3′-Azido-3′-deoxythymidine. *Cardiovascular Toxicology*, 4(2):133-53, 2004.
19. Campen M.J., Tagaito Y., Li J., Balbir A., Tankersley C.G., Smith P., Schwartz A., and O'Donnell CP. Phenotypic variation in cardiovascular responses to acute hypoxic and hypercapnic exposure in mice. *Physiol. Genom.* 20(1):15-20, 2004.
20. Campen, M.J., Tagaito, Y, Jenkins, T.P., Balbir, A., and O'Donnell. Heart rate variability responses to hypoxic and hypercapnic exposures in different mouse strains. *J Appl. Physiol*. 99:807-813, 2005.
21. Campen, M.J., Shimoda, L.A., and O'Donnell, C.P. The acute and chronic cardiovascular effects of intermittent hypoxia in C57BL/6J mice. *J Appl Physiol* 99:2028-2035, 2005.
22. Campen, M.J., Babu, N.S. Helms, G.A., Pett, S., Wernly, J., Mehran, R., and McDonald, J.D. Nonparticulate Components of Diesel Exhaust Promote Constriction in Coronary Arteries from ApoE-/- Mice. *Toxicological Sciences* 88:95-102, 2005.
23. Tesfaigzi, Y., McDonald, J.D., Reed, M.D., Hahn, F.F., Singh, S.P., Eynott, P.R., Campen, M.J., Mauderly, J.L. Low Level Subchronic Exposure to Wood Smoke Exacerbates Inflammatory Responses in Allergic Rats. *Toxicol. Sci*., 88:505-513, 2005.
24. Zhuang, J., Xu, F., Campen, M.J., Hernandez, J., Shi, S., and Wang, R. Transient carbon monoxide inhibits the ventilatory responses to hypoxia through peripheral mechanisms in the rat. *Life Sciences*, 78:2654-2661, 2006.
25. Reed, M. D., M.J. Campen, A. P. Gigliotti, K. S. Harrod, J. D. McDonald, JC. Seagrave, S. K. Seilkop, and J. L. Mauderly. Health Effects of Subchronic Exposure To Environmental Levels Of Hardwood Smoke. *Inhal. Toxicol.* 18(8):523-39, 2006.
26. Obot Akata CJ, Blair LF, Barr EB, Storch S, Vigil G, and Campen MJ. Development of a head-out plethysmograph system for non-human primates in an animal biosafety level 3 facility. *J. Pharmacol. Toxicol. Meth.*, 55(1):96-102, 2006.
27. Campen MJ, Milazzo ML, Fulhorst C, Obot Akata CJ, and Koster F. Characterization of Shock in a Hamster Model of Hantavirus Infection. *Virol*, 356(1-2):45-49, 2006.
28. March, T.H., Wilder, J.A., Esparza, D.C., Cossey, P.Y., Blair, L.F., Herrera, L.K., McDonald, J.D., Campen, M.J., Mauderly, J.L., Seagrave, J. Modulators of Cigarette Smoke-Induced Pulmonary

Emphysema in A/J Mice. *Toxicol Sci.* 92(2):545-59, 2006.
29. Campen, M.J., McDonald, J.D., Reed, M.D., and Seagrave, J. Fresh Gasoline Emissions, Not Paved Road Dust, Trigger Alterations in Cardiac Repolarization in ApoE-/- Mice. *Cardiovasc Toxicology* 6(3-4):199-210, 2006.
30. Rowan, WH, Campen, MJ, Wichers, LB, Watkinson WP. Heart Rate Variability in Rodents — Uses and Caveats in Toxicological Studies. *Cardiovasc Toxicol*, 7:28-51, 2007.
31. Lund, A.K., Knuckles, T.L., Obot Akata, C., Shohet, R., McDonald, J.D., Gigliotti, A., Seagrave, J., and Campen, M.J. Gasoline Exhaust Emissions Induce Vascular Remodeling Pathways Involved in Atherosclerosis. *Toxicol. Sci,* 95(2):485-94, 2007.
32. Chang B, Crowley M, Campen M, Koster F. Hantavirus cardiopulmonary syndrome. Semin Respir Crit Care Med.28(2):193-200, 2007.
33. McDonald JD, Reed MD, Campen MJ, Barrett EG, Seagrave J, Mauderly JL. Health effects of inhaled gasoline engine emissions. *Inhal. Toxicol.* 19(Suppl 1):107-116, 2007.
34. Aragon AC, Kopf PG, Campen MJ, Huwe JK, and Walker MK. In utero and lactational 2,3,7,8-tetrachlorodibenzo-p-dioxin exposure: Effects on fetal and adult cardiac gene expression and adult cardiac and renal morphology. Toxicol Sci. 101(2):321-330, 2008.
35. Knuckles TL, Lund AK, Lucas SN, and Campen MJ. Diesel Exhaust Exposure Enhances Venoconstriction through Uncoupling of eNOS. *Toxicol Appl Pharmacol*., 230:346-351, 2008.
36. Seagrave JC, Campen MJ, McDonald JD, Mauderly JL, and Rohr AC. Oxidative Stress, Inflammation, and Pulmonary Function Assessment in Rats Exposed to Laboratory-Generated Pollutant Mixtures. *J Toxicol Environ Health*, 71:1352-1362, 2008.
37. Mishra NC, Rir-sima-ah J, Langley RJ, Singh SP, Peña-Philippides JC, Koga T, Razani-Boroujerdi S, Hutt J, Campen M, Kim KC, Tesfaigzi Y, and Sopori ML. Nicotine Primarily Suppresses Lung Th2 but not Goblet Cell and Muscle Cell Responses to Allergens. *J Immunol*, 180:7655-7663, 2008.
38. Zhuang, J., Xu, F., Campen, M.J., Zhang, C., Pena-Philippides, J.C., and Sopori, M.L. Inhalation of the Nerve Gas Sarin Impairs Ventilatory Responses to Hypercapnia and Hypoxia in Rats. *Toxicol and Appl Pharmacol.* 232(3):440-447, 2008.
39. Reed MD, Barrett EG, Campen MJ, Divine KK, Gigliotti AP, McDonald JD, Seagrave JC, Seilkop SK, Swenberg JA, and Mauderly JL. Health Effects of Subchronic Inhalation Exposure to Gasoline Engine Emissions. Inhal Toxicol, 20(13):1125-43, 2008.
40. Lund AK, Lucero JA, Lucas S, Madden MC, McDonald JD, Seagrave JC, Knuckles TL, and Campen MJ. Vehicular Emissions Induce Vascular MMP-9 Expression and Activity via Endothelin-1 Mediated Pathways. *Arterioscler Thromb Vasc Biol*, 29(4):511-517, 2009.
41. Cherng TW, Campen MJ, Knuckles TL, Gonzalez-Bosc L and Kanagy NL. Impairment of coronary endothelial cell ET_B receptor function following short-term inhalation exposure to whole diesel emissions. *Am J Physiol Regul Integr Comp Physiol*, 297:640-647, 2009.
42. Singh SP, Rir-sima-ah J, Mishra N, Campen M, Kurup V, and Sopori ML. Maternal exposure to secondhand cigarette smoke primes the lung for allergen-induced inflammation, muscarinic receptor overexpression, airway hyperreactivity, and atopy; rolipram attenuates the hyperreactivity but not the inflammatory/IgE responses. *J Immunol*, 183:2115-2121, 2009.
43. Campen MJ. Nitric oxide synthase: "enzyme zero" in air pollution-induced vascular toxicity. Toxicol Sci. 110:1-3, 2009.
44. Campen MJ, Lund AK, Knuckles TL, Conklin DJ, Bishop B, Young D, Sielkop SK, Seagrave JC, Reed MD, and Jacob D. McDonald JD. Inhaled Diesel Emissions Alter Atherosclerotic Plaque Composition in $ApoE^{-/-}$ Mice*. Toxicol Appl Pharmacol,* 242:310-317, 2010.
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64. Seagrave J, Campen MJ. Role of Low Density Lipoprotein Oxidation In Second-Hand Smoke-Induced Cardiovascular Disease. *Am J Resp Crit Care Med*, May 2011.
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74. Campen MJ, Lund AK, McDonald JD. Cardiovascular Outcomes of Simulated, Contrasting Ambient Air Pollution Environments. *Am J Resp Crit Care Med*, May 2012.
75. Campen MJ, Channell MC, Devlin RB, Madden M. Circulating Factors Following Nitrogen Dioxide and Diesel Engine Exhaust Exposure Induce Adhesion Molecule Expression in Human Coronary Artery Endothelial Cells. *Am J Resp Crit Care Med*, May 2012.
76. Campen MJ, Chen LC. Role Of Circulating Factors In Mediating Systemic Toxicity Of Inhaled Substances. Society of Toxicology Annual Meeting, Phoenix, AZ, March 2014.
77. Aragon M, Erdely A, Campen MJ. Endothelial Cells as Biosensors to Assess the Systemic Inflammatory Impact of Multi Walled Carbon Nanotubes. Society of Toxicology Annual Meeting, Phoenix, AZ, March 2014.
78. Campen MJ, Aragon M, Erdely A. Induction of Serum Inflammatory Potential by Pulmonary Exposure to Multi-Walled Carbon Nanotubes. *Am J Resp Crit Care Med*, San Diego, May, 2014
79. Chrobak I, Brower J, Aragon MJ, Kheirandish N, Robertson S, Fredenburgh L, McDonald JD, and Matthew Campen, MJ. Impact of test atmosphere composition on serum bioactivity and endothelial toxicity. Presented at the Annual United States Environmental Protection Agency Clean Air Research Center Meeting, Atlanta, GA, September 19, 2014.
80. Zychowski K, Herbert G, Tyler C, Lucas SN, Sanchez B, Cerrato J, Avasarala S, Muttil P, Kunda N, Campen MJ. Navajo Mine Dust Exposure and Subsequent Toxicological Implications. Oral presentation at the Society of Toxicology Annual Conference, Baltimore, MD, March 14, 2017.
81. Zychowski K, Herbert G, Lucas SN, Kunda N, Muttil P, Brearley A, Bleske B, Cerrato J, Campen MJ. Health effects from respirable uranyl-vanadate and uranyl-silicate particulates from an abandoned mine sites in the Southwestern United States. Abstract submitted to the Society of Toxicology Annual Conference, San Antonio, TX, 2018.
82. Begay J and Baldwin, Jr, F. Assessment of Metal Contaminants and Toxicity of Windblown Particulates from the Claim 28 Uranium Mine. Navajo Nation Environmental Protection Agency (EPA) Conference: June 20-22, 2018
83. Begay J, Ordonez Y, Sanchez B, Wheeler A, Lucas S, Baldwin, Jr. F, Herbert G, Shuey C, Harkema J, Wagner J, Morishita M, Bleske B, Campen MJ. In Vivo Toxicity Assessments of Metal Contaminated Windblown Particulate Matter from an Abandoned Uranium Mine on the Navajo Reservation. Society of Toxicology (SOT) Mountain West Regional Meeting: September 19-21, 2018
84. Begay J, Ordonez Y, Sanchez B, Wheeler A, Lucas S, Baldwin, Jr. F, Herbert G, Shuey C, Harkema J, Wagner J, Morishita M, Bleske B, Campen MJ. In Vivo Toxicity Assessments of Metal Contaminated Windblown Particulate Matter from an Abandoned Uranium Mine on the Navajo Reservation. 10th Conference on Metal Toxicity & Carcinogenesis: October 28-31, 2018
85. Begay J, Ordonez Y, Lucas S, Sanchez B, Wheeler A, , Baldwin, Jr. F, Herbert G, Shuey C, Harkema J, Wagner J, Morishita M, Bleske B, Campen MJ. In Vivo Toxicity Assessment of Metal Contaminated Wind Blown Particulate Matter from an Abandoned Uranium Mine on the Navajo Reservation. SOT Annual Meeting: March 10-14, 2019
86. Begay J, Ordonez Y, Lucas S, Sanchez B, Wheeler A, , Baldwin, Jr. F, Herbert G, Shuey C, Harkema J, Wagner J, Morishita M, Bleske B, Campen MJ. In Vivo Toxicity Assessment of Metal Contaminated Windblown Particulate Matter from an Abandoned Uranium Mine on the Navajo Reservation. American Indian Science and Engineering Society (AISES) Region 3 Meeting: March 28-30, 2019
87. Begay J, Sanchez B, Wheeler A, Baldwin, Jr. F, Lucas S, Herbert G, Ordonez Y, Shuey C, Harkema J, Wagner J, Morishita M, Bleske B, Campen M. Using the Mobile Air Research Lab to for in vivo assessment of Metal Contaminated Wind-Blown Particulates from Abandoned Uranium Mines within U.S. American Indian Tribal Lands. 13th International Particle Toxicity Conference, Salzburg, Austria, Sept 12, 2019
88. Campen M. Mechanisms of Vascular Inflammation and Cardiometabolic Health in Indigenous Peoples. American Heart Association Scientific Sessions, Philadelphia, PA, Nov 17, 2019.
89. K. E. Zychowski[1], B. Sanchez[1], X. Zhou[1], A. S. Gardiner[1], G. Herbert[1], S. Lucas[1], M. Morishita[2], J. G. Wagner[2], J. Harkema[2], C. Shuey[3], and M. J. Campen. Serum-Borne Factors Alter Cerebrovascular Endothelial microRNA Expression following Particulate Matter Exposure Near an Abandoned Uranium Mine on the Navajo Nation. Society of Toxicology, March 2020.
90. E. El Hayek, S. Medina, J. Guo, A. Noureddine, K. Zychowski, R. Hunter, C. Velasco, A. Brearley, M. Spilde, T. Howard, F. Lauer, G. Herbert, M. Wiesse, S. Cabaniss, A. Ali, S. Burchiel, M. Campen, and J.

Cerrato. Uptake and Toxicity of Respirable Uranium-Carbon-Bearing Particulate Matter in A549 Lung Epithelial Cells. Society of Toxicology, March 2020.

91. R. P. Hunter, A. Bolt, A. Brearley, J. Cerrato, C. Velasco, J. Weaver, D. McChesney, P. Muttil, G. Herbert, M. Campen, and K. Zychowski. DNA Damage from Regional Metal-Enriched Particulate Matter in a549 Lung Epithelial Cells. Society of Toxicology, March 2020.
92. J. Begay[1], Y. Ordonez[1], S. Lucas[1], B. Sanchez[1], A. Wheeler[1], F. Baldwin, Jr.[1], G. Herbert[1], C. Shuey[1], J. Harkema[2], J. Wagner[2], M. Morishita[3], B. Bleske[1], K. Zychowski[1], and M. Campen[1] Physicochemical Characterization and Toxicological Assessment of Regional Particulates Adjacent Abandoned Uranium Mines within Native American Communities. Society of Toxicology, March 2020.
93. K. Burton, C. McVeigh, E. Barr, G. Herbert, R. Hunter, S. Medina, S. Lucas, A. Ali, M. Campen, and A. M. Bolt. Acute Effects of Inhaled Tungsten Particles on the Lung Microenvironment. Society of Toxicology, March 2020.

Invited Lectures, Prepared Symposia:

1. "Cardiovascular Effects of Air Pollution." Michigan State University, East Lansing, MI. July 12, 2005.
2. "Cardiovascular Effects of Air Pollution: More than Just Particles." East Carolina University, Greenville, NC. July 18, 2005.
3. "Electrocardiographic Impact of Whole Emissions in the ApoE$^{-/-}$ Mouse." Environmental Protection Agency, Research Triangle Park, NC. January 31, 2006
4. "Acute and Chronic Cardiovascular Health Effects of Gasoline and Diesel Engine Emissions." University of Louisville, Louisville, KY. February 23, 2006.
5. "Air Pollution and Atherosclerosis", Society of Toxicology, Symposium Chair, Charlotte, NC, March 27, 2007.
6. "Diesel and Gasoline Exhaust Exposure Induces Biomarkers of Vascular Remodeling and Oxidative Stress" American College of Sports Medicine, New Orleans, LA. May 31, 2007.
7. "Vascular Toxicity of Complex Emissions", Seminar for the Department of Environmental and Occupational Health, School of Public Health, University of Washington, July 16, 2007.
8. "Vascular Toxicity of Inhaled Pollutants", Invited Lecture for the Department of Pulmonary Medicine, University of New Mexico, Albuquerque, NM, October 3, 2007.
9. "The Comparative Toxicity Test Program of the National Environmental Respiratory Center: Vascular Toxicity of Complex Emissions", Toxicology Forum European Meeting, Brussels, Belgium, October 24, 2007.
10. "Essentials of Respiratory Safety Pharmacology", American College of Toxicology Meeting, Charlotte, NC, November 13, 2007.
11. "Vascular Toxicity of Complex Emissions", Invited Lecture for the Department of Physiology, West Virginia University, Morgantown, WV, November 15th, 2007.
12. "Air Pollution and Atherosclerosis", Symposium Chair, American Association for the Advancement of Science, Annual Meeting, Boston, MA, February, 2008.
13. "Endothelial Dysfunction: More than just a No NO Phenomenon" Society of Toxicology, Symposium Chair, Seattle, WA, March, 2008.
14. "Cardiovascular Effects in Animal Models of Exposure to Defined Sources" Health Effects Institute Annual Meeting, Philadelphia, April, 2008.
15. "Shock in a Hamster Model of Hantavirus Cardiopulmonary Syndrome" Respiratory Physiology in Laboratory Animal Models: An Advanced Course, Battelle Eastern Science & Technology Center Aberdeen, MD, April, 2008.
16. "Atherosclerosis and Vehicular Emissions Exposure: More than Just Airborne Particles" Physiology Seminar, Johns Hopkins School of Public Health, Baltimore, MD, April, 2008.
17. "Gasoline Emissions and Vascular Remodeling", American Heart Association Scientific Sessions, New Orleans, LA November 9th, 2008.
18. "Complex Interactions of Urban Air Pollution: Impact on Vascular Pathophysiology" College of Veterinary Medicine, Louisiana State University, Baton Rouge, LA, November 12th, 2009.
19. "Biochemical Pathways for Smooth Muscle Atrophy in Pulmonary Arterial Hypertension," Department of Pulmonary Medicine, University of New Mexico, Albuquerque, NM, December 2, 2009.
20. "Environmental Influence on Vascular Remodeling Pathways" Department of Physiology, West Virginia University, Morgantown, WV, April 8th, 2010.
21. "Endothelial Function and Lipid Peroxidation" NIEHS-EPA Symposium on Air Pollution and

Cardiovascular Disease, Seattle, WA, 2010.

22. "Environmental Influence on Vascular Remodeling Pathways" Department of Environmental Medicine, New York University, Tuxedo Park, NY, August 5th, 2010.
23. "Complex Responses to Complex Mixtures: Vascular Effects of Air Pollution", Department of Gerontology, University of Southern California, March 14th, 2011.
24. "Environmental Influences on Cardiovascular Health", Rio Grande Chapter of the American Industrial Hygiene Association Annual Meeting, October 27th, 2011.
25. "Cardiovascular Toxicity of Simulated Complex Air Pollution Mixtures" Health Effects Institute Annual Meeting, Chicago, April, 2012.
26. "How Does Inhalation Exposure Cause Systemic Vascular Toxicity?" Allegheny-Erie Regional Chapter of the Society of Toxicology Annual Meeting, Pittsburgh, PA, May, 2012.
27. "Impact of inhaled nitrogen air pollutants on cardiovascular function" RCN Human Health Conference Impacts of Excess Nitrogen in the Environment on Human Health, Bethesda, MD, November 14th, 2012.
28. "Complex Mixtures of Air Pollutants and Cardiopulmonary Health" National Vehicle & Fuel Emissions Laboratory, United States Environmental Protection Agency, Ann Arbor, MI, February 26th, 2013.
29. "Mechanisms Mediating Systemic Vascular Toxicity Following Inhalation Exposure to Nanomaterials" Mountain West Society of Toxicology Regional Chapter Annual Meeting, Albuquerque, NM, September 19th, 2013.
30. "Pathways Mediating Systemic Vascular Insult Following Inhalation Exposure to Airborne Toxicants" University of Utah, Salt Lake City, UT, February 3rd, 2014.
31. "Impacts of Environmental Factors on Endothelial 'Micro-Exposome': Implications for Chronic Vascular Disease", Department of Biochemistry and Molecular Biology, University of New Mexico School of Medicine, September 29th, 2014.
32. "Cardiovascular Impacts of Inhaled Pollutant Mixtures" Umeå University, Sweden, December 11th, 2014.
33. Air Pollution and Neuroinflammation: Can Smoke Cause Fire?" Department of Preventive Medicine, University of Southern California, March 27th, 2015.
34. "Gasoline, Diesel Engine and Mixed Emissions Effects on Oxidized Lipids and Vascular Function" American Heart Association Scientific Sessions, November 2015.
35. "Air Pollution and Health Effects Beyond the Lung: Traveling Sterile Inflammation" Infectious Disease and Inflammation Program, University of New Mexico School of Medicine, May 2016.
36. "Inhalation of particulates and gases and systemic inflammatory effects: Modification of circulating components promotes cerebrovascular endothelial inflammation and dysfunction." Japanese Society of Toxicology Annual Conference, Nagoya, Japan, June 2016.
37. "Circulating Inflammatory Bioactivity Resulting from Environmental Exposures" National Institute of Occupational Health Sciences, Cincinnati, OH, July 19th, 2016.
38. "Environmental Health Concerns Associated with Uranium Mines Sites in Southwestern Tribal Communities" Department of Environmental Health, University of Cincinnati, July 20th, 2016.
39. "Vascular Toxicity from Inhaled Toxins: Refining our understanding of "indirect" effects", Division of Cardiology, University of Louisville, October 24, 2016.
40. "Uranium and Vanadium Drive Cardiopulmonary Toxicity of Respirable Dusts Derived from Abandoned Uranium Mine Sites in the Southwest" 9th Metals Toxicity and Carcinogenesis Conference, Lexington, KY, October 25, 2016.
41. "Inhalation Toxicity of Dusts Derived from Uranium Mines Sites in Southwestern Tribal Communities", Superfund Research Program, University of Arizona, Tucson, AZ, January 19, 2017.
42. "Pipe Cleaners in the Pipeline: Mechanisms of Action for Novel Cardiovascular Drugs on the Clinical Horizon", New Mexico Pharmacists Association Annual Meeting, Albuquerque, NM, June 25, 2017.
43. "Cardiopulmonary Consequences of Respirable Dusts Derived from Uranium Mines on the Navajo Nation", Ohio State University College of Public Health, Division of Environmental Health, Columbus, OH, September 13, 2017.
44. "Air Pollution and Health Effects Beyond the Lung: Traveling Sterile Inflammation", Nationwide Children's Hospital, Columbus, OH, September 14, 2017.
45. "Inhaled Toxicants and Neuroinflammation: Connecting the Dots", Department of Internal Medicine, College of Medicine, University of Arizona-Phoenix, AZ, February 23, 2018.
46. "Neurovascular effects of inhaled toxicants", Zhejiang Chinese Medical University, Hangzhou, China, March 26, 2018.
47. "Impact of a High-Risk Environment on Tribal Lands: Assessing Cardiorespiratory Risk from Uranium Mines", Clinical Translational Research Infrastructure Network (CTR-IN) Annual Conference, University of Nevada-Las Vegas, June 12, 2018.

48. “Respiratory and Cardiovascular Toxicity Related to Windblown Dusts from Abandoned Uranium Mines on Tribal Lands in the Southwest”, Biomedical Research Seminar, New Mexico State University, Las Cruces, NM, August 31, 2018.
49. “Assessing Cardiorespiratory Risk from Dusts Arising from Uranium Mines on Tribal Lands” Mountain West Society of Toxicology Annual Conference, University of Arizona-Phoenix, AZ, September 20, 2018.
50. “Assessing Cardiorespiratory Risk from Dusts Arising from Uranium Mines on Tribal Lands”, Molecular Toxicology Lectureship (EHS 411), University of California at Los Angeles, December 6, 2018.
51. “Neuroinflammatory Consequences of Inhaled Pollutants: Role of Circulating Factors”, Cardiology Grand Rounds, University of California at Los Angeles, December 7, 2018.
52. “Circulating Molecular Shrapnel: Identifying links between inhaled toxicants and neurological outcomes”, Michigan State University Institute for Integrative Toxicology Seminar Series, January 11, 2019.
53. “Cardiovascular and Respiratory Toxicity of Particulates from Abandoned Uranium Mines on Navajo Nation”, Department of Comparative Biomedical Sciences, School of Veterinary Medicine, Louisiana State University, May 16, 2019.
54. “Respiratory Tract Toxicology”, invited lecture for Advanced Comprehensive Toxicology course organized by the American College of Toxicology, Gaithersburg, MD, August 7, 2019.
55. “Pulmonary-derived circulating factors promote cerebrovascular inflammatory mechanisms following inhalation of particles and gases” Keynote lecture for International Particle Toxicology Conference, Salzburg, Austria, September 12, 2019.
56. “Inhalation Toxicity of Dusts from Uranium Mine Sites *plus* Update on Vaping Health Hazards” Invited Seminar for New Mexico Tech, October 4, 2019.
57. “Mechanisms of Vascular Inflammation and Cardiometabolic Health in Indigenous Peoples”, Oral Presentation at the American Heart Association Annual Meeting, Philadelphia, PA, November 17, 2019.
58. “Let’s think about mom for a change: How gestational exposures to inhaled toxicants may uniquely impact maternal cardiovascular health” Program in Toxicology, Texas A&M Univeristy, College Station, TX, December 2, 2019.
59. “What the heck is going on with vaping?” Outreach presentation for Santa Fe (NM) Preparatory School Students (Middle, High School) and Parents, December 3,4, 2019.
60. “From Cardiovascular Disease, to Fetal Effects, to Neurological Outcomes: Can Air Pollution Really Cause Everything?” University of Connecticut Toxicology Scholars Colloquium Seminar, April 6, 2020.
61. “Chemistry and Toxicity of Contaminants from Uranium Mine Sites on Native American Lands of the Southwest” Webinar for the North Carolina School of Science and Mathematics, Earth Day, April 22nd, 2020.
62. “Harmful Effects of Vaping: Lung Toxicity and Impairment of Immune Function” New Mexico Pharmacy Association, Virtual Annual Meeting, September 13th, 2020.
63. “Chemistry and Toxicity of Respirable Contaminants from Uranium Mine Sites on Native American Lands of the Southwest” Department of Chemistry Webinar, State University of New York College of Environmental Science and Forestry, October 29, 2020.
64. “Air Pollution Impacts on Diverse Vascular Beds: Brain and Placenta as Targets” Webinar for Case Western’s Cardiovascular Research Institute, November 17, 2020.

INSTITUTIONAL SERVICE

COMMITTEES

Environmental Health Signature Program Steering Committee, University of New Mexico, 2008-present; Chair, 2013-present

Cardiovascular and Metabolic Disease Signature Program Steering Committee, University of New Mexico, 2009-present

Biomedical Graduate School Program Admissions Committee, University of New Mexico, 2010-2012

Biomedical Graduate School Program Qualifying Exams Review Service, University of New Mexico, 2010-2013

Search Committee, Dean of Pharmacy Vacancy, University of New Mexico, 2010-11, hired Lynda Welage, Pharm.D.

Organizational Planning and Evaluation Committee, 2010-11

Graduate Education Committee, College of Pharmacy, University of New Mexico, 2010-11

Search Committee, Pharmaceutical Sciences Faculty Position, University of New Mexico, 2010-

11, hired Pamela Hall, Ph.D.
Curriculum Committee, College of Pharmacy, University of New Mexico, 2011-2013
Pharmacy Student Portfolio Advisor, 2011-12
Awards Committee, UNM HSC Faculty Research Excellence Awards, 2012-2014.
Management of Conflict of Interests (MCOI) Committee, UNM HSC, 2012-2017.
Graduate Affairs Committee, 2012-2016; Chair, 2014-2016
Chair, Search Committee for Director of UNM Community Environmental Health Program, 2014-2015
College of Pharmacy Student Affairs Committee, 2015-present; Chair of Academic Dishonesty Investigations, 2016-present
Research Steering and Planning Committee (HSC), 2015-present.
SAGE Committee (CTSC Pilot Funding Reviews) 2015-present.
Promotion and Tenure Committee Chair, Department of Pharmaceutical Sciences, 2018-present. External P&T support for College of Nursing and Dept of Pharmacy Practice, 2020

INSTRUCTION

Lectures:

Cardiovascular Toxicology (as part of Gen. Toxicology), University of New Mexico, 2003-2009
Cardiovascular Pharmacology (as part of Gen. Pharmacology), University of New Mexico, 2003-2008
PHRM 731-732, Mechanisms of Drug Action, 2009-2014, mechanisms of therapy for pulmonary hypertension, heart failure, hyperlipidemia, arrhythmia, and anemia
PHRM 593, Pharmaceutical Sciences Research Seminar. Instructor on Record, Spring 2011.
PHRM 731, Mechanisms of Drug Action, Instructor on Record, Fall 2011.
PHRM 580, Toxicology, Cardiovascular & Respiratory Toxicology lectures, 2012-2016, Instructor on Record, 2017
PHRM 593, Pharmaceutical Sciences Research Seminar. Instructor on Record, Spring 2013.
PHRM 705, Pathophysiology, Anemia, Hypoxia, Coagulation, 2011-2019.

Undergraduate Trainees:

Lauren Heine, 2015 (Michigan State University Ph.D. program)
Valeria Rivero, 2015-2016
Bethany Sanchez, 2015-2017 (Yale University MSPH program)
Raul Salazar, 2016-2019
Bryan Villalva, 2017-2018
Abigail Wheeler, 2017-2018 (Johns Hopkins University PhD program)
Rita Saracino, 2020-present

Pharm.D. Research Trainees:

Heidi Cung, 2013-2015
Yoselin Ordonez Suarez, 2016-2019
Alex Wehner, 2016
Catherine Smith, 2016-2017
Marcus Garcia, 2016-2020
Raul Salazar, 2019-present
Thomas Wilson, 2019-2020

Doctoral/Masters Candidate Committees († indicates principal advisor):

Kyan Allahdadi, PhD, 2004-2006
Andrea Aragon, MS, 2005-2007
Phillip Kopf, 2004-2009
Salina Torres, 2004-2008
†Tom Cherng, 2006-2010
Njotu Larry Agbor, 2009-2013

†Molly Harmon, MS, 2010-2015
Azita K. Madrid, PhD 2010-2012 (from NYU)
†Mario Aragon, 2011-2015
Amber McBride, 2012-2014
Elani Fourie, 2013-2016
Christina Termini, 2013-2016
Moriah Castleman, 2013-2015
†Roberto Mota, 2014-2016 (MS)
Kayla Zehr, 2015-2017
†Tamara Young, 2016-present
Griffith Davis, 2016-2019, (University of North Texas)
†Jessica Begay, 2017-2019 (MS), 2020-present (PhD)
†Marsha Bitsui, 2017-present
†Russell Hunter, 2019-present
†David Scieszka, 2020-present

Graduate Student Rotations (1st year): Alexandra Fowler, 2017
Srinivas Rao Gadam, 2018
Nathan Cruz, 2020

Dissertation Opponent/Assessment Committee:
Jon Unosson, 2014, Umeå University, Sweden (Opponent to Defense)
Daniel Vest Christophersen, 2016, University of Copenhagen, Denmark (Assessor)

Post-Doctoral Trainees: Andrew Helms, MD. 2003-04, Cardiothoracic Surgical Fellow, currently a Thoracic Surgeon at WellStar Health System, Marietta, Ga
Sathish Babu, MD. 2004-05, Cardiothoracic Surgical Fellow, currently President & CEO at Chicago Life Sciences Med Corp, Chicago, USA
Travis Knuckles, Ph.D. 2005-2008, now Assist Professor at WVU
Amie Lund, Ph.D. 2005-2009, now Assist Professor, University of North Texas. Received F32 and K99/R00.
Michael Paffett, Ph.D. 2009-2013, Now Scientist and Technical Rep, Olympus Microscopes
Elizabeth Sage Colombo, M.D., Ph.D., 2011-2012, now Chief Resident, Quality, University of New Mexico
Sarah Robertson, Ph.D., 2012-2013, now Environmental Health Scientist, Public Health England
Katherine Zychowski, Ph.D., 2014-2018, from Texas A&M University. Received K99/R00.
Christina Tyler, Ph.D., 2015-2016, now at Los Alamos National Labs

Faculty Advisement:
Dawn Delfin, Ph.D. 2013-2016, Clinical and Translational Science Center KL2 Scholar, Assistant Professor, UNM
Hector Olvera, Ph.D., 2014-2016, Assistant Professor, UTEP, as part of the Harvard University School of Public Health JPB Environmental Health Scholars Program
Through KL2 Mentored Career Development Program: Brandi Fink, PhD; Justin Baca, MD PhD; Kathryn Frietze, PhD; Eliseo Castillo, PhD; Daryl Domman, PhD
Through NM CMBM COBRE: Alicia Bolt, PhD; Rama Gullapali, MD, PhD; Xiang Xue, PhD; Xixi Zhou, PhD

SYMPOSIA AND WORKSHOPS ORGANIZED

Mountain West Society of Toxicology Annual Meeting, *Environmental Cardiology*, Sante Fe, NM, Keynote Speaker: Ken Ramos, University of Louisville, 2005.

Air Pollution and Atherosclerosis: Impact on Vascular Oxidative Stress, Dyslipidemia, and Remodeling. Symposium organized / chaired at the Society of Toxicology Annual Meeting, Charlotte, NC, 2007.

Air Pollution and Atherosclerosis: Impact on Vascular Oxidative Stress, Dyslipidemia, and Remodeling. Symposium organized / chaired at the American Association for the Advancement of Science Annual Meeting, Boston, MA, 2008.

Endothelial Dysfunction: More than Just a No NO Phenomenon. Symposium organized / chaired the Society of Toxicology Annual Meeting, Baltimore, MD, 2008.

UNM Cardiovascular and Metabolic Disease Signature Program Research Day, Albuquerque, NM, Keynote Speaker: David Harrison, Vanderbilt University, 2011.

Cooperative Epidemiology and Toxicology Research: HEI's National Particle Component Toxicity (NPACT) Initiative. Workshop organized / chaired for the 2012 Society of Toxicology Conference.

UNM Cardiovascular and Metabolic Disease Signature Program Research Day, Albuquerque, NM, Keynote Speaker: James Sowers, University of Missouri, 2012.

UNM Cardiovascular and Metabolic Disease Signature Program Research Day, Albuquerque, NM, Keynote Speaker: Christopher P. O'Donnell, University of Pittsburgh, 2013.

Role of Metabolic Syndrome and Perivascular Adipose in Exposure-Induced Vascular Dysfunction, Symposium organized / chaired the Society of Toxicology Annual Meeting, San Antonio, TX, 2013.

Role of Circulating Factors In Mediating Systemic Toxicity Of Inhaled Substances. Workshop organized / chaired the Society of Toxicology Annual Meeting, Phoenix, AZ, 2014.

Circulatory Mechanisms Underlying the Systemic Effects of Inhaled Nanoparticles and Complex Combustion Mixtures: Common Pathways for Diverse Toxicants. Workshop organized / chaired the Society of Toxicology Annual Meeting, Baltimore, MD, 2017.

Not Your Father's ED: Expanding the Definition and Understanding of Endothelial Dysfunction (ED) Due to Inhaled Toxicants. Symposium organized / chaired the Society of Toxicology Annual Meeting, Baltimore, MD, 2019.

HOT TOPICS Session. E-cigarette and Vaping Product Use-Associated Lung Injury (EVALI): Outbreak Analysis from an Epidemiological, Clinical, Forensic and Mechanistic Perspective. Symposium organized / chaired the Society of Toxicology Annual Meeting, Anaheim, CA, 2020. (Presented as webinar after Covid19 cancellation)

STATE OF NEW MEXICO
BEORE THE ENVIRONMENTAL IMPROVEMENT BOARD
AND THE
ALBUQUERQUE-BERNALILLO COUNTY AIR QUALITY CONTROL BOARD

IN THE MATTER OF: PROPOSED 20.2.91 NMAC –	)	
***NEW MOTOR VEHICLE EMISSION STANDARDS*,**	)	**EIB No. 21-66 (R)**
and	)	
THE PETITION TO REPEAL EXISTING RULE	)	
20.11.104 NMAC AND ADOPT PROPOSED	)	
REPLACEMENT 20.11.104 NMAC.	)	**AQCB No. 2022-01**
	)	

WRITTEN DIRECT TESTIMONY OF JOANNA STROTHER

Q. Please state your name for the record.

A. JoAnna Strother.

Q. And where do you work?

A. The American Lung Association, in Phoenix, Arizona.

Q. What is your position at the American Lung Association?

A. I am Senior Director for Advocacy.

Q. For whom are you testifying?

A. I am testifying on behalf of NRDC, Conservation Voters New Mexico, Prosperity Works, the Sierra Club, Southwest Energy Efficiency Project, Western Resource Advocates, New Mexico Voices for Children, New Mexico Environmental Public Health Network, and the Center for Civic Policy (collectively, "Clean Air Advocates").

Q. Could you describe the American Lung Association and what it does?

A. The American Lung Association is a national non-profit organization founded more than 115 years ago by a group of volunteers. Our mission is to save lives by improving lung health and preventing lung disease. We do this through education, advocacy, and research.

CAA
EXHIBIT
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Q. Could you describe your qualifications, including your education and relevant work experience?

A. I have a Bachelor of Science in Health Education, focusing on community health, from the University of New Mexico. I was a Robert Wood Johnson Fellow at the Robert Wood Johnson Foundation and Center for Creative Leadership.

I have been working for the American Lung Association since 2007. I have had several positions at the organization, including Lung Health Coordinator, Director of Programs, Director for Advocacy, and Senior Director for Advocacy, the position I now hold.

Q. What are your responsibilities as Senior Director for Advocacy?

A. I direct federal, state, and local lobbying efforts and develop strategies for passage of laws and regulations that advance the American Lung Association's Public Policy Agenda. I am responsible for advocacy in Arizona, Colorado, Nevada, New Mexico, Oklahoma, Texas, and Utah. I also draft, track, and research legislation, and I develop and coordinate multi-state strategies that advance American Lung Association's mission. I testify before U.S. House and Senate committees, and state legislators.

Q. Is your resume Clean Air Advocates Exhibit 13?

A. Yes, it is.

Q. Are you familiar with a Report from the American Lung Association entitled *Zeroing in on Healthy Air: A National Assessment of Health and Climate Benefits of Zero-Emission Transportation and Electricity*?

A. Yes, I am.

Q. Is that the document marked as Clean Air Advocates Exhibit 15?

A. Yes.

Q. When was the report released?

A. Quite recently. It was released on March 30, 2022.

Q. Who authored the report?

A. The primary author is William Barrett, my colleague at the American Lung Association. The report is based on modeling conducted by ICF Incorporated. ICF, which has its headquarters in Fairfax, Virginia, has been conducting air pollution modeling since the 1980s. It is a major contractor to U.S. Environmental Protection Agency air programs.

Q. Could you describe the report, please?

A. Yes. *Zeroing in on Healthy Air* is a report by the American Lung Association illustrating the public health urgency of policies and investments for transitioning to zero-emission transportation in the coming decades. The report also examines zero-emission electricity generation, which I understand is not covered in this rulemaking proceeding. So, where possible, I will focus on transportation.

The transportation sector is a leading sources of unhealthy air in the United States. Today, over four in ten Americans – more than 135 million people – live in communities impacted by unhealthy levels of air pollution. Research demonstrates that the burdens of unhealthy air include increased asthma attacks, heart attacks and strokes, lung cancer, and premature death. These serious adverse health effects are not shared equitably, with many communities of color and lower income communities at greater risk due to increased exposure to transportation pollution. The transportation sector is also the largest source of greenhouse gas emissions that drive climate change, which threatens clean air progress and amplifies a wide range of health risks and disparities.

Q. What are some of the key findings of the report?

A. First, accelerating the shift to zero-emission transportation will generate major reductions in harmful pollutants. Key pollutants included in this research are oxides of nitrogen

(NOx), volatile organic compounds (VOCs), and fine particulates (PM2.5). All of these pollutants can cause pulmonary and cardiovascular disease. Some VOCs, such as benzene, are carcinogens. NOx and VOCs also contribute to the formation of ground-level ozone, which is also a harmful air pollutant. Another pollutant included in the report is carbon dioxide (CO), which is a greenhouse gas.

Second, the 2020 passenger vehicle fleet represents approximately 94 percent of the nation's on-road vehicle fleet and generates over 1 million tons of NOx emissions, and over 33,400 tons of fine particles annually. Heavy-duty vehicles represent approximately six percent of the on-road fleet in 2020, but generate 59 percent of NOx emissions and 55 percent of the particle pollution (including brake and tire particles).

Third, shifting to zero-emission transportation and non-combustion electricity generation could yield major health benefits throughout the nation in the coming decades. Here, the report includes the health benefits of shifting to both zero-emission transportation and zero-emission electricity generation. It does not break the benefits out by sector.

Cumulatively, the national benefits of transitioning toward 100 percent zero-emission vehicles and non-combustion electricity generation could generate over $1.2 trillion in health benefits across the United States between 2020 and 2050. These benefits include approximately 110,000 lives saved, over 2.7 million asthma attacks avoided (among those aged 6-18 years), 13.4 million lost works days avoided, and a wider range of other negative health impacts avoided due to cleaner air. In addition to these health benefits, this analysis found that over $1.7 trillion in global climate benefits could be achieved with a reduction of over 24 billion metric tons of greenhouse gas emissions by mid-century.

Q. You mentioned that NOx and VOCs in the atmosphere lead to the formation of ground-level ozone, another harmful pollutant. Do the health and economic benefits you just described include the benefits of reduced ozone pollution?

A. No, they do not. The report addressed only the benefits of reducing those pollutants directly emitted from gasoline-powered motor vehicles – NOx, VOCs, fine particles, and CO2. The report did not look at the benefits of reducing ozone pollution. If we also look at ozone, the benefits are greater.

Q. What are the report's findings as to New Mexico?

A. In New Mexico, the benefits of transitioning to 100 percent zero-emission vehicles and non-combustion electricity generation could generate over $3 billion in health benefits between 2020 and 2050. These benefits include approximately 273 lives saved, 7,380 asthma attacks avoided (among those aged 6-18 years), and 32,300 lost works days avoided.

Q. What does the report say about the harmful effects of motor vehicle emissions on disadvantaged communities?

A. Exposure to pollution with its associated negative health consequences is determined by where someone lives, attends school or works. In general, the higher the exposure to air pollutants, the greater the risk of harm. Many communities face disproportionate burdens due to pollution generated from production, transportation, refining, and combustion of fuels along the transportation and electricity generating systems. Lower income communities and communities of color are often the most over-burdened by pollution sources today due to decades of inequitable land use decisions and systemic racism. For example, a person of color in the United States is up to three times more likely to be breathing the most polluted air than a white person.

The report highlights a salient quote from the U.S. Environmental Protection Agency fact sheet on transportation and environmental justice. EPA states: "Pollution from the transportation sector has been a long-standing obstacle to advancing environmental justice, as many communities of color and low-income families live near areas where pollution from vehicles and engines is abundant, and therefore experience disproportionate exposures to this pollution."

Q. What are some of the report's recommendations?

A. The report includes a list of recommendations for federal, state, and local government. Probably the most pertinent recommendation for this proceeding is the recommendation that states adopt state standards for passenger vehicles and medium- and heavy-duty trucks to require that 100 percent of sales of motor vehicles are zero-emission vehicles.

Q. The report, as you noted, is based on total transition to zero-emission electricity generation. The report is also based on *total* transition from fossil fuel to electric powered vehicles. How does that bear on this rulemaking proceeding?

A. Every reduction in harmful air pollutants such as NOx, VOCs, and fine particulates, will reduce adverse health effects. And every reduction in carbon dioxide emissions will contribute to mitigation of global climate change. Motor vehicles are a major source of these pollutants.

And we view this rulemaking as a crucial first step. But it is important that New Mexico continue on this path. New Mexico needs to adopt the advanced California standards for new motor vehicles. New Mexico also needs to adopt the California standards for heavy-duty trucks and buses.

Q. I want to ask you about two other American Lung Association reports. The first one is entitled *Updated Evaluation of the National Health Benefits from the Transition to Zero-Emission Transportation Technologies*. Are you familiar with it?

A. Yes. It is the more technical background document to *Zeroing In on Healthy Air*, the report we just discussed. It was also released in March of this year.

Q. Is that Clean Air Advocates Exhibit 16?

A. Yes it is.

Q. And the second report is entitled *The Road to Clean Air: Benefits of a Nationwide Transition to Electric Vehicles*. Are you familiar with it?

A. Yes. That was an earlier report published in 2020. Ms. Harris discusses it in her testimony.

Q. Is that Clean Air Advocates Exhibit 14?

A. Yes it is.

Q. Have you reviewed the rules that the New Mexico Environment Department is proposing in this proceeding?

A. Yes.

Q. Does the American Lung Association support the adoption of these rules?

A. Yes, we certainly do. Without reservation.

Q. Thank you, I have no further question.

JoAnna Strother
700 W Oriole Way ■ Chandler ■ Arizona ■ 85286 ■ (812) 205-1505 ■ joannastrother@gmail.com

SUMMARY
Dynamic leader who is passionate about public policy and health outcomes with 15 years of experience in the nonprofit sector. I thrive in fast paced and high-pressured environments. I pride myself on being an energetic team player who is reliable.

PROFESSIONAL EXPERIENCE

American Lung Association
Senior Director, Advocacy 2019-Present
Director, Advocacy 2015-2019
Director of Programs 2011- 2015
Lung Health Coordinator 2008-2011
Intern 2007-2008

- Direct federal, state and local lobbying efforts and develop successful messaging and strategies for passage of American Lung Association's Public Policy Agenda for Arizona, Colorado, Nevada, New Mexico, Oklahoma, Texas, and Utah.
- Draft, track and research legislation; testify before House and Senate committees; develop and coordinate multi-state strategies that advance American Lung Association's mission.
- Analyze and assess state political climate to determine whether resources should be dedicated for policy change.
- Develop and maintain strong relationships which local, state, and federal key decision makers including but not limited to: legislators, governors, executive agencies, trade associations, think tanks, and third-party allies, news/media outlets.
- Build coalitions including grassroots and grasstops campaigns that have yielded successful policy changes at the federal, state and local level.
- Lead staff and volunteer trainings; provide strategic leadership for high-level media advocacy and communications program in seven states to both internal and external audiences; ensure integration of advocacy activities with other strategic initiatives in the region to effectively move the association's mission forward.
- Manage external consultants and lobbyists.

Director of Programs/Lung Health Coordinator

- Lead the American Lung Association in New Mexico's advocacy program, tracked and researched legislation that would affect the mission of the association.
- Testified in House and Senate committees and in City Council.
- Created, directed and led the Smokefree@home program creating relationships with property owns and managers of multi-unit housing and successfully helped 29 properties implement a smokefree policy.
- Maintained strong relationship with our tobacco control partners and healthy air partners.
- Created and administered content for the American Lung Association in New Mexico's Facebook and Twitter pages.
- Trained facilitators statewide in five of the American Lung Association's curriculum-based programs
- Managed program staff and budgets of $400,000
- Created, directed and lead the New Mexico COPD Coalition
- Assisted on all major fundraising events helping to secure sponsorships, teams and auction items.
- Responded to community requests for information on tobacco, asthma, air quality, and lung disease.
- Maintained and strengthened cooperative networks with other agencies and increased community partnerships.
- Assisted the Executive Director in donor relationships and special events.

Other Responsibilities include:

- Co-Chair, New Mexico Allied Council on Tobacco (a tobacco policy group of the, Chronic Disease Prevention Council 501c3) Formally known as New Mexican Concerned about Tobacco.

CAA
EXHIBIT
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Sandia BMW — Sept. 2003- Aug. 2007
Receptionist/File Clerk — Albuquerque, NM

- Provided customer service for all departments
- Accurately balanced cash drawer
- Handled mutli phone line system
- Assisted in Accounts Receivable and Accounts Payable
- In charge of closing store

Los Alamos National Laboratory — May 2001-Aug. 2002
Receptionist — Los Alamos, NM

- Provided customer service for staff
- Organized travel arrangements
- Scheduled meetings for staff members
- Assisted in payroll preparation

Pueblo of Pojoaque Gaming, Inc. — Jan. 2000-May 2001
Accounts Receivable — Pojoaque, NM

- Database management
- Guided in day to day actives in accounts receivable
- Assisted in payroll preparation

EDUCATION

Robert Wood Johnson Fellow
Robert Wood Johnson Foundation and the Center for Creative Leadership
Albuquerque, NM

Bachelor of Science in Health Education: Community Health
University of New Mexico
Albuquerque, NM

AWARDS AND COMMUNITY INVOLVEMENT

- Greater Albuquerque Chamber of Commerce- Leadership Albuquerque, Class of 2014
- **Woman on the Move**, Honoree, 2013, presented by the YWCA, Middle Rio Grande Chapter
- **40 Under Forty**, Nominee, 2013, presented by the *New Mexico Business Weekly* (now *Albuquerque Business First*)
- American Lung Association National Staff of the week May 9, 2011

American Lung Association.

The Road to Clean Air

Benefits of a Nationwide Transition to Electric Vehicles

CAA
EXHIBIT
14

Executive Summary

"The Road to Clean Air" is a national report by the American Lung Association highlighting the potential for major public health benefits of widespread electrification of the transportation sector. Across the United States, the transportation sector is a leading source of harmful air pollution threatening the health of the public. Transportation pollution and poor air quality are associated with an increased risk of a wide range of negative health outcomes including asthma attacks, lost work days and premature deaths. People who live near major roadways, lower-income communities and communities of color often face disproportionate exposures to harmful pollution, along with poor health outcomes, making health and climate equity key to the electric vehicle discussion. Children, seniors and those living with respiratory, cardiovascular and other chronic health conditions are also more vulnerable to poor air quality. The transportation sector is also the leading contributor to climate change, which harms health in a number of ways, including by degrading air quality.

Our air quality and climate crises demand steady, consistent progress toward moving our passenger vehicles, transit and school buses, delivery vans and the broad trucking sector away from combustion and toward non-polluting vehicles powered by more non-combustion renewable energy. The analysis illustrates that transitioning to zero-emission transportation solutions along with increasing levels of renewable energy by mid-century will save thousands of lives, avoid tens of thousands of asthma attacks, hundreds of thousands of other health impacts, and avoid tens of billions of dollars in health costs as a result of significant pollution reductions. In addition, moving to eliminate combustion from the transportation sector will yield significant reductions in greenhouse gases that drive wide-ranging climate change impacts on air quality and public health. The dual air pollution and climate change health crises facing America today must be addressed immediately, with electric vehicles and clean energy playing a leading role in the solution.

About this Report

This new American Lung Association report highlights the public heath, air quality and climate change benefits that could be achieved if steps are taken now to ensure widespread transportation electrification in the coming decades.

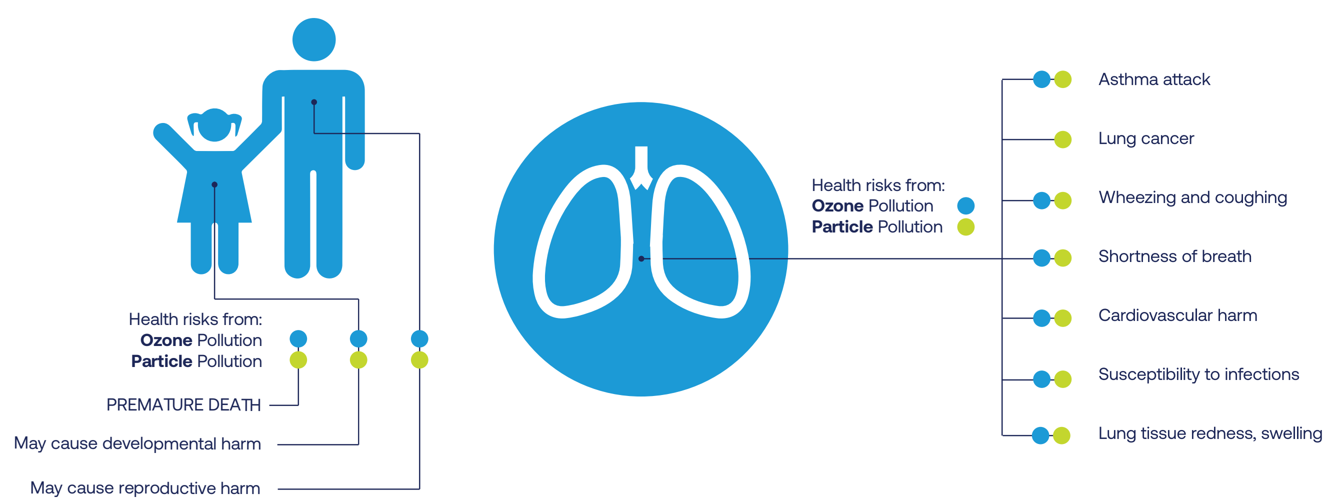
To develop this new research, the American Lung Association worked with ICF to assess a pathway toward an ambitious but achievable transition to electric vehicles powered by increasing levels of renewable energy. This work was conducted using a variety of transportation and energy sector emissions models and United States Environmental Protection Agency public health benefits modeling tools. ICF conducted a comprehensive analysis of the potential health and climate benefits of this transition as a consultant to the American Lung Association, which is solely responsible for the content this report. Additional detail on the structure of the report is found below, and a full methodology and assumptions about future vehicle fleets, changes in the electric power grid and citations are detailed in the technical report document prepared by ICF for the American Lung Association that is available online at **Lung.org/ev**.

Air Pollution and Climate Change Threaten Public Health

Too many Americans are breathing air that can harm their health. The American Lung Association's "State of the Air" 2020 report found that close to five in ten people—150 million Americans—live in counties affected by unhealthy ozone and/or particle pollution, the two most widespread air pollutants in the United States.[1] Our changing climate is contributing to worsening air quality in the form of extreme heat, drought and catastrophic wildfires. Increasing temperatures lead to greater formation of ground-level ozone pollution, and smoke from more frequent and intense wildfires contributes to particle pollution that can travel hundreds of miles.

The health impacts of ozone and particle pollution are well documented based on decades of scientific research. Exposure to ozone and particle pollution contribute to a wide range of negative health effects and are especially dangerous to children, seniors, people living with asthma and other health conditions, lower-income communities and communities of color. Transportation is a leading source of harmful air pollution in the United States, representing over half of the total ozone- and particle-forming oxides of nitrogen (NOx) emissions and represents the largest source of carbon pollution in the United States. Transportation sources also contribute to particle pollution and local diesel exhaust impacts that threaten lung health.[2]

Air pollution remains a major danger to the health of children and adults.



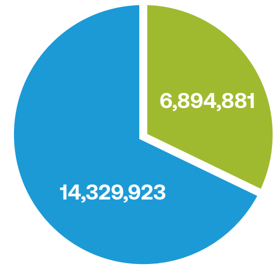
Transportation pollution poses a significant risk to public health. For example, the Health Effects Institute's comprehensive 2010 review of traffic-related health effects noted that up to 45 percent of the urban population in North America may be within close enough proximity to major roadways to increase immediate, negative health outcomes. The review of over 700 scientific studies concluded that traffic pollution causes asthma attacks in children and may cause a wide range of other effects including the onset of childhood asthma, impaired lung function, premature death and death from cardiovascular diseases and cardiovascular morbidity.[3] Major trucking corridors, warehouse distribution centers and other diesel hot spots close to major population sectors inflict serious harms to human health, and often highlight disparities in the impacts of transportation pollution burdens.

Climate change represents a public health crisis on many fronts and is making it harder to protect public health from poor air quality. Driven by fossil fuel combustion, climate change amplifies current public health challenges and threatens to increase risks into the future. The 4th National Climate Assessment issued by the United States Center on Global Change Research in 2018 noted that the "health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change."[4] Climate change threatens 50 years of clean air progress made under the Clean Air Act by increasing the risk that air pollution, including ozone and particle pollution, will worsen. Because ozone pollution is more likely to form in warmer weather, climate change will make it harder to continue cleaning up this widespread pollutant. Rising temperatures intensify drought, and dust and wildfires add to particle pollution burdens. These risks and exposures are not equally shared across our society, and many communities face greater exposures and are more vulnerable to the impacts of poor air quality and climate change.

"Far too often, clean air is out of reach for communities living near major pollution sources, including highways, ports and power plants. Communities of color are disproportionately harmed by poor air quality in the United States. The time to act on electric transportation is now."

Harold Wimmer, President and CEO American Lung Association

The American Lung Association's 2020 "State of the Air" report found significant disparities in terms of people of color residing in counties with failing grades for ozone and/or particle pollution. For example, people of color were 1.5 times more likely to live in a county with at least one failing grade, and 3.2 times more likely to live in a county with a failing grade for unhealthy ozone days, particle pollution days and annual particle levels. Disparities in exposure to neighborhood-level transportation pollution specifically was documented in a 2019 assessment by the Union of Concerned Scientists, which highlighted the ethnic and racial disparities in air pollution exposure burdens, with people of color largely facing far greater exposures than the national average. For example, 74 percent of Black and Latino people in New York State live where particle pollution levels from on-road transportation exceed the state average and are exposed to far greater levels than white residents.[5]



Shifting to electric vehicle technology and renewable power is vital to achieving clean, healthy air for all communities

The transition to zero-emission transportation will benefit the health of children riding school buses, daily commuters and transit riders, truckers and local delivery drivers and especially those residents nearest major roadways, warehouse distribution centers and other pollution hotspots. People who live downwind of major urban areas will also benefit. Further, the transition away from burning harmful fossil fuels in the power sector to non-combustion renewable energy, including wind and solar, is critical to addressing the impacts on communities most burdened by emissions generated at fossil-fueled power plants. The transportation sector must move comprehensively to zero-emission solutions, including both electric vehicles and their fuels, as rapidly as possible.

Healthy Electric Transportation Scenario Results

The widespread transition to zero-emission transportation technologies could produce emission reductions in 2050 that could add up to $72 billion in avoided health harms, saving approximately 6,300 lives and avoiding more than 93,000 asthma attacks and 416,000 lost work days annually due to significant reductions in transportation-related pollution.[I II]

In addition to the health benefits noted above, the benefits to our environment in the form of avoided climate change impacts, as expressed as the Social Cost of Carbon,[III] could surpass $113 billion in 2050 as the transportation systems combust far less fuel and our power system comes to rely on cleaner, non-combustion renewable energy. This value reflects a range of negative consequences to health, agricultural productivity, flood risk and other adverse impacts generated by carbon emissions in the form of global climate change. The transition to electric vehicles powered by increasingly clean power sources like wind and solar yields significant climate benefits in the form of avoided carbon emissions across the transportation sector.

[I] In all cases, the results presented here reflect the benefits of emission reductions estimated for 2050, utilizing the American Lung Association's on-road and upstream emissions scenarios. Health results include the number of avoided adverse health impacts and the economic value of these health risk reductions at a 3% discount rate and reflect higher range estimates associated with the Lepeule et al. (2012) health study. Mortality estimates are grown from EPA 1990 value of a statistical life using standard income growth data while non-fatal costs are presented in 2017$ values. Greenhouse gas emission benefits are presented for 2050 emissions per Obama-era estimates of the global climate impacts of CO2 emissions; climate benefits are also presented in 2017$ values at a 3 percent discount rate.

[II] Note that the analysis and report includes ozone-precursor emissions data. However, ozone-related health effects are not included in this report. US EPA's COBRA model relies on PM2.5 health effects to assess and monetize impacts. Results therefore do not include significant health burdens posed by ozone pollution throughout the United States independent of those related to PM reductions, as described in the health effects section of this report.

[III] The social cost of CO2 emissions (SC-CO2) is a measure, in dollars, of the long-term damage done by a ton of carbon dioxide (CO2) emissions in a given year. This dollar figure also represents the value of damages avoided for a small emission reduction (i.e., the benefit of a CO2 reduction). SC-CO2 is intended to be a comprehensive estimate of climate change damages and includes changes in net agricultural productivity, human health, property damages from increased flood risk, and value of ecosystem services. However, not all important damages are included due to data limitations. The high range estimate of the Social Cost of Carbon presented here reflects a broader suite of global climate impacts and pollutants, as discussed in the full technical document prepared by ICF for the American Lung Association.

These benefits accrue from the reduction in on-road pollution attributed to the shift to electric vehicles. Comparing the emissions from the "Business as Usual" fleet modeling run with the electric vehicle scenario yields major reductions in harmful air and climate pollution. In 2050, the on-road Electric Vehicle scenario would cut:

- ozone- and particle-forming oxides of nitrogen (NOx) by 1 million tons in 2050 (an 82% reduction compared with the "Business As Usual" Scenario)
- directly emitted fine particle pollution (PM2.5) by 30,599 tons in 2050 (a 62% reduction)
- greenhouse gas emissions that cause climate change by over 1.4 billion metric tons in 2050 (a 90% reduction).

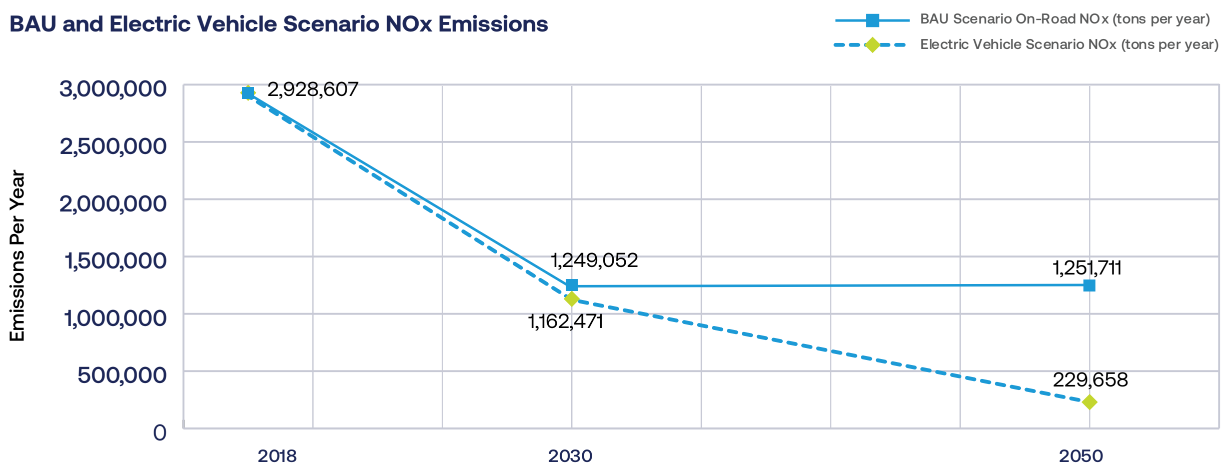
American Lung Association Healthy Transportation Scenario Results

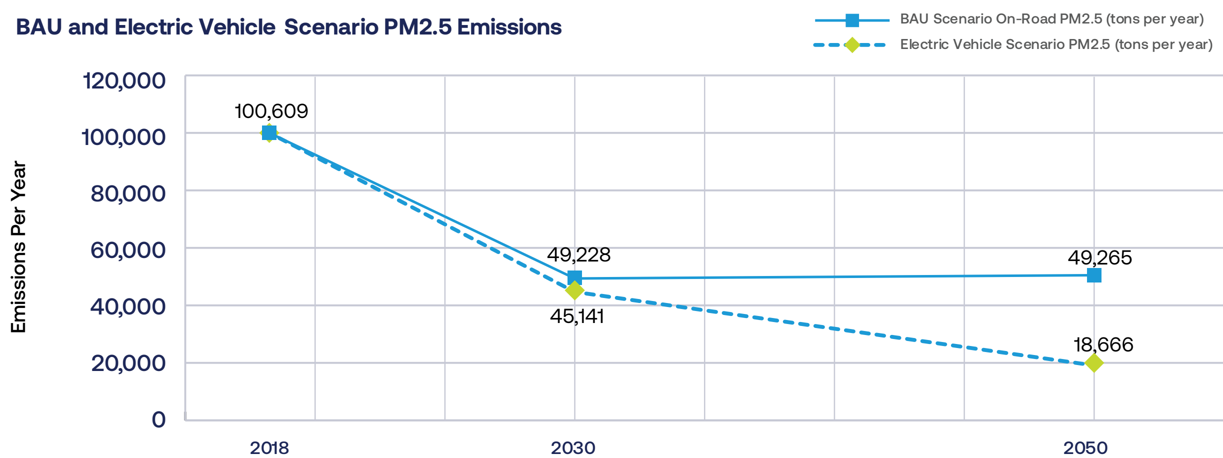
Health Benefits in 2050			Value of Benefits in 2050	
Premature Deaths Avoided	Asthma Attacks Avoided	Lost Work Days Avoided	Health Benefits	Climate Benefits
6,300	93,000	416,000	$72 Billion	$113 Billion

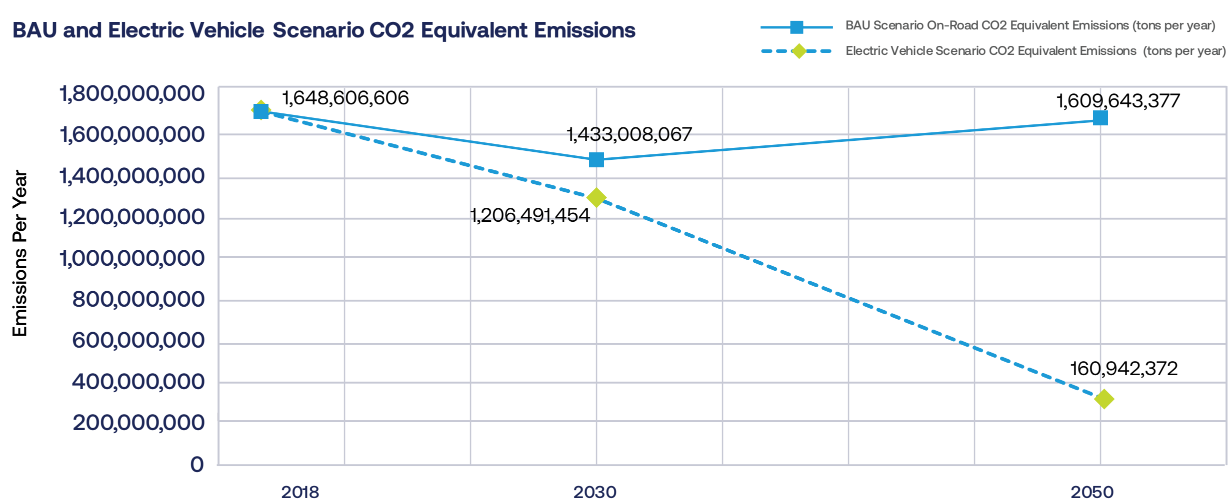
Factoring in the emissions associated with the production and distribution of fuel for the on-road combustion and electric vehicle fleets, the benefits grow further as cleaner energy sources are considered, achieving reductions in excess of total emissions generated by the on-road Business As Usual fleet in 2050. These results are included in the total health and climate impacts noted in the table above.

- Ozone- and particle-forming oxides of nitrogen (NOx) are reduced by 1.3 million tons (100% reduction compared with the "Business As Usual" Scenario)
- directly emitted fine particle pollution (PM2.5) is reduced by more than 53,000 tons in 2050 (a 108% reduction below on-road fleet emissions)
- greenhouse gas emissions that cause climate change are reduced by more than 1.5 billion metric tons in 2050 (a 94% reduction) compared with the on-road emissions generated by the baseline fleet.

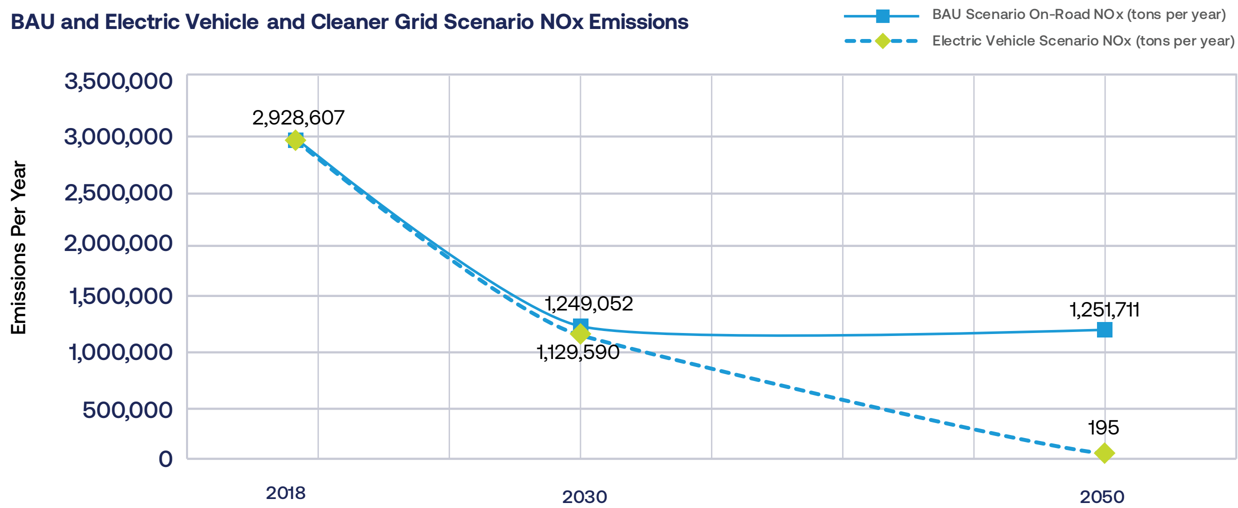
Comparison of On-Road Emissions Between Baseline and Electric Vehicle Case

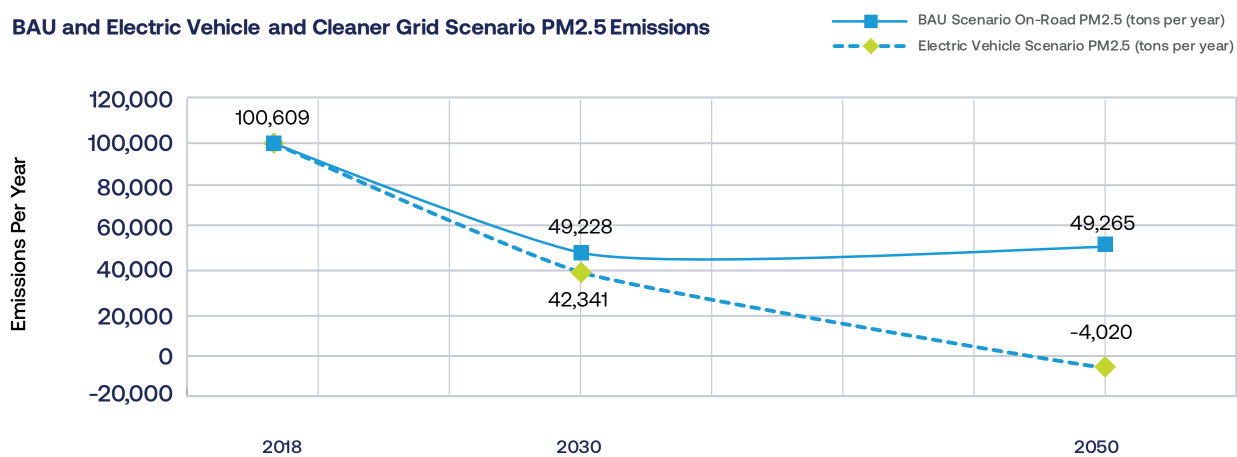


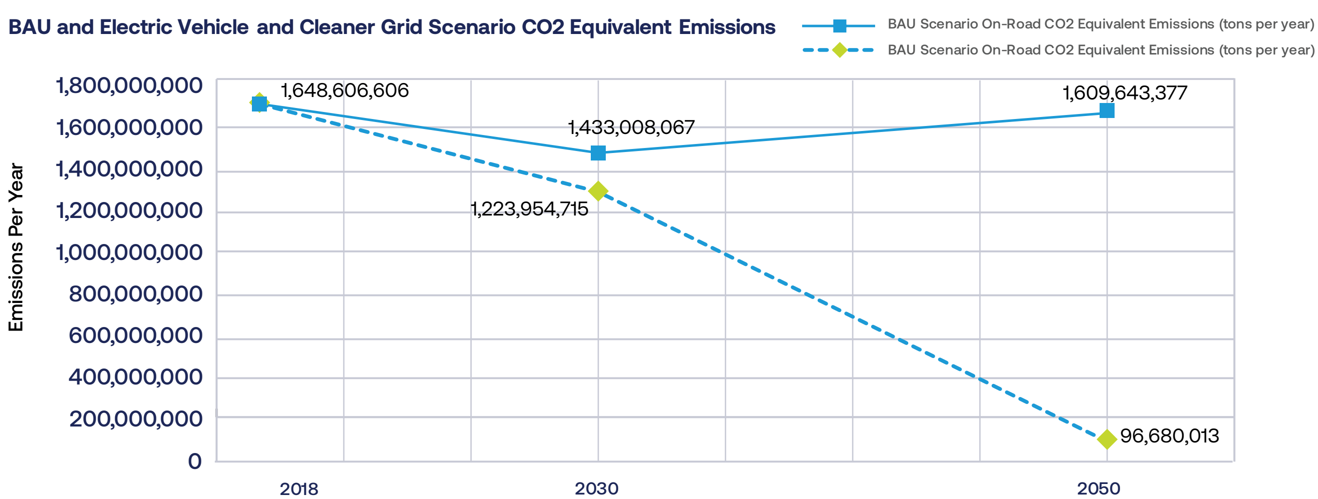




Comparison of Emissions including Changes in Upstream Emissions With Electric Vehicles and Cleaner Energy Scenario







Benefits Across the United States

Transportation sources pose a risk to residents in every region of the United States, and residents in every region stand to benefit from the elimination of on-road traffic pollution and clean, renewable electric generation. Across the United States, the annual health benefits of reduced exposures to transportation range from the tens of millions per year into the billions. Eighteen states show annual benefits reaching $1 billion or more in 2050 while even the smallest states see benefits in the tens to hundreds of millions. Under the American Lung Association's zero-emission transportation scenario, all states will experience health benefits as the result of reduced pollution from on-road vehicles and the transition to cleaner power grids.

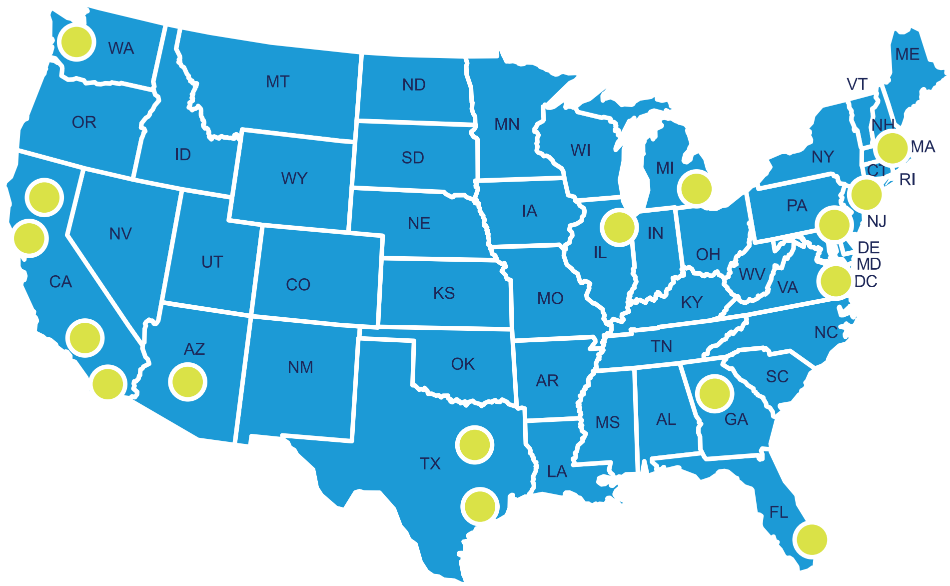
The following pages illustrate the estimated State—and major Metropolitan Area—level benefits possible through the emission reductions estimated under the 2050 Healthy Electric Transportation Scenario.

State	Avoided Health Impact Cost in 2050	Premature Deaths Avoided in 2050	Asthma Attacks Avoided in 2050	Work Loss Days Avoided in 2050
California	$22,026,904,800	1,924	26,292	122,047
Texas	$6,690,000,982	582	11,554	46,914
New York	$4,027,731,052	351	5,153	24,974
Florida	$3,698,618,418	323	3,564	17,612
Illinois	$3,155,062,850	274	4,106	18,735
Ohio	$2,369,377,792	207	2,860	12,208
Pennsylvania	$2,359,678,447	206	2,399	10,814
New Jersey	$1,938,971,167	169	2,306	10,725
Georgia	$1,686,021,026	147	2,665	12,045
Michigan	$1,662,382,013	145	1,837	8,253
North Carolina	$1,617,991,214	141	2,384	10,527
Arizona	$1,446,667,053	126	1,956	8,475
Washington	$1,424,476,544	124	1,970	8,938
Maryland	$1,349,126,363	118	1,649	7,497
Virginia	$1,324,456,174	115	1,783	8,189
Tennessee	$1,236,196,031	107	1,684	7,309
Missouri	$1,102,005,533	96	1,519	6,437
Indiana	$1,053,581,012	92	1,533	6,296
Massachusetts	$947,969,253	83	1,059	5,293
Wisconsin	$834,519,169	73	1,156	4,930

State	Avoided Health Impact Cost in 2050	Premature Deaths Avoided in 2050	Asthma Attacks Avoided in 2050	Work Loss Days Avoided in 2050
Louisiana	$781,955,933	68	961	3,937
Nevada	$746,431,012	65	767	3,724
Minnesota	$744,387,115	65	1,159	5,093
Colorado	$690,027,423	60	1,296	5,691
Oklahoma	$674,830,366	59	1,026	3,961
South Carolina	$672,435,708	59	743	3,167
Connecticut	$637,321,723	55	726	3,479
Kentucky	$561,522,369	49	737	3,122
Alabama	$431,124,811	38	527	2,271
Arkansas	$420,138,060	37	554	2,275
Utah	$410,642,433	36	1,007	3,330
Kansas	$385,190,452	34	654	2,517
Oregon	$355,292,368	31	434	1,983
West Virginia	$326,495,859	28	304	1,362
Iowa	$304,671,140	27	452	1,788
New Mexico	$263,532,370	23	334	1,305
Mississippi	$230,611,840	20	285	1,134
Idaho	$194,297,781	17	321	1,188
New Hampshire	$191,446,788	17	178	898
Maine	$181,518,670	16	151	724
Rhode Island	$178,274,742	16	170	835
Nebraska	$176,049,712	15	325	1,231
Delaware	$163,712,559	14	207	934
Washington, DC	$117,397,617	10	142	829
Montana	$100,943,248	9	118	476
North Dakota	$78,339,494	7	95	368
Vermont	$73,383,492	6	63	320
South Dakota	$64,069,035	6	106	384
Wyoming	$46,588,545	4	67	252
Total	$72,154,369,558	6,293	93,337	416,793

Note: Data for Alaska and Hawaii are not presented in this report because COBRA Model provides health outputs for the continental United States.

Selected Metropolitan Area Results



Metropolitan Area	2050 Health Benefits	Deaths Avoided	Asthma Attacks Avoided
Los Angeles, CA	$14,185,163,117	1,239	16,297
New York, NY	$5,191,191,434	452	6,766
San Francisco, CA	$3,638,114,607	318	4,489
Chicago, IL	$2,875,776,986	250	3,754
Dallas, TX	$2,094,390,070	182	3,676
Washington, DC	$2,007,786,421	175	2,739
San Diego, CA	$1,934,303,928	169	2,100
Houston, TX	$1,704,274,597	148	3,333
Miami, FL	$1,442,342,868	126	1,389
Philadelphia, PA	$1,441,391,523	126	1,660
Atlanta, GA	$1,358,920,809	118	2,256
Boston, MA	$1,185,120,806	103	1,286
Detroit, MI	$1,145,075,305	100	1,220
Seattle, WA	$1,018,047,240	89	1,416
Phoenix, AZ	$959,667,714	84	1,463
Sacramento, CA	$893,473,382	78	1,164

The counties assigned to a metropolitan area follow the groupings determined by the White House Office of Management and Budget (OMB) and used by the U.S. Census Bureau. The Metropolitan Statistical Areas and Combined Statistical Areas are used as the basis for considering populations at risk in these urban areas because they reflect the "high degree of social and economic interaction as measured by commuting ties," as OMB describes them.

Achieving Significant Health Benefits through Transportation Electrification

The benefits are clear and should spur action at all levels of government to speed and scale the electric vehicle transition and ensure these potential benefits become a reality for all Americans, especially those communities most impacted and vulnerable to pollution burdens.

Actions taken today to transition away from combustion technologies set a crucial course to healthier air in communities across the United States. Below is a sampling of actions that can be taken at the household, local government, state government and federal levels in partnership with industry, utilities and other stakeholders to spur the transition to zero-emission technologies throughout the transportation sector, and support clean air for all communities.

Key Points

- At all levels, governments must align toward zero-emission transportation through policy change, investment, public education and partnership with public agencies, private entities and the public working together to reduce air pollution and climate change.
- Investments in zero-emission transportation infrastructure and incentive programs must be designed to address equity issues and correct disparities in pollution burdens caused by the transportation sector, including the heavy-duty sector.
- State authority under the Clean Air Act to enact zero-emission vehicle standards must be protected and implemented.
- Consumers must have full access to electric vehicle options that meet their needs and the benefits of zero-emission vehicles must be available to all communities.

Federal Actions

- Establish stronger vehicle standards for passenger vehicles and medium- and heavy-duty trucks, and and support state authority to adopt stronger standards.
- Prioritize zero-emission transportation and energy sources as central to federal climate change policy to maximize health benefits in the most heavily polluted US communities and support attainment of Clean Air Act health-based air quality standards.
- Establish health-protective clean air standards based on the current state of science and ensure an adequate level of safety for protection of vulnerable communities as required by the Clean Air Act.
- Designate zero-emission infrastructure a national priority program for economic recovery from the COVID-19 pandemic.
- Increase grant funding support for zero-emission truck and bus purchases and manufacturing and maintain existing consumer and business tax credits for zero-emission vehicle purchases.
- Increase incentives to ensure widespread deployment of zero-emission transportation infrastructure and technologies.

State Actions

- Use Clean Air Act authority to adopt the California zero-emission standards for passenger vehicles and medium- and heavy-duty trucks.
- Pursue fully electric public fleets and support zero-emission infrastructure including in all public buildings and garages.
- Support accelerated fleet turnover through incentive programs targeting older vehicles, consumer purchase decisions via point-of-purchase rebates and non-financial incentives.
- Ensure vehicle registration fees are structured to support electric vehicle deployment and complement —rather than counteract—consumer incentives.
- Invest in publicly available charging infrastructure along major highways and roads to ensure both personal and commercial charging opportunities exist.

Local Actions

- Support affordable zero-emission infrastructure readiness and deployment through electric vehicle-ready building codes, access to utility infrastructure for charging connections, streamlined permitting processes and parking policies that support accessible charging infrastructure for all communities, including for multi-unit housing.
- Commit to local zero-emission fleet purchases for garbage collection, transit, school buses and other fleets, with priority for fleets operating in heavily-polluted communities.
- Seek partnerships with utilities and clean air agencies to provide local incentives to complement state and federal tax credits or rebates; promote higher zero-emission rebates for lower-income consumers in the used car market.
- Adopt local climate action plans and integrate zero-emission vehicle infrastructure within healthier community planning that includes support for walking, biking, transit and other clean air choices.
- Enact local incentive and pilot projects related to zero-emission transit, carsharing and other mobility options, preferred parking and free—or reduced—cost charging in public garages.

Individual Actions

- Test drive a zero-emission vehicle at your local vehicle dealership - if they don't yet offer zero emission vehicles, engage with local ride-and-drive events to get a first-hand experience with knowledgeable vehicle enthusiasts.
- If you need a new personal vehicle, consider a zero-emission vehicle. Each year brings new models of zero-emission vehicles including motorcycles, pickups and SUVs.
- Consider local utility clean energy programs (i.e. opting into a 100 percent wind power plan if available) or going solar at home to increase non-combustion electric power.
- Advocate for clean air in your community, your state and nationally at Lung.org/policy-advocacy/take-action
- Visit Lung.org/ev to sign our petition calling on your Governor to make electric vehicles and infrastructure a priority.

Conclusion

Air pollution and climate change are harming the health of Americans today. The transition to zero-emission transportation solutions will yield major health and climate benefits across the United States, according to new research published by the American Lung Association. Thousands of lives will be saved, along with tens of thousands of asthma attacks and hundreds of thousands of other negative health outcomes avoided due to cleaner air throughout the United States as the majority of on-road transportation shifts to zero-emission technologies and increasing levels of non-combustion, renewable energy sources. These annual benefits could yield over $72 billion in avoided health costs in the United States and over $113 billion in avoided global climate change impacts. There is no time to delay - the nation must get on the pathway to zero-emission transportation, and actions taken at all levels of government can support healthier air.

Report Description, Technical Documentation and Methodology

This report relies on a series of modeling exercises comparing a business-as-usual on-road vehicle scenario reliant on combustion technologies versus an ambitious transition to increasing levels of sales of zero-emission vehicles, buses and trucks over the next three decades. The American Lung Association hired ICF as a technical consultant to run the models described below related to fleet characteristics, emissions and health benefits. The electrification scenario was developed by the American Lung Association to illustrate the benefits possible if local, state and federal actions were to meaningfully prioritize the transition away from the combustion of fuels. This ALA electrification scenario is scoped to achieve full transition to zero-emission passenger vehicle sales by 2040. It also includes penetrations of a range of electrified heavy-duty vehicles on pathways to fully zero-emission technologies over the coming decades. The vehicle electrification scenario considered here would have significant national and international benefits resulting from the cleaner air the scenario would create, including dramatic reductions in pollution from on-road sources. The climate benefits from reductions of greenhouse gas are expected to reach into the hundreds of billions of dollars globally, while the domestic health benefits would range in the tens of billions of dollars, including thousands of avoided deaths due to reduced air pollution.

The report illustrates only the incremental benefit for powering zero-emission transportation with increasing levels of non-combustion renewables; the full suite of public health and climate benefits from a cleaner grid powering non-transportation end uses (e.g. industrial operations, commercial and residential buildings, etc.), is beyond the scope of this evaluation. Our power sector approach may be considered conservative in that all analyses reflect national-scale simulations and rely on an average power approach. We do not assume that electric vehicle demand causes low carbon energy growth, nor do we implement an incremental approach to future electricity generation that pairs the increased demand with cleaner electricity only.

These scenarios were compared based on the tailpipe and other vehicle related emissions (utilizing the U.S. Environmental Protection Agency's MOVES model), emissions upstream of the vehicle such as the extraction, refining and transportation of fossil fuels or the power generation needs associated with growing zero-emission vehicle fleets (utilizing the Argonne National Lab GREET model), and finally the change in pollution burdens possible under the zero-emission fleet scenario utilizing the US EPA COBRA model for health benefit analysis. It is important to note that these modeling tools provide outputs for the continental United States; Alaska and Hawaii are not included. Using county-level results, the American Lung Association presents results for the continental United States, individual states and a sampling of the largest metropolitan areas in the nation to highlight the potential benefits of widespread zero-emission transportation in the coming decades.

For more information about this report, including the comprehensive report findings and methodology prepared by ICF for the American Lung Association, please visit **Lung.org/ev**

American Lung Association Resources

- **State of the Air**
  - Health Effects of Ozone and Particle Pollution
    http://www.stateoftheair.org/health-risks/
  - Living Near Highways and Air Pollution
    https://www.lung.org/clean-air/outdoors/who-is-at-risk/highways

- **Stand Up for Clean Air**
  https://www.lung.org/clean-air/stand-up-for-clean-air

- **Health Professionals for Clean Air and Climate Action**
  https://www.lung.org/policy-advocacy/healthy-air-campaign/health-pros-clean-air-climate

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[1]American Lung Association. State of the Air 2020. April 2020. www.lung.org/sota
[2]US Environmental Protection Agency. Air Pollutant Emissions Trends Data; U.S. Inventory of Greenhouse Gas Emissions and Sinks. https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data; https://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-inventory-2020-main-text.pdf
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American Lung Association.

Zeroing in on Healthy Air

A National Assessment of Health and Climate Benefits of Zero-Emission Transportation and Electricity

About this Report

Zeroing in on Healthy Air finds that a widespread transition to zero-emission cars, trucks, buses and other vehicles, coupled with non-combustion, renewable energy resources would yield tremendous air quality, public health and climate benefits across the United States. To illustrate the potential benefits, a transition to 100 percent sales of light-duty passenger vehicles and medium-and heavy-duty vehicles were assumed over the coming decades, along with a transition to non-combustion electricity generation.

Zeroing in on Healthy Air builds off the 2020 Road to Clean Air report by the American Lung Association, and illustrates the potential scale of benefits to public health, air quality and climate change if the United States accelerates the course to a zero-emission transportation sector coupled with non-combustion renewable sources like wind and solar energy. While similar to the 2020 “Road to Clean Air” report on zero-emission transportation, this report stands alone. Updates to technical models, assumptions and methods do not allow for direct comparisons between “Road to Clean Air” and this new analysis.

The American Lung Association developed this project with the assistance and technical support of ICF Incorporated, LLC (ICF). Using a series of modeling tools, ICF provided estimated fleet characteristics and emissions profiles (US EPA MOVES2021 model, ICF’s custom fleet modeling), emissions associated with fuel and electricity generation (Argonne National Lab GREET Model, ICF’s custom IPM model) and health outcomes associated with changes in emissions (US EPA COBRA health model). ICF conducted a comprehensive analysis of the potential health and climate benefits of this transition as a consultant to the American Lung Association, which is solely responsible for the content this report. Additional details on the structure of the report, a full methodology and assumptions about future vehicle fleets, changes in the electric power grid and citations are detailed in the technical report document prepared by ICF for the American Lung Association. Available online at Lung.org/ev.

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Executive Summary

Zeroing in on Healthy Air is a report by the American Lung Association illustrating the public health urgency of policies and investments for transitioning to zero-emission transportation and electricity generation in the coming decades. These sectors are leading sources of unhealthy air in the United States. Today, over four in ten Americans — more than 135 million people — live in communities impacted by unhealthy levels of air pollution. Research demonstrates that the burdens of unhealthy air include increased asthma attacks, heart attacks and strokes, lung cancer and premature death. These poor health outcomes are not shared equitably, with many communities of color and lower income communities at greater risk due to increased exposure to transportation pollution. The transportation sector is also the largest source of greenhouse gas emissions that drive climate change, which threatens clean air progress and amplifies a wide range of health risks and disparities.

This report finds that a national shift to 100 percent sales of zero-emission passenger vehicles (by 2035) and medium- and heavy-duty trucks (by 2040), coupled with renewable electricity would generate over $1.2 trillion in public health benefits between 2020 and 2050. These benefits would take the form of avoiding up to 110,000 premature deaths, along with nearly 3 million asthma attacks and over 13 million workdays lost due to cleaner air. This report calculates the emission reductions possible from shifting to vehicles without tailpipes, as well as eliminating fuel combustion from the electricity generation sector so that neither those living near roads or near electricity generation would be subjected to unacceptable doses of toxic air pollution. The report also highlights the fact that the shift to zero-emission transportation and electricity generation in the United States will yield avoided global climate damages over $1.7 trillion.

By expediting investments and policies at the local, state and federal levels to reduce harmful pollution, all communities stand to experience cleaner air. Policies and investments must prioritize low-income communities and communities of color that bear a disproportionate pollution burden. State and local jurisdictions should act to implement policies as soon as possible, including in advance of the benchmarks used in this report's methodology. These actions are needed to achieve clean air, reduce health disparities and avoid even more dire consequences of climate change.

Zeroing in on Healthy Air

In the United States, transportation and electricity generation are leading sources of unhealthy air and the pollutants that cause climate change.

Those living near highways, ports, railyards, warehouses, and other transportation hubs are at greater health risk, as are those impacted by fuel refining, electricity generation and processes.

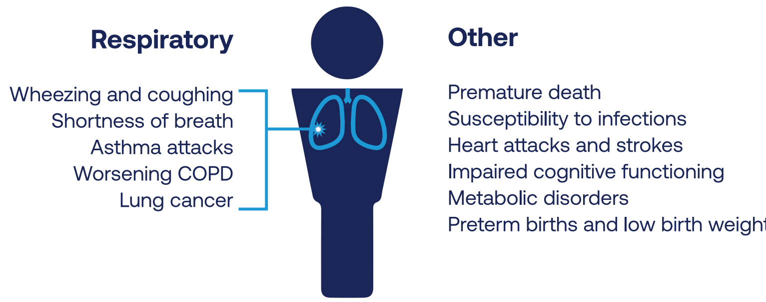
The widespread, rapid shift to zero-emission transportation and electricity generation is critical to healthy air, and can yield more than $1.2 trillion in health benefits and 110,000 pollution-related deaths avoided over the coming decades along with over $1.7 trillion in global climate benefits.

The Public Health Need for Zero Emissions

Air Pollution Remains a Major Threat to Americans' Health

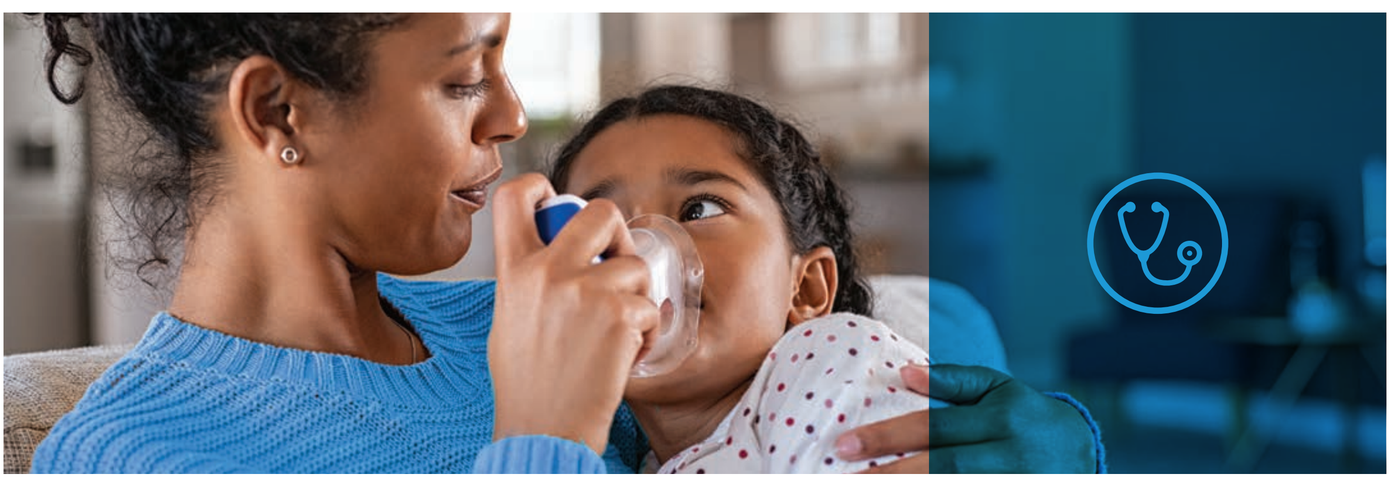
Despite decades of progress to clean the air, more than 4 in 10 of all Americans — 135 million — still live in a community impacted by unhealthy levels of air pollution.[ii] Those impacted by polluted air face increased risk of a wide range of poor health outcomes as the result of increased ozone and/or particle pollution.[iii] The adverse impacts of pollution from the transportation and electricity generation sectors are clear, and must be recognized as a threat to local community health, health equity and a driver of major climate change-related health risks. Even with certification to meet existing standards, it is clear that combustion technologies often generate far greater levels of pollution in the real world than on paper.

Air pollution can harm children and adults in many ways



"The shift to zero-emission transportation and electricity generation will save lives and generate massive health benefits across the United States. It is critical that we ensure these benefits are realized in the near term in communities most impacted by harmful pollution today."

Harold Wimmer, American Lung Association President and CEO



Location Matters: Disparities in Exposure Burden

Exposure to pollution with its associated negative health consequences is dictated by where someone lives, attends school or works. In general, the higher the exposure, the greater the risk of harm. Many communities face disproportionate burdens due to pollution generated from production, transportation, refining and combustion of fuels along the transportation and electricity generating systems. Lower income communities and communities of color are often the most over-burdened by pollution sources today[iv] due to decades of inequitable land use decisions and systemic racism.

The American Lung Association's State of the Air 2021 report illustrated the disparities in pollution burdens across the United States, noting that a person of color in the United States is up to three times more likely to be breathing the most polluted air than white people.[v] All sources of harmful air and climate pollution must shift rapidly away from combustion and toward zero-emission technologies to ensure all Americans have access to the benefits of less-polluting technologies.

"Pollution from the transportation sector has been a long-standing obstacle to advancing environmental justice, as many communities of color and low-income families live near areas where pollution from vehicles and engines is abundant, and therefore experience disproportionate exposures to this pollution."

US EPA
Transportation and Environmental Justice
Fact Sheet March 2022

"Rapidly eliminating emissions from the transportation and electricity generation sectors must be a national priority. The nationwide transition to electric vehicles is urgently needed to improve lung health and advance health equity."

Harold Wimmer
American Lung Association President and CEO

For those living in close proximity to major transportation hubs like highways, ports, railyards or warehouses, tailpipe (or "downstream") emissions yield an outsized risk to community health.

Similarly, "upstream" emissions from transportation fuels generate localized health burdens near oil and gas extraction sites, refineries and even local gas stations, all of which generate toxic air pollution and threaten community health.

Health of communities all along the electricity production system — from the extraction of fossil fuels such as coal, oil and gas, transportation of these fuels, and combustion at the power plant itself — can be adversely impacted.

Estimated Benefits of Zero-Emission Transportation and Electricity Generation

The combustion of fuels in the electricity generation and transportation sectors is a major contributor to the health and climate burdens facing all Americans. These sources of pollution also create significant disparities in pollution burdens and poor health, especially in lower-income communities and communities of color. The transition to non-combustion technologies is underway and must continue to accelerate to protect the health of communities today and across the coming decades. Key findings are presented below:

Pollution Reduction Benefits from Zero-Emission Transportation

Accelerating the shift to zero-emission transportation and non-combustion electricity generation will generate major reductions in harmful pollutants. Key pollutants included in this research are described below along with projected on-road pollution reductions with the shift to zero-emission technologies when compared with a modeled "Business As Usual" case for the on-road fleet.

Pollutant	Impact	On-Road Pollution Reductions by Year		
		2030	2040	2050
Nitrogen Oxides (NOx)	NOx and VOCs are building blocks for ozone ("smog") and contribute to particle pollution formation and a wide range of health impacts including asthma attacks, heart attacks, strokes, and premature death. Breathing VOCs can irritate the eyes, nose and throat, can cause difficulty breathing and nausea, and can damage the central nervous system as well as other organs. Some VOCs can cause cancer. NO2 is associated with increased risk of asthma attacks, ER visits, hospitalizations and a range of other health consequences.	-6% ↓	-56% ↓	-92% ↓
Volatile Organic Compounds (VOC)		-8% ↓	-42% ↓	-78% ↓
Fine Particle Pollution (PM2.5)	Particle pollution can increase the risk of heart disease, lung cancer and asthma attacks and can interfere with the growth and work of the lungs. Major health impacts include asthma attacks, heart attacks, stroke, COPD, lung cancer and death.	-8% ↓	-43% ↓	-61% ↓
Sulfur Dioxide (SO2)	Contributes to wheezing, shortness of breath and chest tightness, reduced lung function, increased risk of hospital admissions or emergency room visits.	-15% ↓	-67% ↓	-93% ↓
Greenhouse Gases (GHG)	Drives climate change health risks, including extreme weather, wildfires and degraded air quality among others.	-14% ↓	-66% ↓	-93% ↓

Benefits of Moving All Vehicle Classes to Zero-Emissions

All vehicles must move to zero-emission technologies to ensure the most robust public health benefits occur. The 2020 passenger vehicle fleet represents approximately 94 percent of the nation's on-road vehicle fleet and generates over 1 million tons of ozone- and particle-forming NOx emissions, and over 33,400 tons of fine particles annually. Heavy-duty vehicles represent approximately six percent of the on-road fleet in 2020, but generate 59 percent of ozone- and particle-forming NOx emissions and 55 percent of the particle pollution (including brake and tire particles).

Differentiating the relative impacts of fleet segments is particularly important when considering the concentrations of heavy-duty vehicles in environmental justice areas near highways, ports, railyards and warehouse settings. For greenhouse gases (GHG), the 2020 light duty vehicle fleet generates approximately 69 percent of GHG emissions, while the heavy-duty fleet produces 31 percent.

The table below illustrates the relative emission reduction benefits of on-road transportation electrification for each the light-duty fleet and the medium- and heavy-duty segments compared with the "Business-As-Usual" case. It is important to note that these on-road reductions could yield major benefits within each class, with light-duty vehicles reducing nearly twice the GHGs as heavy-duty, while heavy-duty engines could yield approximately eight times the smog- and particle-forming NOx emissions when compared with the light-duty fleet. Ultimately, all segments produce harmful pollutants and must move quickly to zero-emissions to protect health and reduce climate pollution.

Pollutant	**Light Duty:** On-Road Emission Reductions (Tons per Year, Percent Reduction)			**Heavy Duty:** On-Road Emission Reductions (Tons per Year, Percent Reduction)		
	2030	**2040**	**2050**	**2030**	**2040**	**2050**
Nitrogen Oxides	-23,124 **-8%**	-80,975 **-61%**	-111,168 **-92%**	-51,274 **-6%**	-478,879 **-55%**	-887,640 **-92%**
Volatile Organic Compounds	-49,080 **-9%**	-195,520 **-41%**	-347,094 **-76%**	-4,316 **-5%**	-41,379 **-51%**	-80,375 **-87%**
Fine Particles	-2,903 **-10%**	-11,369 **-42%**	-16,170 **-58%**	-644 **-4%**	-5,737 **-43%**	-9,682 **-68%**
Greenhouse Gases **(CO2e, Short Tons)**	-198 M **-18%**	-733 M **-70%**	-1.0 B **-94%**	-37 M **-7%**	-322 M **-58%**	-572 M **-92%**

National Results: Public Health and Climate Benefits

The shift to zero-emission transportation and non-combustion electricity generation could yield major health benefits throughout the nation in the coming decades. Cumulatively, the national benefits of transitioning away from combustion in the transportation sector toward 100 percent zero-emission sales and a non-combustion electricity generation sector could generate over $1.2 trillion in health benefits across the United States between 2020 and 2050. These benefits include approximately 110,000 lives saved, over 2.7 million asthma attacks avoided (among those aged 6-18 years), 13.4 million lost works days and a wider range of other negative health impacts avoided due to cleaner air.[1,2] IIn addition to these health benefits, this analysis found that over $1.7 trillion in global climate benefits could be achieved with a reduction of over 24 billion metric tons of GHGs by mid-century.[3]

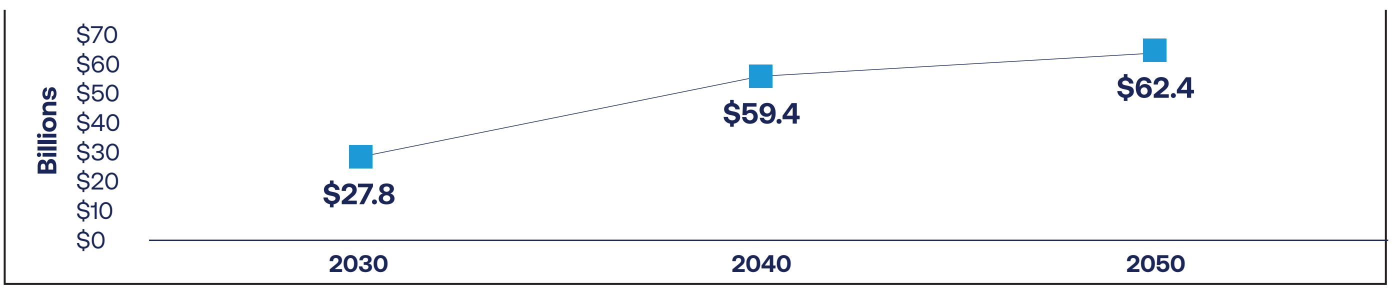
National Scale Benefits to Health and Climate (Cumulative: 2020-2050)

Public Health Benefits 2020-2050			Value of Benefits 2020-2050	
Premature Deaths Avoided	Asthma Attacks Avoided	Lost Work Days Avoided	Public Health Benefits	Climate Benefits
110,000	2.78 M	13.4 M	$1.2 T	$1.7 T

Near-Term Health Benefits

While the benefits noted above are cumulative between 2020 and 2050, this analysis also finds that annual health benefits could reach into the tens of billions by the end of this decade – nearly $28 billion in 2030 alone. Health benefits increase significantly as deployments of zero-emission technologies in the transportation and electricity generating sectors expand.

Annual Health Benefits (Billions)



Note: Total values presented for all vehicles using high estimate of benefits using a 3% discount rate and using 2017$.

[1]Note that the analysis and report include ozone-precursor emissions data. However, ozone-related health effects are not included in this report. US EPA's COBRA model relies on PM2.5 health effects to assess and monetize impacts. Results therefore do not include significant health burdens posed by ozone pollution throughout the United States independent of those related to PM reductions, as described in the health effects section of this report.

[2]In all cases, avoided health costs are presented in 2017 dollars. The value of avoided mortality estimates is grown from EPA's 1990 value of a statistical life to future years using standard income growth data and are presented in 2017 dollars. These results reflect the benefits of cumulative emission reductions estimated between 2020 and 2050, utilizing the American Lung Association's on-road and upstream emissions scenarios. Health results include the number of avoided adverse health impacts and the economic value of these health risk reductions at a 3% discount rate and reflect higher range estimates associated with the Di et al. (2017) health study. Greenhouse gas emission benefits are based on interim SCC values published in February 2021 by the Interagency Working Group on Social Cost of Greenhouse Gases, United States Government.; climate benefits are also presented in 2017$ values at a 3 percent discount rate.

[3]The social cost of CO2 emissions (SC-CO2) is a measure, in dollars, of the long-term damage done by a ton of carbon dioxide (CO2) emissions in a given year. This dollar figure also represents the value of damages avoided for a small emission reduction (i.e., the benefit of a CO2 reduction). SC-CO2 is intended to be a comprehensive estimate of climate change damages and includes changes in net agricultural productivity, human health, property damages from increased flood risk, and value of ecosystem services. However, not all important damages are included due to data limitations. Note that the climate change benefits of clean electricity generation are limited to the transportation-driven marginal increases in emissions, and do not include all benefits from the entire grid shifting to non-combustion sources, which differs from the whole-grid approach to air pollutants.

State Results: Public Health Benefits Across the United States

Every state in the U.S. stands to experience significant public health benefits from the widespread implementation of zero-emission transportation and electricity resources over the coming decades. As shown below, more than half of the states could experience more than $10 billion in cumulative public health benefits. Two states (California and Texas) could exceed $100 billion in health benefits, and six more states (Pennsylvania, Florida, Ohio, New York, Illinois, and Michigan) could see benefits exceeding $50 billion by 2050. These benefits cover a wide range of avoided health impacts, three of which (premature deaths, asthma attacks, lost workdays) are shown in the table below.

State	Cumulative Health Benefits, 2020 - 2050			
	Health Benefits (Billions)	Premature Deaths Avoided	Asthma Attacks Avoided	Lost Work Days Avoided
California	$169.0	15,300	440,000	2,160,000
Texas	$104.0	9,320	346,000	1,520,000
Pennsylvania	$86.8	7,940	148,000	735,000
Florida	$85.6	7,760	142,000	766,000
Ohio	$68.5	6,280	137,000	635,000
New York	$68.2	6,200	159,000	825,000
Illinois	$59.5	5,410	138,000	670,000
Michigan	$51.4	4,700	97,400	466,000
New Jersey	$43.6	3,960	92,400	464,000
Indiana	$36.8	3,360	83,000	373,000
North Carolina	$35.3	3,210	79,100	387,000
Virginia	$29.7	2,700	70,900	350,000
Georgia	$29.3	2,640	78,500	385,000
Maryland	$27.8	2,530	63,600	315,000
Tennessee	$24.9	2,180	53,800	255,000
Kentucky	$20.4	1,850	43,000	200,000
Wisconsin	$19.2	1,760	39,300	186,000
Missouri	$18.8	1,710	41,300	193,000
Massachusetts	$18.0	1,640	35,500	195,000
Louisiana	$17.8	1,610	40,800	184,000
South Carolina	$17.0	1,550	32,000	154,000
Arizona	$15.1	1,360	38,500	182,000
Minnesota	$14.9	1,350	36,600	171,000
Alabama	$14.3	1,300	28,300	134,000

State	Cumulative Health Benefits, 2020 - 2050			
	Health Benefits (Billions)	Premature Deaths Avoided	Asthma Attacks Avoided	Lost Work Days Avoided
Connecticut	$13.7	1,250	27,400	143,000
Oklahoma	$12.3	1,120	31,700	136,000
Iowa	$10.8	989	24,500	108,000
West Virginia	$9.8	898	16,100	81,200
Colorado	$9.5	857	31,200	151,000
Arkansas	$9.5	865	20,300	90,700
Mississippi	$8.5	773	18,300	80,600
Nevada	$7.5	676	14,800	78,900
Kansas	$6.9	625	18,100	77,400
Washington	$5.9	531	15,000	73,200
Utah	$5.7	506	26,100	94,300
Nebraska	$5.2	476	14,300	60,500
Delaware	$5.1	462	11,200	55,100
Maine	$4.5	402	5,870	31,000
New Hampshire	$3.9	356	5,860	32,800
Rhode Island	$3.8	348	6,570	35,600
New Mexico	$3.0	273	7,380	32,300
Oregon	$2.7	242	5,600	28,300
Vermont	$2.0	183	2,880	15,700
Idaho	$1.8	166	4,850	20,000
District of Columbia	$1.7	149	5,680	36,400
South Dakota	$1.6	143	4,140	16,500
North Dakota	$1.5	133	3,300	14,800
Montana	$1.3	122	2,550	11,800
Wyoming	$0.9	81	2,290	9,870

Note: Health results include the number of avoided adverse health impacts and the economic value of these health risk reductions at a 3% discount rate and reflect higher range estimates associated with the Di et al. (2017) health study. Mortality estimates are grown from EPA 1990 value of a statistical life using standard income growth data while non-fatal costs are presented in 2017$ values.

Note: Data for Alaska and Hawaii are not presented in this report because the US EPA COBRA Model provides health outputs for the contiguous United States.

Local Results: Public Health Benefits Across America

Communities across the United States stand to benefit from the widespread transition to zero-emission transportation and electricity generation. As transportation emissions are a dominant source of local exposures in many communities, a carefully and equitably designed shift to non-combustion transportation can mean cleaner air for all, and especially those most burdened by pollution from these sources today. Similarly, a shift away from fossil-fueled electricity generation is critical to improving the health of those most impacted by emissions from power plants, including in lower-income, rural communities across the United States.

This analysis found that the 100 U.S. counties (roughly 3 percent of all counties assessed) with the highest percent populations of People of Color could experience approximately 13 percent of the cumulative health benefits of this transition ($155 billion, between 2020-2050). Expanding this further, the 500 U.S. Counties (16 percent of counties assessed) with the highest percent populations of People of Color could experience 40 percent of the benefits, or $487 billion cumulatively between 2020 and 2050. It is also clear that the presence of benefits within these counties does not directly translate to benefits to individual neighborhoods or residents, however. This is an indicator of the urgent need to center equity in policies and investments to ensure access to the benefits of pollution-free mobility and power.

Additional analysis of the benefits in rural communities, lower-income communities, and neighborhood exposure levels could provide deeper insights into more equitable policy and investment designs. At a broader scale, this analysis shows a leveling of benefits across the country as the locations of power plants and transportation hubs are often impacting communities with varying socioeconomic characteristics.

As shown in the table on the next page, communities across the United States could experience billions in public health benefits, and significantly reduce premature deaths, asthma attacks and other negative health consequences of polluted air through 2050. The table includes the 25 Metropolitan Areas across the United States showing the largest cumulative health benefits by 2050 considering the shift to non-combustion electricity generation and zero-emission transportation.

Top 25 Metro Areas, Public Health Benefits	Cumulative Public Health Benefits 2020-2050			
	Health Benefits (Billions)	Premature Deaths Avoided	Asthma Attacks Avoided	Lost Work Days Avoided
1. Los Angeles-Long Beach, CA	$95.5	8,680	241,000	1,210,000
2. New York-Newark, NY-NJ-CT-PA	$84.2	7,660	206,000	1,070,000
3. Chicago-Naperville, IL-IN-WI	$46.5	4,230	113,000	552,000
4. San Jose-San Francisco-Oakland, CA	$42.5	3,850	113,000	561,000
5. Philadelphia-Reading-Camden, PA-NJ-DE-MD	$41.1	3,760	86,600	424,000
6. Washington-Baltimore-Arlington, DC-MD-VA-WV-PA	$38.9	3,540	104,000	516,000
7. Miami-Port St. Lucie-Fort Lauderdale, FL	$36.5	3,320	62,300	342,000
8. Houston-The Woodlands, TX	$33.4	3,000	130,000	568,000
9. Detroit-Warren-Ann Arbor, MI	$29.2	2,690	55,100	268,000
10. Dallas-Fort Worth, TX-OK	$28.0	2,530	88,300	405,000
11. Boston-Worcester-Providence, MA-RI-NH-CT	$22.7	2,070	43,000	238,000
12. Atlanta-Athens-Clarke County-Sandy Springs, GA-AL	$20.9	1,890	59,400	296,000
13. Cincinnati-Wilmington-Maysville, OH-KY-IN	$20.7	1,900	51,600	233,000
14. Cleveland-Akron-Canton, OH	$20.3	1,870	31,500	153,000
15. Pittsburgh-New Castle-Weirton, PA-OH-WV	$19.9	1,830	26,100	138,000
16. Orlando-Lakeland-Deltona, FL	$12.9	1,160	22,400	121,000
17. San Diego-Chula Vista-Carlsbad, CA	$12.4	1,100	29,200	151,000
18. Indianapolis-Carmel-Muncie, IN	$12.2	1,120	32,000	144,000
19. St. Louis-St. Charles-Farmington, MO-IL	$12.2	1,120	25,800	122,000
20. Minneapolis-St. Paul, MN-WI	$11.7	1,070	30,700	145,000
21. Phoenix-Mesa, AZ	$11.0	994	30,700	145,000
22. Tampa-St. Petersburg-Clearwater, FL	$10.9	988	20,100	108,000
23. Charlotte-Concord, NC-SC	$9.2	833	23,200	113,000
24. Harrisburg-York-Lebanon, PA	$8.8	805	16,500	78,700
25. San Antonio-New Braunfels-Pearsall, TX	$8.8	791	25,200	112,000

Note: Health results include the number of avoided adverse health impacts and the economic value of these health risk reductions at a 3% discount rate and reflect higher range estimates associated with the Di et al. (2017) health study. Mortality estimates are grown from EPA 1990 value of a statistical life using standard income growth data while non-fatal costs are presented in 2017 $ values.

Note: The counties assigned to a metropolitan area follow the groupings determined by the White House Office of Management and Budget (OMB) and used by the U.S. Census Bureau. The Metropolitan Statistical Areas and Combined Statistical Areas are used as the basis for considering populations at risk in these urban areas because they reflect the “high degree of social and economic interaction as measured by commuting ties,” as OMB describes them. In some cases, metropolitan area results may exceed state results due to geographies of metropolitan areas crossing state lines.

Policy Recommendations to Achieve Public Health and Climate Benefits

At every level of government, transportation and energy decisions are essentially public health decisions. The phase-out of combustion in the transportation and electricity generation sectors is critical as the nation transitions to a healthier future. Continued investments in combustion technologies may prolong the use of harmful fuels or otherwise delay investment in healthier choices today. Public leaders must align transportation and energy decisions and investments with the protection of public health and reductions in harmful emissions.

Recommended Federal Policies to Achieve Public Health Benefits of Zero-Emission Transportation and Electricity Generation

The Federal Government has a critical opportunity to move the nation to healthier, pollution-free transportation and power systems through a combination of strong policies and investments in zero-emission technologies and infrastructure, actions that enjoy broad public support according to a recent American Lung Association poll.[vi] A key down payment was made in the transition to zero-emission transportation with the President signing the Bipartisan Infrastructure Law in November 2021. This law invests $2.5 billion in zero-emission school buses and set $7.5 billion in motion to expand the national infrastructure for zero-emission vehicles — an important start to the larger, and longer-term public/private investments needed. These investments must not only continue and scale up, but must be paired with stronger laws and rules to reduce harmful air and climate pollution:

- Fully implementing the provisions of the bipartisan infrastructure and vehicle investments and continuing to increase funding for non-combustion electricity generation and transportation as the nation continues to invest in a healthier future.
- Extending and increasing incentive and grant programs to support zero-emission vehicle purchases by consumers, transit agencies, school districts and other entities.
- Leading by example by converting public fleets to zero-emission vehicles immediately.
- Congress must pass legislation to accelerate the transition to zero-emission transportation more broadly than contained in the Bipartisan Infrastructure Law and to ensure more equitable distribution of clean air benefits.
- US EPA must act quickly to update National Ambient Air Quality Standards (NAAQS) for NO2, SO2, carbon monoxide, lead, ozone and particle pollution in line with the scientific understanding of what levels are appropriate with an adequate margin of safety of the most vulnerable communities.
- US EPA and the National Highway Traffic Safety Administration (NHTSA) must adopt standards that drive the complete transition to zero-emission passenger vehicles.
  - EPA has finalized regulations that help clean up carbon pollution from the light-duty vehicle sector through Model Year 2026. NHTSA must finalize the Corporate Average Fuel Economy Standards (CAFE) regulations through 2026 for light-duty vehicles.
  - These actions must be followed by increasingly stronger rules beyond 2026 that deliver on President Biden's goal for 50 percent of vehicles sold in the United States to be zero-emission by 2030, and a more complete transition to follow shortly thereafter.

- US EPA must move quickly to approve the next generation standards for heavy-duty trucks in 2022 that acknowledge the growing market for combustion-free medium- and heavy-duty vehicles:
  - More stringent greenhouse gas emission standards for heavy trucks by 2027
  - 90 percent reduction in smog-forming NOx emissions for new trucks by 2027
  - These actions must be followed by stronger rules for subsequent years that drive a complete transition to zero-emission heavy-duty vehicles
- The Biden Administration's Justice40 initiative must ensure that major investments are made in environmental justice communities throughout the United States. These investments must ensure that the benefits of zero-emission technologies are felt in historically underserved and over-polluted communities.
  - Treat 40 percent investment as a minimum requirement
  - Ensure that investments are located in communities of concern, and that health, climate and other benefits actually accrue within these communities
- Increase and sustain policies, incentives and investments to accelerate non-combustion renewable electricity generation and the retirement of combustion-based power plants to achieve the Biden Administration's target for 100 percent carbon pollution-free electricity by 2035.

Broad Public Support for Transportation Electrification

70% of American voters believe the federal government should:

- implement policies that support a transition to zero-emission vehicles; and
- require that by 2040 all new freight trucks, buses and delivery vans sold in the U.S. must produce zero tailpipe emissions.

American Lung Association Poll, 2021

Recommended State Policies to Achieve Public Health Benefits of Zero-Emission Transportation and Electricity Generation

Under the Federal Clean Air Act, California holds the authority to seek a waiver to enact stronger-than-national standards to address its air pollution challenges, while states can — and increasingly do — follow these more health-protective rules. At present, 15 states have adopted zero-emission vehicle standards and increasing numbers are pursuing zero-emission truck requirements. In addition to adopting these standards, states must invest in the fueling infrastructure needed to support the growing market, while also supporting the transition to non-combustion renewable power.

State	Zero Emission Vehicle Standard	Zero Emission Truck Standard	Zero Emission Truck MOU
California	●	●	●
Colorado	●		●
Connecticut	●		●
Hawaii			●
Maine	●		●
Maryland	●		●
Massachusetts	●	●	●
Minnesota	●		
Nevada	●		
New Jersey	●	●	●
New York	●	●	●
North Carolina			●
Oregon	●	●	●
Pennsylvania			●
Rhode Island	●		●
Vermont	●		●
Virginia	●		●
Washington	●	●	●
Washington, DC			●

Note: The California Zero Emission Vehicle standard sets increasing requirements for zero-emission passenger vehicle sales. The California Advanced Clean Truck standard sets similar sales percentages for medium- and heavy-duty truck sales. The Multi-State Memorandum of Understanding creates a coordinated approach to achieving 30 percent zero-emission truck sales by 2030 and 100 percent sales by 2050.

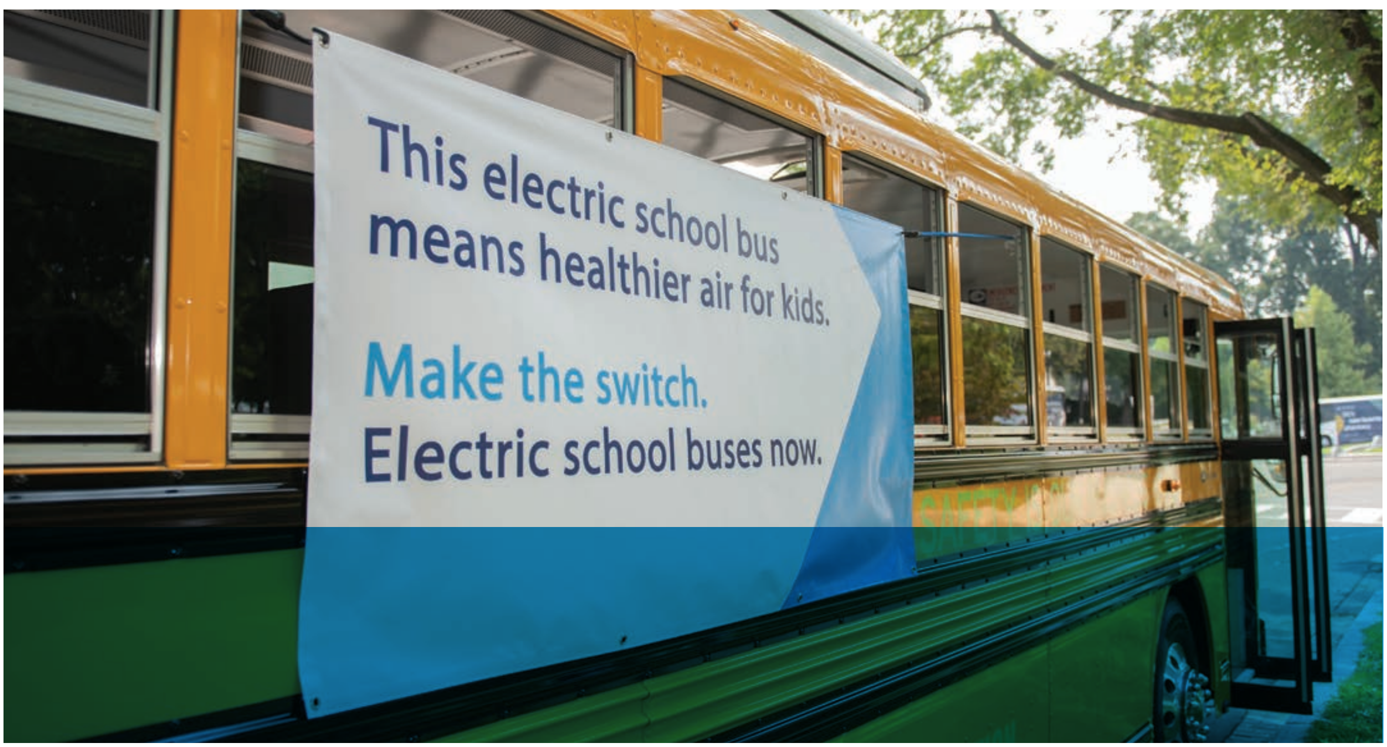
- States must adopt state standards for passenger vehicles and medium- and heavy-duty trucks to require that 100 percent of sales are zero-emissions.
- States must lead by example by converting public fleets to zero-emission vehicles.
- States must establish incentive programs to accelerate zero-emission mobility options and set clear requirements for the equitable distribution of incentive funding and infrastructure investments so that all communities (including urban, rural, lower-income, etc.) have access to the benefits of zero-emission mobility.
- States must remove barriers to equitable utility investments in zero-emission infrastructure serving all communities, and invest in upgrades needed to integrate light-, medium- and heavy-duty zero-emission vehicles across the grid.
- California must utilize its unique Clean Air Act authority to develop and implement stringent near- and long-term zero-emission standards (e.g., Advanced Clean Cars, Advanced Clean Trucks) that support attainment of NAAQS and state climate policies while also ensuring equity is central to policy design.
- States must enact programs and investments in infrastructure, consumer rebates and other supportive programs to join the growing list of jurisdictions following these more health-protective Advanced Clean Cars and Advanced Clean Trucks standards.
- States must not preempt actions by local governments seeking to expand zero-emission fueling infrastructure and clean electricity installations or to set more protective building codes.
- States can also join regional or other partnerships such as the Regional Electric Vehicle Midwest Coalition or the Multi-State Memorandum on Zero Emission Trucks to leverage broader resources to achieve healthier transportation.
- States must adopt and accelerate clean electricity standards, modernize electric grids and ensure equitable access to clean electricity to ensure full benefits of non-combustion electricity generation and transportation.

Recommended Local Policies to Achieve Public Health Benefits of Zero-Emission Transportation and Electricity Generation

In planning and building bike lanes and sidewalks, transit routes and carpool lanes, local government decisions impact how we move, and how safely and easily it is we do so. Local decisions can also ease the transition to zero-emissions. There are examples across the nation of public agencies, rural and urban transit fleets and school districts incorporating or fully converting to zero-emission technologies within their own fleets and make it easier for residents and businesses to make the switch and capture the benefits of cleaner air. Local governments must:

- Develop resources with utilities, manufacturers, local and regional governments and others to accelerate regional deployment of zero-emission vehicles, electricity and associated infrastructure
- Shift public fleets to zero-emissions across all weight classes.
- Establish simplified renewable energy and zero-emission fueling infrastructure installation processes for businesses, homeowners, renters and apartment managers.
- Coordinate with local agencies to implement zero-emission mobility options for lower-income neighborhoods, including car share, bike share, on-demand transit, etc.
- Ensure building code requirements follow best practices for charging readiness.
- Develop non-financial incentives such as preferred parking, sidewalk charging or other, visible measures to support residents in this transition.

At all levels, local, state and federal partners must collaborate and coordinate to deliver the framework for accessible, sustainable and reliable deployment of zero-emission transportation.



Conclusion

Too many Americans face unhealthy air that is being polluted by the transportation and electricity generation sectors. Climate change is making air pollution worse. This is especially true in lower-income communities and communities of color experiencing highly concentrated doses of pollution from diesel hotspots, refineries, power plants and other fossil fuel facilities. To reduce air pollution burdens and disparities, and to protect public health against the worst impacts of climate change, policies and investments must align with rapid reduction and elimination of combustion in these sectors. Doing so could yield over $1.2 trillion in public health benefits across the United States between 2020 and 2050 and $1.7 trillion in climate benefits. Acting now provides opportunities for major benefits in the near term and establishes pathways for generations to breathe healthier air.

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[i] American Lung Association. Health Impact of Air Pollution. April 2021. https://www.lung.org/research/sota/health-risks
[ii] American Lung Association. State of the Air 2021. April 2021. www.lung.org/sota
[iii] American Lung Association. State of the Air 2021. April 2021. www.lung.org/sota
[iv] United States Environmental Protection Agency. Transportation and Environmental Justice Fact Sheet. March 2022. https://www.epa.gov/system/files/documents/2022-03/420f22008.pdf
[v] American Lung Association. State of the Air 2021. April 2021. www.lung.org/sota
[vi] American Lung Association poll. June 2021. https://www.lung.org/media/press-releases/seventy-percent-of-voters-support-federal-action

Updated Evaluation of the National Health Benefits from the Transition to Zero-Emission Transportation Technologies

American Lung Association

Final Report, March 4, 2022

American Lung Association.

CAA EXHIBIT 16

ICF

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Updated Evaluation of National Health Benefits from the Transition to Zero Emission Transportation Technologies

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1. Executive Summary

Electric vehicles produce fewer emissions that contribute to climate change and smog than conventionally fueled vehicles.[1] As recently as 2018, transportation was responsible for about 28% of the nation's greenhouse gas emissions.[2] Direct emissions from on-road vehicles alone were responsible for accounting for about 33% of the nation's total nitrogen oxides and about 13% of its emissions of volatile organic species, together the primary contributors to smog, about 39% of the nation's emissions of carbon monoxide, and about 3% of the nation's primary emissions of fine particulate matter.[3] More than 45 million people in the U.S. live within 300 feet of a major transportation facility such as a busy roadway, and thus bear the increased exposure risk from traffic-related air pollution. Such adverse health effects may include asthma, cardiovascular disease, and premature death.[4] Vehicle electrification has the potential to signifcantly reduce air pollutant emissions, improve air quality, slow climate change, and reduce the public health burden associated with exposure to vehicular emissions.

In 2020, ICF conducted a comprehensive analysis for the American Lung Association[5] of the potential health and climate benefits of a scenario for increasing on-road vehicle electrification across the United States. ICF's analysis was the basis for the Lung Association's Road to Clean Air report.[6] The electrification scenario analyzed in that report included both light- and heavy-duty vehicles and both

- *downstream* (tailpipe exhaust, evaporative, brake and tire wear) and

1 US Department of Energy, Reducing Pollution with Electric Vehicles (2020). https://www.energy.gov/eere/electricvehicles/reducing-pollution-electric-vehicles.
2 US EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018 (2020). https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2018.
3 US EPA, National Annual Emissions Trends: Criteria pollutants National Tier 1 for 1970 – 2019 (2020). https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data. All are relative to national totals from all sources excluding wildfires.
4 US EPA, Research on Near Roadway and Other Near Source Air Pollution (2020). https://www.epa.gov/air-research/research-near-roadway-and-other-near-source-air-pollution.
5 https://www.lung.org/getmedia/b9efc73e-aeba-4cd8-b789- 942166c38ca6/ev_technical_documentation.pdf
6 https://www.lung.org/clean-air/electric-vehicle-report

- *upstream* (reduced fuel production, transport, and refining activities for internal combustion vehicles and increased electricity generation for electric vehicles)

emissions components along with two potential Cases for the nation's future electricity production. It presented results for both a short-term (2030) and long-term (2050) projection years including the emissions that could be avoided and resulting public health and climate benefits from these reduced emissions. The Scenario was considered aggressive but realistic in terms of both upstream generation and vehicle adoption. It did not consider cumulative impacts, nor did it address any potential disparities in exposure burden that may be addressed through such a transition.

Since the report's release, electric vehicles (EV) and other zero emission vehicle (ZEV) technology have continued to gain market share in the U.S. For example, in 2021:[7]

- President Biden and major automakers had set a target of 50 percent EV sales by 2030.
- Five states had adopted the California Advanced Clean Truck (ACT) rule – MA, NY, OR, WA, and NJ, while others had begun public proceedings.
- The infrastructure bill became law, allocating more than $30 billion in EV related funding including $7.7 billion in dedicated funding.
- Utilities and automakers continued to invest in EVs. In Q3 utilities proposed $781 million in EV investments, twice the amount of Q1 and Q2 combined. Automakers have announced investments of $108 billion for EVs in the US.
- By 2021 Q3, EVs comprised 5 percent of all light duty sales, more than doubling the sales rate from 2020.
- New EV models continued to come on-line, notably including Ford's F-150 Lightning, the electric version of the most popular new and used vehicle sold in the country last year.

The impacts of air pollution and the potential for EVs to address it are receiving substantial attention, with the disparate impacts of the air pollution burden as a recent focus of EV programs. The Biden Administration's original proposal included grants to electrify 20 percent of all school buses and $20B to transportation projects in underserved communities, while its latest Justice40 Initiative draft guidance specifies that at least 40 percent of the benefits from federal energy and environmental spending reach disadvantaged communities.[8] CA continues to dedicate more than half of the California Climate Investments (CCI) program funded through Cap-and-Trade to underserved communities. CO, NY, and NJ have recently prioritized transportation electrification investment to projects enhancing environmental justice.[9] Reducing electricity generating emissions are another critical component to realizing the benefits of EVs. President Biden's proposal for a clean electricity standard would require utilities to meet goals of 80 percent clean electricity by 2030 and 100% by 2035, where clean is defined as renewable or emissions-free power, including nuclear.[10]

This report documents an updated analysis of the potential benefits of a nationwide EV Scenario. This analysis modernizes the findings from the 2020 study to address current trends and available data. Some of the key changes include:

- More aggressive adoption of EVs, including 100 percent ZEV[11] passenger sales by 2035 and more aggressive ZEV truck sales, roughly in line with the final ACT.
- A simplified vehicle scheme that tracks the impacts of light duty and heavy-duty vehicles separately.

7 Based in part on a summary published January 3, 2022 by EV Hub, "8 Big EV Stories from 2021".
8 E&E News: White House details environmental justice plans, Adam Aton, 07/20/2021.
9 EV Hub, April 5, 2021
10 E&E News: Clean electricity standard carries $1.8T upside — study, Miranda Willson, 07/12/2021.
11 As with the 2020 study, the scope of this analysis was determined to focus exclusively on battery electric vehicles (BEV) as a marker for all ZEVs. This is discussed in Section 3.

- Consideration of a more aggressive transition to renewables on the electric grid, with accelerated retirement of coal and the dramatic push to renewables. The reduced emissions and resulting benefits to human health also apply to the base load on the grid, not only that related to the additional load from new EVs, emphasizing the potential benefits of a cleaner electric grid. The non-combustion electricity case was determined through an optimization modeling approach using ICF's IPM model.
- Modernization of all modeling tools, including the latest version of the COBRA, GREET, and MOVES models. COBRA version 4.0 includes updates to default emissions and sources that account for air quality policymaking through 2018. MOVES3 represents EPA's current estimate and projection of the US vehicle fleet and its emissions. GREET2021 is Argonne National Laboratory's current approach for simulating lifecycle emissions output of vehicle/fuel systems.
- Updated function for avoided mortality estimates are updated to those in the latest version of EPA's BenMAP model, reflecting current understanding of the health impacts of pollution.
- Cumulative health and climate benefits are estimated from the simulated years to illustrate the total impact of changes over the entire period considered (2020-2050).
- Including an analysis of demographic-specific impacts to provide insight into the effects of emissions scenarios on people of color.

Our approach and results are documented in the following sections of this report:

- Section 3 describes the analysis of national-scale, business-as-usual (BAU), on-road vehicle population, engine technology, age distribution, and emissions and our approach to determine the vehicle fleet under our aggressive but achievable vehicle electrification Scenario.
- Section 4 discusses the national level emissions and emission changes resulting from implementation of the vehicle electrification scenario, including both upstream and downstream emissions and two potential Cases for upstream electricity generation associated with the Scenario.
- Section 5 describes the results and approach taken to quantify and monetize the change in adverse health outcomes resulting from air quality changes under the scenario.
- Section 6 summarizes and monetizes the climate benefits anticipated due to reductions in greenhouse gas (GHG) emissions from the vehicle electrification scenario.

Our modeling of the baseline and BAU national vehicle fleet, its related activity, fuel use, population, engine technology, age distribution, and downstream emissions relied on national default values from US EPA's MOVES3 emission model. We simulated emissions of:

- Volatile organic compounds (VOC),
- Oxides of nitrogen (NOx),
- Fine particulate matter less than 2.5 μm in size ($PM_{2.5}$),
- Sulfur dioxide (SO_2),[12]
- Ammonia (NH_3),

These are the criteria pollutants, and precursors for secondary PM, included to capture benefits in health modeling from both directly emitted PM pollution and that formed in the atmosphere. We also modeled emissions of

- GHGs, characterized as CO_2-equivalent (CO_2e).

This study directly models the calendar years:

12 In this analysis, SO_2 and SOx are considered identical.

- 2020,
- 2030,
- 2040, and
- 2050

The US vehicle fleet is grouped into four vehicle categories for analysis:

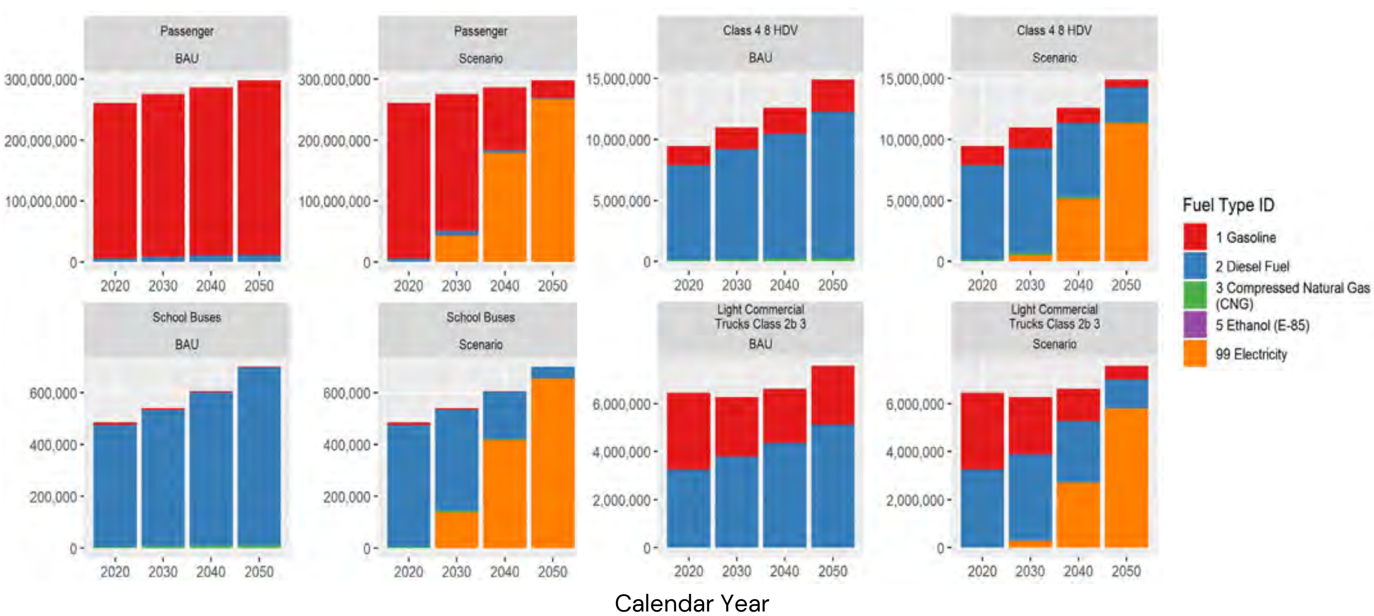
- Passenger vehicles,
- Light heavy-duty trucks,
- Medium-heavy and heavy-trucks, and
- School buses

The aggressive but achievable vehicle electrification Scenario assumes 100 percent sales penetration for EVs by 2029 for school buses, 2035 for passenger vehicles, and 2040 for heavy-duty vehicles. These four categories are tracked through the emissions modeling, but aggregated into two vehicle classes:

- Light duty
- Heavy-duty, and
- Total

for determining the health benefits associated with each Class. Figure ES-1 illustrates how the sales rates listed above determine the population of EVs in the overall fleet. This figure shows the resulting vehicle populations by fuel type and vehicle category under the BAU and vehicle electrification Scenario, for the four modeled calendar years. (Note that sets are paired, with the BAU on the left and scenario on the right. So, the two panels in the top left show passenger vehicles, with the leftmost showing the BAU and the Scenario just to its right.)

Figure ES-1. Modeled vehicle populations in the four vehicle categories and five fuel types under the BAU and vehicle electrification Scenario



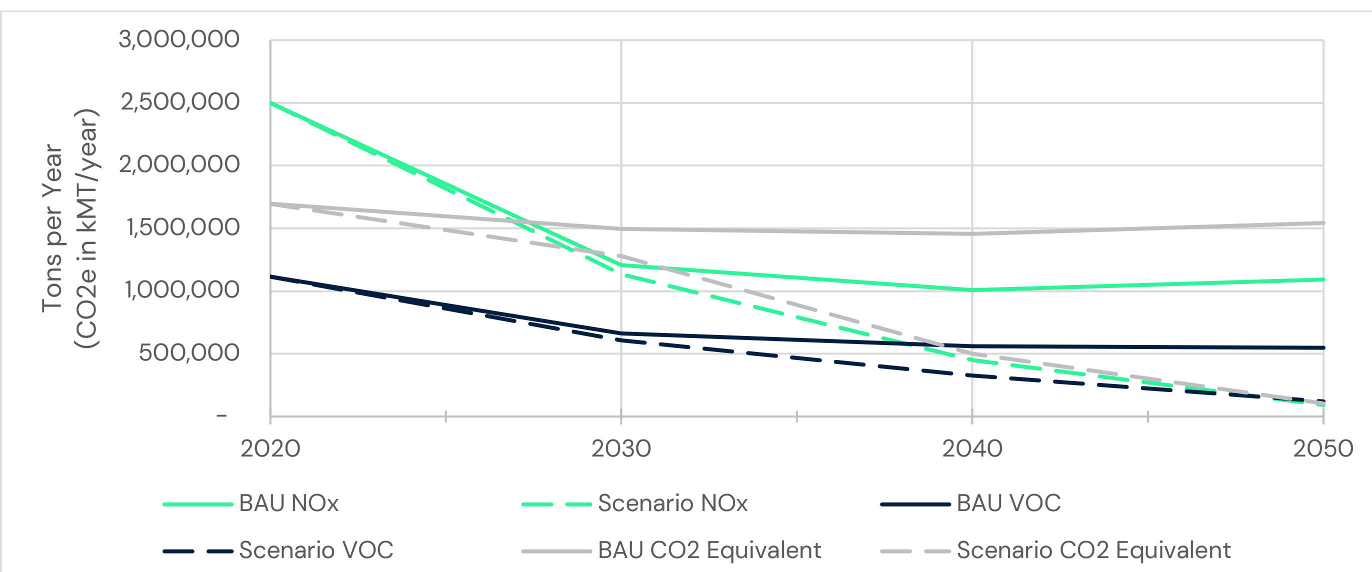
We assessed changes in emissions nationwide resulting from the electrification Scenario considering both downstream and upstream emissions components. Furthermore, we considered the implications of two potential Cases for future electricity production on the upstream emissions to the Scenario.

1. *The Base electricity generation Case*: A more business-as-usual projection for the grid, based on the Bloomberg New Energy Outlook (BNEO) 2019 analysis employed by the 2020 study.
2. *The Non-Combustion electricity generation Case*: A more ambitious renewables projection, with a heavy emphasis on emissions free, renewables, such as from wind and solar.

All analyses reflect national-scale simulations and rely on an average power approach. We do not assume that EV demand causes low carbon intensity electricity growth or implement an incremental approach to future electricity generation that pairs the increased demand with cleaner electricity only. However, the level of emissions associated with baseline and additional power load are coupled with the electric Case. Thus, the health benefits from the Non-Combustion Case also include benefits associated with cleaning the grid regardless of load changes due to EVs.

We calculated the reduction in direct (downstream) emissions of vehicular pollutants nationally for the BAU and vehicle electrification Scenario. Downstream emissions consider both tailpipe emissions and the ongoing contribution of brake and tire wear PM emissions, including for EVs. Comparing these shows national, downstream emissions are significantly lower under the Scenario than the BAU. In 2050, annual downstream emissions of NOx, VOC, and $PM_{2.5}$, and tailpipe GHG emissions (reported as CO_2e) are reduced below the values of a BAU scenario by approximately 1,000,000, 430,000, and 26,000, and 1.6 billion short tons, respectively. These values are 92, 78, 61, and 93 percent below the BAU levels of emissions, respectively. That is, while there is a general trend toward lower downstream criteria pollutant emissions (NOx and VOC) nationally, and a flat-to-increasing trend for and GHGs, under the BAU, the EV Scenario provides dramatic reductions over the modeled period. Figure ES-2 shows these trends for NOx, VOC, and CO_2e.

Figure ES-2. Trends in downstream emission for NOx, VOC, and CO_2e under the BAU and Scenario. All units are short tons per year except CO2e, shown in thousands of metric tons per year.



When combined with the change in upstream emissions, the total net change in emissions (domestic for criteria pollutants; global for GHGs) from combined upstream and downstream under the Non-Combustion

Case electrification show savings of 1,400,000, 830,000, 55,000, and 2.0 billion short tons per year by 2050 relative to the BAU values for NOx, VOC, and $PM_{2.5}$, GHG emissions, respectively.

Figure ES-3 shows the relative contribution of upstream and downstream emissions for the affected sectors modeled here, broadly electricity generation, fuels production, and vehicle use. These are total, national emissions for the sectors under the BAU and the EV Scenario, with the latter coupled to the two different approaches for upstream electrification. Note that the grid assumptions of each Case are applied to both new load from increased EVs and baseline load on the grid. The downstream differs between the BAU and Scenario but is identical between the two electrification Cases implementing the Scenario, so the only difference between the right two columns is the upstream electrification component. No calculation of the total upstream GHG emissions nationwide is made, so only downstream results are shown for CO_2e.

Figure ES-3. Emissions from up- and downstream components for each pollutant (downstream only for GHG) under the Base, Non-Combustion, and Non-Combustion for All Load electrification Case and the national BAU.

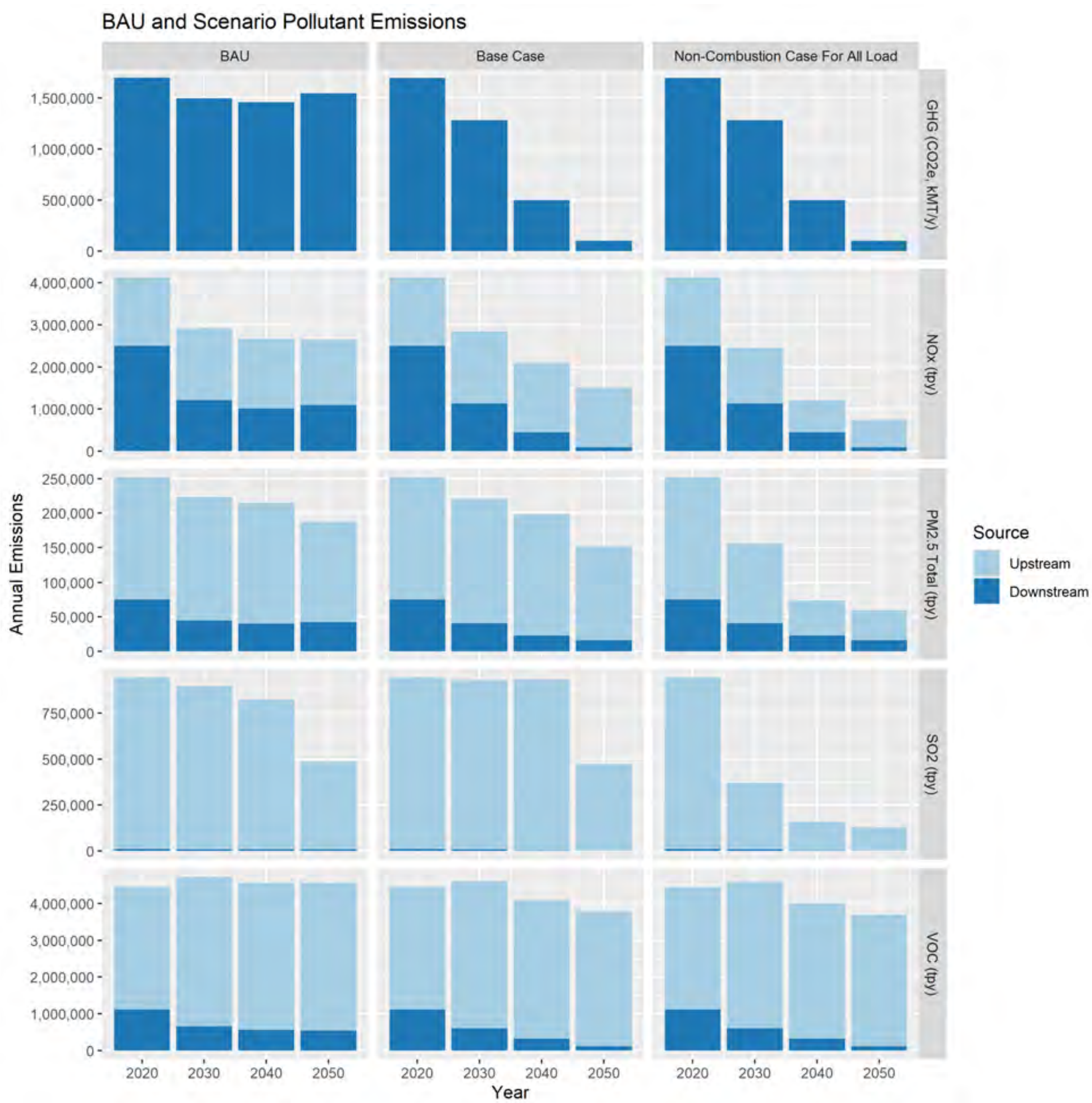
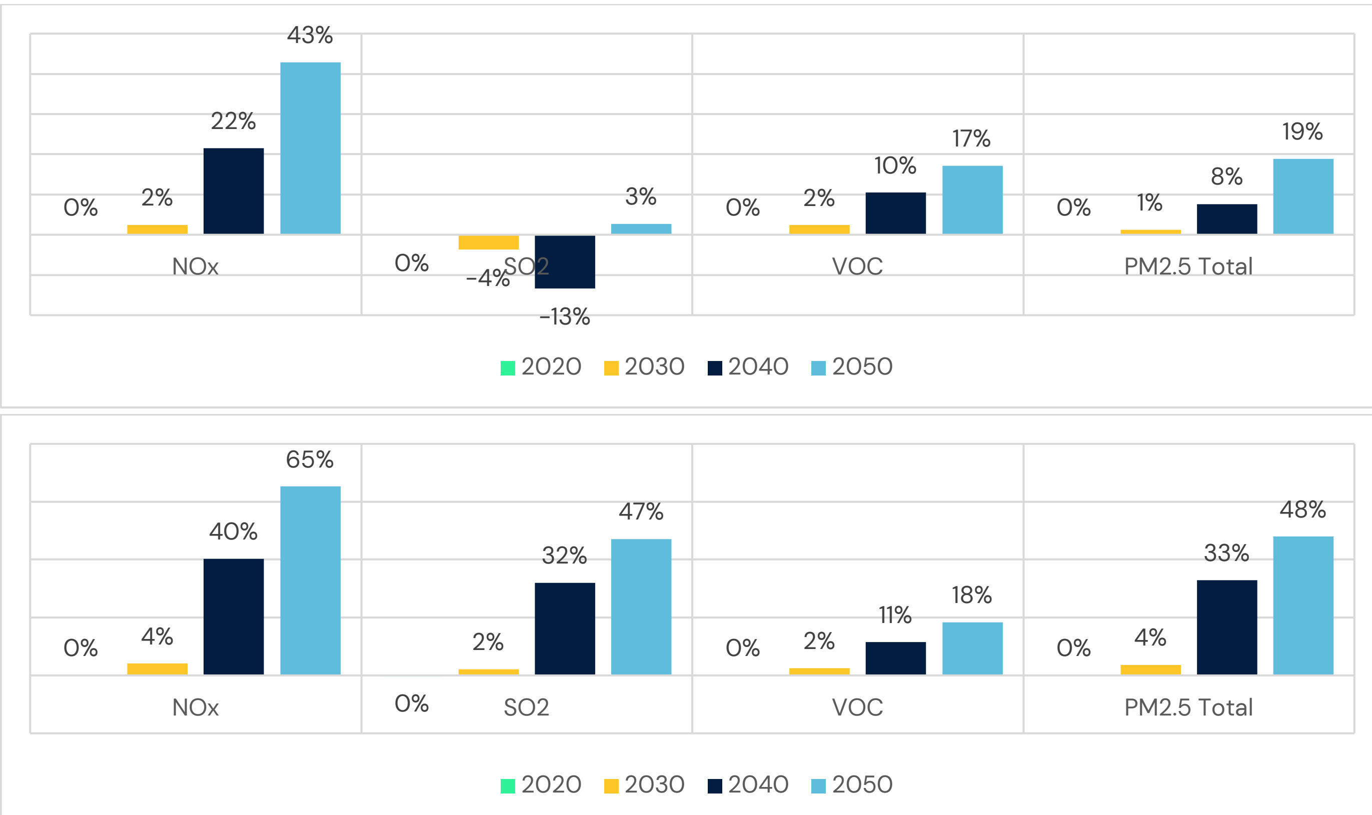


Figure ES-4 illustrates the relative reduction in total (up- and downstream), national emissions of criteria pollutants for the EV Scenario with the Base (top) and Non-Combustion (bottom) Cases. Under the Non-Combustion Case, total, national $PM_{2.5}$ is reduced 48 percent by 2050, or more than twice that of the 19 percent reduction seen in the Base Case. No pollutants show increases in national emissions in any year except SO_2 under the Base Case, which sees increases in emissions due to the new load on the relatively dirtier grid in the mid-term.

Figure ES-4. Relative reduction in emissions by pollutant between the national BAU and the EV Scenario with the Base Case (upper panel) and the Non-Combustion Case (lower panel) Reductions are for combined emissions (up- and downstream). Each set of bars represents different pollutants: NOx, SO_2, VOC, and $PM_{2.5}$. Bars in each set represent the four modeled years.



We then used these national-scale criteria pollutant emissions in EPA's COBRA model to evaluate the potential health benefits of the vehicle electrification Scenario. We quantified and monetized changes in the incidence of adverse health impacts resulting from reduced human exposure to downstream and upstream $PM_{2.5}$ emissions from the Scenario with both electrification Cases. We also determined the contributions to changes from both light- and heavy-duty vehicles and processed each through COBRA separately, as well as the total of all vehicles.

Employing a 3 percent discount, total monetized public health benefits range from approximately $4.5 million in 2020 to $33.1 billion in 2050 under the Base Case considering all vehicle classes. The same approach under the Non-Combustion Case shows benefits ranging from approximately $4.9 million in 2020 to $62.4 billion in 2050. Adult mortality is the main driver of benefits of emissions changes under all electricity generation and vehicle scenarios, with an estimated decrease in the number of premature deaths among adults between 2,650 and 2,830 under the 2050 Base Case and between 5,010 and 5,350 under the 2050 Non-Combustion Case.

We also postprocessed health benefits results from COBRA to show cumulative impacts of the proposed scenarios from 2020 to 2050. At a 3 percent discount, cumulative monetized public health benefits from 2020 to 2050 range from approximately $318 billion to $339 billion in the Base Case and total vehicles scenario. Under the Non-Combustion Case, cumulative benefits from 2020 to 2050 range from approximately $1.1 trillion to $1.2 trillion. Adult mortality is the main driver of monetized benefits from emissions changes under all electricity generation and vehicle scenarios, with an estimated decrease in the number of premature deaths among adults between 28,500 and 30,000 under the Base Case, considering all total vehicles, and between 105,000 and 110,000 under the Non-Combustion Case also considering all vehicles.

Under the Base electricity Case, the cumulative number of avoided adverse health effects is greater for the heavy-duty vehicle scenario compared to the light duty vehicles scenario. For example, estimates indicate between 11,600 and 12,200 avoided mortality cases under the Scenario for light duty vehicles with Base Case electrification and between 16,900 and 17,800 avoided mortality cases from heavy-duty vehicles with Base Case electrification. The difference between light- and heavy-duty avoided adverse health effects shrinks in the Non-Combustion Case, where estimates indicate between 85,400 and 89,300 avoided mortality cases under the light duty Non-Combustion Case scenario and between 83,100 and 86,900 avoided mortality cases under the heavy-duty Non-Combustion Case scenario. However, the light- and heavy-duty vehicles are not directly comparable under the Non-Combustion Case because of the additional benefit from the cleaner grid for the baseline load relative to the BAU, which is independent of vehicle electrification. (That is these additional benefits appear in both the light and heavy vehicle results).

We also calculated the health benefits to populations individually in 25 of the nation's largest metropolitan areas. Total health benefits in these areas under the Base electricity Case in year 2050 range from about $129 million (Portland, OR) to $5.41 billion (Los Angeles, CA). Under the Non-Combustion electricity Case in 2050, total health benefits range from about $152 million (Portland, OR) to $6.81 billion (Los Angeles, CA). Considered cumulatively, from 2020-2050, benefits for these metro areas under the Base electricity Case range from $1.34 billion (St. Louis, MO) to $63.1 billion (Los Angeles, CA). Under the Non-Combustion electricity Case, cumulative benefits are roughly 50% larger, ranging from $2.09 billion (Portland, OR) to $95.5 billion (Los Angeles, CA).

As an indication of, "who would benefit" from the transition described by the scenario, we consolidated the predicted health benefits with county-level demographics. We ranked counties by the percent of the population identifying as people of color (POC). Considering cumulative impacts, 2020-2050, the counties that fall into the top 100 in terms of the proportion of POC are expected to receive $82 billion, or 24 percent, of the national health benefits from the Scenario under the Base electricity Case and $155 billion, 13 percent, under the Non-Combustion electricity Case. These shares of the benefits are notable given that the top 100 counties comprise only 3 percent of all counties in the studied area - 48 contiguous states and the District of Columbia.

Finally, we also evaluated the global climate-change costs that may be avoided due to reductions in GHG emissions for the vehicle electrification Scenario. This considered both the reduction in direct (downstream) emissions from increased vehicle electrification in the country and the associated changes in upstream emissions from reduced fuel production and increased load on the electric grid under both electricity Cases. As not all upstream emissions associated with crude refined for traditional vehicle (internal combustion engine vehicles; ICEVs) fuels is domestic, we include global changes in upstream emissions of these fuels. We then monetized these values using the Social Cost of Carbon (SCC). It is important to note that GHG benefits valued here only consider *changes* in the up- and downstream emissions associated with vehicle electrification. That is, we included the changes in tailpipe, fuels production, and electricity generation emissions directly due to vehicle electrification. As we did not compute a sector-wide BAU curve for GHG emissions, the additional climate benefits of the Non-Combustion case attributable to the baseline load (i.e., that part independent of vehicle electrification) will be significant but are not included here. (These benefits are included in the health-based results.)

The EV Scenario with the Base Case electricity grid shows net avoided climate change-related costs from reductions in 2050 levels of GHG emissions of $116 billion with 1.4 million metric tons of CO_2e emissions avoided. With the Non-Combustion electricity grid, net avoided climate costs are $145 billion from 1.8 million metric tons of CO_2e emissions avoided. We also explored the cumulative avoided costs from GHG reductions from the entire 2020-2050 period. When consolidated over the period, the Scenario with the Base Case electricity grid is expected to reduce GHG emissions by 18.6 billion metric tons for a net avoided cost of $1.36 trillion. With the Non-Combustion electricity grid, 24.2 billion metric tons of CO_2e emissions could be avoided, resulting in $1.76 trillion in avoided climate costs. These values underestimate the true, total benefit due to omitting changes in emissions associated with the base load.

2. Background and Overview

In 2020 ICF prepared an analysis for the American Lung Association on the *Health Benefits of Transition to Zero Emission Transportation Technologies*. That analysis quantified the potential air quality, health, and climate benefits of an ambitious but achievable scenario for on-road vehicle electrificationacross the United States. The purpose of this project is to provide an update to the 2020 study to modernize its methodology and approach and enhance elements of its reporting.

This project was conducted in four tasks. Task 1 focused on developing a detailed business as usual (BAU), and vehicle electrification Scenario fleet model. Task 2 used the fleet profiles of the vehicle electrification Scenario in an emissions modeling exercise to determine the change in both downstream and upstream national emissions under the new Scenario. Upstream emissions were determined for two Cases representing potential pathways for the national electric grid in the future. Task 3 then assessed the potential health and climate impacts associated with the modeled, national emission reductions. The fourth task addresses reporting.

This report consolidates the emissions reductions from Tasks 1 and 2 with the health and climate impacts analysis of Task 3. Section 3 provides a brief discussion and summary of the results from the fleet modeling approach and results. This includes a discussion of the vehicle categories and the BAU and Scenario vehicle fleets. Section 4 documents the resulting changes in emissions associated with the Scenario. It first summarizes the different modeling tools and methodology applied for the downstream and upstream emissions. For upstream emissions, it introduces the two potential Cases for the future national electric grid. It then presents the BAU emissions for both up- and downstream and the change in each expected because of the Scenario. It then summarizes the net change for the BAU and Scenario under both electric Cases. Section 5 summarizes the human health benefits that accrue from the vehicle Scenario. This Section provides a discussion of the methodology and results of the COBRA modeling, resolving impacts from both electrification Cases as well as impacts from light- and heavy-duty vehicles separately from the cumulative impacts. Notably in these results, the baseline grid activities are treated identically to additional grid load from new electric vehicles. This average power approach demonstrates the substantial electricity generation reductions from the cleaner grid under the Non-Combustion Case. Results are shown for the individually modeled years, as well as cumulative impacts over the 2020-2050 period. Finally, to help identify who benefits most from the EV Scenario modeled here, this section summarizes the impacts in 20 of the largest metropolitan areas of the country and reports impacts according to population demographics. Section 4 also provides a summary of deviations in the present analysis from the 2020 study.

A note on terminology in this report: **Scenario** refers to the single vehicle electrification Scenario (EV Scenario), which is compared to a BAU scenario based on the national defaults in the MOVES3 model. **Case** refers to the different electrification Cases describing options for the future national electric grid. When resolving the different impacts from the upstream and downstream emissions according to light- and heavy-vehicles, these vehicle categories are referred to as **Classes**. The mixture of all these different elements, in addition to different possible values of the discount rate, are all presented in output from this analysis.

3. Vehicle Fleet BAU and Scenario Modeling

Task 1 focused on developing the BAU and Scenario models for the national vehicle fleet. These models for the on-road vehicle fleet are the basis for the energy consumption and emissions expected with and without the advancement of EVs[13] considered here. Specifically, this work determines the vehicle categories considered, the sales fractions for EVs under the Scenario for each vehicle category, and the resulting penetration of EVs into the total national vehicle fleet. This is needed for comparison of EV and for establishing baseline emissions by vehicle type, model year, and calendar year and their associated activity (VMT).

3.1. Analysis Years

This study models years:

- 2020
- 2030
- 2040, and
- 2050

Relative to the previous analysis, we have updated the start year 2020 from 2018 to 2020 and maintained the end year at 2050. We added the year 2040 to provide equal increments for use in displaying timeseries and cumulative impacts of the analysis.

3.2. Vehicle Categories

For purposes of this analysis, we consider the entire vehicle fleet to be subject to electrification. We considered the entire vehicle fleet as occurring in one of four vehicle categories.

- Passenger vehicles
- Light heavy-duty trucks
- Medium- and heavy-trucks, and
- School buses

Table 1 provides the definitions used for these categories. These vehicle categories are based on definitions in EPA's MOVES3 vehicle emissions model.[14] Accordingly, Table 2 defines the vehicle types ("sourceTypeID") and regulatory classification ("RegClassID") mapping used in the MOVES3 model.

13 Note that the scope of this analysis was determined to focus exclusively on battery electric vehicles (BEV), excluding traditional hybrid, plug in hybrid (PHEV), and other zero emission vehicle (ZEV) technologies such as hydrogen fuel cell vehicles (FCEV). This strategy was selected to be simpler and cleaner for messaging and presentation of results. For example, this approach avoids complications of both down- and upstream emissions from hybrids and characterization of upstream emissions for H2 fuel, which varies widely depending on feedstock, and highlights the benefits of BEVs over PHEVs which are likely to become disfavored under pushes for increasing decarbonization.

14 https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves

Table 1. Scenario Vehicle Category Definitions.

Vehicle Type ID	Description	Notes
1	Passenger Vehicles	Defined as MOVES vehicle types (sourceTypeID) 11, 21, 31, and the part of 32 that are not Class 2b or 3. Note that there are some Class 2b3 passenger trucks (veh type 31). These vehicles are included in Type 1.
2	Light Heavy Trucks Class 2b-3 that are not school buses or passenger trucks	Defined as all vehicles in MOVES' new regulatory class 41 (RegClassID=41) that are not school buses (MOVES sourceTypeID=43) or Passenger Trucks (sourceTypeID=31)
3	Medium-Heavy and Heavy-Heavy Trucks and Buses, Class 4-8 that are not school buses.	Defined as all MOVES RegClassID=42-49 that are not sourceTypeID=43.
4	School Buses (all)	Defined as all school buses of any size (MOVES vehicle type 43; all regClassIDs)

Table 2. MOVES3 Source Type Definitions.[15]

		Source Use Types												
		Motorcycles	Passenger Cars	Passenger Trucks	Light Commercial Trucks	Other Buses	Transit Buses	School Buses	Refuse Trucks	Short-Haul Single Unit Trucks	Long-Haul Single Unit Trucks	Motor Homes	Short-Haul Combination Trucks	Long-Haul Combination Trucks
Regulatory Classes		11	21	31	32	41	42	43	51	52	53	54	61	62
MC	10	X												
LDV	20		X											
LDT	30			X	X									
LHD2b3	41			X	X			X	X	X	X	X		
LHD45	42					X	X	X	X	X	X	X		
MHD67	46					X	X	X	X	X	X	X	X	X
HHD8	47					X	X	X	X	X	X	X	X	X
Urban Bus	48						X							
Gliders	49													X

3.3. BAU Fleet Modeling

All national fleet and activity data for the baseline and BAU scenario is based on data in US EPA's MOVES3 model. MOVES3 is now the official version of MOVES, posted to the Federal Register and approved for official use in January 2021.

15 These definitions and tables are provided in, "Population and Activity of Onroad Vehicles in MOVES3", EPA-420-R-20-023, November 2020. See Table 2-7. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1011TF8.pdf

Notable changes to MOVES3 relative to MOVES2014b include updates to vehicle miles travelled (VMT) and vehicle population inputs with newer historical data from FHWA and updated forecasts from DOE.[16] Multiple pollutant emission rates from different vehicle and fuel types have been updated, as has fuel supply information. Some differences in vehicle types and classification scheme are included. Notably, MOVES3 incorporates changes resulting from the Heavy-Duty Greenhouse Gas Phase 2 rule and the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule. (The SAFE rule was repealed December 20, 2021.[17]) MOVES3 also continues to model all-electric passenger cars as having zero penetration nationally. EPA states this is due to EV penetration varying geographically with MOVES unable to capture this variation at the national scale.[18]

This study includes a single, national vehicle fleet for the BAU and another for the Scenario. The BAU is based on modeling with MOVES3. The default MOVES3 fleet is modeled for the 48 contiguous U.S. states plus the District of Columbia, with results at a national scale.[19] The BAU fleet uses MOVES' default values of VMT, vehicle age distribution, and population by MOVES vehicle types, which are combined into the four Scenario vehicle types, as described in Section 3.2.

We also used the same MOVES simulation to determine the BAU levels on on-road (downstream) emissions for all vehicles across the US. In this case, downstream includes criteria and GHG emissions from both exhaust and evaporative processes. It also includes fugitive $PM_{2.5}$ emissions from brake and tire wear. This is discussed in Section 4.1.

Table 3. BAU Vehicle Populations.

Vehicle Type ID	Year			
	2020	2030	2040	2050
1	260,470,263	275,236,460	286,075,820	298,109,711
2	6,447,695	6,269,072	6,609,708	7,575,780
3	9,480,537	10,981,869	12,604,199	14,916,760
4	484,750	538,782	604,119	700,740
Grand Total	276,883,245	293,026,184	305,893,846	321,302,991

3.4. Scenario Fleet Modeling

3.4.1. Zero Emission Sales Trajectories for Light, Medium, and Heavy-Duty Vehicles

Relative to the previous analysis, this study uses different vehicle categories (Section 3.2) and BAU fleet and activity assumptions from MOVES3 (Section 3.3) It also includes a more aggressive approach to vehicle electrification. The objective is to hit 100% ZEV sales by 2035 for passenger vehicles (less than 8,500 lbs. GVWR) and by 2040 for the rest of the fleet (i.e., above 8,500 lbs. GVWR). This study continues to use Battery Electric Vehicles (BEVs) as a marker for zero emission technologies, as we anticipate the market for most ZEVs will be addressed through EVs. Also, for simplicity as before it substitutes EVsfor traditional vehicles (internal combustion engine vehicles; ICEVs) one-to- one, excluding any replacement of existing EVs.

This section discusses the EV sales targets used in the remainder of the study.

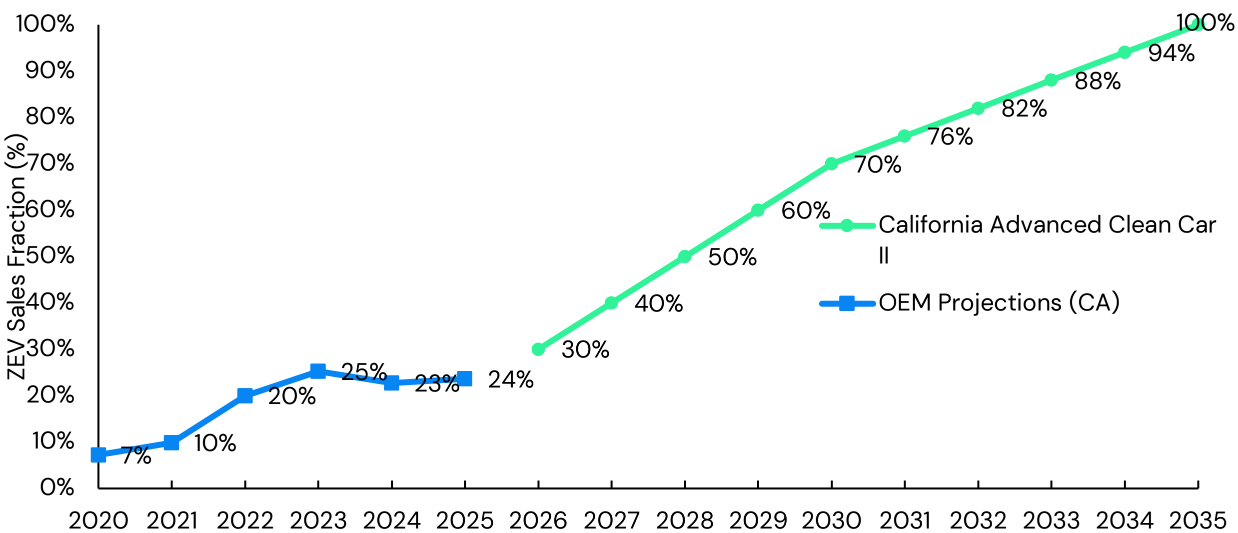
16 EPA-420-F-20-050, November 2020. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1010M06.pdf.
17 https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-revise-existing-national-ghg-emissions
18 EPA-420-R-21-012. Available at: https://www.epa.gov/sites/production/files/2021-04/documents/420r21012.pdf
19 Throughout this analysis, the focus is on the 48 contiguous U.S. states (excluding Hawaii and Alaska) plus DC. This is because the EPA's COBRA model, used to estimate public health impacts, does not include impacts in Alaska, Hawaii, or the U.S. territories.

Light Duty Vehicles

According to latest data from Alliance for Automotive Innovation, the national sales of light duty ZEVs have been increasing rapidly over the past two years. More than 168,000 zero emission vehicles (battery, plug-in hybrid, and fuel cell electric vehicles, BEV, PHEV, and FCEV) were sold in the second quarter of 2021, a 33 percent increase over the first quarter and 122,000 units more than the same period in 2020. For the months of April – June 2021, ZEVs represented 3.8 percent of the overall market, the highest for any quarter to date. The data reveals a ZEV market share of approximately 3.5% in 2021 as compared to 2.5% in 2020[20].

In the meantime, California is proposing the Advanced Clean Cars 2 regulation which will set a ZEV sales target of 100% by 2035. In doing so, California Air Resources Board (CARB) have analyzed sales projection from various manufacturers for model years 2021 through 2025 and conducted a cost analysis to determine their initial ZEV sales stringencies for 2026 and subsequent model years as shown in Figure 1 below.[21]

Figure 1 Proposed ZEV stringencies under California Advanced Clean Cars 2



Considering that the market share of ZEVs is much lower at national level (e.g., 2.5% in 2020), we developed a separate curve that starts at lower levels than California in earlier years and eventually meet 100% ZEV sales target by 2035. As illustrated in Figure 2, we started with historical national ZEV market share in 2020/2021 and employed a logit function that join a California's ZEV sales target of 70% by 2030[22] and ultimately reaches 100% target by 2035. The use of logit function is in line with the diffusion of innovations' theory. Under this theory, the transition to a new technology can be characterized by an early emergent phase in which growth appears small, but then it gathers momentum as the technology become established and enter a phase of widespread diffusion characterized by exponential rates of growth. This is followed by a culmination phase when the pace of diffusion slows as the new technology stabilizes and its deployment begins to saturate. In the case of zero emissions vehicles, it is expected that majority of the market to transition to ZEV in the next 10 years at a rapid rate. However, it is expected that high mileage vehicles (e.g., long-distance commuters) in

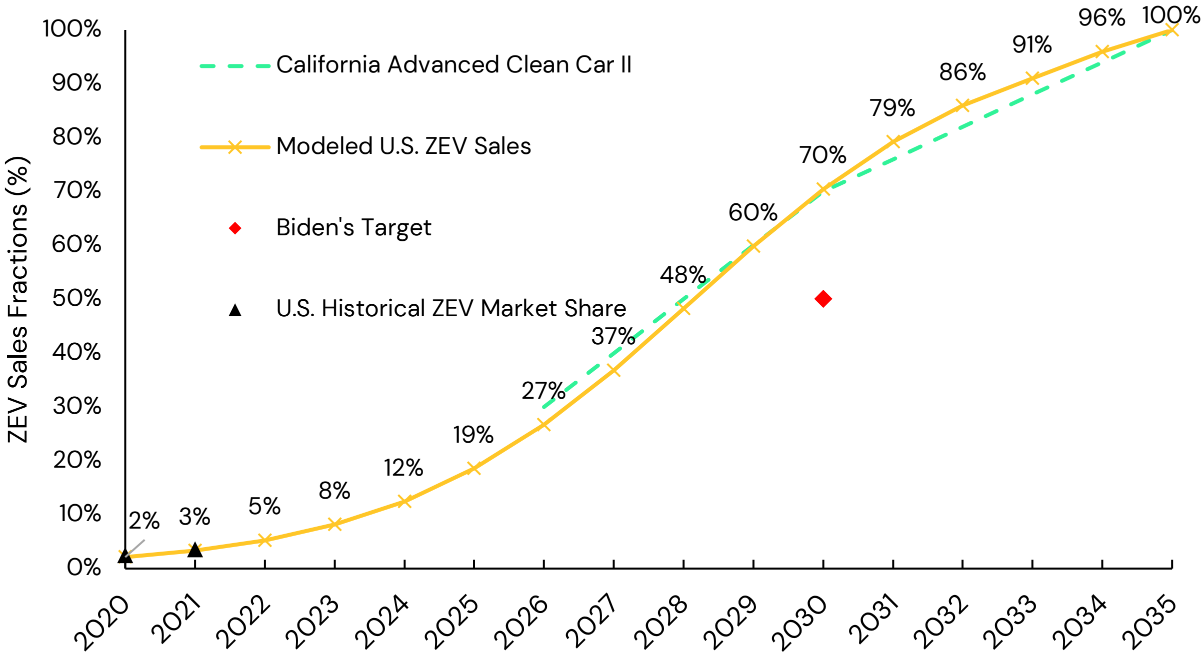
20 https://www.autosinnovate.org/posts/papers-reports/Get%20Connected%20Electric%20Vehicle%20Quarterly%20Report%20Q2%202021.pdf

21 We note that CARB's initial proposal is not as ambitious as its own modeling suggests is needed, and far behind the cost parity estimates of Bloomberg and others.

22 While Biden's administration has set a target of 50% electric vehicle sales share in 2030, hitting the 100% ZEV target by 2035 would require higher market share in 2030.

regions with lack of sufficient infrastructure availability or other factors to slow down the rate of penetration in the last couple of years before the 100% of sales transition to ZEV.

Figure 2 Light Duty Zero Emission Vehicle Sales Trajectories



Medium and Heavy-Duty Vehicles

In 2020, California adopted the Advanced Clean Truck (ACT) regulation[23] which sets the first in the nation ZEV sales requirements for MD/HD vehicle manufacturers. Washington, Oregon, Massachusetts, New York, New Jersey have now adopted the California ACT rule.

As shown in Table 4, the ACT sales requirements starts with 2024 model year medium and heavy-duty vehicles, and the stringency increases through 2035 model year vehicles. These sales requirements were developed based on the operational characteristics of various truck vocations, the cost and availability of zero emission MD/HD trucks, as well as the timeline for infrastructure buildout (e.g., line haul trucks need state/national network of infrastructure, whereas for return to base trucks – e.g., delivery trucks – the charging infrastructure might be limited to truck depots). Upon the adoption of the ACT regulation in California, 15 states and the District of Columbia announced a joint memorandum of understanding (MOU)[24], committing to work collaboratively to advance and accelerate the market for electric medium- and heavy-duty vehicles, with the goal of reaching 100 percent of all new medium- and heavy-duty vehicle sales to be zero emission vehicles by 2050 with an interim target of 30 percent zero-emission vehicle sales by 2030.

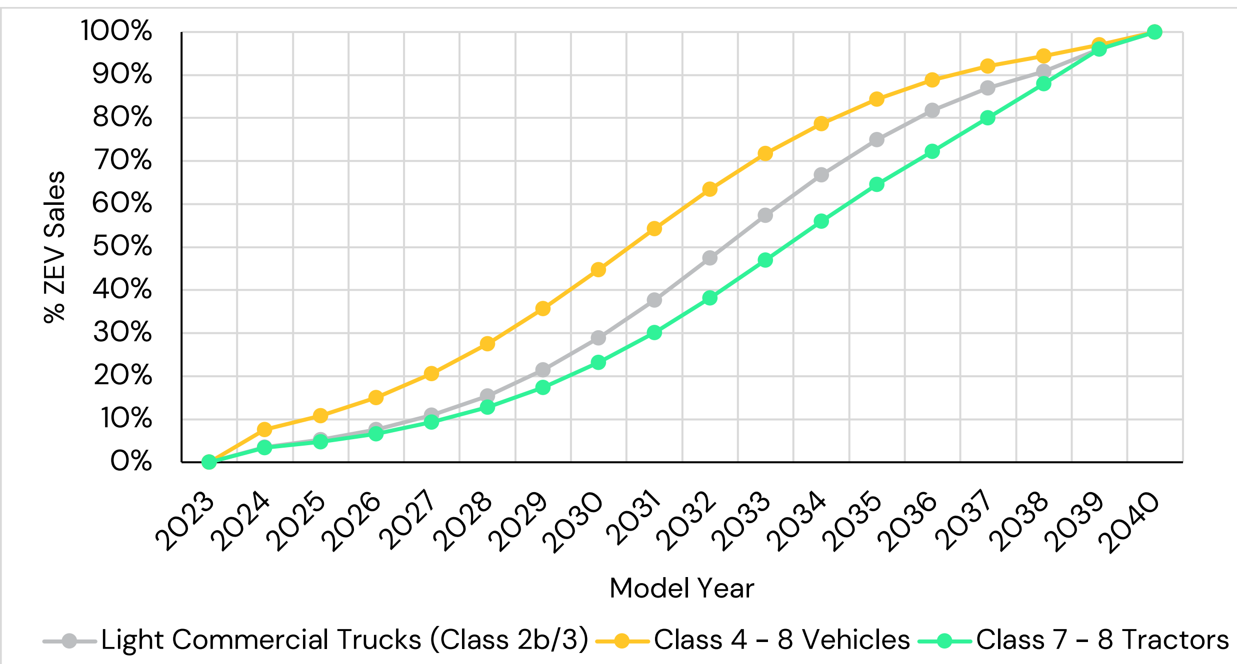
23 https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks
24 https://ww2.arb.ca.gov/sites/default/files/2020-07/Multistate-Truck-ZEV-Governors-MOU-20200714.pdf

Table 4 ACT manufacturers ZEV sales requirement.

Model Year	Class 7-8 Tractor	Class 4-8 Vocational	Pickup/Vans
2024	5%	9%	5%
2025	7%	11%	7%
2026	10%	13%	10%
2027	15%	20%	15%
2028	20%	30%	20%
2029	25%	40%	25%
2030	30%	50%	30%
2031	35%	55%	35%
2032	40%	60%	40%
2033	40%	65%	45%
2034	40%	70%	50%
2035	40%	75%	55%

To project the ZEV market share for medium- and heavy-duty vehicles with the goal of achieving 100 percent ZEV sales by 2040, we started with the ACT ZEV sales requirements and utilized a logit function to develop trajectories for sales of various MD/HD vehicles classes as illustrated in Figure 3.

Figure 3 MD/HD Sales Trajectories



As shown in Figure 3, the sales trajectory of zero emission light commercial, single unit and combination trucks, starts in 2024, follows an S-shaped curve, and reaches 100 percent by 2040. Between 2024 and 2030, the ZEV sales percentage for these three categories are similar to California's ACT requirements, and they diverge between 2030 and 2040 as the new curves reach for 100% ZEV sales by 2040, while California's requirements plateau in 2035 at 40-75 percent. While California's ACT requires 55% of Class 2b-3 vehicle sales to be ZEV by 2035, the diffusion curves illustrated in Figure 3 calls for 75% of sales to be zero emission by that time. This is also consistent with the California's proposed advanced Clean Fleet (ACF) regulation[25] which proposes to increase the sales of medium and heavy-duty ZEVs beyond the ACT requirements.

School Buses

For school buses California's Innovative Clean Transit (ICT) regulation[26] requires large transit agencies to have 25 percent, 50 percent, and 100 percent of their new purchases to be zero emission starting from 2023, 2026, and 2029, respectively. These categories are "beachheads" for zero emission technology adoption in the MD/HD space and while the proposed sales percentages seem to be very ambitious, these trajectories are consistent with and in certain cases even less stringent than the Truck and Engine Manufacturer Association (EMA) proposal.[27]

These values are consistent with the previous analysis for target years but use a gradual increase rather than the step functions assumed previously.

Summary

Table 5 below provides detailed ZEV sales percentages for each vehicle category and calendar/model year.[28]

25 https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets
26 https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2018/ict2018/ictfro.pdf
27 Those are: 100 percent of new school buses and municipal step vans to be zero emission by 2023; 100 percent of new public utility vehicles and yard tractors to be zero emission by 2024; 100 percent of non-airport shuttle buses and new step vans to be zero emission by 2025; and 100 percent of new refuse haulers to be zero emission by 2026. https://www.arb.ca.gov/lists/com-attach/142-act2019-WjAAY1A1AAwEbwdm.pdf
28 Because this considers new vehicle sales only, model year and calendar year sales targets are identical.

Table 5 ZEV Sales percentage by model year

Vehicle Type ID	1	2	3	4
Description	Passenger	Light Commercial Trucks (Class 2b/3)	Class 4-8 HDV	School Buses
Year				
2020	2%	0%	0%	0%
2021	3%	0%	0%	3%
2022	5%	0%	0%	10%
2023	8%	0%	0%	25%
2024	12%	4%	4%	30%
2025	19%	5%	5%	40%
2026	27%	8%	8%	50%
2027	37%	11%	11%	63%
2028	48%	15%	15%	76%
2029	60%	21%	20%	100%
2030	70%	29%	28%	100%
2031	79%	38%	36%	100%
2032	86%	48%	46%	100%
2033	91%	57%	55%	100%
2034	96%	67%	65%	100%
2035	100%	75%	73%	100%
2036	100%	82%	80%	100%
2037	100%	87%	86%	100%
2038	100%	91%	90%	100%
2039	100%	96%	96%	100%
2040	100%	100%	100%	100%
2041	100%	100%	100%	100%
2042	100%	100%	100%	100%
2043	100%	100%	100%	100%
2044	100%	100%	100%	100%
2045	100%	100%	100%	100%
2046	100%	100%	100%	100%
2047	100%	100%	100%	100%
2048	100%	100%	100%	100%
2049	100%	100%	100%	100%
2050	100%	100%	100%	100%

3.4.2. EV Penetration Modeling

We then used a fleet modeling approach to determine the penetration of electric vehicles into the national vehicle fleet. This estimates the share of EVs in the national fleet following their introduction via new vehicle sales.

EV fleet penetration for each of the four vehicle categories was calculated using the ZEV sales fractions and the national BAU vehicle population by vehicle category, fuel type, and model year in each of the four simulated years (2020, 2030, 2040, and 2050). EVs were assumed to have the same scrappage schedule as non-EV vehicles. Additionally, EVs were assumed to replace non-EV fuel type vehicles proportional to the makeup of non-EV fuel type vehicles. For example, if the BAU fleet of model year 2026 vehicles consisted of 75% gasoline and 25% diesel vehicles, and the sales fraction of EVs is 27%, the Scenario fleet of model year 2026 vehicles could consist of 27% EVs, with the EVs replacing 27% × 75% gasoline vehicles and 27% × 25% diesel vehicles. These fuel distinctions are then propagated through the calculations since the Energy Efficiency Ratio (Section EER) is dependent on the fuel and also incorporates the vehicle's in-use duty cycle.

Fleet aggregation calculations were performed for the four analysis years. The appropriate sales ratio was assigned to each row of this inventory by model year and vehicle type grouping. The total number of EVs was then calculated by multiplying the appropriate sales ratio by the population for each sub-group and summing. In the Scenario fleet, the number of non-EV vehicles were decremented by the number of EVs that replaced them.

3.5. Results

Figure 4 shows the makeup of the overall fleet, under the BAU and EV Scenario. Figure 5 shows the same data, but with additional stratification by vehicle type.

Figure 4: BAU Fleet and Modified Fleet

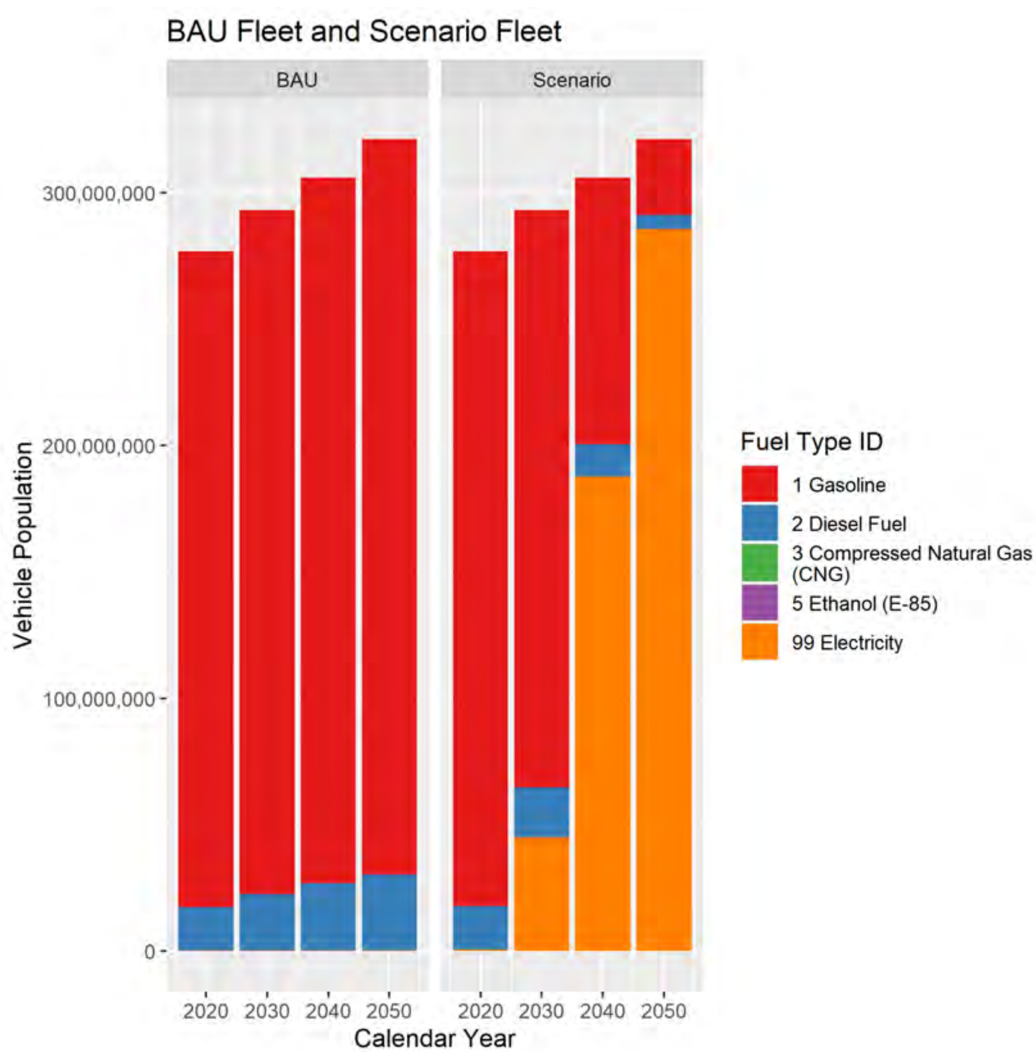
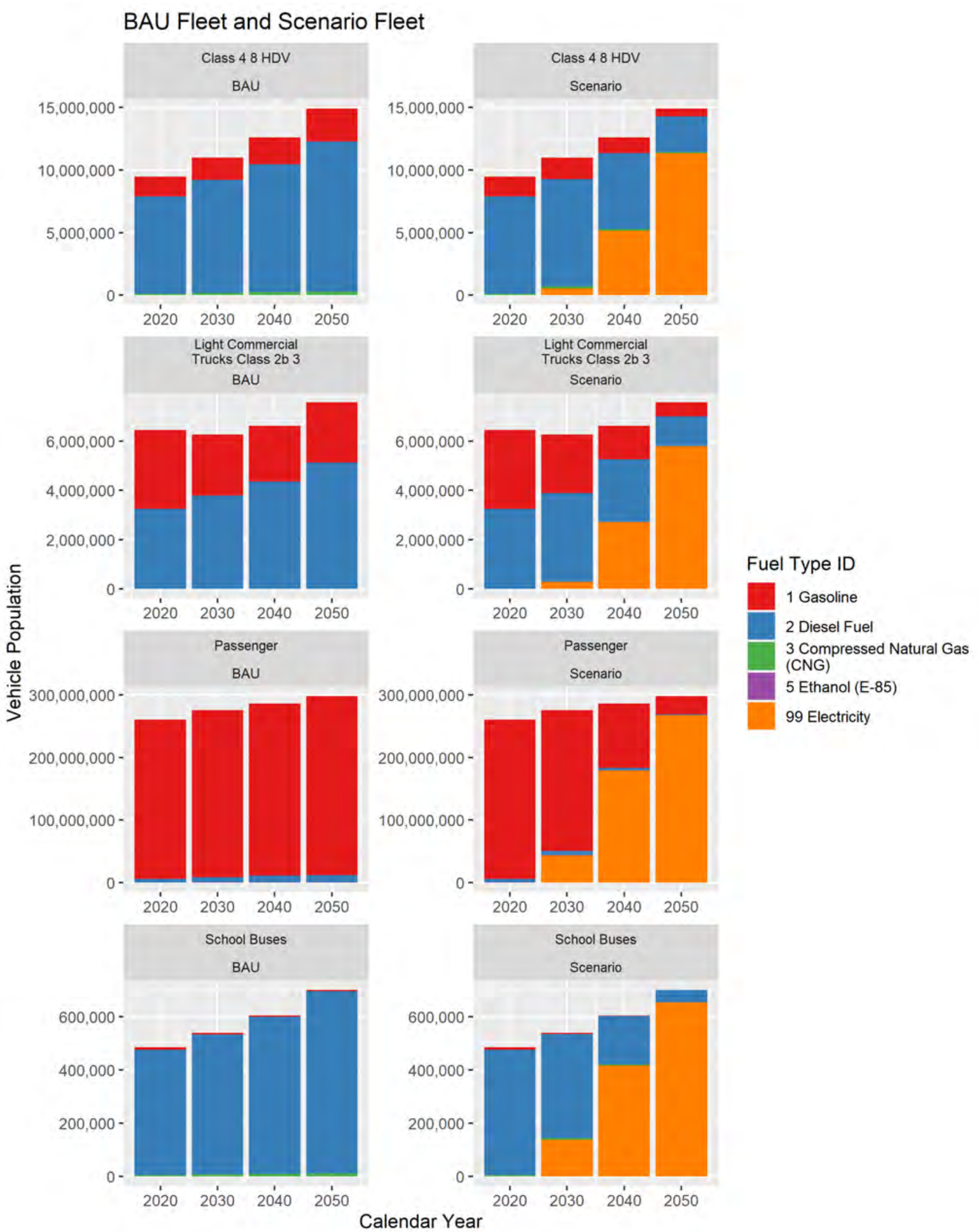


Figure 5: BAU Fleet and Modified Fleet, Stratified by Vehicle Type Group



4. BAU and Scenario Emissions Modeling

ICF modeled emissions nationally under both the BAU and Scenario. The modeled emissions included direct PM from:

- $PM_{2.5}$ exhaust
- $PM_{2.5}$ brake wear (BW)
- $PM_{2.5}$ tire wear (BW)

PM is the focus as it is the basis for health modeling to be conducted under Task 3. In addition, we computed emissions of:

- nitrogen oxides (NOx)
- ammonia (NH_3)
- sulfur oxides (SO_2), and
- volatile organic compounds (VOC).

And greenhouse gases (GHGs) as:

- CO_2e

determined from:

- carbon dioxide (CO_2)
- methane (CH_4), and
- nitrous oxide (N_2O).

combined using the global warming potential values currently in MOVES3, which are those from IPCC's AR4.[29]

This modeling included both downstream processes – pollutants released directly from the vehicle fleet- and upstream emissions. The downstream emissions include exhaust, evaporative, and fugitive emissions processes, such as brake and tire wear. Notably, while EVs release no tailpipe emissions, they continue to produce fugitive emissions. Downstream emissions are determined with the MOVES3 model.

Upstream emissions include emissions associated with conventional ICEV fuel extraction, transport, refining, and related emissions and emissions associated with both the feedstock and fuels used in electricity generation (via electric generating units; EGUs). For this analysis, we modeled *changes* in upstream emissions associated with changes in activity (reduced ICEV fuel consumption; increased electricity demand to power additional EVs) driven by the Scenario. Upstream emissions are determined from a combination of models, including emission factors derived from the Argonne National Laboratory's latest Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET2021[30]). Upstream electricity production is strongly associated with the power production "grid mix". This analysis considers two potential "cases" for the future electric grid:

1. *The Base electricity generation Case*: A more business-as-usual projection for the grid, based on the Bloomberg New Energy Outlook (BNEO) 2019 analysis employed by the 2020 study.
2. *The Non-Combustion electricity generation Case*: A more ambitious renewables projection, with a heavy emphasis on emissions free, renewables, such as from wind and solar.

The IPM model was employed to determine the grid mix to meet the Non-Combustion Case.

There will be both upstream and downstream emissions even after 100 percent ZEV sales have been reached due to the lag in time between new EV sales and the turnover of the overall fleet population, and the fugitive emissions that emanate from ZEVs. Furthermore, some emissions associated with crude oil sourced outside of

29 E.g., https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf.
30 https://greet.es.anl.gov/

the U.S. are emitted outside the boundaries of the continental US. We consider changes in domestic criteria emissions, but present both domestic and global emissions of GHGs.[31]

There are also emissions from the refining and electricity generation sectors that are independent of those used for vehicles but appear in the BAU for these sectors. This study also estimates a national BAU estimate of the relevant upstream emission components. Resulting net emissions are determined by combining the changes in upstream emissions resulting from the Scenario with the BAU estimate of emissions from the sectors. Not all the upstream emissions are related to the on-road fleet. This analysis is not intended to simulate a marginal grid mix that would differ by sources. Thus the “BAU” emissions curve under the Non-Combustion Case should also be reduced below that of the Base Case due to the cleaner grid, regardless of any additional load from EVs. This assumes that the entire grid is becoming cleaner under the Non-Combustion Case. To demonstrate this difference, we show the Non-Combustion Case results two ways. The first maintains the Base Case level of emissions independent of any new EV load, then adds emissions from new EV load assuming the power for these is met with the Non-Combustion grid. This demonstrates impact of new EV load with a very clean grid, but only applies the change to the new load, roughly consistent with the approach used in the 2020 study. The second uses the Non-Combustion Case electric grid emission factors for the baseline load and the additional load from new EVs. This has the effect of dramatically reducing both the emissions from the base load on the grid and emissions associated with new load from EVs and is consistent with using an “average grid” approach but show impacts to the grid not directly attributed to EVs.

4.1. Downstream Emissions Modeling

4.1.1. MOVES BAU Modeling

To model the BAU downstream emissions, ICF used data from EPA’s current mobile source emissions model, MOVES3. This modeling is the same as that used to determine the BAU fleet and described in Section 3.3. We split national total emissions and energy consumption into the four vehicle categories and four fuel types. All emission processes were considered for each pollutant. That is, running, starting, evaporative, extended idle, and APU were all modeled for the relevant vehicle types and pollutants. These were aggregated into total emissions per year for each decade from 2020 to 2050.

All exhaust processes were computed with a single, national MOVES3 simulation. This used the national scale approach, with the 48 states plus DC combined in the analysis and used annual preaggregation for all four modeled years. The simulations for evaporative emissions were similar, but due to the very long run times for these simulations, only January and July were simulated for each of the modeled years. The annual emissions were then computed by assuming these two summer and wintertime emissions each applied for half the year.

4.1.2. Scenario Fleet Modeling

To compute the emissions under the national Scenario, we used the BAU vehicle populations and emissions to determine per-vehicle, annual emissions and energy consumption. Emissions are tracked by pollutant, fuel type, vehicle type, decade, and model year.

For pollutants excluding brake wear and tire wear, electric vehicles produce no downstream emissions. Thus, to compute the emissions under the Scenario, we began with the outputs of the Scenario fleet modeling (Section 3.4) to determine the population by vehicle and fuel type under the Scenario (including EVs). For the ICEVs remaining in the fleet, we calculated the product of the Scenario fleet populations and the BAU annual

31 Only crude/feedstock emissions are assumed to occur outside of the US. All other upstream components (refining and transport for traditional fuels and electricity production) are assumed to occur domestically and within the bounds of this study. .

emissions, essentially zeroing out all emissions for internal combustion engine vehicles (ICEVs) that were displaced by EVs.

We then added back in the fugitive emissions associated with $PM_{2.5}$ brake and tire wear emissions from these new EVs. Following the approach implemented by the CARB, we assumed that EV brake wear emissions are half that of the ICEVs they replace, and that there are no changes to the tire wear emission rates.[32] We determined ICEV brake and tire wear annual emissions as above for exhaust emissions, applied these CARB-based scaling factors, and added these to the Scenario downstream emission totals.

4.1.3. Resulting Downstream Emission Changes

Table 6 and Table 7 show the changes in national-level, on-road, downstream emissions from the implementation of the Scenario. Note in Table 7 that all values are reductions, and thus not shown here as negative values. Figure 6 shows these same changes graphically for three pollutants. Please note that the scale for each of the three pollutants differs.

Table 6. Total Downstream Emission Reduction Nationwide, tons per year

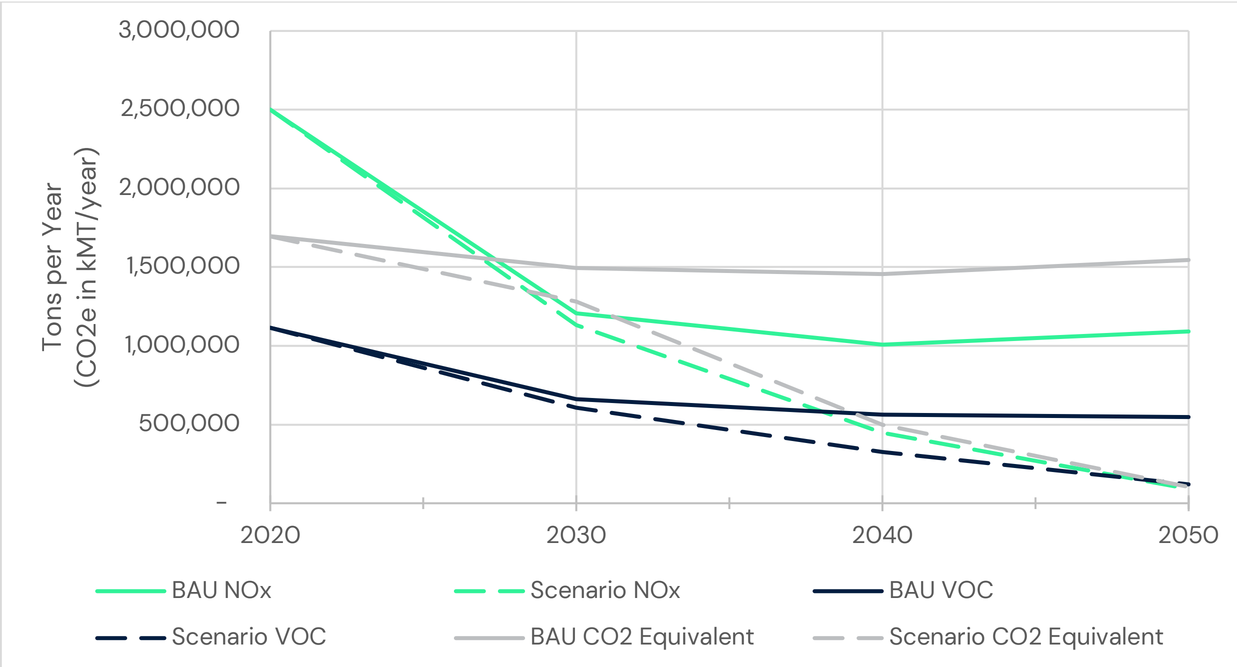
Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO_2 Equivalent	NH_3
2020	284	10	473	24	1,653,148	101
2030	74,398	1,309	53,395	3,547	234,692,666	14,480
2040	559,853	5,529	236,899	17,106	1,054,670,878	65,233
2050	998,808	8,134	427,469	25,851	1,587,872,845	100,265

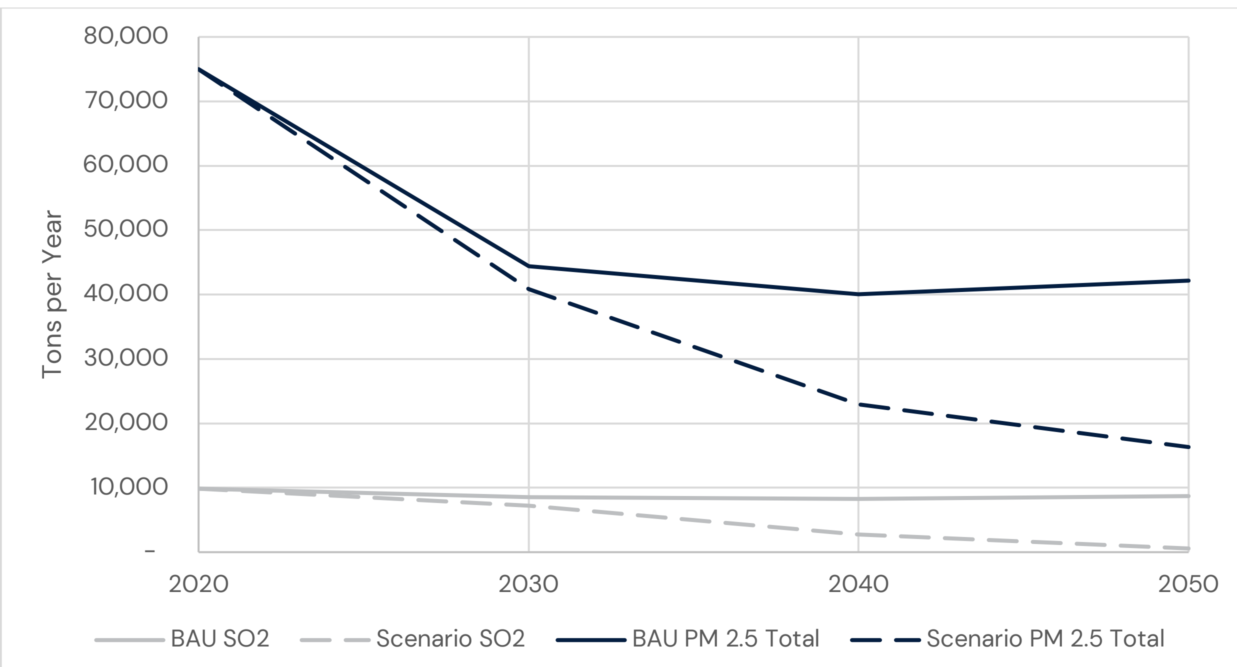
Table 7. Total Downstream Emission Reduction Nationwide, percent

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO_2 Equivalent	NH_3
2020	0	0	0	0	0	0
2030	6	15	8	8	14	15
2040	56	67	42	43	66	65
2050	92	93	78	61	93	93

32 https://ww2.arb.ca.gov/sites/default/files/2021-03/emfac2021_volume_3_technical_document.pdf. Also confirmed in email from CARB, "Currently, we're planning to follow a similar approach to what we modeled in ACT regarding brake and tire wear PM emissions, where a ZEV will see 50% reduced brake wear PM and equivalent tire wear PM to their combustion-powered counterparts. This is due to the impact of regenerative braking decreasing the usage of the friction brakes. We do not have any plans to update these assumptions at the moment as we have not seen any data beyond what we cited in ACT." From William Barrett to Seth Hartley, December 20, 2021.

Figure 6. Downstream emission trends for the modeled years, BAU and Scenario (all units are short tons per year except CO2e, shown in thousands of metric tons per year)





In addition to the emissions reductions, the EV scenario would result in dramatic reductions in the amount of fossil energy consumed. Table 8 shows the reductions in fuel consumed by on-road vehicles (only). This excludes any change in energy that occurs upstream, such as to produce these fuels. Units are in millions of gallons, or millions of SCF for CNG.

Table 8. Total National reductions in energy consumed by vehicles (Downstream energy consumption only), millions of gallons (millions of SCF for CNG)

Year	Gasoline (Mgal)	Diesel Fuel (Mgal)	CNG (Mscf)	E-85 (Mgal)
2020	162	7	0	0
2030	19,610	3,809	8,403	46
2040	74,880	28,281	74,566	195
2050	105,696	48,468	134,250	271

4.2. Upstream Emissions Modeling

The changes in upstream (well-to-tank) life cycle emissions due to reduced consumption of transportation fuels due to the Scenario were based on calculations using a series of models. We determined upstream emission factors from refining for VOC, NO_x, PM_{10}, $PM_{2.5}$, SO_x, and GHG. Inputs included the GREET model, custom analysis of grid mix using the IPM model, the energy consumption of conventional ICEVs from MOVES, and for EVs based on their BAU counterparts with information from CARB. The next sections discuss these.

4.2.1. EER

We used energy efficiency ratios from CARB along with energy consumption rates from MOVES3 to estimate the amount of additional energy required by the electric grid to fuel EVs.

Along with the BAU emissions and fleet information, we extracted from MOVES total energy consumption, in J, again for the BAU fleet subject to electrification. As with emissions, this value is normalized to the vehicle population to produce the BAU energy consumption rate by vehicle, age, and fuel type. The additional electricity consumed was calculated according to the energy consumption of the type of vehicle the EV replaced. That is, if a gasoline passenger vehicle is replaced with an EV, the energy consumption of the EV was assumed to equal that of the gasoline vehicle.

To account for the energy efficiency differences from ICEVs and EVs, we included the increased efficiency of electric engines over internal combustion – such as the energy lost to heat and never converted to mechanical energy in ICEVs – via Energy Efficiency Ratios (EER) for each vehicle and fuel type. For this study, we used the CARB's EERs,[33] which were assigned to the four vehicle types considered here. We also accounted for a 10% difference in the EER of diesel engines relative to gasoline and CNG. Table 9 shows these factors.

Table 9. Selected EER Values by vehicle category, for electricity with respect to the base fuel

Vehicle type ID	Diesel	CNG/ Gasoline/ E85
1	3.1	3.4
2	5.0	5.6
3	5.0	5.6
4	5.0	5.6

33 As included in the leftmost column of Table 5 of CARB's LCFS regulation (page 73), available at: https://ww2.arb.ca.gov/sites/default/files/2020-07/2020_lcfs_fro_oal-approved_unofficial_06302020.pdf.

4.2.2. GREET

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET2021) model, developed by Argonne National Laboratory[34] is an analytical tool that simulates the fuel lifecycle, also known as well-to-wheels (WTW), energy use and emissions output of vehicle/fuel systems. GREET model is widely recognized as a reliable tool for life cycle analysis (LCA) of transportation fuels and has been used by several regulatory agencies (e.g., US Environmental Protection Agency for the Renewable Fuel Standard (RFS) and California Air Resource Board for the Low-Carbon Fuels standard (LCFS)) for evaluation of various fuels. We used GREET only for the upstream (well-to-tank) emissions, which do not include the tailpipe emissions generated from burning the fuels.

The upstream emissions of liquid fuels (i.e., gasoline, diesel, E85) include crude extraction and recovery, feedstock, refining, transportation, and distribution of the final product. The gasoline in the U.S. contains 10% ethanol, thus the upstream emissions of corn ethanol production in the U.S. were included in the calculations as well. For E85, we assumed a gasoline-ethanol blend with 83% ethanol[35]. Finally, for CNG, the upstream emissions include the extraction and recovery of fossil natural gas, gas processing, transportation and compression.

The upstream emissions factors representing electricity generation from the utility grid associated with powering EVs were also included and also based on GREET. The original GREET emission factors were based on EPA's Emissions and Generation Resource Integrated Database (eGRID) and allocated according to the average resource mix used in the U.S. grids. For this analysis, we have created two new grid mix Cases (described in Section 4.2.3). We developed emission factors in GREET corresponding to these mixes. Table 11. National, upstream electricity emission factors determined with GREET Table 11 summarizes these factors. This analysis does not model marginal power mixes.

Table 10 and Table 11 show the upstream fuel and electricity emission factors. Upstream fuel includes emissions from extraction, refining, transport, and distribution. Upstream electricity generation emission factors include contributions from both feedstock and fuels. Because of this, emission factors can be non-zero even when the electricity mix represents only non-combustion fuel mix.

Table 10. Total upstream refining emission factors from GREET, in g/gal or g/MJ (for CNG)

Pollutant	Diesel				Gasoline			
Year	2020	2030	2040	2050	2020	2030	2040	2050
VOC	0.946	0.944	0.942	0.945	3.296	3.287	3.285	3.287
NOx	2.294	2.277	2.258	2.330	2.840	2.759	2.734	2.801
PM_{10}	0.168	0.165	0.162	0.166	0.319	0.312	0.307	0.312
$PM_{2.5}$	0.142	0.141	0.139	0.144	0.214	0.209	0.207	0.212
SO_2	0.611	0.600	0.578	0.605	0.803	0.776	0.742	0.778
CO_2e	2097.5	2031.5	2005.7	2031.1	2593.6	2512.2	2477.6	2507.8
	E-85				CNG			
VOC	4.363	4.307	4.303	4.300	0.010	0.010	0.010	0.010
NOx	6.105	5.561	5.536	5.503	0.039	0.038	0.038	0.038
PM_{10}	1.075	1.034	1.029	1.018	0.001	0.001	0.000	0.000
$PM_{2.5}$	0.421	0.387	0.385	0.381	0.001	0.000	0.000	0.000
SO_2	1.719	1.572	1.544	1.466	0.012	0.012	0.011	0.011

34 https://greet.es.anl.gov/
35 https://afdc.energy.gov/fuels/ethanol_e85_specs.html

CO_2e	4121.2	3909.1	3872.9	3811.5	16.3	15.9	15.1	15.1

Table 11. National, upstream electricity emission factors determined with GREET, in g/kWh, for the two upstream electricity cases

Pollutant	Case 1: Base Case					Case 2: Non-Combustion Case			
Year	2020	2023	2030	2040	2050	2020	2030	2040	2050
VOC	0.048	0.046	0.040	0.038	0.034	0.048	0.025	0.000	0.000
NOx	0.300	0.292	0.246	0.220	0.158	0.291	0.113	0.001	0.001
PM_{10}	0.044	0.045	0.036	0.031	0.015	0.043	0.010	0.000	0.000
$PM_{2.5}$	0.025	0.025	0.021	0.019	0.012	0.025	0.009	0.000	0.000
SO_2	0.251	0.260	0.204	0.172	0.064	0.246	0.040	0.000	0.000
CO_2e	433.7	423.2	363.4	330.0	252.7	432.5	189.0	0.293	0.273

Note that Emission Factors of fuel combustion for Stationary Applications are the same between GREET2019 and GREET2021. However, there is a decrease in the Power Plant Energy Conversion Efficiency assumption between GREET2019 and GREET2021 that leads to a difference in emission factors for some pollutants relative to the 2020 analysis, even when the Case definitions are identical.

4.2.3. Electric Grid Cases and IPM

This analysis explored the potential impacts on upstream electrification of two potential future Cases for the electric grid. These 2 scenarios for upstream electrification were defined at the beginning of Section 4.

The Base Case was defined based on the "ALA Case" in the previous 2020 analysis. For this, we used the U.S. Energy Information Administration's 2021 Annual Energy Outlook projections (in BkWh) for the years 2020, 2030, and 2040, and converting these values into percentages of grid generation mix for GREET2021 input. The 2050 BkWh projections were taken from the Bloomberg 2020 New Energy Outlook.

The Non-Combustion Case was crafted uniquely for this analysis, based on the potential for a highly renewable grid being considered by several states and the Federal government. President Biden had stated a proposal of sourcing all electricity from carbon-free sources by 2035 (100% by 2035), in a goal to hit economywide net zero by 2050.[36] In California, SB100 set goals of 60% renewable, zero-carbon grid by 2030 and 100% by 2045.[37] New York State's Clean Energy Standard mandates 70% renewable electricity by 2030 and 100% by 2040.[38] We based the Non-Combustion Case on these standards to set goals of 70% clean by 2030 and 100% clean grid by 2035. The definition of "clean" was specified to mean non-combustion-based generating sources only. As such, biomass, RNG, CCS and other such options were not allowed.

To model the feasibility and resulting grid mix of the Non-Combustion Case, we used ICF's proprietary Integrated Planning Model[39] to create national annual projections of generation and emissions in the U.S. IPM is a least-cost optimization capacity expansion model of the North American electric power sector. The model used default assumptions (ISO/RTO/NERC energy and peak demand forecasts, NREL ATB renewable and storage costs, static transmission, all mandatory RPS/CES state-level policies, etc.) We added a constraint forcing a 100% clean grid by 2035 and an interim target of 70% clean by 2030. By 2040, IPM meets demand

36 https://www.bloomberg.com/news/features/2021-02-22/after-texas-blackouts-biden-s-climate- agenda-focuses-on-power-grid.
37 https://ww2.arb.ca.gov/sites/default/files/2021-11/CEC-sp22-electricity-ws-11-02-21.pdf
38 https://www.nyserda.ny.gov/All-Programs/Clean-Energy-Standard
39 https://www.icf.com/technology/ipm

without combustion through a capacity mix of about 60% renewables (mostly solar and wind) and 30% battery storage capacity, with the rest being mostly hydro & nuclear. By 2040, the generation mix is 80% wind and solar, with the remaining 20% coming from mostly nuclear and hydro. The first of these is capacity mix, and the second is generation. Capacity mix includes storage which is not counted in the generation mix. Once the generation mix was specified, it was utilized in GREET2021 as percentages of the national grid mix to specify grid emission factors.[40] Importantly, IPM also specifies emission factors for a portion of the pollutants included here. The factors from IPM and GREET were compared and seen to agree well, however IPM is not a lifecycle model and only considers emissions from the "stack" where full lifecycle (fuel plus feedstock) emissions from GREET are used here. Table 12 shows the grid mix resulting from both Cases, corresponding to the emission factors shown by Table 11.

Table 12. Electricity grid mix corresponding to upstream electricity Case 1, the Base Case, in percent

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydro-electric	Geo-thermal	Wind	Solar	Other
2020	0	40	19	19	0	8	0	9	2	1
2030	0	35	16	14	0	7	1	16	10	2
2040	0	35	13	12	0	7	1	16	15	1
2050	0	43	2	12	0	6	1	22	13	1

Table 13. Electricity grid mix corresponding to upstream electricity Case 2, the Non-Combustion Case, in percent

Year	Oil	Natural Gas	Coal	Nuclear	Biomass	Hydro-electric	Geo-thermal	Wind	Solar	Other
2020	0	41	19	19	1	7	0	9	2	1
2030	0	33	1	16	0	6	1	18	24	1
2040	0	0	0	14	0	6	0	28	51	0
2050	0	0	0	13	0	6	0	27	54	0

4.2.4. Business-As-Usual Levels of Upstream Emissions

BAU emissions for the upstream emission sectors of fuel production and electricity generation are used to place the calculated change in these values in context. This was not included in the previous (2020) analysis, where changes in upstream emissions were presented then compared only to the downstream emissions under the BAU scenario. However, the projected BAU values for criteria pollutants are needed for the health impact modeling. Here we estimate a BAU level of emissions for the same upstream sectors affected by vehicle electrification – ICEV fuel production and electricity generation – and for the same analysis years. Furthermore, the Non-Combustion Case of electrification would modify the entire grid, not just the portion powering EVs. Thus, we also calculate upstream emissions for the entire grid, under this Case. These upstream components against which these changes may be compared and later be incorporated consistently in the health impact modeling.

GREET reports three elements for upstream fuels production:

- Fuels refining

40 Note that this IPM run does not answer the question of whether there is enough capacity on the grid to handle the shift to EVs envisioned by the Scenario. That is, the IPM simulation did not include a load shaping exercise. This work considered only the generation mix and thus the grid's emission factors under the given constraints and the average power assumption that the generation mix for EVs would be the same as the rest of the grid. Thus, the predicted emissions are addressed here, while the question of available infrastructure required to support this increased load due to increased vehicle (and building) electrification is considered beyond this study's scope.

- Fuels transport
- Crude and other feedstock

and two for electricity production:

- Fuel consumption
- Feedstock

To estimate the BAU upstream national inventory in a manner consistent with later health modeling, we began with emissions data within the COBRA model for year 2023. The 2023 COBRA emissions are based on EPA's 2016v1 Air Emissions Modeling Platform, which is a product from the National Emissions Inventory (NEI).[41] ICF scaled these emissions to the analysis years by estimating relative changes in the emissions intensity of the upstream processes based on GREET emission factors and in the relative change in activity based on projections from different resources. US AEO 2021[42, 43] was used to help scale the change in Crude, Refining, and Transport activities for the transportation fuels and for the baseline electricity case scenario for EGUs. The ICF IPM run was the source to quantify the net electric power sector generation activities for the Non-Combustion Case. The product of these two ratios across years – one for activity and one for emissions, both pollutant specific – multiplied by the COBRA-based 2023 emissions provided the BAU national inventory for the years 2020, 2030, 2040, and 2050. Note that as COBRA does not include GHG emissions, we did not determine a national, BAU upstream inventory for GHGs for these sectors. Similarly, as GREET does not produce NH_3 emissions, upstream BAU NH_3 emissions were grown based solely on changes in activity for the ICEV fuels. For electricity generating emissions NH_3 was grown as for other pollutants, but the ratio of NOx emissions factors was used as NOx-generating applications are closely correlated to NH_3 use in stationary EGUs applications.[44]

The emission inventory in COBRA is based on the NEI, reported in a series of Tiers. EPA provided a crosswalk between these Tiers and the Source Classification Codes.[45] ICF then determined a list of Tiers that best match the upstream emission sectors simulated by GREET. The sum of emissions in the selected Tiers are those that were scaled to the upstream sectors by year. We rely on emissions as reported in COBRA for consistency with the health analysis.

For electricity production, we include additive emissions from both upstream categories to the BAU upstream inventory. For upstream ICEV fuels where emissions are reduced, the matching is more critical to ensure that more emissions are not removed with our MOVES- and GREET-based approach than is in the BAU upstream sectors based on the NEI. Emissions reduction from all three upstream categories were combined and removed from the upstream BAU inventory, based on the list of Tiers best matching the petroleum sector and emissions

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41 These baseline emissions estimates account for federal and state regulations as of May 2018. More details about the development of the 2023 baseline emissions case are available in the supporting information for the 2016v1 Emissions Modeling Platform, available at: https://www.epa.gov/airemissions-modeling/2016v1-platform.

42 Electricity Electric Power Sector Net Available to the Grid (Case Reference case) for electricity generation, available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=8-AEO2021&region=0-0&cases=ref2021&start=2019&end=2050&f=A&linechart=~ref2021-d113020a.24-8-AEO2021&ctype=linechart&sid=ref2020-d112119a.5-11-AEO2020&sourcekey=0. Liquid Fuels (Case Reference case) for ICEV fuels activity, available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=11-AEO2021&region=0-0&cases=ref2021&start=2019&end=2050&f=A&linechart=~ref2021-d113020a.42-11-AEO2021~ref2021-d113020a.10-11-AEO2021&ctype=linechart&sid=ref2020-d112119a.5-11-AEO2020&sourcekey=0.

43 Sources: 2020: U.S. Energy Information Administration (EIA), Short-Term Energy Outlook, October 2020 and EIA, National Energy Modeling System run ref2021.d113020a. Projections: EIA, AEO2021 National Energy Modeling System run ref2021.d113020a. Table 11. Petroleum and Other Liquids Supply and Disposition – Liquid Fuels: Crude Oil: Total Crude Supply.

44 For example, see, "Estimating Ammonia Emissions from Stationary Power Plants", Electric Power Research Institute, April 2009. Available at: https://www.epri.com/research/products/000000000001017985.

45 Email from Emma Zinsmeister to Kate Munson, January 12, 2022 5:23 PM.

from ethanol and biodiesel production. This COBRA-based BAU provided sufficient margin for the MOVES- and GREET-based predicted emission reductions. This agreement lends confidence to the national, upstream BAU values determined here. In Task 3, the health impact modeling will be based on the net upstream emissions consistent with all five upstream sectors modeled here. Appendix B lists all the Tiers from the default COBRA inventory included in developing the upstream BAU inventory shown here.

Finally, the Non-Combustion Case results in an emissions profile that drops dramatically and quickly. This is demonstrated by the emission factors in Table 11. Emissions are based on year 2023 values in COBRA but the Non-Combustion Case is much cleaner by 2023 than envisioned there. When this approach is used to estimate year 2020 estimates under the Non-Combustion Case for the entire grid it results in 2020 emissions much higher than in COBRA or the Base Case. To accommodate this, we scaled down the Non-Combustion Case emissions, when applied to the entire grid's load, so that the Base Case and Non-Combustion Case agree for year 2020.

Table 14 shows the resulting estimates of national, total upstream emissions for the relevant sectors. As discussed in Section 4 and above, we show two different values for the BAU EGU emissions, according to the two different paths for the future electric grid.

Table 14. National total upstream BAU emissions inventory for the relevant sectors, tons per year

Year	NOx	VOC	$PM_{2.5}$	SO_2	GHG (CO_2e)	NH_3
BAU Upstream Emissions from Crude, Feedstock, Refining & Transport, Domestic						
2020	850,275	3,291,868	59,550	199,282	N/A	8,988
2030	1,018,118	4,023,830	71,528	236,889	N/A	11,016
2040	1,000,679	3,964,229	70,144	225,161	N/A	10,926
2050	1,023,491	3,976,403	71,755	234,962	N/A	10,885
BAU Upstream Emissions from EGUs with Baseline Load attributed to the Base Case Electric Grid, Domestic						
2020	777,070	38,047	117,826	735,976	N/A	38,552
2030	693,679	34,516	107,747	651,186	N/A	34,415
2040	667,268	35,270	104,856	590,550	N/A	33,104
2050	530,525	34,936	73,315	243,265	N/A	26,320
BAU Upstream Emissions from EGUs with Baseline Load attributed to the Non-Combustion Case Electric Grid, Domestic						
2020	777,070	38,047	117,826	735,976	N/A	38,552
2030	334,382	22,297	45,751	133,923	N/A	16,589
2040	3,947	346	234	113	N/A	196
2050	3,965	348	235	115	N/A	197
Total BAU Upstream Emissions, Base Case Electric Grid, Domestic						
2020	1,627,345	3,329,915	177,376	935,258	N/A	47,540
2030	1,711,797	4,058,346	179,275	888,074	N/A	45,431
2040	1,667,947	3,999,499	175,000	815,711	N/A	44,030
2050	1,554,016	4,011,338	145,070	478,227	N/A	37,206
Total BAU Upstream Emissions, Non-Combustion Case Electric Grid, Domestic						
2020	1,627,345	3,329,915	177,376	935,258	N/A	47,540
2030	1,352,499	4,046,127	117,279	370,812	N/A	27,605
2040	1,004,626	3,964,576	70,378	225,274	N/A	11,121
2050	1,027,456	3,976,751	71,990	235,077	N/A	11,082

4.2.5. Changes in Upstream Emissions due to Vehicle Electrification

We calculated changes in upstream emissions associated with increased vehicle electrification under the Scenario as follows.

1. Calculate the total downstream fuel consumption values in gallons (or scf for CNG) for the BAU vehicle fleet. This is determined from the same MOVES outputs discussed in Section 3.3. As MOVES does not report fuel use in volume units, this was determined by dividing CO_2 emissions by fuel-specific emission factors (g CO_2 per gallon).[46]
2. Calculate fuel-consumption-per-year-and-per-vehicle emission factors by dividing the calculated values above by the BAU vehicle population.
3. Multiply the factors from in Step 2 by the ICEV population under the Scenario to obtain the Scenario-specific fuel consumption and resulting avoided fuel consumption in gallons (or scf for CNG).
4. Multiply the Avoided fuel consumption values with the GREET2021 fuel-and year-specific emission factors to obtain values for total avoided NOx, VOCs, SO_2, $PM_{2.5}$, and GHGs upstream emissions from the Scenario implementation.
5. Similarly, calculate the additional emissions resulting from the additional load to the grid from the EVs in the fleet Scenario
    a. Calculate energy factors in Joules per vehicle category and year, by dividing the BAU total energy use (in Joules) numbers by the BAU Vehicle Population
    b. Multiply these energy factors by the year and vehicle category-specific EV population breakdown resulting from the Scenario modeling and divide with their respective energy efficiency ratios (EER) to obtain the additional grid load resulting from these additional EVs.
    c. Multiply the grid load values obtained in step 6b with the GREET2021 EGU emission factors to obtain the additional electricity emissions under the Base and Non-Combustion Cases.

Note that GREET simulates global emissions from upstream activities. To account for the domestic portion of the crude and feedstock emissions, we applied a factor of 74% based on the GREET estimate of crude that is domestic. Note also that all grid emissions are assumed to be domestic.

Table 15 shows the global changes in total upstream emissions associated with the Scenario under the Base Case grid mix. Table 16 shows the same information but for domestic emissions. Note that the Additional Upstream Emissions due to Additional Grid Load line is not repeated in Table 16 since it is the same both domestically and globally under this EV Scenario. Table 17 shows the same global change in total upstream emissions resulting from the Scenario, but under the Non-Combustion Case grid mix. Similarly, Table 18 shows the same information as Table 16, but for the Non-Combustion Case grid mix.

46 Source: EPA 2021 Emission Factors for GHG Inventories. Available at: https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf

Table 15. Global changes total upstream emissions for the relevant sectors, Base Case electrification, tons per year

year	NOx	VOC	$PM_{2.5}$	SO_2	GHG (CO2e)	NH_3
Upstream Feedstock, Crude, Refining, and Transportation Emissions Reductions (Global)						
2020	-526	-596	-39	-149	-479,894	N/A
2030	-69,843	-75,336	-5,138	-19,476	-63,178,128	N/A
2040	-300,331	-302,279	-21,535	-80,509	-269,111,064	N/A
2050	-458,082	-436,290	-32,569	-124,962	-404,082,264	N/A
Additional Upstream Emissions due to Additional Grid Load						
2020	564	90	48	472	814,384	N/A
2030	62,208	10,209	5,271	51,557	91,735,747	N/A
2040	236,890	40,357	19,902	184,649	354,537,666	N/A
2050	250,195	53,207	19,526	101,807	400,155,528	N/A
Global Net Changes from Avoided Crude, Feedstock, Refining and Transport, and Additional EGUs						
2020	38	-506	8	324	334,490	N/A
2030	-7,635	-65,128	133	32,081	28,557,620	N/A
2040	-63,441	-261,922	-1,633	104,140	85,426,602	N/A
2050	-207,887	-383,083	-13,043	-23,154	-3,926,737	N/A

Table 16. Domestic changes total upstream emissions for the relevant sectors, Base Case electrification, tons per year

year	NOx	VOC	$PM_{2.5}$	SO_2	GHG (CO2e)	NH_3
Upstream Feedstock, Crude, Refining, and Transportation Emissions Reductions, Domestic						
2020	-444	-559	-35	-128	-423,762	N/A
2030	-58,969	-70,405	-4,592	-16,772	-55,843,321	N/A
2040	-253,090	-281,490	-19,250	-69,370	-237,717,792	N/A
2050	-384,751	-405,604	-28,989	-106,847	-355,975,180	N/A
Net Upstream Emissions Change: Avoided Crude, Feedstock, Refining and Transport Emissions, and Additional EGUs, Base Case, Domestic						
2020	120	-469	12	344	390,621	N/A
2030	3,239	-60,196	679	34,786	35,892,426	N/A
2040	-16,199	-241,133	652	115,279	116,819,874	N/A
2050	-134,556	-352,398	-9,463	-5,040	44,180,347	N/A
Percent Net Change in Emissions from BAU, Base Case Electrification, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	0%	-1%	0%	4%	N/A	N/A
2040	-1%	-6%	0%	14%	N/A	N/A
2050	-9%	-9%	-7%	-1%	N/A	N/A

Table 17. Global changes total upstream emissions for the relevant sectors, Non-Combustion Case electrification, tons per year

year	NOx	VOC	$PM_{2.5}$	SO_2	GHG (CO2e)	NH_3
Feedstock, Crude, Refining, and Transportation Emissions Reductions (Global)						
2020	-526	-596	-39	-149	-479,894	N/A
2030	-69,843	-75,336	-5,138	-19,476	-63,178,128	N/A
2040	-300,331	-302,279	-21,535	-80,509	-269,111,064	N/A
2050	-458,082	-436,290	-32,569	-124,962	-404,082,264	N/A
Additional Emissions due to Additional Grid Load						
2020	546	90	47	462	812,076	N/A
2030	28,484	6,418	2,208	10,188	47,719,961	N/A
2040	1,314	389	44	34	315,064	N/A
2050	1,799	533	61	47	431,504	N/A
Global Net Changes from Avoided Crude, Feedstock, Refining and Transport, and Additional EGUs						
2020	20	-506	7	314	332,183	N/A
2030	-41,359	-68,918	-2,930	-9,288	-15,458,166	N/A
2040	-299,017	-301,889	-21,491	-80,476	-268,796,000	N/A
2050	-456,283	-435,757	-32,509	-124,915	-403,650,761	N/A

Table 18. Domestic changes total upstream emissions for the relevant sectors, Non-Combustion Case electrification, tons per year

year	NOx	VOC	$PM_{2.5}$	SO_2	GHG (CO2e)	NH_3
Feedstock, Crude, Refining, and Transportation Emissions Reductions, Domestic						
2020	-444	-559	-35	-128	-423,762	N/A
2030	-58,969	-70,405	-4,592	-16,772	-55,843,321	N/A
2040	-253,090	-281,490	-19,250	-69,370	-237,717,792	N/A
2050	-384,751	-405,604	-28,989	-106,847	-355,975,180	N/A
Net Upstream Emissions Change: Avoided Crude, Feedstock, Refining and Transport Emissions, and Additional EGUs, Non-Combustion Case, Domestic						
2020	102	-469	12	334	388,314	N/A
2030	-30,485	-63,987	-2,384	-6,583	-8,123,360	N/A
2040	-251,776	-281,101	-19,206	-69,336	-237,402,729	N/A
2050	-382,952	-405,071	-28,928	-106,800	-355,543,677	N/A
Percent Net Change in Upstream Emissions from Upstream BAU, National Scenario, with Baseline Load attributed to the Non-Combustion Case Electric Grid, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-2%	-2%	-2%	-1%	N/A	N/A
2040	-25%	-7%	-27%	-31%	N/A	N/A
2050	-37%	-10%	-40%	-45%	N/A	N/A

Figure 7. Net domestic upstream criteria pollution emissions changes from electrification scenario, with the Base Case

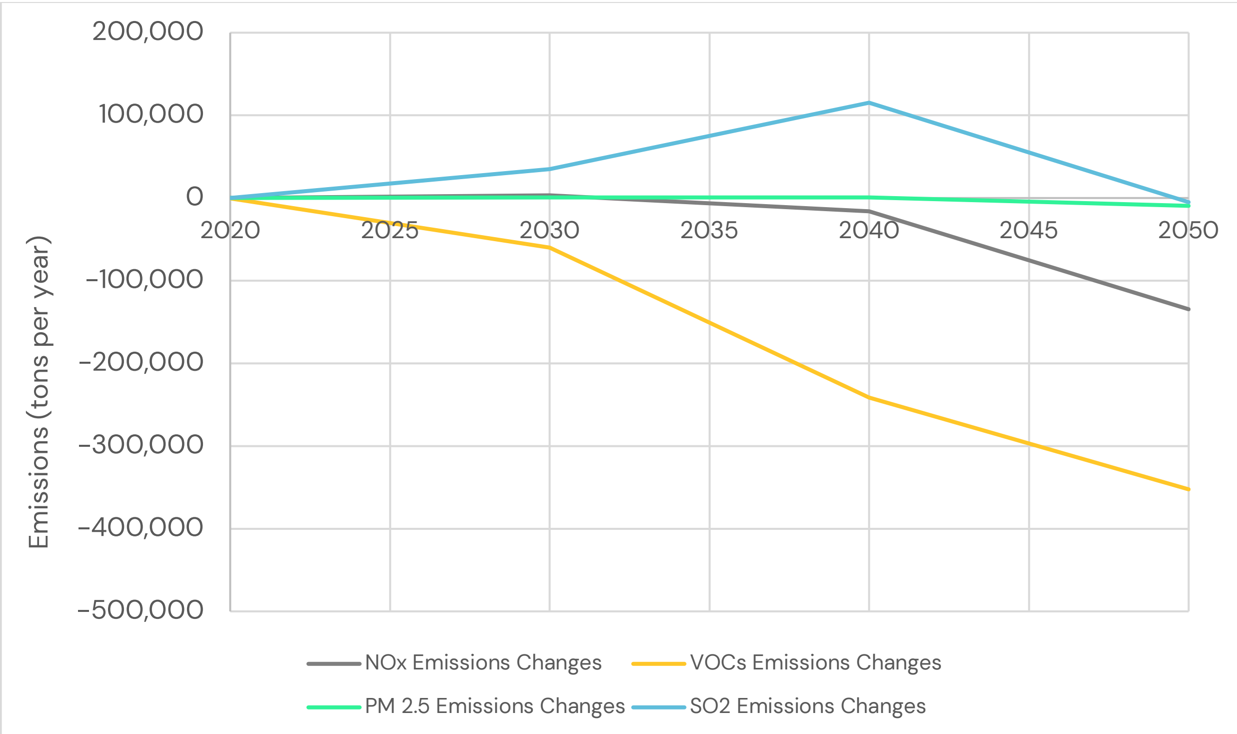


Figure 8. Global change in upstream GHG emissions with the Base Case and total number of electric vehicles under the Scenario

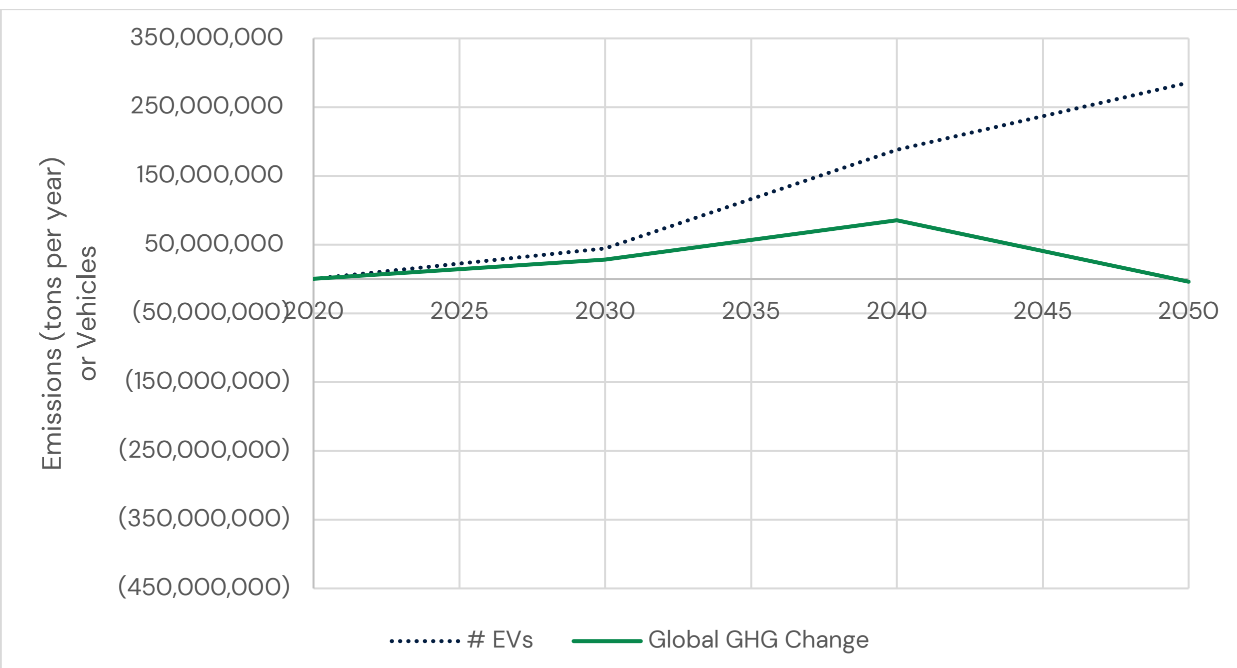


Figure 9. Net domestic upstream criteria pollution emissions changes from electrification scenario, with the Non-Combustion Case

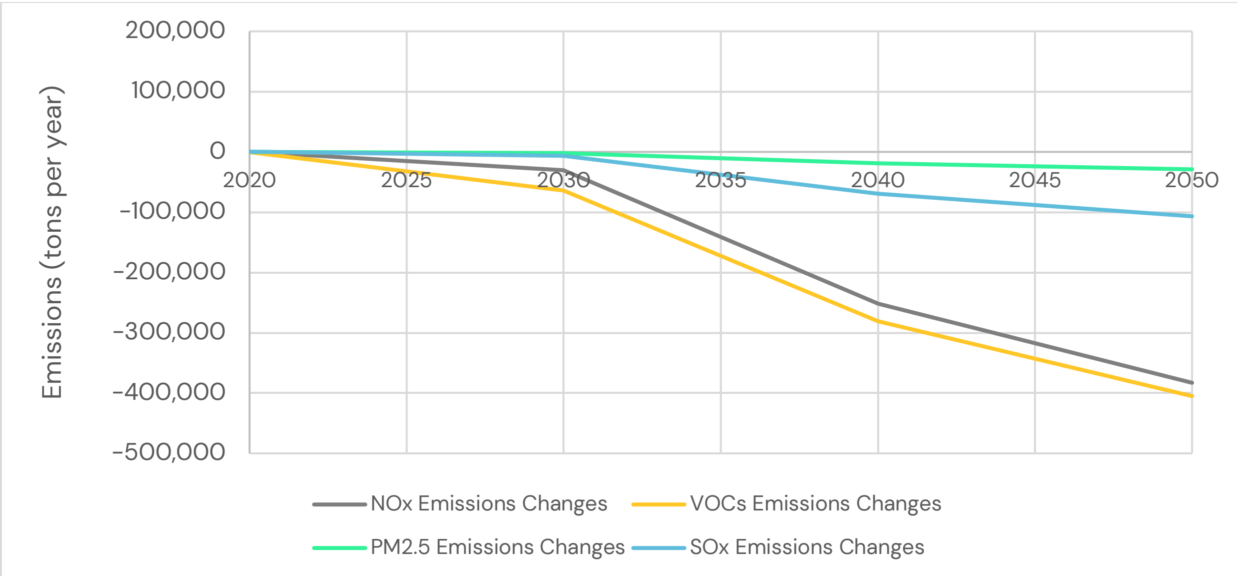
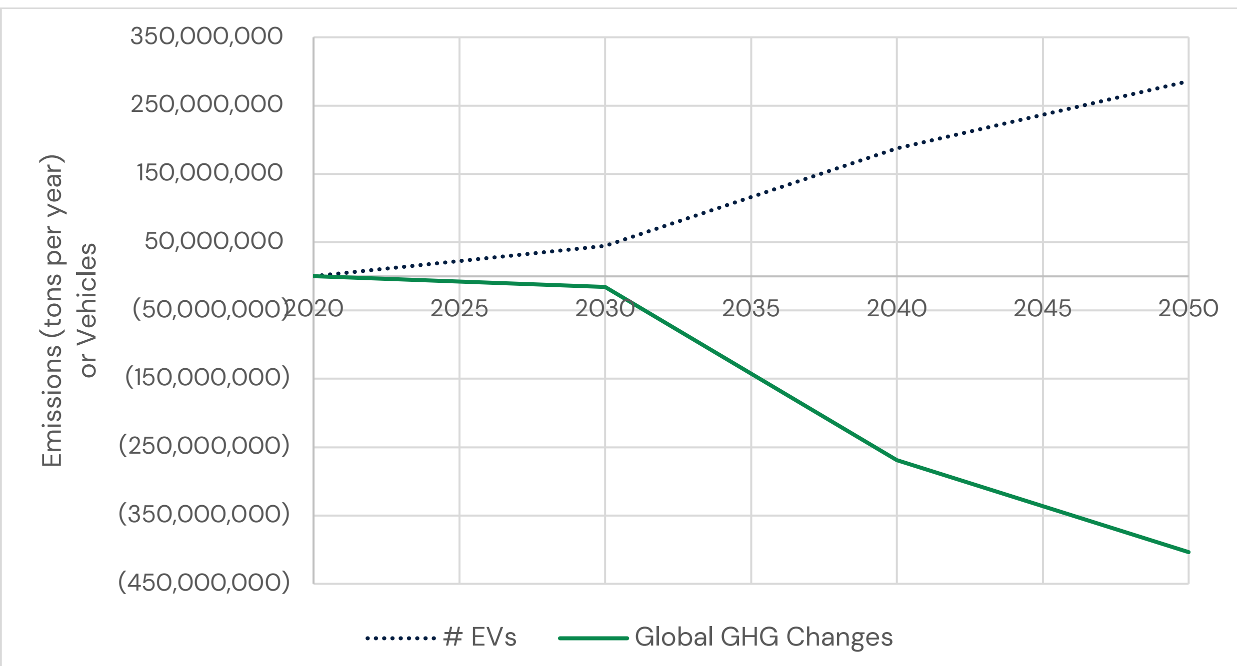


Figure 10. Global change in upstream GHG emissions with the Non-Combustion Case and total number of electric vehicles under the Scenario



4.3. Net Emissions

Finally, we calculated the net emissions nationally by combining the overall upstream BAU emissions and the overall downstream BAU emissions into a total BAU set of emissions. We combined the overall change in the upstream and in downstream emissions into an overall change in emissions under the Scenario, with each electrification Case. The upstream values are associated with the changes in refining, transportation, and crude/feedstock emissions from ICEV fuels and the emissions associated with EGUs (Section 4.2.4). The downstream changes are the changes tailpipe and fugitive emissions from the vehicles.
For this comparison, only domestic values are considered except for GHGs, where global values are presented. As discussed in Section 4.2.4, no upstream estimates of BAU GHGs are computed. Similarly, GREET does not produce NH_3 emissions, so no calculations of upstream changes in NH_3 emissions are included.

Table 19, and Table 20 show summaries of the national, total emissions under the Scenario, and the relative change in emissions. These include both the upstream and downstream activities. The two tables correspond to the two different potential approaches to representing upstream emissions, discussed at the beginning of Section 4 and in Section 4.2.4. Table 19 shows the total change in up and downstream emissions using the Base Case electrification. Table 20 is based on the Non-Combustion Case electrification, using the Non-Combustion Case electric grid emission factors for the baseline load and the additional load from new EVs.

Appendix A provides tables with additional details supporting this summary. Figure 11 and Figure 12 show the same net reduction in national, criteria pollutant emissions from the EV Scenario with the two electrification Cases. As with Table 19, and Table 20, the first figure shows net reductions as percent reductions relative to the national BAU value determined with the Base Case electrification. The second shows the reductions relative to a BAU curve based on the Non-Combustion Case for both new and existing loads on the electric grid. All are combined up- and down-stream emissions. Note that values here are reductions, such that positive values show decreasing emissions.

Figure 13 shows the upstream and downstream components of the national total emissions separately, for the two electrification Cases and the BAU. As above, the two rightmost columns represent the two different approaches to the upstream electrification Cases, with the rightmost illustrating the Non-Combustion Case applied to both new and baseline load. This demonstrates the relative magnitude of the up- and downstream components to the total and allows direct comparison between the two electrification scenarios. Note that both electrification Cases share the same EV Scenario, thus only the upstream electrification component differs. Also note that for GHGs (top row), no upstream emissions are shown. This is because there is no national, BAU predicted here for GHG emissions, as there is for the other pollutants (only the change in upstream emissions due to vehicle electrification).

Table 19. Total net change in emissions (domestic for criteria pollutants; global for GHGs) from combined upstream and downstream and corresponding total BAU emissions for the relevant sectors, with Base Case electrification, tons per year

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO_2 Equivalent	NH_3
Net Emissions Change, Nationally						
2020	-165	334	-942	-12	-1,318,658	N/A
2030	-71,159	33,476	-113,592	-2,868	-206,135,046	N/A
2040	-576,052	109,751	-478,032	-16,455	-969,244,276	N/A
2050	-1,133,364	-13,174	-779,867	-35,314	-1,591,799,582	N/A
National BAU (Upstream BAU Emissions from Fuels Production, Electricity Generation, and Downstream Vehicles)						
2020	4,127,515	945,119	4,444,636	252,367	N/A	148,576
2030	2,918,601	896,634	4,718,699	223,682	N/A	149,107
2040	2,675,300	823,977	4,561,125	215,044	N/A	154,626
2050	2,644,017	486,934	4,558,861	187,239	N/A	167,424
Percent Net Change in Emissions from BAU, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-2%	4%	-2%	-1%	N/A	N/A
2040	-22%	13%	-10%	-8%	N/A	N/A
2050	-43%	-3%	-17%	-19%	N/A	N/A

Table 20. Total net change in emissions (domestic for criteria pollutants; global for GHGs) from combined upstream and downstream and corresponding total BAU emissions for the relevant sectors, with Non-Combustion Case electrification applied to both new and baseline load, tons per year

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO_2 Equivalent	NH_3
Net Emissions Change, Nationally						
2020	-182	324	-941	-13	-1,320,965	N/A
2030	-104,883	-7,892	-117,382	-5,931	-250,150,832	N/A
2040	-811,629	-74,865	-517,999	-36,313	-1,323,466,879	N/A
2050	-1,381,760	-114,935	-832,540	-54,779	-1,991,523,606	N/A
National BAU						
2020	4,127,515	945,119	4,444,636	252,367	N/A	149,604
2030	2,559,304	379,372	4,706,480	161,686	N/A	124,846
2040	2,011,979	233,540	4,526,202	110,422	N/A	110,883
2050	2,117,457	243,784	4,524,273	114,159	N/A	118,978
Percent Net Change in Emissions from BAU, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-4%	-2%	-2%	-4%	N/A	N/A
2040	-40%	-32%	-11%	-33%	N/A	N/A
2050	-65%	-47%	-18%	-48%	N/A	N/A

Figure 11. Relative reduction in total (up- and downstream), national emissions of criteria pollutants for the EV Scenario with the Base Case and the national BAU.

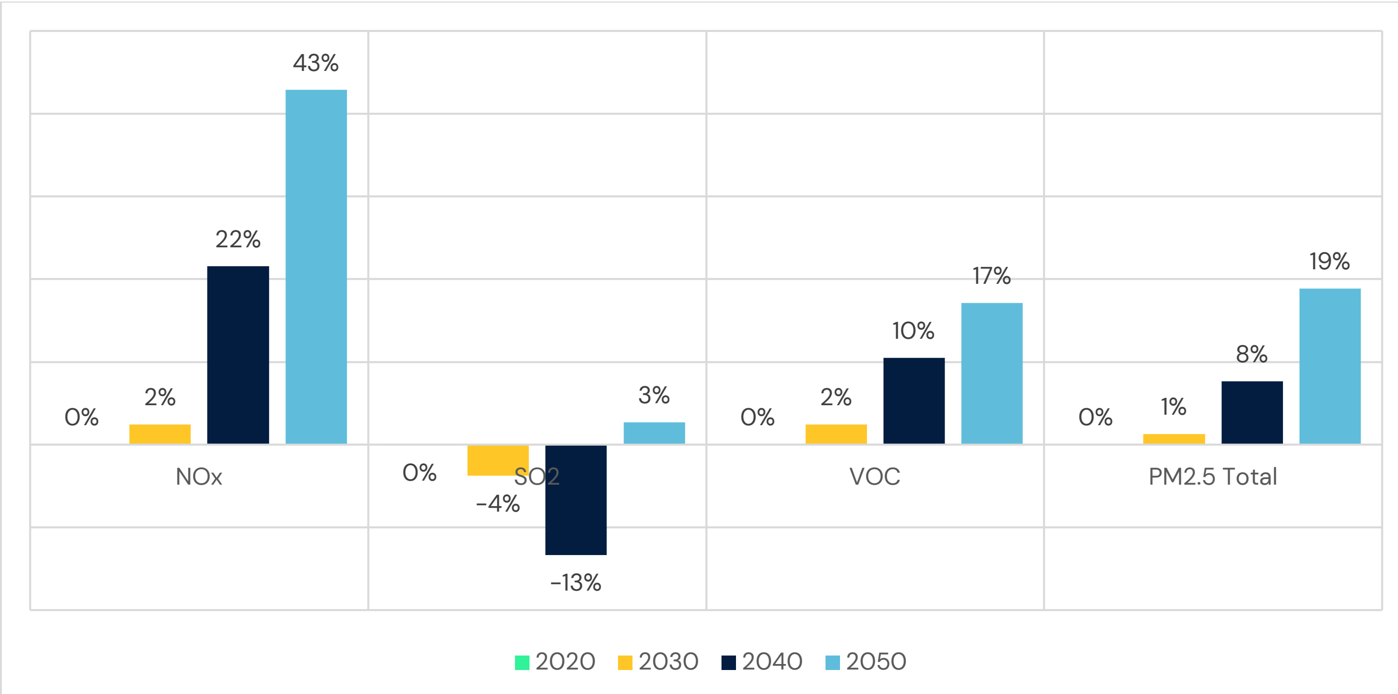


Figure 12. Relative reduction in total (up- and downstream), national emissions of criteria pollutants for the EV Scenario with the Non-Combustion Case and the national BAU (using the Non-Combustion Case electrification for both baseline and new load).

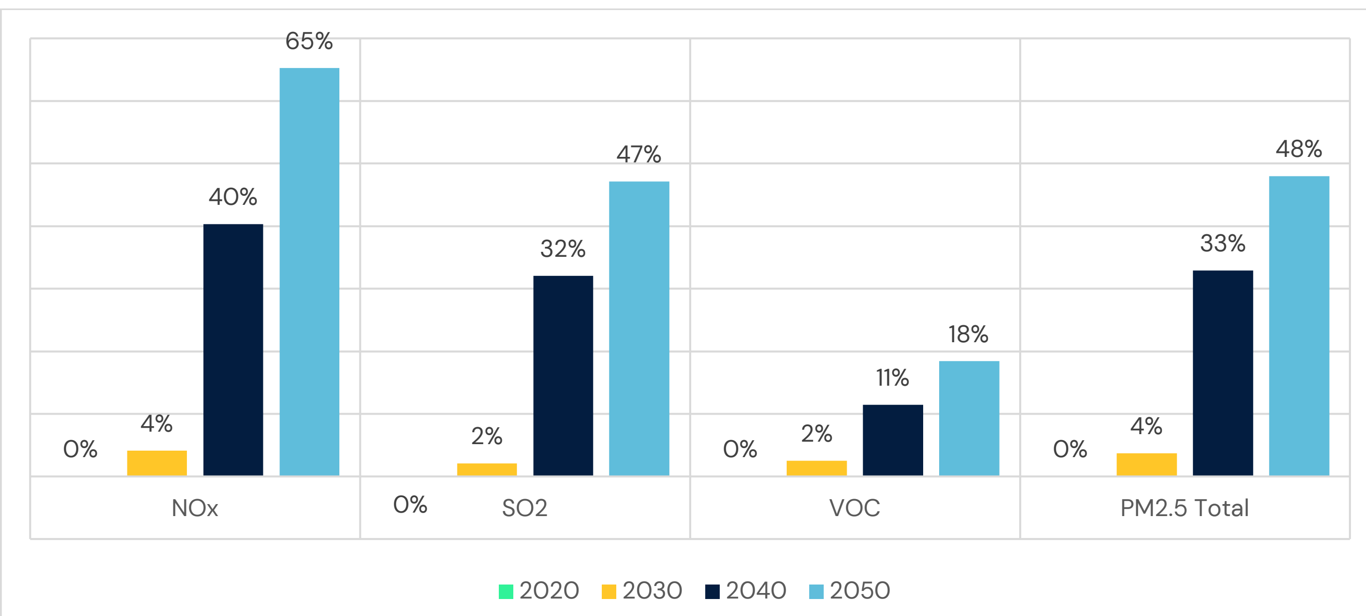
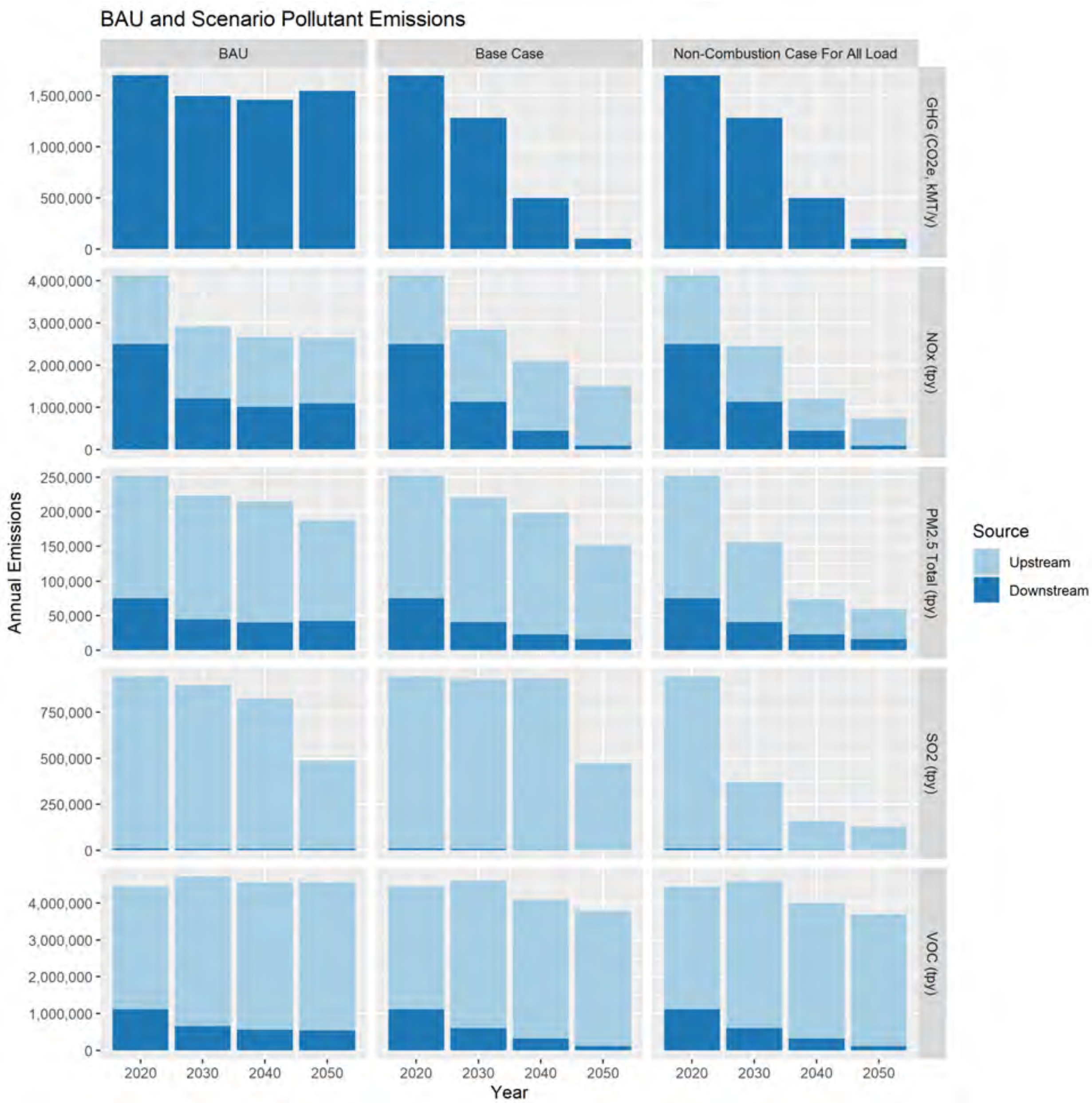


Figure 13. Emissions from up- and downstream components for each pollutant (downstream only for GHG) under the Base, Non-Combustion, and Non-Combustion for All Load electrification Case and the national BAU.



5. Human Health Benefits

5.1. COBRA Health Effects Modeling

We used the U.S. EPA Co-Benefits Risk Assessment (COBRA Version 4.1) model[47,48] to quantify and monetize changes in the incidence of adverse health impacts resulting from changes in human exposure to $PM_{2.5}$ following the transition to zero emission transportation technologies. COBRA is a screening-level air quality health benefits model that provides estimates of the impact of air pollution emissions changes on ambient $PM_{2.5}$ concentrations, associated health effect impacts, and the monetary value of avoidable health impacts.[49]

COBRA uses a source-receptor (S-R) matrix to translate changes in emissions of air pollutants into changes in ambient $PM_{2.5}$ concentrations. The S-R matrix consists of fixed transfer coefficients that relate annual average $PM_{2.5}$ concentrations at a single receptor in each county and the contribution of $PM_{2.5}$ precursors to this concentration from each emission source. The S-R matrix is based on the Climatological Regional Dispersion Model (CRDM), which includes summary data collected in 1990 from meteorological sites throughout North America.[50] The CRDM relies on simple dispersion-transport functions and chemical conversions at the receptor location.

The COBRA model contains detailed county- and source type-specific emissions estimates for the year 2023 in discrete categories. These estimates account for federal and state regulations as of May 2018.[51]

The COBRA health effects modeling analysis is similar to the 2020 "ALA Case" analysis but differs based on the following:

- **COBRA model version.** The COBRA model has been updated since the 2020 analysis, which relied on COBRA version 3.2. COBRA version 4.0 includes updates to default emissions data that accounts for air quality policymaking through 2018.
- **Updated function for avoided mortality estimates.** ICF implements a health impact function from a more recent study of the impact of changes in emissions levels on adult mortality incidence (Di et al., 2017).[52] Section 5.2.5 below discusses this change.
- **Investigating the potential impacts of electrification in different vehicle categories.** The updated analysis estimates the human health benefits from light duty (passenger) and heavy-duty (trucks) vehicles separately to tease out effects by vehicle class.
- **Pushing the grid to 100 percent renewables.** The updated analysis considers the extent to which the accelerated retirement of coal and the dramatic push to renewables make a difference in human health benefits. This Non-Combustion Case considers health benefits from all emissions reductions on the

47 https://www.epa.gov/cobra

48 A later version of COBRA, Version 4.1, was released November 2021, after this project was in progress. An EPA contact confirmed that none of the underlying COBRA data sources changed between version 4.0 and 4.1. The only changes are improved connectivity with the AVERT tool, which enables users to estimate the impacts of different energy efficiency and/or renewable energy programs based on temporal energy savings and hourly generation profiles. Therefore, we do not expect the COBRA release version to have material impacts on the results presented here.

49 COBRA relies on a suite of health impact functions and valuation functions that closely approximate what EPA used in developing the Final 2006 National Ambient Air Quality Standards (NAAQS) for PM.

50 The CRDM does not fully account for all chemical interactions that take place in the secondary formation of PM2.5.

51 Projected EGU emissions comply with the Cross-State Air Pollution Rule Update (CSAPR Update) finalized December 27, 2016, the Mercury and Air Toxics Rule (MATS), and the Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources.

52 Di, Q., Wang, Y., Zanobetti, A., Wang, Y., Koutrakis, P., Choirat, C., Dominici, F. and Schwartz, J.D. 2017. Air pollution and mortality in the Medicare population. New Engl J Med 376(26): 2513-2522.

grid, meaning that both incremental load from new EVs and the base load on the grid are subject to the same grid mix, and the effects of both cleaner incremental and base loads are compared against the BAU electricity generation emissions for health effects. The implication is that health benefits from the Non-Combustion Case include benefits not related to EVs.[53]

- **New emissions modeling.** As discussed above, the latest versions of the MOVES and GREET models were implemented, resulting in changes to the baseline vehicle fleet and its associated emissions, along with that from the upstream activities.
- **New upstream emissions changes approach.** This updated analysis uses the full mass upstream emissions data calculated above for health impacts in COBRA for both the control and scenario emissions. National-level emissions by category are scaled to the county and COBRA emission tiers using the distribution of county- and tier-specific default 2023 COBRA emissions. The previous analysis did not include this level of consistency. Instead, it relied on an adjustment factor approach to determine future year BAU emissions.[54]
- **Reporting cumulative impacts and different analysis years.** The COBRA model assesses annual changes in cases of adverse health effects and the monetary benefits or disbenefits associated with those changes for years 2020, 2030, 2040, and 2050. The previous analysis considered 2018, 2030, and 2050. We also used a linear interpolation method to assess the cumulative impacts of proposed emissions scenarios over the entire period 2020 to 2050.
- **Including an analysis of demographic-specific impacts.** The updated analysis provides insight into the effects of emissions scenarios on people of color.

In addition to the health outputs, we also report the population-weighted change in annual average $PM_{2.5}$ concentrations under the scenario calculated based on COBRA's estimates of county-level changes in $PM_{2.5}$ and the total population in each county. This metric is useful as an approximation of the overall affect the Scenario will have on regional air quality.

5.2. Modeling Inputs and Approach

5.2.1. Emissions Changes

ICF adjusted emissions for the categories of emissions sources related to the emissions changes driven by two electricity generation Cases, three vehicle classes (light duty, heavy-duty, and total), and four analysis years (2020, 2030, 2040, and 2050). The emission sources adjusted for the BAU and scenarios include three main categories:

1. Downstream exhaust, fugitive, and evaporative emissions from highway vehicles;

53 This makes the sum of light- and heavy-vehicle results under the Non-Combustion Case much greater than the total-vehicle class since the benefits of the cleaner grid for baseline load appear in both. This does not happen for the Base Case because the BAU and Base Case use the same grid emission factors (See Table 11).

54 Default COBRA data in version 3.2 was for the year 2025, while the updated COBRA model version 4.0 default data reflect emissions in the year 2023. We scaled default 2025 COBRA emissions to future years, based on pollutant-specific adjustment factors and developed based on BAU emissions modeling in 2025 and future years (2030 and 2050 for the previous analysis). Reduced upstream emissions in the previous analysis were based on mass emissions and the distribution of upstream emissions in the 2025 default COBRA dataset for the EGU emissions category, similar to that done here for all upstream emissions. However, to accommodate discrepancy in calculated differences in upstream reductions and default BAU inventory, ICF reduced emissions in the refining category using a single percentage reduction for each modeled scenario in the previous analysis. The present study resolved these issues. See Section 4.2.4.

2. Upstream emissions from electric utilities; and
3. Upstream emissions from crude/feedstock production, fuel refining, and fuel transport.[55]

ICF did not adjust emissions for the remaining categories in the default COBRA emissions dataset.

ICF mapped the MOVES simulations used to determine the BAU downstream exhaust, fugitive, and evaporative emissions to highway vehicle emission source categories in COBRA. For the upstream emissions categories, ICF estimated BAU emissions based on factors derived from GREET modeling and total net electric power sector generation estimates (electric utilities) or total crude supply estimates (crude/feedstock production, fuel refining, and fuel transport) for the years 2020, 2023 (the year of COBRA default emissions data), 2030, 2040, and 2050 from the U.S. Energy Information Administration Annual Energy Outlook (AEO) for 2021.[56,57,58]

To develop base case and scenario emissions for the two electricity generation cases and three vehicle electrification scenarios, we distributed modeled mass emissions (described in detail in Section 4) for each relevant emission source category to county-level base case and scenario emissions proportional to the magnitude of county-level emissions in the default 2023 COBRA emissions. Base case and scenario emissions for the natural gas extraction and asphalt manufacturing sub-categories of petroleum production are unchanged here. For the highway vehicle emission source category, modeled mass emissions changes varied by vehicle type sub-category, to capture the COBRA model's encapsulation of the different S-R matrix values by different vehicle types. Modeled mass emission changes for the electric utilities and crude/feedstock production, fuel refining, and fuel transport emission source categories did not vary by emission source sub-category. The emissions in COBRA are organized around different sectors and subsectors and calculated with different models than employed here.

5.2.2. Vehicle Classes for Outcome Reporting

ICF evaluated the impacts of changes in emissions on human health separately for the following three vehicle classes:

1. **Total**: evaluation of emissions changes among both light duty and heavy-duty vehicles together;
2. **Light duty**: evaluation of both up and downstream emissions changes related to light duty vehicles only; and
3. **Heavy-duty**: evaluation of emissions changes related heavy-duty vehicles only.

As with the 2020 study, the three different vehicle categories modeled for emissions were allocated to the two vehicle (light and heavy-duty) and fuel type categories in COBRA. Section 3.2 summarized the vehicle categories considered for electrification in this study. For cross-referencing purposes, those four categories are numbered as:

1. Passenger vehicles

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55 In COBRA, these upstream emissions categories correspond to categories (described as "tiers") for industrial fuel combustion, petroleum and related industries, storage & transport, and other industrial processes (specifically miscellaneous ethanol production). ICF did not adjust emissions for the subcategory of petroleum and related industries that relates to asphalt or natural gas manufacturing.

56 U.S. Energy Information Administration (U.S. EIA). 2021. Annual Energy Outlook 2021. Table 8: https://www.eia.gov/outlooks/aeo/pdf/AEO_Narrative_2021.pdf

57 U.S. Energy Information Administration (U.S. EIA). 2021. Annual Energy Outlook 2021. Table 11: https://www.eia.gov/outlooks/aeo/pdf/AEO_Narrative_2021.pdf

58 Note that COBRA operates on annual emissions and does not include seasonality that may be present in pollution sources, including evaporative emissions. As described in Section IV, all emissions calculated and used here represent annual totals.

2. Light heavy-duty trucks
3. Medium- and heavy-trucks, and
4. School buses

The first two columns of Table 21 list the vehicle-fuel categories in version 4.0 of the COBRA model. The third lists the two vehicle classes into which benefits are aggregated. The fourth column provides a cross-walk between vehicle categories. This mapping applies to the six vehicle classes modeled in COBRA.

Table 21. COBRA and Scenario vehicle-fuel combinations used in this study

COBRA Tier 1	Fuel	COBRA Vehicle Class	Corresponding EV Scenario Vehicle Categories
Highway Vehicles	Compressed Natural Gas (CNG)	Heavy-Duty	(3) Medium- and heavy-trucks and (4) School buses
Highway Vehicles	Diesel Fuel	Heavy-Duty	(2) Light heavy-duty trucks, (3) Medium- and heavy-trucks, and (4) School buses
Highway Vehicles	Diesel Fuel	Light Duty	(1) Passenger vehicles
Highway Vehicles	Ethanol (E-85)	Light Duty	(1) Passenger vehicles
Highway Vehicles	Gasoline	Heavy-Duty	(2) Light heavy-duty trucks, (3) Medium- and heavy-trucks, and (4) School buses
Highway Vehicles	Gasoline	Light Duty	(1) Passenger vehicles

5.2.3. Vehicle Emissions

Section 4 provided the emissions changes under the vehicle scenario, with both electricity Cases. To allocate vehicle emissions changes to the two vehicle classes amongst which benefits were attributed, we first split the up- and downstream emissions changes into the same two classes. These are the emission values used in COBRA for each simulation segregating impacts by vehicle class. Table 22 summarizes the emissions changes. Note that GHGs are not relevant for COBRA and thus are not reported here. Note also that upstream emissions are not calculated for ammonia as it is not included in the GREET model.

Table 22. Summary of changes In up- and downstream emissions allocated to light and heavy vehicle classes.

Year	NOx (tpy)	VOC (tpy)	$PM_{2.5}$ (tpy)	SO_2 (tpy)	NH_3 (tpy)	NOx (tpy)	VOC (tpy)	$PM_{2.5}$ (tpy)	SO_2 (tpy)	NH_3 (tpy)
Net Upstream Emissions Change: Avoided Crude, Feedstock, Refining and Transport Emissions, and Additional EGUs, Base Case, Domestic										
Base Case										
	Light Duty Vehicles					Heavy-Duty Vehicles				
2020	120	-469	12	344	N/A	0	0	0	0	N/A
2030	3,677	-57,359	579	31,110	N/A	-438	-2,837	100	3,675	N/A
2040	-6,449	-215,133	323	90,484	N/A	-9,750	-26,000	329	24,794	N/A
2050	-87,239	-303,536	-7,158	-1,829	N/A	-47,317	-48,862	-2,305	-3,212	N/A
Non-Combustion Case										
	Light Duty Vehicles					Heavy-Duty Vehicles				
2020	102	-469	12	334	N/A	0	0	0	0	N/A
2030	-26,338	-60,733	-2,147	-5,710	N/A	-4,147	-3,254	-237	-874	N/A
2040	-189,008	-246,106	-15,066	-52,583	N/A	-62,768	-34,995	-4,140	-16,755	N/A
2050	-268,323	-341,935	-21,349	-76,015	N/A	-114,628	-63,136	-7,580	-30,788	N/A
Downstream Emissions Changes										
	Light Duty Vehicles					Heavy-Duty Vehicles				
2020	-284	-473	-24	-10	-101	0	0	0	0	0
2030	-23,123	-49,079	-2,903	-1,176	-13,305	-51,275	-4,316	-644	-133	-1,175
2040	-80,974	-195,520	-11,369	-4,360	-54,801	-478,879	-41,379	-5,737	-1,169	-10,432
2050	-111,168	-347,094	-16,170	-6,050	-81,460	-887,640	-80,375	-9,681	-2,085	-18,805

5.2.4. Impacts from a Cleaner Grid

In addition to differences in health impacts among the three vehicle classes, we also simulated differences in health impacts among two grid electrification Cases summarized in Section 4:

- The **Base Case**: A more business as usual projection for the grid, based on the BNEO analysis from the 2020 study; and
- The **Non-Combustion Case**: A more ambitious renewables projection, with a heavy emphasis on non-emissions free power, such as from wind and solar.

As noted in Section 5.1, the BAU and Base Case have different loads due to the new EVs, but use the same grid mix, and thus the same emission factors. The Non-Combustion Case uses different grid emission factors. (See Table 11.) this study uses an average grid approach, which applies the same emission rate (g/kWh) to both existing/baseline and new loads. Thus, the emissions and health benefits of the Non-Combustion Case include load changes from new EVs and emission changes from the baseline load which has the same level of activity, but lower emissions than the BAU, due to the cleaner grid mix. Thus, the health benefits from the Non-Combustion Case compared against the BAU include benefits not related to EVs.

5.2.5. Health incidence and impact functions

COBRA relies on baseline incidence rates for each health endpoint and pre-loaded health impact functions to estimate the absolute change in annual incidence of mortality. We obtained age-, health endpoint-, and county-specific incidence rates in the United States projected for years 2020, 2030, 2040, and 2050 from the U.S. EPA Environmental Benefits Mapping and Analysis Program (BenMAP[59]) model database.

COBRA includes several pre-loaded health impact functions that estimate the change in adverse health effects from changes in air pollutant concentrations based on epidemiological studies. Each function was developed based on data from cohort studies performed in various locations throughout the U.S. and uses different formulas and coefficients. The applicable ages for each health impact function reflect the age groups examined in the cohort studies. COBRA employs these health impact functions to assess the impact of $PM_{2.5}$ reductions on mortality incidence (for both infants and adults), nonfatal heart attacks, hospital admissions for respiratory and cardiovascular events, acute bronchitis, upper and lower respiratory symptoms, emergency room visits, minor restricted activity days, work loss days, and asthma exacerbation. (Note that COBRA does not determine health outcomes related to changes in ambient ozone.) For certain health endpoints, such as adult mortality and nonfatal heart attacks, COBRA employs multiple functions to obtain a lower bound and an upper bound estimate of potential health impacts. This is consistent with methods EPA employed when analyzing proposed National Ambient Air Quality Standards.[60]

BenMAP, EPA's comprehensive model for estimating health impacts from air pollution, was updated in May 2021 to include more recent studies of the relationship between mortality:

- Di et al. (2017), based on an analysis of Medicare beneficiaries in the U.S. from 2000-2012 (applies to ages 65 to 99); and

59 Environmental Benefits and Mapping Program-Community Edition (BenMAP-CE). BenMAP is US EPA's detailed model for estimating the health impacts from air pollution. Unlike COBRA, it relies on detailed input on air pollutant concentration changes, then applies concentration-response (C-R) health impact functions. See https://www.epa.gov/benmap For more information.

60 U.S. EPA. (2006). Final Regulatory Impact Analysis: PM2.5 NAAQS. Research Triangle Park, NC: Office of Air and Radiation, Office of Air Quality Planning and Standards; U.S. EPA. (2009). Proposed NO2 NAAQS Regulatory Impact Analysis (RIA). Research Triangle Park, NC.: Office of Air and Radiation, Office of Air Quality Planning and Standards

- Turner et al. (2016),[61] based on analysis of participants in the American Cancer Society (ACS) Cancer Prevention Study II from 1982-2004 (applies to ages 30-99).

To remain consistent with the most recent research on particulate matter and mortality, ICF used the health impact function from Di et al. (2017) in place of the older study from Lepeule et al. (2012)[62] from the COBRA default health impact function dataset. However, the Turner et al. (2016) health impact function is based on estimated $PM_{2.5}$ levels measured during the warm season (April-September) and is therefore not applicable to annual average $PM_{2.5}$ estimates produced by COBRA. Therefore, ICF retained the Krewski et al. (2009) analysis of the ACS data as the basis for the mortality impact calculations.

As in the 2020 study, we classify mortality impacts as, "high" and "low". However, these classifications are not directly comparable to the previous study. Like Lepeule et al. (2012), the relative risk value per 10 $\mu g/m^3$ increase in $PM_{2.5}$ from Di et al. (2017) (1.07) is higher than the relative risk value per 10 $\mu g/m^3$ increase in $PM_{2.5}$ from Krewski et al. (2009)[63] (1.03) indicating that, in most cases, Di et al. (2017) will produce a higher estimate of avoided mortality cases than Krewski et al. (2009). However, the relative risk value per 10 $\mu g/m^3$ increase in $PM_{2.5}$ from Di et al. (2017) is smaller than the relative risk value from Lepeule et al. (2012) (1.14) and the health impact function based on Di et al. (2017) applies to a smaller subset of the population (those aged 65 to 99). Still, the health impact function based on Di et al. (2017) will more often generate a larger estimate of avoided mortality cases compared to Krewski et al. (2009), even though Krewski et al. (2009) applies to a larger subset of the population (those aged 30 to 99) because the Di et al. (2017) relative risk value is much larger and because baseline mortality incidence among the elderly is high. We would especially expect larger estimates of avoided mortality cases from Di et al. (2017), compared to Krewski et al. (2009), in future years, when estimates of the proportion of the total population that is aged 65 to 99 is expected to grow due to medical advancements leading to increased lifespan and reduced mortality incidence.

Appendix C summarizes the health impact functions and their applicable age ranges used here.

5.2.6. Population

The exposed population is the number of people affected by the reduction in $PM_{2.5}$ levels resulting from the transition to zero emission transportation technologies. ICF obtained county- and age-specific population estimates for the 2020, 2030, 2040, and 2050 scenario years from the BenMAP model database. These are based on the 2010 U.S. Census[64] with annual population growth rates developed by Woods and Poole (2015).[65]

5.2.7. Valuation

The final step in the health benefits analysis is to estimate the economic value of avoided health impacts. COBRA includes several pre-loaded valuation functions for health endpoints associated with $PM_{2.5}$ concentrations. Depending on the health endpoint being considered, valuation methods may involve estimates

61 Turner, M.C., Jerrett, M., Pope, A., III, Krewski, D., Gapstur, S.M., Diver, W.R., Beckerman, B.S., Marshall, J.D., Su, J., Crouse, D.L. and Burnett, R.T. 2016. Long-term ozone exposure and mortality in a large prospective study. Am J Respir Crit Care Med 193(10): 1134-1142.

62 Lepeule J, Laden F, Dockery D, Schwartz J. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. Environ Health Perspect, 120(7), 965-970.

63 Krewski, D., M. Jerrett, R. Burnett, R. Ma, E. Hughes, Y. Shi, M. C. Turner, C. A. I. Pope, G. Thurston, E. Calle and M. J. Thun. 2009. Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality. HEI Research Report, 140, Health Effects Institute, Boston, MA.

64 Because county-level data is based on the 2010 Census, FIPS county codes may be outdated. ICF did not adjust any FIPS-level county population information for the health impacts analysis.

65 Woods & Poole Economics Inc. 2015. Complete Demographic Database. Washington, DC. http://www.woodsandpoole.com/index.php.

of willingness to pay to avoid certain illnesses, the medical costs of treating illnesses, the value of lost wages, and the EPA-estimated value of a statistical life (VSL; applicable to mortality endpoints only).

Default valuation data for all health points in COBRA are reported in 2017$. For non-mortality health endpoints, ICF did not adjust valuation data to reflect changes in willingness to pay values, medical costs, or lost wages in 2020, 2030, 2040, and 2050. This makes the present results more directly comparable to those from the previous (2020) study.

Mortality, however, is typically found to be the driver for valuation given the magnitude of the VSL. Following EPA's guidance for economic analysis,[66] we use the VSL ($4.8 million in 1990$)[67] to estimate the value of avoided mortality. ICF used projected income growth data from the Organization for Economic Cooperation and Development (OECD) and consumer price index data from the Bureau of Labor Statistics (BLS) to project the original $4.8 million VSL estimate in 1990$ to the 2020, 2030, 2040, and 2050 analysis years.[68,69,70]

We do not consider other consumer costs in this valuation, such as differences in vehicle operations and maintenance, fuel costs, any tax revenue issues, etc. This valuation focuses entirely on monetized health and climate (Section6) benefits.

5.3. Results

5.3.1. Analysis Year Specific Impacts

Table 23 and Table 24 present total, national, annual estimates of the number of avoided adverse health effects and the economic value of these health risk reductions at 3% and 7% discount rates[71] from the Base and Non-Combustion Cases, respectively. Each is reported for the total vehicle class. That is, light- and heavy-duty vehicles modeled together. These economic values reflect the US population's willingness to pay to reduce risks of premature mortality or certain illnesses.[72] As such, these economic values represent monetized US public health benefits.

In addition to the national summaries for all vehicles presented here, Appendix D provides the same results resolved at a state level for each of the 48 states modeled plus DC.

At a 3% discount, total monetized public health benefits range from approximately $4.5 million in 2020 to $33.1 billion in 2050 under the Base Case considering all vehicle classes. The same approach under the Non-Combustion Case shows benefits ranging from approximately $4.9 million in 2020 to $62.4 billion in 2050. Adult mortality is the main driver of benefits of emissions changes under all electricity generation and vehicle

66 U.S. EPA. 2010. Guidelines for Preparing Economic Analyses. EPA 240-R-10-001.
67 Our approach is consistent with EPA regulatory impact analyses which use this value for VSL and adjust it for inflation and changes in income over time.
68 OECD (2020), "Long-term baseline projections, No. 103", OECD Economic Outlook: Statistics and Projections (database): https://www.oecd-ilibrary.org/economics/data/oecd-economic-outlook-statistics-and-projections/long-term-baseline-projections-no-103_68465614-en
69 Bureau of Labor Statistics, 2020 (Series ID: CUUR0000SA0,CUUS0000SA0): https://data.bls.gov/pdq/SurveyOutputServlet
70 Because ICF adjusted VSL for the mortality endpoint, but not other health endpoints, results may have a minor downward bias.
71 The 3% discount rate reflects society's valuation of differences in the timing of benefits; the 7% discount rate reflects the opportunity cost of capital to society.
72 For some health endpoints, the economic value estimates are based on the non-market valuation studies that estimate people's willingness to pay for reductions in these health risks. For other endpoints, non-market valuation studies are not readily available, and valuation is approximated using cost-of-illness methods that estimate medical costs and illness-related productivity losses.

scenarios, with an estimated decrease in the number of premature deaths among adults between 2,650 and 2,830 under the 2050 Base Case and between 5,010 and 5,350 under the 2050 Non-Combustion Case.

On a national level, reductions are seen in population weighted, annual $PM_{2.5}$ concentrations under the Base and Non-Combustion Cases. The annual concentration reductions under the Base Case are 0.000046 $\mu g/m^3$ in 2020, 0.012 $\mu g/m^3$ in 2030, 0.077 $\mu g/m^3$ in 2040, and 0.163 $\mu g/m^3$ in 2050. The annual concentration reductions under the Non-Combustion Case are 0.000048 $\mu g/m^3$ in 2020, 0.143 $\mu g/m^3$ in 2030, 0.294 $\mu g/m^3$ in 2040, and 0.297 $\mu g/m^3$ in 2050.

At a 3% discount and under the Base Case, total monetized public health benefits for the light duty vehicle class range from approximately $4.5 million in 2020 to $13.8 billion in 2050, while total monetized public health benefits for the heavy-duty vehicle class range from $0 in 2020 (before heavy vehicle electrification begins) to $19.2 billion in 2050. At a 3% discount and under the Non-Combustion Case, total monetized public health benefits for the light duty vehicle class range from approximately $4.9 million in 2020 to $41.1 billion in 2050, while total monetized public health benefits for the heavy-duty vehicle class range from $0 in 2020 to $42.9 billion in 2050.

Prior to completing this analysis, we were unsure if the sum of light duty and heavy-duty benefits would equal the total benefits, due to nonlinearities in the COBRA modeling. However, these results indicate that the light duty and heavy-duty benefits essentially equal the total vehicle class benefits under the Base Case. This implies that calculated benefits can be allocated to the light and heavy vehicles for the Base Case. However, as discussed above, benefits due to cleaning of the electric grid associated with baseline activity appear in both light and heavy vehicle results for the Non-Combustion Case, thus these results cannot be combined.

Table 23. Estimated annual health benefits under the Base Case, considering all vehicle classes combined for years 2020, 2030, 2040, and 2050

Health Endpoint	2020			2030		
	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount		3% Discount	7% Discount
Mortality, low estimate[c,d]	0.48	$4,690,000	$4,220,000	171.00	$1,730,000,000	$1,560,000,000
Mortality, high estimate[d,e]	0.45	$4,360,000	$3,930,000	173.00	$1,740,000,000	$1,570,000,000
Infant Mortality	0.004	$35,000	$31,500	0.95	$9,630,000	$8,680,000
Nonfatal Heart Attacks, low estimate[f]	0.03	$4,890	$4,760	15.80	$2,500,000	$2,430,000
Nonfatal Heart Attacks, high estimate[g]	0.28	$45,500	$44,200	147.00	$23,200,000	$22,600,000
Hospital Admits, All Respiratory	0.10	$3,750	$3,750	42.90	$1,610,000	$1,610,000
Hospital Admits, Cardiovascular (except heart attacks)	0.10	$5,000	$5,000	41.20	$2,110,000	$2,110,000
Acute Bronchitis	1.04	$633	$633	275.00	$168,000	$168,000
Upper Respiratory Symptoms	18.70	$792	$792	4,970.00	$210,000	$210,000
Lower Respiratory Symptoms	13.20	$352	$352	3,490.00	$93,300	$93,300
Emergency Room Visits, Asthma	0.30	$171	$171	93.00	$52,400	$52,400
Minor Restricted Activity Days	560.00	$48,600	$48,600	148,000.00	$12,800,000	$12,800,000
Work Loss Days	95.90	$19,200	$19,200	25,100.00	$5,030,000	$5,030,000
Asthma Exacerbation	19.30	$1,420	$1,420	5,160.00	$379,000	$379,000
Total, low estimate		**$4,810,000**	**$4,340,000**		**$1,760,000,000**	**$1,590,000,000**
Total, high estimate		**$4,520,000**	**$4,090,000**		**$1,800,000,000**	**$1,620,000,000**
Population-Weighted Average Delta $PM_{2.5}$ (µg/m3)		0.000046			0.012	

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 µg/m^3 increase in $PM_{2.5}$), which applies to adults aged 30 to 99.

[d]Note: In some cases, the "low" estimate may be larger than the "high" estimate. This happens occasionally depending on county-specific population distribution and baseline health incidence.

[e]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 µg/m^3 increase in $PM_{2.5}$), which applies to adults aged 65 to 99.

[f]Low estimate based on four acute myocardial infarction (AMI) studies.

[g]Low estimate based on Peter et al. (2001).

Health Endpoint	2040			2050		
	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount		3% Discount	7% Discount
Mortality, low estimate[c]	1,220.00	$13,000,000,000	$11,700,000,000	2,650.00	$30,000,000,000	$27,100,000,000
Mortality, high estimate[d]	1,270.00	$13,600,000,000	$12,200,000,000	2,830.00	$32,100,000,000	$28,900,000,000
Infant Mortality	6.26	$66,600,000	$60,000,000	13.10	$148,000,000	$134,000,000
Nonfatal Heart Attacks, low estimate[e]	132.00	$20,800,000	$20,200,000	323.00	$50,900,000	$49,600,000
Nonfatal Heart Attacks, high estimate[f]	1,220.00	$193,000,000	$188,000,000	2,990.00	$472,000,000	$460,000,000
Hospital Admits, All Respiratory	345.00	$13,000,000	$13,000,000	822.00	$30,900,000	$30,900,000
Hospital Admits, Cardiovascular (except heart attacks)	331.00	$16,900,000	$16,900,000	792.00	$40,400,000	$40,400,000
Acute Bronchitis	1,930.00	$1,180,000	$1,180,000	4,310.00	$2,630,000	$2,630,000
Upper Respiratory Symptoms	35,000.00	$1,480,000	$1,480,000	78,200.00	$3,310,000	$3,310,000
Lower Respiratory Symptoms	24,600.00	$657,000	$657,000	54,900.00	$1,470,000	$1,470,000
Emergency Room Visits, Asthma	686.00	$386,000	$386,000	1,580.00	$892,000	$892,000
Minor Restricted Activity Days	1,040,000.00	$89,800,000	$89,800,000	2,310,000.00	$200,000,000	$200,000,000
Work Loss Days	176,000.00	$35,200,000	$35,200,000	392,000.00	$78,500,000	$78,500,000
Asthma Exacerbation	36,400.00	$2,670,000	$2,670,000	81,500.00	$5,980,000	$5,980,000
Total, low estimate		**$13,200,000,000**	**$11,900,000,000**		**$30,600,000,000**	**$27,600,000,000**
Total, high estimate		**$14,000,000,000**	**$12,600,000,000**		**$33,100,000,000**	**$29,900,000,000**
Population-Weighted Average Delta $PM_{2.5}$ (µg/m3)		0.077			0.163	

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 µg/m^3 increase in $PM_{2.5}$), which applies to adults aged 30 to 99. \

[d]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 µg/m^3 increase in $PM_{2.5}$), which applies to adults aged 65 to 99.

[e]Low estimate based on four acute myocardial infarction (AMI) studies.

[f]Low estimate based on Peter et al. (2001).

Table 24. Estimated health benefits under the Non-Combustion Case, considering all vehicle classes combined for years 2020, 2030, 2040, and 2050

Health Endpoint	2020			2030		
	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount		3% Discount	7% Discount
Mortality, low estimate[c,d]	0.52	$5,090,000	$4,580,000	2,610.00	$26,300,000,000	$23,700,000,000
Mortality, high estimate[d,e]	0.49	$4,750,000	$4,280,000	2,670.00	$27,000,000,000	$24,300,000,000
Infant Mortality	0.00	$37,300	$33,600	12.60	$128,000,000	$115,000,000
Nonfatal Heart Attacks, low estimate[f]	0.03	$5,590	$5,440	289.00	$45,700,000	$44,500,000
Nonfatal Heart Attacks, high estimate[g]	0.32	$52,000	$50,500	2,680.00	$424,000,000	$412,000,000
Hospital Admits, All Respiratory	0.11	$4,120	$4,120	685.00	$25,500,000	$25,500,000
Hospital Admits, Cardiovascular (except heart attacks)	0.11	$5,500	$5,500	671.00	$34,300,000	$34,300,000
Acute Bronchitis	1.09	$666	$666	3,250.00	$1,980,000	$1,980,000
Upper Respiratory Symptoms	19.70	$833	$833	58,800.00	$2,490,000	$2,490,000
Lower Respiratory Symptoms	13.90	$370	$370	41,300.00	$1,100,000	$1,100,000
Emergency Room Visits, Asthma	0.33	$183	$183	1,280.00	$722,000	$722,000
Minor Restricted Activity Days	589.00	$51,100	$51,100	1,750,000.00	$152,000,000	$152,000,000
Work Loss Days	101.00	$20,200	$20,200	296,000.00	$59,200,000	$59,200,000
Asthma Exacerbation	20.40	$1,490	$1,490	61,500.00	$4,510,000	$4,510,000
Total, low estimate		**$5,220,000**	**$4,700,000**		**$26,800,000,000**	**$24,100,000,000**
Total, high estimate		**$4,920,000**	**$4,450,000**		**$27,800,000,000**	**$25,100,000,000**
Population-Weighted Average Delta $PM_{2.5}$ (µg/m3)		0.000048			0.143	

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 µg/m^3 increase in $PM_{2.5}$), which applies to adults aged 30 to 99.

[d]Note: In some cases, the "low" estimate may be larger than the "high" estimate. This happens occasionally depending on county-specific population distribution and baseline health incidence.

[e]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 µg/m^3 increase in $PM_{2.5}$), which applies to adults aged 65 to 99.

[f]Low estimate based on four acute myocardial infarction (AMI) studies.

[g]Low estimate based on Peter et al. (2001).

Health Endpoint	2040			2050		
	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount		3% Discount	7% Discount
Mortality, low estimate[c]	5,170.00	$55,000,000,000	$49,500,000,000	5,010.00	$56,700,000,000	$51,100,000,000
Mortality, high estimate[d]	5,410.00	$57,600,000,000	$51,900,000,000	5,350.00	$60,500,000,000	$54,500,000,000
Infant Mortality	24.80	$264,000,000	$238,000,000	24.30	$275,000,000	$247,000,000
Nonfatal Heart Attacks, low estimate[e]	619.00	$97,600,000	$95,100,000	639.00	$101,000,000	$98,200,000
Nonfatal Heart Attacks, high estimate[f]	5,730.00	$904,000,000	$880,000,000	5,920.00	$934,000,000	$910,000,000
Hospital Admits, All Respiratory	1,500.00	$55,900,000	$55,900,000	1,570.00	$58,800,000	$58,800,000
Hospital Admits, Cardiovascular (except heart attacks)	1,460.00	$74,500,000	$74,500,000	1,530.00	$77,900,000	$77,900,000
Acute Bronchitis	7,190.00	$4,390,000	$4,390,000	7,800.00	$4,760,000	$4,760,000
Upper Respiratory Symptoms	130,000.00	$5,520,000	$5,520,000	142,000.00	$5,990,000	$5,990,000
Lower Respiratory Symptoms	91,400.00	$2,440,000	$2,440,000	99,300.00	$2,650,000	$2,650,000
Emergency Room Visits, Asthma	2,800.00	$1,570,000	$1,570,000	2,980.00	$1,680,000	$1,680,000
Minor Restricted Activity Days	3,870,000.00	$336,000,000	$336,000,000	4,190,000.00	$364,000,000	$364,000,000
Work Loss Days	655,000.00	$131,000,000	$131,000,000	711,000.00	$142,000,000	$142,000,000
Asthma Exacerbation	136,000.00	$10,000,000	$10,000,000	148,000.00	$10,900,000	$10,900,000
Total, low estimate		**$56,000,000,000**	**$50,500,000,000**		**$57,700,000,000**	**$52,100,000,000**
Total, high estimate		**$59,400,000,000**	**$53,600,000,000**		**$62,400,000,000**	**$56,300,000,000**
Population-Weighted Average Delta $PM_{2.5}$ (µg/m3)		0.294			0.297	

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 µg/m^3 increase in $PM_{2.5}$), which applies to adults aged 30 to 99.

[d]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 µg/m^3 increase in $PM_{2.5}$), which applies to adults aged 65 to 99.

[e]Low estimate based on four acute myocardial infarction (AMI) studies.

[f]Low estimate based on Peter et al. (2001).

The adoption of light duty vehicle scenario emission reductions results in immediate changes in 2020 health benefits, whereas changes in health benefits do not appear in these decade-resolved, annual results until 2030 under the heavy-duty vehicle scenario. This is expected based on the varied EV penetration rates of the two vehicle classes.

Although nationally benefits start immediately, there are some states that show disbenefits early in the Scenario. This is notable in cases where the power grid is particularly "dirty" such that baseline EGU emissions are high. In those cases, adopting the light duty vehicle Scenario could result in disbenefits in the near-term. For example, estimates for the light duty vehicles scenario Base Case in Florida indicate disbenefits in 2020 and 2030, with positive benefits beginning in 2040 and continuing through 2050. However, estimates for the light duty vehicles scenario Non-Combustion Case in Florida indicate disbenefits only in 2020 (when the two Cases are nearly identical), with positive benefits beginning in 2030 and continuing through 2050. Due to the alignment of the heavy-duty vehicles Scenario phase in with the reduced grid emissions, estimated health benefits in Florida are never negative, and range from $46 million to $1.3 billion under the Base Case and from $1.7 billion to $3.5 billion under the Non-Combustion Case. Overall, the analysis indicates that the electrification of light duty vehicles proceeding faster than the electrification of heavy-duty vehicles could be more taxing to public health in some locations if emissions from the electrification grid are not reducing at a similar rate. Because of the more synergistic progression of vehicle emissions reductions and electrification grid emissions reductions under the heavy-duty vehicles scenario, this option results in fewer disbenefits to those individual states subject to seeing negative benefits in the near term.

5.3.2. Cumulative Impacts

We also postprocessed health benefits results from COBRA to show cumulative impacts of the proposed scenarios covering the entire period from 2020 to 2050. We calculated cumulative impacts using piecewise linear interpolation of the discounted monetized health benefits between the modeled years: 2020, 2030, 2040, and 2050. Under vehicle scenarios where 2020 monetized health benefits were zero (heavy-duty vehicle class scenarios), we interpolated between zero dollar values in 2020 and nonzero dollar values in 2030 to reflect nonzero heavy-duty zero emission vehicle sales that occur within the period (e.g., from 2021 to 2029; see Table 5).

Table 25 and Table 26 present cumulative estimates of the total national number of avoided adverse health effects and the economic value of these health risk reductions at 3% and 7% discount rates[73] from the Case and Non-Combustion Cases, respectively, when coupled with the light duty, heavy-duty, and total vehicle scenarios.[74] These economic values reflect the US population's willingness to

73 The 3% discount rate reflects society's valuation of differences in the timing of benefits; the 7% discount rate reflects the opportunity cost of capital to society.

74 We use linear interpolation between estimated number of cases and monetary benefits during the years 2020, 2030, 2040, and 2050 to calculate cumulative benefits. Because the value of a statistical life used to determine mortality health benefits differs for each year evaluated in COBRA, this approach results in a cumulative disbenefit for the mortality, low estimate but a positive cumulative monetized benefit in Ohio under the Base electricity Case light duty vehicle class scenario, under which disbenefits are estimated until 2050. Note that this is unusual, only occurring in OH.

pay to reduce risks of premature mortality or certain illnesses.[75] As such, these economic values represent monetized US public health benefits.

At a 3% discount, cumulative monetized public health benefits from 2020 to 2050 range from approximately $318 billion to $339 billion in the Base Case and total vehicles scenario. Under the Non-Combustion Case, cumulative benefits from 2020 to 2050 range from approximately $1.1 trillion to $1.2 trillion. Cumulative monetized public health benefits from 2020 to 2050 under the Base Case are shown for all vehicle classes at 3% and 7% discount rates, respectively, in Figure 13 and Figure 14. Cumulative monetized public health benefits from 2020 to 2050 under the Non-Combustion Case are shown for all vehicle classes at 3% and 7% discount rates, respectively, in Figure 15 and Figure 16. Note that these figures show cumulative values from 2020 through the charted year. That is the values corresponding to 2030 in these charts represent cumulative impacts from 2020 through 2030.

Adult mortality is the main driver of benefits of emissions changes under all electricity generation and vehicle scenarios, with an estimated decrease in the number of premature deaths among adults between 28,500 and 30,000 under the Base Case, total vehicles Class and between 105,000 and 110,000 under the Non-Combustion Case, total vehicles Class.

Under the Base Case, the cumulative number of avoided adverse health effects is greater for the heavy-duty vehicles scenario compared to the light duty vehicles scenario. For example, estimates indicate between 11,600 and 12,200 avoided mortality cases under the light duty Base Case scenario and between 16,900and 17,800 avoided mortality cases under the heavy-duty Base Case scenario. The difference between light duty and heavy-duty avoided adverse health effects shrinks in the Non-Combustion Case, where estimates indicate between 85,400 and 89,300 avoided mortality cases under the light duty Non-Combustion Case scenario and between 83,100 and 86,900 avoided mortality cases under the heavy-duty Non-Combustion Case scenario. As indicated above, benefits for the Non-Combustion Case include changes to emissions from the baseline grid which appear in both light- and heavy vehicle classes. Thus, the total vehicle class benefits do not equal the sum of light and heavy vehicle classes.

75 For some health endpoints, the economic value estimates are based on the non-market valuation studies that estimate people's willingness to pay for reductions in these health risks. For other endpoints, non-market valuation studies are not readily available, and valuation is approximated using cost-of-illness methods that estimate medical costs and illness-related productivity losses.

Table 25. Estimated cumulative health benefits under the Base Case from 2020 to 2050, for each vehicle Class.

Health Endpoint	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount
2020-2050, Base Case, Light Duty Vehicle Class			
Mortality, low estimate[c]	11,600.00	128,000,000,000	115,000,000,000
Mortality, high estimate[d]	12,200.00	134,000,000,000	121,000,000,000
Infant Mortality	60.30	659,000,000	594,000,000
Nonfatal Heart Attacks, low estimate[e]	1,240.00	195,000,000	190,000,000
Nonfatal Heart Attacks, high estimate[f]	11,500.00	1,810,000,000	1,760,000,000
Hospital Admits, All Respiratory	3,350.00	126,000,000	126,000,000
Hospital Admits, Cardiovascular (except heart attacks)	3,190.00	163,000,000	163,000,000
Acute Bronchitis	19,600.00	12,000,000	12,000,000
Upper Respiratory Symptoms	356,000.00	15,000,000	15,000,000
Lower Respiratory Symptoms	250,000.00	6,680,000	6,680,000
Emergency Room Visits, Asthma	6,880.00	3,880,000	3,880,000
Minor Restricted Activity Days	10,500,000.00	914,000,000	914,000,000
Work Loss Days	1,790,000.00	359,000,000	359,000,000
Asthma Exacerbation	370,000.00	27,100,000	27,100,000
Total, low estimate		**$130,000,000,000**	**$117,000,000,000**
Total, high estimate		**$138,000,000,000**	**$125,000,000,000**
2020-2050, Base Case, Heavy-Duty Vehicle Class			
Mortality, low estimate[c]	16,900.00	$185,000,000,000	$167,000,000,000
Mortality, high estimate[d]	17,800.00	$195,000,000,000	$176,000,000,000
Infant Mortality	84.00	$919,000,000	$828,000,000
Nonfatal Heart Attacks, low estimate[e]	2,010.00	$317,000,000	$309,000,000
Nonfatal Heart Attacks, high estimate[f]	18,700.00	$2,950,000,000	$2,870,000,000
Hospital Admits, All Respiratory	5,050.00	$189,000,000	$189,000,000
Hospital Admits, Cardiovascular (except heart attacks)	4,890.00	$249,000,000	$249,000,000
Acute Bronchitis	26,200.00	$16,000,000	$16,000,000
Upper Respiratory Symptoms	474,000.00	$20,100,000	$20,100,000
Lower Respiratory Symptoms	333,000.00	$8,910,000	$8,910,000
Emergency Room Visits, Asthma	9,620.00	$5,420,000	$5,420,000
Minor Restricted Activity Days	14,000,000.00	$1,220,000,000	$1,220,000,000
Work Loss Days	2,380,000.00	$476,000,000	$476,000,000
Asthma Exacerbation	494,000.00	$36,300,000	$36,300,000
Total, low estimate		**$188,000,000,000**	**$170,000,000,000**
Total, high estimate		**$201,000,000,000**	**$182,000,000,000**
2020-2050, Base Case, Total Vehicle Class			

Health Endpoint	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount
Mortality, low estimate[c]	28,500.00	$312,000,000,000	$281,000,000,000
Mortality, high estimate[d]	30,000.00	$329,000,000,000	$297,000,000,000
Infant Mortality	144.00	$1,580,000,000	$1,420,000,000
Nonfatal Heart Attacks, low estimate[e]	3,250.00	$513,000,000	$499,000,000
Nonfatal Heart Attacks, high estimate[f]	30,200.00	$4,750,000,000	$4,630,000,000
Hospital Admits, All Respiratory	8,400.00	$316,000,000	$316,000,000
Hospital Admits, Cardiovascular (except heart attacks)	8,080.00	$413,000,000	$413,000,000
Acute Bronchitis	45,800.00	$28,000,000	$28,000,000
Upper Respiratory Symptoms	830,000.00	$35,100,000	$35,100,000
Lower Respiratory Symptoms	582,000.00	$15,600,000	$15,600,000
Emergency Room Visits, Asthma	16,500.00	$9,290,000	$9,290,000
Minor Restricted Activity Days	24,500,000.00	$2,130,000,000	$2,130,000,000
Work Loss Days	4,170,000.00	$835,000,000	$835,000,000
Asthma Exacerbation	864,000.00	$63,400,000	$63,400,000
Total, low estimate		**$318,000,000,000**	**$287,000,000,000**
Total, high estimate		**$339,000,000,000**	**$307,000,000,000**

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 µg/m^3 increase in PM2.5), which applies to adults aged 30 to 99.

[d]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 µg/m^3 increase in PM2.5), which applies to adults aged 65 to 99.

[e]Low estimate based on four acute myocardial infarction (AMI) studies.

[f]Low estimate based on Peter et al. (2001).

Table 26. Estimated cumulative health benefits under the Non-Combustion Case from 2020 to 2050 for each vehicle Class.[76]

Health Endpoint	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount
2020-2050, Non-Combustion Case, Light Duty Vehicle Class			
Mortality, low estimate[c]	85,400.00	908,000,000,000	817,000,000,000
Mortality, high estimate[d]	89,300.00	949,000,000,000	855,000,000,000
Infant Mortality	410.00	4,350,000,000	3,920,000,000
Nonfatal Heart Attacks, low estimate[e]	10,200.00	1,610,000,000	1,570,000,000
Nonfatal Heart Attacks, high estimate[f]	94,500.00	14,900,000,000	14,500,000,000
Hospital Admits, All Respiratory	24,500.00	915,000,000	915,000,000
Hospital Admits, Cardiovascular (except heart attacks)	23,900.00	1,220,000,000	1,220,000,000
Acute Bronchitis	117,000.00	71,500,000	71,500,000
Upper Respiratory Symptoms	2,120,000.00	89,700,000	89,700,000
Lower Respiratory Symptoms	1,490,000.00	39,800,000	39,800,000
Emergency Room Visits, Asthma	45,900.00	25,900,000	25,900,000
Minor Restricted Activity Days	63,000,000.00	5,460,000,000	5,460,000,000
Work Loss Days	10,700,000.00	2,140,000,000	2,140,000,000
Asthma Exacerbation	2,220,000.00	163,000,000	163,000,000
Total, low estimate		**$924,000,000,000**	**$833,000,000,000**
Total, high estimate		**$978,000,000,000**	**$884,000,000,000**
2020-2050, Non-Combustion Case, Heavy-Duty Vehicle Class			
Mortality, low estimate[c]	83,100.00	$885,000,000,000	$797,000,000,000
Mortality, high estimate[d]	86,900.00	$926,000,000,000	$834,000,000,000
Infant Mortality	398.00	$4,230,000,000	$3,810,000,000
Nonfatal Heart Attacks, low estimate[e]	10,000.00	$1,590,000,000	$1,540,000,000
Nonfatal Heart Attacks, high estimate[f]	93,000.00	$14,700,000,000	$14,300,000,000
Hospital Admits, All Respiratory	24,000.00	$896,000,000	$896,000,000
Hospital Admits, Cardiovascular (except heart attacks)	23,500.00	$1,200,000,000	$1,200,000,000
Acute Bronchitis	114,000.00	$69,300,000	$69,300,000
Upper Respiratory Symptoms	2,060,000.00	$87,000,000	$87,000,000
Lower Respiratory Symptoms	1,440,000.00	$38,600,000	$38,600,000
Emergency Room Visits, Asthma	44,600.00	$25,100,000	$25,100,000
Minor Restricted Activity Days	61,000,000.00	$5,300,000,000	$5,300,000,000

76 Note that light and heavy vehicle classes do not sum to total for the Non-Combustion Case due to allocating the base electric load, as discussed earlier.

Health Endpoint	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount
Work Loss Days	10,300,000.00	$2,070,000,000	$2,070,000,000
Asthma Exacerbation	2,150,000.00	$158,000,000	$158,000,000
Total, low estimate		**$901,000,000,000**	**$812,000,000,000**
Total, high estimate		**$955,000,000,000**	**$862,000,000,000**
2020-2050, Non-Combustion Case, Total Vehicle Class			
Mortality, low estimate[c]	105,000.00	$1,120,000,000,000	$1,010,000,000,000
Mortality, high estimate[d]	110,000.00	$1,180,000,000,000	$1,060,000,000,000
Infant Mortality	508.00	$5,430,000,000	$4,890,000,000
Nonfatal Heart Attacks, low estimate[e]	12,600.00	$1,990,000,000	$1,940,000,000
Nonfatal Heart Attacks, high estimate[f]	117,000.00	$18,400,000,000	$17,900,000,000
Hospital Admits, All Respiratory	30,500.00	$1,140,000,000	$1,140,000,000
Hospital Admits, Cardiovascular (except heart attacks)	29,700.00	$1,520,000,000	$1,520,000,000
Acute Bronchitis	147,000.00	$89,900,000	$89,900,000
Upper Respiratory Symptoms	2,670,000.00	$113,000,000	$113,000,000
Lower Respiratory Symptoms	1,870,000.00	$50,100,000	$50,100,000
Emergency Room Visits, Asthma	57,200.00	$32,200,000	$32,200,000
Minor Restricted Activity Days	79,200,000.00	$6,870,000,000	$6,870,000,000
Work Loss Days	13,400,000.00	$2,690,000,000	$2,690,000,000
Asthma Exacerbation	2,790,000.00	$205,000,000	$205,000,000
Total, low estimate		**$1,140,000,000,000**	**$1,030,000,000,000**
Total, high estimate		**$1,220,000,000,000**	**$1,100,000,000,000**

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c]Low estimate based on Krewski et al. (2009) (relative risk of 1.03 associated with a 10 μg/m^3 increase in $PM_{2.5}$), which applies to adults aged 30 to 99.

[d]High estimate based on Di et al. (2017) (relative risk of 1.07 associated with a 10 μg/m^3 increase in $PM_{2.5}$), which applies to adults aged 65 to 99.

[e]Low estimate based on four acute myocardial infarction (AMI) studies.

[f]Low estimate based on Peter et al. (2001).

Figure 13. Estimated cumulative health benefits at 3% discount rate under the Base Case from 2020 to 2050

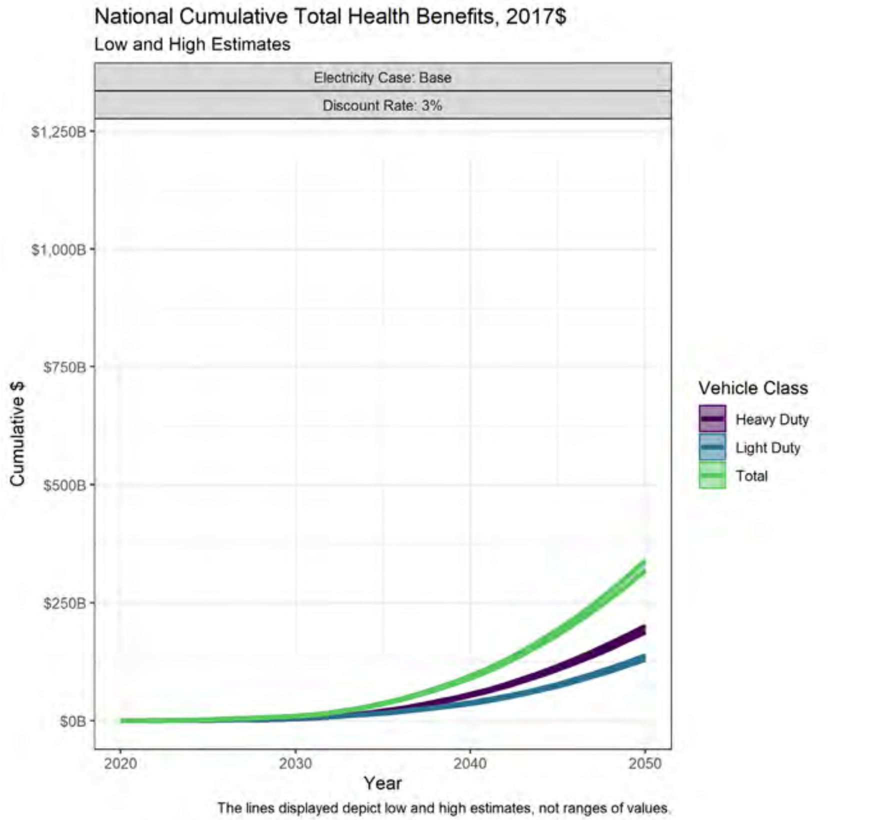


Figure 14. Estimated cumulative health benefits at 7% discount rate under the Base Case from 2020 to 2050

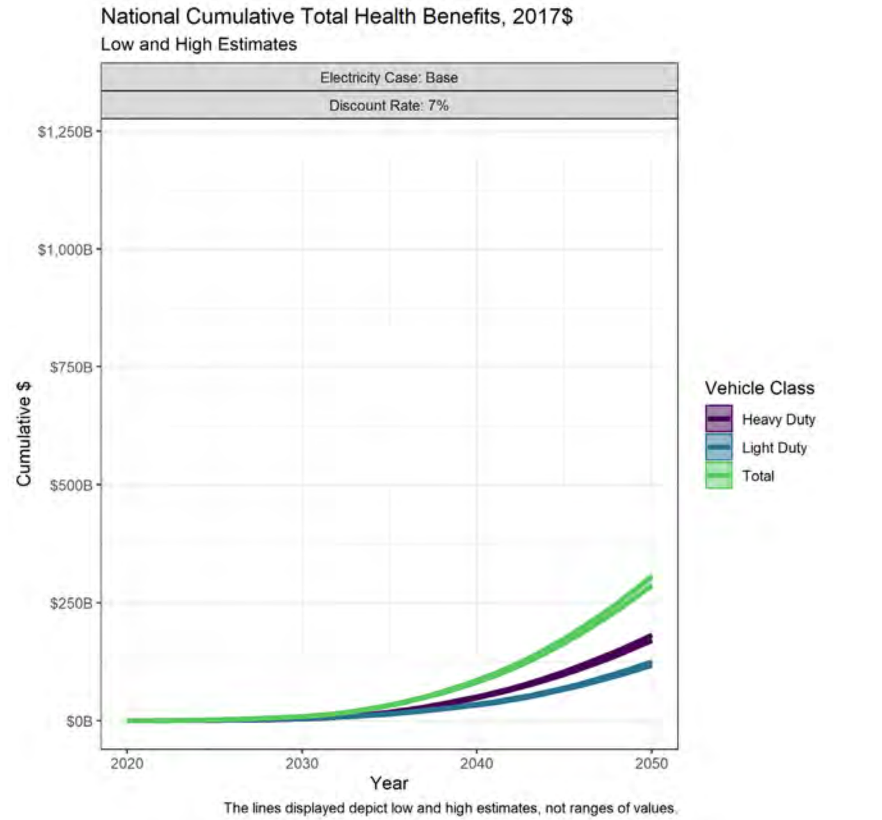


Figure 15. Estimated cumulative health benefits at 3% discount rate under the Non-Combustion Case from 2020 to 2050

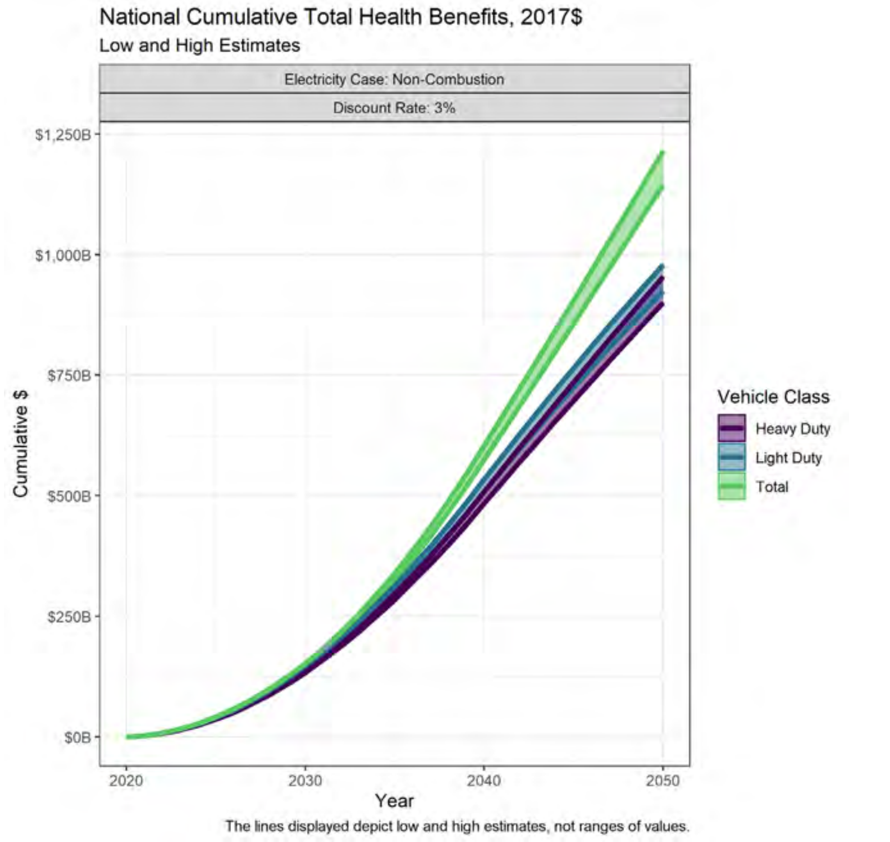


Figure 16. Estimated cumulative health benefits at 7% discount rate under the Non-Combustion Case from 2020 to 2050

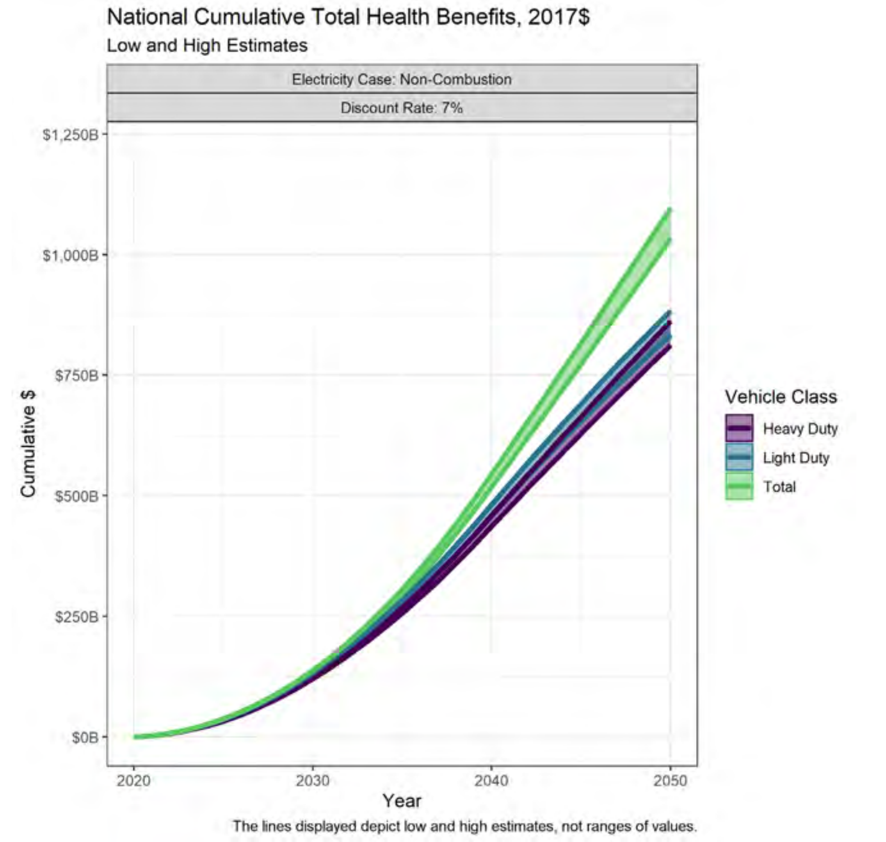


Figure 17 and Figure 18 show estimated cumulative health benefits by state in 2050 for each electrification Case and for the Total vehicle Class. Our estimates indicate that California and Texas will experience the greatest monetized health benefits. Note that these results are not per-capita. This is likely due to the large populations and proximity of those populations to major roadways in these states. The health impact estimates indicate that states like Pennsylvania and Florida will experience large health benefits, but these benefits trail those of states such as California and Texas likely due to populations and the benefits of cleaning the electric grid. States with large populations of older residents, potentially including Florida, may experience greater health benefits because such populations are more sensitive to changes in baseline mortality, respiratory, and cardiovascular health effect incidence. Appendix D contains state cumulative total health benefits for both the Base and Non-Combustion Cases, all vehicle classes, and both discount rates.

Figure 17: Estimated cumulative health benefits by state at 3% discount rate under the Base Case and all vehicle classes by 2050

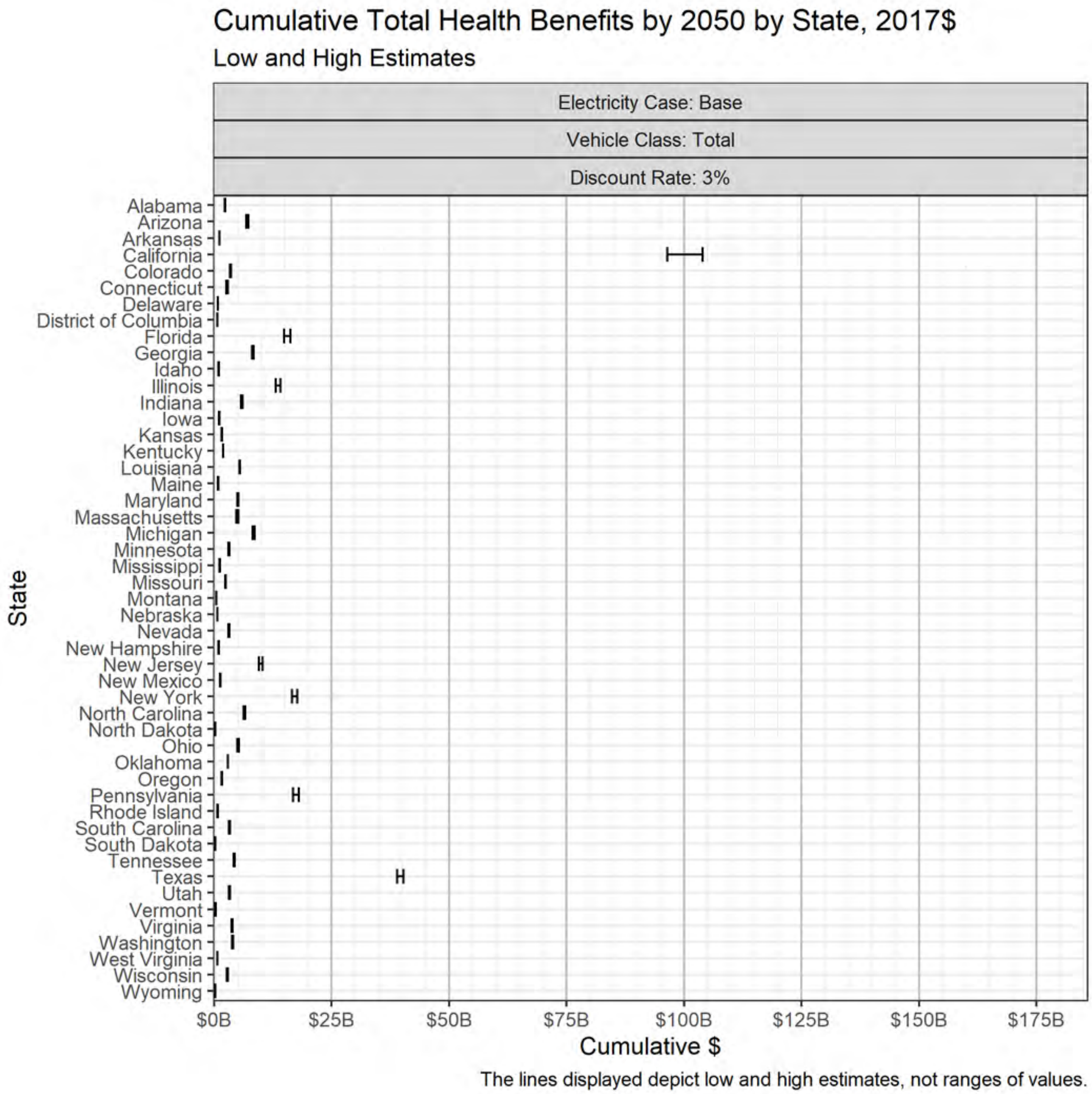
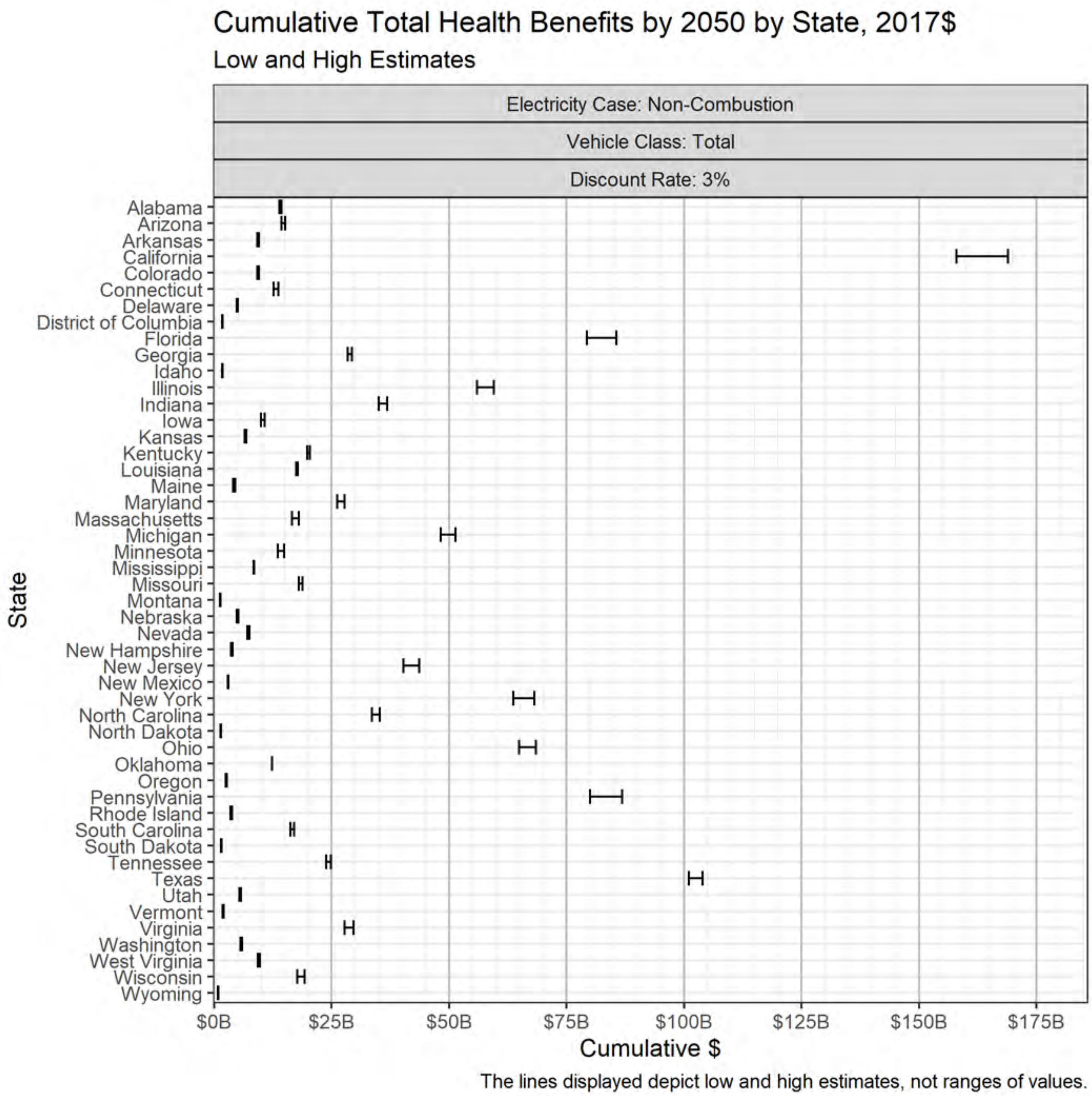


Figure 18: Estimated cumulative health benefits by state at 3% discount rate under the Non-Combustion Case and all vehicle classes by 2050



5.3.3. Demographic and Metro Area Resolution of Impacts

We also determined how the benefits of each electrification Case would be shared among communities and demographic groups. This section summarizes those benefits.

We first calculated summary results for each modeled year (2020, 2030, 2040, and 2050) and cumulative results (2020–2050) for two categories:

- a list of 25 of the largest metropolitan areas in the country; and
- groups of counties across the country sorted into bins by the percent of the population that identifies as people of color (POC).

The list of the 25 metropolitan ("metro") areas of interest were identified by the American Lung Association.[77] The geographic boundaries of these metro areas are defined by the counties included in the 2020 Census Bureau's definitions for that metro's Combined Statistical Areas (CSA),[78] except for San Diego, CA. The San Diego, CA metro area is equivalent to San Diego County in our analysis, as San Diego does not belong to a CSA.

The percent of the population identifying as a person of color is defined using Annual County Resident Population Estimates by Age, Sex, Race, and Hispanic Origin for 2020 from the Census Bureau's Vintage 2020 Population Estimates.[79] "Person of color" is defined here as the sum of the male and female estimates of all racial and ethnic groups other than *Not Hispanic, White alone*.[80] Note that many counties may have much higher share of POC than the aggregated metro areas shown in Table 29 and Table 30.

Summary by Metro Area

Table 27 shows total monetized health benefits per capita at a 3% discount rate, total monetized health benefits at a 3% discount rate, and avoided premature mortality cases (shown as the sum of adult and infant mortality cases; see Appendix C) for each modeled year by metro area for all vehicle classes under the Base electricity Case.

Total health benefits under the Base electricity Case in 2050 range from about $129 million (Portland, OR) to $5.41 billion (Los Angeles, CA). In the earliest modeled year, 2020, estimated total health benefits under the Base electricity Case are highest for the Los Angeles, CA,[81] San Francisco, CA, followed by the Houston, TX metro area. Benefits in the New York, NY metro area exceed benefits in the Houston area by 2030 and exceed benefits in the San Francisco, CA area by 2040. Patterns in the number of avoided mortality cases correspond to patterns shown in the estimated total monetized health benefits. Per capita, total health benefits under the Base electricity Case in the horizon year, 2050, range from about $28 (Portland, OR) to $217 (Los Angeles, CA). The Houston, TX, Los Angeles, CA, and San Francisco, CA metro areas show the greatest per capita benefits in both 2020 and 2030. In the near term, 2030, per capita benefits range from –$1.30 (a disbenefit) in the St. Louis area to a benefit of nearly $22 in Los Angeles. In both 2040 and 2050, the Los Angeles, CA, San Francisco, CA, and Pittsburgh, PA metro areas show the greatest per capita benefits.

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77 Email from William Barrett to Seth Hartley, Anna Belova, and Kate Munson, December 20, 2021. Originally, 28 were considered. The 25 published here are the top 25 ranked by population of the original 28 metros. Kansas City, Las Vegas, and Fresno ranked lower than 25th in this definition, and are not shown.

78 A map of the Census Bureau's 2020 CSA definitions can be found here: https://www.census.gov/geographies/reference-maps/2020/geo/csa.html

79 Census Bureau County Population by Characteristics: 2010-2020 https://www.census.gov/programs-surveys/popest/technical-documentation/research/evaluation-estimates/2020-evaluation-estimates/2010s-county-detail.html

80 Specifically, this is defined as: NHBA_male + NHBA_female + NHIA_male + NHIA_female + NHAA_male + NHAA_female + NHNA_male + NHNA_female + NHTOM_male + NHTOM_female + H_male + H_female. In this formulation: NHBA refers to "not Hispanic, Black or African American alone", NHIA is "Not Hispanic, American Indian and Alaska Native alone", NHAA is "Not Hispanic, Asian alone", NHNA is "Not Hispanic, Native Hawaiian and Other Pacific Island alone", NHTOM is "Not Hispanic, two or more races", and H is "all Hispanic".

81 Here we refer to the metro areas by their dominant or most well-known city. The full name is provided in the tables.

As discussed in Section 5.3.1 with respect to state-level benefits, there are some metro areas that show disbenefits under the Base Case electrification. In 2020 (Cleveland, OH, Miami, FL, Orlando, FL, and St. Louis, MO), while Washington, D.C. showed a small total disbenefit (de minimus on a per capita basis). By 2030, only the St. Louis, MO area showed disbenefits, and benefits among all metro areas were positive in the later years. Again, this is attributable to cases where local power generation is particularly "dirty" such that electricity generation emissions are high. In such cases, adopting the electrification Scenario results in overall disbenefits in these metro areas in the near-term. Even under the Base electrification Case, however, these become net benefits in the longer-term years.

For comparison, under the Non-Combustion electricity Case in 2050 (shown by Table 28) total health benefits range from about $152 million (Portland, OR) to $6.81 billion (Los Angeles, CA). Estimated total health benefits under the Non-Combustion electricity Case in 2020 are highest for the Los Angeles, CA, San Francisco, CA, and Houston, TX metro areas. In 2050, estimated total health benefits under the Non-Combustion electricity Case are highest for the Los Angeles, CA, New York, NY, and San Francisco, CA metro areas. Per capita, total health benefits under the Non-Combustion electricity Case in 2050 range from about $33 (Portland, OR) to $363 (Pittsburgh, PA). Per capita, total health benefits under the Non-Combustion electricity Case are highest for the Los Angeles, CA, San Francisco, CA, and Houston, TX metro areas in 2020, while estimated per capita benefits are greatest for the Pittsburgh, PA, Cleveland, OH, and Detroit, MI metro areas in 2030 and 2040. In 2050, estimated per capita benefits are greatest for the Pittsburgh, PA, Los Angeles, CA, and Philadelphia, PA metro areas.

Similar to the Base electricity Case, some metro areas show disbenefits in 2020. In this Case, they were limited to Cleveland, OH, Miami, FL, Orlando, Fl, St. Louis, MO, and Washington, D.C. (Miami and DC were neutral on a per-capita basis). However, under the Non-Combustion electricity Case, disbenefits are remediated more quickly, such that no metro areas that show disbenefits in 2030. This is due to the synergistic cleanup of the grid with reduced vehicle emissions under the Non-Combustion electricity Case in years 2030 to 2050.

Table 29 shows cumulative annual health benefits between 2020 and 2050. These tables show calculated benefits, including total monetized health benefits at a 3% discount rate, avoided premature mortality cases (including both adult and infant mortality cases), avoided hospital admits (all respiratory), avoided upper respiratory symptoms, avoided lower respiratory symptoms, and avoided emergency room visits for asthma for all vehicle classes under the Base electricity Case.

Cumulative benefits for the metro areas of interest under the Base electricity Case range from $1.34 billion (St. Louis, MO) to $63.1 billion (Los Angeles, CA). The top three greatest total cumulative health benefits under the Base electricity Case accrue to Los Angeles, CA ($63 billion), New York, NY ($25 billion), and San Francisco, CA ($23 billion). The top three greatest avoided premature mortality cases and avoided hospital admissions for respiratory symptoms also accrue to these metro areas. The top three metro areas with the greatest number of avoided respiratory symptoms and emergency room visits for asthma are Houston, TX, Los Angeles, CA, New York, NY.

Table 30 displays the same metrics for all vehicle classes under the Non-Combustion electricity case. Cumulative benefits for the metro areas of interest under the Non-Combustion electricity Case are roughly 50% larger than under the Base Case, ranging from $ 2.09 billion (Portland, OR) to $95.5 billion (Los Angeles, CA). The top three greatest total cumulative health benefits under the Non-Combustion electricity Case accrue to Los Angeles, CA ($96 billion), New York, NY ($84 billion), and

Chicago, IL ($46 billion). These three metro areas also show the highest values for avoided premature mortality cases, avoided hospital admissions for respiratory symptoms, and emergency room visits for asthma under this electricity Case. However, the top three metro areas with the greatest number of avoided respiratory symptoms are Los Angeles, CA, New York, NY, and Houston, TX.

Overall, variability in the health benefits outcomes among metro areas is driven by the magnitude and distribution of emissions changes between the affected sectors (i.e., on-road, electricity generation, refining) and their proximity to the metro area's population. In other words, across all Scenarios, metro areas with large, dense populations, particularly those close to roadways, tend to have higher benefits compared to less densely populated metro areas, while metro areas near the largest, dirtiest power plants, particularly coal-fired plants, tend to show disbenefits until the Scenario eliminates those emissions.

Table 27: Estimated annual health benefits by metro under the Base Case, considering all vehicle classes and 3% DR for years 2020, 2030, 2040, and 2050

	Total Health Benefits (High Estimate) Per Capita, 2017$				Total Health Benefits (High Estimate), Million 2017$				Avoided Premature Mortality Cases (High Estimate)			
Metro Area	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Atlanta--Athens-Clarke County--Sandy Springs, GA-AL	$0.01	$3.83	$30.40	$62.70	$0.055	$30.9	$281	$653	0.0054	2.96	25.6	55.9
Boston-Worcester-Providence, MA-RI-NH-CT	$0.02	$4.57	$30.00	$62.20	$0.134	$40.1	$274	$580	0.0134	3.87	25.1	49.9
Charlotte-Concord, NC-SC	$0.01	$3.72	$28.30	$60.10	$0.03	$12.3	$108	$260	0.00294	1.18	9.82	22.3
Chicago-Naperville, IL-IN-WI	$0.05	$11.10	$65.40	$135.00	$0.528	$120	$733	$1,550	0.0527	11.6	66.9	133.0
Cleveland-Akron-Canton, OH	-$0.01	$2.69	$31.80	$99.10	-$0.044	$9.73	$114	$345	-0.00439	0.942	10.5	29.8
Dallas-Fort Worth, TX-OK	$0.01	$4.77	$33.50	$69.80	$0.112	$45.9	$377	$907	0.0111	4.40	34.4	77.7
Denver-Aurora, CO	$0.03	$4.76	$25.30	$46.90	$0.096	$19.7	$119	$246	0.0095	1.89	10.8	21.0
Detroit-Warren-Ann Arbor, MI	$0.02	$7.45	$53.30	$121.00	$0.111	$40.0	$284	$631	0.0112	3.88	26.2	54.6
Houston-The Woodlands, TX	$0.08	$14.30	$70.00	$125.00	$0.61	$126	$724	$1,500	0.0604	12.0	65.7	128.0
Los Angeles-Long Beach, CA	$0.12	$21.90	$123.00	$217.00	$2.38	$470	$2,860	$5,410	0.239	45.7	264.0	470.0
Miami-Port St. Lucie-Fort Lauderdale, FL	-$0.01	$2.51	$28.90	$74.20	-$0.046	$20.4	$265	$756	-0.00456	1.96	24.3	65.1
Minneapolis-St. Paul, MN-WI	$0.01	$3.44	$23.40	$53.60	$0.042	$15.7	$117	$288	0.00417	1.51	10.7	24.8
New York-Newark, NY-NJ-CT-PA	$0.02	$6.21	$42.00	$88.80	$0.524	$152	$1,060	$2,270	0.0521	14.6	96.5	195.0
Orlando-Lakeland-Deltona, FL	-$0.01	$1.37	$18.30	$48.30	-$0.027	$6.48	$99.7	$300	-0.00278	0.613	9.03	25.6
Philadelphia-Reading-Camden, PA-NJ-DE-MD	$0.05	$10.30	$60.80	$126.00	$0.336	$79.2	$483	$1,020	0.0337	7.64	44.3	88.0
Phoenix-Mesa, AZ	$0.02	$5.39	$33.80	$61.10	$0.121	$32.3	$238	$498	0.0121	3.11	21.8	42.9
Pittsburgh-New Castle-Weirton, PA-OH-WV	$0.04	$12.50	$78.00	$179.00	$0.114	$32.5	$199	$438	0.0115	3.16	18.3	38.0
Portland-Vancouver-Salem, OR-WA	$0.02	$3.20	$16.50	$28.20	$0.064	$11.9	$68.7	$129.	0.00643	1.15	6.3	11.2
Sacramento-Roseville, CA	$0.05	$9.78	$52.50	$93.90	$0.142	$29.4	$174	$339	0.0142	2.83	15.9	29.2
Salt Lake City-Provo-Orem, UT	$0.02	$5.67	$38.00	$74.10	$0.055	$17.1	$130	$283	0.00553	1.64	11.9	24.3
San Diego-Chula Vista-Carlsbad, CA	$0.06	$12.30	$73.60	$139.00	$0.211	$47.7	$314	$646	0.0209	4.56	28.5	55.2
San Jose-San Francisco-Oakland, CA	$0.10	$17.70	$91.00	$163.00	$1.02	$189	$1,050	$1,980	0.102	18.3	96.0	171.0
Seattle-Tacoma, WA	$0.02	$3.50	$19.20	$33.30	$0.094	$19.2	$117	$224	0.00943	1.85	10.8	19.3

Metro Area	Total Health Benefits (High Estimate) Per Capita, 2017$				Total Health Benefits (High Estimate), Million 2017$				Avoided Premature Mortality Cases (High Estimate)			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
St. Louis-St. Charles-Farmington, MO-IL	-$0.04	-$1.30	$12.40	$55.50	-$0.108	-$4.03	$39.5	$179.	-0.0108	-0.391	3.61	15.4
Washington-Baltimore-Arlington, DC-MD-VA-WV-PA	$0.00	$2.10	$21.50	$58.40	-$0.031	$24.3	$277	$831	-0.00314	2.34	25.3	71.4

Table 28: Estimated annual health benefits by metro under the Non-Combustion Case, considering all vehicle classes and 3% discount rate for years 2020, 2030, 2040, and 2050

	Total Health Benefits (High Estimate) Per Capita, 2017$				Total Health Benefits (High Estimate), Million 2017$				Avoided Premature Mortality Cases (High Estimate)			
Metro Area	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Atlanta--Athens-Clarke County--Sandy Springs, GA-AL	$0.01	$52.00	$112.00	$111.00	$0.06	$420	$1,030	$1,160	0.00593	40.3	94.2	98.9
Boston-Worcester-Providence, MA-RI-NH-CT	$0.02	$60.50	$124.00	$119.00	$0.141	$530	$1,130	$1,110	0.0141	51.2	103.0	95.9
Charlotte-Concord, NC-SC	$0.01	$59.20	$120.00	$112.00	$0.032	$195	$456	$484	0.00321	18.8	41.7	41.5
Chicago-Naperville, IL-IN-WI	$0.05	$95.60	$202.00	$215.00	$0.543	$1,030	$2,260	$2,480	0.0542	99.1	206.0	213.0
Cleveland-Akron-Canton, OH	-$0.01	$159.00	$278.00	$240.00	-$0.034	$575	$994	$834	-0.00344	55.7	91.4	72.1
Dallas-Fort Worth, TX-OK	$0.01	$58.00	$122.00	$122.00	$0.119	$557	$1,370	$1,590	0.0118	53.5	125.0	136.0
Denver-Aurora, CO	$0.03	$29.30	$65.70	$72.60	$0.097	$121	$308	$381	0.00967	11.6	28.0	32.4
Detroit-Warren-Ann Arbor, MI	$0.02	$143.00	$272.00	$246.00	$0.123	$766	$1,450	$1,280	0.0124	74.2	133.0	111.0
Houston-The Woodlands, TX	$0.08	$63.90	$154.00	$180.00	$0.616	$562	$1,590	$2,160	0.061	53.8	144.0	184.0
Los Angeles-Long Beach, CA	$0.12	$58.00	$196.00	$273.00	$2.39	$1,250	$4,560	$6,810	0.24	121.0	422.0	592.0
Miami-Port St. Lucie-Fort Lauderdale, FL	$0.00	$93.50	$198.00	$192.00	-$0.036	$760	$1,820	$1,950	-0.00355	73.2	166.0	168.0
Minneapolis-St. Paul, MN-WI	$0.01	$59.80	$116.00	$109.00	$0.046	$272	$576	$585	0.00456	26.2	52.8	50.3
New York-Newark, NY-NJ-CT-PA	$0.02	$76.90	$165.00	$170.00	$0.549	$1,880	$4,150	$4,340	0.0546	181.0	379.0	373.0
Orlando-Lakeland-Deltona, FL	-$0.01	$55.40	$116.00	$116.00	-$0.024	$262	$631	$718	-0.00244	25.1	57.4	61.4
Philadelphia-Reading-Camden, PA-NJ-DE-MD	$0.05	$127.00	$256.00	$249.00	$0.349	$974	$2,030	$2,010	0.035	94.0	186.0	173.0
Phoenix-Mesa, AZ	$0.02	$28.90	$75.40	$88.30	$0.123	$173	$530	$721	0.0124	16.7	48.6	62.0
Pittsburgh-New Castle-Weirton, PA-OH-WV	$0.05	$201.00	$381.00	$363.00	$0.122	$524	$972	$891	0.0123	50.9	89.6	77.3
Portland-Vancouver-Salem, OR-WA	$0.02	$7.31	$23.60	$33.00	$0.064	$27.2	$98.3	$152.	0.00645	2.64	9.02	13.1
Sacramento-Roseville, CA	$0.05	$40.90	$109.00	$136.00	$0.143	$123	$363	$491	0.0143	11.8	33.2	42.3
Salt Lake City-Provo-Orem, UT	$0.02	$21.30	$66.30	$95.10	$0.056	$64.1	$227	$364	0.00561	6.16	20.7	31.2
San Diego-Chula Vista-Carlsbad, CA	$0.06	$44.10	$136.00	$189.00	$0.213	$171	$582	$876	0.021	16.3	52.8	74.9
San Jose-San Francisco-Oakland, CA	$0.10	$65.00	$178.00	$225.00	$1.03	$696	$2,050	$2,730	0.103	67.3	188.0	236.0
Seattle-Tacoma, WA	$0.02	$8.42	$27.60	$39.00	$0.095	$46.2	$169	$263	0.00947	4.46	15.5	22.6

Metro Area	Total Health Benefits (High Estimate) Per Capita, 2017$				Total Health Benefits (High Estimate), Million 2017$				Avoided Premature Mortality Cases (High Estimate)			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
St. Louis-St. Charles-Farmington, MO-IL	-$0.03	$115.00	$186.00	$151.00	-$0.102	$356.	$593.	$487.	-0.0102	34.3	54.3	41.8
Washington-Baltimore-Arlington, DC-MD-VA-WV-PA	$0.00	$77.90	$148.00	$138.00	-$0.019	$902	$1,910	$1,960	-0.00188	86.8	175.0	169.0

Table 29: Estimated cumulative annual health benefits, 2020-2050, by metro area under the Base Case, considering all vehicle classes and 3% discount rate

Metro Area	2020 Population	Total Health Benefits (High Estimate), Billion 2017$	Avoided Premature Mortality Cases (High Estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma	Asthma Exacerbation
Atlanta--Athens-Clarke County--Sandy Springs, GA-AL	6,930,000	$6.71	593	182	19,000	13,400	457	20,100
Boston-Worcester-Providence, MA-RI-NH-CT	8,290,000	$6.33	564	152	11,800	8,310	361	12,500
Charlotte-Concord, NC-SC	2,850,000	$2.63	233	72	7,110	5,000	166	7,420
Chicago-Naperville, IL-IN-WI	9,770,000	$17.0	1,520	455	39,200	27,500	1,030	40,800
Cleveland-Akron-Canton, OH	3,580,000	$3.13	278	71	4,880	3,420	113	5,060
Dallas-Fort Worth, TX-OK	8,190,000	$9.22	815	236	29,000	20,400	653	30,300
Denver-Aurora, CO	3,650,000	$2.74	242	76	9,520	6,700	190	10,000
Detroit-Warren-Ann Arbor, MI	5,320,000	$6.71	601	125	13,000	9,100	289	13,300
Houston-The Woodlands, TX	7,340,000	$16.8	1,480	450	64,400	45,200	1,380	66,500
Los Angeles-Long Beach, CA	18,600,000	$63.1	5,690	1,440	150,000	105,000	2,020	156,000
Miami-Port St. Lucie-Fort Lauderdale, FL	6,910,000	$7.01	620	197	11,900	8,340	321	12,300
Minneapolis-St. Paul, MN-WI	4,050,000	$2.91	258	56	7,840	5,510	99	8,050
New York-Newark, NY-NJ-CT-PA	22,500,000	$24.6	2,180	616	61,900	43,500	1,440	63,500
Orlando-Lakeland-Deltona, FL	4,230,000	$2.71	237	107	4,130	2,910	125	4,370
Philadelphia-Reading-Camden, PA-NJ-DE-MD	7,210,000	$11.2	1,000	271	24,800	17,400	773	25,800
Phoenix-Mesa, AZ	5,110,000	$5.45	485	115	14,500	10,200	289	15,300
Pittsburgh-New Castle-Weirton, PA-OH-WV	2,590,000	$4.72	424	72	6,260	4,390	161	6,520
Portland-Vancouver-Salem, OR-WA	3,280,000	$1.52	136	23	3,740	2,640	71	3,890
Sacramento-Roseville, CA	2,650,000	$3.9	348	78	9,560	6,710	147	9,970
Salt Lake City-Provo-Orem, UT	2,670,000	$3.03	269	55	13,400	9,430	100	14,100
San Diego-Chula Vista-Carlsbad, CA	3,330,000	$7.17	635	192	15,900	11,200	379	16,700

Metro Area	2020 Population	Total Health Benefits (High Estimate), Billion 2017$	Avoided Premature Mortality Cases (High Estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma	Asthma Exacerbation
San Jose-San Francisco-Oakland, CA	9,610,000	$23.2	2,080	609	58,200	40,800	884	60,800
Seattle-Tacoma, WA	4,950,000	$2.6	232	41	6,720	4,720	127	6,870
St. Louis-St. Charles-Farmington, MO-IL	2,910,000	$1.34	117	39	3,010	2,110	68	3,100
Washington-Baltimore-Arlington, DC-MD-VA-WV-PA	9,870,000	$7.59	669	206	20,100	14,100	475	20,600

Table 30: Estimated cumulative annual health benefits by 2050 by metro under the Non-Combustion Case, considering all vehicle classes and 3% discount rate

Metro Area	2020 Population	Total Health Benefits (High Estimate), Billion 2017$	Avoided Premature Mortality Cases (High Estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma	Asthma Exacerbation
Atlanta--Athens-Clarke County--Sandy Springs, GA-AL	6,930,000	$20.9	1,890	552	56,300	39,500	1,350	59,400
Boston-Worcester-Providence, MA-RI-NH-CT	8,290,000	$22.7	2,070	539	40,700	28,600	1,250	43,000
Charlotte-Concord, NC-SC	2,850,000	$9.17	833	239	22,200	15,600	520	23,200
Chicago-Naperville, IL-IN-WI	9,770,000	$46.5	4,230	1,250	108,000	75,800	2,840	113,000
Cleveland-Akron-Canton, OH	3,580,000	$20.3	1,870	456	30,300	21,200	707	31,500
Dallas-Fort Worth, TX-OK	8,190,000	$28.0	2,530	705	84,600	59,300	1,910	88,300
Denver-Aurora, CO	3,650,000	$6.39	574	173	21,400	15,000	428	22,500
Detroit-Warren-Ann Arbor, MI	5,320,000	$29.2	2,690	544	53,200	37,300	1,210	55,100
Houston-The Woodlands, TX	7,340,000	$33.4	3,000	893	126,000	88,200	2,700	130,000
Los Angeles-Long Beach, CA	18,600,000	$95.5	8,680	2,180	231,000	162,000	3,130	241,000
Miami-Port St. Lucie-Fort Lauderdale, FL	6,910,000	$36.5	3,320	1,060	60,300	42,200	1,770	62,300
Minneapolis-St. Paul, MN-WI	4,050,000	$11.7	1,070	225	29,800	20,900	368	30,700
New York-Newark, NY-NJ-CT-PA	22,500,000	$84.2	7,660	2,040	200,000	140,000	4,570	206,000
Orlando-Lakeland-Deltona, FL	4,230,000	$12.9	1,160	479	21,200	14,900	631	22,400
Philadelphia-Reading-Camden, PA-NJ-DE-MD	7,210,000	$41.1	3,760	988	83,400	58,400	2,630	86,600
Phoenix-Mesa, AZ	5,110,000	$11.0	994	232	29,000	20,400	579	30,700
Pittsburgh-New Castle-Weirton, PA-OH-WV	2,590,000	$19.9	1,830	318	25,000	17,500	688	26,100
Portland-Vancouver-Salem, OR-WA	3,280,000	$2.09	189	32	5,100	3,590	97	5,310
Sacramento-Roseville, CA	2,650,000	$7.56	683	154	18,600	13,100	288	19,400
Salt Lake City-Provo-Orem, UT	2,670,000	$4.91	440	92	22,500	15,800	173	23,600

Metro Area	2020 Population	Total Health Benefits (High Estimate), Billion 2017$	Avoided Premature Mortality Cases (High Estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma	Asthma Exacerbation
San Diego-Chula Vista-Carlsbad, CA	3,330,000	$12.4	1,100	331	27,900	19,600	662	29,200
San Jose-San Francisco-Oakland, CA	9,610,000	$42.5	3,850	1,070	108,000	75,300	1,610	113,000
Seattle-Tacoma, WA	4,950,000	$3.6	324	57	9,250	6,510	174	9,460
St. Louis-St. Charles-Farmington, MO-IL	2,910,000	$12.2	1,120	331	25,000	17,500	593	25,800
Washington-Baltimore-Arlington, DC-MD-VA-WV-PA	9,870,000	$38.9	3,540	1,050	101,000	70,700	2,390	104,000

Summary by Demographics

As an indication of, "who would benefit" from the transition described by the scenario, we consolidated the COBRA-based, county-resolved health benefits with county demographics. Per direction from the Lung Association, the demographic metric we considered is the share of the county population that identifies as People of Color (POC). As noted above, POC here is defined as identifying as any racial or ethnic groups other than *Not Hispanic, White alone*.[80]

We ranked counties by the percent of the population identifying as POC and then aggregated results into bins corresponding to the top 10, 50, 100, and 500 county and county equivalents based on county share of POC.[82,83] Figure 19 shows the counties in each of the selected bins in the national context as a map. Our results are limited to the top 500 counties by share of POC. After approximately the 700th county in ranked order, the share of POC reaches the national average value of 38.4%.[84]

Figure 19: Distribution of counties by % population persons of color

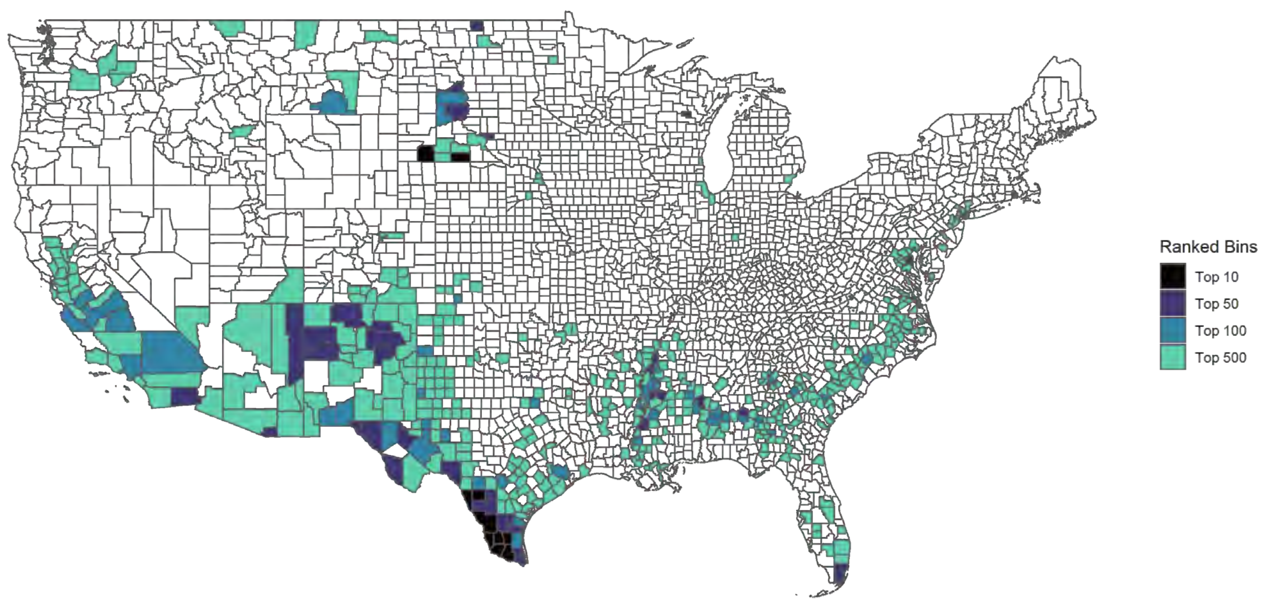


Table 32 shows total monetized health benefits per capita at a 3% discount rate, total monetized health benefits at a 3% discount rate, and percent of total national monetized health benefits at a 3% discount rate for each modeled year and by counties with the highest percentage of the population identifying as a person of color for all vehicle classes under the Base electricity Case.

82 For context, the U.S. has just over 3,100 county and county equivalents in the lower 48 states and Washington, D.C.
83 Importantly, this metric is share of population within the county, not the count of population by county. Thus high ranked counties by POC share may also be low in total population.
84 Calculated by subtracting percent white alone from 100%.
https://www.census.gov/library/stories/2021/08/improved-race-ethnicity-measures-reveal-united-states-population-much-more-multiracial.html

On a per-capita basis, total health benefits under the Base electricity Case are similar among the top 10 and top 50 counties ranked by POC share. For example, in 2050 the value is $61.30 among top 10 counties and $74.70 among the top 50 counties. However, per capita total health benefits under the Base electricity Case increase significantly among the top 100 counties ($139.00 in 2050) and then reduce somewhat among the top 500 counties ($105.00 in 2050).

Monetized health benefits among the top 100 ranked counties account for over 60% of total national health benefits in 2020, but this percentage decreases in later years (32% in 2030, 25.7% in 2040, and 21.9% in 2050). The large percent of total national health benefits values in 2020 among the top 100 ranked counties (60%) and the top 500 ranked counties (141%) are both likely due to the presence of counties with disbenefits. That is, the total benefits in the top 500 counties can be greater than the national total (all counties) because the estimated health impacts among several of the remaining 2,608 counties show disbenefits. (See Section 5.3.1.) Thus, the national total benefits estimate is smaller than the benefit accrued to the top 500 counties. The smaller share in later years is likely due to the reduced occurrence of estimated disbenefits among individual counties as the Scenario unfolds. For reference, in 2050 under the Base electricity Case for all vehicles, the top 100 POC counties make up just over 3% of all counties modeled but see nearly 22% of the national health benefits.

Table 33 shows the same metrics, but for the Non-Combustion electricity Case. These follow a similar trend as under the Base electricity Case, with increasing benefits among the top 10, 50, and 100 counties and a reduction in per capita benefits among the top 500 counties (except for 2030). Per capita benefits are $103 among the top 10 counties, $134 among the top 50 counties, $195 among the top 100 counties, and $163 among the top 500 counties in 2050. In 2020, the top 100 ranked counties account for over 55% of total national health benefits. The influence of disbenefits in some counties can also be seen here in the top 500 ranked county percent of total national health benefits metric for 2020.

Interestingly, while the total benefits estimate under the Non-Combustion electricity Case is significantly larger than that under the Base electricity Case, the share of national benefits in each bin – although still relatively large – is smaller under the Non-Combustion electricity case. This is likely due to the increased importance of electricity generating emissions reductions to total benefits under the Non-Combustion electricity Case, which may be spread around the country more evenly in terms of demographics (i.e., high POC vs. other counties).

Table 34 shows cumulative annual health benefits between 2020 and 2050, including total monetized health benefits at a 3% discount rate, percent of total national monetized health benefits at a 3% discount rate, avoided premature mortality cases (including both adult and infant mortality cases), avoided hospital admissions (all respiratory), avoided upper respiratory symptoms, avoided lower respiratory symptoms, and avoided emergency room visits for asthma for under the Base electricity Case. Total monetized health benefits in counties ranked as having high populations of people of color range from $1.57 billion (top 10 counties) to $209 billion (top 500 counties). As with the individual years, the percent of total cumulative health benefits increases as additional top ranked counties are added, but the benefits are somewhat top-loaded: 0.46% of national benefits among the top 10 counties ranked by POC (0.3% of all counties in the lower 48 states plus DC), 2.83% of benefits among top 50 counties (1.6% of counties), 24.0% among top 100 counties (3% of counties), and 61.7% among top 500 counties ranked by POC share (16% of counties). The numbers of avoided cases of adverse health endpoints follow a similar trend. Note that we do not present per capita results for cumulative impacts due to the changing populations over time.

Similarly, Table 35 shows cumulative annual health benefits between 2020 and 2050 under the Non-Combustion electricity Case. Total monetized health benefits in counties ranked as having high populations of people of color range from $4.19 billion (top 10 counties) to $487 billion (top 500 counties). The percent of total health benefits increases as additional top ranked counties are added: 0.34% among top 10 counties, 2.39% among top 50 counties, 12.8% among top 100 counties, and 40.1% among top 500 counties. The numbers of avoided health endpoint cases follow a similar trend.

Total health benefits under the Non-Combustion electricity Case are roughly double the total health benefits under the Base electricity Case for all top rank categories. As above, compared to the Non-Combustion electricity Case, the Base electricity Case shows a larger share of national cumulative benefits among the top 100 and top 500 counties ranked as share of POC. This is likely due to the increased benefits of cleaning the grid (including reductions in the base load) relative to transportation, and the trends of demographics near different source categories.[85]

85 Frumkin, Howard. "Guest editorial: health, equity, and the built environment." Environmental health perspectives 113.5 (2005): A290-A291; Austin, Elena, et al. "Distinct ultrafine particle profiles associated with aircraft and roadway traffic." Environmental science & technology 55.5 (2021): 2847-2858.

Table 31: Estimated annual health benefits by counties ranked by % population persons of color under the Base Case, considering all vehicle classes and 3% discount rate for years 2020, 2030, 2040, and 2050

		Total Health Benefits (High estimate) Per Capita, 2017$				Total Health Benefits (High estimate), Million 2017$				Percent of Total National Health Benefits (High Estimate)			
County Rank	**Range of 2020 % Population POC**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Top 10 Counties	92.40% to 97.30%	$0.01	$3.82	$27.50	$61.30	$0.02	$6.87	$60.4	$162.	0.44%	0.38%	0.43%	0.49%
Top 50 Counties	80.10% to 97.30%	$0.01	$4.35	$33.40	$74.70	$0.113	$45.4	$389.	$955.	2.51%	2.53%	2.78%	2.89%
Top 100 Counties	70.60% to 97.30%	$0.07	$13.00	$74.40	$139.00	$2.72	$577.	$3,600.	$7,250.	60.20%	32.00%	25.70%	21.90%
Top 500 Counties	44.60% to 97.30%	$0.05	$9.39	$54.80	$105.00	$6.38	$1,430.	$9,120.	$18,900.	141.00%	79.70%	65.30%	57.20%

Table 32: Estimated annual health benefits by counties ranked by % population persons of color under the Non-Combustion Case, considering all vehicle classes and 3% discount rate for years 2020, 2030, 2040, and 2050

		Total Health Benefits (High estimate) Per Capita, 2017$				Total Health Benefits (High estimate), Million 2017$				Percent of Total National Health Benefits (High Estimate)			
County Rank	**Range of 2020 % Population POC**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Top 10 Counties	92.40% to 97.30%	$0.01	$38.80	$90.60	$103.00	$0.021	$69.7	$199.	$274.	0.42%	0.25%	0.34%	0.44%
Top 50 Counties	80.10% to 97.30%	$0.01	$53.00	$121.00	$134.00	$0.121	$553.	$1,400.	$1,720.	2.46%	1.99%	2.36%	2.75%
Top 100 Counties	70.60% to 97.30%	$0.07	$56.40	$153.00	$195.00	$2.75	$2,500.	$7,410.	$10,200.	55.80%	8.99%	12.50%	16.30%
Top 500 Counties	44.60% to 97.30%	$0.05	$59.60	$141.00	$163.00	$6.5	$9,100.	$23,500.	$29,300.	132.00%	32.70%	39.60%	46.90%

Table 33: Estimated cumulative annual health benefits, 2020-2050, by counties ranked by % population persons of color under the Base Case, considering the Total vehicle class and 3% discount rate

County Rank	Range of 2020 % Population POC	Total Health Benefits (High estimate), Billion 2017$	Percent of Total National Health Benefits (High estimate)	Avoided Premature Mortality Cases (High estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma
Top 10 Counties	92.40% to 97.30%	$1.57	0.46%	138	45	7,150	5,010	130
Top 50 Counties	80.10% to 97.30%	$9.6	2.83%	852	223	28,900	20,300	569
Top 100 Counties	70.60% to 97.30%	$81.6	24.0%	7,310	1,960	235,000	165,000	3,680
Top 500 Counties	44.60% to 97.30%	$209.0	61.7%	18,700	5,260	566,000	397,000	10,600

Table 34: Estimated cumulative annual health benefits, 2020-2050, by counties ranked by % population persons of color under the Non-Combustion Case, considering the Total vehicle class and 3% discount rate

County Rank	Range of 2020 % Population POC	Total Health Benefits (High estimate), Billion 2017$	Percent of Total National Health Benefits (High	Avoided Premature Mortality Cases (High estimate)	Hospital Admits, All Respiratory	Upper Respiratory Symptoms	Lower Respiratory Symptoms	Emergency Room Visits, Asthma
Top 10 Counties	92.40% to 97.30%	$4.19	0.34%	376	121	19,800	13,900	358
Top 50 Counties	80.10% to 97.30%	$29.0	2.39%	2,630	660	85,300	59,700	1,610
Top 100 Counties	70.60% to 97.30%	$155.0	12.8%	14,000	3,710	459,000	321,000	7,570
Top 500 Counties	44.60% to 97.30%	$487.0	40.1%	44,100	12,500	1,310,000	919,000	26,000

6. Climate Benefits

6.1. Social Cost of Carbon

In addition to the direct health benefit to populations who will be exposed to improved levels of air quality from the Scenario, we also evaluated the benefits anticipated due to reductions in GHG emissions for the vehicle electrification Scenario. We considered both the reduction in direct (downstream) emissions from increased electrification as well as the global upstream emission changes from fuel production and increased load on the electric grid under both the Base and Non-Combustion Cases.[86] We monetized these values using the Social Cost of Carbon (SCC).

The Social Cost of CO_2 emissions (SC-CO_2) is a measure, in dollars, of the long-term damage done by a ton of carbon dioxide (CO_2) emissions in a given year. We used the interim SCC values published in February 2021 by the Interagency Working Group on Social Cost of Greenhouse Gases, United States Government[87]. Final values are expected to be published in the next few months. This dollar figure also represents the value of damages avoided for a small emission reduction (i.e., the benefit of a CO_2 reduction). As emission reductions include all GHG emissions quantified in this analysis and reported in terms of CO_2-equivalent, we applied the SC-CO_2 metric to estimate the benefits from avoided greenhouse gas emissions due to implementation of the vehicle electrification scenario.

SC-CO_2 is intended to be a comprehensive estimate of climate change damages and includes changes in net agricultural productivity, human health, property damages from increased flood risk, and value of ecosystem services. However, not all important damages are included due to data limitations. Once published, the final Biden administration values could differ substantially from those used here. They are anticipated to "consider climate risk, environmental justice, and intergenerational equity"[88].

For reference, the Social Cost of CO_2, in 2020 dollars per metric ton of CO2, for emissions occurring in year 2020, with a 3 percent discount rate is $51. For emissions in 2050, the same metric is valued at $85.

6.2. Calculated Benefits

Table 27 summarizes the results of the calculated benefits of the changes in GHG emissions expected under the electrification Scenario with both the Base and Non-Combustion Cases. These results use a 3 percent average discount rate. We have also updated the values to 2017 dollars to be consistent with the calculated health results using the Bureau of Labor Statistics CPI Inflation calculator. Values are shown in 2017 dollars and metric tons of GHG pollutant (as CO_2e).

Please note that CO_2e reductions here are calculated as the sum in changes from up- and downstream activities associated with vehicle electrification. That is, no BAU curve for sector-wide emissions for refining and electricity generation was developed for GHGs. (See Sections 4.2 and 4.3.)

86 The grid mixes used for each Case were discussed in Section 4.2. Note that the GREET emission factors used with these grid mixes include fugitive CH4 emissions during natural gas extraction and transport.
87 https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf
88 https://www.eenews.net/articles/here-comes-the-social-cost-of-carbon-will-it-address-ej/

Thus, there are no additional SCC benefits from "cleaning the grid" under the Non-Combustion case reflected here, only the incremental changes associated with vehicle electrification (under each electricity Case). This is consistent with the previous (2020) study but differs from the reductions used for health benefits (Section 5).

Table 35. Avoided Social Costs from GHG Reductions (metric tons of CO_2e), in 2017$ with a 3% Discount Rate.

Year	Base Case GHG Reduction (MT CO_2e)	Base Case Avoided Social Cost of CO_2e emissions	Non-Combustion Case GHG Reduction (MT CO_2e)	Non-Combustion Case Avoided Social Cost of CO_2e emissions
2020	1,200,000	$57,800,000	1,200,000	$57,900,000
2030	187,000,000	$11,000,000,000	227,000,000	$13,300,000,000
2040	879,000,000	$60,800,000,000	1,200,000,000	$83,000,000,000
2050	1,440,000,000	$116,000,000,000	1,810,000,000	$145,000,000,000
Cumulative 2020-2050	18,600,000,000	$1,360,000,000,000	24,200,000,000	$1,760,000,000,000

Appendix A: Detailed Emissions Summaries

Base Case Electrification, full emissions breakdown. Note that all GHG values shown here are domestic. (Global net GHG values are shown in Table 19)

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO2 Equivalent	NH_3
Downstream: Total Onroad Emissions						
Scenario						
2020	2,499,886	9,851	1,114,249	74,967	1,868,232,366	101,963
2030	1,132,406	7,251	606,958	40,860	1,411,442,122	82,761
2040	447,500	2,737	324,728	22,937	549,889,901	34,529
2050	91,194	573	120,053	16,318	114,362,760	7,632
BAU						
2020	2,500,170	9,861	1,114,721	74,991	1,869,885,514	102,064
2030	1,206,804	8,560	660,353	44,407	1,646,134,788	97,241
2040	1,007,353	8,266	561,626	40,044	1,604,560,779	99,762
2050	1,090,001	8,707	547,522	42,169	1,702,235,605	107,896
Change in Emissions, Nationally						
2020	-284	-10	-473	-24	-1,653,148	-101
2030	-74,398	-1,309	-53,395	-3,547	-234,692,666	-14,480
2040	-559,853	-5,529	-236,899	-17,106	-1,054,670,878	-65,233
2050	-998,808	-8,134	-427,469	-25,851	-1,587,872,845	-100,265
Change, percent						
2020	0%	0%	0%	0%	0%	0%
2030	-6%	-15%	-8%	-8%	-14%	-15%
2040	-56%	-67%	-42%	-43%	-66%	-65%
2050	-92%	-93%	-78%	-61%	-93%	-93%
Upstream: 1-Base (National) Electricity Case						
Crude, Feedstock, Refining and Transportation Emissions Avoided from Electrification, Domestic						
2020	-444	-128	-559	-35	-423,762	N/A
2030	-58,969	-16,772	-70,405	-4,592	-55,843,321	N/A
2040	-253,090	-69,370	-280,342	-19,250	-237,717,792	N/A
2050	-384,751	-106,847	-405,604	-28,989	-355,975,180	N/A
Additional Emissions due to Additional Grid Load						
2020	564	472	90	48	814,384	N/A
2030	62,208	51,557	10,209	5,271	91,735,747	N/A
2040	236,890	184,649	40,357	19,902	354,537,666	N/A
2050	250,195	101,807	53,207	19,526	400,155,528	N/A
Net Emissions Change from Avoided Crude, Feedstock, Refining and Transport Emissions, and Additional EGUs, Domestic						
2020	120	344	-469	12	390,621	N/A
2030	3,239	34,786	-60,196	679	35,892,426	N/A
2040	102,888	115,279	-239,985	652	116,819,874	N/A

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO2 Equivalent	NH_3
2050	-134,556	-5,040	-352,398	-9,463	44,180,347	N/A
Total BAU Emissions, Domestic						
2020	1,627,345	935,258	3,329,915	177,376	N/A	47,540
2030	1,711,797	888,074	4,058,346	179,275	N/A	45,431
2040	1,667,947	815,711	3,999,499	175,000	N/A	44,030
2050	1,554,016	478,227	4,011,338	145,070	N/A	37,206
Percent Net Change in Emissions from BAU, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	0%	4%	-1%	0%	N/A	N/A
2040	-1%	14%	-6%	0%	N/A	N/A
2050	-9%	-1%	-9%	-7%	N/A	N/A
Combined						
Net Emissions Change, Nationally						
2020	-165	334	-942	-12	-1,262,526	N/A
2030	-71,159	33,476	-113,592	-2,868	-198,800,240	N/A
2040	-576,052	109,751	-478,032	-16,455	-937,851,005	N/A
2050	-1,133,364	-13,174	-779,867	-35,314	-1,543,692,498	N/A
National BAU						
2020	4,127,515	945,119	4,444,636	252,367	N/A	149,604
2030	2,918,601	896,634	4,718,699	223,682	N/A	142,672
2040	2,675,300	823,977	4,561,125	215,044	N/A	143,792
2050	2,644,017	486,934	4,558,861	187,239	N/A	145,102
Percent Net Change in Emissions from BAU, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-2%	4%	-2%	-1%	N/A	N/A
2040	-22%	13%	-10%	-8%	N/A	N/A
2050	-43%	-3%	-17%	-19%	N/A	N/A

Non-Combustion Case Electrification, full emissions breakdown. Note that all GHG values shown here are domestic. (Global net GHG values are shown in). Here both baseline and new load from the Scenario are assigned to the Non-Combustion Case electric grid.

Year	NOx	SO2	VOC	$PM_{2.5}$ Total	CO2 Equivalent	NH3
Downstream: Total Onroad Emissions						
Scenario						
2020	2,499,886	9,851	1,114,249	74,967	1,868,232,366	101,963
2030	1,132,406	7,251	606,958	40,860	1,411,442,122	82,761
2040	447,500	2,737	324,728	22,937	549,889,901	34,529
2050	91,194	573	120,053	16,318	114,362,760	7,632
BAU						
2020	2,500,170	9,861	1,114,721	74,991	1,869,885,514	102,064
2030	1,206,804	8,560	660,353	44,407	1,646,134,788	97,241
2040	1,007,353	8,266	561,626	40,044	1,604,560,779	99,762
2050	1,090,001	8,707	547,522	42,169	1,702,235,605	107,896
Change in Emissions, Nationally						
2020	-284	-10	-473	-24	-1,653,148	-101
2030	-74,398	-1,309	-53,395	-3,547	-234,692,666	-14,480
2040	-559,853	-5,529	-236,899	-17,106	-1,054,670,878	-65,233
2050	-998,808	-8,134	-427,469	-25,851	-1,587,872,845	-100,265
Change, percent						
2020	0%	0%	0%	0%	0%	0%
2030	-6%	-15%	-8%	-8%	-14%	-15%
2040	-56%	-67%	-42%	-43%	-66%	-65%
2050	-92%	-93%	-78%	-61%	-93%	-93%
Upstream: 3-Non-Combustion Renewables Case, for additional EV load and rest of grid						
Feedstock, Crude, Refining, and Transportation Emissions Reductions, Domestic						
2020	-444	-128	-559	-35	-423,762	N/A
2030	-58,969	-16,772	-70,405	-4,592	-55,843,321	N/A
2040	-253,090	-69,370	-281,490	-19,250	-237,717,792	N/A
2050	-384,751	-106,847	-405,604	-28,989	-355,975,180	N/A
Additional Upstream Emissions due to Additional Grid Load, Non-Combustion Case						
2020	546	462	90	47	812,076	N/A
2030	28,484	10,188	6,418	2,208	47,719,961	N/A
2040	1,314	34	389	44	315,064	N/A
2050	1,799	47	533	61	431,504	N/A
Net Upstream Emissions Change: Avoided Crude, Feedstock, Refining and Transport Emissions, and Additional EGUs, Non-Combustion Case, Domestic						
2020	102	334	-469	12	388,314	N/A
2030	-30,485	-6,583	-63,987	-2,384	-8,123,360	N/A
2040	-251,776	-69,336	-281,101	-19,206	-237,402,729	N/A
2050	-382,952	-106,800	-405,071	-28,928	-355,543,677	N/A

Year	NOx	SO2	VOC	$PM_{2.5}$ Total	CO2 Equivalent	NH3
Total BAU Upstream Emissions, Non-Combustion Case with Non-Combustion BAU, Domestic						
2020	1,627,345	935,258	3,329,915	177,376	N/A	47,540
2030	1,352,499	370,812	4,046,127	117,279	N/A	27,605
2040	1,004,626	225,274	3,964,576	70,378	N/A	11,121
2050	1,027,456	235,077	3,976,751	71,990	N/A	11,082
Percent Net Change in Upstream Emissions from Upstream BAU, Non-Combustion Case, Non-Combustion Load, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-2%	-2%	-2%	-2%	N/A	N/A
2040	-25%	-31%	-7%	-27%	N/A	N/A
2050	-37%	-45%	-10%	-40%	N/A	N/A
Combined						
Net Emissions Change, Nationally						
2020	-182	324	-941	-13	-1,264,834	N/A
2030	-104,883	-7,892	-117,382	-5,931	-242,816,026	N/A
2040	-811,629	-74,865	-517,999	-36,313	-1,292,073,607	N/A
2050	-1,381,760	-114,935	-832,540	-54,779	-1,943,416,522	N/A
National BAU						
2020	4,127,515	945,119	4,444,636	252,367	N/A	149,604
2030	2,559,304	379,372	4,706,480	161,686	N/A	124,846
2040	2,011,979	233,540	4,526,202	110,422	N/A	110,883
2050	2,117,457	243,784	4,524,273	114,159	N/A	118,978
Percent Net Change in Emissions from BAU, National Scenario, Domestic						
2020	0%	0%	0%	0%	N/A	N/A
2030	-4%	-2%	-2%	-4%	N/A	N/A
2040	-40%	-32%	-11%	-33%	N/A	N/A
2050	-65%	-47%	-18%	-48%	N/A	N/A

Appendix B: COBRA Emission Tiers Incorporated in Calculating the BAU Emission Inventory

Tier 1 Number	Tier 2 Number	Tier 3 Number	Tier 1 Name	Tier 2 Name	Tier 3 Name	Notes
Upstream Petroleum – Refining, Storage, and Transport						
2	2	1	Fuel Combustion: Industrial	Oil	Residual	
2	2	2	Fuel Combustion: Industrial	Oil	Distillate	
2	2	99	Fuel Combustion: Industrial	Oil	Other	
2	3	1	Fuel Combustion: Industrial	Gas	Natural	
2	3	2	Fuel Combustion: Industrial	Gas	Process	
2	3	99	Fuel Combustion: Industrial	Gas	Other	
2	4	99	Fuel Combustion: Industrial	Other	Other	
6	1	1	Petroleum & Related Industries	Oil & Gas Production	Natural Gas	*Included in BAU. However, Scenario reductions in upstream emissions will not be applied to natural gas production Tiers in health modeling.*
6	1	99	Petroleum & Related Industries	Oil & Gas Production	Other	
6	2	1	Petroleum & Related Industries	Petroleum Refineries & Related Industries	Fluid Catalytic Cracking Units	
6	2	2	Petroleum & Related Industries	Petroleum Refineries & Related Industries	Vacuum Distillation	
6	2	3	Petroleum & Related Industries	Petroleum Refineries & Related Industries	Process Unit Turnarounds	
6	2	4	Petroleum & Related Industries	Petroleum Refineries & Related Industries	Petroleum Refinery Fugitives	

Tier 1 Number	Tier 2 Number	Tier 3 Number	Tier 1 Name	Tier 2 Name	Tier 3 Name	Notes
6	2	99	Petroleum & Related Industries	Petroleum Refineries & Related Industries	Other	
6	3	99	Petroleum & Related Industries	Asphalt Manufacturing	Other	*Included in BAU. However, Scenario reductions in upstream emissions will not be applied to asphalt manufacturing Tiers in health modeling.*
7	99	1	Other Industrial Processes	Miscellaneous Industrial Processes	Ethanol Production	
9	1	1	Storage & Transport	Bulk Terminals & Plants	Fixed Roof	
9	1	2	Storage & Transport	Bulk Terminals & Plants	Floating Roof	
9	1	3	Storage & Transport	Bulk Terminals & Plants	Variable Vapor Space	
9	1	4	Storage & Transport	Bulk Terminals & Plants	External Floating Roof With Seals	
9	1	5	Storage & Transport	Bulk Terminals & Plants	Internal Floating Roof With Seals	
9	1	6	Storage & Transport	Bulk Terminals & Plants	Underground Tanks	
9	1	7	Storage & Transport	Bulk Terminals & Plants	Area Source: Gasoline	
9	1	99	Storage & Transport	Bulk Terminals & Plants	Other	
9	2	1	Storage & Transport	Petroleum & Petroleum Product Storage	Fixed Roof Gasoline	
9	2	2	Storage & Transport	Petroleum & Petroleum Product Storage	Fixed Roof Crude	
9	2	3	Storage & Transport	Petroleum & Petroleum Product Storage	Floating Roof Gasoline	
9	2	4	Storage & Transport	Petroleum & Petroleum Product Storage	Floating Roof Crude	
9	2	5	Storage & Transport	Petroleum & Petroleum Product Storage	External Floating Roof / Seal Gasoline	
9	2	6	Storage & Transport	Petroleum & Petroleum Product Storage	External Floating Roof / Seal Crude	

Tier 1 Number	Tier 2 Number	Tier 3 Number	Tier 1 Name	Tier 2 Name	Tier 3 Name	Notes
9	2	7	Storage & Transport	Petroleum & Petroleum Product Storage	Internal Floating Roof / Seal Gasoline	
9	2	8	Storage & Transport	Petroleum & Petroleum Product Storage	Internal Floating Roof / Seal Crude	
9	2	9	Storage & Transport	Petroleum & Petroleum Product Storage	Variable Vapor Space Gasoline	
9	2	10	Storage & Transport	Petroleum & Petroleum Product Storage	Area Source: Gasoline	
9	2	99	Storage & Transport	Petroleum & Petroleum Product Storage	Other	
9	3	1	Storage & Transport	Petroleum & Petroleum Product Transport	Gasoline Loading: Normal / Splash	
9	3	2	Storage & Transport	Petroleum & Petroleum Product Transport	Gasoline Loading: Balanced / Submerged	
9	3	3	Storage & Transport	Petroleum & Petroleum Product Transport	Gasoline Loading: Normal / Submerged	
9	3	4	Storage & Transport	Petroleum & Petroleum Product Transport	Gasoline Loading: Clean / Submerged	
9	3	5	Storage & Transport	Petroleum & Petroleum Product Transport	Marine Vessel Loading: Gasoline	
9	3	99	Storage & Transport	Petroleum & Petroleum Product Transport	Other	
9	4	99	Storage & Transport	Service Stations: Stage I	Other	
9	5	99	Storage & Transport	Service Stations: Stage II	Other	
9	6	99	Storage & Transport	Service Stations: Breathing & Emptying	Other	
Electricity Generating Units						
1	1	1	Fuel Combustion: Electric Utility	Coal	Bituminous	
1	1	2	Fuel Combustion: Electric Utility	Coal	Subbituminous	

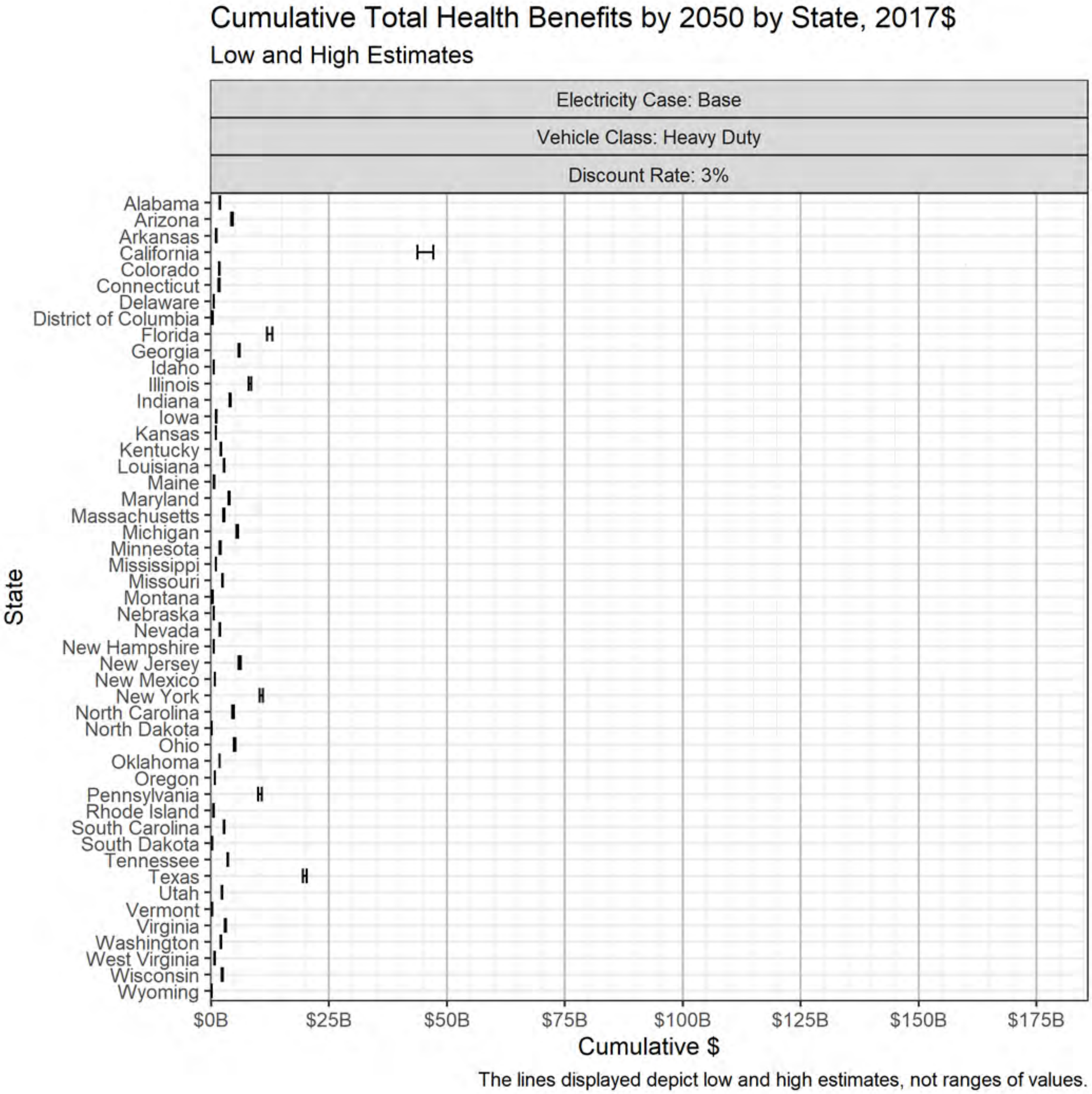
Tier 1 Number	Tier 2 Number	Tier 3 Number	Tier 1 Name	Tier 2 Name	Tier 3 Name	Notes
1	1	3	Fuel Combustion: Electric Utility	Coal	Anthracite & Lignite	
1	2	1	Fuel Combustion: Electric Utility	Oil	Residual	
1	2	2	Fuel Combustion: Electric Utility	Oil	Distillate	
1	3	1	Fuel Combustion: Electric Utility	Gas	Natural	
1	3	2	Fuel Combustion: Electric Utility	Gas	Process	
1	4	99	Fuel Combustion: Electric Utility	Other	Other	
1	5	99	Fuel Combustion: Electric Utility	Internal Combustion	Other	

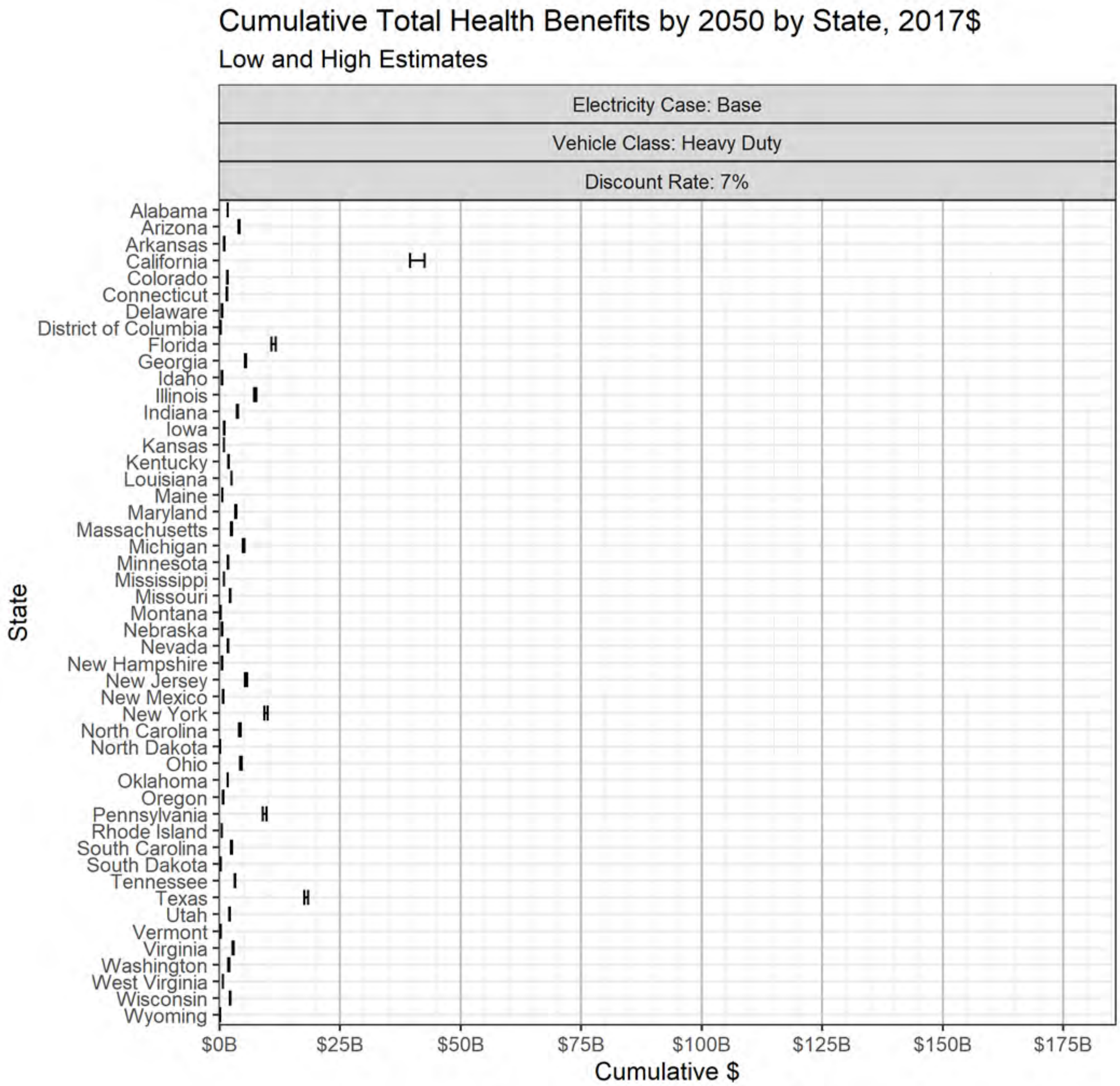
Appendix C: COBRA Health Endpoints

Health Endpoint	Author(s)	Year	Applicable Ages
Acute Bronchitis	Dockery et al.	1996	8-12
Acute Myocardial Infarction, Nonfatal (high)	Peters et al.	2001	18-99
Acute Myocardial Infarction, Nonfatal (low)	Pope et al.	2006	0-99
Acute Myocardial Infarction, Nonfatal (low)	Sullivan et al.	2005	0-99
Acute Myocardial Infarction, Nonfatal (low)	Zanobetti and Schwartz	2006	0-99
Acute Myocardial Infarction, Nonfatal (low)	Zanobetti et al.	2009	0-99
Asthma Exacerbation, Cough	Mar et al.	2004	6-17
Asthma Exacerbation, Cough	Ostro et al.	2001	6-17
Asthma Exacerbation, Shortness of Breath	Mar et al.	2004	6-17
Asthma Exacerbation, Shortness of Breath	Ostro et al.	2001	6-17
Asthma Exacerbation, Wheeze	Ostro et al.	2001	6-17
Asthma Exacerbation, Cough	Mar et al.	2004	18-18
Asthma Exacerbation, Cough	Ostro et al.	2001	18-18
Asthma Exacerbation, Shortness of Breath	Mar et al.	2004	18-18
Asthma Exacerbation, Shortness of Breath	Ostro et al.	2001	18-18
Asthma Exacerbation, Wheeze	Ostro et al.	2001	18-18
Emergency Room Visits, Asthma	Mar et al.	2010	0-99
Emergency Room Visits, Asthma	Slaughter et al.	2005	0-99
Emergency Room Visits, Asthma	Glad et al.	2012	0-99
HA, All Cardiovascular (less Myocardial Infarctions)	Moolgavkar	2000	18-64
HA, All Cardiovascular (less Myocardial Infarctions)	Bell et al.	2008	65-99
HA, All Cardiovascular (less Myocardial Infarctions)	Peng et al.	2008	65-99
HA, All Cardiovascular (less Myocardial Infarctions)	Peng et al.	2009	65-99
HA, All Cardiovascular (less Myocardial Infarctions)	Zanobetti et al	2009	65-99
HA, All Respiratory	Zanobetti et al	2009	65-99
HA, All Respiratory	Kloog et al.	2012	65-99
HA, Asthma	Babin et al.	2007	0-17
HA, Asthma	Sheppard	2003	0-17
HA, Chronic Lung Disease	Moolgavkar	2000	18-64
Lower Respiratory Symptoms	Schwartz and Neas	2000	7-14
Minor Restricted Activity Days	Ostro and Rothschild	1989	18-64
Mortality, All Cause (low)	Krewski et al.	2009	30-99
Mortality, All Cause (high)	Di et al.	2017	65-99
Infant Mortality	Woodruff et al.	1997	0-0
Upper Respiratory Symptoms	Pope et al.	1991	9-11
Work Loss Days	Ostro	1987	18-64

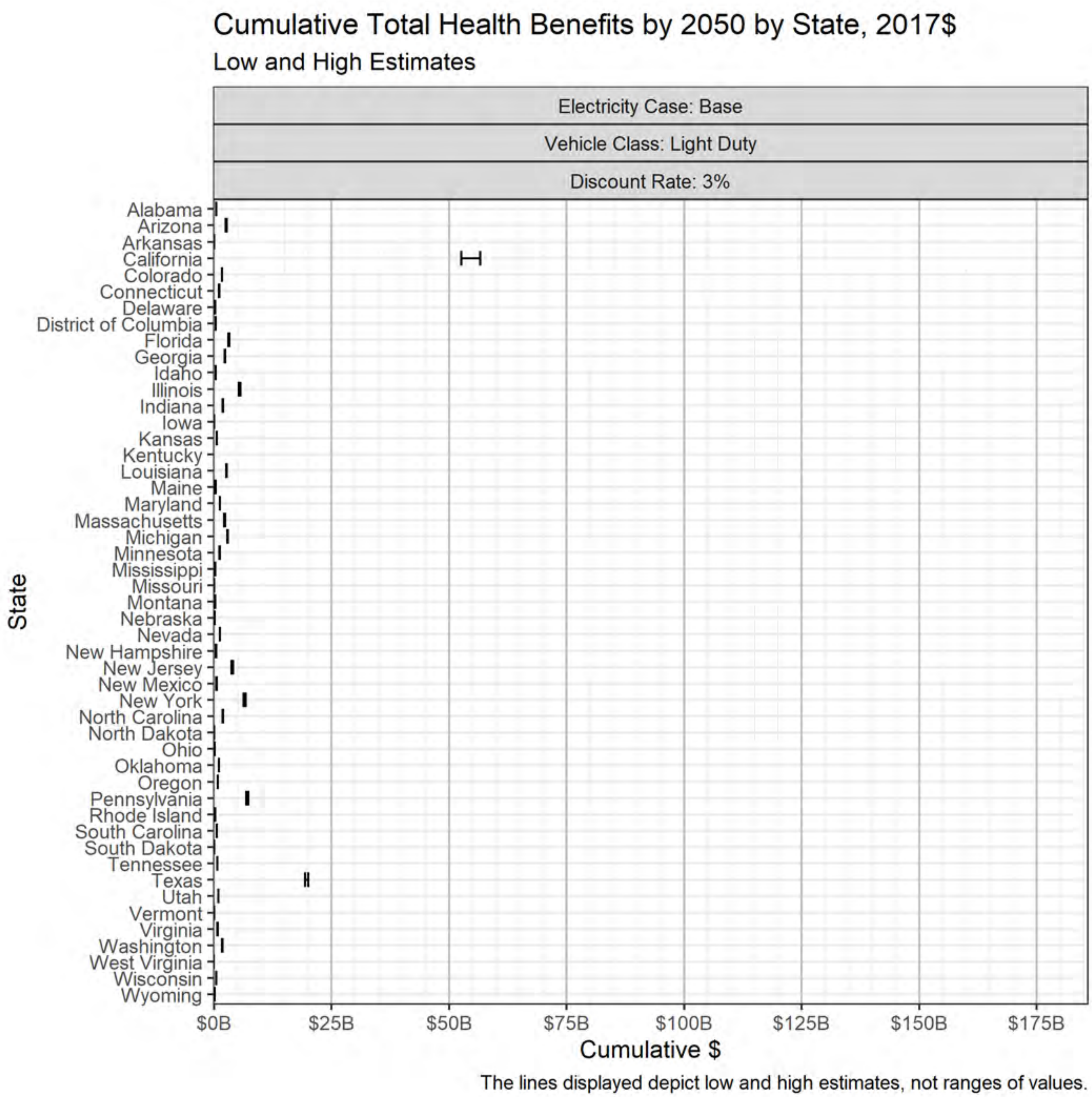
Appendix D: Cumulative Total Health Benefits by State by 2050

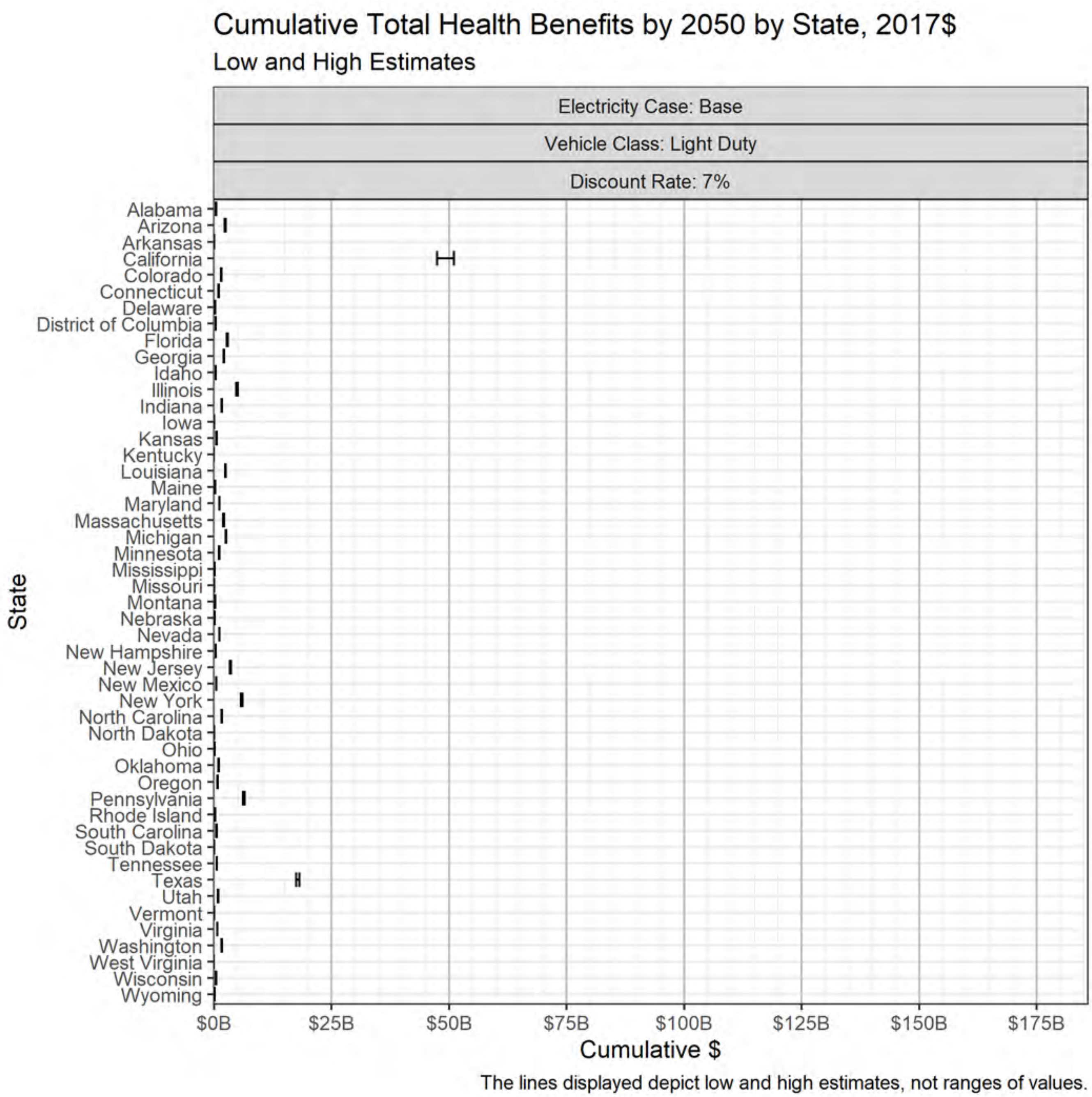
The following plots show the cumulative total health benefits by State by 2050 for each electricity case, vehicle class, and discount rate.

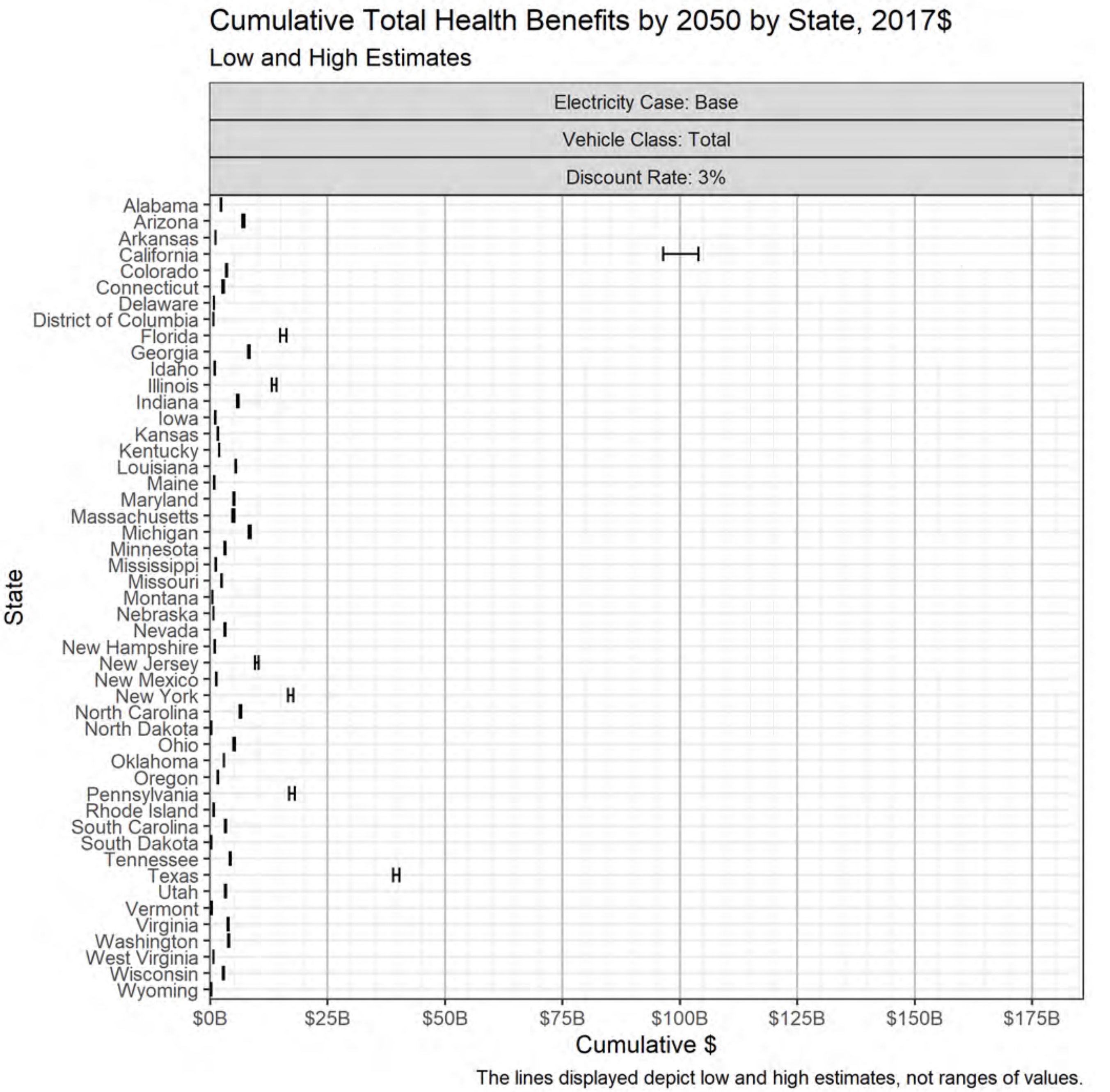


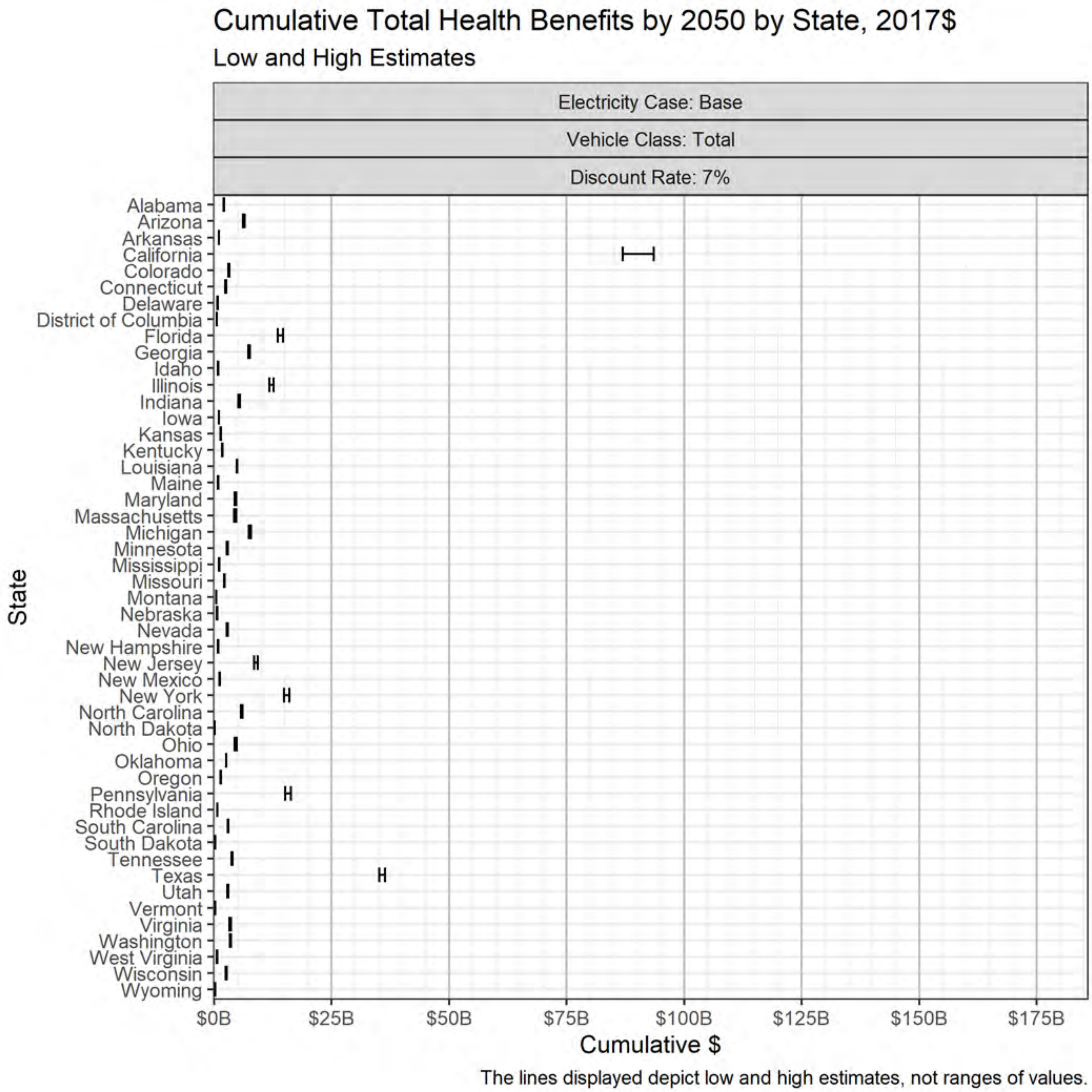


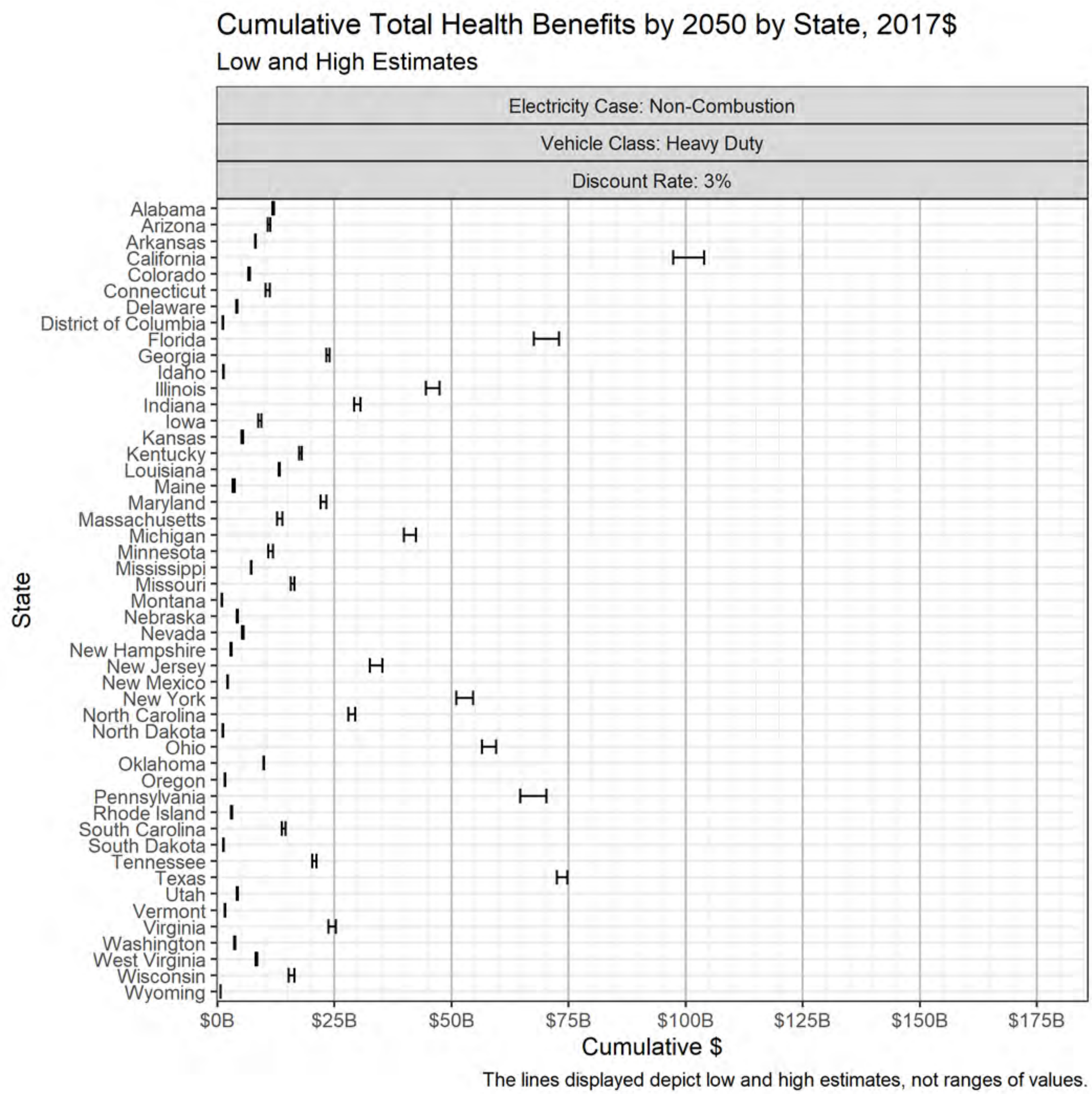
The lines displayed depict low and high estimates, not ranges of values.

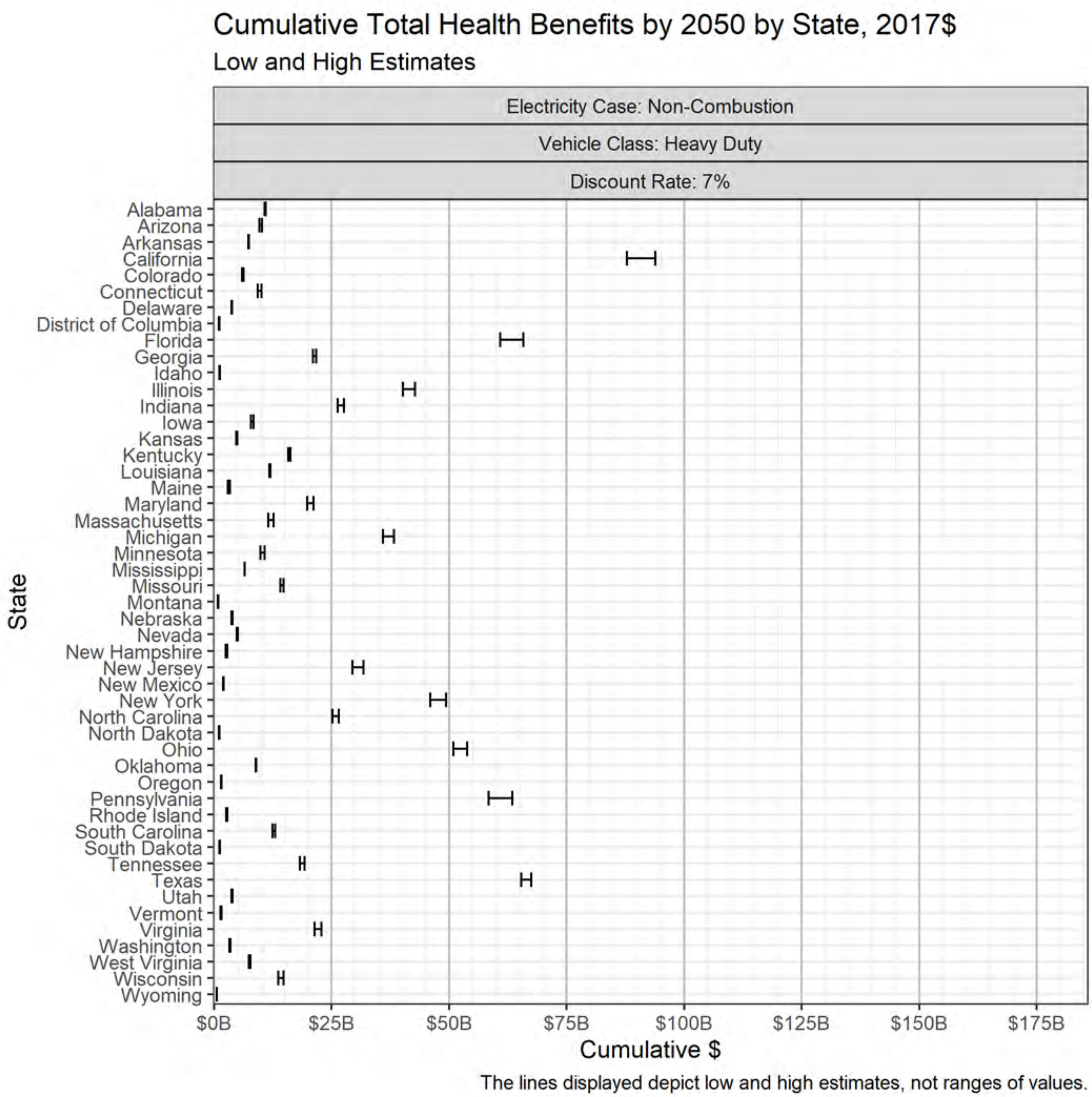

Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Base
Vehicle Class: Light Duty
Discount Rate: 3%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.

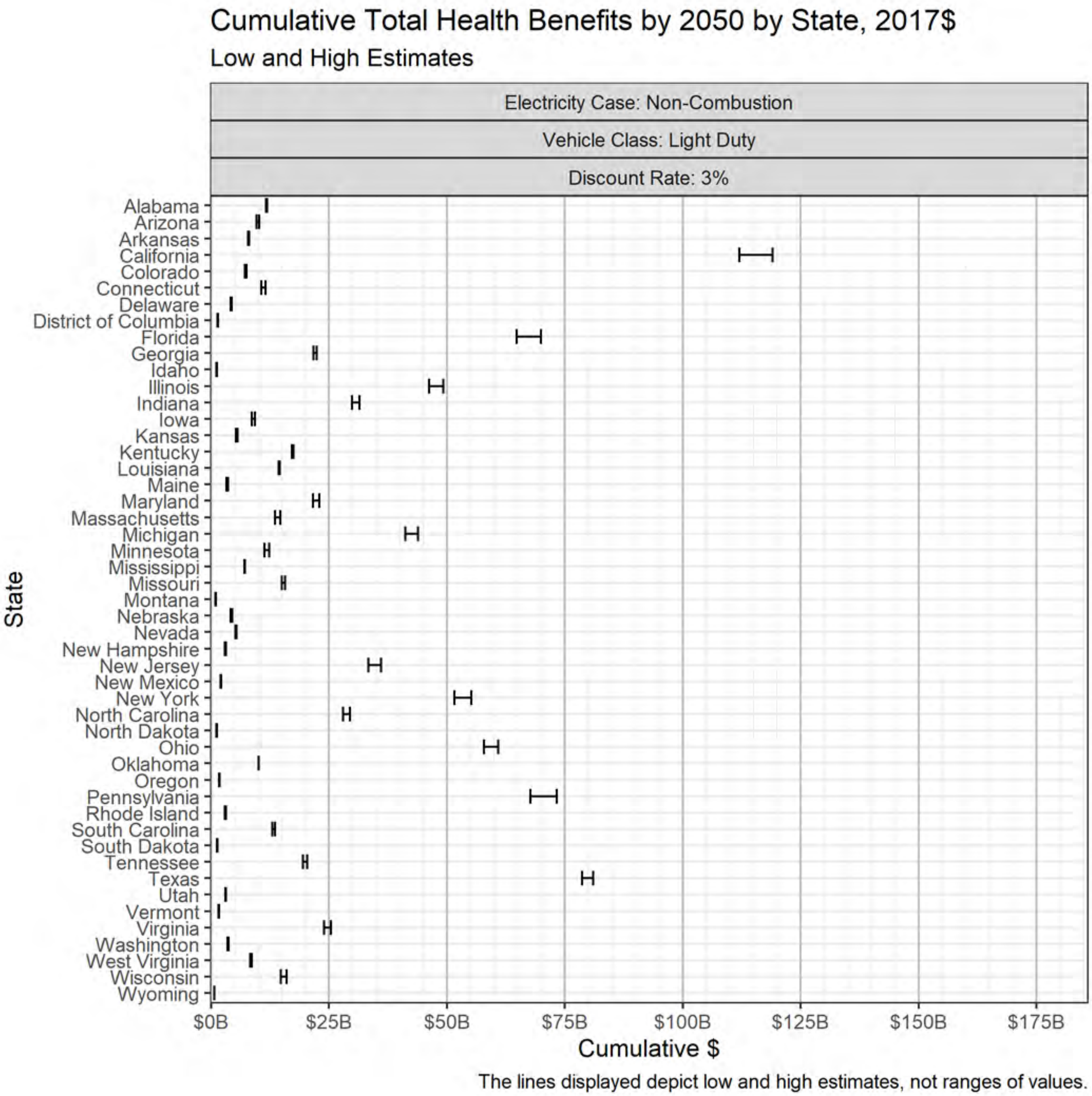

Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Base
Vehicle Class: Light Duty
Discount Rate: 7%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.

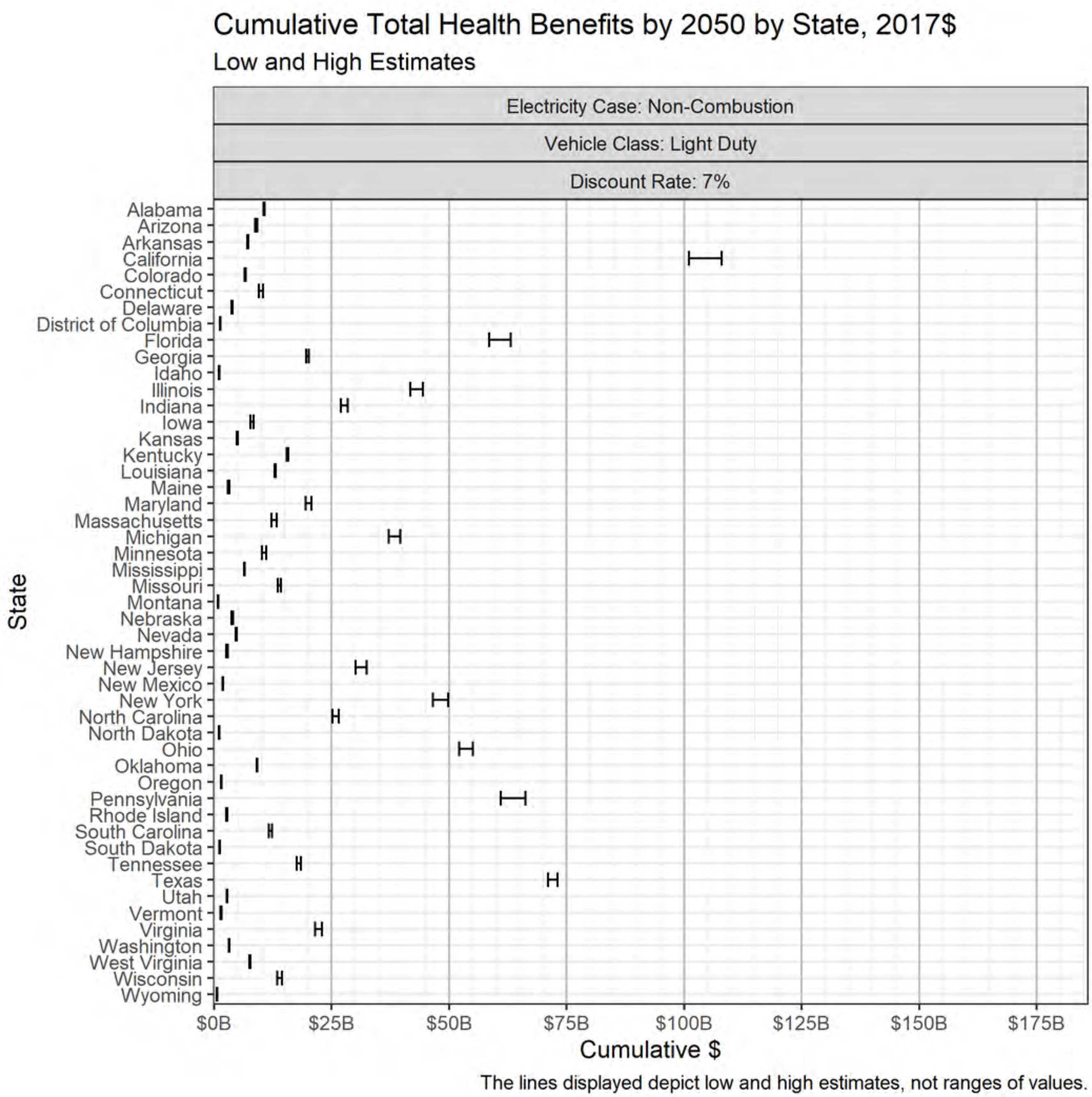

Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Base
Vehicle Class: Total
Discount Rate: 3%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.


Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Base
Vehicle Class: Total
Discount Rate: 7%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.


Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Heavy Duty
Discount Rate: 3%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.


Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Heavy Duty
Discount Rate: 7%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.


Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Light Duty
Discount Rate: 3%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.


Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Light Duty
Discount Rate: 7%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
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Vermont
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Washington
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Wisconsin
Wyoming
$0B
$25B
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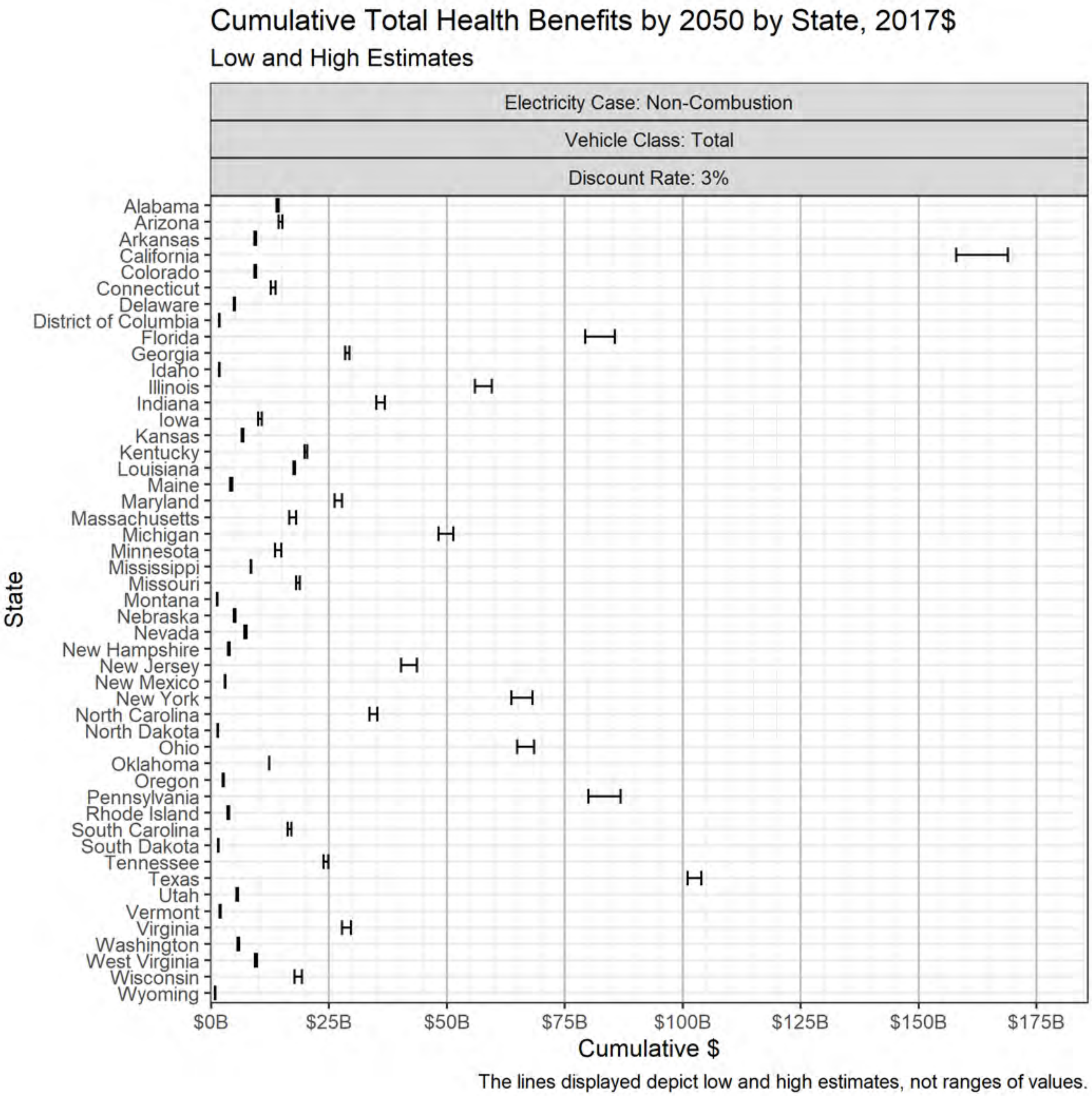
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.


Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Total
Discount Rate: 3%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
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Maryland
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Missouri
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New Hampshire
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North Carolina
North Dakota
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Washington
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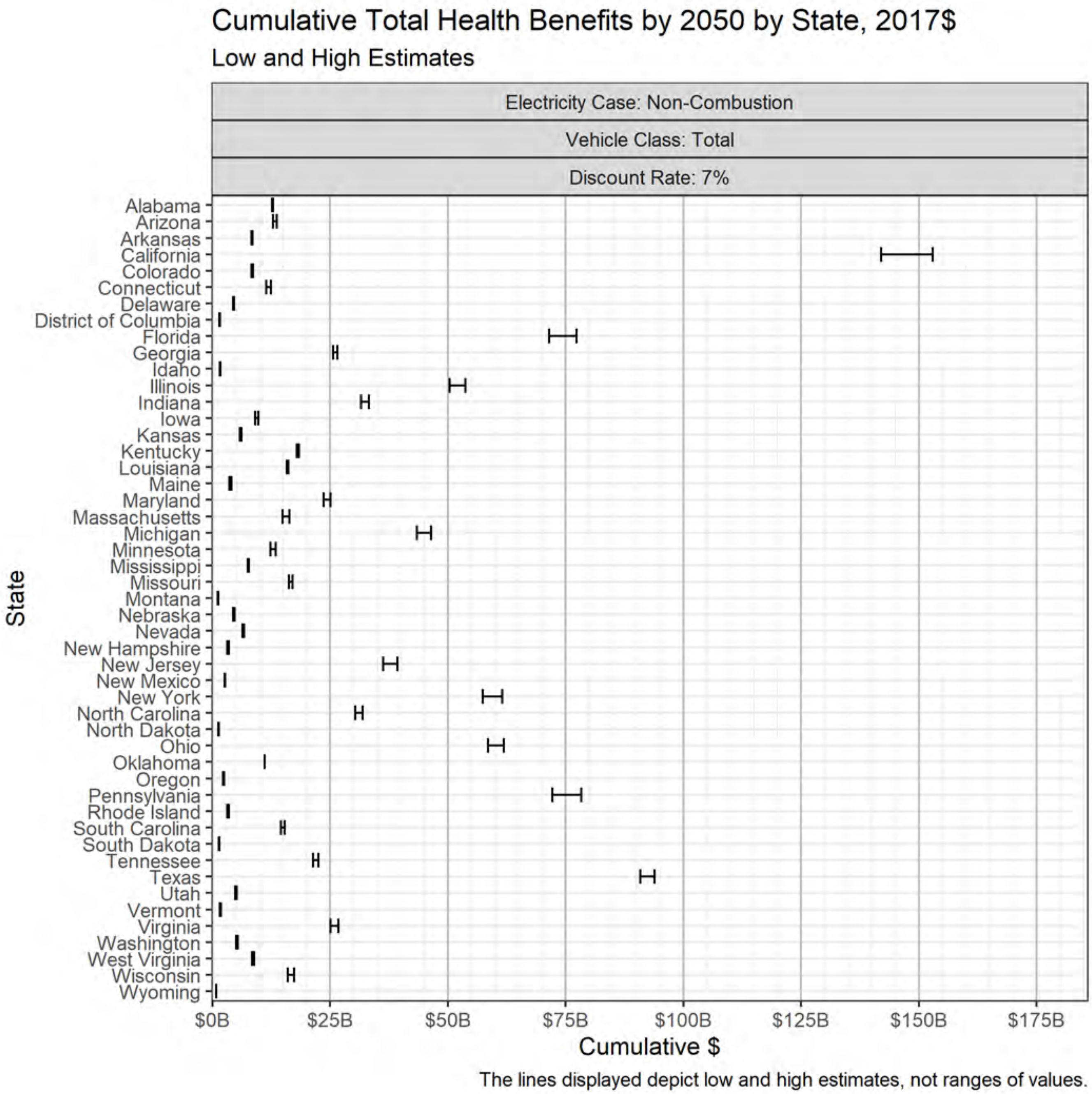
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.



Cumulative Total Health Benefits by 2050 by State, 2017$
Low and High Estimates
Electricity Case: Non-Combustion
Vehicle Class: Total
Discount Rate: 7%
State
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
District of Columbia
Florida
Georgia
Idaho
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Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
$0B
$25B
$50B
$75B
$100B
$125B
$150B
$175B
Cumulative $
The lines displayed depict low and high estimates, not ranges of values.

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Sacramento, CA 95819
(916) 607-4543
williamjbarrett4@gmail.com

William Barrett

Professional Experience:

American Lung Association — Jan 2009 – Present
National Senior Director, Clean Air Advocacy — Sacramento, CA

- Develop and implement California air quality and climate policy agenda
- Engage policymakers at the local, state and federal levels
- Act as a national media spokesperson on air quality and climate change priorities
- Recruit and supervise the work of advocacy staff, interns and consultants in multiple states
- Author research and advocacy materials for field staff, volunteers and coalition partners
- Develop grant funding proposals, track progress and prepare annual grant reports
- Represent the organization within coalitions, agency work groups and policy committees

California Voter Foundation — Jan 2007 – Dec 2008
Program Manager — Sacramento, CA

- Managed national "Campaign Disclosure Project" related to state election practices
- Conducted research, state agency surveys, report preparation and media outreach
- Coordinated work of researchers, technology and design consultants and partner organizations (UCLA School of Law and the Center for Governmental Studies)
- Provided constituent support and public education via the "California Online Voter Guide"

Community Services Planning Council — Nov 2003 – Jan 2007
Program Coordinator — Sacramento, CA

- Supported projects related to local allocation of federal HIV/AIDS grant funding
- Drafted Council policies, procedures, service standards and constituent updates
- Facilitated constituent committee and Council meetings

Independent Consultant — 2003 - 2009
Campaign Finance and Lobbying Research — Sacramento, CA

- Managed client research projects and reports on industry political influence campaigns

Education:

The Evergreen State College — 2003
Bachelor of Arts, Political Science — Olympia, WA

Yale School of Public Health — 2019
Climate Change and Health Certificate Program

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EXHIBIT
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