

1 **Title**

2 California's early transition to electric vehicles: observed health and air quality co-benefits

3

4 **Authors name and affiliations**

5 Erika Garcia<sup>1</sup>, Jill Johnston<sup>1</sup>, Rob McConnell<sup>1</sup>, Lawrence Palinkas<sup>1,2</sup>, Sandrah P. Eckel<sup>1</sup>

6

7 <sup>1</sup>University of Southern California, Population and Public Health Sciences,

8 Los Angeles, California, United States

9 <sup>2</sup>University of Southern California, Suzanne Dworak Peck School of Social Work,

10 Los Angeles, California, United States

11

12 **Corresponding author**

13 Erika Garcia

14 Keck School of Medicine of USC

15 1845 N. Soto Street

16 SSB1 Rm 225F MC 9237

17 Los Angeles, CA 90089-9237

18 Tel: (323) 442-1092

19 Email: [garc991@usc.edu](mailto:garc991@usc.edu)

1 **ABSTRACT**

2

3 The transition to electric vehicles is projected to have considerable public health co-benefits, but most  
4 evidence regarding air quality and health impacts comes from projections rather than real-world data.  
5 We evaluated whether population-level respiratory health and air quality co-benefits were already  
6 detectable at the relatively low levels of zero-emissions vehicles (ZEV): battery electric, plug-in hybrid,  
7 hydrogen fuel cell vehicle) adoption in California, and evaluated the ZEV adoption gap in underserved  
8 communities. We conducted a zip code-level ecologic study relating changes in annual number of ZEVs  
9 (nZEV) per 1000 population from 2013-2019 to: (i) annual average monitored nitrogen dioxide (NO<sub>2</sub>)  
10 concentrations and (ii) annual age-adjusted asthma-related emergency department (ED) visit rates,  
11 while considering educational attainment. The average nZEV increased from 1.4 per 1,000 population in  
12 2013 (standard deviation [SD]: 2.1) to 14.7 per 1,000 in 2019 (SD: 14.7). ZEV adoption was considerably  
13 slower in zip codes with lower educational attainment (p<0.0001). A within-zip code increase of 20 ZEVs  
14 per 1,000 was associated with a -0.41 ppb change in annual average NO<sub>2</sub> (95% confidence interval [CI]:-  
15 1.12, 0.29) in an adjusted model. A within-zip code increase of 20 ZEVs per 1,000 population was  
16 associated with a 3.2% decrease in annual age-adjusted rate of asthma-related ED visits (95% CI:-5.4, -  
17 0.9). Findings were supported by a variety of sensitivity analyses. Observational data on the early phase  
18 ZEV transition in California provided a natural experiment, enabling us to document the first real-world  
19 associations between increasing nZEV and changes in air quality and health. Results suggest co-benefits  
20 of the early-phase transition to ZEV but with an adoption gap among less affluent populations which  
21 threatens the equitable distribution of possible co-benefits.

22

23 **Keywords:**

24 asthma; air pollution; climate change; respiratory health; traffic-related pollution

25

26 **Abbreviations**

27 ACS: American Community Survey

28 CHHS: California Health and Human Services

29 ED: Emergency department

30 EV: Electric vehicles

31 ICD: International Classification of Diseases

32 NO<sub>2</sub>: Nitrogen dioxide

33 NO<sub>x</sub>: Oxides of nitrogen

34 nZEV: Number of zero-emissions vehicles

35 O<sub>3</sub>: Ozone

36 PM<sub>2.5</sub>: Particulate matter <2.5µm

37 SD: Standard deviations

38 TRAP: Traffic-related air pollution

39 ZEV: Zero-emissions vehicles

40 **1. INTRODUCTION**

41

42 The transition to electric vehicles (EV) is not only an important climate change mitigation strategy but is  
43 also projected to have considerable co-benefits for public health.<sup>1,2</sup> On-road vehicles are major  
44 contributors to harmful ambient air pollution through tailpipe-related emissions, including carbon  
45 monoxide, particulate matter <2.5µm (PM<sub>2.5</sub>), and oxides of nitrogen (NO<sub>x</sub>) including nitrogen dioxide  
46 (NO<sub>2</sub>). Exposure to traffic-related air pollution (TRAP) is associated with a range of adverse health  
47 outcomes, including respiratory symptoms, development of asthma, asthma exacerbations, reduced  
48 lung function, cardiovascular disease, and premature death.<sup>3-8</sup>

49

50 Projected impacts of the EV transition on air quality and health (“co-benefits”) have been calculated for  
51 hypothetical scenarios for several locations around the world, with results depending on local features  
52 such as the electrical power generation mix used for EV charging. Air quality co-benefit projections  
53 anticipate reductions in NO<sub>x</sub>, PM<sub>2.5</sub>, carbon monoxide, volatile organic compounds, and ground-level  
54 ozone (O<sub>3</sub>)—although some predict some occasional increases in O<sub>3</sub> due to lower NO<sub>x</sub> emissions.<sup>2,9-17</sup>  
55 Health co-benefits of EV adoption have been estimated for Turin, Italy,<sup>14</sup> Paris, France,<sup>18</sup> Rotterdam,  
56 Netherlands,<sup>19</sup> Toronto/Hamilton area, Canada,<sup>17</sup> Houston, Texas,<sup>9</sup> Seattle, Washington,<sup>20</sup> and for the  
57 entire US<sup>1,2</sup> with projections anticipating reductions in premature mortality, asthma exacerbations, and  
58 respiratory and cardiovascular hospitalizations. Indeed, in the United States (U.S.), a complete shift to  
59 EVs is projected to produce more than \$1.2 trillion in cumulative health benefits by 2050, including: over  
60 2.7 million avoided pediatric asthma exacerbations; 57,200 fewer asthma-related emergency  
61 department (ED) visits; and 110,000 lives saved.<sup>2</sup>

62

63 The transition to EVs has already begun, but there is little real-world data on observed co-benefits of the  
64 early transition. There is also serious concern that EV adoption is not equitably distributed across the  
65 population. Underserved communities potentially have most to gain from the transition because they  
66 are overburdened with TRAP<sup>21-23</sup> and TRAP-related diseases;<sup>5,7,24</sup> however, these communities tend to  
67 lag in the EV transition due to multiple barriers, such as access to charging infrastructure, concerns  
68 about charge time, range, and real/perceived expense related to purchase, maintenance, and charging,  
69 as well as limited knowledge of financial incentives.<sup>25,26</sup>

70  
71 Asthma is a leading chronic health conditions with documented increased exacerbations (leading to  
72 emergency department [ED] visits) in response to tailpipe emission pollutants,<sup>5,27-30</sup> thus a compelling  
73 outcome to examine as early markers of respiratory health response to increased EV adoption. The  
74 annual cost of asthma in the US is approximately \$56 billion, including \$50 billion in direct healthcare  
75 costs.<sup>31</sup> Persons of lower socioeconomic status and from historically marginalized communities and the  
76 uninsured comprise a disproportionate amount of asthma-related ED visits,<sup>32-35</sup> highlighting a health  
77 equity issue.

78  
79 We conducted an ecologic study across California to evaluate the associations between adoption of  
80 zero-emissions vehicles (ZEV: battery electric, plug-in hybrid, hydrogen fuel cell vehicle) and air quality  
81 and asthma outcomes. Specifically, in this study we relate within-zip code number of ZEVs to: (a) annual  
82 averages of monitored NO<sub>2</sub> concentrations and (b) asthma-related ED visits, from 2013 through 2019  
83 (prior to the COVID-19 pandemic), while considering zip code-level educational attainment which serves  
84 as a proxy for socioeconomic status. We aimed to evaluate whether population-level air quality and  
85 respiratory health and co-benefits were already detectable at the still relatively low levels of ZEV  
86 adoption and evaluate the ZEV adoption gap in underserved communities. California is a socio-

87 economically diverse state heavily impacted by TRAP and is a pioneer in the early adoption of ZEVs<sup>36</sup>  
88 making it an ideal setting for this analysis. Observational data on the early phase ZEV transition in  
89 California provided a natural experiment, enabling us to quantify some of the first evidence of real-  
90 world co-benefits of the transition to a zero-tailpipe-emissions transportation sector.

91

## 92 **2. METHODS**

93

### 94 **2.1 Data**

#### 95 **2.1.1. Number of zero-emissions vehicles**

96 Annual counts of light-duty vehicles registered in California, by fuel type, have been publicly released by  
97 the California Energy Commission through a partnership with the California Department of Motor  
98 Vehicles.<sup>37</sup> We tabulated the total number of ZEV vehicles (battery electric, plug-in hybrid, hydrogen fuel  
99 cell) for each zip code and year starting in 2013, to coincide with the availability of asthma ED visit data  
100 (described below in section 2.1.3.). Years with no records of ZEV vehicles occurred most frequently in  
101 the earliest years of the study period and were assigned counts of 0. The number of ZEV (nZEV) per  
102 1,000 population was calculated using the American Community Survey (ACS) estimates of population  
103 size (described below in section 2.1.4.).

104

#### 105 **2.1.2. Ambient NO<sub>2</sub> air pollution**

106 We selected NO<sub>2</sub> as the air pollutant of interest due to on-road vehicles being its largest source of  
107 emissions<sup>38</sup> and the greater availability of monitoring sites measuring NO<sub>2</sub> compared with other traffic-  
108 related air pollutants (e.g., PM<sub>2.5</sub>). We obtained annual average NO<sub>2</sub> measurements from the U.S.  
109 Environmental Protection Agency's (EPA) AirData website as pre-generated data files, dated 2022-11-  
110 14, from all available air monitoring stations operating in California<sup>39</sup> from 2013-2019 to coincide with

111 the availability of asthma ED visit data (described below in section 2.1.3.). Secondary analyses  
112 considered additional data from 2020-2021. State and local monitoring plans guide placement of air  
113 monitoring stations, which might include areas with larger populations or thought to have higher  
114 pollution concentrations.<sup>40</sup> We used annual data calculated according to the NO<sub>2</sub> Annual 1971 pollutant  
115 standard, with all monitoring sites reporting 1 hour sample duration.<sup>41</sup> We processed these data to  
116 ensure only one NO<sub>2</sub> annual average estimate per site per year. In the few cases where multiple records  
117 existed for a given site-year (22 out of 843 [2.6%] site-years), we selected a single record using the  
118 following criteria. First, if there were records from multiple instruments, we selected the instrument  
119 with the longest duration of records at that site during the study period. Second, if there were records  
120 from two versions of the annual average including or excluding exceptional events as defined by the EPA  
121 (i.e., events that affect air quality but which the local agency has no control over, such as wildfires),<sup>41</sup> we  
122 selected the record excluding exceptional events since exceptional events are unlikely to be related to  
123 local number of ZEV. Finally, if multiple records remained, we selected the record with the largest  
124 number of days contributing to the annual average. In primary analyses, we used annual average NO<sub>2</sub>  
125 records based on at least 50% complete data and in secondary analyses we used records with ≥75%  
126 complete (i.e., satisfying the regulatory completeness criteria by the monitor for the year).<sup>41</sup>

127

### 128 **2.1.3. Asthma emergency department visits**

129 Data on zip code-level annual age-adjusted rate (per 10,000) of asthma-related emergency department  
130 (ED) visits from 2013-2019 were obtained from the California Health and Human Services (CHHS) Open  
131 Data Portal. These data are produced by the California Department of Public Health, California Breathing  
132 Asthma Program, based on a database of ED visits from all licensed hospitals in California maintained by  
133 the California Department of Health Care Access and Information.<sup>42</sup> These data reflect the number of ED  
134 visits related to asthma during each calendar year for a given zip code, including ED visits that results in

135 hospitalization, normalized for zip code population.<sup>42</sup> Age-adjusted rates of asthma ED visits were  
136 calculated by the California Breathing Asthma Program using yearly population estimates from the  
137 California Department of Finance which are then age-adjusted to the 2000 U.S. standard population  
138 from the U.S. Census Bureau using weights for the 24 age groups from Centers for Disease Control and  
139 Prevention<sup>43</sup> (L. Avendaño, California Breathing, personal communication, December 19-20, 2022). The  
140 use of age-adjusted rates controls for possible confounding by differences in population age distribution  
141 across zip codes. Asthma-related ED visits were identified based on the International Classification of  
142 Diseases (ICD) primary discharge codes: ICD-9 493.xx or ICD-10 J45.<sup>42</sup> Rates are approximate since they  
143 are based on total number of visits rather than the number of unique individuals and CHHS suppressed  
144 rates calculated from small counts (e.g., <12) due to statistical instability and/or de-identification  
145 purposes.

146

#### 147 **2.1.4. Population characteristics**

148 Zip code-level population size and educational attainment, defined as percent of the population over  
149 age 25 years with at least a bachelor's degree, were obtained from the 2015-2019 American Community  
150 Survey (ACS) 5-Year Estimates.<sup>44</sup> Educational attainment serves as a proxy for socioeconomic status,  
151 representing the structural and financial barriers driving disparities rather than the lack of education  
152 itself. In secondary analyses we considered alternative measures of socioeconomic status, including:  
153 percentage of the population over age 25 with at least a high school degree, median household income,  
154 and percentage poverty defined as the percentage of the population whose income in past 12 months  
155 was below the poverty level.

156

#### 157 **2.1.5. Final analysis datasets**

158 There were 629 records of annual average NO<sub>2</sub> from 107 air monitoring stations in 95 zip codes available  
159 from 2013-2019, after excluding one site located in a zip code with no asthma ED visit data (Miramar, ≤1  
160 ZEV during study period) and dropping 30 site-year records where the annual averages had used <50%  
161 complete data. There were 8,170 observations of non-missing annual age-adjusted rates of asthma ED  
162 visits in 1,240 zip codes from 2013-2019. In our analyses, we considered only zip codes with non-missing  
163 population size greater than 0, which reduced the final asthma ED visit dataset to 8,163 observations in  
164 1,238 zip codes. ZEV data were available for all years/zip codes in the NO<sub>2</sub> and asthma ED visit datasets.  
165 All datasets used in this study were not collected for the purpose of our study and none of our study  
166 team had access to any subject identifiers (only publicly available de-identified, aggregated data were  
167 used). According to the Office for Human Research Protection of U.S. Department of Health and Human  
168 Services, these analyses do not constitute human subjects research requiring Institutional Review Board  
169 approval or consent.

170

## 171 **2.2. Statistical Methods**

### 172 **2.2.1. Descriptive statistics**

173 Data distributions were summarized using means and standard deviations (SD). Differences in  
174 characteristics between zip codes with and without NO<sub>2</sub> monitor data were compared using t-tests.  
175 Longitudinal trends in the: nZEV per 1,000 population, annual average NO<sub>2</sub>, and age-adjusted rate of  
176 asthma-related ED visits were visualized using spaghetti plots color coded by zip-code level educational  
177 attainment (% bachelor's degree). Differences in the baseline level (in 2013) and annual rate of change  
178 of each of these variables by educational attainment were assessed using linear mixed effects models  
179 with a linear function of year (centered on 2013) and educational attainment, along with their  
180 interaction, and a zip code (or monitoring site) level random intercept and slope on year.

181

182 **2.2.2. Analyses relating nZEV and NO<sub>2</sub>**

183 The crude association between nZEV and NO<sub>2</sub> was evaluated using predicted 7-year change from 2013  
184 to 2019 estimated from separate simple linear regression models. For example, to obtain predicted 7-  
185 year change in nZEV a separate simple linear regression model was fit relating nZEV per 1,000 to  
186 calendar year for each zip code to predict the 7-year change in nZEV per 1,000 for that zip code. To  
187 obtain predicted 7-year change in NO<sub>2</sub>, a separate simple linear regression model was fit relating annual  
188 average NO<sub>2</sub> to calendar year for each monitoring site to predict the 7-year change in NO<sub>2</sub> for that site.  
189 For the 102 sites in 91 zip codes with >1 year of NO<sub>2</sub> data, we plotted the monitoring site predicted 7-  
190 year change in NO<sub>2</sub> versus the zip code (for that site) predicted 7-year change in nZEV, and calculated  
191 Pearson's correlation coefficient.

192

193 The adjusted association between annual average NO<sub>2</sub> ( $Y_{ijk}$ ) at monitoring site  $k$  in zip code  $i$  at year  $j$   
194 and nZEVs per 1,000 population ( $X_{ij}$ ) in zip code  $i$  at year  $j$  was estimated using the linear mixed effects  
195 model:

196 
$$Y_{ijk} = (\beta_0 + U_{0i} + U_{0ik}) + \beta_1 X_{ij} + \beta_2 Z_i + (\beta_3 + U_{1i})(t_{ij} - 2013) + \beta_4 (t_{ij} - 2013)^2 + \varepsilon_{ijk}$$

197 where  $\beta_1$  quantifies the association of within-zip code changes in nZEV with within-monitoring site  
198 changes in annual average NO<sub>2</sub>, adjusting for educational attainment ( $Z_i$ ) and calendar year ( $t_{ij}$ ,  
199 centered at 2013; linear and quadratic effects included) to account for secular trends. Random  
200 intercepts for zip code ( $U_{0i}$ ) and site within zip code ( $U_{0ik}$ ) account for correlation in the longitudinal,  
201 multilevel data and the zip code-level random slope on the linear effect of year ( $U_{1i}$ ) allowed for  
202 variation in secular trends by zip code. No random slope was specified for year squared due to  
203 convergence issues, likely due to the smaller number of zip codes in this analysis (N=95) and the  
204 complexity of random intercepts for monitoring sites nested in zip codes. All random effects were

205 assumed to be normally distributed and zip-code level random effects ( $U_{0i}, U_{1i}$ ) were allowed to be  
206 correlated.

207

208

209

### 210 **2.2.3. Analyses relating nZEV and asthma ED visits**

211 The adjusted association between log transformed annual age-adjusted rate of asthma ED visits ( $Y_{ij}$ ) in  
212 zip code  $i$  at year  $j$  and nZEVs per 1,000 population ( $X_{ij}$ ) in zip code  $i$  at year  $j$  was estimated using the  
213 linear mixed model:

$$214 \quad Y_{ij} = (\beta_0 + U_{0i}) + \beta_1 X_{ij} + \beta_2 Z_i + (\beta_{3i} + U_{1i})(t_{ij} - 2013) + (\beta_{4i} + U_{2i})(t_{ij} - 2013)^2 + \varepsilon_{ij}$$

215 where  $\beta_1$  quantifies the association of within-zip code changes in nZEV with within-zip code changes in  
216 log annual age-adjusted rate of asthma-related ED visits, adjusting for educational attainment ( $Z_i$ ) and  
217 calendar year ( $t_{ij}$ , centered at 2013; linear and quadratic effects included) to account for secular trends.

218 Zip code level random intercepts ( $U_{0i}$ ) and random slopes on both terms for year ( $U_{1i}, U_{2i}$ ) allowed for  
219 variation across zip codes in baseline age-adjusted rate of asthma ED visits and in secular trends. All  
220 random effects were assumed to be normally distributed and zip-code level random effects ( $U_{0i},$

221  $U_{1i}, U_{2i}$ ) were allowed to be correlated. Age-adjusted rate of asthma ED visits was natural log

222 transformed to better satisfy modeling assumptions. Secondary analyses included investigating a

223 nonlinear association with nZEV, using a generalized additive mixed model (GAMM)<sup>45</sup> analogous to the

224 linear mixed model above but that replaces the term  $\beta_1 X_{ij}$  with the smooth function,  $s(X_{ij})$ , estimated

225 using a thin plate regression spline basis with automated selection of effective degrees of freedom.

226

227 When developing the primary models presented above, a variety of models were evaluated to identify

228 key model features, and to assess the sensitivity of the results to various model specification and data

229 inclusion choices. Results of sensitivity analyses are presented. Models were estimated using lme() and  
230 gamm() in the nlme<sup>46,47</sup> and mgcv<sup>45</sup> packages of R version 4.2.1.<sup>48</sup>

231

### 232 **3. RESULTS**

#### 233 **3.1. Descriptive statistics**

234 Distributions of selected zip code demographic and socioeconomic characteristics are presented in Table  
235 1. Among the 1,238 zip codes in the asthma ED visit analysis, the mean population size was 31,296 (min:  
236 702 and max: 111,165) and the total population size across all 1,238 zip codes was 38,743,804. Zip code  
237 level educational attainment ranged from 1.1% to 87.1% of adults over age 25 years with at least a  
238 bachelor's degree, with a mean (SD) of 33.4% (20.1%). The zip code level nZEV per 1,000 population had  
239 a mean (SD) of 1.4 (2.0) in 2013 and 14.7 (14.7) in 2019 (Supplemental Table 1). Zip code level number  
240 of ZEV per 1,000 in 2019 was highly correlated with measures of socioeconomic status, with Pearson's  
241 correlation of: 0.84 for % bachelor's degree, 0.83 for median household income, 0.55 for % high school  
242 degree, and -0.51 for % poverty. Zip code level annual age-adjusted asthma ED visit rates had a mean  
243 (SD) of 49.5 (30.5) per 10,000 in 2013 and 43.0 (27.5) per 10,000 in 2019 (Supplemental Table 1).

244

245 Annual NO<sub>2</sub> data were available from 107 monitoring locations, which were located in a subset of 95 of  
246 the 1,238 zip codes. The 95 zip codes covered a total of 4,246,931 people, representing 11.0% of the  
247 population included in the asthma ED visit analysis. Compared to zip codes without NO<sub>2</sub> monitors, the  
248 95 zip codes with NO<sub>2</sub> monitors had higher average population size (p<0.001), lower educational  
249 attainment (p=0.01-0.02), lower household income (p=0.005), higher level of poverty (p=0.003), fewer  
250 ZEV per 1,000 in 2019 (p<0.001), and higher age-adjusted rates of asthma ED visits in 2019 (p=0.006;  
251 Table 1 and Supplemental Table 1). Extensive longitudinal data were available over the 7-year study  
252 period, from 2013-2019, with 100% of zip codes having nZEV data for all 7 years, 80.4% of included

253 monitoring sites having 5 or more years of NO<sub>2</sub> data, and 93.0% of included zip codes having 5 or more  
254 years of asthma ED visit data.

255

### 256 **3.2. Longitudinal trends in nZEV, annual average NO<sub>2</sub>, and asthma-related ED visits**

257 There was considerable growth in nZEV from 2013-2019 in California (Figure 1a), and growth in nZEV  
258 was slower for zip codes with lower educational attainment ( $p < 0.0001$ ). For example, we estimated that  
259 a typical zip code at the 25<sup>th</sup> percentile of educational attainment (17.1% bachelor's degree) had an  
260 annual increase in nZEV per 1,000 of 0.70 (95% Confidence Interval [CI]: 0.61, 0.78) while a typical zip  
261 code at the 75<sup>th</sup> percentile of educational attainment (47.2% bachelor's degree) had an annual increase  
262 in nZEV per 1,000 of 3.55 (95% CI: 3.47, 3.63). Declines in annual average NO<sub>2</sub> and in age-adjusted rates  
263 of asthma-related ED visits were more modest over the study period (Figure 1b-c). The 2013 level of  
264 annual average NO<sub>2</sub> was negatively associated with educational attainment ( $p < 0.001$ ), but the annual  
265 rate of change was not ( $p = 0.48$ ). Similarly, the 2013 level of age-adjusted asthma-related ED visits was  
266 negatively associated with educational attainment ( $p < 0.001$ ), but the annual rate of change was not  
267 ( $p = 0.30$ ).

268

### 269 **3.3. Associations of nZEV with monitored annual average NO<sub>2</sub> concentrations**

270 Higher nZEV was associated with lower annual NO<sub>2</sub> concentrations measured at monitoring sites,  
271 though not statistically significant in the primary model. Results were consistent both in a crude analysis  
272 (Figure 2) and in a linear mixed model adjusting for confounders (Table 2) where we estimated that a  
273 within-zip code increase of 20 ZEVs per 1,000 population was associated with a -0.41 ppb change in  
274 annual average NO<sub>2</sub> concentration (95% CI: -1.12, 0.29;  $p$ -value=0.25). The estimated association  
275 remained negative in a variety of sensitivity analyses (Supplemental Table 2) and had even greater  
276 magnitude of associations, some statistically significant, when: adjusting for alternative measures of

277 socioeconomic status, adjusting for a fixed effect of monitoring site, or excluding the random slope on  
278 year. Inclusion of additional data from 2020-2021 or only 2021 (to avoid 2020, which was heavily  
279 impacted by the COVID-19 pandemic) resulted in greater magnitude negative associations that were  
280 statistically significant, even when restricting to the subset of observations that satisfied regulatory  
281 requirements for completeness ( $\geq 75\%$ ; Supplemental Table 2).

282

### 283 **3.4. Associations of nZEV with asthma-related emergency department visits**

284 Higher nZEV was statistically significantly associated with fewer ED visits for asthma. Adjusting for zip  
285 code educational attainment and secular trends (Table 2), we estimated that a within-zip code increase  
286 of 20 ZEVs per 1,000 population was associated with a 3.2% decrease in annual age-adjusted rate of  
287 asthma-related ED visits (95% CI: -5.4, -0.9;  $p$ -value=0.006). The estimated association remained  
288 negative and statistically significant in a variety of sensitivity analyses (Supplemental Table 3). In a  
289 secondary analysis evaluating nonlinearity (Supplemental Figure 1), there was statistical evidence of the  
290 association being nonlinear ( $p$ -value = 0.002 for a test of nonlinear vs linear) with a negative association  
291 between nZEV and asthma ED visits which was stronger at higher levels of nZEV. However, much of the  
292 evidence for nonlinearity was driven by the 4 observations with nZEV greater than 82 (from zip codes  
293 94022 and 95070 in Santa Clara County, in 2018 and 2019). Upon excluding these observations evidence  
294 for nonlinearity was more modest ( $p=0.03$ ).

295

## 296 **4. DISCUSSION**

### 297 **4.1. Air quality and health co-benefits of ZEV adoption**

298 This study provides real-world evidence supporting air quality and respiratory health co-benefits from  
299 the ZEV transition, using observational data during a natural experiment of the early phase ZEV  
300 transition in California. We found statistically significant evidence that within-zip code increases in ZEV

301 adoption were associated with decreases in rates of asthma ED visits. There was some evidence that this  
302 inverse association was nonlinear, with a suggested greater health co-benefit at higher levels of ZEV  
303 adoption—but caution must be taken not to overinterpret these nonlinear effect estimates at this early  
304 stage of the ZEV transition. As the number of ZEV increases in future years, researchers will increasingly  
305 be better positioned to evaluate evidence of nonlinear exposure-response functions. For air quality co-  
306 benefits, while the association of ZEV with annual average monitored NO<sub>2</sub> concentrations was not  
307 statistically significant, it was in the hypothesized direction (inverse association) and relatively large in  
308 magnitude. We considered only air quality data from U.S. EPA monitoring sites, and these tended to be  
309 in zip codes that also had lower levels of ZEV adoption during the study period. We observed an  
310 adoption gap, wherein zip codes with a greater percentage of residents with lower educational  
311 attainment lagged in the ZEV transition. The strong evidence for health co-benefits and suggestive  
312 evidence for air quality co-benefits is remarkable given the still low rate of ZEV adoption in California in  
313 2013-2019. Taken together, these results suggest that increasing ZEV adoption has the potential to  
314 improve both air quality and neighborhood-level asthma health outcomes, but the already evident  
315 adoption gap raises equity concerns.

316

317 While most studies have estimated environmental health impacts of EV adoption under hypothetical  
318 scenarios,<sup>9,14,17,18,20</sup> our findings are consistent with the few studies that have investigated real world co-  
319 benefits of the transition to EVs or other alternative fuels.<sup>49,50</sup> Lovasi et al. evaluated the air quality  
320 effects of the Clean Fuel Bus Program, which adopted lower-emissions buses including compressed  
321 natural gas, hybrid-electric, and ultra-low-sulfur diesel buses, in New York City, New York from 2009 to  
322 2014.<sup>49</sup> They reported that the shift toward clean bus service was associated with larger improvements  
323 in local NO and NO<sub>2</sub> concentrations and areas with more bus service and higher proportional shifts  
324 towards clean buses had the largest declines in these pollutants.<sup>49</sup> Adar et al. evaluated the air pollution

325 and pulmonary health effects of adopting clean air technologies (e.g., diesel oxidation catalysts and  
326 crankcase ventilation systems used to reduce tailpipe and engine emissions) and fuels (e.g., ultra-low-  
327 sulfur diesel and a biodiesel mixture) on school buses in Seattle and Tahoma, Washington from 2005 to  
328 2009.<sup>50</sup> With these adoptions they found lower in-vehicle concentrations of fine and ultrafine particulate  
329 matter and lower pulmonary inflammation, improved lung growth, and reduced risk of school  
330 absenteeism among the schoolchildren bus riders.<sup>50</sup> These studies provide important critical data on the  
331 environmental health impacts of vehicle technology/fuel transitions, and the present study furthers the  
332 literature by presenting the first results from a large, state-wide, population-based observational  
333 analysis of light duty vehicles.

334

#### 335 **4.2. ZEV adoption gap**

336 Historically marginalized communities disproportionately experience higher exposure to air pollution,  
337 including TRAP,<sup>21-23</sup> and adverse TRAP-related health outcomes such as asthma-related ED visits;<sup>33,35</sup> thus  
338 ZEV adoption can be particularly beneficial in these communities. During this early phase of the ZEV  
339 transition, most adopters have been of higher education and income,<sup>26</sup> aligning with the Diffusion of  
340 Innovation theory that early adopters of new technologies tend to be of higher socioeconomic status.<sup>51</sup>  
341 This highlights a challenge for equitable transition to ZEVs and equitable distribution of related co-  
342 benefits for air quality and health. Indeed, we observed evidence for an adoption gap, with communities  
343 with lower educational attainment lagging in the ZEV transition—educational attainment here serving as  
344 a proxy for socioeconomic status and representing structural and financial barriers propelling disparities  
345 rather than the lack of education itself. While multiple potential barriers exist,<sup>25,26</sup> increasing ZEV  
346 adoption in and around underserved and health-disparate communities could potentially help to  
347 improve local air quality and subsequently reduce adverse health impacts through a reduction in tailpipe  
348 emissions.<sup>52</sup> Our results provide evidence to inform policy makers for the development of programs to

349 ensure a just ZEV transition where underserved communities are able to fully realize health and air  
350 quality co-benefits.

351

### 352 **4.3. Strengths and limitations**

353 Our study has several strengths. First, is the use of publicly available data from the large and diverse  
354 state of California, which is at the forefront of the ZEV transition in the U.S., and contains one of the  
355 densest air quality monitoring networks in the U.S. This study setting is ideal to evaluate the  
356 environmental health co-benefits of the early ZEV transition. Second, using monitored NO<sub>2</sub>  
357 concentration to study air quality benefits avoided potential issues with spatial-temporal ambient air  
358 pollutant models which might not yet fully account for the changing transportation fleet. Third, by  
359 studying within-zip codes trends over time, we were able to take advantage of the natural experiment  
360 afforded by the early phase ZEV transition. Finally, the study period ended in 2019, avoiding potential  
361 confounding related to the COVID-19 pandemic. Considerable growth in ZEVs has continued.

362

363 Our study also has limitations which should be taken into consideration when interpreting results. First  
364 is the use of number of ZEVs per zip code population as our measure for ZEV adoption, which does not  
365 consider ZEV miles driven or if internal combustion engine vehicles are taken off the road in response to  
366 ZEV adoption. Furthermore, the use of this metric only evaluates local, zip code level effects (based on  
367 the vehicle registration zip code); it does not consider impacts in other localities as vehicles are in  
368 operation, nor are we directly considering the air pollution from the power generation mix used to  
369 charge the vehicles or the total life cycle impacts of ZEVs which have been evaluated elsewhere.<sup>52</sup>

370 Second, we only evaluated the impact of light duty ZEV and did not include zero-emissions public transit  
371 or freight transport which are also key components of the ZEV transition, since these data were  
372 unavailable. Many public agencies and regulatory efforts are shifting towards low- and zero-emissions

373 transport and continued release of temporally and spatially resolved data would allow for better  
374 evaluation of associated health co-benefits, potentially beneficial for cost-benefits analyses of such  
375 policy efforts. Third, due to the realities of relying on data from an air monitoring network—which is  
376 relatively extensive in California compared with other U.S. states—our analysis on the air pollution  
377 effects of the ZEV transition was in only 96 zip codes across the state. Although these locations do not  
378 represent the full spatial coverage across California, monitors are generally placed near population  
379 centers. Fourth, our ecologic analyses were conducted at the zip code level, which is a suboptimal  
380 geographic unit for population health studies because zip codes were designed for postal delivery. They  
381 represent varying geographic and population sizes, they can cross city/county/census boundaries, and  
382 they may change over time. This, however, was the finest spatial resolution available for the publicly  
383 available ZEV data. The challenges with zip code-level analyses are outweighed by the advantages of fine  
384 spatial resolution, especially in a state like California where a county-level analysis effectively combines  
385 a large percentage of the state’s population because some counties are so large (e.g., Los Angeles  
386 County contains ~25% of California’s population). Last, as in most observation studies, unmeasured  
387 confounding might have biased our estimated associations. We did adjust for area-level educational  
388 attainment—as a proxy for socioeconomic status—and our analyses included random intercepts for zip  
389 code which provides some control for possible unmeasured zip code-level confounding factors, and we  
390 additionally conducted various sensitivity analyses changing model specifications, adjusted covariates,  
391 and other data inclusions/exclusions; however, caution is warranted not to overinterpret results.

392

#### 393 **4.4. Future research**

394 This study of the co-benefits of the early phase ZEV transition lays the foundation for future work.  
395 Research studying trends in the adoption of EV technology suggests that the U.S. entered the “takeoff”  
396 phase of EV adoption in 2017, marking the transition from an introductory phase to a phase of growth

397 and mass adoption.<sup>53</sup> With increasing numbers of ZEV, future studies can focus solely on the EV  
398 transition (excluding plug-in hybrids which are included in the present analysis) and/or with co-benefits  
399 analysis investigating a variety of health outcomes (including differences by vulnerable subgroups) and  
400 investigating a full set of ambient air pollutants (e.g., not only NO<sub>2</sub> which has key tailpipe sources, but  
401 also PM<sub>2.5</sub> which is impacted by brake and tire wear and might have a more complex association with EV  
402 adoptions given that EVs are on average heavier than their gasoline combustion counterparts<sup>54</sup>).  
403 Evaluation of possible nonlinear associations with co-benefits across a broader numerical range of ZEVs  
404 will be possible as their numbers increase. Additionally, the impact of electrification of other vehicle  
405 classes (e.g., such as heavy-duty on-road vehicles used in freight transport) or of transit systems (e.g.,  
406 public transit, school buses) will enable new studies of observed associated public health co-benefits,  
407 including in high-traffic communities who are disproportionately exposure to TRAP.

408

## 409 **5. CONCLUSIONS**

410 This study leveraged a natural experiment and documents the first real-world associations between  
411 increasing nZEV and changes in air quality and health, suggesting co-benefits of the early-phase  
412 transition to ZEV in California, along with the adoption gap which threatens the equitable distribution of  
413 these co-benefits. These early results provide crucial evidence for informing future policies for a just and  
414 equitable transition to an electrified transportation sector, to both mitigate climate change and realize  
415 environmental and health co-benefits for all.

416

## 417 **ACKNOWLEDGEMENTS**

418 This work was supported by the University of Southern California Office of Research Strategic Directions  
419 for Research Award and the National Institute of Environmental Health Sciences [grants P30ES007048  
420 and P2CES033433].

421

422 **DATA SHARING**

423 The data that support the findings of this study are openly available in California Health and Human  
424 Services (CHHS) Open Data Portal at [https://data.chhs.ca.gov/dataset/asthma-emergency-department-](https://data.chhs.ca.gov/dataset/asthma-emergency-department-visit-rates)  
425 [visit-rates](https://data.chhs.ca.gov/dataset/asthma-emergency-department-visit-rates); American Community Survey Data at [https://www.census.gov/programs-](https://www.census.gov/programs-surveys/acs/data.html)  
426 [surveys/acs/data.html](https://www.census.gov/programs-surveys/acs/data.html); U.S. Environmental Protection Agency's (EPA) AirData website at  
427 [https://aqs.epa.gov/aqsweb/airdata/download\\_files.html](https://aqs.epa.gov/aqsweb/airdata/download_files.html); and California Energy Commission at  
428 <http://www.energy.ca.gov/zevstats>.

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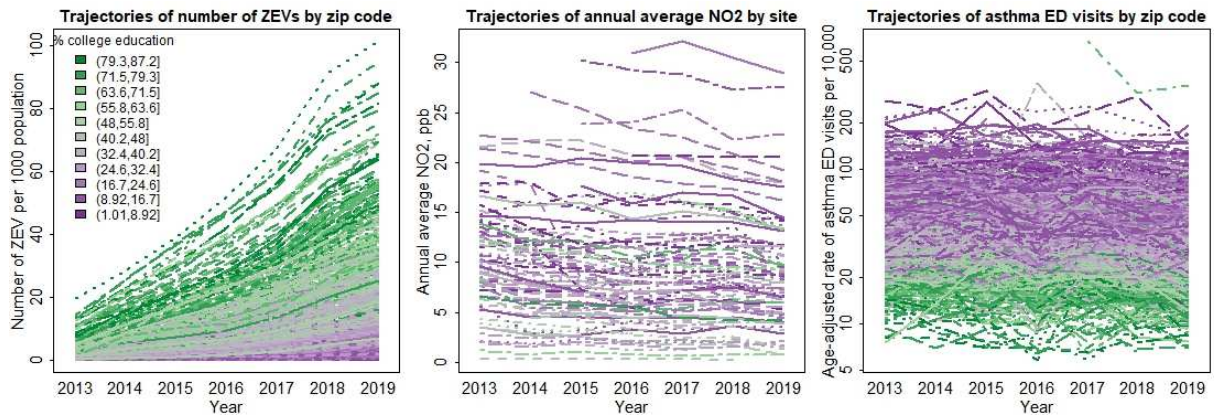
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564

1 **FIGURES AND FIGURE LEGENDS**

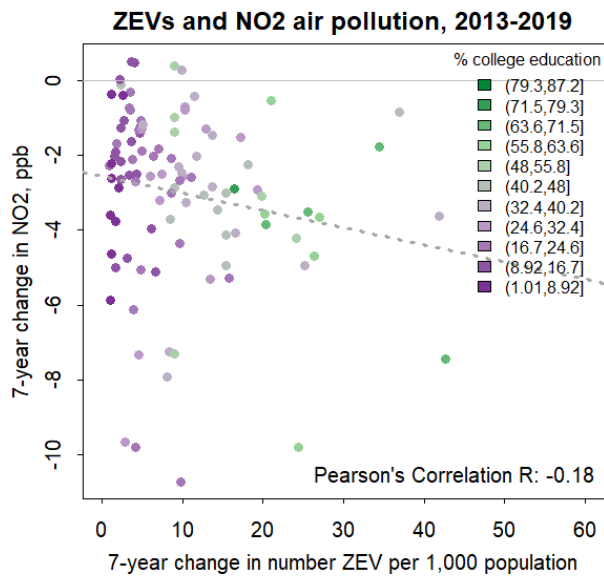


2

3

4 **Figure 1.** Longitudinal trends, from 2013-2019 in: (a) number of zero-emissions vehicles (ZEVs) per 1,000  
5 population in 1,238 California zip codes, (b) annual average nitrogen dioxide (NO<sub>2</sub>) concentrations  
6 observed at 107 California monitoring stations, and (c) annual age-adjusted rate of asthma-related  
7 emergency department (ED) visits per 10,000 in 1,238 California zip codes. Color indicates educational  
8 attainment (% of adults age 25+ with at least a bachelor's degree) at the zip code level, from lower  
9 (purple) to higher (green).

10



11

12

13 **Figure 2.** Crude association between predicted 7-year change in nitrogen dioxide (NO<sub>2</sub>) versus 7-year  
 14 change in number of zero-emissions vehicles (ZEVs) based on data from 102 air monitoring sites in 91 zip  
 15 codes in California, with color indicating zip code level educational attainment (low: purple; high: green).

1 TABLES

**Table 1.** Distribution of selected demographic and socioeconomic characteristics among zip codes included in the asthma ED visit rate and nitrogen dioxide (NO<sub>2</sub>) analysis. Mean (standard deviation) presented, unless otherwise indicated.

Characteristic	Zip codes in asthma ED visit analysis	Zip codes in NO <sub>2</sub> analysis	P-value <sup>a</sup>
N	1,238	95	
Population size	31,295.5 (21,311.5) (min: 702; max: 111,165)	44,704.5 (19,253.9) (min: 1771; max: 88,979)	<0.001
<i>Educational attainment</i> <sup>b</sup>			
% Bachelor's degree or higher	33.4 (20.1)	29.2 (17.8)	0.019
% High school degree or higher	83.8 (13.1)	80.7 (12.2)	0.013
<i>Income</i>			
Median household income	\$79,385 (\$34,477)	\$71,248 (\$28,645)	0.005
% Poverty <sup>c</sup>	13.7 (8.6)	16.3 (8.6)	0.003

<sup>a</sup> P-value from t-tests comparing differences in characteristics between zip codes with and without NO<sub>2</sub> monitor data.

<sup>b</sup> Among adults over age 25 years.

<sup>c</sup> Percentage of the population whose income in past 12 months was below the poverty level.

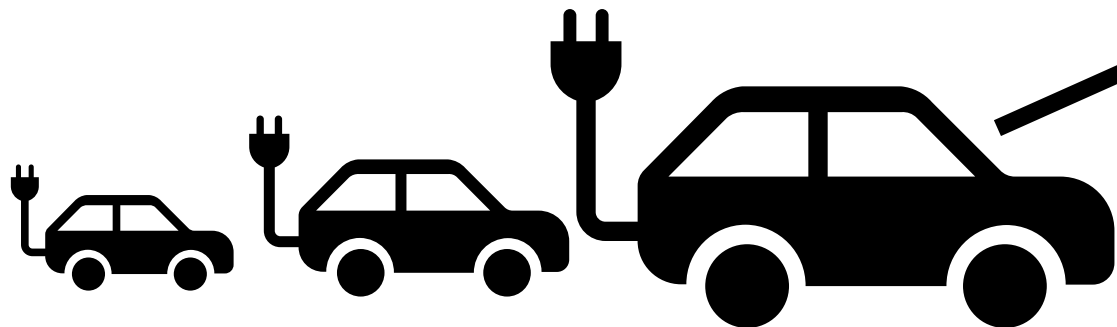
**Table 2.** Adjusted model results for change in annual average nitrogen dioxide (NO<sub>2</sub>) concentration (ppb) and percent difference in age-adjusted asthma-related emergency department (ED) visits associated with a within-zip code increase of 20 zero-emissions vehicles (ZEVs) per 1,000 population.

<b>Model</b>	<b>Estimate</b>	<b>95% CI</b>	<b>P-value</b>
NO <sub>2</sub> and ZEVs <sup>a</sup>	-0.41	(-1.12, 0.29)	0.252
Asthma ED visit rate and ZEVs <sup>b</sup>	-3.2	(-5.4, -0.9)	0.006

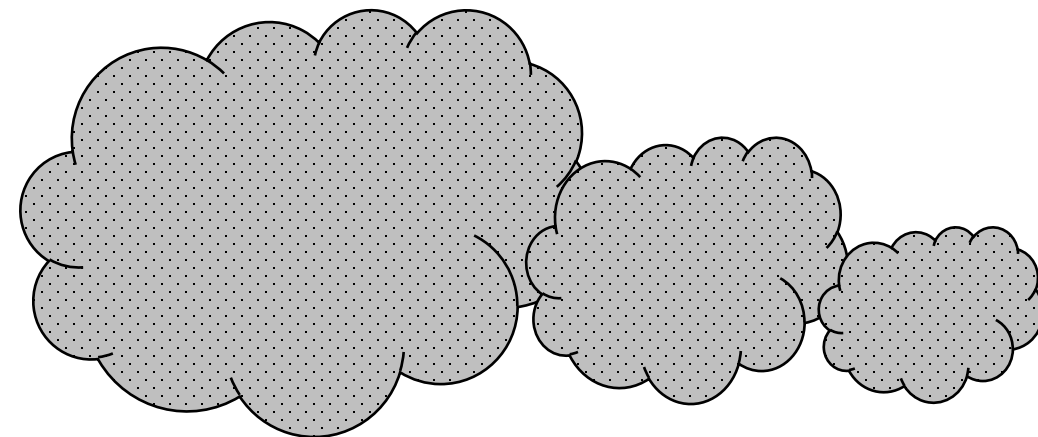
<sup>a</sup> NO<sub>2</sub> model estimated using a linear mixed effects model adjusted for % bachelor's degree, calendar year (linear and quadratic effect, centered at 2013), with random intercepts for zip code and site within zip code, and a zip code-level random slope on the linear effect of year.

<sup>b</sup> Asthma ED visit rate model estimated using a linear mixed effects model adjusted for % bachelor's degree, calendar year (linear and quadratic effect, centered at 2013), with random intercepts for zip code, and a zip code-level random slope on the linear and quadratic effects of year.

Within California zip codes, 2013-2019



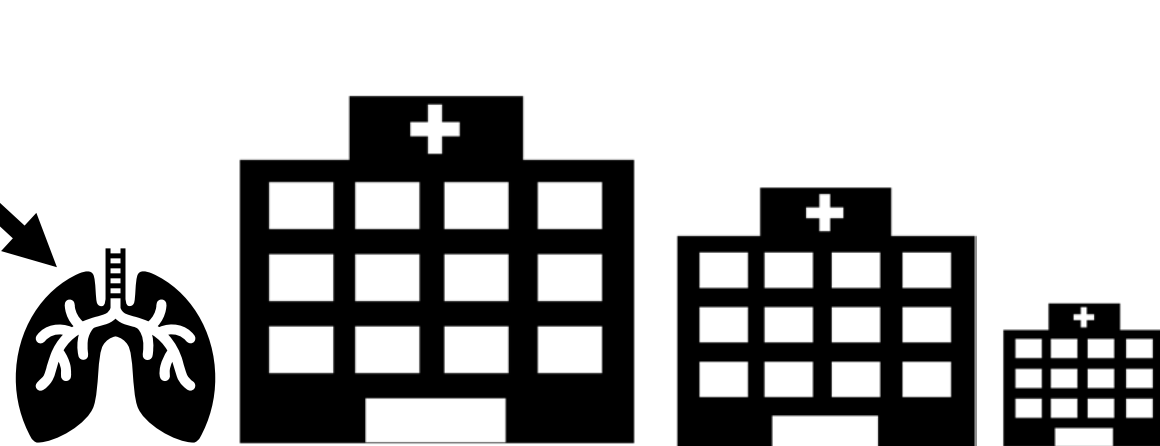
Increasing numbers of zero-emissions vehicles



(non-significantly) lower NO<sub>2</sub> air pollution



ADOPTION GAP



lower rates of asthma-related emergency departments visits