Appendix

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| Table A1: first month of state standard testing windows for grade 3-8 students, 2010-2016 | | | | | | | |
| State | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
| Alabama | 5 | 5 | 5 | 5 | 3 | 3 | 3 |
| Alaska | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Arizona | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Arkansas | 4 | 4 | 4 | 4 | 4 | 3 | 4 |
| California | 3 | 3 | 3 | 3 | 1 | 1 | 1 |
| Colorado | 3 | 3 | 3 | 3 | 3 | 4 | 4 |
| Connecticut | 3 | 3 | 3 | 3 | 3 | 4 | 4 |
| Delaware | 3 | 5 | 5 | 5 | 5 | 3 | 3 |
| District of Columbia | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Florida | 4 | 4 | 4 | 4 | 4 | 3 | 3 |
| Georgia | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Hawaii | 4 | 4 | 4 | 4 | 4 | 2 | 2 |
| Idaho | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Illinois | 2 | 2 | 2 | 2 | 2 | 2 | 3 |
| Indiana | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Iowa | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Kansas | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Kentucky | 5 | 5 | 4 | 4 | 4 | 4 | 4 |
| Louisiana | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Maine | 10 | 10 | 10 | 10 | 10 | 4 | 3 |
| Maryland | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Massachusetts | 5/3 | 5/3 | 5/3 | 5/3 | 5/3 | 5/3 | 5/3 |
| Michigan | 10 | 10 | 10 | 10 | 10 | 4 | 4 |
| Minnesota | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Mississippi | 5 | 5 | 5 | 5 | 5 | 5 | 4 |
| Missouri | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Montana | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Nebraska | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Nevada | 4 | 4 | 4 | 4 | 4 | 2 | 2 |
| New Hampshire | 10 | 10 | 10 | 10 | 10 | 3 | 3 |
| New Jersey | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| New Mexico | 3 | 3 | 3 | 3 | 3 | 4 | 4 |
| New York | 5/4 | 5 | 4 | 4 | 4 | 4 | 4 |
| North Carolina | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| North Dakota | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Ohio | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Oklahoma | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Oregon | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Pennsylvania | 4 | 3 | 3 | 4 | 3 | 4 | 4 |
| Rhode Island | 10 | 10 | 10 | 10 | 10 | 3 | 3 |
| South Carolina | 5 | 5 | 5 | 5 | 5 | 4 | 5 |
| South Dakota | 3 | 4 | 4 | 4 | 3 | 3 | 3 |
| Tennessee | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Texas | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Utah | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Vermont | 10 | 10 | 10 | 10 | 10 | 3 | 3 |
| Virginia | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Washington | 5 | 5 | 5 | 5 | 5 | 3 | 3 |
| West Virginia | 5 | 5 | 5 | 5 | 5 | 4 | 4 |
| Wisconsin | 10 | 10 | 10 | 10 | 10 | 3 | 3 |
| Wyoming | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 1. For state-years that tests were administered in October, these tests were given at the beginning of the school year, i.e., the previous calendar year. | | | | | | | |
| 1. For most state-years, math and ELA tests were given in the same testing window. For the few state-years where math and ELA tests were given in separate testing windows, the test months are presented as "math test month/ ELA test month". | | | | | | | |

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| Table A2: Full regression results of GSD-level standardized test scores on 12-month average ambient air pollutions and covariates | | | | | | |
|  | Math: β (se) | | | ELA: β (se) | | |
|  | (1) | (2) | (3) | (1) | (2) | (3) |
| PM2.5 (ug/m3) | -0.01061\*\*\* | -0.00776\*\*\* | -0.00663\*\*\* | -0.00292\*\*\* | -0.00427\*\*\* | -0.00381\*\*\* |
| (0.00103) | (0.00105) | (0.00105) | (0.00081) | (0.00083) | (0.00083) |
| NO2 (ppb) | 0.00063 | -0.00067 | -0.00389\*\*\* | -0.01584\*\*\* | -0.01101\*\*\* | -0.01195\*\*\* |
| (0.00106) | (0.00109) | (0.00109) | (0.00083) | (0.00086) | (0.00086) |
| Ozone (ppm) | -0.00564\*\*\* | -0.00557\*\*\* | -0.00513\*\*\* | 0.00457\*\*\* | 0.00207\*\*\* | 0.00234\*\*\* |
| (0.00056) | (0.00058) | (0.00058) | (0.00044) | (0.00045) | (0.00045) |
| Native American |  | -0.31832\*\*\* | -0.31005\*\*\* |  | -0.32604\*\*\* | -0.32448\*\*\* |
|  | (0.03365) | (0.03355) |  | (0.02736) | (0.02734) |
| Asian |  | 0.54887\*\*\* | 0.47209\*\*\* |  | 0.27733\*\*\* | 0.23849\*\*\* |
|  | (0.02736) | (0.02737) |  | (0.02137) | (0.02142) |
| Hispanic/Latino |  | -0.31952\*\*\* | -0.27947\*\*\* |  | -0.25598\*\*\* | -0.23973\*\*\* |
|  | (0.01388) | (0.01388) |  | (0.01084) | (0.01086) |
| Black |  | -0.49511\*\*\* | -0.50608\*\*\* |  | -0.51326\*\*\* | -0.51843\*\*\* |
|  | (0.01857) | (0.01860) |  | (0.01488) | (0.01496) |
| Free-lunch eligible |  | -0.08292\*\*\* | -0.06080\*\*\* |  | -0.03388\*\*\* | -0.02531\*\*\* |
|  | (0.00551) | (0.00552) |  | (0.00420) | (0.00421) |
| Reduced-price lunch eligible |  | 0.03201\*\*\* | 0.03776\*\*\* |  | -0.00571 | -0.00397 |
|  | (0.00997) | (0.00995) |  | (0.00805) | (0.00805) |
| Economically disadvantaged |  | -0.11780\*\*\* | -0.11758\*\*\* |  | -0.14415\*\*\* | -0.14396\*\*\* |
|  | (0.00470) | (0.00469) |  | (0.00372) | (0.00372) |
| English language learner |  | -0.00894 | -0.03435\*\* |  | -0.34666\*\*\* | -0.35848\*\*\* |
|  | (0.01688) | (0.01685) |  | (0.01263) | (0.01264) |
| Urban |  |  | 0.00256 |  |  | -0.00087 |
|  |  | (0.00277) |  |  | (0.00216) |
| Town |  |  | -0.01820\*\*\* |  |  | -0.01707\*\*\* |
|  |  | (0.00232) |  |  | (0.00185) |
| Rural |  |  | -0.02360\*\*\* |  |  | -0.02143\*\*\* |
|  |  | (0.00188) |  |  | (0.00150) |
| Log of median income |  |  | 0.02794\*\*\* |  |  | -0.00510 |
|  |  | (0.00776) |  |  | (0.00618) |
| Bachelor's degree rate |  |  | 0.27423\*\*\* |  |  | 0.24110\*\*\* |
|  |  | (0.02356) |  |  | (0.01870) |
| Poverty rate |  |  | -0.07045\*\*\* |  |  | -0.01385\* |
|  |  | (0.00957) |  |  | (0.00764) |
| SNAP receipt rate |  |  | -0.67302\*\*\* |  |  | -0.26343\*\*\* |
|  |  | (0.02100) |  |  | (0.01683) |
| Single-mom household rate |  |  | -0.01512 |  |  | -0.02816\* |
|  |  | (0.02133) |  |  | (0.01699) |
| Observations | 361,852 | 348,119 | 347,468 | 383,121 | 367,958 | 367,285 |
| R2 | 0.00053 | 0.01185 | 0.01107 | 0.00052 | 0.0155 | 0.01559 |
| Adjusted R2 | -0.20925 | -0.20503 | -0.20590 | -0.19792 | -0.18925 | -0.18906 |
| a) Time fixed effects and cohort fixed effects were adjusted in all models. \*p<0.1; \*\*p<0.05; \*\*\*p<0.01   |  |  |  | | --- | --- | --- | | Table A3: Coefficients of pollutant concentrations and interaction terms in the EMM analysis | | | |  | Math | ELA | | EMM by integer grades: pollutant concentration coefficient / interaction term coefficients | | | | PM2.5 (IQR) | -0.03973\*\*\*/0.00622\*\*\* | -0.02715\*\*\*/0.00425\*\*\* | | NO2 (IQR) | 0.01049\*\*\*/-0.00273\*\*\* | -0.02659\*\*\*/0.00268\*\*\* | | Ozone (IQR) | -0.02288\*\*\*/0.00338\*\*\* | -0.02878\*\*\*/0.00569\*\*\* | | EMM by Black > 1.7%: pollutant concentration coefficient/ interaction term coefficients | | | | PM2.5 (IQR) | -0.00696\*\*\*/0.00049 | -0.00451\*\*\*/0.00105\*\*\* | | NO2 (IQR) | -0.00414\*\*\*/0.00035 | -0.01238\*\*\*/0.00061 | | Ozone (IQR) | -0.00489\*\*\*/-0.00031\*\*\* | 0.00230\*\*\*/0.00006 | | EMM by Hispanic/Latino > 4.6%: pollutant concentration coefficient / interaction term coefficients | | | | PM2.5 (IQR) | -0.00816\*\*\*/0.00256\*\*\* | -0.00401\*\*\*/0.00033 | | NO2 (IQR) | -0.00487\*\*\*/0.00134\*\* | -0.01171\*\*\*/-0.00033 | | Ozone (IQR) | -0.00541\*\*\*/0.00043\*\*\* | 0.00225\*\*\*/0.00014 | | EMM by SES Composite > 0: pollutant concentration coefficient / interaction term coefficients | | | | PM2.5 (IQR) | -0.00326\*\*\*/-0.00482\*\*\* | -0.00165\*/-0.00270\*\*\* | | NO2 (IQR) | 0.00024/-0.00528\*\*\* | -0.00953\*\*\*/-0.00293\*\*\* | | Ozone (IQR) | -0.00491\*\*\*/-0.00038\*\*\* | 0.00271\*\*\*/-0.00045\*\*\* | | a) \*p<0.1; \*\*p<0.05; \*\*\*p<0.01 | | | | b) the pollutant concentrations coefficients for EMM by integer grades do not have a direct interpretation. The coefficients for grade g students should be calculated as: main effect coefficient + g\*interaction term coefficient. Assumption for linearity in EMM by grade was made. | | | | | | | | | |

A4. Model comparisons

We compared the two-way fixed effects model (model 3) with two one-way fixed effects models nested in it: one with cohort fixed effects but no time fixed effects and another with time fixed effects but no cohort fixed effects. Both one-way fixed effects models included the same set of covariates and weights as model 3. Model 3 has significantly better fit compared to the model with only cohort fixed effects (Math: F6,284948 = 612.72, p < 0.0001; ELA: F6,304069 = 564.08, p < 0.0001) and the model with only year fixed effects (Math: F62493,284948 = 11.42, p < 0.0001; ELA: F63189,304069 = 9.79, p < 0.0001). Since the multivariate linear regression model with the same set of covariates and weights but no fixed effect is nested in both one-way fixed effects models, it can be derived that model 3 has significantly better fit than the multivariate linear model with no fixed effect. In addition, model 3 provides control for unmeasured confounders across time and across school district and grade.

A5. Stratification Analysis of GSDs at lower exposure levels

We also explored the differential effects for low and high exposure levels by stratifying for observations with pollutant concentrations below the national standards of PM2.5, NO2 and O3, respectively. For PM2.5 and NO2, the stratification thresholds were chosen at the 12-month primary standard levels of the Environmental Protection Agency’s (EPA) National Ambient Air Quality Standards (NAAQS) (12.0 μg/m3 for PM2.5 and 53 ppb for NO2).66 Since there is no 12-month standard for ozone, an arbitrary stratification threshold of 50ppm was chosen, which was above the 75th percentile and below the maximum GSD-level 12-month average ozone concentrations for all school years in the study period.

Since all GSD-years had 12-month average NO2 concentrations below the 53 ppb NAAQS standard (Table 3), only PM2.5 and ozone stratification results were reported. The stratified regression results are presented in Table A5. The associations between ambient PM2.5 levels and standardized test scores at lower exposure levels were of similar magnitude for Math and smaller magnitude for ELA. The associations between ambient ozone levels and standardized Math test scores persisted at lower exposure levels with similar magnitudes.

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| Table A5: Regression results of standardized test scores and 12-month ambient air pollution, for all GSDs and GSDs with low exposure levels, controlling for covariates and two-way fixed effects | | | | | | |
|  | Full data | | PM2.5 < 12 ug/m3 | | Ozone < 50 ppm | |
|  | Math: β (95% CI) | | | | | |
| PM2.5 (IQR) | -0.00663 | (-0.00869, -0.00457) | -0.00525 | (-0.00746, -0.00304) | -0.00055 | (-0.00231, 0.00121) |
| NO2 (IQR) | -0.00389 | (-0.00602, -0.00175) | -0.00538 | (-0.00759, -0.00317) | -0.00990 | (-0.01166, -0.00814) |
| Ozone (IQR) | -0.00513 | (-0.00626, -0.00400) | -0.00427 | (-0.00545, -0.00309) | -0.00462 | (-0.00576, -0.00348) |
| observations | 347,468 | | 335,098 | | 345,477 | |
|  | ELA: β (95% CI) | | | | | |
| PM2.5 (IQR) | -0.00381 | (-0.00543, -0.00218) | -0.00055 | (-0.00231, 0.00121) | -0.00479 | (-0.00644, -0.00314) |
| NO2 (IQR) | -0.01195 | (-0.01364, -0.01026) | -0.00990 | (-0.01166, -0.00814) | -0.01096 | (-0.01267, -0.00925) |
| Ozone (IQR) | 0.00234 | (0.00145, 0.00323) | 0.00134 | (0.00042, 0.00226) | 0.00275 | (0.00185, 0.00365) |
| observations | 367,285 | | 354,241 | | 365,013 | |