Supplementary Information: Online Resource 1

Monitoring-based assessment of spatial and seasonal air-quality associations with low-emission zones in South Korea

Environmental Monitoring and Assessment

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S1 Monthly panel and event-study diagnostics

The common sample contains 247 districts after excluding Ongjin-gun and Ulleung-gun. The 2012–2024 and 2013–2024 panels contain 156 and 144 months, or 38,532 and 35,568 district-months, respectively.

Both periods use the 12 controls listed in main-text Table 2. All four period–estimator combinations use not-yet-treated comparisons, a universal month -1 reference, and 1,999 multiplier-bootstrap iterations.

For district i and pre-adoption contrast j, let $\widehat{\psi}_{ij}$ denote the fitted influence function and let

$$\widehat{s}_j = \frac{\sqrt{\sum_i \widehat{\psi}_{ij}^2}}{n}.$$

The maximum-$|t|$ statistic is $\max_j |\widehat{ATT}_j/\widehat{s}_j|$. Its multiplier reference distribution uses $\max_j |n^{-1}\sum_i \xi_i \widehat{\psi}_{ij}/\widehat{s}_j|$, where each ξ_i is independently -1 or 1 with equal probability and the same draw is used across all contrasts of district i. This preserves their joint dependence without inverting the pre-period covariance. Independent district multipliers do not accommodate cross-district dependence or policy interference. These diagnostic tests and bands are distinct from the score-HAC inference for the SDM.

Table S1: Maximum-$|t|$ pre-adoption diagnostic p-values

Period	Estimator	NO_2	CO	SO_2	O_3	PM_{10}
2012–2024	reg	$< 0.001^{***}$	$< 0.001^{***}$	$< 0.001^{***}$	$< 0.001^{***}$	$< 0.001^{***}$
2012–2024	dr	$< 0.001^{***}$	$< 0.001^{***}$	0.0065^{***}	$< 0.001^{***}$	$< 0.001^{***}$
2013–2024	reg	$< 0.001^{***}$	$< 0.001^{***}$	$< 0.001^{***}$	$< 0.001^{***}$	$< 0.001^{***}$
2013–2024	dr	$< 0.001^{***}$	$< 0.001^{***}$	0.0065^{***}	$< 0.001^{***}$	$< 0.001^{***}$

Entries are pre-trend test p-values.
Stars indicate rejection of the pre-trend test null.
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Notes: `reg`: regression adjustment; `dr`: doubly robust estimation. The 2012 and 2013 starts have 231 and 195 non-reference pre-period restrictions, respectively, with full numerical covariance rank. All joint Wald p-values are below 0.001. Multiplier p-values use the +1 correction, giving a minimum of 0.0005. The 2020 cohort contains only 13 districts.

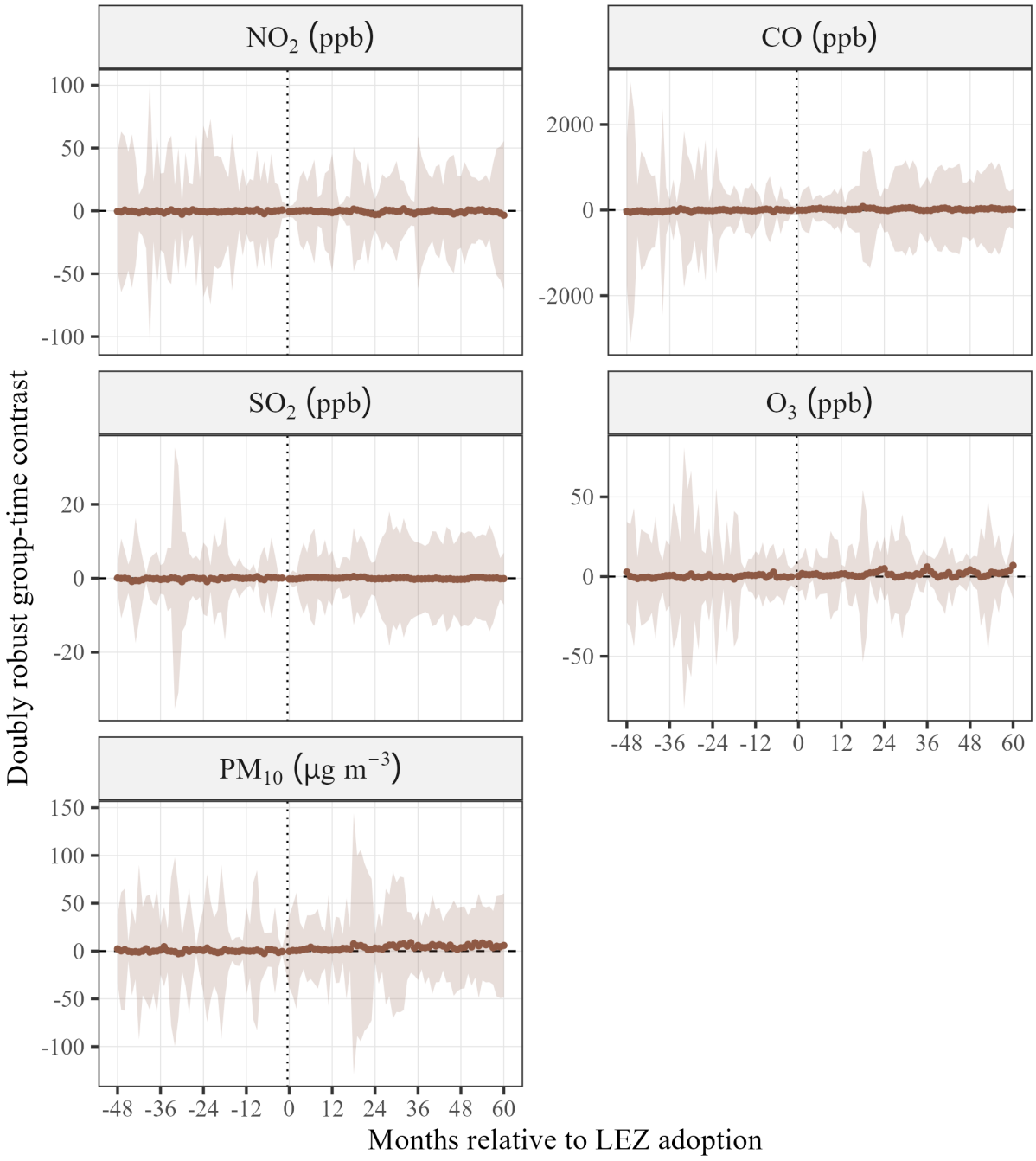


Figure S1: Doubly robust counterpart of the main event-study diagnostics, 2012–2024. Points aggregate available cohorts at each event month; the 2020 cohort does not contribute at month 60. Shading indicates simultaneous 95% bands, with month −1 as the universal reference. Intervals containing zero do not establish equivalence.

S2 Seasonal spatial quantities and trend sensitivity

Table S2: Seasonal SDM components and trend-adjusted totals underlying main-text Figure 3

Season	Outcome	Direct	Indirect	Total	Trend-adjusted total
Winter	NO_2	0.157	-1.340**	-1.183*	1.326
		(0.135)	(0.588)	(0.663)	(1.272)
	CO	2.905	-16.649*	-13.743	27.212**
		(2.321)	(9.566)	(9.287)	(12.329)
	SO_2	-0.094***	-0.374***	-0.468***	-0.108
		(0.031)	(0.058)	(0.073)	(0.077)
	O_3	-0.164**	-0.486*	-0.650**	-0.013
		(0.079)	(0.287)	(0.303)	(0.542)
	PM_{10}	-1.079***	-0.167	-1.246	-0.834
		(0.341)	(0.926)	(0.828)	(1.241)
Spring	NO_2	0.213	-2.189***	-1.976***	0.235
		(0.168)	(0.577)	(0.525)	(0.923)
	CO	5.194	-11.832*	-6.639	5.596
		(3.633)	(6.444)	(6.614)	(11.854)
	SO_2	-0.073**	-0.074	-0.147	-0.083
		(0.029)	(0.118)	(0.133)	(0.177)
	O_3	-0.106	1.472***	1.366***	0.628
		(0.215)	(0.502)	(0.492)	(0.988)
	PM_{10}	-0.614*	1.362	0.749	1.208
		(0.357)	(1.188)	(1.372)	(2.330)
Summer	NO_2	-0.042	-2.134***	-2.176***	-0.561
		(0.106)	(0.427)	(0.388)	(0.587)
	CO	5.894	-9.379	-3.485	5.760
		(3.663)	(6.195)	(6.629)	(8.408)
	SO_2	0.004	0.110	0.114	-0.157
		(0.025)	(0.109)	(0.111)	(0.159)
	O_3	0.211*	1.672***	1.882***	-0.378
		(0.126)	(0.543)	(0.559)	(1.217)
	PM_{10}	-0.500*	0.845	0.345	-0.036
		(0.270)	(0.866)	(0.735)	(1.209)
Autumn	NO_2	0.061	-1.910***	-1.849**	1.178
		(0.146)	(0.736)	(0.727)	(1.117)
	CO	7.166***	-16.037*	-8.871	21.140
		(2.519)	(8.260)	(8.861)	(13.578)
	SO_2	-0.037	0.007	-0.030	0.056
		(0.024)	(0.069)	(0.079)	(0.091)
	O_3	-0.017	0.008	-0.009	-1.429
		(0.123)	(0.339)	(0.400)	(0.946)
	PM_{10}	-0.852***	0.939	0.087	-1.227
		(0.322)	(1.022)	(0.959)	(1.109)

HAC(12) standard errors in parentheses.
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Notes: Each fit uses 247 districts and 39 months, separate coefficients and fixed effects, and a common five-neighbor matrix. Parentheses: score-HAC(12) delta-method standard errors, retaining calendar gaps. Gases: ppb; PM_{10}: $\mu g/m^3$. Winter retains individual December–February months and their designation indicators. The last column adds three cohort trends and their spatial lags.

The supplementary May–June O_3 model uses 6,422 district-months and yields a total of 2.680 ppb (HAC SE 0.741). The main text gives the atmospheric rationale for this overlapping window.

S3 Geographic, control, period, and timing sensitivity

Table S3 changes one main specification feature at a time. Three- and seven-neighbor matrices preserve the full 247-unit sample. Omitting transport controls removes both daily vehicle distance and cars per capita and their spatial lags. The 2013-start comparison retains the original covariates, isolating sensitivity to the observation window. The land-use omission removes industrial area, commercial area, and green area per capita and their spatial lags. The January 2018 timing check moves only the second cohort's designation six months earlier.

Table S3: Additional sensitivity of total monthly spatial quantities

Specification	NO_2	CO	SO_2	O_3	PM_{10}
$k = 3$	-1.917***	-14.676**	-0.191**	0.712**	-0.322
	(0.522)	(7.153)	(0.080)	(0.361)	(0.706)
$k = 7$	-1.075**	-4.102	-0.156*	0.387	-0.540
	(0.456)	(6.585)	(0.089)	(0.407)	(0.896)
Omit transport controls	-1.974***	-10.595	-0.072	0.472	0.007
	(0.548)	(6.465)	(0.083)	(0.335)	(0.705)
Start in 2013	-1.956***	-4.527	-0.061	0.721**	-0.586
	(0.558)	(6.839)	(0.097)	(0.360)	(0.704)
Omit land-use controls	-2.042***	-7.936	-0.076	0.546	0.024
	(0.525)	(6.687)	(0.081)	(0.371)	(0.738)
2018 cohort starts January	-1.840***	-10.333	-0.075	0.464	-0.445
	(0.502)	(6.287)	(0.081)	(0.363)	(0.832)

HAC(12) standard errors in parentheses.
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Notes: Score-HAC standard errors with a 12-calendar-month bandwidth are in parentheses. All models include district and calendar year-month fixed effects. The 2013-start specification has 35,568 observations and other specifications have 38,532. Values use the outcome units of the main tables. Cohort-exclusion estimates are in the main text.

S4 Full monthly SDM coefficient estimates

Table S4 reports full primary-model coefficients with HAC(12) standard errors. All fits use 38,532 observations and absorbed district and year-month fixed effects. Continuous controls are standardized before constructing spatial lags; outcomes and designation remain unscaled. The coefficient on WY is ρ; the spatial multiplier converts coefficients to the associations reported in the main text.

Table S4: Monthly SDM coefficients with standardized covariates

Term	NO_2	CO	SO_2	O_3	PM_{10}
ρ	0.844^{***}	0.793^{***}	0.837^{***}	0.859^{***}	0.882^{***}
	(0.005)	(0.006)	(0.005)	(0.007)	(0.006)
LEZ	0.212^{*}	6.303^{**}	-0.039^{*}	-0.073	-0.804^{***}
	(0.110)	(2.668)	(0.023)	(0.104)	(0.290)
Population density	-0.101	-36.818^{***}	0.729^{***}	-0.775^{***}	-0.182
	(0.236)	(5.488)	(0.090)	(0.264)	(0.302)
Industrial area/person	0.073^{***}	1.984^{**}	-0.008	-0.151^{***}	0.185^{***}
	(0.019)	(0.825)	(0.009)	(0.037)	(0.037)
Commercial area/person	0.039	-1.042	0.015	0.155^{***}	-0.201^{***}
	(0.025)	(1.149)	(0.016)	(0.032)	(0.037)
Green area/person	-0.355^{***}	0.254	-0.016	-0.031	0.067
	(0.048)	(1.840)	(0.020)	(0.077)	(0.097)
Daily vehicle distance	0.160^{***}	1.057	0.025^{**}	-0.038	0.185^{**}
	(0.043)	(0.789)	(0.011)	(0.033)	(0.084)
Cars/person	-0.100^{***}	-0.197	-0.006	0.046^{*}	-0.052
	(0.022)	(0.698)	(0.005)	(0.024)	(0.037)
Temperature	-6.897^{***}	-127.998^{***}	-0.755^{***}	12.222^{***}	-7.287^{***}
	(0.534)	(15.575)	(0.269)	(0.952)	(1.267)
Sunshine	0.280^{**}	9.382^{***}	0.086^{**}	-0.419^{***}	0.017
	(0.124)	(2.519)	(0.041)	(0.120)	(0.130)
Low-wind equivalent days	0.237^{***}	2.100	0.088^{***}	0.144	0.226^{**}
	(0.051)	(1.811)	(0.034)	(0.103)	(0.099)
Wind speed	-0.043	1.148	0.065^{**}	0.153	0.526^{***}
	(0.108)	(2.619)	(0.028)	(0.113)	(0.120)
Humidity	-0.432^{**}	-3.258	0.052	-0.240^{*}	-0.122
	(0.172)	(3.455)	(0.046)	(0.128)	(0.172)
Precipitation	0.037	-1.121	0.001	0.057	-0.095
	(0.090)	(1.539)	(0.017)	(0.088)	(0.088)
$W \times$ LEZ	-0.504^{***}	-7.782^{***}	0.026	0.153	0.791^{**}
	(0.158)	(2.829)	(0.021)	(0.109)	(0.318)
$W \times$ Population density	-1.671^{***}	-1.100	-0.401^{***}	1.147^{***}	-0.544^{**}
	(0.425)	(6.015)	(0.069)	(0.268)	(0.276)
$W \times$ Industrial area/person	0.121^{***}	3.638^{***}	-0.077^{***}	-0.247^{***}	-0.026
	(0.046)	(0.855)	(0.019)	(0.078)	(0.143)
$W \times$ Commercial area/person	0.396^{***}	2.023	0.023	0.133	-0.141
	(0.089)	(1.366)	(0.022)	(0.115)	(0.183)
$W \times$ Green area/person	-0.598^{***}	-11.001^{***}	0.069	0.165	0.179
	(0.214)	(3.422)	(0.067)	(0.202)	(0.186)
$W \times$ Daily vehicle distance	-0.161^{*}	-0.981	-0.005	0.087	-0.236^{*}
	(0.094)	(1.958)	(0.020)	(0.065)	(0.140)
$W \times$ Cars/person	0.182^{***}	3.118^{***}	-0.021	-0.046	0.058
	(0.066)	(0.986)	(0.023)	(0.057)	(0.048)
$W \times$ Temperature	4.994^{***}	77.497^{***}	0.280	-9.692^{***}	4.796^{***}
	(0.535)	(14.222)	(0.211)	(0.853)	(1.260)
$W \times$ Sunshine	-0.234^{*}	-8.823^{***}	-0.083^{**}	0.450^{***}	0.021
	(0.133)	(2.583)	(0.041)	(0.120)	(0.137)
$W \times$ Low-wind equivalent days	-0.196^{***}	-1.738	-0.087^{***}	-0.107	-0.241^{**}
	(0.049)	(1.357)	(0.032)	(0.099)	(0.113)
$W \times$ Wind speed	-0.052	-1.283	-0.071^{**}	-0.004	-0.625^{***}
	(0.103)	(2.561)	(0.029)	(0.116)	(0.126)
$W \times$ Humidity	0.379^{*}	2.519	-0.053	0.196	-0.030
	(0.193)	(3.867)	(0.045)	(0.131)	(0.181)
$W \times$ Precipitation	-0.111	0.410	-0.027	0.029	-0.016
	(0.097)	(1.559)	(0.019)	(0.102)	(0.084)

Table S4 (continued)

Term	NO_2	CO	SO_2	O_3	PM_{10}

HAC(12) standard errors in parentheses.
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

S5 Residual dependence and uncertainty estimation

Table S5 summarizes residual dependence under the within-transformed SDM criterion. Temporal correlations use matched calendar months within districts; monthly Moran's I uses centered residuals and the fitted five-neighbor matrix.

Table S5: Dependence diagnostics for the primary monthly SDM

Outcome	Lag-1 median	Lag-1 IQR	Lag-12 median	Moran's I median
NO_2	0.776	[0.700, 0.847]	0.469	0.033
CO	0.709	[0.631, 0.781]	0.341	0.006
SO_2	0.761	[0.679, 0.816]	0.369	0.002
O_3	0.711	[0.628, 0.763]	0.386	0.007
PM_{10}	0.705	[0.640, 0.773]	0.366	-0.016

Notes: Lag-1 and lag-12 entries summarize 247 district-level correlations at one- and twelve-calendar-month separations. IQR: interquartile range. Moran's I is summarized by its median across 156 months.

Let $\widetilde{y}_t$ and $\widetilde{X}_t$ be the two-way within-transformed outcome and design, with the design containing own and spatially lagged regressors. To match the implemented `splm` criterion, define $z_t = W\widetilde{y}_t$ and $e_t = \widetilde{y}_t - \rho z_t - \widetilde{X}_t b$. For $\omega = \log \sigma^2$ (distinct from the spatial-control vector η in the main text), its contribution, up to a constant, is

$$\ell_t = \log |I - \rho W| - \frac{n}{2}\omega - \frac{e_t' e_t}{2\exp(\omega)}.$$

Writing $Q = (I - \rho W)^{-1} W$, the joint score is

$$s_t = \begin{pmatrix} -\operatorname{tr}(Q) + z_t' e_t/\sigma^2 \\ \widetilde{X}_t' e_t/\sigma^2 \\ -n/2 + e_t' e_t/(2\sigma^2) \end{pmatrix}.$$

Let $H = -\sum_t \partial^2 \ell_t / \partial\vartheta \partial\vartheta'$ be the joint observed information, where $\vartheta = (\rho, b', \omega)'$; the bread is H^{-1}. We retain its off-diagonal blocks rather than treating ρ as independent of the regression coefficients.

Scores are centered over observed months. With $\bar{s}_t$ denoting the centered score, the HAC meat is

$$M_L = \sum_t \bar{s}_t \bar{s}_t' + \sum_{h=1}^{L} \left(1 - \frac{h}{L+1}\right) \sum_t \left(\bar{s}_t \bar{s}_{t-h}' + \bar{s}_{t-h} \bar{s}_t'\right),$$
$$\widehat{V}_L = H^{-1} M_L H^{-1}.$$

The primary bandwidth is 12 calendar months; sensitivity choices are 6 and 24. In seasonal or May–June fits, unobserved months contribute zero scores, preserving actual calendar gaps. Cross-sectional aggregation retains contemporaneous score dependence among districts. The construction assumes weak temporal dependence and sufficient time information, with seasonal inference approximate for 39 observed months. Covariance adjustment leaves coefficients unchanged and does not address mean misspecification or interpolation uncertainty.

For any direct, indirect, or total quantity $q(\rho, b)$, its variance is $\nabla q' \widehat{V}_L \nabla q$, with a zero derivative for ω. Approximate intervals use $q \pm 1.96\,\mathrm{SE}(q)$. Table S6 compares the total SE from H^{-1}, denoted OIM, against the three score-HAC choices. All SDM tables and the seasonal figure use HAC(12), except the explicitly labeled covariance comparison. Non-spatial benchmarks use district-clustered errors, while group-time diagnostics use their separate multiplier procedure.

Table S6: Total-association uncertainty under alternative covariance estimates

Outcome	Estimate	OIM SE	HAC(6) SE	HAC(12) SE	HAC(24) SE	HAC(12) 95% CI
NO_2	-1.868***	0.168	0.445	0.519	0.585	[-2.886, -0.850]
CO	-7.128	2.971	5.793	6.315	7.158	[-19.506, 5.250]
SO_2	-0.084	0.045	0.086	0.082	0.063	[-0.246, 0.077]
O_3	0.563	0.192	0.367	0.367	0.364	[-0.156, 1.283]
PM_{10}	-0.108	0.325	0.734	0.778	0.840	[-1.632, 1.417]

Stars on estimates are based on HAC(12) p-values.
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Notes: All columns use the same point estimates. OIM: joint observed information; HAC(6), HAC(12), and HAC(24): calendar-month Bartlett bandwidths. Gases: ppb; PM_{10}: $\mu g/m^3$.

S6 Cross-season comparisons and multiplicity

Let $q_s = (\beta_s + \theta_s)/(1 - \rho_s)$ be the total spatial association in season s, H_s its full joint observed information, and $\bar{s}_{st}$ its centered score at calendar month t. For $g_s = \nabla_{\vartheta_s} q_s$, the only nonzero gradient entries are

$$\frac{\partial q_s}{\partial \rho_s} = \frac{\beta_s + \theta_s}{(1 - \rho_s)^2}, \qquad \frac{\partial q_s}{\partial \beta_s} = \frac{\partial q_s}{\partial \theta_s} = \frac{1}{1 - \rho_s}.$$

Define the scalar influence contribution $a_{st} = g_s' H_s^{-1} \bar{s}_{st}$ for observed months of season s and zero otherwise. Centering uses the 39 observed months within that seasonal fit, before padding onto the

complete 156-month calendar. For seasons s and r, the joint covariance estimate is

$$\widehat{V}_{sr} = \sum_{t=1}^{156}\sum_{u=1}^{156} k_{12}(t-u)a_{st}a_{ru}, \qquad k_{12}(h) = \max\left(1 - \frac{|h|}{13}, 0\right).$$

The covariance estimator preserves calendar separation and cross-season score dependence; its diagonal elements are the season-specific HAC(12) variances.

Let $\widehat{q} = (\widehat{q}_{\text{winter}}, \widehat{q}_{\text{spring}}, \widehat{q}_{\text{summer}}, \widehat{q}_{\text{autumn}})'$ and $C = [-\mathbf{1}_3\ I_3]$. The omnibus statistic is

$$T = (C\widehat{q})'(C\widehat{V}C')^{-1}(C\widehat{q}),$$

compared with an approximate χ^2_3 reference distribution. Pairwise seasonal differences use their corresponding contrast vector and the same joint covariance. The calculation is repeated for baseline and cohort-trend models. Its target is equality of model-implied seasonal associations conditional on each specification.

Holm adjustment uses three separate families: ten omnibus tests; 60 pairwise comparisons (six pairs, five pollutants, two specifications); and five pooled baseline total-association tests. These are exploratory comparisons. Displayed intervals are marginal normal approximations, not simultaneous or multiplicity-adjusted intervals; other sensitivity analyses remain outside these families.

Table S7: Equality tests for the four seasonal total spatial associations

Specification	Outcome	χ^2	df	p	Holm p
Baseline	NO_2	3.34	3	0.342	1.000
Baseline	CO	2.28	3	0.517	1.000
Baseline	SO_2	27.72	3	< 0.001	< 0.001
Baseline	O_3	25.68	3	< 0.001	< 0.001
Baseline	PM_{10}	3.95	3	0.266	1.000
Cohort trends	NO_2	4.93	3	0.177	1.000
Cohort trends	CO	5.22	3	0.156	1.000
Cohort trends	SO_2	3.14	3	0.370	1.000
Cohort trends	O_3	4.89	3	0.180	1.000
Cohort trends	PM_{10}	1.59	3	0.662	1.000

Notes: Each test compares winter, spring, summer, and autumn for one pollutant and specification. Covariance retains cross-season dependence using the calendar-month HAC(12) kernel. Holm p-values adjust across all ten rows. df: degrees of freedom.

For the baseline ozone contrasts discussed in the main text, spring minus winter is 2.016 ppb (SE 0.427; marginal 95% interval $[1.180, 2.852]$; Holm pairwise $p = 0.000138$), and summer minus winter is 2.532 ppb (SE 0.557; $[1.440, 3.624]$; adjusted $p = 0.000325$). In the separate pooled-baseline family, the adjusted NO_2 p-value is 0.00162 and the remaining adjusted p-values are at least 0.499.

S7 Interpolation validation and regression sensitivity

S7.1 Station prediction performance

For each eligible station–month–variable observation, leave-one-out validation removes that station and predicts its value using the other eligible stations in the same month. IDW uses power 2 in projected meters; nearest prediction uses the closest remaining eligible station. Table S8 reports pooled absolute and squared-error summaries for the five urban ambient outcomes and six meteorological controls. Holdouts are station-month predictions, not independent sampling units.

Table S8: Leave-one-station-out prediction errors for analysis variables

		IDW		Nearest	
Variable	Holdouts	MAE	RMSE	MAE	RMSE
NO_2 (ppb)	53,342	3.486	4.630	3.624	4.961
CO (ppb)	52,839	73.451	98.241	89.349	121.845
SO_2 (ppb)	52,992	0.753	1.191	0.916	1.511
O_3 (ppb)	53,603	3.086	4.155	3.677	4.928
PM_{10} ($\mu g/m^3$)	52,989	4.229	5.793	5.105	7.009
Temperature (°C)	14,584	0.849	1.188	0.948	1.364
Sunshine (h/day)	14,551	0.462	0.617	0.568	0.759
Low-wind equivalent (days)	14,578	5.862	7.595	6.737	9.218
Wind speed (m/s)	14,578	0.565	0.886	0.674	1.019
Relative humidity (%)	14,581	3.943	5.074	4.963	6.366
Precipitation (mm/day)	14,555	0.806	1.422	0.890	1.636

Notes: MAE: mean absolute error; RMSE: root mean squared error. Methods use identical holdouts within each variable; counts differ with variable-specific eligibility. Errors retain the variable's units and assess point prediction, not district-area accuracy.

Although IDW has lower station-holdout RMSE for all 16 environmental series, its urban NO_2 mean signed error is 1.319 ppb, versus 0.513 for nearest prediction. The low-wind equivalent has an IDW RMSE of 7.595 days.

For precipitation only, the additional spatial test excludes all stations in the held-out station's 100-km square grid block. With 14,555 held-out station-months, IDW and nearest RMSEs are 1.700 and 1.769 mm/day, compared with 1.422 and 1.636 under single-station exclusion. Their blocked MAEs are 0.989 and 0.983 mm/day, respectively. This is not a 100-km exclusion radius: nearby stations across block boundaries can remain. The two designs therefore assess station prediction under different local data availability.

S7.2 Common-support model comparison

Table S9 compares pooled totals using the IDW and nearest-station fields described in the main-text Materials and methods. Eligible station-months, grid, and aggregation weights are shared; annual covariates, designation, estimation sample, and policy-neighbor matrix remain fixed. Outcomes and weather change jointly, so their contributions to measurement sensitivity are not separated.

Table S9: Pooled total associations under common-support interpolation alternatives

Specification	NO_2	CO	SO_2	O_3	PM_{10}
IDW baseline	-1.868***	-7.128	-0.084	0.563	-0.108
	(0.519)	(6.315)	(0.082)	(0.367)	(0.778)
Nearest baseline	-1.831***	5.007	-0.487***	0.810	-2.377***
	(0.507)	(7.343)	(0.116)	(0.530)	(0.714)
IDW + cohort trends	0.530	14.481**	0.001	-0.254	0.159
	(0.864)	(7.289)	(0.086)	(0.858)	(0.847)
Nearest + cohort trends	-0.415	21.603*	-0.132	0.524	0.332
	(1.026)	(11.097)	(0.119)	(1.162)	(0.907)

HAC(12) standard errors in parentheses.
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Notes: IDW and nearest-station grid predictions use identical area-aggregation weights. All fits use 247 districts and 156 months. Parentheses give score-HAC(12) delta-method standard errors. Gas units are ppb; PM_{10} units are $\mu g/m^3$. Intervals are marginal and exploratory; no additional multiplicity-adjusted claim is made for this sensitivity table.

The nearest-panel baseline SO_2 and PM_{10} marginal 95% intervals are $[-0.714, -0.260]$ ppb and $[-3.776, -0.977]$ $\mu g/m^3$, respectively, supplementing the point estimates and standard errors in Table S9. The main text interprets the pollutant-specific interpolation and trend comparisons.

S8 Policy-date evidence and timing sensitivity

Table S10 links the assigned permanent-LEZ rollout months to documentary evidence or explicit assumptions. As defined in the main text, this geographic measure is distinct from enforcement intensity and other vehicle-restriction schemes.

Table S10: Source-to-code mapping for the permanent-LEZ rollout

Geographic cohort	Documentary support	Monthly coding and qualification
Seoul (25 units)	Government rollout announcement (4 August 2016): 2017. Weekly Gonggam, No. 387 (9 January 2017), printed p. 36: January 2017 Seoul-wide expansion.	January 2017. Expansion of narrower pre-existing restrictions, not first-ever diesel regulation. District-specific first camera operation and compliance are unobserved.
Incheon and 17 Gyeonggi cities (35 units)	Government announcement: 2018. MECAR permanent-restriction page: integrated operation from 1 July 2018.	July 2018. January 2018 is an alternative coding scenario, allowing for earlier administrative rollout. Neither assignment verifies every district's enforcement history.
Further 11 Gyeonggi cities (13 units)	Government announcement: expansion in 2020. MECAR describes coverage extending to 28 Gyeonggi cities by 2020.	January 2020 is assumed. July and December 2020 are mid- and late-year sensitivity scenarios, not documented common enforcement dates.

Sources: Ministry of Environment rollout announcement; Weekly Gonggam, No. 387; MECAR permanent-restriction information.

Each alternative changes only one cohort's start month. The 247 districts, 156 months, environmental fields, controls, and five-neighbor matrix remain fixed. Cohort-specific trend indicators are defined by geographic cohort and are unchanged across timing scenarios. The second-phase scenario changes designation for 35 districts over six months (210 district-months). The July and December third-phase scenarios change 13 districts over six or eleven months (78 or 143 district-months). All scenarios are reported for all five pollutants, with and without cohort trends; no scenario is selected using its estimate or p-value.

Table S11 reports every timing scenario. All baseline intervals for pollutants other than NO_2 include zero. The marginal positive trend-adjusted CO interval persists under July 2020 but not January 2018 or December 2020; the main text summarizes the NO_2 comparison.

Table S11: Pooled total associations under alternative assigned rollout months

Scenario	Outcome	Baseline (SE)	95% interval	Cohort trends (SE)	95% interval
Assigned months	NO_2	-1.868 (0.519)	[-2.886, -0.850]	0.530 (0.864)	[-1.164, 2.223]
	CO	-7.128 (6.315)	[-19.506, 5.250]	14.481 (7.289)	[0.194, 28.767]
	SO_2	-0.084 (0.082)	[-0.246, 0.077]	0.001 (0.086)	[-0.167, 0.170]
	O_3	0.563 (0.367)	[-0.156, 1.283]	-0.254 (0.858)	[-1.934, 1.427]
	PM_{10}	-0.108 (0.778)	[-1.632, 1.417]	0.159 (0.847)	[-1.501, 1.819]
Phase 2: Jan. 2018	NO_2	-1.840 (0.502)	[-2.824, -0.856]	0.650 (0.782)	[-0.883, 2.183]
	CO	-10.333 (6.287)	[-22.657, 1.990]	5.000 (9.983)	[-14.567, 24.566]
	SO_2	-0.075 (0.081)	[-0.234, 0.084]	0.028 (0.079)	[-0.128, 0.183]
	O_3	0.464 (0.363)	[-0.247, 1.176]	-0.583 (0.854)	[-2.258, 1.091]
	PM_{10}	-0.445 (0.832)	[-2.077, 1.186]	-0.809 (0.870)	[-2.514, 0.896]
Phase 3: July 2020	NO_2	-1.852 (0.527)	[-2.884, -0.819]	0.606 (0.880)	[-1.119, 2.330]
	CO	-7.449 (6.357)	[-19.909, 5.011]	13.725 (6.916)	[0.170, 27.280]
	SO_2	-0.089 (0.083)	[-0.252, 0.074]	-0.011 (0.086)	[-0.180, 0.157]
	O_3	0.489 (0.380)	[-0.256, 1.235]	-0.483 (0.903)	[-2.252, 1.286]
	PM_{10}	-0.127 (0.787)	[-1.670, 1.417]	0.061 (0.852)	[-1.609, 1.731]
Phase 3: Dec. 2020	NO_2	-1.844 (0.531)	[-2.884, -0.804]	0.654 (0.881)	[-1.072, 2.380]
	CO	-8.242 (6.303)	[-20.596, 4.112]	11.793 (6.471)	[-0.891, 24.477]
	SO_2	-0.094 (0.084)	[-0.258, 0.071]	-0.026 (0.087)	[-0.196, 0.143]
	O_3	0.513 (0.377)	[-0.226, 1.252]	-0.429 (0.874)	[-2.142, 1.283]
	PM_{10}	0.027 (0.822)	[-1.584, 1.639]	0.425 (0.924)	[-1.386, 2.237]

Notes: Assigned months are January 2017, July 2018, and January 2020; each alternative changes only the named phase. Standard errors and marginal intervals use score-HAC(12) and the delta method, without multiplicity adjustment. Gases: ppb; PM_{10}: $\mu g/m^3$.