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Technical Appendix to

KEEP YOUR CLUNKER IN THE SUBURB: LOW-EMISSION ZONES AND ADOPTION OF GREEN VEHICLES

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Appendix A: Comparative Results of Recent Urban PM_{10} Studies

Table A1

Comparative Results of Recent Urban PM_{10} Studies

			PM_{10} sources				
Study	Country	Station type	Motor vehicle exhaust (%)	Resuspension (dust) (%)	Combustion (industry and Individual) (%)	Natural sources (%)	Other (%)
Lenschow *et al.* (2001)	Germany (Berlin)	Traffic	38	12[†]	24	12[‡]	NA
		Background	23	8[§]	33	14[‡]	NA
Querol *et al.* (2004)	EU	Traffic	35–55	NA	15–25	17–24	NA
Querol *et al.*(2001)	Spain	Traffic	54	NA	NA	30	17[¶]
Furusjö *et al.* (2007)	Sweden	Traffic	36	23	14	NA	26[††]
		Background	13	23	19	NA	34[††]
Rodríguez *et al.* (2004)	Spain	Traffic	25	33	16	11[‡‡]	NA
		Background	8	42	20	11[‡‡]	NA
Chow *et al.* (1996)	US (CA)	Traffic	30–42	25–37	NA	18–23[‡‡]	NA
Harrison *et al.* (1997)	UK	Traffic	32	50	NA	NA	18[§§]

Notes.[†]The authors attribute 50% of PM_{10} levels to motor vehicles and then split this into 38% from emissions/tyre abrasion and 12% from the resuspension of dust caused by traffic. [‡]The residual is attributed to natural sources such as pollen and wind-borne soil. [§]The authors attribute 31% of PM_{10} levels to traffic and then split this into 23% from emissions/tyre abrasion effect on background levels and 8% from resuspension of dust. [¶]Source is undetermined. [††]Long range transport of pollution or dust particles from outside of Sweden. [‡‡]The specific natural source is marine aerosol. [§§]They identify the residual as secondary ammonium salts and are unable to determine whether these arise from combustion or are the effect of marine air.

Appendix B: Characteristics of German Attainment Cities, Non-attainment Cities and LEZ

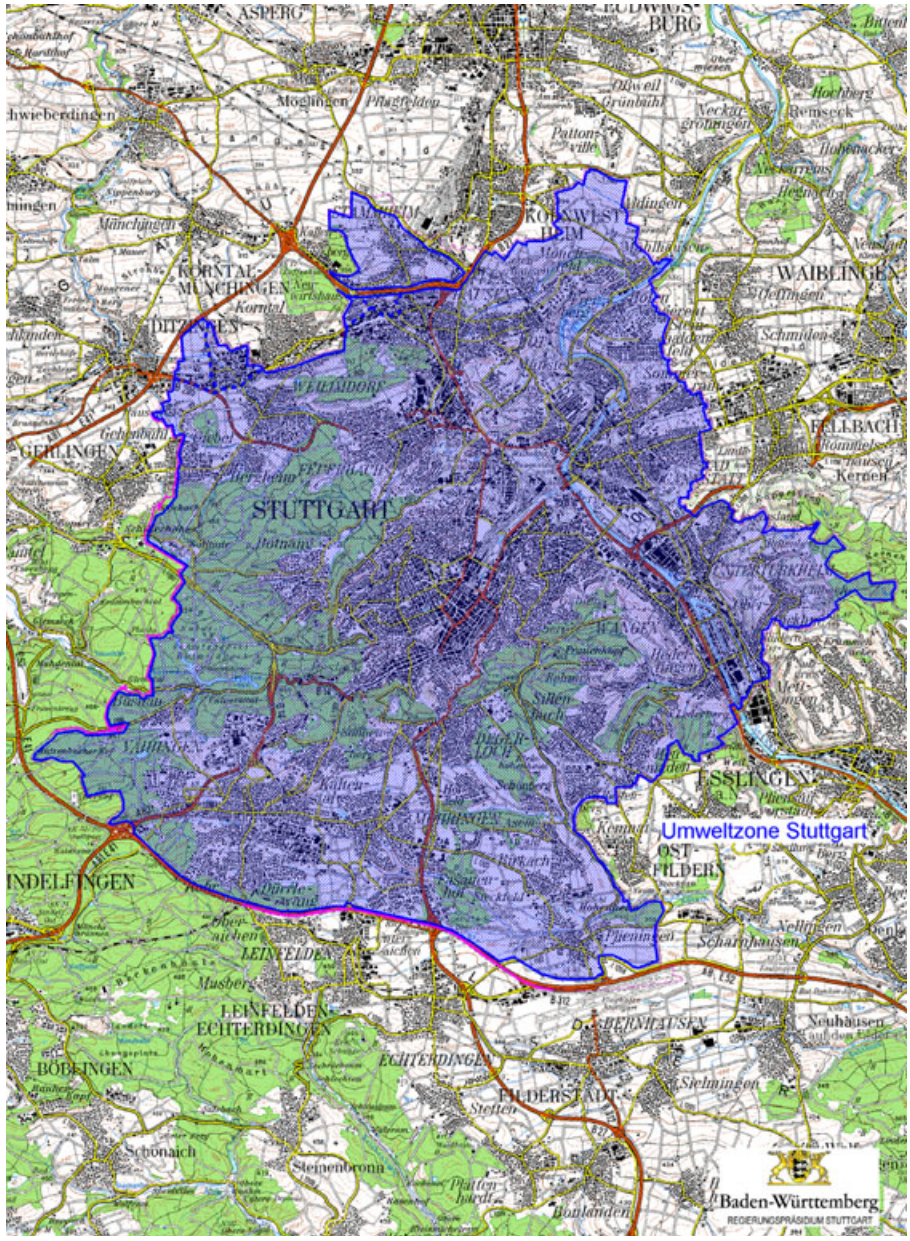

Fig. B1. *The LEZ of Stuttgart*

Notes. Copyright: Landesvermessungsamt Baden-Württemberg, Bundesamt für Kartographie und Geodäsie 2003. The English term 'Low-emission Zones' is commonly known in German as *Umweltzone* (Environmental Zone).

Table B1

Current and Future German LEZs

City	Start date	Excluded vehicles	Size of LEZ: new	Inhabitants that live within the LEZ	Dates of future restrictions (2nd, 3rd round)	Future excluded vehicles (2nd, 3rd round)
Berlin	1/1/2008	No sticker	88 km^2	1.1 million	1/1/2010	Red + yellow
Cologne	1/1/2008	No sticker	16 km^2	130,000	1/1/2010	Red
Hannover	1/1/2008	No sticker	50 km^2	218,000	01/01/09, 01/01/10	Red, yellow
Dortmund (Brackeler Road)	1/12/2008	No sticker + red	<0.1 km^2	300	1/1/2010	Not yet planned
Ilsfeld	3/1/2008	No sticker	2.5 km^2	4,000	1/1/2012	Red
Leonberg	3/1/2008	No sticker	30 km^2	40,000	1/1/2012	Red
Ludwigsburg	3/1/2008	No sticker	30 km^2	55,000	1/1/2012	Red
Mannheim	3/1/2008	No sticker	7.5 km^2	93,900	1/1/2012	Red
Reutlingen	3/1/2008	No sticker	<10 km^2	Unknown	1/1/2012	Red
Schwäbisch Gmünd	3/1/2008	No sticker	5 km^2	20,000	1/1/2012	Red
Stuttgart	3/1/2008	No sticker	207 km^2	590,000	1/1/2012	Red
Tübingen	3/1/2008	No sticker	≈13 km^2	Unknown	1/1/2012	Red
Pleidelsheim	7/1/2008	No sticker	7 km^2	7,000	1/1/2012	Red
Bochum	10/1/2008	No sticker	58.1 km^2	150,000	End of 2010	Red + yellow
Bottrop	10/1/2008	No sticker	≈25 km^2	Unknown	End of 2010	Red + yellow
Dortmund	10/1/2008	No sticker	19.1 km^2	587,137	1/1/2011	Red
Duisburg	10/1/2008	No sticker	≈43 km^2	Unknown	End of 2010	Red + yellow
Essen	10/1/2008	No sticker	140 km^2	14,000	1/1/2011	Red
Frankfurt	10/1/2008	No sticker	110 km^2	Unknown	01/01/10, 01/01/12	Red, yellow
Gelsenkirchen	10/1/2008	No sticker	20 km^2	Unknown	End of 2010	Red + yellow
Mülheim	10/1/2008	No sticker	≈14.2 km^2	Unknown	End of 2010	Red + yellow
München	10/1/2008	No sticker	44 km^2	431,000	1/1/2010	Red
Oberhausen	10/1/2008	No sticker	23.8 km^2	91,000	End of 2010	Red + yellow
Recklinghausen	10/1/2008	No sticker	<20 km^2	Unknown	Unknown	Unknown
Bremen	1/1/2009	No sticker	7 km^2	56,000	1/1/2010	Red
Heilbronn	1/1/2009	No sticker	≈22.5 km^2	Unknown	1/1/2012	Red
Herrenberg	1/1/2009	No sticker	≈4 km^2	28,000	1/1/2012	Red
Karlsruhe	1/1/2009	No sticker	≈12 km^2	Unknown	1/1/2012	Red
Mühlacker	1/1/2009	No sticker	≈1.5 km^2	Unknown	2012	Red
Pforzheim	1/1/2009	No sticker	≈2 km^2	Unknown	1/1/2012	Red

Table B1
(*Continued*)

City	Start date	Excluded vehicles	Size of LEZ: new	Inhabitants that live within the LEZ	Dates of future restrictions (2nd, 3rd round)	Future excluded vehicles (2nd, 3rd round)
Ulm	1/1/2009	No sticker	≈27 km^2	Unknown	1/1/2012	Red
Düsseldorf	2/15/2009	No sticker	13.8 km^2	36,500	1/1/2011	Red
Wuppertal	2/15/2009	No sticker	≈15 km^2	Unknown	1/1/2011	Red
Augsburg	7/1/2009	No sticker	5.2 km^2	Unknown	1/1/2010	Red
Neu-Ulm	11/1/2009	No sticker	≈2.7 km^2	Unknown	1/1/2012	Red
Bonn	1/1/2010	No sticker	≈5 km^2	Unknown	7/1/2011	Red + yellow
Freiburg	1/1/2010	No sticker	28 km^2	120,000	1/1/2012	Red + yellow
Heidelberg	1/1/2010	No sticker	10.3 km^2	170,000	1/1/2012	Red
Münster	1/1/2010	No sticker + red	≈1.5 km^2	Unknown	Unknown	Unknown
Osnabrück	1/4/2010	No sticker	14 km^2	7,000	1/4/2011	Red
Pfinztal	1/1/2010	No sticker	31 km^2	18,000	1/1/2012	Red
Dresden	2012	No sticker	4.2 km^2	6,500	Unknown	Unknown
Leipzig	1/1/2011	No sticker-yellow	≈239 km^2	Unknown	Unknown	Unknown
Cities with proposed LEZs (no final start date yet):	Arnsbach, Arzberg, Aschersleben, Bayreuth, Bernau, Brandenburg an der Havel, Braunschweig, Burgdorf, Burghausen, Castrop-Rauxel, Chemnitz, Cottbus, Darmstadt, Eberswalde, Erfurt, Erwitte, Frankfurt an der Oder, Gera, Görlitz, Halle (Saale), Hambach, Hamburg, Ingolstadt, Itzehoe, Jena, Kassel, Krefeld, Lahn-Dill, Landshut, Lindau, Ludwigshafen, Lutherstadt Wittenberg, Mainz, Magdeburg, Mühlheim an der Ruhr, Nauen, Neuruppin, Neuwied, Neuss, Passau, Potsdam, Regensburg, Rhein-Main, Schwandorf, Speyer, Trier, Warstein, Weiden, Weimar, Worms, Wuppertal, Würzburg					

Note. All dates are shown month/day/year.

Table B2

Characteristics of all Attainment and Non-attainment Cities

City	Average 2005 PM_{10} at highest polluting station	2005 Exceedance days	Violate limit in 2005-06	Treatment status	LEZ start date	Population
Wascheid	12.0	0	0	Attainment		
Netphen	12.6	0	0	Attainment		
Neuglobsow	13.8	3	0	Attainment		
Simmerath	14.0	0	0	Attainment		
Welzheim	16.2	4	0	Attainment		
Andechs, Gde.teil Rothenfeld	16.5	4	0	Attainment		3,237
Dunzweiler	16.6	2	0	Attainment		974
Hummelshain	16.6	1	0	Attainment		641
Bad Arolsen/ Kohlgrund	17.0	5	0	Attainment		
Wittenberge	17.3	2	0	Attainment		
Dreißigacker	17.5	0	0	Attainment		
Rehlingen-Siersburg	17.7	3	0	Attainment		15,805
Klötze	17.8	2	0	Attainment		5,243
Kiel	18.7	5	0	APO-no violation		234,470
Güstrow	19.4	4	0	Attainment		105,071
Saarlouis	19.6	3	0	Attainment		209,719
Westerland	19.6	7	0	Attainment		
Kempten (Allgäu)	19.7	8	0	Attainment		61,442
Pfullendorf	20.1	8	0	Attainment		
Soest	20.4	6	0	Attainment		308,211
Wörth	20.5	8	0	Attainment		17,500
Tauberbischofsheim	20.5	13	0	Attainment		
Gülzow	20.6	9	0	Attainment		1,288
Wilhelmshaven	20.8	11	0	Attainment		83,245
Ratingen	20.8	5	0	Attainment		
Leverkusen	20.8	2	0	Attainment		161,030
Zarrentin	20.8	9	0	Attainment		4,672
Solingen	20.9	7	0	Attainment		163,291
Naila	21.1	7	0	Attainment		8,305
Walsrode	21.1	8	0	Attainment		
Michelstadt	21.2	7	0	Attainment		
Zella-Mehlis	21.3	4	0	Attainment		12,245
Göhlen	21.3	11	0	Attainment		407
Tübingen	21.6	9	1	LEZ	3/1/2008	216,616
Biberach	21.6	13	0	Attainment		188,693
Klingenthal	21.6	9	0	Attainment		8,831
Pforzheim	21.7	13	1	'Future' LEZ	1/1/2009	119,168
Eisenach	21.8	10	0	Attainment		43,703
Jork	21.8	11	0	Attainment		
Völklingen	21.9	3	0	Attainment		40,794
Nettetal	22.1	8	0	Attainment		
Reidstadt	22.2	9	0	Attainment		
Eggenstein	22.3	10	0	Attainment		
Neuruppin	22.4	13	0	APO-no violation		
Wiesloch	22.4	12	0	Attainment		
Dillingen	22.5	4	0	Attainment		21,431
Friedrichshafen	22.5	14	0	Attainment		
Kleinwallstadt	22.6	9	0	Attainment		5,823
Fulda	22.7	7	0	Attainment		219,600
Neu Zauche	22.7	16	0	Attainment		

Table B2
(*Continued*)

City	Average 2005 PM_{10} at highest polluting station	2005 Exceedance days	Violate limit in 2005-06	Treatment status	LEZ start date	Population
Aalen	22.8	16	0	Attainment		
Bonn	22.9	4	0	'Future' LEZ -no violation	1/1/2010	313,291
Raunheim	23.1	12	0	Attainment		
Zeitz	23.1	16	0	Attainment		31,045
Hattingen	23.2	7	0	Attainment		
Wesel	23.2	15	0	Attainment		475,923
Radebeul	23.2	14	0	Attainment		33,091
Greiz	23.2	16	0	Attainment		115,387
Waiblingen	23.3	13	0	Attainment		
Bebra	23.3	10	0	Attainment		
Neustadt a.d. Donau	23.3	14	0	Attainment		12,738
Schwerte	23.5	9	0	Attainment		
Lünen	23.5	11	0	Attainment		
Osnabrück	23.6	13	1	'Future' LEZ -no violation	1/4/2010	163,330
Konstanz	23.6	18	0	Attainment		274,571
Plochingen	23.6	13	0	Attainment		
Delitzsch	23.7	12	0	Attainment		122,500
Buckow	23.8	21	0	Attainment		
Schwäbisch Hall	23.9	13	0	Attainment		189,579
Saalfeld	24.0	16	0	Attainment		27,861
Heidelberg	24.0	11	0	'Future' LEZ -no violation	1/1/2010	143,897
Burg	24.0	6	0	Attainment		25,000
Lingen	24.4	21	0	Attainment		
Meiningen	24.4	10	0	Attainment		21,448
Hof	24.4	21	0	Attainment		48,443
Hoyerswerda	24.4	20	0	Attainment		42,048
Bernburg	24.4	9	0	Attainment		64,860
Rostock	24.7	15	0	APO-no violation		199,325
Zwickau	24.7	18	0	Attainment		97,296
Hürth	24.7	8	0	Attainment		
Suhl	24.8	2	0	Attainment		42,283
Speyer	24.8	18	0	APO-no violation		50,567
Kulmbach	24.9	12	0	Attainment		76,890
Mönchengladbach	25.0	24	0	Attainment		261,216
Ulm	25.1	18	1	'Future' LEZ	1/1/2009	120,748
Schweinfurt	25.1	14	0	Attainment		54,097
Altenburg	25.2	27	0	Attainment		37,236
Coburg	25.4	15	0	Attainment		41,768
Aschaffenburg	25.6	12	0	Attainment		68,645
Wiesbaden	25.8	18	0	Attainment		275,085
Bernhausen	25.9	21	1	APO		13,216
Bautzen	25.9	20	0	Attainment		148,945
Stralsund	26.2	22	0	Attainment		58,563
Heilbronn	26.2	22	1	'Future' LEZ	1/1/2009	121,498
Lindau (Bodensee)	26.3	28	1	APO		79,636
Emden	26.3	20	0	Attainment		51,666
Nauen	26.4	25	0	APO-no violation		16,674
Hanau	26.5	20	0	Attainment		88,251
Königs Wusterhausen	26.5	20	0	Attainment		33,201

Table B2
(*Continued*)

City	Average 2005 PM_{10} at highest polluting station	2005 Exceedance days	Violate limit in 2005-06	Treatment status	LEZ start date	Population
Weißenfels	26.6	32	0	Attainment		73,624
Pirmasens	26.6	16	0	Attainment		42,761
Bamberg	26.7	20	0	Attainment		69,746
Freiberg	26.7	33	0	Attainment		144,094
Leonberg	26.8	16	1	LEZ	3/1/2008	45,537
Stendal	26.9	18	0	Attainment		130,436
Gelsenkirchen	27.0	24	0	'Future' LEZ	10/1/2008	267,418
Cologne	27.0	14	0	LEZ-no violation	1/1/2008	986,317
Mülheim	27.0	21	0	'Future' LEZ-no violation	10/1/2008	169,651
Zittau	27.0	31	0	Attainment		29,898
Arzberg	27.0	24	0	APO-no violation		5,893
Itzehoe	27.1	21	0	APO-no violation		33,800
Dessau	27.2	18	0	Attainment		77,914
Schwandorf	27.3	30	0	APO-no violation		144,644
Worms	27.5	27	1	APO		81,984
Würzburg	27.7	30	0	APO-no violation		134,080
Glauchau	27.8	24	0	Attainment		25,760
Norderney	27.8	17	0	Attainment		5,986
Aachen	28.0	18	0	APO		258,055
Wuppertal	28.0	20	0	'Future' LEZ	2/15/2009	358,813
Plauen	28.1	33	1	APO		68,614
Magdeburg	28.3	22	1	APO		229,344
Erlangen	28.3	22	0	APO		103,469
Gera	28.4	31	1	APO		103,446
Reutlingen	28.5	17	1	LEZ	3/1/2008	281,933
Saarbrücken	28.5	18	0	Attainment		340,702
Ratzeburg	28.8	28	0	APO-no violation		13,671
Datteln	29.0	30	0	Attainment		36,297
Krefeld	29.0	24	1	APO		237,336
Borna	29.1	31	0	Attainment		22,561
Neu-Ulm	29.1	34	1	'Future' LEZ	11/1/2009	163,477
Jena	29.6	29	1	APO		102,291
Landshut	29.7	39	1	APO		61,757
Nürnberg	29.7	33	0	APO-no violation		498,936
Weimar	29.8	35	1	APO		64,541
Trier	29.9	26	0	APO-no violation		100,198
Karlsruhe	29.9	22	1	'Future' LEZ	1/1/2009	285,756
Bottrop	30.0	33	0	'Future' LEZ	10/1/2008	119,195
Fürth	30.1	30	0	Attainment		113,596
Ansbach	30.2	29	1	APO		40,531
Regensburg	31.6	37	1	APO		130,153
Ludwigshafen	31.7	37	1	APO		163,536
Görlitz	31.8	42	1	APO		57,418
Hagen	32.0	27	1	APO		196,295

Table B2
(*Continued*)

City	Average 2005 PM_{10} at highest polluting station	2005 Exceedance days	Violate limit in 2005-06	Treatment status	LEZ start date	Population
Halle/Saale	32.2	51	1	APO		236,576
Kassel	32.2	48	1	APO		193,842
Aschersleben	32.2	38	1	APO		31,717
Freiburg	32.5	21	1	'Future' LEZ	1/1/2010	216,448
Münster	32.5	33	0	'Future' LEZ-no violation	1/1/2010	271,404
Frankfurt	32.5	48	1	'Future' LEZ	10/1/2008	648,925
Mannheim	33.4	43	1	LEZ	3/1/2008	307,847
Mainz	33.7	47	1	APO		195,178
Hamburg	33.7	46	1	APO		1,748,544
Darmstadt	34.0	42	1	APO		140,366
Erfurt	34.3	49	1	APO		202,723
Bayreuth	34.9	54	1	APO		73,617
Dresden	34.9	78	1	'Future' LEZ	2011	500,471
Potsdam	35.2	55	1	APO		148,126
Pleidelsheim	35.6	55	1	LEZ	7/1/2008	6,239
Essen	35.9	61	1	'Future' LEZ	10/1/2008	584,136
Frankfurt (Oder)	36.9	65	1	APO		63,177
Augsburg	37.1	61	1	'Future' LEZ	7/1/2009	262,492
Hannover	37.5	63	1	LEZ	1/1/2008	515,559
Düsseldorf	38.0	69	1	'Future' LEZ	2/15/2009	576,090
Berlin	38.1	74	1	LEZ	1/1/2008	3,399,896
Leipzig	38.2	75	1	'Future' LEZ	1/1/2011	504,798
Dortmund	39.5	82	1	'Future' LEZ	10/1/2008	587,870
Duisburg	40.0	83	1	'Future' LEZ	10/1/2008	500,217
Ludwigsburg	41.1	78	1	LEZ	3/1/2008	513,799
München	44.8	107	1	'Future' LEZ	10/1/2008	1,278,559
Stuttgart	54.5	187	1	LEZ	3/1/2008	593,244
Berghausen	NA	NA	1	APO		
Bernau	NA	NA	0	APO-no violation		
Burgdorf	NA	NA	0	APO-no violation		
Edertal-Hemfurth	NA	NA	0	Attainment		
Flensburg	NA	NA	0	Attainment		86,365
Heidenheim	NA	NA	0	Attainment		134,722
Heppenheim	NA	NA	0	Attainment		
Herrenberg	NA	NA	1	'Future' LEZ	1/1/2009	
Ilsfeld	NA	NA	1	LEZ	3/1/2008	8,307
Markgröningen	NA	NA	0	Attainment		
Mühlacker	NA	NA	1	'Future' LEZ	1/1/2009	
Possen	NA	NA	0	Attainment		
Sproitz	NA	NA	0	Attainment		
Wlzbachtal-Jöhlingen	NA	NA	0	Attainment		

Notes. All dates are shown month/day/year. Shaded area used in PM_{10} matching analysis. List only includes stations with sufficient data. 'Future' LEZs came into effect on or after 10/1/2008. 'No violation' refers to cities with APs despite not violating the PM_{10} standard.

Appendix C: Average Daily PM_{10} Level by LEZ Treatment Status

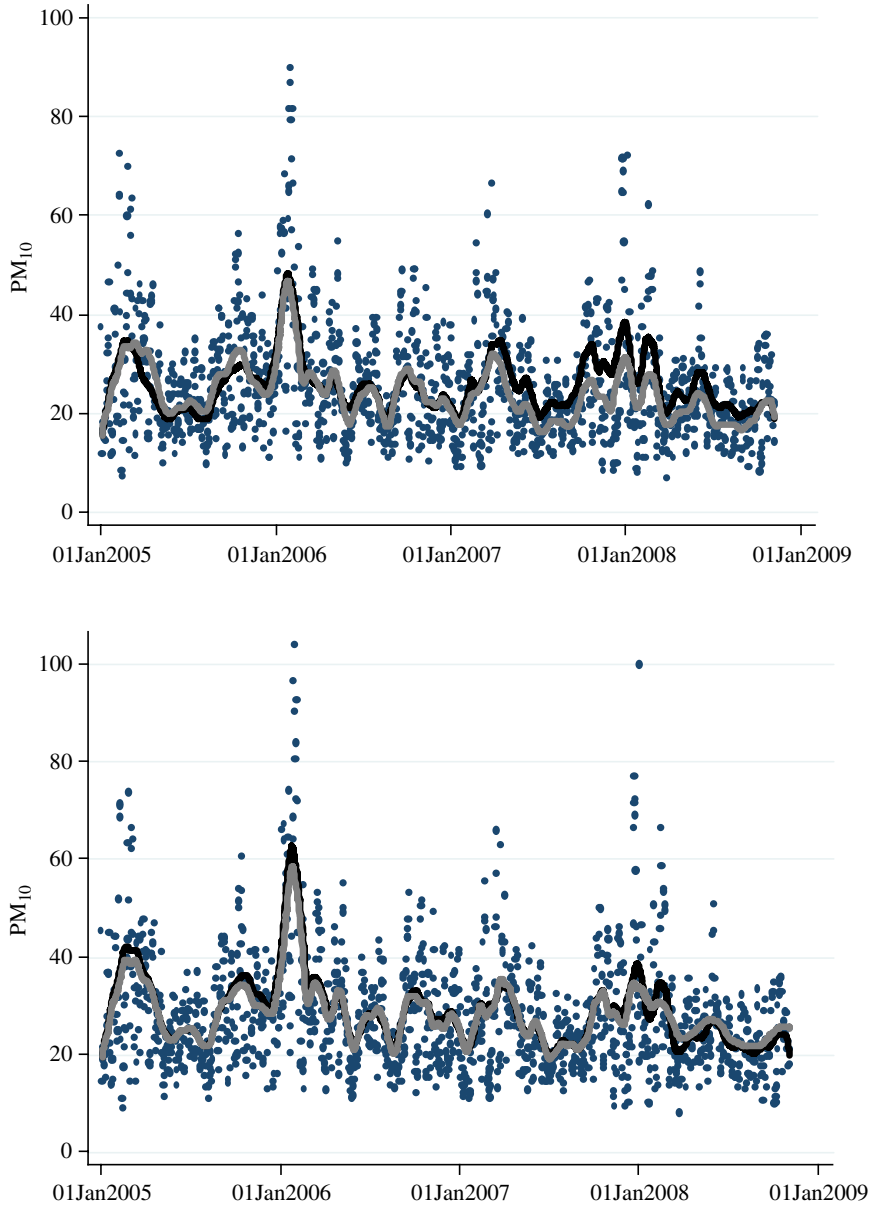

Fig. C1. *Average Daily PM_{10} Level by LEZ Treatment Status. (a) 2005 PM_{10} Matching Approach (b) Geographical Matching Approach*

Notes. Each dot represents the average daily PM_{10} level of the samples described under each of the two approaches (The sample of the 2005 matching approach is described in subsection 3.2 and the sample of the geographical approach is described in subsection 3.3.). The bold light grey line displays average daily PM_{10} level for control cities and the black bold black line the average daily PM_{10} level for treatment cities both estimated by the locally weighted scatter plot smoothing method with bandwidth of 0.04.

Appendix D: Test of Alternative Specifications

With respect to robustness in covariates, the Table below lists the effects of including/omitting the following set of regressors:

(*i*) original regression including all covariates;
(*ii*) without any weather covariates;
(*iii*) without Holiday covariates;
(*iv*) without Population covariates; and
(*v*) without any covariate, except the necessary dummies to identify the differences-in-differences treatment effects.

Table D1

LEZ versus Attainment Cities (Matching Based on 2005 PM_{10} in Range 25–35)

	With all covariates		Without weather covariates		Without holiday covariates	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)	Traffic stations (5)	Background stations (6)
LEZ versus attainment cities – all cities						
LEZ treatment	−0.0910***	0.00724	−0.105***	0.0100	−0.0912***	0.00722
	(0.0241)	(0.0285)	(0.0244)	(0.209)	(0.0247)	(0.0287)
Observations	6,723	7,704	6,723	7,704	6,723	7,704
Adjusted R^2	0.657	0.591	0.314	0.197	0.649	0.558
LEZ versus attainment cities – cities > 100,000						
LEZ treatment	−0.0686*	0.0448	−0.0663*	0.0559*	−0.0685*	0.0454
	(0.0302)	(0.0354)	(0.0307)	(0.0265)	(0.0310)	(0.0357)
Observations	2,896	4,280	2,896	4,280	2,896	4,280
Adjusted R^2	0.653	0.612	0.300	0.193	0.641	0.608

	With all covariates		Without population covariates		Without any covariates	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)	Traffic stations (5)	Background stations (6)
LEZ versus attainment cities – all cities						
LEZ treatment	−0.0910***	0.00724	−0.0910***	0.00724	−0.106***	0.0102
	(0.0241)	(0.0285)	(0.0241)	(0.0285)	(0.0248)	(0.209)
Observations	6,723	7,704	6,723	7,704	6,723	7,704
Adjusted R^2	0.657	0.591	0.657	0.591	0.299	0.187
LEZ versus attainment cities – cities > 100,000						
LEZ treatment	−0.0686*	0.0448	−0.0686*	0.0448	−0.0669*	0.0564*
	(0.0302)	(0.0354)	(0.0302)	(0.0354)	(0.0313)	(0.0265)
Observations	2,896	4,280	2,896	4,280	2,896	4,280
Adjusted R^2	0.653	0.612	0.653	0.612	0.283	0.181

Notes. Except where indicated in the column header, all regressions include year–month fixed effects, weather, holiday, station type and population covariates. Regressions include data for April to October 2007 *versus* 2008. Robust standard errors in brackets are clustered by city, ***p < 0.01, **p < 0.05, *p < 0.1.

These alternative specifications of Table 8 show that our results are qualitatively similar overall to those when all covariates are included.

Appendix E: Sample Details on Geographical Matching Approach

For the regional regressions, the following control cities are used for each LEZ city:

Table E1

Control Cities for Individual LEZ Regressions

Stuttgart, Tübingen, Reutlingen & Ludwigsburg	Leonberg	Mannheim	Cologne	Hannover	Berlin
Heidelberg	Herrenberg	Heidelberg	Essen	Bremen	Leipzig
Karlsruhe	Mühlacker	Karlsruhe	Dortmund	Osnabruck	Dresden
Pforzheim			Dusseldorf	Göttingen	
Ulm			Duisburg	Braunschweig	
Heilbronn					
Freiburg Herrenberg					
Mühlacker					

Table E2

Effect of Individual LEZs on log PM_{10}

Matching based on regional approach									
	Berlin (1)	Stuttgart (2)	Hannover (3)	Cologne (4)	Mannheim (5)	Reutlingen (6)	Tubingen (7)	Ludwigsburg (8)	Leonberg (9)
Traffic stations									
LEZ treatment	−0.120***	−0.0288	−0.0939**	−0.0742	−0.0992	−0.0582**	−0.0296	0.0489*	0.0687
	(0.0352)	(0.0218)	(0.0215)	(0.0416)	(0.0553)	(0.0246)	(0.0213)	(0.0212)	(0.0819)
Observations	4,376	6,507	2,188	2,996	2,050	4,836	4,879	4,880	1,202
Adjusted R^2	0.59	0.712	0.579	0.685	0.633	0.667	0.647	0.668	0.436
Background stations									
LEZ treatment	−0.0442	0.262***	0.0516	−0.0837	0.114*	0.118**	0.159***	0.0217	
	(0.0494)	(0.0243)	(0.0330)	(0.0425)	(0.00894)	(0.0244)	(0.0240)	(0.0370)	
Observations	2,186	1,712	2,735	2,568	856	1,712	1,712	1,712	
Adjusted R^2	0.591	0.619	0.461	0.612	0.639	0.596	0.591	0.593	

Notes. All regressions include year–month fixed effects, weather, holiday, station type and population covariates. Robust standard errors in parenthesis are clustered by city, ***p < 0.01, **p < 0.05, *p < 0.1.

Appendix F: Cost–benefit Analysis

F.1. *Benefits*

We use improvements in long-term mortality attributable to the decreased PM_{10} in LEZs as our measure of benefits. Long-term mortality measures the decrease in life expectancy caused by long-term exposure to PM_{10}. We ignore acute mortality, or the increase in mortality due to a short-term increase in PM_{10}, since this may just be measuring the 'harvesting' effect where people who were near death die a few days or weeks earlier. To calculate the effect of PM_{10} on long-term mortality, we use estimates of the link between PM_{10} and mortality and morbidity in France, Switzerland and Austria. These estimates were derived by the World Health Organisation (WHO) and have been used extensively in the epidemiology literature, that is, in Medina *et al.* (2004), Kunzli *et al.* (2000), Seethaler (1999), van Zelm (2008).[1] Specifically, the WHO study found that for every one million residents in Switzerland and France, each 10 $\mu g/m^3$ increase in PM_{10} is associated with an additional 340 premature mortalities. Since these studies find that the effect of PM_{10} on mortality is close to linear over the relevant range of PM_{10}, this means that each 1 $\mu g/m^3$ increase in PM_{10} is associated with 34 deaths per million residents. From these numbers using procedure described in Section 6, we calculate the number of lives saved by each LEZ using the number of inhabitants within each LEZ. We multiply this by the EPA's value of statistical life (VSL) of \$7,900,000 (2008\$)[2] to monetise these benefits (EPA 2000). Using this method, as summarised in Table F1 we find that the benefit from LEZs is approximately \$1.98 billion (\$1,978,395,825).

Table F1

Value of Mortality Benefits From Decreased PM_{10}

Fixed baseline mortality increment per 10 $\mu g/m^3$ PM_{10} and one million inhabitants	340
Deaths per person per 1 $\mu g/m^3$	0.000034

City	Traffic station coefficient	Average 2007 Traffic station PM_{10}	Amount PM_{10} decreases in 2008	Inhabitants of LEZ	Number of lives saved
Berlin	−0.1500[†]	28.86	4.33	1,300,000	191.33
Ludwigsburg	0.0489	34.65	−1.69	55,000	−3.17
Tubingen	−0.0296	31.26	0.93	78,300	2.46
Reutlingen	−0.0582	38.12	2.22	78,523.2	5.92
Stuttgart	−0.0288	33.01	0.95	590,000	19.07
Hannover	−0.0939	26.02	2.44	218,000	18.11
Leonberg	0.0687	33.42	−2.30	40,000	−3.12
Koln	−0.0742	32.98	2.45	130,000	10.82
Mannheim	−0.0992	28.43	2.82	93,900	9.00
Total number of lives saved		250			

	EPA Estimate
Value of statistical life	\$7,800,000
Value of lives saved	\$1,953,352,840

Note. [†]This estimate is derived from the stations that reside inside of the LEZ of Berlin (column 3 of Table 14).

[1] These estimates are based on two cohort studies, Pope *et al.* (1995) and Dockery *et al.* (1993), as re-estimated by Krewski *et al.* (2000). In their extensive review of the literature, the EPA singled out these two as the best studies for their cost–benefit analysis of the Clean Air Act Amendments (EPA 1999).

[2] This value has been adjusted to 2008 dollars from the value for 1999 specified in the cited report. Kiesner *et al.* (2012) estimate a range of VSL from 7 to 12 million.

This estimate of benefits is conservative for many reasons. First, we only count the improvement in mortality among people who reside within the LEZs studied. As our results show, however, PM_{10} also decreased in traffic areas outside of LEZs, most likely because of the adoption of cleaner vehicles, so if these areas were also included, the number of lives saved would be higher. If each city's entire population was used instead of just inhabitants of the LEZ, the benefits would jump to \$5.22 billion (\$5,217,522,677).

The second way in which our estimates are conservative is that we only consider long-term mortality. PM_{10} is also associated with non-lethal morbidity, however. In the above studies, health effects from respiratory hospital admissions, cardiovascular hospital admissions, adult chronic bronchitis, child bronchitis and adult and child asthmatic attacks are also considered. If these conditions and parameters are included in our benefits calculation in the same manner as above,[3] then Table F2 shows how our measure of the benefits increases by \$13,661,332.

F.2. *Costs*

To measure the costs LEZs have imposed on Germans, we estimate the total cost of upgrading vehicles to be able to enter the LEZs. Since we measure the health benefits realised between 2007 and 2008, we also look at the costs of upgrading vehicles over this time period. To do this, we use our spatial vehicle registration data to fit regressions of the change in share of green-sticker cars and trucks from 2008 to 2009 on distance from an LEZ. Since we do not want to count vehicles that would have switched to green sticker vehicles in the absence of the LEZ regulation, we use the change in share of green stickers for the point furthest away from an LEZ (0.0110 and 0.0828 at 244 km from an LEZ for cars and trucks respectively) as the baseline change in share of green stickers. For each location, we subtract this 0.0110 (0.0828) from our regression's predicted change in share of green stickered cars (trucks). This is the change in share of green stickers due to the LEZ, which we then multiply by the number of cars (trucks) for that location in 2008 to get the number of new green cars attributable to LEZs. We sum these numbers for all locations to get the total number of new cars and trucks due to the LEZ and multiply this by the average cost for upgrading a vehicle (\$1,650 for cars, \$14,500 for trucks) to get the total cost of upgrading cars and trucks because of LEZs. In other words, we estimate cost using the following formula:

$$\text{Total Cost} = \sum_{i=cars,\,trucks} p_i \sum_{j=1}^{J} N_{ij}(\widehat{C}_{ij} - C_{i0}),$$

where i represents cars and trucks, j indexes counties, N is the number of vehicles in 2008, $\widehat{C}_{ij}$ is fitted value of change in share of green cars, C_{i0} is the baseline change in share of green vehicles, and p equals the cost of upgrading each vehicle type.

We find that the total cost of upgrading cars is \$475,185,312 and the total cost of upgrading trucks is \$618,133,842. The combined total cost is \$1,093,319,154. This cost is nearly half of our primary measure of benefits, \$1,978,395,825. If one considers the benefits for those who live close to but outside of an LEZ, as well as morbidity benefits, then the benefits of LEZs will exceed the costs by even more.

[3] For the conditions that differentiate between adults and children, we adjust the population numbers, using 14% as the proportion of children under 14 in Germany. http://www.countryreports.org/people/ageStructure.aspx?countryid=91&countryname=

Table F2

Value of Morbidity Benefits From Decreased PM_{10}

Condition	Fixed baseline mortality increment per 10 μg/m³ PM_{10} and one million inhabitants cases	Deaths per person per 1 μg/m³	Willingness to pay to avoid condition (1996 euro)
Respiratory hospital admission	140	0.000014	$7,870.00
Cardiovascular hospital admissions	255	0.0000255	$7,870.00
Chronic bronchitis incidence (adult)	410	0.000041	$20,900.00
Bronchitis (child)	4,725	0.0004725	$131.00
Asthmatic attacks (children)	2,500	0.00025	$31.00
Asthmatic attacks (adult)	6,280	0.000628	$31.00

					Number of incidents avoided					
City	Traffic station coefficient	Average 2007 traffic station PM_{10}	Amount PM_{10} decreases in 2008	Inhabitants of LEZ	Respiratory hospital admission	Cardiovascular hospital admissions	Chronic bronchitis incidence (adult)	Bronchitis (child)	Asthmatic attacks (adult)	Asthmatic attacks (children)
Berlin	−0.15	28.86	4.33	1,300,000	78.78	143.50	198.42	372.25	3039.26	196.96
Ludwigsburg	0.0489	34.65	−1.69	55,000	−1.30	−2.38	−3.29	−6.17	−50.34	−3.26
Tubingen	−0.0296	31.26	0.93	78,300	1.01	1.85	2.55	4.79	39.13	2.54
Reutlingen	−0.0582	38.12	2.22	78,523	2.44	4.44	6.14	11.52	94.09	6.10
Stuttgart	−0.0288	33.01	0.95	590,000	7.85	14.30	19.78	37.10	302.92	19.63
Hannover	−0.0939	26.02	2.44	218,000	7.46	13.58	18.78	35.24	287.69	18.64
Leonberg	0.0687	33.42	−2.30	40,000	−1.29	−2.34	−3.24	−6.07	−49.60	−3.21
Koln	−0.0742	32.98	2.45	130,000	4.45	8.11	11.22	21.05	171.83	11.14
Mannheim	−0.0992	28.43	2.82	93,900	3.71	6.75	9.34	17.52	143.03	9.27
Total incidents avoided					103.12	187.82	259.71	487.23	3978.00	257.80
Willingness to pay (1996 euro)					$811,540	$1,478,162	$5,427,949	$63,828	$123,318	$7,992
Willingness to pay total (1996 euro)			$7,912,789							
Willingness to pay total (2008 USD)			$13,661,332							

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