Urban Transport Pollution: Revisiting the Environmental Kuznets Curve

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ABSTRACT

An inverted-U relationship between GDP per capita and three urban transport-related emissions is tested (using data from 84 cities). Per capita urban transport-related emissions of CO, VHC, and NOx increase and then decline at observed income levels—a result driven by a similar inverted-U relationship between income and emissions technology (i.e., emissions per passenger-km). However, for urban transport energy consumed, the estimated turning point was well beyond the sample bounds. Passenger-km per capita and car ownership both rise, and public transport's share of those passenger-km falls monotonically with income.

Keywords: transport and urban environment; environmental Kuznets curve; city-based data; urban density.

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1. Introduction and background

This paper tests the well-known Environmental Kuznets Curve[1] (EKC) hypothesis by using a city-based dataset and by examining urban emissions of three transport-caused pollutants—carbon monoxide (CO), nitrogen oxide (NOx), and volatile hydrocarbons (VHC). Carbon monoxide is caused by incomplete combustion, and its urban emissions are nearly all from vehicles. Carbon monoxide reduces oxygen delivery to the body's organs and tissues, and thus, is most harmful to those who suffer from heart and respiratory disease. However, high levels of CO may cause visual impairment and headaches in healthy people. Nitrogen oxides form when (fossil) fuel burns at high temperatures; they are caused primarily by motor vehicles and the burning of fossil fuels in electricity generation. Nitrogen oxides are both a local and regional pollutant, and contribute to ozone, smog, acid rain, and the formation of particulate matter. Transport-based volatile hydrocarbon emissions result from incomplete fuel combustion (fuel evaporation also causes VHC emissions). Hydrocarbons are a precursor to ground-level ozone—which is a key component of smog. Ground-level ozone can lead to difficulty breathing, lung damage, and reduced cardiovascular function. In addition, several hydrocarbons are considered toxic.

Urban density and fuel price are considered as well; because several studies have shown a negative relationship between vehicle miles traveled or energy consumed in private transport and both (i) urban density (e.g., Newman and Kenworthy 1989; Kenworthy and Laube 1999; Romero Lankao et al. 2009; Karathodorou et al. 2010; and Liddle 2013) and (ii) fuel price (e.g., Karathodorou et al. 2010 and Liddle 2013), using city-based data.

[1] The name references Simon Kuznets who found an inverted U-shaped relationship between income inequality and economic growth (Kuznets, 1955).

One might expect transport pollution—particularly pollution with local impacts—to eventually decline with income, i.e., to have a negative income elasticity at higher levels of income. Indeed, one of the main explanations in the EKC literature for the idea that emissions would fall as income rises is that the income elasticity of environmental *quality* demand is in excess of unity, i.e., a clean environment is a luxury good (Dinda 2004). Thus, one expects that an EKC relationship is most likely to occur for pollutants whose negative impacts are rather immediate and can be controlled locally (i.e., the people affected by the pollution can institute policies that will control that pollution). Indeed, since both CO's and VHC's impacts are more local than NOx's, and since both CO and VHC are controlled primarily through improvements in engine (combustion) efficiency, one might expect CO and VHC to fall at lower levels of income than NOx (which is controlled through vehicle efficiency and fuel switching). In addition, vehicle emissions of CO, VHC, and NOx have been regulated in OECD countries for decades.

Few EKC studies have focused on transport-related pollutants, and perhaps only one other EKC study employed city-based data.[2] Cole et al. (1997) estimated EKC relationships for carbon monoxide as well as for transport sector emissions of nitrogen dioxide, sulfur dioxide, and suspended particulate matter by analyzing panels consisting of about 20 years of national data from seven to nine OECD countries. They determined GDP per capita turning-points within their sample range for all of those pollutants, but they found that energy use by transport increased monotonically throughout the observed income range (Cole et al. 1997). Hilton and Levinson (1998) looked at automotive lead emissions using data for 48 countries over 20 years; they found that despite the fact that gasoline consumption increased with income monotonically,

[2] Several EKC analyses have considered city-based pollution *concentrations* (as opposed to emission flows), but income and the control variables considered were based on national statistics. This combination of city-level pollution with national-level variables potentially is problematic because, for example, large cities tend to have higher incomes than their national average, and urban density is only partially correlated with national density (Liddle 2013).

lead emissions and income had an inverted-U shaped relationship because pollution intensity (i.e., the amount of lead contained in gasoline) declined with income. Liddle (2004) similarly rejected an EKC for road energy use per capita using national-level data from 23 OECD countries because the implied turning-point was well outside the sample range. Lastly, Romero Lankao et al. (2009) employed the present city database, too; however, they examined the so-called STIRPAT model, which considers aggregate energy/emissions as the dependent variable and population among the independent variables, and thus, was not a traditional EKC analysis. Furthermore, we consider additional dependent variables (e.g., NOx and VHC per capita and several efficiency/intensity-type measures, such as pollution per passenger-km) and additional independent variables (e.g., fuel price) that Romero Lankao et al. did not.

Hence, in addition to employing city-based data, this study considers some combination of data from more countries and/or more environmental impacts than the previous transport-based analyses. Furthermore, this paper goes beyond the typical EKC analysis by examining some of the underlying causes of the inverted-U, i.e., the impact of income, urban density, and fuel price on mobility demand, modal choice, car ownership, and emissions per passenger-km.

2. Data and model

The Millennium Cities Database for Sustainable Transport (Kenworthy and Laube 2001) allows for the examination of three transport pollutants, carbon monoxide (CO), nitrogen oxide (NOx), and volatile hydrocarbons (VHC) (as well as energy consumed in transport).[3] That database is a cross-section—taken from 1995—of data from 84 cities in both developed and developing countries (Appendix Table A.1 lists the cities included along with their GDP per

[3] The database also reports sulfur dioxide emissions; however, since those emissions primarily are caused by the sulfur content of coal used in energy generation and by industrial activities such as metal smelting, sulfur emissions are not considered here.

capita in 1995 USD and urban density).[4] A major goal of the Millennium Cities Database was to achieve as high a level of data consistency as possible. The data were collected over three years (from 1998-2000), and data collection involved direct contact with authorities in each city through on-site visits and follow-up communications (Kenworthy and Laube 1999 and 2002). All of the data (emissions, passenger-km, energy consumption, GDP) are based on activities within metropolitan areas and on passenger transport only (i.e., freight is not considered). The definition of metropolitan area does differ some by world region, and, not surprisingly, is influenced by the functional urban region for which data are kept (Kenworthy and Laube 1999).[5]

The Millennium Cities Database is old; however, cross-national, city-based data clearly are important for drawing insights about transport. (A newer version of the database, UITP 2005, takes data from 2001 for 50 primarily European cities, and thus, it does not contain the income/development variation needed for an EKC-type analysis. Furthermore, the UITP 2005 database has pollution data for only 26 European cities, and it aggregates the three pollutants—CO, NOx, and VHC—into a single measure; such an aggregation likely is inappropriate/less meaningful given the pollutants' different impacts, sources, and, as will be demonstrated, income turning points.) Indeed, the Millennium Cities Database has been employed in several recent papers (e.g., Romero Lankao et al., 2009; Karathodorou et al. 2010; Souche 2010; and Liddle 2013). Furthermore, Environmental Kuznets Curve analyses are heavily dependent on cross-sectional variation—even when time variant data are available/considered—since very few countries have themselves achieved the transition from developing to developed within the time-frame for which data typically are available (perhaps only Korea). Hence, data from 1995 should

[4] Data were collected from 100 cities; however, the complete dataset is available for only 84 cities.
[5] Millennium Cities Database (which is in CD-ROM form) does not contain detailed information. However, an earlier, related database of 46 cities (from OECD and developing Asian cities), Kenworthy et al., 1999 (which was published in book form), does include detailed data sources for each city including maps of the metropolitan areas.

give some indication as to whether transport-related pollution varies with income levels (especially since less developed countries like China are not heavily relying on vehicle technologies that did not exist in 1995).

The following model is used to test for an EKC for urban transport CO, VHC, and NOx emissions:

$$\ln(E/P)_i = \alpha + \beta_1 \ln(GDP/P)_i + \beta_2 (\ln\left(\frac{GDP}{P}\right))_t^2 + \beta_3 \ln(Z)_i + \varepsilon_i \qquad (1)$$

where *E* is emissions from all transport within the metropolitan area, *P* is population in the metropolitan area, *GDP* is metropolitan gross domestic (or regional) product, and *Z* is a vector of other drivers that includes (i) urban density—i.e., the ratio between the population and the urbanized surface area of the metropolitan area (it does not include water within the urban boundary); and (ii) fuel price (which has a negative relationship with transport energy use, e.g., Karathodorou et al. 2010). Metropolitan GDP was calculated using the production approach and was converted to 1995 US dollars using average 1995 exchange rates (from the IMF).[6] Fuel price (measured in 1995 USD/MJ) is the average (weighted by distance travelled and energy consumed) price of fuel for private cars and motorcycles.[7] Also, to compare with previous studies, we estimate Equation 1 with total (private and public) metropolitan transport energy use per capita as a dependent variable. Table 1 displays the units and descriptive statistics for each of the main variables considered.

Table 1

[6] Kenworthy and Laube (1999, p. 699) argue against the use of Purchasing Power Parities (PPP) because of biases particular to transportation and urban form. Furthermore, applying country-level PPP conversions to city-level GDP may exacerbate (not mitigate) problems with international comparisons since, as mentioned before, city-level GDP tends to be higher than country-level GDP (i.e., cities in developing countries may be more similar to cities in developed countries than developing countries as a whole are similar to developed countries as a whole).

[7] Following Karathodorou et al. (2010), fuel price was calculated as the price of fuel per kilometre divided by the energy use per private passenger vehicle-kilometre.

Since NOx emissions from passenger transport include emissions from electricity generation used to power rail modes (the modes most likely to be powered by electricity), two additional variables are considered: (i) rail modes'[8] share of public transport vehicle kilometres;[9] and (ii) the share of (national) electricity generated from nonfossil fuels (technologies like hydro and wind do not emit NOx). The Millennium Cities Database for Sustainable Transport has information describing the extent of urban rail. Ideally, one would want metropolitan-based data on electricity generation; however, to our knowledge no such database exists. The International Energy Agency supplies national-based data on the sources of electricity generation.

An EKC relationship between emissions per capita and income is said to exist if the coefficient β_1 is statistically significant and positive, while the coefficient β_2 is statistically significant and negative. Furthermore, when the above situation is the case, the implied *turning point*, τ, or the level of GDP at which the relationship between income and emissions changes from positive to negative—can be calculated by:

$$\tau = exp\left(-\beta_1/(2\beta_2)\right) \qquad (2)$$

3. Results and discussion

Table 2 displays the results of the four EKC regressions (both the rail modes' share of public transport vehicle kilometres and the share of nonfossil fuel use were insignificant in the NOx model and thus are not included in the reported regressions).[10] For CO, VHC, NOx, and total transport energy use (i.e., Regressions I, II, III, and IV, respectively) the coefficients for urban density and fuel price are negative, highly significant, and fairly large. Since all the variables are in natural logs, the estimated coefficients can be thought of as elasticities. Thus, a one percent increase in urban density leads to a 0.55 percent drop in CO emissions and a nearly

[8] In the database these modes are termed tramway, light rail, metro, and heavy rail.
[9] A zero-one variable for the existence of passenger rail transport was considered too.
[10] The dummy variable for rail transport was insignificant too.

0.4 and an over 0.5 percent drop in NOx emissions and energy use, respectively—i.e., higher levels of urban density lead to greater use of nonmotorized and public transport modes (Rickwood et al. 2008), and such use leads to lower transport energy consumption per capita and so to lower emissions per capita.

The implied GDP per capita turning points for all pollutants (CO, VHC, and NOx) are well within the sample range. As expected the turning points for CO and VHC are lower than that for NOx—both CO and VHC can be lowered through improvements in basic technologies (e.g., more efficient catalytic converters). Cole et al. (1997) also found a lower turning point for CO than for NOx. The turning point GDP per capita level of $7,322 for CO (from Regression I) is an income level between that of Kuala Lumpur and Rio de Janeiro, and greater than that of 23 of 84 cities. The turning point GDP per capita level of $9,124 for VHC is nearly the same income as for Prague (Regression II). Whereas, the GDP per capita turning point level of just under $16,000 for NOx (from Regression III) is between the income levels of Brisbane and Montreal, and greater than that of 33 cities.

However, the implied turning point for transport energy use, $137,698 (from Regression IV), was well outside the sample bounds (the highest GDP per capita, that of Munich, was less than $55K), and more than eight standard deviations above the OECD-country city average GDP per capita (which was around $28.5K). These results indicate that transport energy use (a normal good) is unlikely to decline with income—although its increase may slow at higher levels of income, i.e., at higher levels of income, transport energy use has an income elasticity of less than one (but is still positive over observed income levels).

Table 2

It is difficult to compare these results to the transport energy use and CO regressions of Romero Lankao et al. (2009) since, as mentioned before, they considered aggregate energy/emissions as the dependent variable and among the independent variables included population but not fuel price. For transport energy use, they typically estimated a positive coefficient for GDP per capita and a negative coefficient for its square; however, it is not clear how to calculate a comparable turning point since those regressions estimated a population coefficient that was statistically significantly greater than one (Romero Lankao et al. did not report turning points). As for CO emissions, in a Romero Lankao et al. regression that included urban density (and a few other variables not considered here), that variable was statistically significant and negative as was the case here, but both GDP per capita forms were insignificant. In a separate (CO emissions) regression with only GDP per capita terms, only the GDP per capita squared term was significant (and negative); thus, implying that CO emissions fall monotonically (throughout the observed range) and rapidly with income—a result that is substantially different from that reported in Table 2, where a within-sample-range turning point was determined.

3.1 Further investigation into the role of mobility demand and emissions technology/energy efficiency

Because the city-based dataset is limited in the types of variables available, and because it would be very difficult to assemble additional data at this city level, it is challenging to delve further into the mechanisms behind the fall of emissions with rising income levels. (A common criticism of the EKC literature is the lack of a full explanation as to why an inverted-U relationship exists, i.e., the assumption that an income-related process can adequately describe pollution generation, e.g., Carson 2010). However, we can investigate some of the basic structural relationships behind lower transport emissions per capita with the same explanatory variables used above.

Public transport plays a potentially important role in urban mobility, and greater use of public transport (perhaps at higher levels of income) should result in lower emissions per capita if mobility (passenger-km travelled) and emissions technology (emissions per vehicle-km driven) are held constant since the higher passenger loads of public transport vehicles would result in fewer polluting vehicles being driven. (It is possible that public transport vehicles, i.e., buses, are more polluting—but this is not necessarily the case: buses can be run on natural gas, and motorcycles in developing-country cities can be very polluting.) Emissions might fall at higher levels of income if mobility demand or car ownership fell at those higher income levels. More likely, emissions of CO and VHC fall because of improved emissions control and because more efficient engines are adopted by high income drivers/cities. However, NOx emissions are more related to fuel consumed than end-of-pipe control technologies; and thus, those emissions might fall even if kilometres driven did not if more fuel efficient vehicles are driven in higher income cities. Table 3 displays regressions analyzing mobility demand (public plus private motorized passenger-km per capita), car ownership (passenger cars per 1000 people), and public transport's share of those total passenger-km.

Table 3

Regression V in Table 3 confirms two previous hypotheses. First, mobility/transport demand is a normal good and consistently increases with income (which has a positive and highly statistically significant elasticity). (In a regression with a GDP per capita squared term, all terms but urban density were highly insignificant, and thus, that regression is not shown.) Second, urban density (which has a negative and highly statistically significant elasticity) reduces the need for motorized transport. That fuel price is insignificant perhaps is not surprising since the dependent variable is comprised of public and private passenger-km, and fuel price is more likely to influence modal choice (see Regression VI) than the need for motorized mobility (which is affected by density). Thus, the finding of lower transport emissions at higher levels of income (i.e., Regressions I, II, and III in Table 2) cannot be caused by less passenger travel at those higher income levels.

Regression VI in Table 3 indicates that as income rises, more people shift from public to private transport (income's elasticity is negative and highly statistically significant). (When a GDP per capita squared term was added to the regression, both GDP terms were highly insignificant; regression not shown.) Also not surprisingly, greater urban density and higher fuel prices facilitate/encourage public transport (from Regression VI, Table 3). Thus, as before, the finding of lower transport emissions at higher levels of income (again, from Regressions I, II, and III in Table 2) cannot be caused by greater use of public transport at those higher income levels.

Lastly, Regression VII shows that car ownership increases monotonically with income—the implied income turning point is beyond the sample range (again, the highest income was less than $55K). That the turning point is not nearly as far beyond the range as the turning point for energy consumption per capita reflects a saturation effect for car ownership as such ownership levels near one vehicle per person. The coefficient for urban density again was negative and significant implying that such density discourages car ownership/reduces the need for private motorized transport.

Table 4

Table 4 displays regressions analyzing emissions technology (CO, VHC, and NOx per motorized passenger-km) as well as fuel/energy efficiency (energy consumption per motorized passenger-km) as a function of the previous explanatory variables. Regressions V, VI, and VII (of Table 3) implied that the determination of an EKC with respect to income and transport emissions is caused by improved emissions technology (fewer emissions per km driven or per passenger-km) at higher levels of income. This hypothesis is confirmed in Regressions VIII, IX, and X of Table 4. Emissions intensity or technology has a turning point at considerably lower levels of income than emissions per capita did (Regressions I, II, and III from Table 2); CO emissions per passenger-km begin to fall at \$4,583 compared to \$7,322 for CO emissions per capita; VHC emissions per passenger-km begin to fall at \$5,118 compared to \$9,124 for VHC emissions per capita, and NOx emissions per passenger-km begin to fall at \$8,527 compared to \$15,939 for NOx emissions per capita. Per capita incomes of \$4,583 and \$5,118 are levels similar to Cape Town and Johannesburg, respectively (and greater than that of only 16 other cities); whereas, per capita income of \$8,527 is a level similar to Rio de Janeiro (and greater than that of 23 cities). Hence, the higher turning points for emissions per capita occur because the improvement in emissions technology at higher levels of income are partly offset by the increase in both total passenger-km travelled (Regression V, Table 3) and reliance on private transport (Regression VI, Table 3) that occur at those higher income levels, too. Those three regressions (Regressions VIII, IX, and X, Table 4) are the only ones for which urban density is not (highly) statistically significant—implying that having more people exposed to pollution (via higher urban density) is not an important motivation to develop/adopt cleaner vehicle technology. (It could be noted that for CO—the most important local pollutant—urban density is significantly negative at the 0.10 level.)

That emissions per passenger-km peaks within the observed income range may seem to imply that emissions technology worsens for some low income cities as they become richer (i.e., before technology eventually improves)—this almost certainly is not the case. Emissions per passenger-km is in effect a weighted average that is comprised of the share of passenger-km for each transport mode and the emissions technology for that mode. A high income city (on the right side of the emissions per passenger-km peak) would have a high percentage of passenger-km from personal vehicle transport, but its vehicles would employ relatively clean technology. Whereas, a low income city (on the left side of the emissions per passenger-km peak) would have a high percentage of passenger-km from public transport modes, but would likely possess relatively "dirty" vehicle technology. Since public transport modes are less emissions intensive than personal vehicle transport, that low income city could have a level of emissions per passenger-km (or weighted average) similar to that of that high income city. And as that low income city developed, emissions technology would likely improve, but perhaps, initially, the shift toward greater use of (motorized) personal transport modes would overwhelm those technological improvements, so that even emissions per passenger-km would increase.

Lastly, energy per passenger-km has a turning point that is well within the range of income levels for OECD-country cities (Regression XI in Table 4). It might be surprising that this measure of energy efficiency falls within the observed income range, whereas energy consumption per capita showed no sign of declining within observed income ranges (Regression IV in Table 2). Possible explanations include that drivers switch to higher fuel efficiency cars as income rises, or that cities in higher income countries adopt traffic management systems that improve the flow of traffic, and thus, improve fuel efficiency.[11] However, the determination of a

[11] Several large cities in less developed Asian countries are noted for traffic congestion, e.g., Bangkok (Kenworthy et al., 1999).

relatively low income turning point for energy efficiency partially is a function of both the timing of the data collection (1995) and the use of exchange rates (as opposed to PPP) to convert income into a common currency. For example, of the 17 cities with the highest incomes, only San Francisco is not located in Asia or Europe (see Appendix Table A.1). Asian and European cities tend to have higher fuel prices and are statistically significantly denser than Australian and North American cities (Liddle 2013). And both fuel price and urban density have been demonstrated to increase transport energy efficiency (e.g., Regression XI of Table 4 here and Liddle 2013). Thus, that this particular cross-section contains a disproportionate number of high-fuel priced, dense Asian and European cities at the high end of the income scale likely is a reason for the relatively low income turning point for energy efficiency.

4. Conclusions and implications

Since most of the world's population now live in cities, cities are an important level of analysis; furthermore, transport is a significant source of both local and global pollution, and there is a demonstrated link between transport and urban density. This paper considered cities as the level of analysis to study the income-transport pollution relationship, i.e., Environmental Kuznets Curve (EKC), employing a unique, large (albeit somewhat old) dataset. Using this city-based dataset that included cities from several developing countries, we confirmed a result of Cole et al. (1997), who examined national-level data from only seven to nine OECD countries: transport-related emissions of CO, VHC, and NOx decline at observed income levels. In addition, we demonstrated that urban density has a strong negative impact on those transport-related emissions. The results of Cole et al. (1997), Hilton and Levinson (1998), and Liddle (2004) were confirmed—that transport energy consumption increased with income monotonically.

The paper went beyond the typical EKC-type regressions to analyze the impact of income, urban density, and fuel price on mobility, modal choice, car ownership, and emissions per passenger-km. Those additional regressions confirmed the hypothesis that lower transport emissions occurring in higher income cities were caused by improvements in technology (typically end-of-pipe improvements) that more than offset the greater mobility demand and shift toward personal transport and car ownership that also accompanied those higher incomes. Thus, similar to what Hilton and Levinson (1998) determined for lead emissions, reductions in transport-related CO, VHC, and NOx emissions are a result of end-of-pipe technologies at higher levels of income and not a result of lower fuel use or switches to alternative transport modes.

The determination of an EKC is sometimes seen in very optimistic terms, i.e., that development itself will solve (rather than contribute to) the pollution problem (e.g., Beckerman 1992). Some optimism may indeed be warranted when the inverted-U is caused by improved technology that more than offsets the increased (otherwise polluting) behavior that also accompanies development—as is the case here with urban transport emissions. That end-of-pipe technologies were better in high income cities combined with the fact that the study used 1995 data suggests there should be technology “leap-frogging” opportunities for lower income, developing cities today.

Yet, there was no evidence that urban density (i.e., more people exposed to emissions) led to improvements in emissions per passenger-km. Thus, there is a kind of density paradox in terms of transport emissions: higher density is associated with a less energy/emissions intensive transport system, but higher density means more people are exposed to localized transport pollution. Since many of the more dense cities are located in developing countries (see Appendix Table 1), these cities may not be able to rely solely on improved emissions technology to avoid the harm of exposing a substantial amount of people to transport emissions. In other words, in the less dense cities of the developed world, the technical solution of transport emissions may have been (relatively) successful because fewer people were exposed to the pollutants as those cities moved up and down the emissions per passenger-km inverted-U curve.

Lastly, the importance of city-level income and urban density (to all the dependent variables except for emissions per passenger-km) suggests that emissions/energy modelers should consider in their models greater (or more refined) resolution than that at the national level. Indeed, city resolution may be particularly important in modeling less developed countries where the differences between city-level and national-level income (and thus car ownership, among other things) can be pronounced (Liddle 2013).

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Table 1. Descriptive statistics (all variables in levels and data from 1995).

Variable	mean	median	std. dev.	min.	max.
CO per capita (kg/person)	94.5	71.9	74.7	8.6	399.7
NOx per capita (kg/person)	16.0	13.3	13.6	0.9	85.7
VHC per capita (kg/person)	14.2	11.7	9.5	1.1	43.7
Total transport energy per capita (MJ/person)	20,525	15,101	18,079	981.5	103,332
GDP per capita (1995 USD/person)	21,601	22,380	14,833	396	54,692
Urban density (persons/ha)	75.3	52.0	74.7	6.4	355.7
Total motorized passenger-km per capita (p.km/person)	8530	7644	4731	1379	25,533
Fuel price (1995 USD/MJ)	0.024	0.022	0.015	0.003	0.091
Rail modes' share of public transport vehicle-km	0.33	0.29	0.27	0.00	0.84
Public transport share of p.km	0.28	0.22	0.23	0.007	0.92
Passenger cars per 1000 people	349	372.5	193	8	746

Table 2. EKC regression results. All variables in natural logs. Dependent variables (i.e., pollutants/energy consumption) are in per capita terms from all urban/metropolitan passenger transport. (Data from 1995.)

Regression **Dependent variable**	**I** **CO**	**II** **VHC**	**III** **NOx**	**IV** **Total Energy**
GDP p. cap.	3.49***	2.95**	3.15***	1.68**
	(0.71)	(1.00)	(0.84)	(0.53)
GDP p. cap. Squared	-0.20***	-0.16**	-0.16**	-0.071*
	(0.041)	(0.056)	(0.048)	(0.029)
Urban density	-0.55***	-0.33**	-0.39***	-0.54***
	(0.077)	(0.099)	(0.083)	(0.051)
Fuel price	-0.42***	-0.43***	-0.43***	-0.25**
	(0.10)	(0.10)	(0.11)	(0.083)
Turning point	$7,322	$9,124	$15,939	$137,698
Adj. R^2	0.55	0.34	0.50	0.88
N	84	84	84	84

Notes: White-heteroskedasticity-consistent standard errors in parentheses. Statistical significance is indicated by: *** p <0.001, ** p <0.01, and * p <0.05.

Table 3. Additional regressions focusing on mobility demand and modal choice. All variables are in natural logs. (Data from 1995.)

Regression	**V**	**VI**	**VII**
Dependent variable	**Tot. Passenger-km per capita**	**Public trans. share of pass.-km**	**Cars per 1000 people**
GDP p. cap.	0.20***	-0.39***	2.51**
	(0.032)	(0.084)	(0.83)
GDP p. cap. Squared			-0.11*
			(0.043)
Urban density	-0.38***	0.62***	-0.49***
	(0.048)	(0.12)	(0.096)
Fuel price	-0.031	0.75***	0.09
	(0.056)	(0.17)	(0.094)
Turning point			$63,457
Adj. R^2	0.78	0.65	0.81
N	84	84	84

Notes: White-heteroskedasticity-consistent standard errors in parentheses. Statistical significance is indicated by: *** p <0.001, ** p <0.01, and * p <0.05.

Table 4. Additional regressions focusing on emissions/energy technology/intensity. All variables are in natural logs. (Data from 1995.)

Regression	**VIII**	**IX**	**X**	**XI**
Dependent variable	**CO per passenger- km**	**VHC per passenger- km**	**NOx per passenger-km**	**Energy per passenger- km**
GDP p. cap.	3.58***	3.04*	3.24***	1.76***
	(0.87)	(1.18)	(0.92)	(0.37)
GDP p. cap. Squared	-0.21***	-0.18**	-0.18***	-0.09***
	(0.049)	(0.065)	(0.052)	(0.021)
Urban density	-0.17	0.05	-0.001	-0.15***
	(0.095)	(0.12)	(0.093)	(0.041)
Fuel price	-0.40***	-0.40***	-0.40**	-0.22***
	(0.11)	(0.11)	(0.13)	(0.06)
Turning point	$4,583	$5,118	$8,527	$25,475
Adj. R^2	0.37	0.23	0.18	0.67
N	84	84	84	84

Notes: White-heteroskedasticity-consistent standard errors in parentheses. Statistical significance is indicated by: *** p <0.001, ** p <0.01, and * p <0.05.

Appendix Table A.1. Dataset: Cities and income and urban density levels.

Atlanta	31,037	6	Amsterdam	28,322	57	Bangkok	6,316	139
Calgary	23,983	21	Athens	11,506	69	Beijing	1,829	123
Chicago	32,110	17	Barcelona	18,124	197	Chennai	396	133
Denver	32,391	15	Berlin	23,480	56	Guangzhou	2,796	119
Houston	30,680	9	Berne	43,469	44	Ho Chi Minh City	1,029	356
Los Angeles	28,243	24	Bologna	27,574	67	Hong Kong	22,968	320
Montreal	16,066	32	Brussels	28,009	72	Jakarta	1,861	173
New York	34,395	18	Budapest	5,679	51	Kuala Lumpur	6,991	58
Ottawa	18,827	31	Copenhagen	37,058	28	Manila	2,217	206
Phoenix	26,920	10	Dusseldorf	43,745	49	Mumbai	913	337
San Diego	26,508	15	Frankfurt	54,571	48	Osaka	39,937	98
San Francisco	37,154	21	Geneva	45,308	52	Sapporo	37,075	72
Toronto	19,456	26	Glasgow	14,698	34	Seoul	10,305	230
Vancouver	25,793	22	Graz	31,612	37	Shanghai	2,474	196
Washington	34,420	14	Hamburg	37,306	38	Singapore	28,578	94
			Helsinki	28,323	33	Taipei	13,036	230
Brisbane	15,036	10	Krakow	3,029	59	Tokyo	45,425	88
Melbourne	21,476	14	London	22,363	59			
Perth	21,995	11	Lyon	41,622	47	Bogota	2,959	116
Sydney	22,397	19	Madrid	17,568	86	Cairo	2,140	272
Wellington	17,972	22	Manchester	14,491	52	Cape Town	4,243	71
			Marseille	29,337	59	Curitiba	6,515	30
			Milan	24,972	77	Dakar	1,116	105
			Munich	54,692	56	Harare	785	34
			Nantes	32,332	36	Johannesburg	5,137	30
			Newcastle	13,816	38	Rio de Janeiro	8,727	58
			Oslo	39,067	24	Riyadh	5,939	44
			Paris	41,305	48	Sao Paulo	5,319	78
			Prague	9,145	49	Tehran	2,551	114
			Rome	25,542	56	Tel Aviv	14,625	72
			Stockholm	33,438	29	Tunis	2,141	91
			Stuttgart	40,342	59			
			Vienna	39,316	69			
			Zurich	50,168	44			

Notes: Cities are listed in alphabetical order within the following regional groupings: North America (Canada and US), Oceania, Europe, Asia, and other. Gross metropolitan/regional product per capita (in 1995 USD) and urban density (in persons/ha) are shown.