Motorization and Road Provision in Countries and Cities

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Abstract

Using panel data from 50 countries and 35 urban areas (both covering a wide range of country incomes), this paper summarizes trends in motorization, road provision, and road transport service production (combining vehicles and roads). The growth of both motorization and road provision is related to incomes, land area, population density, urbanization, gasoline prices, and rail transport at the national level, and to a subset of these variables at the urban area level. The ratio of motor vehicles to roads is examined in a production function framework at both the national and urban area level. Regularities are very strong across countries and urban areas and over time. Economic development increases demand for transport, reliance on cars and trucks, and road provision. At the early stage of motorization, commercial vehicles comprise a large share of the fleet; passenger transport by automobile becomes more prominent with income growth. Motorization expands at the same rate as income per capita, but the auto fleet expands more rapidly, and commercial vehicles less rapidly, than income. Both country and urban data show evidence of similar saturation levels for car and motor vehicle ownership. At the national level, road networks expand more slowly than incomes, but paved road networks expand at the same rate as incomes. Road provision appears to be quite responsive to demand nationally, much less so at the urban level. For specific urban areas, per capita road length varies with initial income level but changes little over time, showing that history or urban endowments matter. Annexation of surrounding developed area appears to play a large role in expanding urban road length. Urban areas average roughly 15 times more road length per unit area, and seven times more vehicles per kilometer of road, than countries, and a saturation level exists for urban road length per unit of area. Vehicles per kilometer of road are positively associated with income, with (proxies for) land prices, and with low gasoline prices.

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1. Introduction

The increasing ownership and use of motor vehicles is a frequent topic of analysis and debate at the global, national, and local (especially urban) level. Motor vehicle ownership and use increase with income, and income growth in large developing countries is expanding motor vehicle markets and increasing fleet sizes. Adverse environmental impacts from the global and national growth of motor vehicle use are viewed as inevitable by some studies (Economist, 1996). Others argue that national patterns of motor vehicle use are sustainable (Prud'homme, et al., 1997). Moreover, motor vehicles are central to the urban transport debate because increased motor vehicle use causes congestion, contributes to low density development, and often reduces transit use. Some analysts have argued that urban development densities must be increased to reduce auto dependence and promote transit use (Newman and Kenworthy, 1989).

Most motor vehicles are privately owned in market economies, and they use roads—most of which result from public investment. In urbanized areas road construction is economically costly and politically contentious. Motor vehicle services are produced by combining privately owned vehicles with publicly owned roads, but relatively little is known about how road provision varies across countries or with vehicle ownership, and few analysts have examined the provision of roads at the national or urban level. Some recent work has related investment in infrastructure to economic growth, typically finding that investments in roads are strongly associated with economic growth (Aschauer, 1989, 1990; Canning and Fay, 1993). However, these studies do not address road provision and its relation to motor vehicles. The analysis presented here examines vehicle ownership and road provision over time and across nations and urban areas.

The country-level and city-level data sets used in this study are compiled from numerous sources. A detailed explanation of the data sources and the definitions of variables used is provided in the Appendix. Appendix Table 1 lists all 50 countries in the sample and their per capita GNP in 1970, 1980, and 1990. The sample covers a wide range of country income levels, ranging in 1990 from $260 to $28,000 per capita in 1987 US dollars at market exchange rates. GNP at market exchange rates—rather than at purchasing power parity exchange rates—is used in this analysis because vehicles are traded goods, and market exchange rate GNP measures the ability of an economy to purchase traded goods. Appendix Table 2 presents the simple statistics for the key variables used in the country-level empirical analyses. The city-level data set includes 35 world cities (both developed and developing). Appendix Table 3 lists the key variables and their simple statistics for all cities included in the city sample.

The national and urban samples do not overlap precisely in geographical terms and in time, but it is useful to compare some summary statistics, shown below for 1980, between the two different samples for developing countries and for high income countries.

Relative to countries, urban areas obviously have much higher population densities, higher road network densities, more motor vehicles per unit of road, somewhat more vehicles per thousand persons, and much less road length per person. This is true for both developing and high income countries. The data suggest that, on average, national road systems are uncongested while urban road systems are congested.

The summary averages also show some key differences between developing and high income cities. Relative to high income cities, developing cities have higher population densities, lower road network densities, fewer motor vehicles per thousand persons, and less road length per person. The result is a relatively small difference in motor vehicles per unit of road between developing and high income cities.

Sample Summary Averages--1980

	Developing countries		High Income countries	
Item	National (29 countries)	Urban (6 cities)	National (21 countries)	Urban (29 cities)
Population per sq. km.	85	12,928	122	5,513
Kilometers of road per sq. km.	0.2	4.3	1.2	10.7
Motor vehicles per km. of road	10	101	31	163
Motor vehicles/1000 persons	34	39	356	448
Meters of road per capita	3.7	0.4	15.3	4.1

Simple economic reasoning produces a number of hypotheses about the relations among the major variables. Although the vehicle fleet grows with income, the fleet mix should change systematically with income. The number of freight vehicles is likely to grow less rapidly than total output because the production of goods increases less rapidly than the production of services, and freight volumes may lag GNP growth. And as incomes rise, labor costs rise relative to capital costs, increasing average truck size, capacity, and load. These latter trends will tend to raise truck load factors.

For passenger travel income growth raises the value of time, shifting demand from slower, cheaper modes to faster, costlier modes (Meyer and Meyer, 1987). In urban areas demand shifts from transit to cars, often degrading transit service as its passenger volumes decline, although migration from rural to urban areas could compensate for this in low income countries. Dispersed urban land use patterns also promote car use. Increases in the value of time make the circuitous routing required to serve multiple passengers by car more costly, lowering the number of passengers per car and raising the demand for cars. And these trends will tend to lower car load factors. For both freight and passenger travel, the presence of potential substitute modes, such as railways, should reduce motorization levels.

Economic reasoning also indicates that the extent of the national road network would increase with output, allowing increased accessibility to the whole country. Holding other variables constant, urbanization's effect on the national road network is difficult to predict. Spatially concentrating people and economic activity in cities may concentrate demand on intra-city roads but specialization associated with urbanization may also increase demand for less heavily traveled roads between cities. The presence of substitute modes, particularly railways, should reduce the need for roads. Motor vehicle speeds rise and operating costs fall as road quality improves, so economic efficiency suggests that road quality—particularly the share of roads that are paved—should increase with income. A substantial question is whether public road providers behave economically, since few face market incentives. In comparing national with urban road provision, the higher cost of road provision in urban areas is likely to be a cause of the smaller per capita road amounts and a slower rate of road network expansion.

Finally, when combining motor vehicles with roads to produce road transport services, some strong hypotheses stem from likely price effects. Motor vehicles are traded goods, and roads are non-traded goods. The ratio of the prices of non-traded to traded goods rises with income. Hence roads will become more costly relative to vehicles as incomes rise (assuming no congestion at the national level), so the ratio of motor vehicles to roads should rise with income. In urban areas where congestion is obviously present, higher levels of congestion will increase travel times, linking the generalized costs of vehicle use with income levels. In this case, income growth may lead to additional road construction to relieve congestion. Such a response would tend to reduce the ratio of motor vehicles to roads in urban areas with high income levels.

The empirical results reported here strongly support most of the hypotheses sketched above. In particular, road provision is very responsive to economic factors at the country level, and the pattern of road provision across countries conforms well to predictions based on economic reasoning. In urban areas, however, road provision involves more complex processes because it is difficult to expand roads in built-up areas, and private travel costs do not correctly reflect congestion.

The analysis is presented in two main sections, the first dealing with the national data and the second with the urban area data. Each section describes the growth of motor vehicles and the growth of roads, and then examines the combining of vehicles and roads to produce road transport services.

2. Analysis with National Data

2.1. Motorization at the National Level

2.1.1. Previous Studies

Motorization describes the transition to higher levels of ownership and use of road going motor vehicles. Over the last four decades, many studies have attempted to model the trends of motorization in various countries and periods. The models were developed mainly for understanding the determinants of motor vehicle ownership and use, and forecasting the future levels of vehicle ownership and use. With few exceptions (Hensher, et al. 1990; Pindyck, 1979; Wheaton, 1980; Button et al., 1993), however, most of these models focused on vehicle ownership instead of vehicle usage. Good surveys of these studies can be found in Glaister (1981, Ch. 7) and Ortuzar and Willumsen (1994, Ch. 13). More thorough discussions of the motor vehicle ownership forecasting problem can be found in Button, et al. (1982), Mogridge (1983), and Train (1986).

Several families of models have been developed over the years. Among the earliest were the time-series extrapolation models which attempted to extrapolate the national or regional motor vehicle ownership trends to future years under an explicit assumption of a saturation level (Tanner, 1974; Mogridge, 1967, 1989). A popular functional form is the S-shaped logistic equation. The second family of models is the household-based car ownership model (Quarmby and Bates, 1970; Bates, et al. 1978), which uses disaggregate data to explain household car ownership behavior (instead of looking at the general trends). This family of models typically uses a logit model specification to estimate the probabilities of owning 0, 1, and 2 or more cars. The third family of models includes a host of econometric models that use demographic variables, income variables, and transport system variables to explain the cross-section variations or changes over time in motor vehicle ownership. Depending on the types of data used, these models can be further divided into three groups: (1) time-series models (Wildhorn, et al. 1974; Sweeney, 1978; Chin and Smith, 1997); (2) cross-section models which produce long-run income elasticity estimates (Beesley and Kain, 1964; Silberston, 1970; Wheaton, 1982; Kain, 1983; Kain and Liu, 1994); and (3) panel data models (Pindyck, 1979).

Representative results from several of the studies mentioned above are summarized in Table 1. This summary suggests that the income elasticities from time series data are typically smaller than those from cross sectional data, and that those from urban level data are less than those from country level data. In addition, the income elasticities for commercial vehicles are generally smaller than for cars. The analyses that follow are based on national and urban area datasets for a wide range of country income levels at two to three points in time. The results will be compared to the previous findings.

Table 1. Income Elasticities of Motor Vehicle Ownership and Usage

Study	Sample	Vehicle Ownership	Vehicle Usage
Beesley and Kain (1964)	45 U.S. cities, 1960	0.73	
Silberston (1970)	38 free-market countries, 1965, automobiles	1.14	
	38 free-market countries, 1965, total vehicles	1.09	
	46 countries including USSR and East European countries, 1965, automobiles	1.21	
Wildhorn et al. (1974)	U.S. national time series, 1950-73	0.88	
Pindyck (1979)	11 Western countries, pooled 1955-73 time series	0.30	0.66
Sweeney (1978)	U.S. national time series, 1950-73	0.82	
Wheaton (1980)	25 countries, early 1970s, automobile fleet	1.38	0.54
	25 countries, early 1970s, total vehicle fleet	1.19	0.53
	42 countries, early 1970s, automobile fleet	1.43	0.33
Kain (1983)	23 OECD countries, 1958	1.95	
	23 OECD countries, 1968	1.59	
	98 non-communist countries, 1977	1.30	
Hensher et al. (1990)	Sydney, Australia survey of 1172 households, 1981-82		0.05 - 0.14
Button et al. (1993)	58 developing countries, time series 1968-87, car fleet	0.53 - 1.12	0.71
	29 developing countries, 1968-87, commercial vehicles	0.84 - 1.50	0.52
Kain and Liu (1994)	52 countries, 1990, passenger cars	1.58	
	52 countries, 1990, commercial vehicles	1.15	
	52 countries, 1990, total motor vehicles	1.44	
	60 world cities, 1980, passenger cars	1.02	
Chin and Smith (1997)	Singapore, time series 1968-89	0.53 - 0.61	

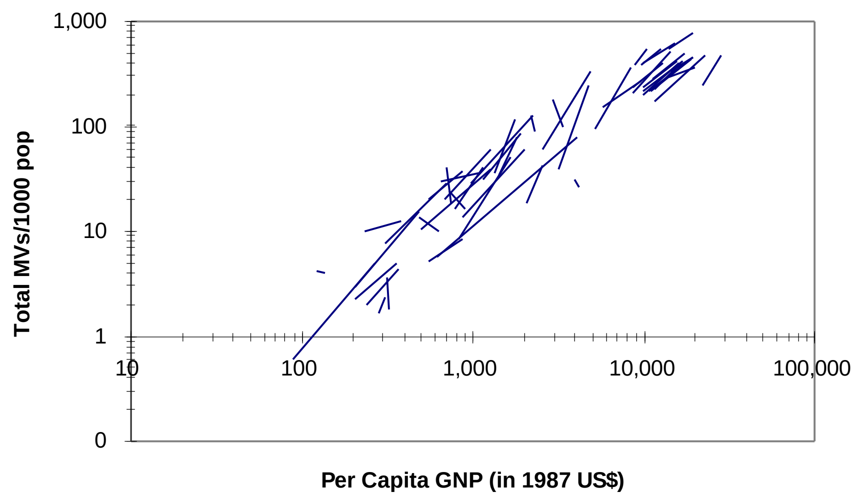
2.1.2. Motorization Trends across Country Income Levels and over Time

Because most motor vehicles are purchased by individuals, households, or firms and are privately owned, motorization is normalized with respect to the population and normally measured per thousand persons.[1] Across countries, there is a strong relation between the level of economic development and the level of motorization. Figure 1 shows the log-log association between GNP per capita (in 1987 US dollars at market prices) and

[1] We have not made adjustments compensating for differences in demographic structure across countries. These may affect auto ownership (children do not buy cars) but may lead to further adjustments in per capita income measures (children may consume less than adults).

total motor vehicle ownership (excluding motorcycles because of lack of data) per thousand population for 50 countries in both 1970 and 1990.[2] In Figure 1 and the following figures, a line segment connects each country's position in 1970 with its position in 1990. Most line segments have a upward slope. Because the level of motor vehicle ownership for every country in 1990 exceeded its level of motor vehicle ownership in 1970, the upward sloping line segments belong to countries whose real per capita income increased between 1970 and 1990. The downward sloping line segments belong to countries whose real per capita income declined between 1970 and 1990. In the logarithm scale for both axes, most of the upward sloping line segments exhibit slopes similar to each other and to the overall cross country relation. They all together exhibit a remarkably linear pattern. There is little evidence in Figure 1 that the growth of motor vehicle ownership with income slows in countries at high income levels.

Figure 1. Changes in Motor Vehicle Ownership



In contrast, Figure 2 shows a weak negative association between motor vehicle ownership and population density across countries. For individual countries, however, the association is typically positive and nearly all individual line segments are upward sloping. Since the land area of a country rarely changes, the upward sloping line segments indicate that both population and motor vehicle ownership increase over time. Yet countries with similar levels of motor vehicle ownership have very different population densities, and vice versa. Both very low population density countries (USA, Canada, and Australia) and very high density countries (Netherlands and Belgium) have very high levels of motor vehicle ownership, while high density countries have widely ranging car ownership levels.

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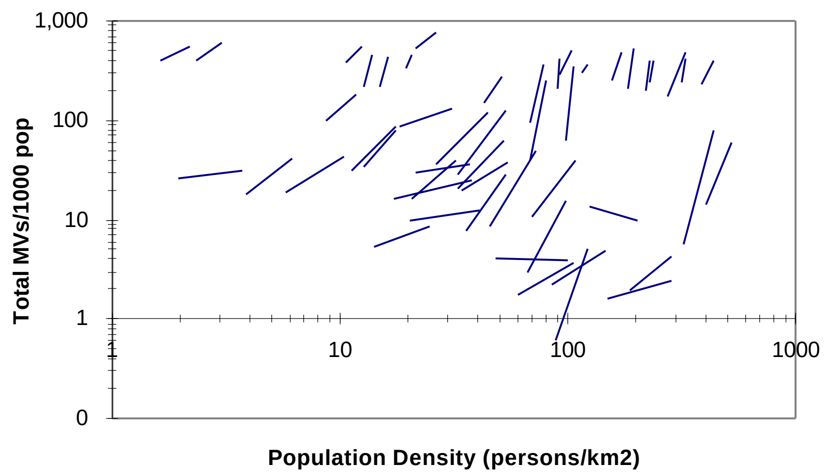
[2] On a log-log diagram, the slope of the line is an elasticity—the ratio of the percentage change in the vertical axis variable to the percentage change in the horizontal axis variable.

Figure 2. Relation between Motor Vehicle Ownership and Population Density



2.1.3. Motor Vehicle Ownership Models

A number of statistical models are estimated to explain more precisely the cross-country variations of total motor vehicle, private car, and commercial vehicle ownership. All models adopt a similar form of functional specification shown below:

$$\log V = b_0 + b_1 \log Y + b_2 D_{80} + b_3 D_{90} + \Sigma\, b_i \log X_i + e$$

where V is level of vehicle ownership per thousand population; Y, real GNP per capita; D_{80} and D_{90}, dummy variables for the years 1980 and 1990, respectively; X_i, other explanatory variables; b_0, ... b_i, parameters to be estimated; and e, error term. The dependent variable and all explanatory variables (except the dummy variables and those expressed in percentage) are logarithms of the variables. In this specification the coefficient estimates are the constant elasticities of the dependent variable with respect to the relevant independent variable.

The results are shown in Table 2. The coefficient estimates of both explanatory variables and dummy variables, except gasoline prices and rail network density, are remarkably similar in terms of signs and magnitude across all equations.

Per capita income. It is statistically the most significant among the explanatory variables. As the R^2 of Eq. 1, Eq. 5, and Eq. 9 indicate, per capita income, along with a constant term, gasoline prices (statistically insignificant), and two year dummies, explain 91 percent of the variance of total motor vehicle ownership, 90 percent of the variance of car ownership, and 76 percent of the variance of commercial vehicle ownership. Adding other explanatory variables only increases the R^2 slightly. Moreover, a comparison of estimates from equations with identical specification suggests that car ownership is more income elastic than commercial vehicle ownership. All these results are broadly consistent with estimates obtained from the previous studies referred to earlier in Table 1.

Table 2. Motor Vehicle Ownership Models
(50 countries for 1970, 1980, and 1990)

Explanatory Variable	OLS Estimates and (Standard Error)											
	ln total MVs/1000 pop.				ln psgr. cars/1000 pop.				ln commercial vehicles/1000 pop.			
	Eq. 1	Eq. 2	Eq. 3	Eq. 4	Eq. 5	Eq. 6	Eq. 7	Eq. 8	Eq. 9	Eq. 10	Eq. 11	Eq. 12
Constant	-4.54	-4.41	-3.90	-3.79	-6.33	-6.21	-5.69	-5.53	-2.87	-2.62	-2.18	-2.21
	(0.38)*	(0.37)*	(0.37)*	(0.37)*	(0.45)*	(0.45)*	(0.45)*	(0.45)*	(0.49)*	(0.46)*	(0.47)*	(0.48)*
ln real GNP per capita	1.09	1.06	0.90	0.90	1.21	1.19	1.02	1.02	0.94	0.79	0.64	0.64
	(0.04)*	(0.04)*	(0.05)*	(0.05)*	(0.04)*	(0.04)*	(0.06)*	(0.06)*	(0.05)*	(0.05)*	(0.06)*	(0.06)*
ln gasoline prices	-0.02	0.09	0.11	0.13	0.07	0.17	0.19	0.22	-0.26	-0.05	-0.04	-0.05
	(0.11)	(0.11)	(0.11)	(0.11)	(0.13)	(0.14)	(0.13)	(0.13)*	(0.15)*	(0.14)	(0.14)	(0.14)
ln population density (p/km2)		-0.10	-0.09	-0.10		-0.09	-0.08	-0.09		-0.19	-0.19	-0.18
		(0.03)*	(0.03)*	(0.03)*		(0.04)*	(0.04)*	(0.04)*		(0.04)*	(0.04)*	(0.04)*
Share of urban population (%)			1.28	1.11			1.32	1.08			1.12	1.16
			(0.29)*	(0.29)*			(0.35)*	(0.36)*			(0.37)*	(0.38)*
ln rail network density (km/km2)				0.02				0.03				-0.005
				(0.01)*				(0.01)*				(0.01)
Year dummy for 1980	0.17	0.20	0.18	0.18	0.21	0.24	0.23	0.23	0.07	0.12	0.11	0.11
	(0.11)	(0.10)*	(0.10)*	(0.10)*	(0.13)	(0.13)*	(0.12)*	(0.12)*	(0.14)	(0.13)	(0.13)	(0.13)
Year dummy for 1990	0.34	0.38	0.34	0.35	0.43	0.47	0.43	0.44	0.22	0.30	0.27	0.26
	(0.11)*	(0.11)*	(0.10)*	(0.10)*	(0.13)*	(0.13)*	(0.12)*	(0.12)*	(0.14)	(0.13)*	(0.13)*	(0.13)*
Adj. R-squared	0.91	0.91	0.92	0.93	0.90	0.90	0.91	0.91	0.76	0.79	0.80	0.80

Note: * Significant at the 0.05 level.

<u>Gasoline price regime</u>. Because gasoline price data for 1970, 1980, and 1990 are not available for many countries (particularly developing countries) in the sample, the gasoline price data used here are those of 1997. They are used as a proxy of gasoline price regime. This is plausible because the gasoline price regime has not changed radically for most countries. As shown in Table 2, the coefficient estimates of gasoline prices are statistically insignificant, and many carry the wrong sign (for cars and total motor vehicles). The insignificant estimates suggest that gasoline prices have little impact on the level of motor vehicle ownership. Other studies have found that gasoline prices affect auto use more than auto ownership (Pindyck, 1979; Wheaton, 1982).

<u>Population density</u>. As anticipated in Figure 2, the coefficient estimates for population density carry a negative sign and are statistically significant. They suggest that holding everything else constant, countries with lower population density have higher levels of vehicle ownership. Low overall population density may increase average trip lengths and spur motorization.

<u>Degree of urbanization</u>. The coefficient estimates for the share of urban population carry a positive sign and are statistically significant. Ex ante, the effect of urbanization on vehicle ownership is ambiguous. First, urbanization may be negatively associated with motor vehicle ownership because motorized road transport is more attractive in rural than in urban areas. Other transport modes are often more competitive

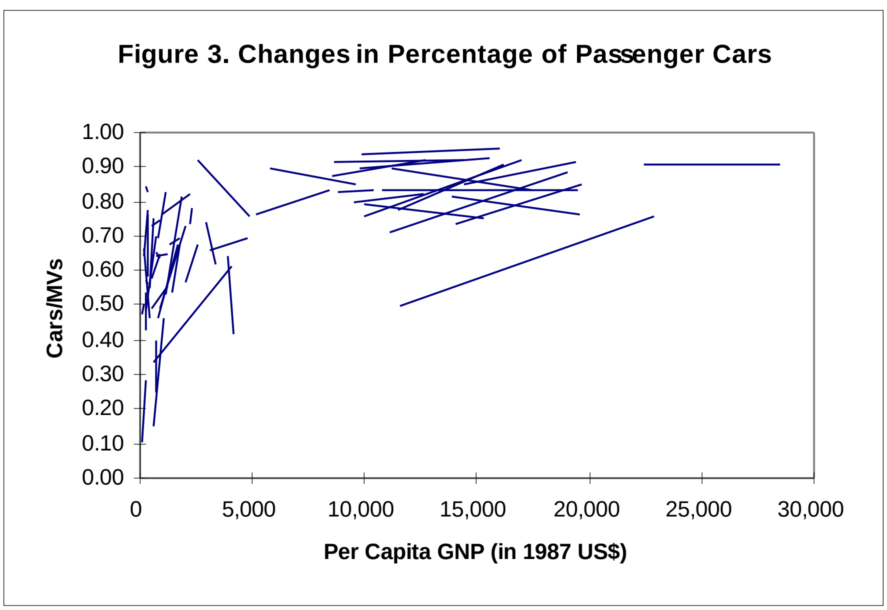
in urban areas where population densities are high and more alternative modes are available. Holding everything else constant, rural households are more likely to own motor vehicles than urban households (Deaton, 1987). Second, urbanization is highly associated with per capita income (Ingram, 1997). The estimates presented here suggest that the collinearity of urbanization with income dominates, as the estimated income elasticities are lowest in the equations that include urbanization.

Year effect. All coefficient estimates for the 1980 and 1990 year dummies carry a positive sign and the estimates for the 1990 year dummies are roughly double (especially for cars) those for 1980. These indicate that vehicle ownership curves have shifted up by a similar proportion each decade, and that the income elasticity estimates obtained from time-series data for individual countries in this sample would likely be greater than estimates obtained from cross-section data at a point of time—contradicting the pattern in Table 1. The year effect may also reflect changes in vehicle technology—the average age of vehicle fleets has been increasing in the past two decades in many countries.

Rail network density. The coefficient estimates for rail network density indicate that higher rail density is positively associated with auto ownership and negatively (though insignificantly) with commercial vehicle ownership.

2.1.4. Car share of the fleet

That car ownership is more income elastic than commercial vehicle ownership implies that the share of cars in total motor vehicle fleet increases with per capita income. Figure 3 confirms this. The percentage of passenger cars in the total motor vehicle fleet increases with per capita income, but at a decreasing rate, exhibiting a classic pattern of convergence or saturation at high income levels. For most countries (except a few with



relatively high per capita income), the percentage of cars increases with the growth of per capita income. Although there is a general pattern of convergence, the wide variation in the car fleet share at high income levels (between 75 percent and 95 percent for most high income countries) is noteworthy—countries appear to be converging to different asymptotes.

These differences in auto fleet shares at high income levels are likely to be driven by differing availability of substitute modes and differing relative prices between commercial vehicles and automobiles. Table 3 presents the results of five regressions attempting to explain the share of cars. Among all explanatory variables, only per capita

Table 3. Passenger Car Share Models
(50 countries for 1970, 1980, and 1990)

Explanatory	OLS Estimate and (Standard Error)				
	Dependent variable: percentage of cars in motor vehicle fleet				
Variable	Eq. 1	Eq. 2	Eq. 3	Eq. 4	Eq. 5
Constant	0.07	0.01	0.09	0.13	0.16
	(0.07)	(0.07)	(0.09)	(0.10)	(0.10)
ln real GNP	0.08	0.08	0.07	0.06	0.06
per capita	(0.01)*	(0.01)*	(0.01)*	(0.02)*	(0.02)*
ln relative price of	-0.03	-0.03	-0.03	-0.04	-0.04
gasoline vs. diesel	(0.05)	(0.04)	(0.05)	(0.05)	(0.05)
ln population		0.01	0.005	0.005	0.01
density (p/km2)		(0.01)	(0.01)	(0.01)	(0.01)
Percentage of			0.08	0.09	0.07
roads paved			(0.05)	(0.05)	(0.05)
Share of urban				0.07	0.03
population (%)				(0.08)	(0.08)
ln rail network					0.005
density (km/km2)					(0.002)*
Year dummy	0.02	0.02	0.02	0.02	0.02
for 1980	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Year dummy	0.04	0.04	0.03	0.03	0.03
for 1990	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Adj. R-squared	0.46	0.47	0.48	0.48	0.49

Note: * Significant at the 0.05 level.

income and rail density are statistically significant—both increasing the car share. This indicates that rail is a stronger substitute for commercial vehicles than for cars. It also suggests that rail is more competitive with trucks for freight than with cars for passengers. Lack of data prevents us from exploring the effect of variables such as relative prices and taxes between private cars and commercial vehicles, however.

2.1.5. Saturation level

Saturation is defined as a level at which the rate of growth in vehicle ownership becomes zero. It is often hypothesized that for high income countries, motor vehicle ownership will grow at a declining rate with per capita income growth, and eventually cease to grow when a saturation level is reached (Mogridge, 1967; Tanner, 1974). As Figure 1 indicates, however, motor vehicle ownership continues to grow even in the highest income countries. Nonetheless, it is useful to examine whether there is a saturation level. This can be done by estimating the S-shaped logistic vehicle ownership regressions with alternative assumed saturation levels. The regression with the highest R^2 gives the saturation level under the "business as usual" scenario[3]. The alternative regressions have the following functional form:

$$V = S / (1 + e^{b0 + b1\,Y + b2\,D + b3\,U + b4\,P + b5\,d80 + b6\,d90}),$$

where V is vehicle ownership; S, saturation level; Y, per capita GNP; D, population density; P, gasoline prices; d80 and d90, year dummies for 1980 and 1990; and b_0, ... b_6, parameters.

The saturation levels are at 770 cars and 1,180 total motor vehicles per thousand population. The R^2 for these regressions are over 0.90 and all the explanatory variables are statistically significant. For comparison, the U.S. ownership levels in 1990 were 574 cars and 755 motor vehicles per thousand population. It should be noted, however, that lower levels of saturation could result if strong changes in underlying factors, such as increase in fuel prices, were induced by high levels of world motorization.

In summary, economic development increases demand for and reliance on autos and trucks. The endowments of other modes affects motor vehicle ownership, as does transport policy, but income growth is an extremely strong determinant of motorization. Developing countries are increasing motorization of both passenger and freight transport. They are closely following the patterns exhibited by industrial countries in the relation between income and motorization. Rapid income growth in developing countries is likely to produce rapid increases in motorization unless there are very strong changes in policies or in the prices of vehicles relative to other goods.

[3] Searching over a single parameter value to maximize R^2 produces a maximum likelihood estimate of the parameter value.

2.2. Provision of Roadways at the National Level

2.2.1. Related Studies

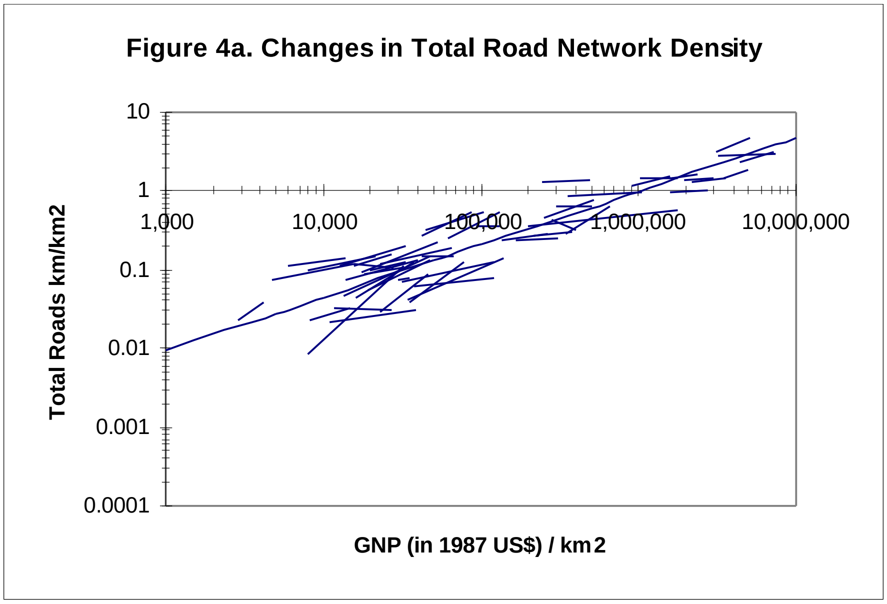
Although many earlier studies examine the impact of economic development on roadway network provision, they tend to be highly descriptive and country-specific. There are very few cross-country empirical studies. Bennathan, et. al (1992) used data from 36 countries to analyze the relations of domestic rail and road freight transport demand (in ton-kilometers) with country income and land area variables. During recent years, a seminal paper by Aschauer (1989) generated a great deal of interest in the impact of highway investment on the rate of economic growth (Aschauer, 1990; Hulten and Schwab, 1991; Holtz-Eakin, 1992; Fernald, 1992; Duffy-Deno and Eberts, 1991; Morrison and Schwartz, 1992; Canning and Fay, 1993; Nadiri and Mamuneas, 1996). In terms of the data analyzed, Canning and Fay (1993) is particularly notable; they used a panel of 96 countries for the period 1960-85 taken at 5-year intervals to examine the effect of transport networks on economic growth. The findings from these studies indicate strong association of transport investment with economic growth.

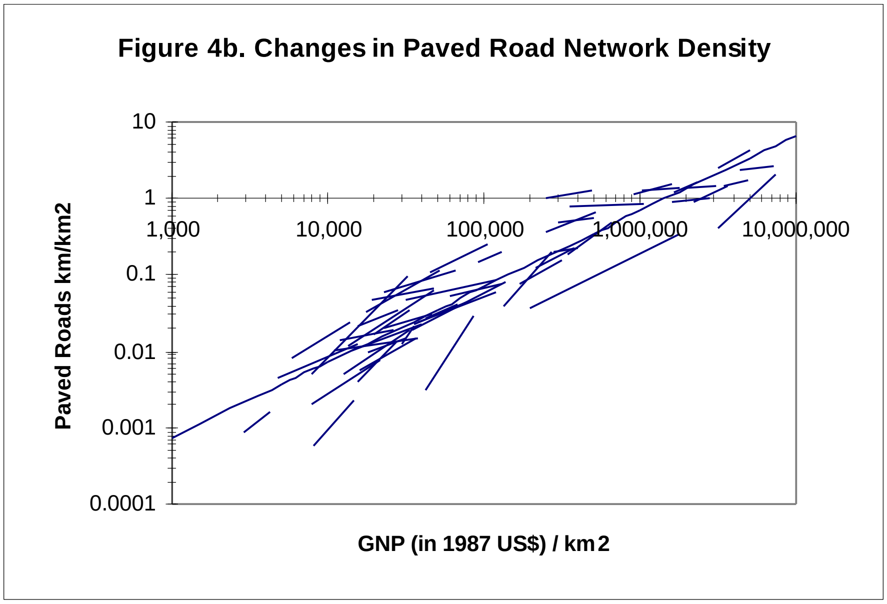
However, there are virtually no studies that examine the regularities of physical provision of roadways across country income levels and over time. This section explores these regularities. It should be noted that the empirical analyses that follow do not attempt to address causal relations between economic growth and roadway provision, but examine the association between the variables.

2.2.2. Roadway Provision across Country Income Levels and Over Time

Roadways complement motorization, but road development is predominantly public investment and often subject to multiple objectives (defense, national unification, and regional equity) while vehicular investment is largely private. Because vehicles are mainly owned and used by individuals, the common measure of motorization (vehicles per 1000 persons) relates vehicles to population. Roads are also used by individuals, but at the national level they provide access to fixed locations. More roads connect more locations and do so more efficiently. Because of the connectivity and inherently spatial aspect of roads, the primary measure of road networks at the national level used here is road network density (road length per unit area) rather than road length per capita (which is more appropriate for urban areas where system capacity matters). The provision of roads per unit area is best explained by income per unit area, which is a measure of the relevant expenditure capacity.

Figure 4a plots the log-log relation of total road network density with income density (defined as income per square kilometer) for the 50 countries in both 1970 and 1990. Similarly, Figure 4b plots the log-log relation of paved road network density with income density. Both total road network density and paved road network density are closely correlated with income density. Within a country both total road and paved road network densities tend to increase with income density, but the paved road network tends to expand faster than the total road network. The strong relation between road provision and income is very similar to that between motorization and income in Figure 1. Both relations are strongly linear in logarithms and in both relations the changes over time for individual countries are very collinear with the cross sectional pattern across countries.





2.2.3. Relations between Road Network Density, Income, and Population Density

Several regressions are estimated to explain the variations in both total road and paved road network densities. The results are shown in Eq. 1 through Eq. 4 in Table 4. The first two are total road network density equations, and the second two, paved road network density equations.

The role of income density vs. per capita income The income variable used in Eq. 1 and Eq. 3 is income density. Because income density is the product of per capita income and population density, these two equations actually restrict the parameters for both per capita income and population density to be equal. The restriction is relaxed in Eq. 2 and

Eq. 4 by estimating the parameters for per capita income and population density separately. As the estimates indicate, both total road and paved road network densities are highly correlated with income density. They also can be explained well jointly by per capita income and population density. Moreover, the coefficients of per capita income and population density are similar in magnitude, indicating that income density is an appropriate specification.

Table 4. Road and Rail Network Density (km/sq. km) Models
(50 countries for 1970, 1980, and 1990)

Explanatory Variable	OLS Estimate and (Standard Error): ln (total road network density) Eq. 1	Eq. 2	ln (paved road network density) Eq. 3	Eq. 4	ln (railroad network density) Eq. 5	Eq. 6
Constant	-8.86 (0.28)*	-8.57 (0.30)*	-13.89 (0.37)*	-13.56 (0.41)*	-10.66 (0.28)*	-10.55 (0.31)*
ln real GNP/km^2	0.67 (0.03)*		0.99 (0.04)*		0.56 (0.03)*	
ln real GNP per capita		0.57 (0.05)*		0.88 (0.07)*		0.52 (0.05)*
ln population density		0.71 (0.03)*		1.04 (0.05)*		0.58 (0.04)*
Share of urban population (%)	-0.60 (0.23)*	-0.10 (0.32)	-0.33 (0.31)	0.23 (0.43)	0.11 (0.25)	0.31 (0.34)
Year dummy 1980	-0.01 (0.11)	-0.01 (0.11)	0.08 (0.15)	0.08 (0.15)	-0.33 (0.11)*	-0.33 (0.11)*
Year dummy 1990	-0.05 (0.11)	-0.07 (0.11)	0.03 (0.15)	0.01 (0.15)	-0.44 (0.11)*	-0.44 (0.11)*
Adj. R-squared	0.84	0.84	0.87	0.87	0.81	0.81

Note: * Significant at the 0.05 level.

The estimated income density elasticities suggest that a one-percent increase in income density would be accompanied by 0.67 percent increase in total road density but by almost one percent increase in paved road density. Holding population density and other variables constant, a one-percent increase in per capita income would also be accompanied by virtually the same responses. Since per capita income is a key determinant of motor vehicle ownership, the increase in road network density is closely related to the growth of motor vehicle ownership. This is particularly true for paved roads, and road paving may be primarily of benefit to motor vehicle traffic.

Population density. There are two ways of increasing income density: holding per capita income constant and increasing population density, or the reverse. Eq. 2 and Eq. 4 indicate that increasing population density has a slightly stronger effect than increasing per capita income. (Recall that population density is negatively associated with car ownership in Table 2.) Similar to per capita income, population density affects paved roads more than total roads, and paved roads are unit elastic with respect to population density. This implies that paved road length per capita is independent of population density at the national level. Higher population density contributes to higher traffic density that requires more efficient roads in terms of carrying capacity and speeds.

Degree of urbanization. The coefficient estimates for the share of urban population are statistically insignificant (except in Eq. 1). As is the case with motorization, the effect of urbanization on road density is likely to be mixed. Urbanization is positively correlated with income, which would indicate a positive relation with road network density. However, urbanization concentrates activity and might lead to fewer roads at the national level—suggesting a potential negative relation with road network density.

Year effect. The coefficient estimates for the year dummies are statistically insignificant, suggesting that there are no important omitted variables that are correlated with time.

2.2.4. Railroad Network Density, Income, and Population Density

For comparison, two regressions are estimated to examine the cross-country variation in rail network density using data from 47 countries. The results are also shown in Table 4. Similarly to the road network equations, either income density or the combination of per capita income and population density explains the variation of rail network density well. Railroad networks are positively associated with per capita income and population, but less than total road and paved road networks.

Experience from many countries suggests that railroad traffic has grown much slower than GNP and, as a result of road transport competition, railroads have been cutting back on branch lines in favor of long haul, high volume traffic. This is confirmed by the coefficient estimates of the year dummies, which carry a negative sign and are statistically significant. The magnitude is greater for the 1990 dummy than the 1980 dummy, reflecting the general trend of rail network contraction over the last three or four decades. The positive correlation of rail network density with income levels may reflect a historical artifact that most high income countries industrialized early during the era when rails were the dominant technology.

2.2.5. Percentage of Roads Paved

The earlier results show that income elasticities of paved roads tend to be greater than those of total roads. In other words, the percentage of roads that are paved tends to increase with income growth. Table 5 presents three regressions that attempt to measure the magnitude of the effect of income on road paving. The pooled sample estimates obtained from Eq. 3 suggest that either a one-percent increase in per capita income or a one-percent increase in population density would be accompanied by roughly a one percent reduction in unpaved roads. In other words, a one-percent increase in income density would be accompanied by a one percent reduction in unpaved roads. Although the coefficient estimate for the 1990 year dummy is positive, implying that the curves for individual years tend to shift up over time, the shift is small and not statistically significant. According to Eq. 3, paved roads comprise 80 percent of total roads at a per capita income level of US$1,000 (in 1987 prices) and a population density of 100 persons per square kilometer, or at US$3,000 per capita and 25 persons per square kilometer. It is fair to say that most road paving activity occurs in low to middle income countries.

Table 5. Regressions of Percentage of Roads Paved
(50 Countries in 1970 and 1990)

Equations were estimated of the form: $P = 1 - k\, Y^a D^b$, where
P = Percentage of roads paved;
Y = Per capita income; D = population density;
and k, a, b = parameters

Explanatory Variable	OLS Estimate and (Standard Error) Eq. 1 (1970)	Eq. 2 (1990)	Eq. 3 (Pooled)
ln (k)	13.62	19.92	10.39
	(2.62)*	(3.07)*	(1.80)*
Per capita income	-1.42	-1.62	-1.11
	(0.30)*	(0.26)*	(0.20)*
Population density	-1.45	-2.21	-0.96
	(0.32)*	(0.41)*	(0.22)*
Year 1990 dummy			0.10
			(0.61)
Adj. R-squared	0.45	0.51	0.34

Note: * Significant at the 0.05 level.

2.3. Production of Road Transport Services at the National Level

2.3.1. Road Service Production

Motor vehicle services are produced with roads and motor vehicles (and many other factors) as inputs. If this process is represented in the context of a typical production function, the first order conditions indicate that the ratio of the inputs will depend on their relative prices and on technological factors that may differ across countries. This can be written as follows.

Assume a country uses motor vehicles (V) and roads (R) to produce road transport services (S):

$$S = k\, V^a\, R^b \qquad a > 0,\ b > 0.$$

If the prices of V and R, (p, q), are given, the economic behavior is to minimize total production cost for a given level of services (S_0):

$$\min\ p\,V + q\,R \qquad \text{s.t. } k\, V^a\, R^b = S_0.$$

Taking the first order conditions yields:

$$V/R = (a/b)\,(q/p).$$

This is a typical production function of a competitive firm. The question is whether a country behaves like a competitive firm in road service production. What really matters in this framework is the government provision of roadways because motor vehicle ownership and use are largely private. To the extent that governments base road investments on economic approaches, such as cost-benefit analysis, road provision may be reasonably efficient in economic terms. Certainly many road authorities use planning models and quantitative approaches to select road investments.

An ideal input ratio would be actual traffic volumes (vehicle kilometers traveled) per kilometer of road network. There is surprisingly little information on aggregate traffic volumes at the national level, and such data are often based on intermediate variables such as fuel consumption. Most traffic volume data are link-specific because traffic volumes on specific network links at specific times are important for the understanding of network use. For most developing countries, road traffic volume statistics for the entire road network simply do not exist. Therefore, we use motor vehicles per kilometer of roads as the ratio of inputs.

The cost of roads will vary systematically across countries reflecting variation in the cost of land and variation in the prices of the (mostly) non-traded inputs (e.g. labor and most construction materials) that are used in road construction. Income density is used as a proxy for national land prices. Income per capita is used as a proxy for variation in the price of non-tradables relative to tradables across countries. The quality of road networks varies across countries, and better road networks will be able to accommodate more motor vehicles per kilometer. The percent of the road network that is paved is used to measure the quality of roads.

The price of motor vehicles should not vary across countries because they are traded goods. Countries obviously impose taxes and fees on motor vehicles, but we do not have data or a reasonable proxy for these taxes. The only vehicle price information that we have is an index of gasoline prices. If a network is congested, then increases in the number of motor vehicles per kilometer of road will reduce speeds and increase the cost of vehicle operation, and these costs will increase with the value of time, best measured by per capita income. If road systems are congested, per capita income would also serve as a proxy for the cost of vehicle services. However, for most of the countries in the sample, the national road network is not congested, and we believe that at the national level the per capita income measure is proxying the relative price of non-traded inputs used in road construction.

2.3.2. Motor Vehicles Per Kilometer of Roads

Figure 5a shows the log-log relation of total motor vehicles per kilometer of total roads with per capita income. Figure 5b shows the similar relation for motor vehicles per kilometer of paved roads. Vehicle traffic on the entire road network tends to increase with income, both within a country and across countries. In contrast, vehicle traffic on the

Figure 5a. Changes in Motor Vehicles Per kilometer of Total Roads

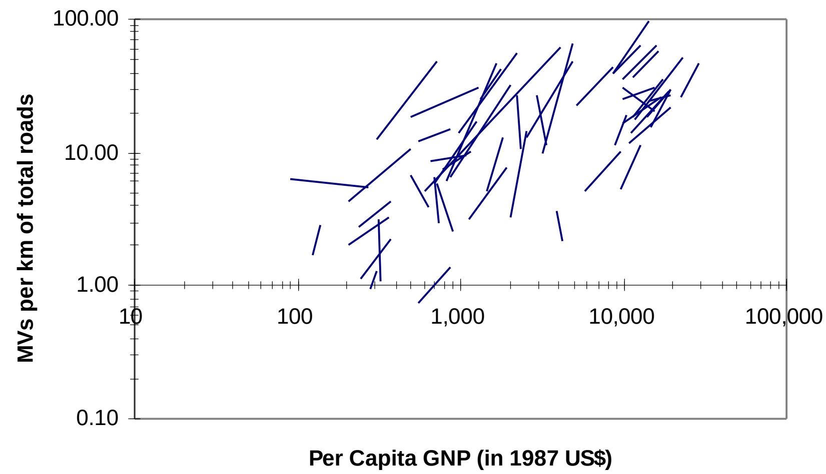
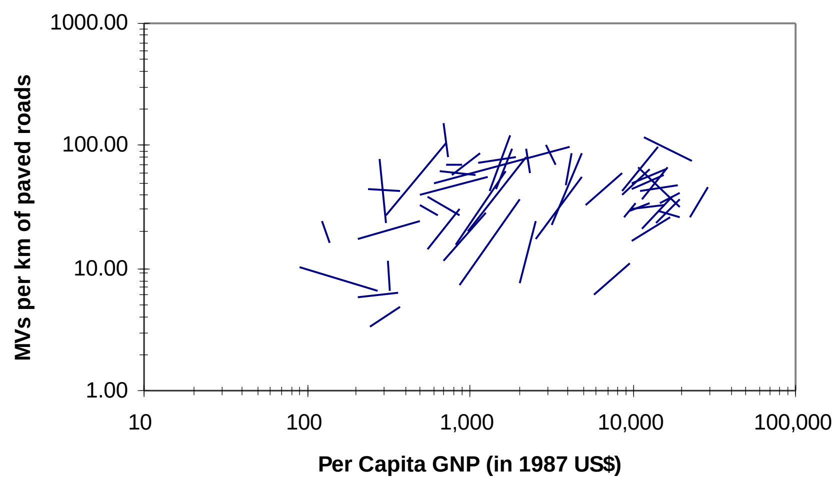


Figure 5b. Changes in Motor Vehicles Per Kilometer of Paved Roads



paved road network tends to increase with income within a country, but to change relatively little across countries. This is consistent with the earlier results showing how roads and vehicle ownership varied with income. The total road network increases more slowly than income while the paved road network and vehicle ownership increase at about the same rate as income. The result is that the density of paved roads across countries increases in step with the growth of the motor vehicle fleet.

2.3.3. Regression Results

Table 6 presents the parameter estimates of vehicle/road ratio regressions for total roads (Eq. 1 to Eq. 3) and paved roads (Eq. 4 to Eq. 6). For total roads, the coefficient

Table 6. Regressions of Motor Vehicles Per Kilometer of Roads
(50 countries for 1970, 1980, and 1990)

Explanatory Variable	OLS Estimate and (Standard Error)					
	ln MVs/km of total roads			ln MVs/km of paved roads		
	Eq. 1	Eq. 2	Eq. 3	Eq. 4	Eq. 5	Eq. 6
Constant	-0.79 (0.60)	-0.67 (0.53)	-0.67 (0.53)	0.52 (0.53)	0.64 (0.48)	0.64 (0.48)
ln real GNP per sq. km.	0.21 (0.06)*	0.09 (0.06)		0.17 (0.05)*	0.06 (0.05)	
ln real GNP per capita		0.35 (0.06)*	0.43 (0.06)*		0.30 (0.05)*	0.36 (0.06)*
ln population density (p/km2)			0.09 (0.06)			0.06 (0.05)
ln gasoline prices	0.01 (0.16)	-0.29 (0.15)*	-0.29 (0.15)*	0.39 (0.15)*	0.12 (0.14)	0.12 (0.14)
Percentage of roads paved	1.45 (0.31)*	1.25 (0.28)*	1.25 (0.27)*	-1.50 (0.28)*	-1.68 (0.25)*	-1.68 (0.25)*
Year dummy for 1980	0.02 (0.17)	0.002 (0.15)	0.002 (0.15)	0.14 (0.14)	0.11 (0.13)	0.11 (0.13)
Year dummy for 1990	0.05 (0.16)	0.04 (0.14)	0.04 (0.14)	0.40 (0.14)*	0.37 (0.13)*	0.37 (0.13)*
Adj. R-squared	0.54	0.63	0.63	0.24	0.38	0.38

Note: * Significant at the 0.05 level.

estimates of income density (proxying land prices), per capita income (proxying the rising costs of other nontradable road inputs), gasoline prices, and percentage of roads paved basically confirm the above road service production hypothesis, although the effect of gasoline prices is barely significant.

Eq. 4 to Eq. 6 parallel Eq. 1 to Eq. 3 in terms of functional specifications, but have less explanatory power, with R^2 below 0.4. The coefficient estimates for income density are smaller and have the correct sign. Because income density variable is used as a proxy of land prices, the smaller coefficients may reflect the fact that most road paving is done on existing unpaved roads, and therefore increases in land prices have less effect on road paving. It is generally true that road paving facilitates traffic movement at low to moderate cost, thus often yielding the highest rate of return among different roadway investments.

Finally, the estimates of year dummies in all regressions show little or no time effect on the vehicle/road ratio.

3. Analysis with Urban Area Data

3.1. Data Problems for Aggregate Urban Analysis

In terms of the analysis of motorization and road networks, an urban area differs from a country in population density and, perhaps more important, in the flexibility of its boundaries. Urban areas have much higher densities than nations, but their boundaries are not fixed and change over time—usually increasing their area. Moreover, urban expansion is typically associated with both population and income growth. Because of this peculiar urban phenomenon of boundary expansion, it is interesting to see how useful the analytical framework used to analyze motorization and roadway provision at the national level is at the urban level.

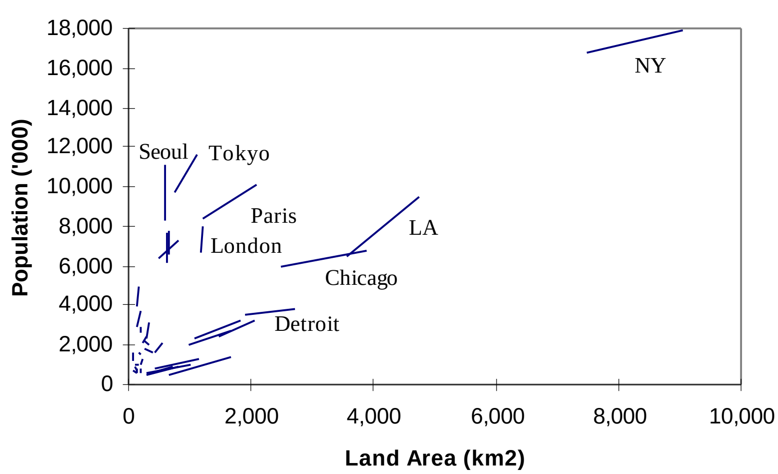
One particular problem in working with urban areas is that the definition of their boundaries may differ across countries, so there can be problems of comparability. Conceptually, the built-up or full functional urban area is the relevant area for urban analysis. However, statistics based on built-up area are unavailable for most cities. Urban areas defined in some countries (such as the USA) for statistical purpose actually include sizable rural land or unused land. In some other countries, urban areas are defined for administrative purposes, and the change of their boundaries may lag behind the change of their actual full functional urban area.

Another problem is that urban land use is affected by government land use policies. While some cities exercise little control on development patterns, others enforce strict land use regulations such as zoning laws and building codes. With aggregate land use data obtained at the level of loosely defined urban areas, it is nearly impossible to distinguish whether the urban land use changes over time take place in the form of in-fill development, or outward expansion, or a combination of both. All these are highly relevant to the changes in urban road network provision and performance.

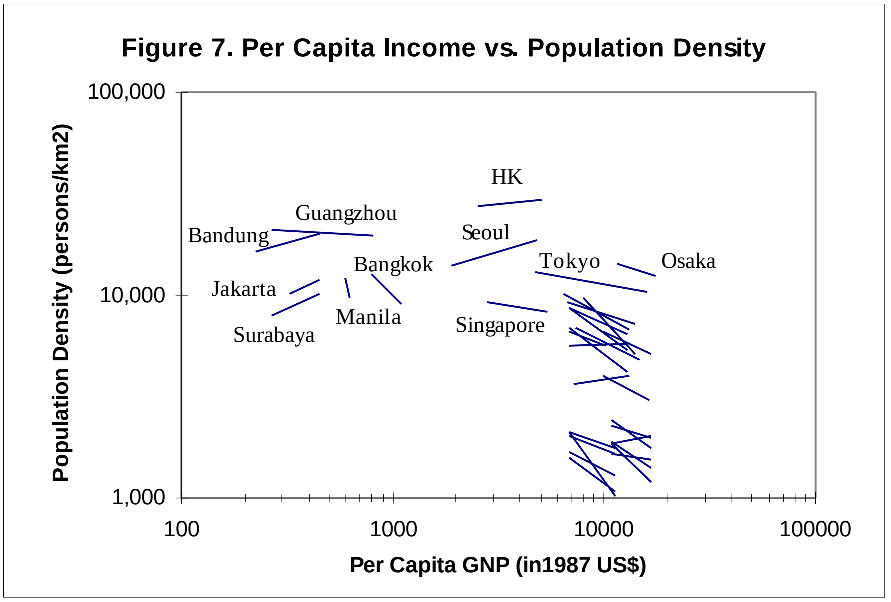
Notwithstanding these data problems, it is worthwhile to compare motorization and road provision at the urban level with those at the national level. The cross-country analyses show the moderate role of population density in motor vehicle ownership and intensity of network use, while paved road density is unit elastic with population density (which implies that road length per capita is independent of population density). It is likely that population density also affects motor vehicle ownership and road network provision in cities, but the magnitude of its effect may be much greater because urban roads are typically congested (as congestion is related to population density) whereas national roads are typically not congested. This hypothesis, along with the role of other variables, are examined in this section.

The urban dataset used in this analysis includes 35 world cities. The upward sloping line segments shown in Figure 6 confirm that both population and land area increase over time for most cities. For many cities, the increase in area has been proportionally greater than the increase in population, and their average population densities have declined. Some cities experienced increases in population density (see Appendix Table 3 for detail), and a few line segments are virtually vertical. These represent cities whose boundaries changed very little (Copenhagen, Jakarta, London, Manila, and Seoul), or whose population growth outpaced land expansion (Bandung, Hong Kong, Surabaya, and Tokyo).

Figure 6. Urban Land Area and Population



A second key relation for urban areas is the association between population density and per capita income—shown in Figure 7. One group of cities has high densities across the full range of income levels. In this group population density remains roughly constant or increases slightly as per capita income increases—indicating that income density increases directly with per capita income growth. A second group of cities has high per capita income levels and widely varying (and usually declining) population densities. Cities are likely to exhibit different, and path dependent, relations between population density and motor vehicle ownership because of the path dependency between population density and per capita income displayed in Figure 7.



Path dependency has at least two causes. First, physical endowments matter: existing patterns of population densities are strongly affected by the existing street layout and stock of buildings—neither of which will change quickly. Second, cities are embedded in environments with very different land prices and land availability. The cities with the highest income densities will be those with high per capita income and high population density, with the latter affected by land use constraints (physically or administratively) such as Hong Kong, Osaka, and Tokyo. It will be interesting to see how far motor vehicle ownership can continue to grow in such cities.

3.2. Motorization at the Urban Level

3.2.1. Trends of Motor Vehicle ownership across Cities and over Time

Figures 8a and 8b plot the relations of motor vehicle ownership with per capita income and population density for 35 urban areas, each at two points of time (mostly a 20-year span). At the urban level, as at the national level, per capita income remains a key determinant of motor vehicle ownership. Although the initial levels of motor vehicle ownership differ among the high income urban areas, they appear to have grown at comparable rates. On the other hand, unlike at the national level (Figure 2), population density has a nonlinear and mainly negative relation with motor vehicle ownership both across cities and over time within cities.

Figure 8a. Changes in Motor Vehicle Ownership

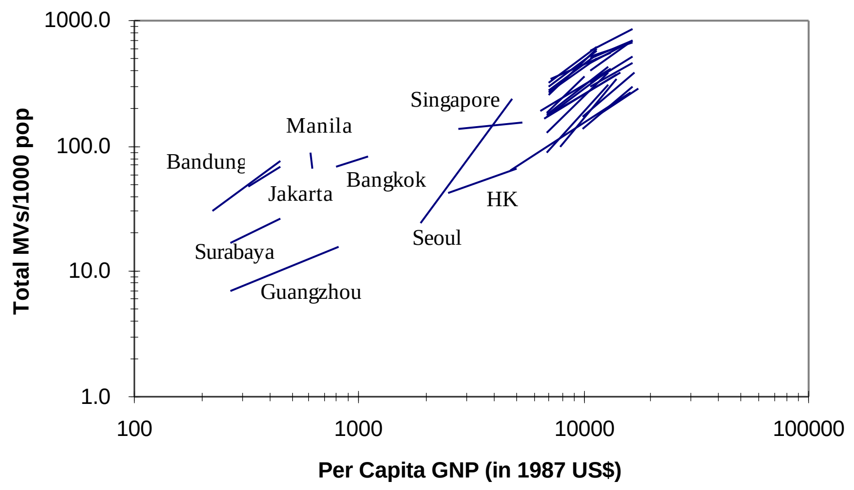
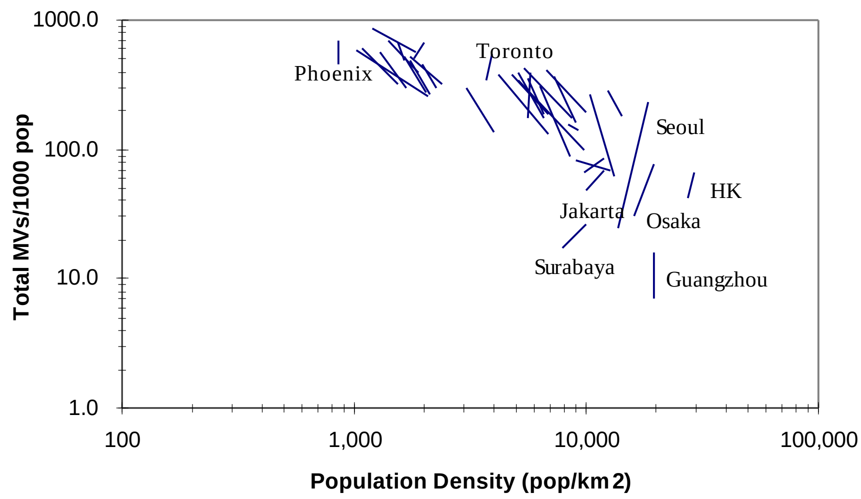


Figure 8b. Changes in Motor Vehicle Ownership



But Figure 8b shows two patterns within cities: a positive relation between motor vehicle ownership and population density for high density cities (such as Surabaya, Jakarta, Seoul, Osaka, and Hong Kong) up to about 100 vehicles per 1000 persons, and then a negative relation culminating in the lowest density cities (such as Phoenix and Perth). This negative relation indicates that among the higher income cities in Figure 8a, higher motor vehicle ownership is associated with lower population density.

3.2.2. Motor Vehicle Ownership Models

Table 7 presents the results of vehicle ownership regressions for total motor vehicles, private cars and commercial vehicles. Similar to the national level estimates, per capita income remains the most statistically significant explanatory variable (Eq. 1, Eq. 3, and Eq. 5). Income elasticities of vehicle ownership at urban level are 20 to 30 percent smaller than the similar estimates obtained with national data. Income elasticities for urban private car ownership are close to unity. The lower income elasticities may be caused by the use of national income data as a measure of urban incomes—which is likely to understate urban incomes in low income countries relative to high income countries.

Table 7. Urban Area Motor Vehicle Ownership Models
(35 world cities, each in two different years)

Explanatory Variable	OLS Estimate and (Standard Error)					
	ln MVs/1000 pop		ln cars/1000 pop		ln com. veh./1000 pop	
	Eq. 1	Eq. 2	Eq. 3	Eq. 4	Eq. 5	Eq. 6
Constant	0.50 (0.46)	4.58 (0.96)*	0.07 (0.61)	5.49 (1.27)*	-0.59 (0.61)	2.44 (1.41)*
ln Real GNP per capita	0.83 (0.05)*	0.52 (0.08)*	0.91 (0.07)*	0.50 (0.10)*	0.60 (0.06)*	0.37 (0.12)*
ln Population density (p/km2)		-0.43 (0.09)*		-0.58 (0.12)*		-0.32 (0.14)*
ln Gasoline prices	-0.61 (0.11)*	-0.06 (0.15)	-0.76 (0.15)*	-0.04 (0.20)	-0.23 (0.15)	0.18 (0.22)
Dummy for ending year	0.23 (0.11)*	0.32 (0.10)*	0.29 (0.14)*	0.42 (0.13)*	0.12 (0.14)	0.19 (0.14)
Adj. R-squared	0.83	0.87	0.77	0.83	0.60	0.63

Note: * Significant at the 0.05 level.

Adding population density to the regressions, as in Eq. 2, Eq. 4, and Eq. 6, tends to increase the explanatory power (R^2) slightly, but reduce the magnitude of income elasticities substantially. Because per capita income growth is the driving force for both population density decline and increased motor vehicle ownership, the income elasticities of vehicle ownership obtained from equations without population density variable, such as Eq. 1, Eq. 3, and Eq. 5 can be regarded as long-run income elasticity estimates.

Finally, the coefficient estimates for gasoline prices become more significant at the urban level than the national level in equations without population density. The estimates for the ending year dummy are positive and significant, suggesting that the size of vehicle fleet tends to grow over time with omitted variables.

3.2.3. Saturation Level

Congestion on urban roads degrades motor vehicle performance, making vehicle ownership less attractive (and contributing to the lower income elasticities of vehicle ownership just discussed). Does congestion lead to a more marked pattern of ownership saturation? The saturation level can be estimated using the similar method discussed in Section 2.1.5 for the national data. The urban saturation levels under the "business as usual" scenario are found to be roughly at 750 cars and 1,080 total motor vehicles per thousand population. These results suggest that saturation effects for auto ownership are little different in urban areas from those at the national level.

3.3. Provision of Roadways at the Urban Level

3.3.1. Roadway Provision and Urban Area Annexation

Roadway provision at the urban level differs from that at the national level in four important respects. First, while national roads are built link by link, depending mostly on the locations of economic centers, urban roads are provided as a dense network to serve closely located properties and high volume activities. Urban roads provide capacity and not just connectivity. Second, at the national level, there is ample space for road network growth. In the built-up area of cities, the road network and the blocks it serves are very durable, and it is extremely expensive to add more roads in the built-up area. Third, because a city's physical area increases over time, much of the increment in total urban road capacity comes from annexing areas with existing roads. Fourth, while inter-city road traffic moves mostly on links, urban road traffic performance has much to do with road intersections. Therefore, urban road network improvement within built-up areas typically involves more work with intersections (traffic signals, interchanges, flyovers, etc.) than addition of roads. Measuring the urban road network by total road length (rather than lane kilometers) per unit area can be misleading. Although a similar problem exists for the national data, it is more serious for urban data. Nonetheless, in order to compare national and urban road provision, it is useful to examine the cross-city regularities using models parallel to those at the national level.

To test for the effect of annexation on urban road length, consider a simple linear model which relates road length (L) to area (A) of the form, $L = b_0 + b_1 A$. Most cities have annexed area, so their end-year area is greater than their base-year area. Regressions of base-year road length (L_1) on base-year area (A_1), and end-year road length (L_2) on base-year area (A_1) and the new area annexed ($A_2 - A_1$), are shown below, with standard errors in parentheses:

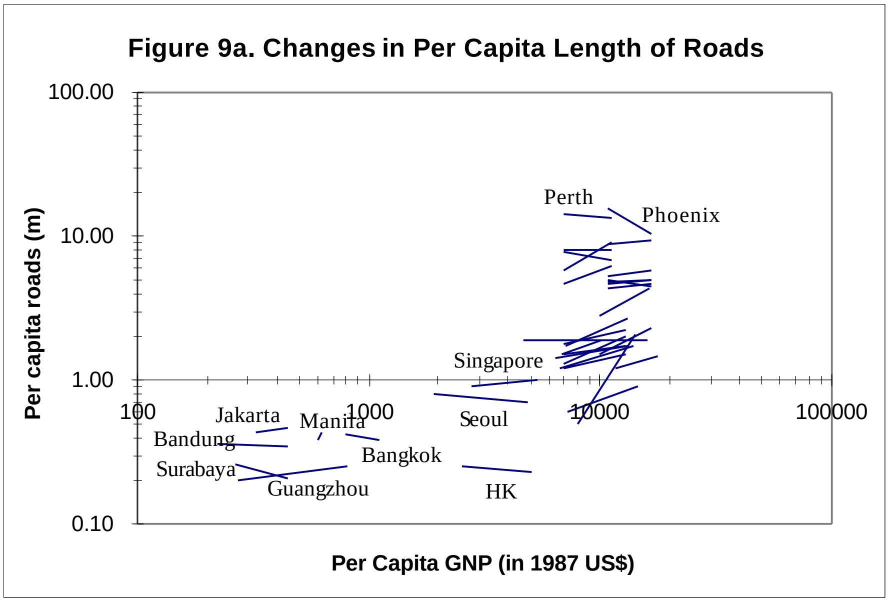
$$L_1 = \underset{(621.1)}{383.8} + \underset{(0.4)}{9.6}\, A_1 \qquad R^2 = 0.95$$

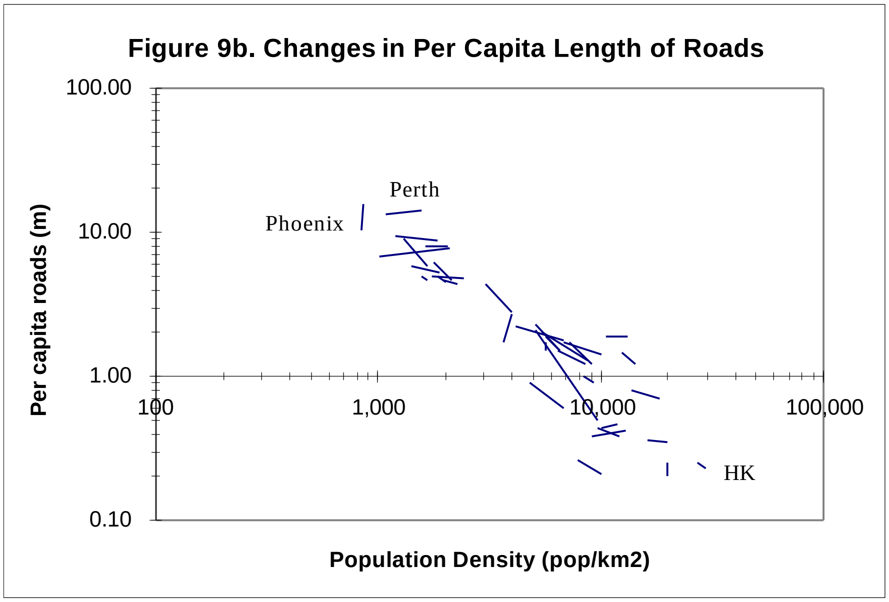
$$L_2 = \underset{(766.3)}{366.4} + \underset{(0.7)}{9.3}\, A_1 + \underset{(2.0)}{8.3}\, (A_2 - A_1) \qquad R^2 = 0.95$$

These results show that the coefficient on base-year area does not change over time. This implies that virtually all of the increase in urban road length comes from annexation. In addition, the road network density of the annexed area is typically lower than that of the base-year area, so annexation reduces road network density.

3.3.2. Road Length Per Person and Urban Road Network Density

Since urban areas have high road densities and need transport capacity rather than point to point connectivity, road length per person should be a more appropriate measure of road supply than road density. The relations of per capita length of urban roads with per capita income, population density and income density are shown in Figures 9a, 9b and 9c. Across cities, higher per capita length of urban roads is associated with higher per capita income, but within cities per capita road length seems to be roughly constant.





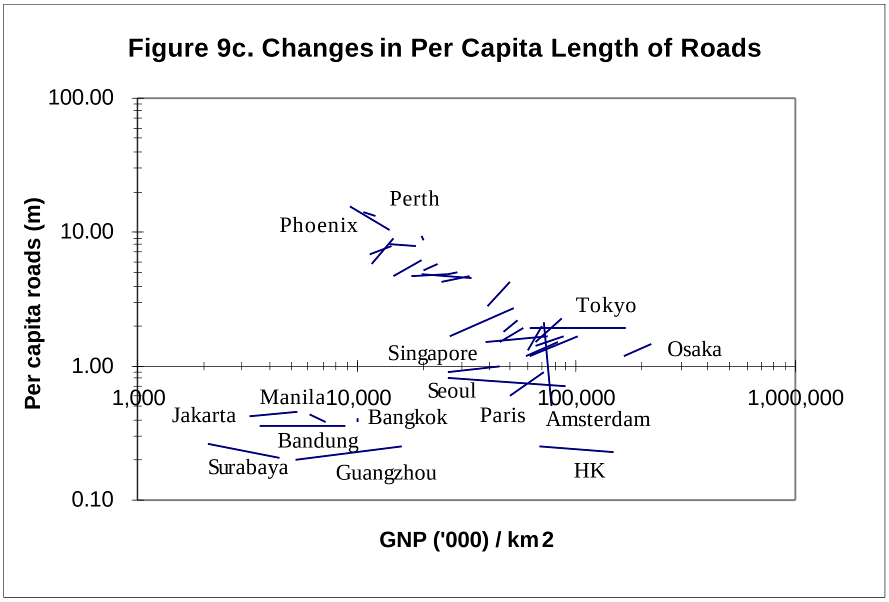


Figure 9a is a mirror image of Figure 7 because of the strong relation between per capita road length and population density shown in Figure 9b. And across income density levels (Figure 9c) two obvious trajectories appear, tending to converge at road lengths of one meter per capita. These two trajectories are for the high and low population density cities in Figure 7, with the lower trajectory representing cities that differ greatly in per capita income but have similar high levels of population densities.

The per capita road length regressions are presented in Table 8. Two variables, per capita income and population density, seem to work reasonably well in determining per capita length of urban roads (Eq. 3 and Eq. 4). Per capita road length increases with per capita income, but the elasticity is 0.3 to 0.4, much lower than at the national level. As shown in Eq. 3, there is unit elasticity of per capita road length with population density—opposite to the relation at the national level where per capita road length is independent of population density. Eq. 2 and Eq. 4 include a variable measuring national income density—used as a proxy for rural land prices. When the cost of urban expansion rises, as indicated by this proxy, urban road per capita falls. Moreover, as indicated by the estimates for the ending year dummy variable, per capita length of urban roads decreases over time if other variables are held constant. This may reflect the effect of annexation of outlying land, the rising cost of providing urban roads, or the use of resources for other infrastructure including transit.

3.3.3. Saturation Level of Road Network Density

Because urban land use is highly intensive, an interesting question is whether there is a limit for urban road network density. Similar to the method used in Section 2.1.5, regressions with the following functional form are estimated with alternative assumed saturation levels:

$$RD = S - k\,e^{\,b0 + b1\,UYD + b2\,NYD},$$

Table 8. Urban Area Per Capita Road Length Models
(35 world cities, each for two different years)

Explanatory Variable	OLS Estimate and (Standard Error) ln road length per person in meters Eq. 1	Eq. 2	Eq. 3	Eq. 4
Constant	-0.01 (1.46)	-4.02 (1.74)*	5.87 (0.78)*	4.18 (1.15)*
ln urban real GNP/sq. km.	0.05 (0.14)	0.65 (0.21)*		
ln national real GNP/sq. km.		-0.36 (0.10)*		-0.07 (0.03)*
ln real GNP per capita			0.31 (0.04)*	0.42 (0.07)*
ln urban pop. density			-0.93 (0.06)*	-0.79 (0.09)*
Dummy for ending year	0.13 (0.29)	0.17 (0.27)	-0.19 (0.09)*	-0.17 (0.09)*
Adjusted R-squared	0.01	0.13	0.91	0.91

Note: * Significant at the 0.05 level.

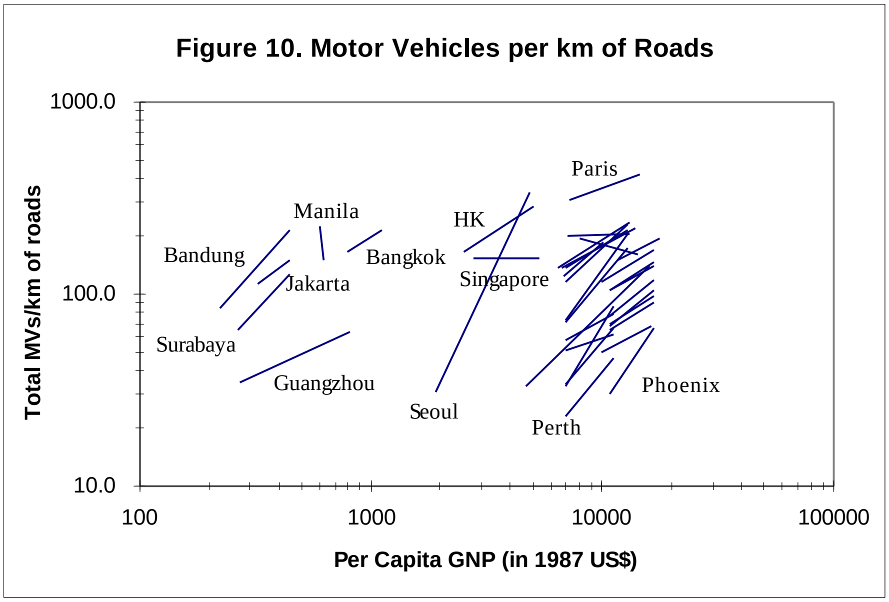
where RD is the length of road network per square kilometer; S, saturation level; UYD, urban income density; NYD, national income density; and k, b_0, b_1 and b_2, parameters. The regression with the highest R^2 gives the saturation level, which is 23 km/km^2 (estimated using the ending year data).

Applying the same method to national road network density, however, does not yield a saturation level (as R^2 continues to increase with assumed saturation level over the 23 km/km^2 urban limit). Because the actual highest national road network density is lower than 5 km/km^2, there is ample space for the growth of national road network. Although road development in some countries is more heavily constrained by geographical features (mountains, rivers, islands, etc.) than in other countries, national road network saturation level, if any, would not be greater than that of the urban road network.

3.4. Production of Road Transport Services at the Urban Level

Similarly to the cross-country data, comparable road traffic data are not available at the city level for a large number of world cities. Therefore, we use the number of motor vehicles per kilometer of roads as a measure of the intensity of urban road network use.

The relation of vehicles per kilometer of road with per capita income is plotted in Figure 10. The average number of vehicles per kilometer is roughly five times greater on urban roads than on national roads for high income countries, and ten times for developing countries. Figure 10 is a reprise of Figure 7, with large differences in vehicle/road ratios among high per capita income urban areas. The similarity between Figures 10 and 7 reflects the underlying positive relation between vehicles per unit of road and population density.



The regressions using the vehicle/road ratio as the dependent variable are shown in Table 9. The coefficients of both urban and national income densities—proxies for urban and rural land prices—have the correct sign, consistent with the hypothesis that rising land prices will increase the cost of roads relative to vehicles and raise the vehicle/road ratio. At the national level, income per capita was used in parallel equations (Table 6) as a proxy for the rise in the ratio of prices of nontradables to tradables. With this interpretation, the sign of per capita income would be positive, which was the case at the national level but is not the case now. This key difference may be explained by congestion in urban areas. At the national level there is no congestion, and increases in the vehicle/road ratio does not degrade vehicle performance. At the urban level, increases in the vehicle/road ratio will increase congestion and degrade performance, potentially giving support to a negative sign for per capita income. However, in this case the negative sign on per capita income more likely reflects the lower vehicle/road ratios in the low density, high per capita income urban areas. This relation is symptomatic of the developmental endowments of cities, rather than of a simple relation between incomes, roads, and motor vehicles.

Unlike at the national level, there is a very strong link at the urban level between population density and intensity of road use. Motor vehicle ownership and road length per

Table 9. Urban Area Motor Vehicles Per Kilometer of Roads
(35 world cities, each for two different years)

Explanatory Variable	OLS Estimate and (Standard Error) ln total motor vehicles per km of urban roads				
	Eq. 1	Eq. 2	Eq. 3	Eq. 4	Eq. 5
Constant	2.00 (0.67)*	2.10 (0.60)*	2.75 (0.78)*	-1.50 (1.24)	-0.06 (1.67)
ln urban real GNP per sq. km.	0.24 (0.11)*	0.52 (0.12)*	0.41 (0.15)*		
ln national real GNP per sq. km.			0.06 (0.05)		0.06 (0.05)
ln real GNP per capita		-0.29 (0.07)*	-0.25 (0.07)*	0.24 (0.10)*	0.15 (0.12)
ln urban population density				0.52 (0.12)*	0.48 (0.12)*
ln gasoline prices	0.001 (0.22)	-0.13 (0.20)	-0.15 (0.20)	-0.13 (0.20)	-0.15 (0.20)
Dummy for ending year	0.45 (0.14)*	0.50 (0.12)*	0.48 (0.12)*	0.50 (0.12)*	0.48 (0.12)*
Adjusted R-squared	0.28	0.44	0.44	0.44	0.44

Note: * Significant at the 0.05 level.

capita both vary inversely with urban population density. Motor vehicles per kilometer of road are high for low income cities but vary greatly across high income cities.

The strong relation between population density and motor vehicle use has led some analysts (Newman and Kenworthy, 1989) to suggest that cities should use population density as a policy instrument and increase densities in order to reduce motor vehicle ownership and use. The direction of causation between population density and motor vehicle use is a real issue for this recommendation. The variation of population density across high income cities strongly suggests that the newer cities—whose growth took place when auto ownership was already high—are the low density cities. Motor vehicle use appears to be one important determinant of densities. If this is true, those who wish to reduce auto use should also focus on the motor vehicles and not only on population densities. The proper pricing of motor vehicle use in urban areas deserves more attention than restrictions on residential density.

4. Conclusions

The empirical work presented in this paper is a first attempt to analyze motorization and road provision together. Much of the analysis is descriptive, and it is potentially foolhardy to claim that it supports strong conclusions. However, the following propositions are offered as preliminary conclusions—although some are better described as findings that were especially surprising.

- Simple economic variables are strongly associated with motorization at both the national level and at the urban level, and the underlying behavior of vehicle owners seems very similar at both levels, with somewhat weaker income effects at the urban level.
- The composition of the vehicle fleet changes is a regular fashion, with the share of cars rising steadily as incomes grow.
- The availability of rail networks has essentially no impact on car ownership; evidence suggests that rail may substitute for commercial vehicles and is therefore more competitive for freight than for passenger travel.
- Vehicle ownership increases with income, and estimated ownership saturation levels are well above currently observed levels and similar for national and urban data.
- Road provision at the national level is very responsive to income, especially for paved roads. Road provision is very consistent across countries even though it is publicly provided. There is little evidence of outliers or pathology in road provision.
- Simple models based on changing relative prices of roads to motor vehicles have substantial power to explain the variation in vehicle/road ratios at the national level.
- Appropriate measures of road provision differ between the national and urban level, with connectivity (measured by road density) being key at the national level and capacity (measured by road length per capita) at the urban level.
- Road provision at the urban level expands more slowly with income than at the national level and it is negatively associated with population density, whereas population density is positively associated with road provision at the national level.
- Urban area road provision is strongly influenced by past physical endowments; per capita road provision and population densities vary substantially across cities with high per capita incomes, but are very similar across cities with low per capita incomes. Finally, cross-city data show that a saturation level exists for urban road network density.

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Appendix: Data Sources

1. Country-Level Data

The country-level data set consists of a panel of 50 countries for 1970, 1980 and 1990. The data are compiled from various sources. Primary sources include: (1) World Bank, World Development Indicators database, various years; (2) World Bank, World Development Report 1994, infrastructure database; (3) International Road Federation, World Road Statistics, various years; and (4) scattered statistics found in various publications, including statistical yearbooks of individual countries. The key variables used in the study are listed below, along with their data sources:

- GNP at market prices in constant 1987 US dollars: from (1);
- Total land area, total population, and urban population: from (1);
- Total motor vehicles, passenger cars: from (2) and (3);
- Length of total roads and length of paved roads: from (2) and (3);
- Length of railroads: from (2) and provided by Louis Thompson

2. City-Level Data

The city-level data are obtained from several sources. The major source of this dataset is Newman and Kenworthy (1989), which provides a total of 86 observations for 32 advanced world cities in different years (mostly 10 years apart) in North America, Europe, and Asia-Pacific Region. We select 25 cities, each at two points in time (1960 and 1980), for the current empirical analyses. These observations are supplemented with 10 other cities (mostly developing cities), also at two points in time, from various sources, including Cervero (1990), KOTI (1994), and Stares and Liu (1996). Reliable income data at the city level are not handily available. Therefore, country-level per capita income data are used as a proxy for city-level per capita income.

Appendix Table 1. Countries in the National Sample

	Per Capita GNP at market prices (1987 US$)		
Country	1970	1980	1990
Algeria	$2,049	$2,598	$2,563
Argentina	$3,403	$3,866	$2,965
Australia	$9,514	$11,274	$12,611
Austria	$9,992	$14,050	$17,011
Belgium	$9,829	$13,065	$15,543
Bolivia	$736	$822	$695
Brazil	$1,132	$1,979	$1,897
Cameroon	$558	$854	$870
Canada	$9,946	$13,174	$15,317
Chile	$1,435	$1,512	$1,794
China	$89	$134	$269
Colombia	$777	$1,086	$1,156
Cote d'Ivoire	$889	$1,156	$719
Denmark	$14,055	$16,473	$19,666
Ecuador	$652	$1,161	$1,080
Egypt, Arab Republic of	$310	$510	$713
Finland	$11,121	$14,822	$19,048
France	$11,214	$14,630	$17,404
Gabon	$4,215	$4,753	$3,928
Germany	$9,919	$12,911	$16,000
Greece	$3,159	$4,599	$4,806
India	$240	$262	$372
Indonesia	$204	$324	$487
Ireland	$5,766	$7,525	$9,653
Italy	$8,649	$11,854	$14,391
Japan	$11,554	$16,065	$22,890
Kenya	$235	$359	$375
Korea, Republic of	$608	$1,894	$4,098
Malawi	$123	$155	$138
Malaysia	$961	$1,618	$2,233
Mauritius	$874	$1,240	$2,039
Mexico	$1,334	$1,853	$1,742
Morocco	$560	$745	$873
Netherlands	$11,461	$14,074	$16,244
New Zealand	$8,776	$9,731	$10,401
Nigeria	$326	$378	$318
Norway	$10,766	$15,709	$19,539
Pakistan	$207	$249	$361
Philippines	$487	$679	$639
Portugal	$2,552	$3,648	$4,919
Rwanda	$279	$344	$308
South Africa	$2,304	$2,444	$2,193
Spain	$5,174	$6,574	$8,444
Sweden	$14,451	$16,790	$19,423
Switzerland	$22,415	$24,957	$28,501
Thailand	$493	$715	$1,283
Tunisia	$687	$1,130	$1,262
Turkey	$823	$1,177	$1,648
United Kingdom	$8,523	$10,172	$12,766
United States	$13,893	$16,608	$19,567

Appendix Table 2. Simple Statistics of Key Variables for 50 Countries

Variable	Year	Mean	Standard Deviation	Minimum Value	Maximum Value
Population	1970	56	138	1	818
(in millions)	1980	67	167	1	981
	1990	79	197	1	1135
GNP per capita	1970	$4,794	$5,382	$89	$22,415
(constant 1987 US$)	1980	$6,094	$6,575	$134	$24,957
	1990	$7,263	$7,969	$138	$28,501
Land area ('000 km2)	1970	1,430	2,594	2	9,573
	1980	1,430	2,595	2	9,573
	1990	1,430	2,595	2	9,573
Population density	1970	88	104	2	407
(persons/km2)	1980	101	116	2	476
	1990	113	126	2	521
Share of urban	1970	49%	25%	3%	94%
population	1980	54%	24%	5%	95%
	1990	58%	23%	6%	97%
Total motor vehicles	1970	113.9	135.9	0.6	533.1
per 1000 pop.	1980	169.5	182.4	1.7	684.5
	1990	215.2	214.9	2.4	755.4
Passenger cars	1970	90.6	113.5	0.1	433.3
per 1000 pop.	1980	139.4	154.2	0.2	520.1
	1990	178.2	183.8	1.0	574.4
Total road network	1970	0.50	0.72	0.01	3.04
density (km/km2)	1980	0.59	0.85	0.03	4.19
	1990	0.64	0.91	0.03	4.56
Paved road network	1970	0.35	0.60	0.00	2.48
density (km/km2)	1980	0.46	0.79	0.00	3.94
	1990	0.52	0.85	0.00	4.28
% roads paved	1970	45%	33%	1%	100%
	1980	51%	32%	3%	100%
	1990	55%	32%	4%	100%
Railroad network	1970	0.027	0.034	0.000	0.141
density (km/km2)	1980	0.025	0.032	0.000	0.131
	1990	0.028	0.035	0.000	0.126

Appendix Table 3. Key Variables and Simple Statistics for 35 World Cities

City	Beginning Year and Ending Year	Urban Population ('000)		Urban Land Area (sq. km.)		Real Per Capita Income (US$)		Population Density (persons/sq km)		Income Density ('000 US$/sq km)		Total Motor Vehicles per 1000 pop.		Passenger Cars per 1000 pop.		Road Network Density (km/km2)		Per Capita Road Length (m)	
		Beginning Year	Ending Year	Beginning Year	Ending Year	Beginning Year	Ending Year	Beginning Year	Ending Year	Beginning Year	Ending Year	Beginning Year	Ending Year	Beginning Year	Ending Year	Beginning Year	Ending Year	Beginning Year	Ending Year
Adelaide	1960-80	588	932	350	722	6,897	11,274	1,680	1,290	11,587	14,543	293	568	228	475	9.74	11.74	5.80	9.10
Amsterdam	1960-80	869	717	89	141	7,938	14,074	9,750	5,080	77,396	71,496	98	342	65	308	4.88	10.67	0.50	2.10
Bandung	1972-87	1,230	1,600	76	81	223	446	16,180	19,750	3,608	8,809	30	76	21	53	5.80	6.94	0.36	0.35
Bangkok	1983-88	6,400	7,320	500	810	793	1,108	12,800	9,040	10,150	10,016	68	82	61	74	5.32	3.47	0.42	0.38
Brisbane	1960-80	622	1,029	296	1,008	6,897	11,274	2,100	1,020	14,484	11,499	261	595	192	458	16.38	7.04	7.80	6.90
Brussels	1960-80	1,023	997	102	148	6,442	13,065	10,030	6,740	64,613	88,058	191	408	157	361	14.04	11.46	1.40	1.70
Chicago	1960-80	5,959	6,780	2,483	3,874	10,780	16,608	2,400	1,750	25,872	29,064	324	518	308	445	11.52	8.75	4.80	5.00
Copenhagen	1960-80	836	582	208	191	9,849	16,473	4,010	3,040	39,494	50,078	138	296	89	246	11.23	13.07	2.80	4.30
Denver	1960-80	804	1,352	432	1,136	10,780	16,608	1,860	1,190	20,051	19,764	573	853	479	666	16.37	11.19	8.80	9.40
Detroit	1960-80	3,538	3,809	1,892	2,702	10,780	16,608	1,870	1,410	20,159	23,417	402	691	366	594	9.72	8.18	5.20	5.80
Frankfurt	1960-80	670	631	77	117	6,875	12,911	8,720	5,400	59,950	69,719	177	427	133	387	11.34	10.80	1.30	2.00
Guangzhou	1980-94	2,900	3,750	138	190	268	807	21,000	19,740	5,628	15,930	7	16	2	13	4.20	4.94	0.20	0.25
Hamburg	1960-80	1,832	1,645	268	395	6,875	12,911	6,830	4,170	46,956	53,839	130	382	96	344	12.29	9.17	1.80	2.20
Hong Kong	1970-80	3,937	4,987	144	170	2,500	5,000	27,340	29,330	68,350	146,650	42	66	27	42	6.84	6.75	0.25	0.23
Jakarta	1980-88	6,580	7,830	656	656	324	446	10,030	11,940	3,250	5,325	48	69	35	52	4.31	5.46	0.43	0.46
L.A.	1960-80	6,489	9,479	3,546	4,740	10,780	16,608	1,830	2,000	19,727	33,216	513	667	459	542	8.97	9.00	4.90	4.50
London	1960-80	7,992	6,713	1,222	1,192	6,841	10,172	6,540	5,630	44,740	57,268	187	356	156	288	9.81	10.70	1.50	1.90
Manila	1982-88	6,200	7,650	636	636	623	603	9,750	12,030	6,074	7,254	66	87	44	58	4.31	4.62	0.44	0.38
Melbourne	1960-80	1,985	2,723	978	1,660	6,897	11,274	2,030	1,640	14,001	18,489	277	528	224	446	16.44	12.96	8.10	7.90
Munich	1960-80	1,046	1,299	185	228	6,875	12,911	5,660	5,690	38,913	73,464	174	398	131	360	8.49	9.67	1.50	1.70
New York	1960-80	16,835	17,925	7,482	9,053	10,780	16,608	2,250	1,980	24,255	32,884	300	459	271	412	9.68	9.31	4.30	4.70
Osaka	1970-83	2,976	2,626	208	210	11,554	17,659	14,308	12,505	165,311	220,822	179	286	56	131	17.14	18.33	1.20	1.47
Paris	1960-80	8,400	10,094	1,224	2,090	7,258	14,630	6,860	4,830	49,790	70,663	185	383	153	338	4.12	4.35	0.60	0.90
Perth	1960-80	475	899	305	832	6,897	11,274	1,560	1,080	10,759	12,176	323	614	239	475	22.00	14.36	14.10	13.30
Phoenix	1960-80	552	1,409	642	1,658	10,780	16,608	860	850	9,271	14,117	461	689	368	499	13.24	8.84	15.40	10.40
S.F.	1960-80	2,431	3,191	1,473	2,059	10,780	16,608	1,650	1,550	17,787	25,742	499	681	407	543	7.76	7.60	4.70	4.90
Seoul	1980-93	8,321	11,156	603	603	1,894	4,819	13,800	18,500	26,137	89,152	25	236	13	168	11.04	12.95	0.80	0.70
Singapore	1970-80	2,075	2,414	224	290	2,787	5,381	9,270	8,320	25,835	44,770	140	155	69	65	8.34	8.32	0.90	1.00
Stockholm	1960-80	808	647	123	126	9,889	16,790	6,550	5,130	64,773	86,133	173	390	143	347	9.83	11.80	1.50	2.30
Surabaya	1976-88	2,280	3,180	292	316	266	446	7,810	10,060	2,077	4,487	17	26	12	18	2.05	2.08	0.26	0.21
Sydney	1960-80	2,290	3,205	1,075	1,821	6,897	11,274	2,130	1,760	14,691	19,842	268	489	219	412	10.01	10.91	4.70	6.20
Tokyo	1960-80	9,684	11,597	739	1,109	4,702	16,065	13,100	10,460	61,596	168,040	63	267	16	156	24.89	19.87	1.90	1.90
Toronto	1960-80	1,621	2,137	440	540	7,149	13,174	3,680	3,960	26,308	52,169	345	554	298	463	6.26	10.69	1.70	2.70
Vienna	1960-80	1,628	1,531	178	212	6,713	14,050	9,140	7,210	61,357	101,301	163	374	94	311	10.97	12.26	1.20	1.70
W. Berlin	1960-80	2,204	2,001	257	315	6,875	12,911	8,560	6,360	58,850	82,114	88	306	66	269	10.27	9.54	1.20	1.50
Mean		3,545	4,167	844	1,201	6,442	11,128	7,541	6,927	34,680	52,352	206	381	163	309	10.27	9.65	3.22	3.44
Standard Deviation		3,568	4,058	1,374	1,738	3,668	5,840	6,053	6,607	31,906	49,430	152	220	136	185	5.07	3.78	3.77	3.36
Minimum Value		475	582	76	81	223	446	860	850	2,077	4,487	7	16	2	13	2.05	2.08	0.20	0.21
Maximum Value		16,835	17,925	7,482	9,053	11,554	17,659	27,340	29,330	165,311	220,822	573	853	479	666	24.89	19.87	15.40	13.30