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Identifying the Critical Factors for High Transit Patronage in Tokyo: A Historical Analysis of Travel Demand from 1920 to 2010

Ryosuke Abe (corresponding author)
Department of Civil Engineering, The University of Tokyo
7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone: +81-3-5841-7451; Fax: +81-3-5841-7496
E-mail: abe-r@ip.civil.t.u-tokyo.ac.jp

Hironori Kato
Department of Civil Engineering, The University of Tokyo
7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone: +81-3-5841-7451; Fax: +81-3-5841-7496
E-mail: kato@civil.t.u-tokyo.ac.jp

Abstract. This study analyzes the critical factors that have affected the trends of urban transportation in Tokyo, using statistical data for the period from 1920 to 2010. Direct demand models for public transportation (PT) ridership and car/motorbike ownership are estimated, with the service levels of transportation, urban form, and socio-economics being incorporated as explanatory variables. The results are summarized as follows: (1) the subway-supply elasticity of subway ridership was much higher than other-PT elasticities of PT ridership during the postwar period; (2) the road supply negatively influenced railway and subway ridership in the long run, and yet, this influence disappeared during the postwar period; (3) the parking supply had positive impacts on bus and tram ridership; (4) public transportation strongly influenced car/motorbike ownership while private transportation weakly influenced public transportation ridership; (5) the population centrality in the ward area had a negative impact on car/motorbike ownership; (6) GRP per capita had a strong impact on car/motorbike ownership; (7) the share of workers in the financial and manufacturing industries and the share of the population aged 15-39 had positive impacts on public transportation ridership; and (8) the share of workers in manufacturing industry also had a positive impact on car/motorbike ownership. In particular, it is highlighted that the subways successfully utilized the existing rail stocks when they were introduced to urban transportation in Tokyo, resulting in high performance.

Keywords: urban transportation, travel demand elasticity, time-series, transportation development

INTRODUCTION

Tokyo is currently one of the most transit-oriented cities in the world and is typically called a "transit metropolis" (*1*). The results of the 2008 Person Trip Survey show that the modal share of railways (including subways) was 30 percent as of 2008, followed by cars (29 percent) in the Tokyo metropolitan area. Tokyo's urban rail market has unique characteristics: private rail companies provide many of the rail services, the rail network was developed under the guidance of the central government, rail users suffered from chronic traffic congestion for many years, and the rail market has in recent years been significantly influenced by a rapidly aging demographic (*2*, *3*).

Tokyo's transportation market has been modernized over a long period following the Meiji Restoration in the late 1860s. The railway was first introduced in Tokyo in the 1870s. Tokyo's intensive rail network was gradually developed by both public and private operators, but the major transportation mode was trams before World War II. Most of the urban rail network except the subway network had been completed by the 1920s. In Japan, private transportation modes including automobiles emerged since the 1940s and rapid motorization commenced in the 1960s. This motorization replaced the tram with the subway during the 1960s to 1970s, but despite the drastic motorization, public transportation has continued to capture a significant number of travelers to date. These historical processes have resulted in the current transit-oriented city of Tokyo. What are the key elements that led to the public-transit-oriented transportation system in Tokyo?

In the context of general patterns of urban transportation development, past studies including Van de Coevering and Schwanen (*4*) and Kenworthy and Laube (*5*) have put forward many factors for describing the patterns of urban transportation with statistical analysis. In addition, time-series analyses highlighting travel demand elasticities have been intensively conducted (*6*). Few studies, however, have shown statistical evidence about historical processes of urban transportation development in Tokyo. This study analyzes the critical factors that have affected the trends of urban transportation in Tokyo, using statistical data covering the period from 1920 to 2010. Direct demand models for public transportation ridership and car/motorbike ownership are estimated, with the service levels of transportation, urban form, and socio-economics being incorporated as explanatory variables.

The remainder of the paper is organized as follows. A literature review of related studies on the development of urban transportation and the elasticities of travel demand is presented next. Then, the analysis methodology, including details on the data used, the model structure, and the estimation method, is presented. Next, the estimation results are discussed. Finally, the findings are summarized and policy implications highlighted.

LITERATURE REVIEW

Urban Transportation from a Developmental Perspective

A number of studies have analyzed overall patterns or trends of urban transportation development. They may be categorized into two types: the first type analyzes the process of urban transportation development in the context of the developing world. They include Morichi and Acharya (*7*), Barter (*8*), Dick and Rimmer (*9*), Hook and Replogle (*10*), and Rimmer (*11*). The second type analyzes the differences in transportation markets between automobile-dependent US cities and transit-oriented/compact-structured European cities. They include Nivola (*12*), Pucher and Lefèvre (*13*), and Pucher (*14*). These studies have unveiled the critical factors affecting the development of urban transportation: a series of public policies including car-related policy, land/house regulation, and subsidies for public transportation and for road construction (*14*); the socio-economic conditions, land-use patterns, transportation policy, and culture and attitude (*15*); and choice of investment in transportation infrastructure, income change and economic growth, interdependence between transportation and land-use, transportation policy, cost of fuel, vehicle, and parking, and choice of technology (*16*). Particularly, urban density has been highlighted as the most influential factor affecting car use and ownership (*5*, *17*, *18*). For example, Van de Coevering and Schwanen (*4*) showed that land-use variables such as employment density and population centrality in an inner area significantly affect the modal share of public transportation. Ingram and Liu (*19*, *20*) also incorporated urban density into a car ownership model in addition to income and gasoline price.

First, these studies suggest that a holistic view is required for analyzing the development of urban transportation, particularly from a long-term perspective. This is mainly due to the interdependency among different travel modes. Second, they indicate that the socio-demographics, land-use characteristics, and transportation policies are critical for describing the trends of urban transportation in addition to prices and income. In particular, land-use patterns should be highlighted in travel demand analysis. Third, the development of urban transportation is highly path-dependent in that once a city has been locked into a local equilibrium point such as a car-dependence condition, the city could face difficulty in shifting from it (*8*).

Elasticities of Travel Demand

Although the elasticities of travel demand are rough approximations of aggregate responses, they have the great attraction of being empirically and directly usable for policy assessment (*21*). Literature reviews and meta-analyses regarding the elasticities of travel demand have been reported in land transportation (*6*, *22*, *23*), road traffic and fuel consumption (*24*, *25*, *26*, *27*), and public transportation (*28*, *29*, *30*, *31*).

Those studies suggest that first, the consideration of intermodal competition is essential especially in urban transportation where alternative travel modes are available. Public transportation demand is particularly highly sensitive to the level of car ownership (*29*, *30*). Note that some studies show evidence of asymmetrical cross-elasticities depending on the situation of intermodal competition among public transportation modes, while others point out that car use tends to be almost independent of bus and underground fares (*30*).

Second, the elasticities could change over time. Income elasticities of both fuel consumption and vehicle-km have declined over time (*22*, *24*) while fare elasticities tend to increase over time (*30*). It should be noted that most studies have used data ranging from around the 1960s. One of the exceptions is Fouquet (*32*), which analyzed income and price elasticities of passenger travel demand (passenger-km) in the UK from 1850 and showed that the elasticities have declined over time.

Third, the behavioral responses to income and/or cost changes take place over time. For example, an individual's modal choice will change in the short run, while all other behaviors may change in the long run (*25*). Goodwin et al. (*24*) showed that the long-run effect is greater than the short-run effect in both price and income elasticities of all types of travel demands.

METHODOLOGY

Urban Transportation in Tokyo

Our empirical analysis uses data collected in Tokyo. FIGURE 1 shows the historical changes in modal share in Tokyo Metropolis from 1870 to 2010. At an early stage from the modernization of Japan in the late 1860s to 1903 when (electric) trams appeared, only non-motorized modes including *jinrikishas* (human-pulled two-wheeled carts), horse-drawn buses (omnibuses), and horse-drawn trams were available as public transportation in the urban areas of Tokyo. In 1872, the first railway commenced its service in Tokyo. In the 1900s, the tram dominated in the central area; the national railway lines were electrified and started operations in the urban areas; and many private rail operators appeared in suburban areas. The basic urban rail network excluding subways in Tokyo was completed by the 1920s. The first subway commenced operations in 1927. Although the urban transportation system was seriously damaged during World War II, it quickly recovered. The subway network replaced the tram network in central Tokyo during the 1950s to 1960s when the road spaces were urgently required for car traffic. Twelve additional subway lines have been constructed to date since World War II, which are currently operated by Tokyo Metro Co. and the Tokyo Metropolitan Government. Automobiles were first introduced into Japan in 1900, but the role of private cars had been limited before the rapid motorization in the 1960s-70s. The highway network has also been developed to handle the sharp increase in traffic demand in Tokyo. The first route of the Metropolitan Expressway in Tokyo was completed in 1962, and the expressway network has been expanded to date. Finally, taxi and bus operators appeared around 1920, in particular, public-owned bus commenced operations in 1924 (*33*, *34*). Throughout the history, the transportation system and land-use patterns in Tokyo have been closely related to railway development, which is one of the most important characteristics of urban transportation development in Tokyo.

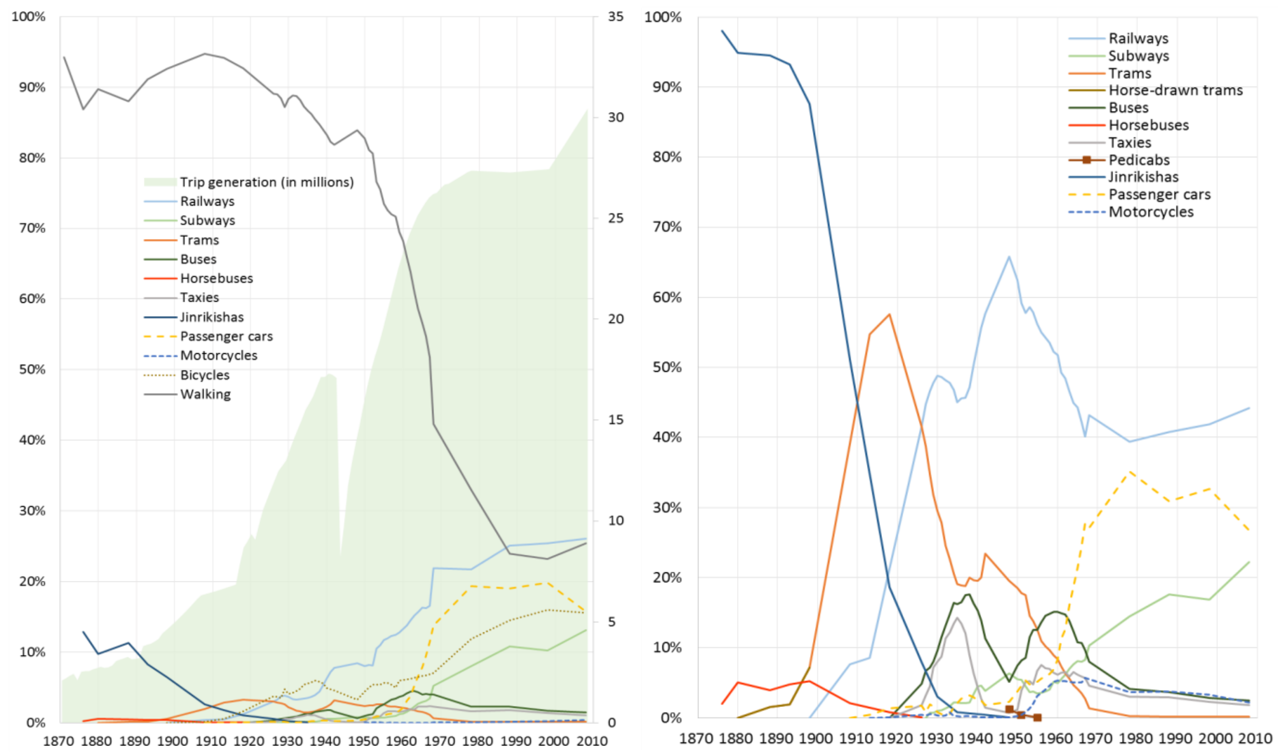

FIGURE 1 Historical changes in the modal share of urban transportation in Tokyo Metropolis.

Note: The left panel shows the modal share of linked trips, including all modes of urban transportation. The right panel shows the fractions excluding bicycles and walking.

Sources: Person-trip survey in the Tokyo metropolitan area (in 1968 and later) and our estimation (before 1968).

Data

All data used in our study are values collected in Tokyo Metropolis (Tokyo-*to*). Tokyo Metropolis is the administrative area of Tokyo and does not correspond to the Tokyo metropolitan area. The metropolitan-based statistics are unfortunately unavailable for the long run, while official statistical reports of Tokyo Metropolis are available. Note that the urban areas of Tokyo were located within the area of Tokyo Metropolis before the 1950s, but they have expanded beyond the area of Tokyo Metropolis since the 1960s. Tokyo Metropolis includes a large part of the urban area of Tokyo throughout the history. Thus, a large part of the urban activities of Tokyo is captured by our study area.

We prepare an annual-based database regarding public and private transportation as well as the socio-demographics in Tokyo Metropolis from 1870 to 2010. The empirical analysis in this study uses data only from 1920 to 2010. This is because first, almost all modes of public transportation have been available since the 1920s, and second, because the national census of Japan commenced in 1920 and since then, reliable and consistent socio-demographic data are available. Note that the data do not cover the period of 1943-1947, which is the war period, since they are not available from the statistical reports.

Two datasets are prepared. One dataset covers the period from 1960 to 2010 while the other dataset covers the period from 1920 to 2010. This is because first, the two datasets contain different qualities of data: the former dataset includes more reliable records than the latter dataset, which includes many estimated data particularly for the pre-1960 period as explained later. Second, the expected impacts of explanatory variables in the period after motorization could be different from those before motorization.

TABLE 1 summarizes the descriptive statistics of the dataset used in the study. The data include transportation performances, service levels of transportation, urban form, and socio-economics.

Transportation Performance

The transportation performances are the per capita ridership of railway, subway, tram, and bus; and car and motorbike ownership per capita. Car ownership is defined as the vehicle stock of passenger cars and four- and three-wheeled vehicles in the category of light vehicles, while motorbike ownership is defined as the vehicle stock of light two-wheeled cars plus two-wheeled vehicles in the category of light vehicles, which are motorbikes having a displacement of over 0.125 liters. Vehicles used as taxis are excluded from car ownership. Since the definition of car/motorbike classification in the statistical reports has changed over time, the ownerships in the period before 1960 for cars and in the period before 1950 for motorbikes are estimated to maintain consistency of definition for cars and motorbikes.

Service Levels of Transportation

The service level parameters of transportation are prices, transit supply, road supply, and parking supply. First, the price of public transportation services is defined as the minimal representative fare of each mode. The price of the railway services is represented as the initial charge on the JR *Yamanote* line, the price of the subway services is represented as the initial charge on the Tokyo Metro lines, and the prices of the tram and bus services are represented as the one-way fare on the *Toei* lines. Second, the price of a car is defined as the purchase cost of a new vehicle with a displacement of 1.5-2 liters (less than 1 liter before 1957) while the price of a motorbike is defined as the purchase cost of a new motorbike. Note that the above definitions of car/motorbike prices do not reflect the change in real values in the long run because these prices are not adjusted for qualities such as fuel efficiency. The variable cost of a car/motorbike is defined as the gasoline price per liter. All values regarding prices are converted to real values in the year 2005 using the consumer price index of Tokyo Metropolis. Third, the transit supply is represented by the service kilometers of public transportation in Tokyo Metropolis. The road supply is represented by the length and areas of expressways, national roads, prefectural roads, and local roads in Tokyo Metropolis. Finally, the parking supply is represented by the total number of cars able to be parked in toll parking lots with an area of over 500 m^2.

Urban Form

The urban form data include the urban areas of Tokyo Metropolis and spatial demographics. First, the urban areas of Tokyo Metropolis are defined as the built-up area of Tokyo Metropolis, which is obtained by excluding water expanses, forests, and wastelands from the total land area of Tokyo Metropolis. The data for land-use patterns are obtained from the results of official land-use surveys. These data are however not available before the 1970s. The urban areas in the period before the 1970s are estimated using existing research (35). This research shows shares of built-up areas in Tokyo from 1910 to 1970. By multiplying these by the total land area of Tokyo Metropolis, the historical urban areas are obtained.

Next, the spatial demographics are represented by four indices: (1) the population centrality of the ward area, which is defined as the ratio of the population in the ward area to the total population in Tokyo Metropolis; (2) the population centrality of the Central Business District (CBD), which is defined as the ratio of the population in the CBD (Chiyoda-*ku*, Chūō-*ku*, Minato-*ku*) to the total population; (3) the employment centrality of the ward area, which is defined as the ratio of workers employed in the ward area to the total employment in Tokyo Metropolis; and (4) the employment centrality of the CBD, which is defined as the ratio of workers employed in the CBD to the total employment. Note that the ward area is located in the central Tokyo and was the City of Tokyo before 1943.

Socio-economics

The socio-economic data include Gross Regional Product (GRP) per capita of Tokyo Metropolis (real price in the year 2005), the shares of GRP by economic sector, population, age distribution, the share of male population, average household size, the share of workers in the population aged over fifteen, the shares of workers by economic sector, and the enrollment rate in higher education. The economic sectors are primary, secondary, and tertiary industries. In addition, sub-categories of economic sectors are also used, including manufacturing, construction, transportation & communications, public utilities, wholesale & retail, commerce & finance, real estate, services, and government services. As the GRP data are available only after 1955, those in 1955 and earlier are estimated using the Gross Domestic Product. The population, age distribution, average household size, and the share of male population are obtained from the national census. As the shares of workers are available only after 1950, those in 1950 or earlier are estimated using the national data. In addition, the shares of workers by economic sector are available only after 1960, thus those in 1960 or earlier are estimated using the national data.

Others

The variables of mode-specific dummy, time trend, and year dummy are used to capture effects that are not specified. Year-dummy variables include, for example, events such as the Great Kanto earthquake in 1923, the Second World War, oil crises, and the Japanese asset price bubble and its aftermath around 1990. Year dummy variables for defined periods (e.g., 1990s and 1980s) are also used.

TABLE 1 Descriptive Statistics

Variable	Definition/unit	Mean	SD	Mean	SD
		Period: 1960-2010		Period: 1920-2010	
Transportation performance					
Ridership of public transportation					
Railway ridership	Number of passengers per capita	458.5	62.7	335.9	167.5
Subway ridership	Number of passengers per capita	171.9	62.6	106.8	93.5
Tram ridership	Number of passengers per capita	11.4	16.8	36.8	35.7
Bus ridership	Number of passengers per capita	70.0	27.7	58.1	31.5
Car ownership	Number of vehicles per 1000 population	192.4	87.5	109.2	114.8
Motorbike ownership	Number of vehicles per 1000 population	24.1	13.9	13.9	15.6
Service levels of transportation and urban form					
Prices (real prices in the year of 2005)					
Price of railway service	JPY	111.1	32.8	93.7	34.4
Price of subway service	JPY	130.3	23.0	108.7	43.8
Price of tram service	JPY	122.1	40.0	108.9	38.3
Price of bus service	JPY	150.6	46.5	138.3	45.0
Price of a new vehicle	Million JPY	1.71	0.29	2.31	1.04
Price of a new motorbike	Million JPY	0.17	0.04	0.44	0.35
Price of gasoline (per 1 liter)	JPY	156.2	39.4	192.4	77.4
Transit supply					
Service kilometers of railway	km per million population	47.1	2.6	55.6	13.8
Service kilometers of subway	km per million population	15.6	5.5	9.5	8.1
Service kilometers of tram	km per million population	5.0	8.4	17.0	15.4
Service kilometers of bus	km per million population	68.4	8.5	57.3	24.1
Road supply					
Length of expressway	m per 1000 population	14.4	6.0	8.1	8.5
Length of national road	m per 1000 population	22.1	3.1	23.0	4.2
Length of prefectural road	m per 1000 population	175.2	6.0	218.0	61.2
Length of local road	m per 1000 population	1,671.0	61.2	2,047.0	547.7
Area of expressway	m^2 per 1000 population	448.8	192.5	-	-
Area of national road	m^2 per 1000 population	516.2	122.4	-	-
Area of prefectural road	m^2 per 1000 population	2,537.0	544.3	-	-
Area of local road	m^2 per 1000 population	8,353.0	1,140.5	-	-
Parking supply	Vehicles per 1000 population	8.8	4.3	-	-
Urban form					
Urban areas in Tokyo Metropolis	km^2	880.5	195.0	573.1	383.2
Population centrality of the ward area	Share of population in the ward area out of total population	0.725	0.056	0.799	0.096

Population centrality of the CBD	Share of population in the CBD out of total population	0.030	0.009	0.067	0.051
Employment centrality of the ward area	Share of employees in the ward area out of total population	0.861	0.031	-	-
Employment centrality of the CBD	Share of employees in the CBD out of total population	0.286	0.008	-	-
Socio-economics					
Economy					
GRP per capita (real price in the year of 2005)	Million JPY per capita	4.917	2.155	3.288	2.601
Share of GRP in primary sector		0.003	0.002	0.010	0.010
Share of GRP in secondary sector		0.276	0.090	0.335	0.100
Share of GRP in tertiary sector		0.706	0.090	0.655	0.108
Population					
Population	Million persons	11.710	0.678	9.529	2.898
Share of population aged <15		0.170	0.043	0.224	0.075
Share of population aged 15-39		0.438	0.062	0.456	0.052
Share of population aged 40-64		0.289	0.054	0.243	0.066
Share of population aged 65+		0.103	0.052	0.074	0.054
Share of male population		0.504	0.005	0.510	0.010
Average household size	Persons	2.816	0.630	3.578	1.057
Employment					
Share of workers in the population aged 15+		0.602	0.034	0.596	0.030
Share of workers in primary sector		0.008	0.005	0.021	0.017
Share of workers in secondary sector		0.300	0.081	0.354	0.087
Share of workers in tertiary sector		0.673	0.066	0.617	0.087
Percentage of enrollment in higher education *	%	27.7	11.3	17.8	14.1

Note 1: Data in italic font are available only during the period of 1960-2010.
Note 2: Data are annually based in Tokyo Metropolis (Tokyo-*to*) except the data marked "*", which are the national values.
Note 3: The population used in standardization is the population of Tokyo Metropolis.

Models and Estimation Method

Two regression models are developed to represent the dynamic changes in urban transportation performance in Tokyo: one is a model to explain the ridership of public transportation (PT) and the other is to explain the ownership of cars/motorbikes. FIGURE 2 shows the hypothetical relationships among the variable sets, these being the service levels of transportation, urban form, and socio-economic variables. It is assumed that both socio-economic variables and the service levels of transportation/urban form influence transportation performance, which connections are depicted as two solid lines. Additionally a causal link from the socio-economic variables to the service levels of transportation and urban form may also be expected, which is depicted as a dotted line. This may lead to an indirect effect of socio-economic variables working through the service levels of transportation/urban form. This means that the socio-economic variables could influence transportation performance both directly and indirectly. For example, the growth of GRP per capita enables individuals to purchase new cars/motorbikes directly, while it also promotes the road supply, which may indirectly increase car ownership. Then the direct effects of socio-economic variables on transportation performance are estimated using all explanatory variables, while the total effects including both direct and indirect effects of socio-economic variables on the transportation performance are estimated using socio-economic variables only.

Most variables are trended and are not stationary. In fact, the augmented Dickey–Fuller test implies that most variables are significantly unit root processes. Regressions among the variables of unit root processes could lead to spurious regression where highly significant relationships among the variables are obtained regardless of their actual relationships. Then we take the log first difference $(\log x_t - \log x_{t-1} = \Delta \log x_t)$ for every variable x in order to transform the variables into stationary processes, and consider the following regression model: $\Delta\log y_t = \sum_i \beta_i \cdot \Delta\log x_{it} + \varepsilon_t$, where y_t is a dependent variable in the period t, x_{it} is the *i*th explanatory variable in the period t, β_i is the coefficient corresponding to x_{it}, and ε_t is an error term in the period t. The coefficients of explanatory variables are regarded as the units of elasticity.

Additionally we apply a partial adjustment model, which is one of the dynamic regression models. Here a lagged dependent variable of one period prior is used as one of the explanatory variables. The partial adjustment model assumes an adjustment equation $y_t - y_{t-1} = (1-\lambda)(y_t^* - y_{t-1})$ where the desired level of y_t is $y_t^* = \alpha + \beta x_t + \varepsilon_t$, where α, β and λ are regression parameters. By solving these equations with respect to y_t, we obtain $y_t = \alpha(1-\lambda) + \beta(1-\lambda)x_t + \lambda y_{t-1} + (1-\lambda)\varepsilon_t = \alpha' + \beta' x_t + \lambda y_{t-1} + \varepsilon_t'$. Note that the short-run effect for x_t is β' while the long-run effect is $\beta = \beta'/(1-\lambda)$. The parameters are estimated consistently and efficiently by the ordinary least squares (OLS) method (*36*).

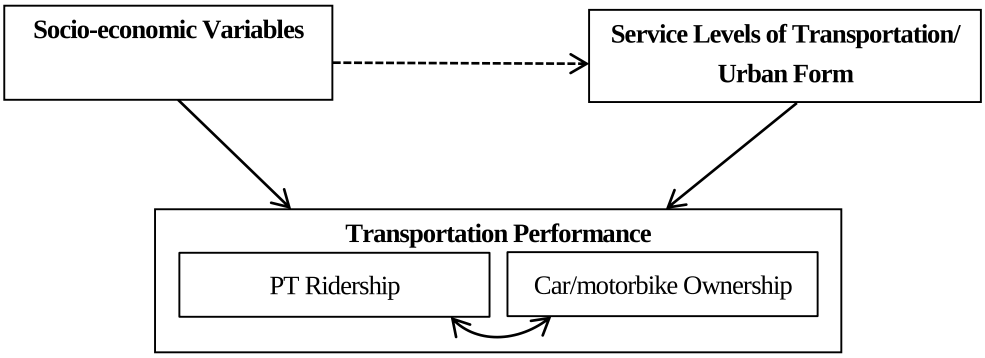

FIGURE 2 Hypothetical relationships in the proposed models.

RESULTS

Public Transportation Ridership

TABLE 2 shows the PT ridership models estimated with the dataset covering 1920-2010 and TABLE 3 shows the PT ridership models estimated with the dataset covering 1960-2010.

First, the results show that the service kilometers of PT have a significant impact on PT ridership in both models. TABLE 2 shows that the PT-service-kilometers elasticity of PT ridership is estimated to be 0.351 in the short run and 0.583 in the long run, except for trams, while TABLE 3 shows that the PT-service-kilometers elasticity of PT ridership is estimated to be 0.287 in the short run and 0.59 in the long run, except for subways. They imply that the PT-service-kilometers elasticity seems nearly constant over time. TABLE 3 also shows that the subway-service-kilometers elasticity of subway ridership is estimated to be 0.514 in the short run and 1.06 in the long run, which is much higher than for other PT modes. This may be because the direct-through connection between suburban railways and subways started in the 1960s, which in particular increased the accessibility of the subways. The service kilometers of subway per capita have rapidly increased in Tokyo for the past fifty years, which shows that Tokyo has aggressively invested in this high-elasticity transportation mode.

Second, TABLE 2 shows that the national and prefectural road length per capita has negative impacts on the ridership of railways, subways, and buses, while it has a positive impact on the ridership of trams. This is reasonable because an improved road supply enhances the service levels of private transportation, which reduces PT demand while also reducing traffic congestion on roads, which improves the service speed of trams. However, TABLE 3 shows that road supply is insignificant, which means the PT ridership has become independent of road supply since the 1960s.

Third, TABLE 2 shows that the price of gasoline has negative effects on the ridership of public transportation except for trams. This result could be counter-intuitive since a higher gasoline price reduces the benefit of car use and thus promotes PT use. One explanation for this result could be that the gasoline price reflects general operational costs in the transportation sector. This understanding is only valid in the long-run perspective since this relationship only appears in the model using a longer dataset (1920-2010). Originally, gasoline prices in Japan were high compared with other countries, since Japan is not an oil-producing country. During this period, the gasoline price has significantly decreased in real terms, which could affect operators' costs in the transportation sector as well as variable costs for car users. The service levels per fare would improve when the costs of operators decrease under fixed service kilometers, which produces a negative impact of gasoline price on ridership. In the history of Tokyo, the effect regarding operators' costs exceeds the other effects of gasoline price.

Fourth, TABLE 3 shows that an improved parking supply has strongly positive impacts on bus and tram ridership while it has minor impacts on rail and subway ridership. These positive effects could also be regarded as unexpected since improved parking supply is expected to increase the benefits of car use. Most parking places have been constructed since the Parking Act was introduced in 1957. The major impact of parking supply in this early stage of motorization is to reduce on-street parking causing traffic congestion, which benefits the bus and tram operations. After this era, parking supply does not aggressively enhance the service levels of car use. This is because the land cost in Tokyo is high compared with other cities in the world, and thus, the high parking costs offset the benefits of car use to a great extent.

Fifth, TABLE 2 shows that the price elasticity of PT ridership is estimated to be –0.099 in the short run while it is estimated to be –0.164 in the long run. TABLE 3 shows that the price elasticity is insignificant. These results mean that price elasticity has changed over time and became less elastic particularly after the 1960s.

Sixth, the estimation results also unveil the key socio-economic factors that affect PT ridership. The results show that the share of the population aged 15-39 has a positive impact on PT ridership. This is because the population aged 15-39 includes students or unmarried individuals, who prefer PT systems due to their affordability.

Finally, TABLE 2 and 3 show that the shares of workers in the financial and manufacturing industries have positive impacts on PT ridership. This is probably because business offices or factories are mainly located near PT stations, to which the employees commute typically by rail or by subway.

TABLE 2 Estimation Results of Public Transportation Models with the Dataset of 1920-2010

All variables				**Socio-economic variables only**			
Variable	**Coefficient**	**t-stat**		**Variable**	**Coefficient**	**t-stat**	
Lag of PT ridership	0.398	(9.3)	***	Lag of PT ridership	0.240	(4.8)	***
Price of PT	–0.099	(–2.3)	*	Share of population aged 15-39	2.471	(3.4)	***
Service kilometers of PT	0.351	(4.6)	***	Share of population aged 15-39*Subway dummy	–3.943	(–2.8)	**
Service kilometers of PT*Tram dummy	–0.228	(–2.5)	*	Share of employment in manufacturing industry*Subway dummy	1.866	(1.8)	
Length of national and prefectural roads	–0.543	(–2.1)	*	Share of employment in manufacturing industry*Tram dummy	1.648	(2.0)	*
Length of national and prefectural roads*Tram dummy	0.674	(1.7)		Share of GRP in construction industry	0.108	(1.6)	
Price of gasoline	–0.229	(–4.0)	***				
Price of gasoline*Tram dummy	0.421	(4.0)	***	Intercept	–0.194	(–0.2)	
Motorbike ownership	0.175	(4.0)	***	Subway dummy	3.134	(1.6)	
Share of GRP in transport & communications and public utilities industries	0.202	(2.2)	*	Tram dummy	–6.931	(–3.7)	***
(Share of GRP in transport & communications and public utilities industries)*Tram dummy	–0.266	(–1.6)		Time trend for years*Subway dummy	–0.002	(–1.6)	
				Time trend for years*Tram dummy	0.004	(3.7)	***
Intercept	–0.013	(–1.9)		Year 1923 dummy	0.172	(3.5)	***
Tram dummy	–0.023	(–2.0)	*	Year 1973 dummy*Tram dummy	0.182	(1.9)	
Year 1923 dummy	0.091	(1.6)		Year 1941 dummy	–0.178	(–3.7)	***
Year 1930s dummy	0.054	(3.5)	***	Year 1941 dummy*Tram dummy	0.355	(3.7)	***
Year 1953 dummy	–0.099	(–2.4)	*	Year 1953 dummy	–0.078	(–3.0)	**
Year 1973 dummy	0.107	(2.5)	*	Year 1953 dummy*Subway dummy	0.096	(2.1)	*
Year 1989 dummy	0.097	(2.4)	*	Year 1953 dummy*Tram dummy	–0.091	(–2.0)	*
				Year 1989 dummy	0.064	(1.5)	
Number of observations	315				315		
Durbin-Watson stat	2.177				1.973		
Adjusted R-squared	0.488				0.459		

Note 1: Dependent variable is the PT ridership (the number of passengers per capita).

Note 2: t-statistic in parentheses: *** $p<0.001$, ** $p<0.01$, * $p<0.05$.

Note 3: "*" in a variable title represents an interaction term between the two variables connected with "*".

TABLE 3 Estimation Results of Public Transportation Models with the Dataset of 1960-2010

All variables				**Socio-economic variables only**			
Variable	**Coefficient**	**t-stat**		**Variable**	**Coefficient**	**t-stat**	
Lag of PT ridership	0.513	(10.5)	***	Lag of PT ridership	0.504	(7.5)	***
Service kilometers of PT	0.287	(8.2)	***	Share of population aged 15-39	1.680	(2.3)	*
Service kilometers of PT*Subway dummy	0.227	(2.0)	*				
Parking supply	1.085	(4.3)	***	Intercept	0.008	(0.9)	

Parking supply*Rail dummy	–0.850	(–2.2)	*	Subway dummy	0.024	(2.1)	*
Parking supply*Subway dummy	–1.012	(–2.4)	*	Tram dummy	–0.030	(–2.7)	**
Share of population aged 15-39	0.741	(1.7)		Year 1973 dummy	0.029	(0.8)	
Share of employment in finance industry	0.465	(2.6)	**	Year 1973 dummy*Tram dummy	0.211	(2.7)	**
				Year 1989 dummy	0.083	(2.6)	**
Intercept	–0.038	(–4.8)	***				
Rail dummy	0.040	(3.0)	**				
Subway dummy	0.042	(2.5)	*				
First-order serial correlation	–0.601				-		
Number of observations	200				200		
Durbin-Watson stat #b	2.574		***		2.354		
Adjusted R-squared #b	0.484				0.415		

Note 1: Dependent variable is the PT ridership (the number of passengers per capita).
Note 2: t-statistic in parentheses: *** p<0.001, ** p<0.01, * p<0.05.
Note 3: "*" in a variable title represents an interaction term between the two variables connected with "*".
Note 4: The first-order serial correlation is considered using GLS when the Durbin–Watson statistic is significant; #b means that the values are obtained from the OLS model.

Car/Motorbike Ownership

TABLE 4 shows the car/motorbike ownership models estimated with the dataset covering 1920-2010 and TABLE 5 shows the car/motorbike ownership models estimated with the dataset covering 1960-2010.

First, TABLE 4 and 5 show that the service kilometers of railway have a negative impact on car/motorbike ownership. TABLE 4 shows that the service kilometers of buses also have a negative impact on car/motorbike ownership, but the service kilometers of trams have a positive impact.

Second, TABLE 4 also shows the positive impact of bus and subway ridership on car/motorbike ownership. This is probably because travelers shift from bus and subway to car/motorbike to avoid the in-vehicle congestion of PT. Note that the coefficients with respect to the bus/subway ridership represent the effects of this ridership on car/motorbike ownership under a constant capacity level for the transit system because the variables for transit supplies are included in the models.

Third, TABLE 4 shows that the population centrality of the ward area has a significantly negative impact on car/motorbike ownership. This is because suburbanization promotes car/motorbike ownership.

Fourth, GRP per capita has a significantly positive impact in both models. TABLE 4 shows that the income elasticity of car/motorbike ownership is estimated to be 0.491 in the short run and 0.687 in the long run, while TABLE 5 shows that it is estimated to be 0.196 in the short run and 0.769 in the long run. The results of TABLE 4 imply that GRP per capita has both direct and indirect effects on car/motorbike ownership, while the results of TABLE 5 imply that GRP per capita has a direct effect only. The direct effects suggest that the growth of GRP per capita increases the individual's purchasing power for cars/motorbikes while the indirect effect suggests impacts on car/motorbike ownership occurring through the service levels of transportation and/or urban form such as suburbanization and transportation investment. Thus, the overall income increase in the postwar period in Tokyo led to growth in car/motorbike ownership only through the rising purchasing power of individuals.

Finally, TABLE 4 and TABLE 5 show that the shares of workers in the secondary sector and in manufacturing industry positively affect car/motorbike ownership. As the share of workers in manufacturing industry also affects the ridership of PT in TABLE 2, employment levels in the manufacturing industry would positively affect total travel demands. One of the possible reasons for this is that the proportion of workers who have to commute to their workplaces is higher in manufacturing industries or secondary sectors than in the agriculture or services sectors.

TABLE 4 Estimation Results of Car/Motorbike Ownership with the Dataset of 1920-2010

All variables				**Socio-economic variables only**			
Variable	**Coefficient**	**t-stat**		**Variable**	**Coefficient**	**t-stat**	
Lag of car/motorbike ownership	0.285	(4.6)	***	Lag of car/motorbike ownership	0.070	(1.0)	
Service kilometers of railway	–1.162	(–2.6)	**	GRP per capita	0.930	(3.1)	**
Service kilometers of bus	–1.265	(–3.0)	**	Share of employment in secondary sector	1.634	(2.0)	*
Service kilometers of tram	0.131	(1.9)					
Population centrality in ward area	–5.547	(–1.9)		Intercept	0.043	(2.1)	
Ridership of subway	0.114	(9.4)	***	Year 1923 dummy	0.435	(3.5)	***
Ridership of bus	0.408	(3.0)	**	Year 1941 dummy	–0.249	(–2.0)	*
GRP per capita	0.491	(1.8)		Year 1948-52 dummy	0.305	(4.7)	***
				Year 1954 dummy	–0.466	(–3.2)	**
Intercept	0.002	(0.1)					
Year 1920s dummy	–0.102	(–2.2)	*				
Year 1923 dummy	0.263	(2.1)	*				
Year 1924 dummy	–0.158	(–1.4)					
Year 1940s dummy	0.448	(2.6)	*				
Year 1941 dummy	–0.784	(–3.6)	***				
Year 1948-52 dummy	0.133	(2.1)	*				
Year 1953 dummy	–0.189	(–1.9)					
Year 1954 dummy	–0.417	(–3.5)	***				
Number of observations	166				166		
Durbin-Watson stat	1.888				2.052		
Adjusted R-squared	0.589				0.290		

Note 1: Dependent variable is car/motorbike ownership (the number of vehicles per 1000 population).

Note 2: t-statistic in parentheses: *** $p<0.001$, ** $p<0.01$, * $p<0.05$.

TABLE 5 Estimation Results of Car/Motorbike Models with the Dataset of 1960-2010

All variables				**Socio-economic variables only**			
Variable	**Coefficient**	**t-stat**		**Variable**	**Coefficient**	**t-stat**	
Lag of car/motorbike ownership	0.745	(12.3)	***	Lag of car/motorbike ownership	0.666	(10.4)	***
Service kilometers of railway	–0.433	(–1.6)		GRP per capita	0.181	(1.5)	
Area of expressway	–0.015	(–6.2)	***	Share of GRP in transport & communications industry	–0.181	(–1.7)	
GRP per capita	0.196	(1.8)		Share of GRP in service industry	–0.357	(–2.5)	*
Share of GRP in real estate industry	–0.128	(–2.8)	**	Share of employment in manufacturing industry	0.983	(1.9)	
Share of GRP in service industry	–0.220	(–1.7)					
Share of employment in manufacturing industry	1.116	(2.4)	*	Intercept	0.037	(2.1)	*
				Year 1980 dummy	0.039	(1.4)	
Intercept	0.039	(2.4)	*				

Year 1960s dummy	0.016	(1.4)		
Number of observations	100		100	
Durbin-Watson stat	1.993		2.329	
Adjusted R-squared	0.799		0.731	

Note 1: Dependent variable is car/motorbike ownership (the number of vehicles per 1000 population).

Note 2: t-statistic in parentheses: *** p<0.001, ** p<0.01, * p<0.05.

CONCLUSION

This study investigated the critical factors that have affected the trends of urban transportation development in Tokyo. The direct demand models were estimated for public transportation ridership and car/motorbike ownership, using the service levels of transportation/urban form and socio-economic variables as explanatory variables. The results are summarized as follows: (1) the subway-supply elasticity of subway ridership was much higher than other-PT elasticity of PT ridership during the postwar period; (2) the road supply negatively influenced railway and subway ridership in the long run, and yet, this influence disappeared during the postwar period; (3) the parking supply had positive impacts on bus and tram ridership; (4) public transportation strongly influenced car/motorbike ownership while private transportation weakly influenced public transportation ridership; (5) the population centrality of the ward area had a negative impact on car/motorbike ownership; (6) GRP per capita had a strong impact on car/motorbike ownership; (7) the share of workers in the financial and manufacturing industries and the share of the population aged 15-39 had positive impacts on public transportation ridership; and (8) the share of workers in manufacturing industry also had a positive impact on car/motorbike ownership.

Our historical analysis unveiled the fact that subways have played an important role in Tokyo, particularly after World War II. As the development of the subway network commenced late compared with the other railway networks in Tokyo, connectivity of subways with existing rail stocks was highlighted, such as the introduction of direct-through connection services between the suburban railways and subways. Utilization of the existing stock of the PT network led to a higher performance of the subway services compared with investments in other forms of PT. This could be one of the critical reasons for the high subway-supply elasticity of subway ridership. Tokyo's approach has inspired Paris, where the collaboration between RATP and SNCF has been successfully realized using Tokyo as a reference model (*37*). The findings suggest that the enhancement of PT's impact on ridership by integrating a newly introduced PT system with existing PT networks could be a crucial factor in creating successful urban transportation markets in metropolitan areas that have a long history of transportation development.

In future research, there could be other ways of using estimation methods. Our approach is one of the available methodologies addressing time-series data. However, where there are many explanatory variables, it may not desirable to conclude that one final model is the best. A more robust methodology can be used to explore further the determinants of urban transportation development.

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