THE IMPACT OF URBAN LAYOUT ON AUTOMOBILE GASOLINE CONSUMPTION IN JAPANESE CITIES
－URBAN CONSOLIDATION BASED ON A RESIDENTIAL SCALE ANALYSIS－

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Abstract: Though a significant number of studies have already indicated that a compact urban layout is one of the most essential factors to reduce automobile usage, the statistical relationship between urban layout and automobile usage level has been analyzed only at the municipal scale. To present realistic countermeasures to reduce gasoline consumption, it is indispensable to identify the factors that affect gasoline consumption at the residential zoning scale, as most countermeasures, such as infrastructure improvement and city planning regulations, are executed at this level. This study adopted individual weekday person trip data from the National Person Trip Survey (NPTS), which included about 67,000 samples from 78 Japanese cities in 1992. Based on this data, 138 groups of residential zones are designated, and factors of gasoline consumption in each group are estimated by the multi-regression model. The results show that a compact urban layout is not the only important factor, but that there are also many other significant factors to reduce gasoline consumption, including the transportation service level, land-use regulation, conditions of infrastructure, and other compound factors.

Key Words: urban layout, automobile usage, residential development

1. INTRODUCTION

Nowadays, many metropolitan areas and cities in the world face problems in their transportation environment caused by automobiles. To protect and improve the environment, there are many kinds of TDM (Transportation Demand Management) measures in place to control urban transportation. These measures include park-and-ride, flextime commuting, and toll roads. Generally speaking, these countermeasures focus only on the transportation behavior and not on the urban layout. Though these TDM measures could be effective for specific transportation problems in each city, it is very difficult to improve the basic trend of increasing automobile usage. The most important requirement for reducing automobile traffic is to identify and control essential factors concerning the urban layout that influence the behavior of the residents.

Building a compact urban layout is the essential measure to improve the form of cities. Several studies have already indicated at the municipal scale that population density is one of the most essential factors in controlling automobile usage. Some statistical analyses have also confirmed the relationship between gasoline consumption level and factors for gasoline consumption. Though these research findings at the municipal level have given us interesting information, they are not enough to indicate real useful guides for improvement projects in urban areas. The scales of these projects are not very large, mostly under 100ha (hereafter referred to as *residential zone* size). These projects include housing complex developments and urban redevelopments. Even though each of these projects only represents a small step to improve the urban layout, their accumulation could change the situation.

This study aims to show quantitative guides for reducing automobile gasoline consumption in each type of residential zone. It is not easy to keep enough trip samples based on the same standards at the detail level of residential zones. To overcome this difficulty, this study selected 78 typical cities in Japan to find the relationship between gasoline consumption and the character of each residential zone, especially concerning factors relating to urban layout. The National Person Trip Survey (NPTS) conducted in 1992 was adopted as the trip data source. The analysis is composed of the following two parts:

1) As an urban area is composed of many different types of residential zones, it is necessary to designate an analysis unit, *Groups of Residential Zones*, for effective analysis. The character of each residential zone, such as location, population density, land-use control, transportation condition, and distance from the city center, is examined as index factors to designate groups of residential zones. Based on these groups, the relationship between urban population density and energy consumption by automobiles is clarified.
2) The relationship among factors concerning urban layout and gasoline consumption by automobiles is analyzed by a multiple regression model. The parameter of each factor for gasoline consumption is estimated. The sample unit is the residential zone defined in 1).

2. URBAN LAYOUT AND AUTOMOBILE USAGE: PREVIOUS STUDIES

The relationship between an urban layout and its transportation network was discussed by Thomson (1977) as an early stage. Though many papers and printings have encouraged a more compact urban layout for sustainable development since then, only few studies could address the real relationship between urban layout and automobile usage from a quantitative viewpoint. Newman and Kenworthy (1989) calculated the relationship between urban population density and annual gasoline consumption per capita at the municipal scale. This result shows very clearly that cities with a low density rely on automobile transportation. As urban and transportation policies need to improve the environment and reduce energy consumption, Newman and Kenworthy (1989) suggested raising urban population density. For example, they indicated that, if the urban population density in a metropolitan area could be changed from 10 persons/ha to 30 persons/ha, gasoline consumption per capita would be reduced by half. Hayashi (1995), Naess (1996), and Roo (2000) also conducted studies to investigate the relationship between urban layout and transportation, and their findings have shed new light on the improvement of the urban layout.

Not only population density but also other factors of gasoline consumption at the municipal scale have been statistically examined by Taniguchi, Murakawa, and Morita (1999). This research has quantitatively clarified the influence of many factors, such as public transportation service level, historical background, and geographical conditions. These research findings have made it clear that it is indispensable to control urban layout to reduce gasoline consumption. Meanwhile, countermeasures that could be obtained from these findings, such as increasing municipal population density three times, appear to be unrealistic alternatives. It would not be easy to utilize these findings to improve the real urban layout, as large-size whole urban layouts, like those at the municipal scale, are difficult to control. To achieve an environmentally friendly urban layout, it is more realistic to control small-size residential developments, as the total urban layout is the accumulated result from each small residential development.

3. THE DATA AND CITIES

In Japan, Metropolitan Person Trip Surveys (MPTS) have been conducted in major cities and metropolitan areas for the past three decades at different times. Though they provide rich information for creating a transportation plan for each metropolitan area, they are not appropriate to utilize for this study. This study requires trip data from many cities based on the same standard and the same survey period. As a result, trip data from the NPTS (National Person Trip Survey) is preferable to the usual MPTS for this study.

NPTSs have been conducted three times so far by the Ministry of Construction of Japan. The first survey was conducted in 1987 in 131 cities, the second survey was conducted in 1992 in 78 cities, and the third survey was in 1999 in 98 cities. To estimate gasoline consumption by each trip maker, it is necessary to use the data of velocity and trip distance by each automobile trip. This study adopts 1992 data for analysis, not the latest 1999

data, as the 1999 survey does not always include this information in several cities. Sample cities of NPTS were selected to cover cities of a variety of types. Specifically, the following three points were considered:
a) The population size of the city,
b) the population size of the metropolitan area that the city belongs to, and
c) the location (e.g., center or periphery) of that city in the metropolitan area.
The NPTS survey was composed of two sheets for each household. One was the questionnaire for the household attributes, and the other was the questionnaire for trips undertaken by each family member. The NPTS also includes questions about the possibility of automobile usage for each family member.

Each sample city distributed questionnaires to at least 360 households. During the 1992 survey, the total number of distributed household questionnaires was 29,502, and that of personal questionnaires was 80,997. Investigators visited all the selected households to distribute and collect the questionnaires. The collected household and personal questionnaires numbered 25,009 and 67,067, respectively. The effective personal return rate was 82.8%. It is statistically guaranteed that this collection rate is large enough to reproduce basic transportation characteristics such as average trip length in each city. This means that errors in the estimation values have already examined to be small enough (Ministry of Construction 1993).

Urban areas in Japan are controlled by city planning laws and are designated *Urban Planning Areas*. Household samples in the NPTS were selected from the Urban Planning Area in each city. As some cities have large non-built-up areas such as mountain regions outside of the Urban Planning Area, an analysis based on the Urban Planning Area gives us more accurate, unbiased results. Based on this, 6 out of 78 cities were excluded from the following analysis, and 72 cities were then adopted for following analysis.

The strong points of the NPTS data are that the data covers many cities using the same survey standards and the same survey period. On the other hand, data from the NPTS also has a few weak points, as follows.
1) Though NPTS data includes what kinds of journeys (e.g., automobile, foot, train, etc.) compose each mixed-mode (e.g., combination) trip, it does not cover information concerning the required time and distance of each journey (e.g., the leg of the trip) on each trip.
2) NPTS data does not include information about the origin and destination of each trip.
3) As NPTS is a survey for only passenger trips, it does not include commodity flow.
4) It is impossible to discriminate between gasoline automobile trips and diesel automobile trips. This study assumes that all automobile trips require the use of gasoline for simplification. (For example, diesel automobile usage in the Tokyo metropolitan government area shares about 20% of the total car usage. As most diesel vehicles are motor trucks used for the transportation of goods, the share of diesel automobiles for this person-trip study must be much lower.)

4. ESTIMATION OF GASOLINE CONSUMPTION AND DESIGNATION OF GROUPS OF RESIDENTIAL ZONES

To estimate accurate gasoline consumption per capita in each residential zone, an adjustment calculation is executed to determine the section of a trip when an automobile was used (automobile journey) during trips of more than one mode (mixed-mode or mixed-automobile trips). As mentioned above, though the NPTS provides very good quality trip data based on the same conditions, it does not cover information concerning the required time and distance of each journey that composes each mixed-mode trip. In other words, if a leg of that trip included using an automobile, it did not mean that that was the only mode used. In other words, it is necessary to extract the real distance and time spent in an automobile on each mixed automobile trip.

This study adopts the extraction method that was introduced by Taniguchi, Murakawa, and Morita (1999). When the trip is composed of a trip by automobile and on foot, the distance and time required by the automobile journey are estimated by using simultaneous equations in which the unknown variables are distance of automobile journey and distance of walking journey of each mixed automobile trip. 99.3% of all mixed automobile trips are covered by this method to extract the estimated real distance and time spent in an automobile.

After the distance and the time spent in an automobile have been clarified, the quantity of gasoline consumption of each trip is estimated using the following equation (Kaneyasu and Kanaizumi 1972). x is calculated from the trip distance and time required, which were obtained from the NPTS.

$$q_{[cc/km]} = 0.290x_{[s/km]} + 49.3 \qquad \cdots\cdots(1)$$

x : (vehicle speed)$^{-1}$

Meanwhile, as the total number of residential zones in NPTS is as high as 1,996, it is necessary to designate *Groups of Residential Zones* for effective analysis. The character of each residential zone, such as the location, population density, land-use control, transportation condition, and distance from the city center, is examined as index factors to designate groups of residential zones. **Table 1** shows the detail of items and categories of these factors. Consequently, 138 groups of residential zones are designated, and each of them indicates a variety of trip patterns by resident in each area.

Figure 1 shows the relationship between population density and gasoline consumption in each municipality. In a residential zone scale, **Figure 2** shows the relationship between population density and gasoline consumption. As seen in this figure, population density is also a very important factor in explaining gasoline consumption in Japanese residential zones. As this study considers only personal automobile journeys, it is necessary to notice that the calculated gasoline consumption volume at each zone tends to be lower than the true value. It can be concluded that, if the figure focused on population density, the distribution pattern of residential zones in this figure could resemble the result by Newman and Kenworthy (1989) and **Figure 1**.

5. Methods and Results of the Model Analysis

On the other hand, **Figure 2** also indicates that the population density is not the only factor to explain gasoline consumption in each residential zone. If we look at zones where the population density is around 30 persons/ha, their gasoline consumption levels range from 500cc to 1300cc. To uncover the influence of other factors on gasoline consumption, it is necessary to introduce the multiple regression analysis for these 138 residential zones.

The dependent variable (Y) of the regression model is gasoline consumption per capita. Several types of regression equations have been tested, and the following linear type model has the best fit and simplest type of all:

$$Y = a_1X_1 + a_2X_2 + \cdots a_nX_n + b \qquad \cdots\cdots(2)$$

To build this model, as many explanatory variables as possible were examined relating to urban layout, land use intensity, infrastructure condition, and transportation condition. The explanatory variables finally adopted after checking to avoid multicollinearity are shown in **Table 2**. The existence of a spurious correlation between per capita gasoline consumption and population density is not assumed in this study, as total gasoline consumption in each zone was not restricted. The parameters and t-values in **Table 3** show a clear image of the relationship between urban layout concerning residential zone development and automobile energy consumption, as follows:

1) In spite of other factors that are taken into consideration, population density is still the most significant factor in explaining gasoline consumption by automobile per capita in each residential zone.
2) If the residential zone is located closer to the city center, gasoline consumption rate decreases. Distance form

Table 1 Characters of a Residential Zone for Grouping of Residential Zones

Items	Categories		
City Type	Central City in Metropolitan Area (CCMA)		
	Satellite City in Metropolitan Area (SCMA)		
	Central City in Local Area (CCLA)		
	Local City in Local Area (LCLA)		
Land Use	Urbanization Control Area Type	Urbanization Control Area	25%～50%
			50%～75%
			75%～
	Residential Type	Low-height Residential District Use	90%～
			60%～90%
		High and Medium-height Residential District Use	90%～
			60%～90%
		General Residential District Use	60%～
	Commercial Type	Neighborhood Commercial District Use	60%～
		Commercial District Use	60%～
	Industrial Type	Light Industrial District Use	60%～
		Industrial and Exclusive Industrial District Use	60%～
	Residential-Commercial Mixed Type (Residential Type: 60%～80%)		
	Mixed Use Type	Mixed-Use Residential (Largest: Residential-Type District)	
		Mixed-Use Commercial (Largest: Commercial-Type District)	
		Mixed-Use Industrial (Largest: Industrial-Type District)	
Population Density	～50 (persons/ha)		
	50～100		
	100～150		
	150～		
Transportation Conditions	Distance to the Nearest Station	Near: ～1km	
		Far: 1km～	
	Frequency of Train Service at the Nearest Station per day	～114	
		114～	
Distance from the City Center	～1.6km		
	1.6km～5km		
	5km～		

city center, which translates exactly into compact residential development, is then found to be very significant. This means that the execution of the infill type development is an effective countermeasure to reduce gasoline consumption.

3) Railway-convenient zones in the local area have been found to discourage automobile usage. On the contrary, Railway-inconvenient zones in a satellite city in the metropolitan area have been found to encourage automobile usage.

4) The city type that each residential zone belongs to also affects the gasoline consumption rate significantly. Especially, if the residential zone is located in the local area, gasoline consumption increases considerably.

5) Residential zoning and neighborhood commercial zoning tend to increase gasoline consumption.

6) Compound factors occupy a very important place in this model. They show not only the limitation of the

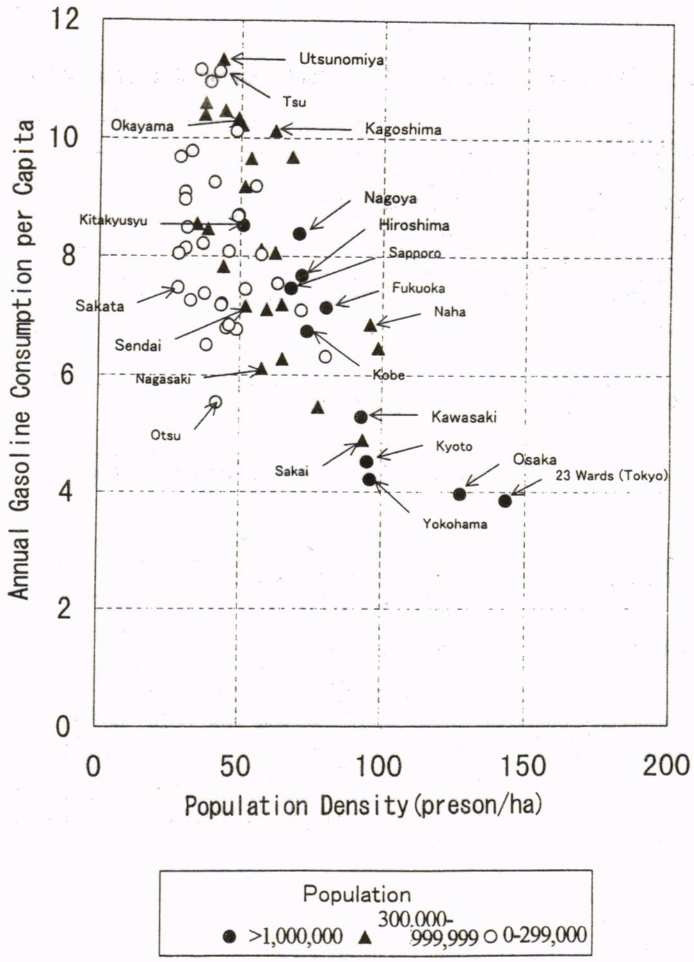

Figure.1 Population Density versus Gasoline Consumption per Capita (Municipal Scale, 1992)

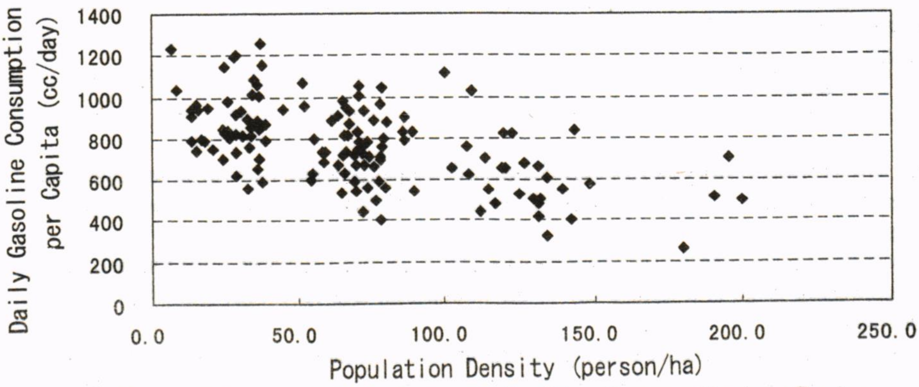

Figure.2 Population Density versus Gasoline Consumption per Capita (138 Groups of Residential Zone Scale, 1992)

Table 2 Definition of Each Variable

Explanatory Variables		Definition
Population	Population Density	Persons/ha
Location	Distance* from City Center	Km
Transportation Conditions	Distance* from Bus Stop	Distance between the center of the zone and the nearest bus stop (km)
	Satellite City in Metropolitan Area: Railway-Inconvenient	Dummy: Distance* to the nearest railway station is more than 2km, or train service at nearest station is less than 260 services per day
	Central City in Local Area: Railway-Convenient	Dummy: Train service at nearest station is more than 160 services per day
	Local City in Local Area: Railway-Convenient	Dummy: Distance* to the nearest railway station is less than 2km, and train service at nearest station is more than 90 services per day
City Type	Central City in Metropolitan Area	Dummy: Cities designated by ordinance or cities with more than one million population
	Central City in Local Area	Dummy: Prefectural capitals and cities with a population of more than 150 thousand
	Local City in Local Area	Dummy: Local cities with a population of less than 150 thousand (excluding prefectural capitals)
Land Use	Residential Zoning	Dummy: Zones in which more than 60% is assigned to residential use
	Neighborhood Commercial Zoning	Dummy: Zones in which neighborhood commercial use exceeds 60%
	Light Industrial Zoning	Dummy: Zones in which light industrial use district exceeds 60%
	Industrial Zoning	Dummy: Zones in which industrial district use exceeds 60%
Compound Factors	LCLA + Large Urbanization Control Area	Dummy: Zones at LCLA in which the urbanization control area covers more than 50%
	CCMA or CCLR + Urbanization Control Area	Dummy: Zones at central cities in which the urbanization control area covers between 25% and 50%
	Local Area + Urbanization Control Area	Dummy: Zones at the local area in which the urbanization control area covers between 25% and 50%
	Adjoining Station + High and Medium-height Residential Zoning	Dummy: Zones adjoining the railway station in which high and medium-height residential district use exceeds 60%
	Metropolitan Area + Mixed-Use Residential Zoning	Dummy: Zones at the metropolitan area, with high population density, and mixed-use residential zoning
	Non CCMA + Mixed-Use Residential Zoning	Dummy: Mixed-use residential zoning (excluding Metropolitan Area + Mixed-Use Residential Zoning)
	Metropolitan Area + Low-height Residential Zoning	Dummy: Zones at the metropolitan area in which low-height residential district use exceeds 90%
	Local Area + Low-height Residential Zoning	Dummy: Zones at the local area in which low-height residential district use exceeds 60%
	Metropolitan Area + Adjoining Station + Low-height Residential Zoning	Dummy: Zones at the metropolitan area adjoining the railway station in which low-height residential district use exceeds 60%

*) All distances are measured from the center of each residential zone

Table 3 Factors that Affect Gasoline Consumption on a Residential Zone Level

Explanatory Variables		Standardized Parameter	t value
Population	Population Density	-0.392	-5.26
Location	Distance from City Center	0.299	3.48
Transportation Conditions	Distance from Bus Stop	0.125	2.13
	Satellite City in Metropolitan Area: Railway-Inconvenient	0.156	2.43
	Central City in Local Area: Railway-Convenient	-0.107	-1.82
	Local City in Local Area: Railway-Convenient	-0.085	-1.46
City Type	Central City in Metropolitan Area	-0.177	-2.21
	Central City in Local Area	0.336	4.41
	Local City in Local Area	0.284	3.16
Land Use	Residential Zoning	0.373	4.38
	Neighborhood Commercial Zoning	0.266	4.49
	Light Industrial Zoning	0.168	2.33
	Industrial Zoning	-0.222	-3.30
Compound Factors	LCLA + Large Urbanization Control Area	0.152	2.47
	CCMA or CCLR + Urbanization Control Area	-0.100	-1.62
	Local Area + Urbanization Control Area	0.154	2.66
	Adjoining Station + High and Medium-height Residential Zoning	-0.109	-1.89
	Metropolitan Area + Mixed-Use Residential Zoning	-0.103	-0.96
	Non CCMA + Mixed-Use Residential Zoning	0.185	3.15
	Metropolitan Area + Low-height Residential Zoning	-0.169	-3.06
	Local Area + Low-height Residential Zoning	0.130	2.40
	Metropolitan Area + Adjoining Station + Low-height Residential Zoning	-0.196	-3.63
Segment			8.65
Adjusted R^2		0.652	

policy but also the possibilities of the combination of different policies.

7) For example, mixed-use residential zoning is a very interesting factor. In a metropolitan area, mixed-use residential zoning shows a minus parameter. On the contrary, in a non-metropolitan area, mixed-use residential zoning indicates a plus parameter. These results show that the popular idea that mixed use is desirable for transportation environment is not always true, especially outside the metropolitan area.

8) If some types of residential zones adjoin the railway station, gasoline consumption becomes much less. This is also a typical example of compound effects.

9) Agglomeration of low-height residences shows a different effect between the metropolitan area and the local area. In the case of the local area, exclusive agglomeration of low-height residences tends to increase gasoline consumption.

The adjusted R^2 of this model is greater than 0.65, and the performance of the parameters is also satisfactory.

It is interesting to compare these findings with findings by Newman and Kenworthy (1989). First, it is important to notice that it is impossible to execute a side-by-side comparison, as this study is a residential-scale analysis aiming to improve a real project, and the former study was a metropolitan-scale analysis. The most important difference is that this study could provide new information, namely, that urban density is not the only factor to influence gasoline consumption. As previously explained, it is newly clarified that many factors concerning urban layout in the residential zone scale have significant influence on gasoline consumption. If we consider urban consolidation to reduce gasoline consumption, these factors must also be considered.

6. CONCLUSION

Based on the processed and adjusted National Person Trip Survey (NPTS) in Japan, this study clarified the relationship between gasoline consumption by automobiles and urban layout by calibrating a multiple regression model at the scale of the residential zone. The findings of this research are as follows:

1) The result of this study shows that gasoline consumption by automobile could be well controlled by improving many kinds of characters at each residential zone.
2) This research investigates the quantitative effects of many factors on gasoline consumption at the residential zone scale for the first time. Land-use regulation, transportation condition, and infrastructure conditions are included in those factors. The effect on gasoline consumption of infill-type residential development is also confirmed.
3) Though a compact urban layout, namely, intensity land-use and infill development, is clarified to be a significant factor in explaining gasoline consumption at each residential zone, it is found that many other factors also have a very important influence. Especially, it is found that a combination of certain countermeasures must be very effective.
4) It is clarified that some factors show compound effects. In other words, 1 plus 1 becomes more than 2. The typical example is the case of a railway station, which falls on high and medium-height residential zoning. In this respect, it is also important to consider combining countermeasures.
5) On the other hand, it is proved that some countermeasures that had been believed to be effective for the reduction of gasoline consumption are not always true any more. For example, though mixed land-use had been believed to be effective to reduce gasoline consumption, the result shows that this is true only in metropolitan areas.

For further study, it is necessary to arrange these research findings into real guidelines for residential area development, like PPG13 in England (Department of the Environment and Department of Transport 1994). Developers of residential areas and decision makers should be required to refer to this guideline. It is also important that the time series data and the holiday data be added to this analysis.

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