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The Relationship Between Population Aging and Travel Demand: Evidence from Taiwan

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***Abstract*— This study employed a recursive mixed-process model to analyze how sociodemographic characteristics affected household transportation expenditures and car ownership in Taiwan. Transportation expenditures were segmented into those for private vehicle use and those for public transport services. Data on households were sourced from Taiwan's Family Income and Expenditure Survey for the years 2002 and 2022. The principal findings were as follows. First, household travel demand varied by household life cycle stage, with middle-aged households exhibiting the highest travel demand. Older households also exhibited substantial travel demand and had higher transportation expenditures and car ownership rates than households headed by individuals under 29 years old did. A finding of increased mobility among households headed by older adults reflected longer life expectancy, improved health, and greater wealth. Second, household composition considerably affected transportation expenditures and car ownership. For example, additional family members were typically associated with increased transportation expenditures. However, additional members aged 14 years or younger were associated with reduced public transportation expenditures because private vehicles often replaced public transit because they were used for caregiving and delivery. By contrast, additional older family members (aged 65 years or older) were associated with reduced private transportation expenditures and increased public transportation expenditures, reflecting older individuals' limited wealth and the high costs of private vehicle use. These results clarify the determinants of transportation expenditures and highlight the characteristics of Taiwanese households reliant on private vehicles. As family structures change and population aging continues, age-friendly public transportation systems should be prioritized in the development of transportation.**

***Keywords*— Car Ownership, Transportation Expenditures, Population Aging, Travel Demand**

I. INTRODUCTION

Advances in medicine and economic growth have increased human life expectancy, resulting in an increasing population of older individuals in numerous countries. For older individuals, maintaining mobility is essential to independence and well-being in later life (Luiu, Tight, & Burrow, 2018). Older individuals' physical and psychological health are closely linked to the accessibility of public transportation and the use of private vehicles (Crotti, Maggi, Pantelaki, & Rossi, 2021). The accessibility of transportation infrastructure shapes residential choices and enhances a location's relative appeal (Vulevic, A., 2016). Taiwan, like many developed countries, is facing the challenges of a rapidly aging population. Taiwan's population aged over 65 years is projected to exceed 20% by 2025, marking Taiwan's transition into a super-aged society. By 2040, older individuals are expected to constitute 30.6% of Taiwan's population (National Development Council, 2022). Additionally, in 2023, 26% of Taiwanese households were headed by individuals aged 65 and older (Directorate-General of Budget, Accounting and Statistics, Executive Yuan, 2023). In terms of regional development, Taiwan's population is unevenly distributed, with 80% concentrated in the six metropolitan municipalities and the remaining 20% residing in rural areas. Rural areas have relatively limited access to public transportation compared to urban areas. Consequently, Taiwan urgently requires strategies that address population aging, create aging-friendly environments, and meet diverse travel needs. However, Musselwhite (2018) noted that transportation policies often prioritize meeting the needs of businesses and working populations and neglect older individuals by failing to consider age when these policies are developed. Examining the associations among population aging, household transportation expenditures, and car ownership is crucial to understanding travel behavior in an aging society.

The literature has reported substantial differences between older and younger individuals' travel behaviors. Nevertheless, the findings of studies examining older individuals' travel demands and choices

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regarding modes of transportation vary. For example, Donaghy et al. (2004) observed changes in travel behavior in older individuals, and they reported that the mobility of older adults has generally increased because of global trends toward increased income, improved health, and diversified lifestyles. The population of older drivers has also increased globally, indicating reduced reliance on public transportation and increased dependence on cars. By contrast, research has suggested that older individuals travel less frequently and less far from their residences than younger individuals do (Collia, Sharp, & Giesbrecht, 2003). Bocker et al. (2017) and Yang et al. (2018) have also reported that older individuals travel less often and closer to their homes than younger individuals do. Bocker et al. (2017) analyzed data from the Netherlands and discovered that older individuals engaged in fewer trips, used cars less frequently, and walked more than younger individuals did. Yang et al. (2018) examined older individuals' travel time, distance, and frequency in the Netherlands, uncovering reductions in these metrics with age, with the notable exception of travel time, which increased with age. Their study also revealed that older individuals traveled more by car than by other modes of transportation. Additionally, Mariotti et al. (2018) discovered that Italians aged 60–69 years were more likely than those aged 70 and older to use buses instead of cars. Moreover, Metz (2012) analyzed the declining car demand in the United Kingdom, attributing this trend to population aging, higher costs that discouraged obtaining driver's licenses, and transportation policies that discourage car use by individuals instead of groups. These findings show that older adults' transportation needs are shaped by diverse factors, such as urban–rural context, lifestyle, travel purpose, health, and demographics, highlighting the heterogeneity in the travel behavior of older individuals.

The literature indicates that developing age-friendly transportation infrastructure can reduce reliance on private transportation and promote sustainable transportation for older individuals (Yang et al., 2018; Hou, 2019; Du et al., 2020). For example, Zhang et al. (2018) investigated urban–rural differences in public transportation use among older individuals in China and revealed that adequate public transportation services and accessible environments near bus stops encouraged public transportation use. Additionally, Shaer and Haghshenas (2021) observed transportation use among older individuals in Iran after the outbreak of the covid-19 pandemic in 2020, with their results indicating that improving bike path systems reduced car use and led to an increase in the use of bicycles as alternatives when public transportation was unavailable. Moreover, Ven den Berg et al. (2016) studied the effects of travel mobility and environmental factors on loneliness among older individuals, demonstrating that utilizing diverse transportation modes mitigated feelings of loneliness and alienation. Cheng et al. (2019) highlighted the importance of active travel to maintaining mobility and well-being among older individuals, noting that the accessibility of an environment influences these individuals' travel behavior more than that of younger people. Akanmu et al. (2022) evidenced that transportation infrastructure significantly affected the livability of cities. The need for transportation infrastructure has been rising in parallel with growing wealth and evolving lifestyles. Studies have also suggested that a lack of transportation alternatives and inadequate public transportation systems may increase dependence on private vehicles. Hence, a well-developed and diverse transportation system may considerably influence transportation mode choices and satisfaction with mobility among older individuals.

To project trends in older individuals' travel demand and transportation mode choices, the determinants of travel consumption decisions in older households must be understood. Studies such as Hong et al. (1999), Jang and Ham (2009), and Ahn et al. (2020) have analyzed the factors influencing such households' travel-related expenditures, with a primary focus on travel or leisure expenditures. Nevertheless, few studies have addressed the determinants of transportation expenditures in such households. Anowar et al. (2018) defined transportation expenditures as the costs of vehicles, fuel, insurance, maintenance, public transportation, tolls, and recreational transportation. Additionally, Bak and Szczecinska (2021) noted that transportation expenditures typically decrease as households progress through the later stages of their life cycles and household heads age.

Studies have also identified sociodemographic characteristics (Bergantino, 1997; Ferdous et al., 2010), economic factors (Bergantino, 1997; Thakuriah, & Liao, 2006), and vehicle ownership (Choo et al., 2007; Thakuriah, & Liao, 2005) as factors influencing household transportation expenditures. Other studies, such

as Aigner-Walder and Doring (2017), Bardazzi and Pazienza (2018), and Travassos et al. (2021), have addressed transportation expenditures in older households. Aigner-Walder and Doring (2017) reported a gradual reduction in transportation expenditures among households of retired individuals in European Union countries. Nevertheless, the current generation of older individuals spends more on transportation than previous generations did because of changes in preferences, lifestyles, and technologies. Bardazzi and Pazienza (2018) examined aging-related changes in household transportation fuel expenditures in Italy, discovering that baby boomers (individuals born between 1946 and 1964) spend more on fuel than other groups do and rely heavily on private vehicles to meet their mobility needs. Finally, Travassos et al. (2021) demonstrated that in Brazil, transportation expenditures accounted for 9.5% of total expenditures for older households, with this percentage being 15.3% for younger households. However, older households also had low expenditure and high price elasticity for transportation, indicating a need for affordable transportation. The findings of these studies indicate that age substantially affects households' transportation budgets.

This study aims to use household data from Taiwan's 2002 and 2022 Family Income and Expenditure Surveys to examine how life cycle transitions and population aging affect transportation spending and car ownership. A recursive mixed-process model addressed endogeneity of car ownership, revealing changes in demographics, expenditures, and car ownership over time. The current study contributes to the literature on travel demand in three respects. First, although numerous studies have examined the determinants of travel, few examine how sociodemographic factors affect household transportation expenditure. This study fills that gap by analyzing these effects through life cycle stages and household composition. Second, studies typically treat household car ownership and transportation spending as separate decisions, estimating them with single equations. This study addresses the endogeneity of car ownership by using simultaneous equations to model both decisions. Third, few studies compare factors affecting public and private transportation expenditures. The current study explored differences in household spending on public transportation versus private vehicle use. Therefore, this study can provide the policy maker with insights to assess the relationship between demographic transitions and travel demand, and to understand how to meet the mobility needs of different age groups.

II. Methods and Data

Car ownership is a key factor influencing household transportation expenditures (Choo et al., 2007; Thakuriah, & Liao, 2005). However, studies on travel behavior or transportation expenditures often neglect to consider the endogeneity of private vehicle ownership. In this context, endogeneity arises when unobservable factors affect both transportation expenditures and car ownership, and it has potential to lead to biased estimates. This study used a recursive mixed-process model with an instrumental variable to analyze the associations among transportation expenditures, car ownership, and sociodemographic factors to address endogeneity and self-selection bias. The following section details the empirical methods and data that were employed.

A. *Recursive mixed-process model*

Household transportation expenditures are a continuous variable, whereas car ownership is a discrete variable. In the model employed in this study, a system of simultaneous equations combining linear and nonlinear components—that is, a recursive mixed-process model— was applied. This model comprised two equations. The first estimated car ownership (owning at least one car versus not owning a car). A probit model was used to represent the Equation (1) for car ownership as follows:

$$AUTO_i^* = X_i\theta_i + Z_i\gamma_i + \varepsilon_{i,auto} \quad \varepsilon_i \backsim N(0,\sigma^2) \tag{1}$$

$$AUTO_i^* = 1 \;\; if \;\; AUTO_i > 0$$

$$AUTO_i^* = 0 \;\; if \;\; AUTO_i \leq 0$$

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where $AUTO_i^*$ represents the unobserved variable for car ownership, $AUTO_i$ is the observed variable for car ownership, and *I* = 1, 2, ..., *n*. *n* is the number of observations. Z_i is the instrumental variable, which is associated with car ownership but does not influence transportation expenditures; X_i is the vector of the explanatory variables; θ_i and γ_i are the vectors of the estimated coefficients; and $\varepsilon_{i,auto}$ is the error term.

The second equation estimated transportation expenditures. This Equation (2) can be expressed as follows:

$$E_i^* = X_i\beta_i + AUTO_i\delta_i + \varepsilon_{i,E} \quad (2)$$

where $E_i^*$is the latent variable of transportation expenditures, β_i and δ_i are the vectors of the estimated coefficients, and $\varepsilon_{i,E}$ is the error term. The estimation of the model simultaneously involved both linear and nonlinear equations. The parameters were obtained using the maximum likelihood estimation method (Roodman, 2011), and the model's goodness of fit was assessed using the likelihood ratio test (Gould et al., 2011). However, there is still limited literature applying the recursive mixed-process model in the field of transportation. Crotti et al. (2021) used the recursive mixed-process model to explore the influence of public transportation and car use on health, adopting a similar strategy to address endogeneity problems. Zimmermann et al. (2018) employed a mixed recursive logit model to analyzing activity-travel scheduling decisions. Besides, in the field of household well-being, Mboko Ibara and Ikiemi (2021) utilized the mixed-process model to analyze how functional literacy affects the living standard of households and the household head's type of employment in Congo.

The advantages of the recursive mixed-process model are handling multiple types of outcome variables simultaneously, allowing for correlated disturbances across equations, and supporting recursive causal chains. However, the application of this model is based on the assumption that a variable that appears as a regressor in one equation is endogenous. Although the literature showed that car ownership would be possibly affect household transportation expenditures (Choo et al., 2007; Thakuriah, & Liao, 2005), a test for the endogeneity of car ownership is required before estimating the recursive mixed-process model. Specifically, the Durbin–Wu–Hausman test was used to assess the endogeneity of car ownership (Davidson, & MacKinnon, 1993). We estimated the following Equations (3) and (4):

$$AUTO_i^* = X_i\varphi_i + v_i \quad (3)$$

$$E_i^* = X_i\pi_i + AUTO_i\sigma_i + \rho\widehat{v_i} + u_i \quad (4)$$

The first step involved estimating Equation (3) and obtaining the estimated residual $\widehat{v_i}$. In the second step, the estimated residual $\widehat{v_i}$ was included as a regressor, and Equation (4) was estimated. If the null hypothesis that the estimated coefficient ρ is 0 is rejected, the endogeneity of car ownership is supported. Once the endogeneity of car ownership is verified, the estimation of a recursive mixed-process model would be suitable. If the endogeneity of car ownership does not exist, whether a household owns a car and its transportation expenditures should be considered as independent decisions; therefore, each should be separately estimated using a single equation. The key steps of the model estimation can be shown in Figure 1.

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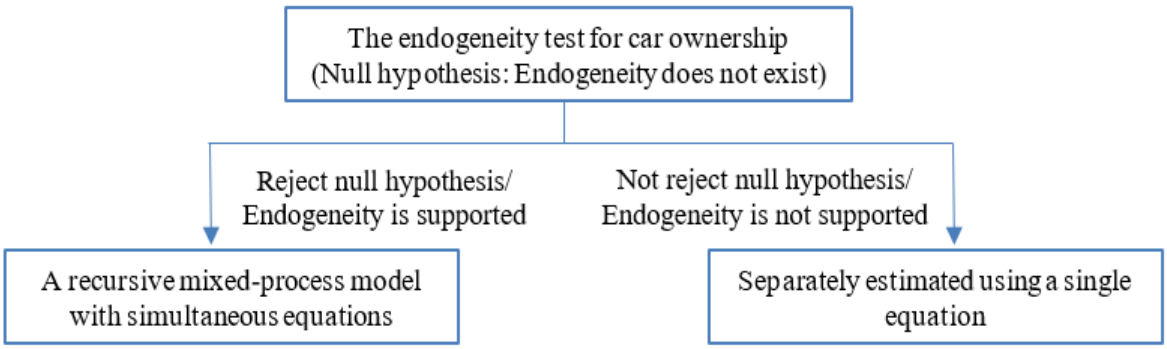

Figure 1. The key steps of the model estimation

B. *Data*

This study examined how sociodemographic factors influenced household transportation expenditures and car ownership over time by using data from Taiwan's Family Income and Expenditure Survey for the years 2002 and 2022 (Directorate-General of Budget, Accounting and Statistics, Executive Yuan, 2023; Directorate-General of Budget, Accounting and Statistics, Executive Yuan (2004). This is nationwide cross-sectional survey, conducted annually by the Taiwanese government. The data are publicly accessible and can be requested by researchers for academic research purposes. In this study, the sample involved 13,677 households in 2002 and 16,520 in 2022. The survey collected household-level data on demographic characteristics, property, facilities, income, and expenditures. The household property data included the number of cars and motorcycles owned and household transportation expenditures.

The Family Income and Expenditure Survey segments transportation expenditures into private vehicle purchases, private vehicle use, and public transportation use. Because vehicle purchases occur irregularly, this study excluded them from calculations of transportation expenditures. Hence, our analysis focused solely on private vehicle and public transportation use. The private vehicle expenditures comprised fuel, maintenance, and insurance costs. The public transportation expenditures comprised fares for buses, railways, and metro systems.

The explanatory variables were segmented into head-of-household characteristics, household demographic characteristics, and economic factors. The head-of-household characteristics comprised age, gender, education level, and marital status. According to the literature, age, gender, education level, and marital status are key socio-demographic factors influencing older adults' participation in out-of-home activities (Spinney et al., 2020; Kim & Kim, 2020). Age was treated as a categorical variable across the following five groups: under 29 years, 30–39 years, 40–49 years, 50–64 years, and 65 years and older, with each represented by a dummy variable. Other studies have similarly used the age of a household's head to capture household life cycle stages and generational effects (Vulevic, 2016; Zhang et al., 2018; Hong et al., 1999). Nevertheless, definitions of older individuals in the literature often vary, with some studies using 55 years and older (kim & Kim, 2020; Moschis, 2003), others 60 years (Crotti et al., 2021; Du et al., 2020), and the World Health Organization defining older individuals as those 65 years and older (Spinney et al., 2020; Peterson, 2001). The present study defined individuals aged 65 and older as "older individuals" and households headed by these individuals as "older households". Gender was represented by a dummy variable equal to 1 if the household head was male and 0 if not. Education level was assessed on the basis of the highest degree obtained by the household head and was segmented across the following four dummy variables: below junior high school, junior high school, senior high school, and bachelor's or graduate degree. Marital status was represented using a dummy variable equal to 1 if the household head was married and 0 if not.

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The household demographic characteristics were household composition and the number of wage-earners in the household. The household composition variables were represented as the number of family members in the age groups 0–14 years, 15–24 years, 25–44 years, 45–64 years, and 65 years and older. Because the travel patterns and mobility of older and younger generations may differ, household composition variables can capture the effects of household member age. The number of employed individuals was also considered because a household's income increases when the number of wage-earning individuals in the household increases.

The economic factors comprised household income and car ownership. Annual household disposable income, which served as a proxy for socioeconomic status, was adjusted for inflation by using the Consumer Price Index (base year: 2021). Car ownership was a binary variable assigned a value of 1 if a household owned at least one car and 0 otherwise. To address the endogeneity of car ownership decisions, house ownership was used as an instrumental variable. The house ownership variable was assigned a value of 1 if a household owned their home and 0 otherwise. The coefficients for the correlation between house and car ownership were 0.30 in 2002 and 0.34 in 2022. The coefficients for the correlation between house ownership and transportation expenditures were 0.10 in 2002 and 0.06 in 2022. Additionally, although house ownership was strongly associated with car ownership, it was weakly associated with transportation expenditures, rendering it a suitable instrumental variable for exploring car ownership. Table 1 presents descriptive statistics for the dependent and explanatory variables.

We further analyzed household transportation expenditures and car ownership across income groups. The results reveal that private vehicle expenditures considerably exceeded public transportation expenditures, with overall transportation expenditures increasing with income levels (Figure 2). Additionally, car ownership was associated with increased income (Figure 3). For example, in 2002, 12% of households in the lowest 10% income bracket owned at least one car, whereas approximately 88% in the top 10% income bracket did.

Table 1. Descriptive Statistics

Variables	2002 dataset			2022 dataset		
	Mean	Media	SD	Mean	Media	SD
Dependent variables						
Total annual transportation expenditures	46.88	40.12	39.51	58.91	52.09	48.55
Annual expenditures on private vehicle usage	38.70	32.73	36.42	51.51	46.92	45.61
Annual expenditures on public transport services	8.18	3.89	12.81	7.40	3.33	13.78
Explanatory variables						
Continuous/Numeric variables	Mean	Median	SD	Mean	Median	SD
Annual household income (thousand NT dollars)	848.94	714.86	621.64	1060.7	899.89	740.91
Number of earners	1.63	1.00	0.81	1.75	2.00	0.84
Household size	3.62	4.00	1.65	2.78	3.00	1.34
Number of members aged 0–14 years	0.74	0	1.00	0.27	0	0.65
Number of members aged 15–24 years	0.53	0	0.86	0.24	0	0.56
Number of members aged 25-44 years	1.09	1.00	0.96	0.65	0	0.83
Number of members aged 45–64 years	0.85	1.00	0.85	0.89	1.00	0.84
Number of members aged 65 years or older	0.41	0	0.67	0.72	0	0.81
Dummy/Categorical variables	freque	%		freque	%	
Age of household head						
Household head aged under 30 years*	1027	7.51		662	4.01	
Household head aged 30-39 years	3347	24.47		2288	13.85	
Household head aged 40-49 years	4241	31.01		3661	22.17	
Household head aged 50-64 years	3236	23.66		5655	34.23	
Household head aged 65 years or older	1826	13.35		4254	25.75	
Gender						
Male	10866	79.45		11172	67.63	
Female*	2811	20.55		5348	32.37	
Education level						
Less than junior high school*	3555	25.99		2159	13.07	
Junior high school	2302	16.83		2101	12.72	
Senior high school	5904	43.17		6876	41.62	
Bachelors or graduate degree	1916	14.01		5384	32.59	
Having a spouse						
Yes	9820	71.80		9063	54.86	
No*	3857	28.20		7457	45.14	

Owning at least one car				
Yes	11058	80.85	13821	83.66
No*	2619	19.15	2699	16.34
House ownership				
Own	11657	85.23	14822	89.72
Rent*	2020	14.77	1698	10.28
Total observations		13677		16520

* is used as the reference category. SD: standard deviation. The income and expenditure variables are deflated using the Consumer Price Index, with the base year of 2021. The unit of income and expenditure is thousands of New Taiwan dollars.

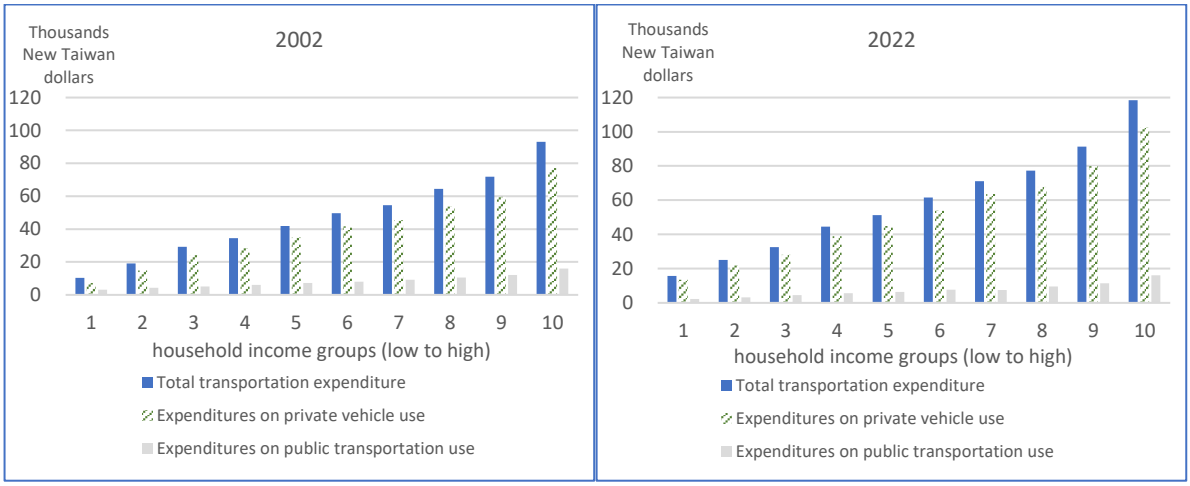

Figure 2. Household transportation expenditures by income groups in 2002 and 2022

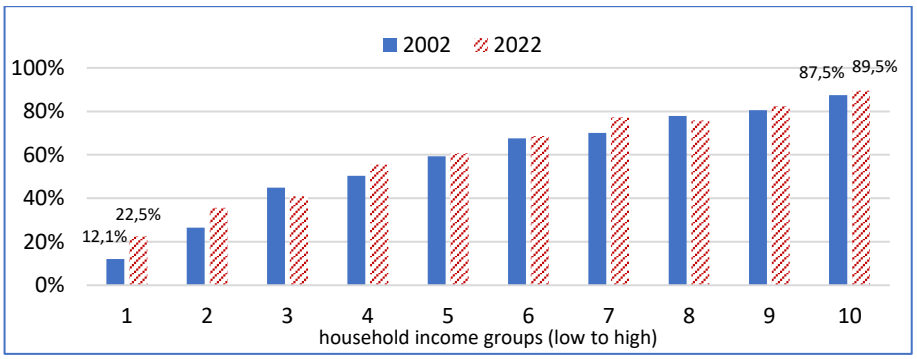

Figure 3. Proportion of households owning at least one car by income group

III. EMPIRICAL RESULTS

This study used a recursive mixed-process model to explore how sociodemographic characteristics influenced household transportation expenditures and car ownership decisions in Taiwan. Three models were used to estimate the following types of transportation expenditures: total expenditures (Model 1), private vehicle expenditures (Model 2), and public transportation expenditures (Model 3). The models were estimated using the software Stata 18.

A. *Endogeneity test for car ownership*

When the determinants of household transportation expenditures are estimated, car ownership is a critical factor. Considering that car ownership may be endogenous, this study conducted an endogeneity test prior to estimating this variable. The Durbin–Wu–Hausman test can be used to assess the endogeneity of car ownership. We examined the endogeneity of car ownership in our three models, reporting the endogeneity test results in Table 2. The results revealed that the estimated coefficient ρ was significantly different from 0 in each

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model, rejecting the null hypothesis. Hence, car ownership was endogenous in Taiwan in 2002 and 2022. Since the endogeneity of car ownership is verified, the appropriateness of using the recursive mixed-process model can be supported.

Table 2. Results of the Endogeneity Test

	Estimated coefficient ρ	
	2002 dataset	2022 dataset
Model 1	3.78**	5.06**
	(0.57)	(0.38)
Model 2	5.33**	5.16**
	(0.51)	(0.34)
Model 3	-1.54**	-1.09**
	(0.26)	(0.17)

*, **, and *** represent significance levels of 10%, 5% and 1%, respectively. The values in parentheses are standard errors.

B. *Estimation results of the recursive mixed-process model*

The recursive mixed-process model comprised two simultaneous equations. The first equation, estimated using probit regression, modeled car ownership as a binary variable, with house ownership serving as an instrumental variable to represent a household's purchasing power. The second equation, estimated using linear regression, modeled transportation expenditures as a continuous variable. Table 3 presents the results for Model 1, with total transportation expenditures as the dependent variable in Equation (2). Table 4 presents the results for Model 2, with private vehicle expenditures as the dependent variable in Equation (2). Table 5 presents the results for Model 3, with private vehicle expenditures used as the dependent variable in Equation (2). All models indicated a significantly positive coefficient for home ownership, suggesting that homeowners were more likely to own cars. This finding validated the suitability of home ownership as an instrumental variable for analyzing car ownership.

We subsequently explored the effects of household head characteristics on transportation expenditures. The age of the household head reflects the influence of the household life cycle. Households whose heads were aged 30–39 years, 40–49 years, and 50–64 years experienced substantial increases in total transportation expenditures in both 2002 and 2022, indicating that households with middle-aged heads spent more on transportation than did those headed by individuals under 29 years. In 2002, individuals aged 30–39 years exhibited the largest marginal effect, whereas in 2022, individuals aged 40–49 years exhibited the largest marginal effect, suggesting a shift in peak travel demand from younger to middle-aged households. Additionally, for households with heads aged 30–39 years and 40–49 years, household age was significantly associated with car ownership, with middle-aged households more likely to own cars than younger households were. However, the effect of having a household head aged 65 and older differed between 2002 and 2022. In 2002, households headed by individuals in this age group exhibited considerably reduced transportation expenditures and car ownership, suggesting lower travel demand and vehicle ownership than those in younger households. By 2022, this age group exhibited considerably greater transportation expenditures and car ownership, reflecting increased travel demand and vehicle ownership among older households.

The results presented in Table 4 reveal that the effects of household head age on private vehicle expenditures were consistent with the findings presented in Table 3. Specifically, households with middle-aged heads exhibited higher private vehicle expenditures. The coefficient for household heads aged 65 and older was significantly negative in 2002 but positive in 2022, reflecting increased private vehicle use among older households due to longer life expectancy, improved health, and superior economic conditions. This shift indicates improvements in mobility for older households over time. Additionally, the results presented in Table 5 demonstrate that for household heads aged 30–39 years, 40–49 years, 50–64 years, and 65 years and older, public transportation expenditures were high in both 2002 and 2022. Notably, households with heads aged 65

and older exhibited a greater demand for public transportation. Hence, we suggest that public transportation systems should address the needs of older individuals by providing user-friendly environments.

Household head gender was associated with substantially increased total transportation expenditures in 2022 and with private vehicle expenditures in both 2002 and 2022, with higher expenditures being noted in households with male heads. By contrast, household head gender was associated with significantly reduced public transportation expenditures, with greater public transportation demand noted in households with female heads. Households with male heads also exhibited a greater likelihood of car ownership. The education level of the household head, which was used as a proxy for socioeconomic status, was significantly associated with increased transportation expenditures and car ownership. Additionally, in the 2022 sample, household head marital status was significantly associated with increased transportation expenditures.

The economic variables in this study comprised household disposable income and car ownership. Household disposable income was employed as a proxy for purchasing power. In all models, disposable income was significantly associated with greater car ownership and positively affected total, private, and public transportation expenditures. Car ownership was significantly associated with increased private transportation costs. Additionally, car ownership was significantly associated with decreased public transportation expenses, reflecting a substitution relationship between private vehicle use and public transportation use.

The household demographic characteristics of this study involved the number of family members in various age groups and the number of wage-earners. The number of family members aged 65 and older was significantly associated with reduced total and private transportation expenditures and car ownership. By contrast, the number of family members in other age groups was significantly associated with increases in these expenditures. The number of older family members was associated with increased public transportation expenditures but reduced private transportation expenditures and car ownership, reflecting older individuals' reduced wealth. However, the necessary expenses and medical care for older individuals may have reduced household discretionary income for private transportation. Consequently, an increase in the number of older household members was associated with increased public transportation expenditures. Additionally, the number of family members aged 0–14 was positively associated with private transportation expenditures and negatively associated with public transportation expenditures, perhaps because having children increased reliance on private vehicles for caregiving or delivery needs. Finally, the number of wage-earners in a household was positively associated with increased transportation expenditures and car ownership, reflecting a need to commute for work and business travel and increased demand for travel due to greater household wealth.

This study examined the influence of sociodemographic factors on household transportation expenditures and car ownership. Our primary findings were as follows. First, the peak in household travel demand shifted from households headed by individuals aged 30–39 to those headed by individuals aged 40–49 between 2002 and 2022. Middle-aged households exhibited greater travel mobility than younger households did. Second, the travel behavior of older households has changed. Older households exhibited higher travel demand, particularly for public transportation, than younger households did, despite having reduced private transportation expenditures and car ownership compared with middle-aged households. Third, households with more family members typically had greater transportation expenditures, with the exception of households with children aged 0–14 years and those with older members. Specifically, an increase in the number of children aged 0–14 years was associated with reduced public transportation expenditures, suggesting a preference for using private vehicles to meet caregiving or delivery needs. By contrast, an increase in the number of older household members was associated with increased public transportation expenditures and reduced private vehicle use, reflecting older individuals' reduced wealth and physical limitations and the high costs of car ownership, which encouraged reliance on public transit.

Table 3. Estimation Results for Total Transportation Expenditures (Model 1)

Variables	2002	2022
	Dependent variable	Dependent variable

	Car ownership Eq (1)	Total transportation expenditures Eq (2)	Car ownership Eq (1)	Total transportation expenditures Eq (2)
	Coefficient (SE)	Coefficient (SE)	Coefficient (SE)	Coefficient (SE)
Constant	-1.889*** (0.074)	-7.810*** (1.269)	-1.220*** (0.068)	-12.923*** (1.881)
Household head aged 30-39 years	0.203*** (0.052)	3.970*** (0.957)	0.142** (0.054)	4.166** (1.638)
Household head aged 40-49 years	0.150*** (0.051)	2.030** (0.931)	0.260*** (0.053)	8.219*** (1.574)
Household head aged 50-64 years	0.039 (0.058)	2.056* (1.104)	0.235*** (0.055)	7.501*** (1.641)
Household head aged 65 years or older	-0.620*** (0.078)	-5.644*** (1.343)	0.207*** (0.062)	4.681*** (1.832)
Gender	0.308*** (0.032)	-0.725 (0.569)	0.185*** (0.021)	5.705*** (0.636)
Education level-Junior high school	0.184*** (0.041)	-1.061 (0.686)	0.121*** (0.033)	3.196*** (0.931)
Education level-Senior high school	0.470*** (0.037)	1.735** (0.686)	0.362*** (0.030)	11.828*** (0.883)
Education level-Bachelors or graduate degree	0.636*** (0.054)	7.086*** (1.136)	0.564*** (0.037)	21.115*** (1.190)
Having a spouse	0.451*** (0.035)	-1.190 (0.621)	0.361*** (0.025)	10.954*** (0.721)
Number of members aged 0–14 years	0.061*** (0.017)	0.752*** (0.323)	0.119*** (0.022)	3.797*** (0.645)
Number of members aged 15–24 years	0.067*** (0.019)	4.222*** (0.359)	0.110*** (0.022)	9.167*** (0.647)
Number of members aged 25-44 years	0.153*** (0.022)	3.400*** (0.451)	0.011*** (0.022)	6.508*** (0.659)
Number of members aged 45–64 years	0.093*** (0.022)	2.119** (0.456)	0.016*** (0.020)	6.811*** (0.613)
Number of members aged 65 years or older	-0.093*** (0.024)	-0.819** (0.413)	-0.033* (0.018)	-0.860** (0.432)
Number of earners	0.050** (0.024)	1.428*** (1.950)	0.050*** (0.019)	4.659*** (0.626)
Household income (thousand NT dollars)	0.0005*** (0.000)	0.017*** (0.001)	0.0004*** (0.000)	0.022*** (0.001)
Automobile ownership	-	50.644*** (1.950)	-	50.754*** (1.509)
Instrumental variable				
House ownership	0.484*** (0.034)		0.088*** (0.020)	
Wald Chi-squared	19182***		14954***	
Log Pseudolikelihood	-70711		-85582	
Total observations	13677		16520	

*, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The values in parentheses are standard errors.

Table 4. Estimation Results for Expenditures on Private Vehicle Use (Model 2)

Variables	2002		2022	
	Dependent variable		Dependent variable	
	Car ownership Eq (1)	Expenditures on private vehicle usage Eq (2)	Car ownership Eq (1)	Expenditures on private vehicle usage Eq (2)
	Coefficient (SE)	Coefficient (SE)	Coefficient (SE)	Coefficient (SE)
Constant	-0.990*** (0.061)	-7.20*** (1.427)	-1.043*** (0.068)	-13.316*** (1.778)

Household head aged 30-39 years	0.189***	3.697***	0.105**	2.873*
	(0.045)	(1.155)	(0.054)	(1.570)
Household head aged 40-49 years	0.179***	2.683***	0.251***	6.528***
	(0.044)	(1.112)	(0.052)	(1.500)
Household head aged 50-64 years	0.120**	2.662**	0.253***	5.589***
	(0.051)	(1.293)	(0.053)	(1.561)
Household head aged 65 years or older	-0.099*	-4.237***	0.222***	3.300**
	(0.060)	(1.508)	(0.060)	(1.630)
Gender	0.199***	5.500***	0.170***	6.023***
	(0.026)	(0.630)	(0.020)	(0.583)
Education level-Junior high school	0.061**	0.191	0.074**	1.960***
	(0.031)	(0.754)	(0.030)	(0.831)
Education level-Senior high school	0.313***	6.927***	0.303***	8.870***
	(0.030)	(0.750)	(0.027)	(0.751)
Education level-Bachelors or graduate degree	0.607***	13.367***	0.547***	14.833***
	(0.048)	(1.263)	(0.034)	(0.997)
Having a spouse	0.289***	6.974***	0.331***	9.629***
	(0.027)	(0.679)	(0.023)	(0.662)
Number of members aged 0–14 years	0.042***	0.788**	0.145***	4.564***
	(0.015)	(0.372)	(0.021)	(0.624)
Number of members aged 15–24 years	0.031*	2.536***	0.066***	5.663***
	(0.016)	(0.400)	(0.022)	(0.595)
Number of members aged 25-44 years	0.133***	5.500***	0.095***	6.513***
	(0.020)	(9.500)	(0.022)	(0.624)
Number of members aged 45–64 years	0.077***	3.699***	0.146***	6.828***
	(0.019)	(0.485)	(0.020)	(0.583)
Number of members aged 65 years or older	-0.087***	-2.639***	-0.032*	-1.032**
	(0.019)	(0.485)	(0.017)	(0.504)
Number of earners	0.054**	3.513***	0.059***	4.845**
	(0.020)	(0.520)	(0.020)	(0.579)
Household income (thousand NT dollars)	0.0005**	0.170***	0.0004***	0.017**
	(0.000)	(0.001)	(0.000)	(0.001)
Automobile ownership	-	8.485**	-	10.258***
		(0.232)		(0.480)
Instrumental variable				
House ownership	0.044***	-	0.040**	-
	(0.017)		(0.019)	
Wald Chi-squared	9599***		15110***	
Log Pseudolikelihood	-67195		-83479	
Total observations	13677		16520	

*, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The values in parentheses are standard errors.

Table 5. Estimation Results for Expenditures on Public Transportation (Model 3)

Variables	2002		2022	
	Dependent variable		Dependent variable	
	Car ownership Eq (1)	Expenditures on public transport services	Car ownership Eq (1)	Expenditures on public transport services
	Coefficient (SE)	Coefficient (SE)	Coefficient (SE)	Coefficient (SE)
Constant	-1.902***	-0.316**	-1.966***	0.440*
	(0.075)	(0.119)	(0.080)	(0.222)
Household head aged 30-39 years	0.208***	1.144***	0.150***	1.041**
	(0.035)	(0.405)	(0.059)	(0.80)
Household head aged 40-49 years	0.157***	2.638***	0.268***	1.294***
	(0.051)	(0.420)	(0.058)	(0.478)
Household head aged 50-64 years	0.044	2.837***	0.204***	1.639**
	(0.058)	(0.530)	(0.060)	(0.516)
Household head aged 65 years or older	-0.594***	3.780***	0.035	1.356**
	(0.078)	(0.605)	(0.071)	(0.592)
Gender	0.304***	-1.278***	0.270***	-0.718***
	(0.032)	(0.288)	(0.024)	(0.230)

Education level-Junior high school	0.179***	1.397***	0.267***	0.849***
	(0.041)	(0.381)	(0.045)	(0.315)
Education level-Senior high school	0.463***	1.780***	0.578***	2.062***
	(0.018)	(0.430)	(0.040)	(0.384)
Education level-Bachelors or graduate degree	0.645***	4.616***	0.796***	5.043***
	(0.055)	(0.853)	(0.047)	(0.583)
Having a spouse	0.448***	-0.438	0.507***	0.530**
	(0.035)	(0.323)	(0.027)	(0.261)
Number of members aged 0–14 years	0.064***	-0.443***	0.140***	-0.897***
	(0.017)	(0.134)	(0.025)	(0.178)
Number of members aged 15–24 years	0.066***	3.147***	0.137***	3.347***
	(0.018)	(0.181)	(0.024)	(0.216)
Number of members aged 25-44 years	0.153***	0.854***	0.173***	0.455**
	(0.023)	(0.220)	(0.025)	(0.216)
Number of members aged 45–64 years	0.097***	0.519***	0.227***	0.374**
	(0.022)	(0.199)	(0.024)	(0.189)
Number of members aged 65 years or older	-0.094***	0.510**	-0.047**	0.329**
	(0.024)	(0.207)	(0.021)	(0.160)
Number of earners	0.032**	1.084***	0.040*	0.231
	(0.016)	(0.320)	(0.021)	(0.224)
Household income (thousand NT dollars)	0.0005***	0.005***	0.0003***	0.005***
	(0.000)	(0.001)	(0.000)	(0.001)
Automobile ownership	-	-0.449**	-	-2.839***
		(0.221)		(0.508)
Instrumental variable				
House ownership	0.482***		0.463***	
	(0.035)		(0.037)	
Wald Chi-squared	4996***		5709***	
Log Pseudolikelihood	-60063		-74228	
Total observations	13677		16520	

*, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The values in parentheses are standard errors.

C. *Transportation expenditures and life cycle stages*

Because household travel patterns and mobility evolve with life cycle stages, examining how transportation expenditures and car ownership vary by life cycle stage is crucial. The age of the head of a household represents a household's life cycle stage. For example, in the current study, households headed by individuals aged 40–49 years had higher transportation expenditures for both private and public transportation than other groups did in both 2002 and 2022, indicating greater travel demand among middle-aged households (Figure 4). Transportation expenses were substantially reduced as households transitioned to later life stages. Table 6 presents the changes in transportation expenditures from 2002 to 2022. All households exhibited an increase in private transportation expenditures during this period, with older households exhibiting the largest increase of 188%. However, changes in public transportation expenditures varied by household life cycle stage. Specifically, households headed by individuals under 29 years old or by those aged 30–39 years exhibited slightly increased public transportation expenditures, whereas households headed by individuals aged 40 years and older exhibited reduced public transportation expenditures. This trend may reflect the public transportation fares set and subsidized by the Taiwanese government, which remained relatively low due to limited adjustments for inflation. Additionally, middle-aged and older households likely prioritized the comfort and mobility of private vehicles and relied heavily on such vehicles to meet their transportation needs.

Figure 5 illustrates the ratios of transportation expenditures to household income by household life cycle stage. Table 7 presents the changes in this ratio between 2002 and 2022. In 2002, households headed by individuals aged 40–49 exhibited the highest ratio (6.47%). By 2022, households headed by individuals aged 50–64 exhibited the highest ratio (6.33%). This observation is consistent with the findings of other studies indicating a shift in peak travel demand to later life cycle stages. Between 2002 and 2022, the ratio of private transportation expenditures to household income increased for households headed by individuals aged 40–49 years, 50–64 years, and 65 years and older. By contrast, the ratio of public transportation expenditures to household income decreased across all age groups. These findings indicate that middle-aged and older households relied more on private vehicles than on public transportation.

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We also examined the percentage of households owning at least one car across life cycle stages. Households with middle-aged heads were the most likely to own a car (Figure 6). Nevertheless, the percentage of older households owning at least one car increased from 14% in 2002 to 38% in 2022. Additionally, the ratio of private transportation expenditures to household income among older households increased from 1.82% in 2002 to 4.15% in 2022, which is a greater increase than that observed among other age groups (Table 7). These results reflect the increased travel demand and enhanced independence of older households due to car ownership and increased wealth.

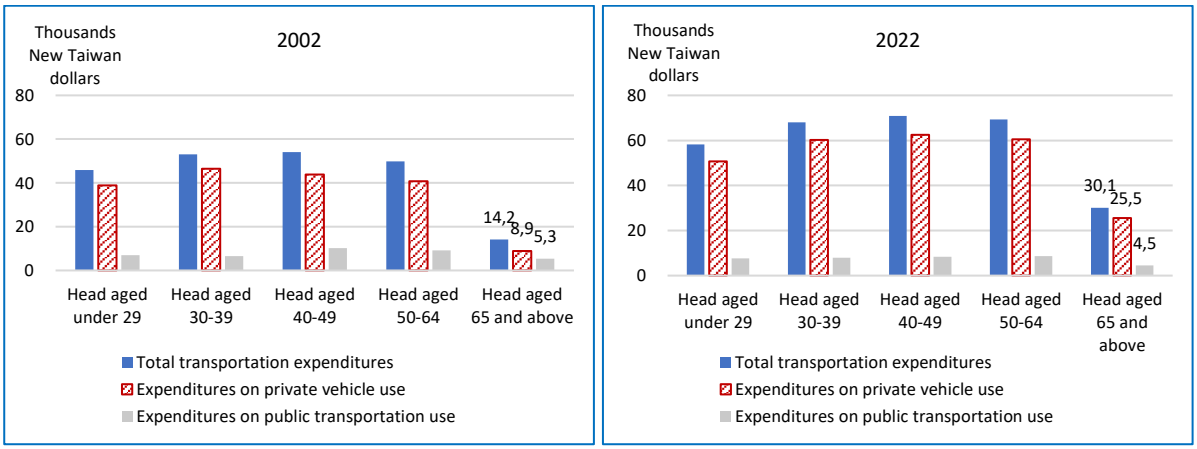

Figure 4. Household transportation expenditures by household head age

Table 6. Changes in Transportation Expenditures Between 2002 and 2022

	Total transportation expenditures			Expenditures on private vehicle use			Expenditures on public transportation use		
	2002	2022	change (%)	2002	2022	change (%)	2002	2022	change (%)
Head aged under 29	45.84	58.27	27%	38.89	50.63	30%	6.95	7.64	10%
Head aged 30-39	53.03	68.07	28%	46.45	60.14	29%	6.58	7.93	20%
Head aged 40-49	54.10	70.86	31%	43.85	62.48	42%	10.25	8.38	-18%
Head aged 50-64	49.84	69.25	39%	40.70	60.56	49%	9.14	8.69	-5%
Head aged 65 and above	14.18	30.07	112%	8.87	25.53	188%	5.31	4.54	-14%
Full sample	46.88	58.91	26%	38.70	51.51	33%	8.18	7.40	-10%

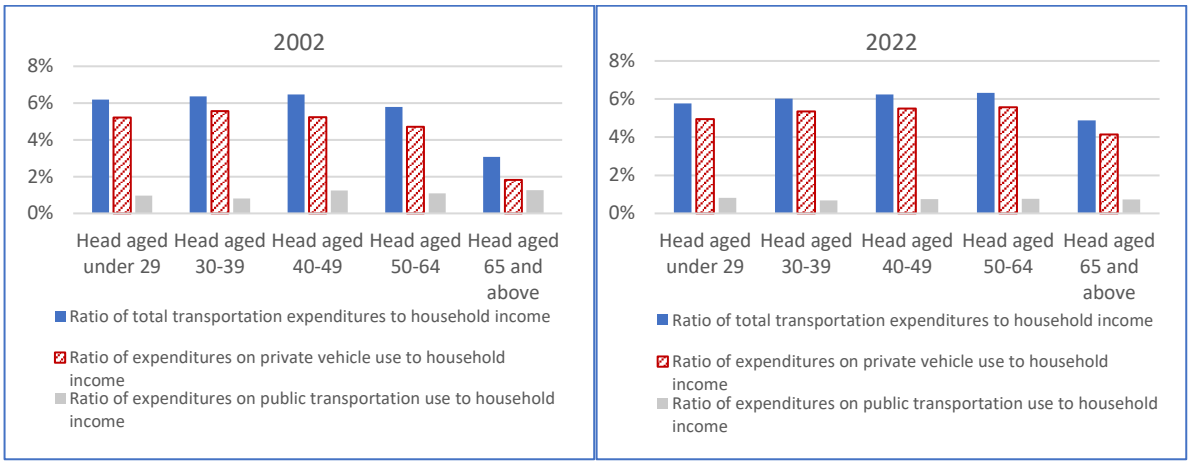

Figure 5. Ratio of transportation expenditures to income by household head age

Table 7. Changes in the Ratio of Transportation Expenditures to Income Between 2002 and 2022

	Ratio of total transportation expenditures to income			Ratio of expenditures on private vehicle use to income			Ratio of expenditures on public transportation use to income		
	2002	2022	change	2002	2022	change	2002	2022	change
Head aged under 29	6.18%	5.76%	-0.42%	5.22%	4.95%	-0.28%	0.96%	0.82%	-0.14%
Head aged 30-39	6.37%	6.02%	-0.35%	5.56%	5.35%	-0.21%	0.81%	0.67%	-0.13%
Head aged 40-49	6.47%	6.24%	-0.23%	5.23%	5.50%	0.27%	1.25%	0.74%	-0.50%
Head aged 50-64	5.79%	6.33%	0.54%	4.70%	5.56%	0.86%	1.09%	0.76%	-0.32%
Head aged 65 and above	3.08%	4.89%	1.81%	1.82%	4.15%	2.33%	1.26%	0.74%	-0.52%
Full sample	5.81%	5.87%	0.06%	4.73%	5.13%	0.40%	1.08%	0.74%	-0.34%

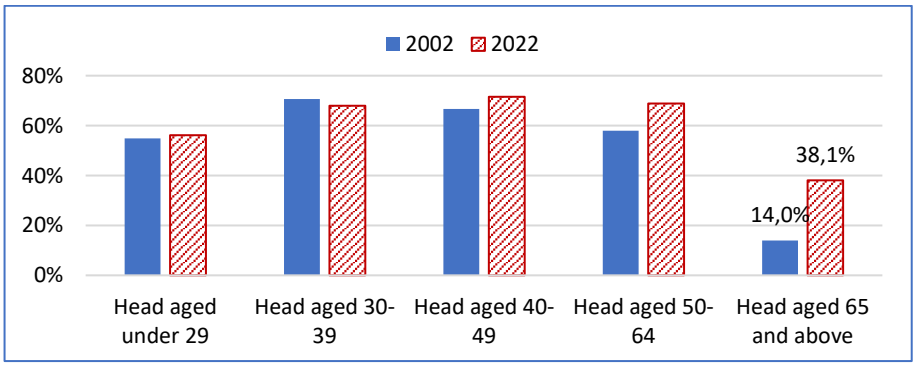

Figure 6. Percentage of households having at least one car, stratified by household head age

IV. Discussion

The empirical results reveal that travel mobility among older households had increased over time. The older households showed an increased demand for private cars, private transportation expenditures, and

public transportation expenditures. The results are consistent with the findings in previous studies, which indicated that a substantial share of older adults express a desire to engage in more out-of-home activities (Luiu et al., 2018), and a significant proportion of older adults still primarily rely on cars (Spinney et al., 2020). However, older drivers face a higher risk of traffic accidents, and the high cost of using private vehicles would pose an economic burden. Thus, to meet the transportation needs of older adults and ensure both convenience and safety, providing accessible and efficient public transportation is essential. Relevant transportation policies, such as the development of age-friendly buses, transfer shuttle systems, and discounted public transportation fares for the elderly, can support the mobility needs of older adults. Moreover, due to urban–rural disparities, rural areas face a high proportion of older adults as younger populations migrate to cities. With limited access to public transportation, elderly residents in these regions may rely heavily on private vehicles. Rural areas especially need government subsidies for public transportation routes and the development of ride-sharing systems. Therefore, future transportation planning must prioritize the mobility needs of aging populations in rural areas.

Middle-aged households have higher travel demand due to greater financial capacity and responsibilities such as transporting children, resulting in higher car ownership and greater private transportation expenditures. This phenomenon can also be found in the studies of Rosqvist and Hiselius (2019) and Wang and Renne (2023). Rosqvist and Hiselius (2019) found that, in Sweden, the middle-age group has the highest car mileage than other age groups. Wang and Renne (2023) showed that those families with young children tended to make a higher proportion of trips by car in the United States. Thus, providing policy incentives that encourage middle-aged households to shift from private vehicles to public transportation is an important goal for reducing emissions and promoting sustainable transportation systems. In Taiwan's metropolitan areas, the transportation system offers a variety of modes, including public buses, metro systems, light rail, and shared bicycles. However, integration and connectivity between these transportation modes still need improvement to enhance punctuality, convenience, and accessibility. As for private vehicle regulations, although the Taiwanese government has planned to ban the sale of fossil fuel vehicles by 2040, the high purchase cost of electric vehicles and insufficient subsidy incentives have led to slow progress in replacing fossil fuel vehicles with electric ones. While existing policies provide incentives, such as license tax reductions and parking discounts, for electric vehicles, increasing subsidies for electric vehicles and raising user costs for fossil fuel vehicles will be required to increase the willingness to purchase electric vehicles.

Household travel demand varied by household life cycle stage, since travel patterns and trip purposes may reflect the social roles in different life cycle stages. Zhao and Zhang (2018) also indicated that people's travel behavior would be shaped by their life stages, with events like starting a job, getting married, or having a child significantly influencing their transportation decisions. Therefore, the design of transportation systems needs to develop a variety of transportation options that accommodate travel demand of all age groups. Besides, sustainable transportation planning should consider future demographic shifts, ensuring that today's transport systems are designed to meet the mobility needs of future generations. With the proportion of elderly populations rising rapidly in many developed countries, transportation policies should proactively incorporate mobility support systems and address the mobility needs of older adults for accessing healthcare services and participating in leisure activities. Although this study focuses on Taiwan, many developed countries also have similarly high proportions of older populations, such as Japan, South Korea, and various European nations. Therefore, the exploration of travel demand among the elderly in this research can also serve as a reference for other aging societies.

V. Conclusion

Life cycle stage transitions and population aging have produced variations in Taiwanese household wealth and mobility. The current study applied a recursive mixed-process model to investigate the associations between sociodemographic characteristics, transportation expenditures, and car ownership in Taiwan, accounting for the endogeneity of car ownership. Transportation expenditures were segmented across private vehicle usage and public transportation services. Household data were obtained from Taiwan's Family

Income and Expenditure Survey for the years 2002 and 2022. The study also analyzed variations in transportation expenditures and car ownership across household life cycle stages and explored changes in the associations between sociodemographic characteristics and travel demand over time.

The empirical findings of this study are addressed as follows. First, household travel demand varied by life cycle stage. Specifically, households with middle-aged heads spent more on private vehicle use and were more likely to own cars than households with heads aged 29 years and younger were. In 2002, households with heads aged 30–39 years exhibited the highest travel demand, whereas in 2022, households with heads aged 40–49 years exhibited the highest demand. This result indicates that peak travel demand has shifted from younger to middle-aged households. Travel demand among household heads aged 65 and older increased from 2002 to 2022. While older households in 2002 had lower transportation spending and car ownership, by 2022, both rose significantly due to longer life expectancy, better health, and improved economic status. Besides, households with middle-aged heads had higher public transportation expenditures than did those with younger heads, indicating greater public transportation use in later life cycle stages. Hence, we recommend that public transportation systems provide user-friendly environments and address the needs of older individuals.

Second, household composition considerably affected transportation expenditures and car ownership. An increase in the number of family members was typically associated with increased household transportation expenditures, except when the number of children aged 0–14 years or the number of household members older than 65 years increased. Having more children aged 0–14 years was associated with reduced public transportation expenditures because households relied on private vehicles for caregiving or delivery needs. Additional older members were associated with increased public transportation expenditures and reduced private vehicle usage, reflecting these individuals' limited wealth and the high costs of private vehicle use. Older individuals were also more likely to use public transportation to meet their travel needs than younger individuals were.

The policy implications mean that although older individuals had less wealth and mobility than younger groups did, their demand for public transportation remained considerable. The demand for mobility is crucial for the lives of the elderly, affecting their life satisfaction and well-being. In terms of the age-friendly mobility services, policies should prioritize the needs of older individuals by enhancing the convenience and safety of public transportation. Moreover, the policymakers should understand future demographic trends to provide diverse transportation options that cater to the needs of all age groups.

Although this study addresses the relationship between population aging and transportation demand and offers valuable policy insights, there still exists some limitations. The analysis is based on household-level data, which lack environmental and spatial variables, preventing examination of external influences. Additionally, the use of cross-sectional data limits the ability to capture changes over time or the impacts of public transportation development. Future research can incorporate external contextual factors, temporal dynamics, and the evolving role of public transit in shaping travel demand.

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Povezava med staranjem prebivalstva in povpraševanjem po potovanjih

Povzetek - V tej študiji je bil uporabljen rekurzivni model mešanega procesa za analizo vpliva sociodemografskih značilnosti na izdatke gospodinjstev za prevoz in lastništvo avtomobila na Tajvanu. Izdatki za prevoz so bili razdeljeni na izdatke za uporabo zasebnih vozil in izdatke za storitve javnega prevoza. Podatki o gospodinjstvih so bili pridobljeni iz tajvanske ankete o družinskih dohodkih in izdatkih za leti 2002 in 2022. Glavne ugotovitve so bile naslednje. Prvič, potovalno povpraševanje gospodinjstev se je razlikovalo glede na fazo življenjskega cikla gospodinjstva, pri čemer so imela gospodinjstva srednjih let največje potovalno povpraševanje. Tudi starejša gospodinjstva so izkazovala precejšnje potovalno povpraševanje ter imela višje izdatke za prevoz in stopnjo lastništva avtomobila kot gospodinjstva, ki so jih vodili posamezniki, mlajši od 29 let. Ugotovitev o večji mobilnosti med gospodinjstvi, ki jih vodijo starejši odrasli, odraža daljšo pričakovano življenjsko dobo, boljše zdravje in večje bogastvo. Drugič, sestava gospodinjstev je znatno vplivala na izdatke za prevoz in lastništvo avtomobila. Na primer, dodatni družinski člani so bili običajno povezani z večjimi izdatki za prevoz. Vendar so bili dodatni člani, stari 14 let ali manj, povezani z manjšimi izdatki za javni prevoz, saj so zasebna vozila pogosto nadomestila javni prevoz, ker so se uporabljala za oskrbo in dostavo. Nasprotno pa so bili dodatni starejši družinski člani (stari 65 let ali več) povezani z manjšimi izdatki za zasebni prevoz in večjimi izdatki za javni prevoz, kar odraža omejeno premoženje starejših posameznikov in visoke stroške uporabe zasebnih vozil. Ti rezultati pojasnjujejo dejavnike, ki določajo izdatke za prevoz, in poudarjajo značilnosti tajvanskih gospodinjstev, ki so odvisna od zasebnih vozil. Ker se družinske strukture spreminjajo in se staranje prebivalstva nadaljuje, je treba pri razvoju prometa dati prednost starostnikom prijaznim sistemom javnega prevoza.

Ključne besede - lastništvo avtomobila, izdatki za prevoz, staranje prebivalstva, potovalno povpraševanje