Journal of Infrastructure Planning and Engineering

Journal homepage: ejournal.warmadewa.ac.id

e-ISSN: 2829-5153

Mobility transition framework for sustainability in rapidly motorizing capitals

Mariano Renato Monteiro Da Cruz[1,2]*, Dewa Made Priyantha Wedagama[1], Putu Alit Suthanaya[1], Anak Agung Gde Agung Yana[1]

[1]*Doctoral Program of Engineering Science, Faculty of Engineering, Udayana University, Bali, Indonesia*
[2]*Department of Civil Engineering, Faculty of Engineering Science and Technology, National University of Timor-Leste (UNTL), Dili, Timor-Leste*
*mr.dacruz@untl.edu.tl

received 27 August 2026; revised 11 October 2026; accepted 13 October 2026; published 20 October 2026

ABSTRACT

Rapid motorization is increasing pressure on urban mobility systems in emerging capital cities where transport infrastructure and public transport services often lag behind growing travel demand. This study develops and empirically tests a perception-based Mobility Transition Framework (MTF) to explain how structural pressures, vehicle ownership, travel behavior, traffic system stress, and mobility sustainability are interconnected in Dili, Timor-Leste. Primary data were collected from 1,001 urban road users between January and March 2025 and analyzed using Structural Equation Modeling (SEM) with AMOS. The measurement model demonstrated satisfactory construct reliability and convergent validity, while the structural model showed good overall fit (CMIN/DF = 1.69, RMSEA = 0.03, CFI = 0.98, TLI = 0.97, GFI = 0.98, and AGFI = 0.97). Population growth showed a strong positive relationship with vehicle ownership pressure (β = 0.74), which was subsequently associated with private vehicle usage (β = 0.50). Private vehicle usage was positively associated with traffic system stress (β = 0.34), while traffic system stress showed the strongest relationship with mobility sustainability (β = 0.83). The model explained 60% of the variance in vehicle ownership pressure, 39% in private vehicle usage, 42% in traffic system stress, and 82% in mobility sustainability. Indirect effects further indicated that upstream structural and behavioral pressures are associated with sustainability through interconnected intermediate pathways rather than direct relationships alone. The findings support the hierarchical and process-based structure of the MTF and reposition traffic system stress as a key operational mechanism linking motorization pressures with mobility sustainability. The framework provides an empirical basis for integrated policies combining travel-demand management, public transport improvement, traffic management, and land-use–transport coordination in rapidly motorizing emerging capitals.

Keywords: motorization pressure; traffic system stress; mobility sustainability; structural equation modeling; emerging capital cities

1 Introduction

Urban mobility in emerging capital cities is increasingly challenged by rapid urbanization, rising motorization, population growth, and limitations in transport-system capacity. Rapidly developing cities frequently experience increasing dependence on motorized travel while public transport provision and sustainable mobility alternatives remain insufficient, contributing to congestion, accessibility constraints, environmental pressures, and declining transport-system performance [1], [2]. Rapid increases in private vehicle ownership can further intensify congestion, air pollution, and carbon emissions, particularly where attractive public transport alternatives remain insufficient [3].

This pattern is evident in Dili, Timor-Leste, where motorcycles and private cars dominate urban travel while formal public transport remains limited [4]. Increasing dependence on private vehicles places substantial pressure on the road network and contributes to deteriorating traffic conditions. Vehicle ownership and travel behavior are shaped by interconnected structural and contextual factors, including population characteristics, urban form, land

https://doi.org/10.22225/jipe.5.2.2026.67-78

2829-5153 ©2026 The Author(s). Published by Master Program of Infrastructure and Environmental Engineering, Postgraduate Program, Warmadewa University. This is an open access article CC BY-SA license (https://creativecommons.org/licenses/by-sa/4.0/)

How to Cite: M. R. M. Da Cruz, D. M. P. Wedagama, P. A. Suthanaya, and A. A. G. A. Yana, "Mobility transition framework for sustainability in rapidly motorizing capitals," *Journal of Infrastructure Planning and Engineering*, vol. 5, no. 2, pp. 67 - 78, October 2026

use, transport-system attributes, socioeconomic conditions, and the availability of alternative travel modes [5]–[8]. Evidence from developing urban contexts further shows that population size and regional characteristics can influence two-wheeler and four-wheeler ownership [6], while built-environment characteristics are associated with vehicle ownership and travel behavior [5], [7]. Car dependency is likewise influenced by a combination of built-environment, public-transport, and travel-cost characteristics [8]. Recent evidence further indicates that transport facilities, land use, and population density interact with car dependency, while built-environment characteristics are associated with automobile ownership and subsequent mode choice [9], [10].

The availability and performance of attractive public transport alternatives are also important in shaping travel behavior. Recent empirical evidence shows that travel-time performance can significantly influence commuters' willingness to shift toward electric railway services, demonstrating the importance of service performance in strengthening alternatives to private motorized travel [11]. Taken together, these findings indicate that motorization, vehicle ownership, public-transport performance, and travel behavior should be understood as interconnected components of a broader urban mobility system rather than as isolated phenomena.

Sustainable mobility consequently requires a system-oriented perspective integrating structural conditions, behavioral responses, accessibility, and operational performance. Built-environment and land-use characteristics are closely associated with vehicle ownership and mobility behavior, indicating that urban form and transport conditions need to be considered jointly when explaining urban mobility patterns [5], [7], [12]. Increasing dependence on private vehicles can subsequently intensify congestion and associated environmental pressures [3]. Mobility sustainability therefore extends beyond traffic efficiency to encompass accessibility, environmental performance, safety, social inclusion, and the availability of sustainable transport alternatives [1], [2]. From a transport-equity perspective, sustainable mobility should also provide adequate and equitable access to opportunities across different population groups rather than evaluating transport performance solely in terms of movement or efficiency [13].

Operational traffic performance is likewise closely related to broader mobility-sustainability objectives. Recent empirical findings demonstrate that targeted traffic-management interventions at congested signalized intersections can substantially reduce delay and improve level of service, illustrating how improvements in operational traffic conditions can contribute to sustainable mobility [14]. These broader considerations reinforce the need to evaluate urban mobility as a multidimensional system in which structural conditions, travel behavior, operational performance, accessibility, and sustainability are interconnected.

Despite growing research on sustainable urban mobility, important knowledge gaps remain. First, empirical evidence from smaller emerging capital cities remains relatively limited compared with that from large metropolitan areas. Second, existing studies have largely examined vehicle ownership, travel behavior, car dependency, traffic conditions, and sustainable mobility either separately or through partially connected relationships [8]–[10], [12], [15]. Recent studies have increasingly demonstrated that the effects of urban and built-environment conditions on travel behavior can operate through intermediate mechanisms such as vehicle ownership and car dependency [10], [12], [15]. However, these relationships are rarely integrated with traffic-system stress and downstream mobility-sustainability outcomes within a unified sequential framework. Consequently, the direct and indirect pathways through which structural pressures propagate through vehicle ownership and travel behavior toward mobility sustainability remain insufficiently understood. More critically, traffic system stress is commonly considered an operational consequence of motorization rather than an intermediate mechanism through which upstream structural and behavioral pressures are transmitted to downstream sustainability outcomes. Existing evidence on public-transport performance and mode shift [11] and on operational traffic management and sustainable mobility [14] further demonstrates the relevance of these individual components, but their integration within a unified structural–behavioral–operational pathway remains limited. These gaps highlight the need for an integrated, context-sensitive, and process-oriented analytical framework for rapidly motorizing emerging capitals.

To address these gaps, this study proposes a perception-based Mobility Transition Framework (MTF) that integrates structural, behavioral, operational, and sustainability dimensions within a unified Structural Equation Modeling (SEM) framework. SEM is particularly suitable for examining interconnected mobility processes because it enables multiple relationships among variables to be estimated simultaneously and allows direct and indirect effects operating through intermediate variables to be evaluated [16]. Within the MTF, structural conditions influence vehicle ownership pressure and private vehicle usage, which subsequently contribute to traffic system stress and ultimately shape mobility sustainability outcomes. The framework therefore conceptualizes urban mobility transition as a hierarchical and process-based sequence rather than as a collection of isolated relationships.

The principal novelty of the MTF lies in three aspects. First, it integrates structural conditions, vehicle ownership pressure, private vehicle usage, traffic system stress, and mobility sustainability within a single analytical framework. Second, it repositions traffic system stress from a conventional terminal operational outcome to a key intermediate mechanism linking upstream structural and behavioral pressures with downstream sustainability outcomes. Third, it introduces a hierarchical and process-based interpretation of mobility transition in which sustainability outcomes emerge through interconnected structural, behavioral, and operational pathways, including indirect effects, rather than exclusively through direct relationships.

Accordingly, this study aims to develop and empirically test the MTF using data from Dili, Timor-Leste. Specifically, it examines the direct and indirect relationships among structural conditions, vehicle ownership pressure, private vehicle usage, traffic system stress, and mobility sustainability; identifies the dominant pathways through which motorization pressures propagate across the urban mobility system; and derives policy implications for rapidly motorizing emerging capital cities. By integrating these relationships within a unified SEM framework, this study advances a mechanism- and process-based understanding of urban mobility transitions and provides an empirical basis for integrated mobility planning in emerging urban contexts.

2 Data and Methods

2.1 Research Design

This study employed a quantitative, perception-based research design to develop and empirically test the Mobility Transition Framework (MTF) for urban mobility in Dili, Timor-Leste. Covariance-Based Structural Equation Modeling (CB-SEM) was applied using AMOS to simultaneously estimate relationships among multiple latent constructs and to examine both direct and indirect effects within the proposed framework [16].

CB-SEM was selected because the study evaluates a theoretically specified framework involving latent constructs represented by multiple observed indicators. The analytical procedure distinguishes between the measurement model, which evaluates the relationships between latent constructs and their observed indicators, and the structural model, which evaluates the hypothesized relationships among latent constructs [16]. This sequential validation ensures that the adequacy of the measurement model is established before interpreting the structural relationships.

2.2 Research Procedure

The research procedure comprised five main stages: (1) identification of urban mobility problems and review of relevant literature; (2) development of the conceptual MTF and its measurable constructs; (3) questionnaire development and primary data collection; (4) measurement-model evaluation using Confirmatory Factor Analysis (CFA); and (5) structural-model estimation and interpretation.

The conceptual framework was operationalized into six latent constructs representing Transport System Performance, Population Growth, Vehicle Ownership Pressure, Private Vehicle Usage, Traffic System Stress, and Mobility Sustainability. Primary data were collected from 1,001 urban road users across five sub-districts of Dili. Before SEM estimation, the dataset was screened for data quality and relevant statistical assumptions.

The measurement model was subsequently evaluated to establish construct validity and reliability. Following satisfactory measurement-model evaluation, the structural model was estimated to examine the hypothesized relationships among the constructs. Model performance was assessed using goodness-of-fit indices, standardized path coefficients (β), statistical significance, coefficients of determination (R^2), and direct, indirect, and total effects. This analytical procedure provided the empirical basis for evaluating the hierarchical and process-based structure of the MTF.

2.3 Study Area

The study was conducted in Dili, the capital of Timor-Leste, covering five sub-districts: Dom Aleixo, Vera Cruz, Nain Feto, Cristo Rei, and Metinaro. These areas represent different urban and mobility environments, including residential areas, commercial and activity centers, major urban corridors, and developing peripheral areas. The spatial coverage was designed to capture variations in mobility experiences and perceptions among road users across the city.

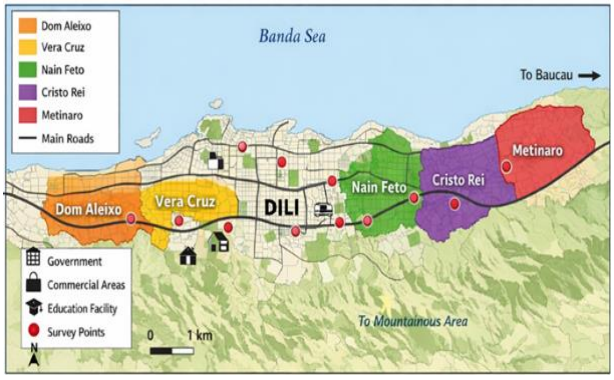


Figure 1. Study area and survey locations in Dili, Timor-Leste
Source: Author's analysis (2025).

Dili provides an appropriate empirical setting for evaluating the MTF because its urban mobility system is characterized by substantial reliance on motorcycles and private cars, limited formal public transport alternatives, and increasing pressure on the urban road network [3]. These characteristics provide

an empirical context for examining how structural conditions influence vehicle ownership and private vehicle use and how these processes subsequently contribute to traffic-system stress and mobility sustainability.

2.4 Data Collection and Sampling

Primary data were collected using a structured, perception-based questionnaire administered between January and March 2025. A total of 1,001 valid responses were obtained from active urban road users across five sub-districts of Dili: Dom Aleixo, Vera Cruz, Nain Feto, Cristo Rei, and Metinaro. Respondents included motorcycle riders, private-car users, and public-transport passengers who regularly experienced urban mobility and traffic conditions in Dili.

A stratified purposive sampling approach was employed to ensure geographical coverage while capturing relevant road-user experiences. The five sub-districts constituted the geographical strata, while respondents within each stratum were purposively selected based on their regular engagement in urban travel. This approach enabled the study to capture variations in perceived mobility conditions across different areas of Dili.

The questionnaire was developed by the researchers with reference to examples of existing transport and urban mobility survey instruments available in the literature and online sources. The measurement items were subsequently adapted to reflect local transport conditions, travel characteristics, and mobility experiences in Dili, Timor-Leste. Prior to data collection, the draft questionnaire was reviewed and approved by the doctoral research supervisor to assess its conceptual relevance, clarity, and suitability for the local context. The instrument formed part of a broader investigation covering multiple dimensions of urban mobility in Dili.

For the present MTF study, relevant questionnaire items were selected according to the conceptual definitions of six latent constructs: Transport System Performance (X1), Population Growth (X2), Vehicle Ownership Pressure (Y1), Private Vehicle Usage (Y2), Traffic System Stress (Y3), and Mobility Sustainability (Z). Responses were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

The resulting dataset was screened before measurement- and structural-model evaluation using Covariance-Based Structural Equation Modeling (CB-SEM) with AMOS. The selected indicators were subsequently evaluated using Confirmatory Factor Analysis (CFA) to assess their measurement properties. The final SEM–AMOS measurement model retained 19 observed indicators, comprising four indicators for Transport System Performance (X1) and three indicators each for Population Growth (X2), Vehicle Ownership Pressure (Y1), Private Vehicle Usage (Y2), Traffic System Stress (Y3), and Mobility Sustainability (Z). Indicators not retained in the final measurement model were excluded from the structural analysis.

Participation in the survey was voluntary, and informed consent was obtained from all respondents before data collection. Respondents were informed that the questionnaire was part of an academic study on urban mobility in Dili and that their responses would be used for research purposes only. The data were analyzed in aggregate form, and respondent characteristics are reported as group percentages (**Table 1**).

2.5 Measurement and Structural Model Evaluation

SEM analysis was conducted sequentially through measurement- and structural-model evaluation. Confirmatory Factor Analysis (CFA) was first applied to assess whether the observed indicators adequately represented their respective latent constructs. Standardized factor loadings were examined for indicator representation, Composite Reliability (CR) was used to assess construct reliability, and Average Variance Extracted (AVE) was used to evaluate convergent validity [20]. $CR \geq 0.70$ and $AVE \geq 0.50$ were adopted as the acceptance criteria [20].

Following establishment of an acceptable measurement model, the structural model was estimated to test the hypothesized relationships among Transport System Performance, Population Growth, Vehicle Ownership Pressure, Private Vehicle Usage, Traffic System Stress, and Mobility Sustainability. Overall model adequacy was evaluated using multiple goodness-of-fit indices, including the chi-square to degrees-of-freedom ratio (CMIN/DF), Root Mean Square Error of Approximation (RMSEA), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Goodness-of-Fit Index (GFI), and Adjusted Goodness-of-Fit Index (AGFI).

Structural relationships were evaluated using standardized path coefficients (β) and their statistical significance. The explanatory capacity of the model was assessed using coefficients of determination (R^2) for the endogenous constructs. Direct, indirect, and total effects were subsequently examined to identify the mechanisms through which upstream structural and behavioral factors were associated with downstream mobility outcomes. This analytical sequence enabled empirical evaluation of both the hierarchical structure and process-based pathways proposed in the MTF.

3 Results and Discussion

3.1 Respondent Characteristics

A total of 1,001 valid respondents were included in the analysis. **Table 1** summarizes the respondents' characteristics according to primary travel mode,

gender, education, and employment status. Motorcycles were the most frequently reported primary travel mode, accounting for 52.8% of respondents, followed by private cars at 31.8% and public transport at 15.4%. This distribution indicates that motorized private modes constituted the dominant travel modes among the surveyed urban road users.

Regarding gender, male respondents accounted for 61.1% of the sample, while female respondents represented 38.9%. In terms of educational attainment, secondary-school graduates constituted the largest group (42.7%), followed by respondents with a diploma or certificate (20.3%), bachelor's degree (16.8%), primary-school education (15.4%), no formal education (2.5%), and postgraduate degree (2.3%).

Employment characteristics also showed a diverse respondent composition. Self-employed respondents represented the largest group (29.4%), followed by private-sector employees (27.3%), government employees (22.2%), students (12.1%), unemployed respondents (5.7%), and other occupational groups (3.3%). Overall, the sample represents road users with diverse socioeconomic backgrounds and travel characteristics, providing an empirical basis for examining perceived urban mobility conditions within the Mobility Transition Framework (MTF).

Table 1. Respondent characteristics (n = 1,001)

Variable	Category	Percentage (%)
Primary travel mode	Motorcycle	52.8
	Private car	31.8
	Public transport	15.4
Gender	Male	61.1
	Female	38.9
Education	No formal education	2.5
	Primary school	15.4
	Secondary school	42.7
	Diploma/Certificate	20.3
	Bachelor's degree	16.8
	Postgraduate degree	2.3
Employment	Unemployed	5.7
	Student	12.1
	Self-employed	29.4
	Private-sector employee	27.3
	Government employee	22.2
	Other	3.3

Source: Author's survey (2025).

3.2 Measurement Model Results

The measurement model was evaluated using Confirmatory Factor Analysis (CFA) to assess the reliability and convergent validity of the six latent constructs included in the Mobility Transition Framework (MTF). Standardized factor loadings were first examined to determine whether the observed indicators adequately represented their respective latent constructs. All retained indicators satisfied the acceptable loading criterion. Construct reliability and convergent validity were subsequently evaluated using Composite Reliability (CR) and Average Variance Extracted (AVE), respectively.

As presented in **Table 2**, the CR values ranged from 0.81 to 0.89, exceeding the recommended minimum criterion of 0.70. The AVE values ranged from 0.57 to 0.72 and were therefore above the minimum criterion of 0.50. Traffic System Stress (Y3) showed a CR of 0.86 and an AVE of 0.67, while Mobility Sustainability (Z) produced the highest reliability and convergent validity values, with CR = 0.89 and AVE = 0.72. Overall, these results demonstrate satisfactory construct reliability and convergent validity, supporting the adequacy of the measurement model for subsequent structural-model evaluation.

Table 2. Construct reliability and convergent validity

Construct	CR	AVE	Evaluation
Transport System Performance (X1)	0.84	0.57	Acceptable
Population Growth (X2)	0.87	0.62	Acceptable
Vehicle Ownership Pressure (Y1)	0.82	0.60	Acceptable
Private Vehicle Usage (Y2)	0.81	0.58	Acceptable
Traffic System Stress (Y3)	0.86	0.67	Acceptable
Mobility Sustainability (Z)	0.89	0.72	Acceptable

Criteria: CR $\geq$ 0.70 and AVE $\geq$ 0.50.
Source: Authors' analysis using AMOS (2025).

3.3 Structural Model Fit

Following validation of the measurement model, the structural model was evaluated to determine its overall goodness-of-fit with the observed data. Multiple fit indices were considered to provide a comprehensive assessment of model adequacy, including the chi-square to degrees-of-freedom ratio (CMIN/DF), Root Mean Square Error of Approximation (RMSEA), Comparative Fit Index (CFI), Tucker–Lewis Index (TLI), Goodness-of-Fit Index (GFI), and Adjusted Goodness-of-Fit Index (AGFI).

As presented in Table 3, the structural model produced a CMIN/DF value of 1.69, which was below the recommended maximum threshold of 3.00. The RMSEA value of 0.03 was also below the threshold of 0.05, indicating a close approximation between the hypothesized model and the observed data. The incremental fit indices showed similarly strong performance, with CFI = 0.98 and TLI = 0.97, both

exceeding the recommended criterion of 0.95. In addition, GFI = 0.98 and AGFI = 0.97 were substantially above the minimum acceptable criterion of 0.90.

Taken together, all evaluated goodness-of-fit indices satisfied their respective acceptance criteria, indicating that the proposed structural model provides a satisfactory representation of the observed data. The acceptable overall model fit therefore supports subsequent evaluation of the hypothesized structural relationships, explanatory power, and direct and indirect pathways within the MTF.

Table 3. Goodness-of-fit indices of the structural model

Fit index	Result	Acceptance criterion	Evaluation
CMIN/DF	1.69	≤ 3.00	Good
RMSEA	0.03	≤ 0.05	Excellent
CFI	0.98	≥ 0.95	Excellent
TLI	0.97	≥ 0.95	Excellent
GFI	0.98	≥ 0.90	Excellent
AGFI	0.97	≥ 0.90	Excellent

Source: Authors' analysis using AMOS (2025).

3.4 Structural and Behavioral Pathways

Following confirmation of an acceptable structural model fit, the standardized structural pathways were examined to identify the relationships among the structural, behavioral, operational, and sustainability dimensions of the MTF. **Table 4** presents the standardized path coefficients (β), statistical significance, and evaluation of the fourteen estimated relationships.

Population Growth (X2) showed a strong and statistically significant positive relationship with Vehicle Ownership Pressure (Y1) ($\beta = 0.74$, $p < 0.001$), whereas the direct relationship between Transport System Performance (X1) and Vehicle Ownership Pressure was not statistically significant ($\beta = 0.07$, $p = 0.21$). This contrast indicates that population-related pressure is more strongly associated with vehicle ownership pressure than transport-system performance at this stage of the mobility-transition process. This finding is consistent with evidence from developing-country contexts indicating that urban population characteristics, city size, and regional conditions are associated with vehicle ownership patterns [5], [6].

Vehicle Ownership Pressure subsequently showed a significant positive relationship with Private Vehicle Usage (Y2) ($\beta = 0.50$, $p = 0.01$), indicating that increasing ownership pressure is associated with greater private vehicle usage. This finding is consistent with evidence from Indonesia showing that private car ownership is shaped by socioeconomic, household, and mobility-related factors [17]. Related research has also identified connections between the built environment, vehicle ownership, and travel behavior [7], [10]. Within the MTF, vehicle ownership represents an intermediate stage through which upstream structural pressures are associated with subsequent private vehicle usage and traffic-system conditions.

Transport System Performance was significantly associated with Private Vehicle Usage ($\beta = 0.27$, $p < 0.001$), while the direct relationship between Population Growth and Private Vehicle Usage was not statistically significant ($\beta = -0.06$, $p = 0.68$). Together with the significant Population Growth → Vehicle Ownership Pressure and Vehicle Ownership Pressure → Private Vehicle Usage pathways, this finding is consistent with an indirect relationship between population-related pressure and travel behavior through vehicle ownership. This interpretation aligns with previous research examining the mediating role of vehicle ownership in the relationship between built-environment conditions and travel behavior [10], [15].

At the downstream stage, Private Vehicle Usage showed a significant positive relationship with Traffic System Stress (Y3) ($\beta = 0.34$, $p < 0.001$). Population Growth ($\beta = 0.35$, $p = 0.02$) and Transport System Performance ($\beta = 0.16$, $p < 0.01$) were also significantly associated with Traffic System Stress. In contrast, Vehicle Ownership Pressure showed a non-significant direct relationship with Traffic System Stress ($\beta = -0.06$, $p = 0.73$). These results indicate that private vehicle usage is more directly associated with perceived traffic-system stress than vehicle ownership pressure itself, while structural conditions also contribute to downstream operational outcomes.

Comparable studies provide further context for interpreting these relationships. Ding et al. [21] demonstrated that car ownership and travel distance mediate the relationships between built-environment characteristics and travel-mode choice in Baltimore, while Ashik et al. [22] identified intermediary roles for car ownership and commuting distance in Dhaka, Bangladesh. Although differences in construct definitions and model specifications limit direct numerical comparisons, these studies support the importance of intermediate behavioral mechanisms. In the present MTF, the standardized coefficients indicate that Population Growth has a stronger association with Vehicle Ownership Pressure ($\beta = 0.74$) than Transport System Performance has with Private Vehicle Usage ($\beta = 0.27$), while Vehicle Ownership Pressure is positively associated with Private Vehicle Usage ($\beta = 0.50$). The MTF extends these earlier approaches by explicitly connecting private vehicle usage with Traffic System Stress ($\beta = 0.34$) and subsequently with Mobility Sustainability ($\beta = 0.83$).

Traffic System Stress exhibited the strongest direct relationship with Mobility Sustainability (Z) ($\beta = 0.83$, $p < 0.001$). In contrast, the direct relationships of Private Vehicle Usage ($\beta = 0.05$, $p = 0.56$), Vehicle Ownership Pressure ($\beta = 0.35$, $p = 0.07$), Transport

System Performance (β = −0.03, p = 0.58), and Population Growth (β = −0.26, p = 0.12) with Mobility Sustainability were not statistically significant. These findings suggest that upstream structural and behavioral conditions are associated with mobility sustainability primarily through intermediate mobility mechanisms rather than through direct pathways alone. The distinctive contribution of the MTF is its integration of structural pressures, vehicle ownership, private vehicle usage, traffic-system stress, and mobility sustainability within a unified hierarchical and process-based framework. The direct, indirect, and total effects are examined further in Section 3.6.

Table 4. Standardized structural and behavioral pathways

No.	Path	β	*p*-value	Result
1	X1 → Y1	0.07	0.21	Not significant
2	X2 → Y1	0.74	<0.001	Significant
3	X2 → Y2	−0.06	0.68	Not significant
4	X1 → Y2	0.27	<0.001	Significant
5	Y1 → Y2	0.50	0.01	Significant
6	Y1 → Y3	−0.06	0.73	Not significant
7	Y2 → Y3	0.34	<0.001	Significant
8	X2 → Y3	0.35	0.02	Significant
9	X1 → Y3	0.16	<0.01	Significant
10	Y3 → Z	0.83	<0.001	Significant
11	Y2 → Z	0.05	0.56	Not significant
12	Y1 → Z	0.35	0.07	Not significant
13	X1 → Z	−0.03	0.58	Not significant
14	X2 → Z	−0.26	0.12	Not significant

Source: Authors' analysis using AMOS (2025).
Note: X1 = Transport System Performance; X2 = Population Growth; Y1 = Vehicle Ownership Pressure; Y2 = Private Vehicle Usage; Y3 = Traffic System Stress; Z = Mobility Sustainability.

The complete structural model of the MTF is presented in **Figure 2**. The model illustrates the simultaneous relationships among Transport System Performance (X1), Population Growth (X2), Vehicle Ownership Pressure (Y1), Private Vehicle Usage (Y2), Traffic System Stress (Y3), and Mobility Sustainability (Z), including both statistically significant and non-significant pathways. This representation provides a comprehensive overview of the structural and behavioral relationships tested within the MTF and forms the basis for identifying the empirically supported mobility-transition pathways.

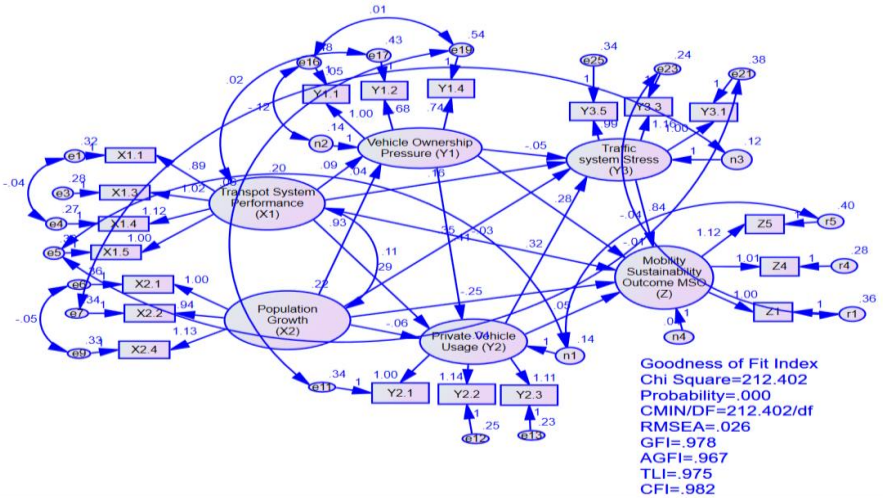


Figure 2. Structural Equation Model of the Mobility Transition Framework (MTF)
Source: Authors' analysis using AMOS (2025).

3.5 Traffic System Stress and Mobility Sustainability

The downstream stage of the MTF identifies Traffic System Stress (Y3) as the principal operational mechanism associated with Mobility Sustainability (Z). Traffic System Stress exhibited the strongest statistically significant direct relationship with Mobility Sustainability (β = 0.83, $p < 0.001$),

highlighting the central role of perceived traffic-system conditions within the mobility-transition process.

The model demonstrated substantial explanatory power for Mobility Sustainability ($R^2 = 0.82$), as illustrated in **Figure 3**. This finding indicates that the MTF accounts for 82% of the observed variance in the final sustainability construct. Together with the non-significant direct relationships between upstream constructs and Mobility Sustainability, the results support a process-based interpretation in which structural and behavioral conditions are associated with sustainability primarily through intermediate mobility mechanisms.

These findings emphasize the importance of addressing traffic-system stress within integrated urban mobility strategies. Rather than focusing exclusively on vehicle ownership or infrastructure provision, sustainable mobility policies in rapidly motorizing cities such as Dili should also consider private vehicle usage, traffic operations, and the structural conditions associated with traffic-system performance.

3.6 Direct, Indirect, and Total Effects

To further examine how upstream structural conditions are associated with downstream mobility outcomes through intermediate mechanisms, the direct, indirect, and total effects were estimated using SEM–AMOS. As presented in **Table 5**, these estimates provide additional insight into the sequential relationships represented in the MTF, beyond the individual structural coefficients discussed in Section 3.4.

Population Growth (X2) exhibited a strong direct effect on Vehicle Ownership Pressure (Y1) (0.740). Although its direct effect on Private Vehicle Usage (Y2) was negative and relatively small (−0.060), its indirect effect through Vehicle Ownership Pressure was positive (0.370), resulting in a total effect of 0.310. Similarly, the total effect of Population Growth on Traffic System Stress (Y3) was 0.411, comprising a direct effect of 0.350 and an indirect effect of 0.061. These findings illustrate how population-related pressures are associated with downstream mobility conditions through both direct and intermediate pathways.

Vehicle Ownership Pressure (Y1) showed a direct effect of 0.500 on Private Vehicle Usage (Y2). Its direct effect on Traffic System Stress was negative (−0.060), whereas its indirect effect through Private Vehicle Usage was positive (0.170), producing a total effect of 0.110. This pattern highlights the role of actual private vehicle usage as an intermediate behavioral mechanism linking ownership pressure to traffic-system conditions.

The effects on Mobility Sustainability (Z) further illustrate the sequential structure of the MTF. Population Growth showed a direct effect of −0.260 and an indirect effect of 0.616, resulting in a total effect of 0.356. Similarly, Transport System Performance (X1) exhibited a direct effect of −0.030 and an indirect effect of 0.255, yielding a total effect of 0.225. Vehicle Ownership Pressure and Private Vehicle Usage also demonstrated positive indirect effects on Mobility Sustainability (0.116 and 0.282, respectively). In contrast, Traffic System Stress (Y3) showed a dominant direct effect of 0.830 on Mobility Sustainability, reinforcing its central position in the downstream stage of the MTF.

Overall, the direct, indirect, and total effects provide further evidence of the process-based structure of the MTF. The findings suggest that the relationships between upstream structural conditions and mobility sustainability are not adequately characterized by direct pathways alone but also involve intermediate stages of vehicle ownership, private vehicle usage, and traffic-system stress. These results support the interpretation of the MTF as an integrated structural–behavioral framework for understanding mobility-transition mechanisms in rapidly motorizing cities.

Table 5. Direct, indirect, and total effects of the MTF

Relationship	Direct Effect	Indirect Effect	Total Effect
X1 → Y1	0.070	0.000	0.070
X2 → Y1	0.740	0.000	0.740
X1 → Y2	0.270	0.035	0.305
X2 → Y2	−0.060	0.370	0.310
Y1 → Y2	0.500	0.000	0.500
X1 → Y3	0.160	0.100	0.260
X2 → Y3	0.350	0.061	0.411
Y1 → Y3	−0.060	0.170	0.110
Y2 → Y3	0.340	0.000	0.340
X1 → Z	−0.030	0.255	0.225
X2 → Z	−0.260	0.616	0.356
Y1 → Z	0.350	0.116	0.466
Y2 → Z	0.050	0.282	0.332
Y3 → Z	0.830	0.000	0.830

Source: Author's analysis using AMOS (2025).

Note: X1 = Transport System Performance; X2 = Population Growth; Y1 = Vehicle Ownership Pressure; Y2 = Private Vehicle Usage; Y3 = Traffic System Stress; Z = Mobility Sustainability. Direct effects were obtained from the standardized regression weights reported by SEM–AMOS. Indirect effects were calculated by summing the products of standardized path coefficients across all relevant mediating pathways in the MTF structural model. Total effects represent the sum of direct and indirect effects. All values are reported to three decimal places using rounded standardized coefficients.

3.7 Empirical Mobility Transition Framework and Theoretical Contribution

The structural results provide empirical support for a hierarchical and process-based interpretation of

urban mobility transition in Dili. Rather than treating mobility sustainability as the direct outcome of individual structural or behavioral factors, the MTF integrates interconnected mechanisms through which upstream structural pressures are associated with vehicle ownership, private vehicle usage, traffic-system conditions, and downstream sustainability outcomes. The empirically supported pathways and explanatory power of the endogenous constructs are synthesized in Figure 3.

The empirical MTF identifies a sequential pattern linking Population Growth (X2), Vehicle Ownership Pressure (Y1), Private Vehicle Usage (Y2), Traffic System Stress (Y3), and Mobility Sustainability (Z). Transport System Performance (X1) also contributes to the framework through its relationships with private vehicle usage and traffic-system stress. Together, these relationships suggest that urban mobility transition is better understood as an interconnected structural–behavioral–operational process than as a set of isolated relationships between individual determinants and sustainability outcomes.

The direct, indirect, and total effects further support this interpretation. Several upstream constructs exhibited statistically non-significant direct relationships with Mobility Sustainability while showing positive estimated indirect effects through intermediate constructs. This distinction highlights the analytical importance of considering the full network of structural pathways rather than relying exclusively on direct associations. The MTF therefore provides a framework for examining how structural conditions are linked to downstream sustainability outcomes through intermediate ownership, behavioral, and operational mechanisms.

The theoretical contribution of the MTF lies not in establishing that population growth, vehicle ownership, travel behavior, traffic conditions, and sustainability are individually related, but in integrating these dimensions within a unified hierarchical and process-based framework. Previous research has examined relationships among built-environment conditions, vehicle ownership, mode choice, car dependency, and travel behavior [10], [12], [15]. Recent quasi-experimental evidence has also highlighted the relationship between built-environment conditions, car ownership, and downstream environmental outcomes, including PM2.5 [18]. Similarly, operational transport research has emphasized the relevance of traffic performance to sustainable mobility [14]. Building on these perspectives, the MTF contributes an integrated representation of the structural, behavioral, and operational mechanisms associated with mobility sustainability, explicitly positioning Traffic System Stress as a central downstream construct.

This contribution is particularly relevant to rapidly motorizing emerging capitals, where growth in private vehicle ownership and usage may outpace improvements in transport infrastructure and sustainable mobility alternatives. In the context of Dili, the empirical findings suggest that sustainability-related mobility conditions cannot be adequately understood through upstream structural pressures alone. Instead, attention must also be directed toward the intermediate processes linking population growth, vehicle ownership pressure, private vehicle usage, and traffic-system stress. Although the cross-sectional research design does not establish causal transitions over time, the MTF provides an empirically supported structural representation of these interconnected mobility mechanisms.

Accordingly, the empirical MTF offers both a theoretical framework for understanding mobility-transition mechanisms and a structured basis for identifying potential policy intervention points. Upstream interventions may address structural and vehicle-ownership pressures, intermediate interventions may influence private vehicle usage, and downstream interventions may focus on reducing traffic-system stress. This hierarchical perspective connects the theoretical contribution of the MTF with the integrated policy implications discussed in the following section.

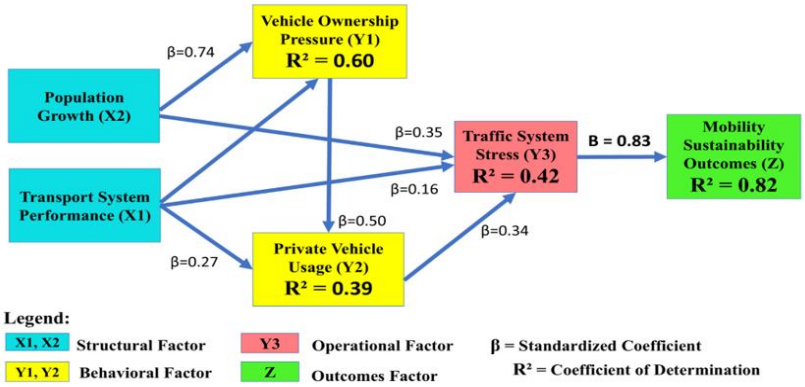


Figure 3. Empirical Mobility Transition Framework
Source: Authors' analysis using AMOS (2025).

Note: Figure 3 illustrates the selected statistically significant pathways and coefficients of determination (R^2) of the empirical MTF. The complete set of estimated structural relationships is presented in **Table 4** and **Figure 2**.

3.8 Policy Implications

The empirical findings of the MTF suggest that mobility sustainability in Dili should be addressed through coordinated interventions across the upstream, intermediate, and downstream stages of the mobility-transition process rather than through isolated policy measures. The identified relationships among population growth, vehicle ownership pressure, private vehicle usage, traffic-system stress, and mobility sustainability provide a structured basis for developing integrated transport and urban-development strategies.

At the upstream level, policy interventions should focus on aligning transport provision with urban growth and managing the structural conditions associated with increasing private motorization. This requires closer coordination between urban development, land-use planning, and transport investment to reduce long-term dependence on private motorized travel. Integrating land-use and transport planning across spatial and institutional scales can help align urban expansion with sustainable mobility objectives [19]. For Dili, such coordination is particularly important in anticipating future travel demand and improving accessibility as urban development progresses.

At the intermediate level, the significant relationship between Private Vehicle Usage (Y2) and Traffic System Stress (Y3) highlights the importance of managing dependence on motorcycles and private cars. Priority measures should include improving the reliability, accessibility, and attractiveness of public transport, complemented by appropriate travel-demand management strategies. Evidence that improvements in public transport performance can encourage shifts toward higher-capacity transport modes [11] supports the provision of viable alternatives to private vehicle use. These measures should be integrated with land-use and transport planning to discourage the continued expansion of private-vehicle-dependent travel patterns.

At the downstream level, Traffic System Stress (Y3) represents a central operational intervention point because of its strong association with Mobility Sustainability (Z). Improving intersection performance, traffic-signal coordination, corridor operations, parking management, and overall network efficiency may help reduce operational traffic pressures in Dili. Previous traffic-management research has demonstrated that targeted operational interventions can reduce delays and improve road level of service [14]. Nevertheless, operational improvements should complement, rather than replace, upstream and intermediate interventions addressing the underlying pressures associated with increasing private motorization.

The direct and indirect effects further reinforce the importance of coordinated interventions across these three levels. Upstream policies can address structural pressures and transport provision, intermediate policies can influence vehicle ownership and usage through improved mobility alternatives and travel-demand management, and downstream policies can improve traffic-system operations. Rather than treating congestion as an isolated problem, this integrated approach recognizes the interconnected structural, behavioral, and operational mechanisms represented in the MTF.

For Dili, the MTF therefore supports a phased mobility-transition strategy combining long-term land-use–transport coordination, medium-term public transport improvements and travel-demand management, and shorter-term traffic-system optimization. These interventions should be implemented as complementary components of an integrated urban mobility policy. Such a strategy may also be relevant to other rapidly motorizing emerging capitals facing similar challenges of urban growth, private vehicle dependence, and limited transport-system capacity.

Nevertheless, the proposed policy directions should be interpreted as evidence-informed planning recommendations rather than definitive causal prescriptions. Given the cross-sectional and perception-based nature of the study, further longitudinal and context-specific evaluations would be required to establish the effectiveness of individual interventions and their combined impacts on mobility sustainability.

4 Conclusion

This study developed and empirically evaluated a perception-based Mobility Transition Framework (MTF) to explain the interconnected relationships among structural conditions, vehicle ownership, private vehicle usage, traffic-system stress, and mobility sustainability in Dili, Timor-Leste. Based on survey data from 1,001 urban road users and Covariance-Based Structural Equation Modeling (CB-SEM), the findings support a hierarchical and process-based interpretation of urban mobility transition, in which upstream structural pressures are associated with downstream sustainability outcomes through intermediate ownership, behavioral, and operational mechanisms.

The empirical findings identify a sequential mobility-transition mechanism linking Population Growth, Vehicle Ownership Pressure, Private Vehicle Usage, Traffic System Stress, and Mobility Sustainability. Transport System Performance also contributes to the framework through its relationships with private vehicle usage and traffic-system stress. The results indicate that upstream structural and behavioral conditions are associated with sustainability outcomes not only through direct relationships but also through indirect pathways

involving intermediate mobility processes. In particular, Traffic System Stress emerges as the principal downstream operational construct associated with Mobility Sustainability.

The main theoretical contribution of the MTF lies in integrating structural pressures, vehicle ownership, private vehicle usage, traffic-system conditions, and sustainability outcomes within a unified hierarchical and process-based framework. Rather than examining these dimensions as isolated determinants, the MTF provides an integrated representation of their interconnected relationships and identifies the intermediate mechanisms through which urban motorization pressures are associated with downstream mobility sustainability. This mechanism-oriented perspective extends existing approaches to understanding mobility challenges in rapidly motorizing cities.

From a policy perspective, the findings highlight the importance of coordinated interventions across the mobility-transition process. For Dili, an integrated strategy should combine land-use–transport coordination, improved public transport provision, travel-demand management, management of private motorization, and traffic-system optimization. Addressing upstream structural conditions, intermediate ownership and usage patterns, and downstream traffic-system stress as complementary intervention points may provide a more comprehensive approach to sustainable urban mobility planning than isolated measures targeting congestion or vehicle ownership alone.

The study is limited by its cross-sectional, perception-based design and its empirical focus on a single emerging capital. Consequently, the estimated relationships should be interpreted as structural associations rather than definitive causal effects. Future research should validate the MTF using longitudinal and objective transport data, examine its applicability across other rapidly motorizing cities, and evaluate the potential effects of alternative transport and land-use policy scenarios on mobility-transition mechanisms.

5 Acknowledgement

The authors gratefully acknowledge the financial and institutional support of the Government of Timor-Leste, the valuable participation of all survey respondents, and the guidance and constructive feedback provided by the academic supervisors throughout this research.

References

[1] Y. D. Tazzie, D. Adugna, and B. Woldetensae, "Sustainable transport strategies and their implementation barriers in Addis Ababa, Ethiopia," *Frontiers in Sustainable Cities*, vol. 7, Art. no. 1524020, 2025, doi: 10.3389/frsc.2025.1524020.

[2] D. Oviedo, C. Cavoli, C. Levy, B. Koroma, J. Macarthy, O. Sabogal, F. Arroyo, and P. Jones, "Accessibility and sustainable mobility transitions in Africa: Insights from Freetown," *Journal of Transport Geography*, vol. 105, Art. no. 103464, 2022, doi: 10.1016/j.jtrangeo.2022.103464.

[3] V. Vasudevan, R. Agarwala, and S. Dash, "Is vehicle ownership in urban India influenced by the availability of high quality dedicated public transit systems?," *IATSS Research*, vol. 45, no. 3, pp. 286–292, 2021, doi: 10.1016/j.iatssr.2020.12.005.

[4] M. R. M. Da Cruz, D. M. P. Wedagama, P. A. Suthanaya, and A. A. G. A. Yana, "Perception-Based Model of Urban Road Level of Service in Dili, Timor Leste," *Civil Engineering and Architecture*, vol. 13, no. 5, pp. 3656–3667, 2025, doi: 10.13189/cea.2025.130514.

[5] A. Soltani, "Social and urban form determinants of vehicle ownership; evidence from a developing country," *Transportation Research Part A: Policy and Practice*, vol. 96, pp. 90–100, 2017, doi: 10.1016/j.tra.2016.12.010.

[6] B. Badarinath, T. N. Mazumder, and A. Das, "Examining effects of city's size and regional context on vehicle ownership levels in the Indian context," *Transportation Research Part D: Transport and Environment*, vol. 108, Art. no. 103279, 2022, doi: 10.1016/j.trd.2022.103279.

[7] C. Doddamani and M. Manoj, "Residential relocation and changes in household vehicle ownership and travel behavior," *Transportation Research Part A: Policy and Practice*, vol. 164, pp. 134–155, 2022, doi: 10.1016/j.tra.2022.08.008.

[8] P. Saeidizand, P. Savieri, and K. Boussauw, "Car dependency contributors in global metropolitan areas over time," *Journal of Transport Geography*, vol. 123, Art. no. 104152, 2025, doi: 10.1016/j.jtrangeo.2025.104152.

[9] N. S. Abdul Sukor, S. F. M. Fisal, K. Zahra, and D. Dissanayake, "The role of transport facilities, land use, and population density in reducing car dependency: A structural equation modelling approach," *Journal of Transport & Health*, vol. 42, Art. no. 101976, 2025, doi: 10.1016/j.jth.2024.101976.

[10] S. Yang, L. Zhou, Z. Zhang, H. Li, L. Guo, X. Sun, and T. Song, "Revisiting the causal relationship between the built environment, automobile ownership, and mode choice using double machine learning," *Journal of Transport Geography*, vol. 128, Art. no. 104379, 2025, doi: 10.1016/j.jtrangeo.2025.104379.

[11] G. Pratidina and M. O. Mahendra, "Modeling commuter mode shift to electric railway services: an integrated performance analysis and stated preference approach for the Rangkasbitung–Merak line," *Journal of Infrastructure Planning and Engineering*, vol. 5, no. 1, pp. 23–32, Apr. 2026, doi: 10.22225/jipe.5.1.2026.23-32.

[12] S. Sabouri, G. Tian, R. Ewing, K. Park, and W. Greene, "The built environment and vehicle ownership modeling: Evidence from 32 diverse regions in the U.S.," *Journal of Transport Geography*, vol. 93, Art. no. 103073, 2021, doi: 10.1016/j.jtrangeo.2021.103073.

[13] K. Martens, M. E. Singer, and A. L. Cohen-Zada, "Equity in Accessibility: Moving From Disparity to Insufficiency Analyses," *Journal of the American Planning Association*, vol. 88, no. 4, pp. 479–494, 2022, doi: 10.1080/01944363.2021.2016476.

[14] R. R. Prakasa *et al.*, "Application of the continuous green-t (CGT) intersection concept at signalized intersection to support sustainable mobility in peatland area," *Journal of Infrastructure Planning and Engineering*, vol. 5, no. 1, pp. 43–50, Apr. 2026, doi: 10.22225/jipe.5.1.2026.43-50.

[15] C. Ding, X. Zhou, X. J. Cao, and J. Yang, "Spatial and mediation analysis of the influences of residential and workplace built environments on commuting by car," *Transportation Research Part A: Policy and Practice*, vol. 171, Art. no. 103662, 2023, doi: 10.1016/j.tra.2023.103662.

[16] M. F. Zhang, J. F. Dawson, and R. B. Kline, "Evaluating the use of covariance-based structural equation modelling with reflective measurement in organizational and management research: A review and recommendations for best practice," *British Journal of Management*, vol. 32, no. 2, pp. 257–272, 2021, doi: 10.1111/1467-8551.12415.

[17] I. Sefriyadi, I. G. A. Andani, A. Raditya, P. F. Belgiawan, and N. A. Windasari, "Private car ownership in Indonesia: Affecting

factors and policy strategies," *Transportation Research Interdisciplinary Perspectives*, vol. 19, Art. no. 100796, 2023, doi: 10.1016/j.trip.2023.100796.

[18] L. Shi, Y. Jiang, F. Chen, K. Zhu, C. P. Nielsen, Y. Wang, F. Tian, J. Wu, and X. Chen, "Built environment, car ownership and PM2.5: Stronger causal estimates from a quasi-experiment," *Journal of Transport Geography*, vol. 127, Art. no. 104301, 2025, doi: 10.1016/j.jtrangeo.2025.104301.

[19] D. Xiao, L. Kamruzzaman, and H. L. Vu, "Land use and transport integration across scales: A review of evolving models and strategies for scaling up," *Transportation Research Interdisciplinary Perspectives*, vol. 32, Art. no. 101544, 2025, doi: 10.1016/j.trip.2025.101544.

[20] J. F. Hair, W. C. Black, B. J. Babin, and R. E. Anderson, Multivariate Data Analysis, 8th ed. Andover, UK: Cengage Learning, 2019.

[21] C. Ding, D. Wang, C. Liu, Y. Zhang, and J. Yang, "Exploring the influence of built environment on travel mode choice considering the mediating effects of car ownership and travel distance," Transportation Research Part A: Policy and Practice, vol. 100, pp. 65–80, 2017, doi: 10.1016/j.tra.2017.04.008.

[22] F. R. Ashik, H. Rahman, N. M. Zafri, A. Antipova, and S. M. Labib, "Car ownership, commute distance, and commute mode choice in the dense megacity of a developing country: The direct and indirect role of the built environment," Transportation Research Record, vol. 2678, no. 12, pp. 1923–1938, 2024, doi: 10.1177/03611981241253578.