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Exploring the Influence of Digital Competence on Older Pedestrians' Engagement with Autonomous Vehicles

Zhiwei LIU[1], Wenli OUYANG[2], Jie WU[3]

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[1] tonyliuzhiwei@whpu.edu.cn, School of Civil Engineering and Architecture, Wuhan Polytechnic University, Wuhan, China
[2] 172955640@qq.com, School of Civil Engineering and Architecture, Wuhan Polytechnic University, Wuhan, China
[3] Corresponding author, wujiemc@whpu.edu.cn, School of Civil Engineering and Architecture, Wuhan Polytechnic University, Wuhan, China

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ABSTRACT

As autonomous vehicles (AVs) become increasingly integrated into urban mobility systems, understanding how older pedestrians interact with these technologies is essential for ensuring inclusive and safe transportation. This study investigates the role of digital competence in shaping the behaviours and attitudes of older pedestrians toward autonomous vehicles (AVs) in China, where the rapid deployment of AVs coincides with an ageing population. Using data from a structured survey of 750 older pedestrians (aged ≥60 years) in Wuhan, this study employs item response theory (IRT) to measure individual digital competence. It integrates the technology acceptance model (TAM) and pedestrian behaviour questionnaire (PBQ) frameworks to explore behavioural mechanisms. Structural equation modelling (SEM) results reveal that perceived ease of use (PEU) significantly influences perceived usefulness (PU) and attitude (ATT), which in turn drive behavioural intention (BIU) to engage with AVs. However, positive pedestrian behaviours (e.g. rule adherence) exhibit a negative relationship with AV acceptance when external human-machine interfaces (eHMIs) are introduced, suggesting that safety-conscious individuals may be more cautious toward unfamiliar AV systems. Mixed-effects ordered logistic regression models, incorporating digital competence as a random effect, confirm its significant moderating role in both AV and eHMI interaction scenarios. Findings highlight the need for intuitive eHMI design, targeted digital literacy interventions, and policy efforts to reduce socioeconomic barriers to AV adoption. This study contributes to the literature by providing a multidimensional analysis of AV-pedestrian interaction grounded in psychometric measurement and behavioural theory, offering valuable implications for age-friendly smart mobility systems.

KEYWORDS

digital competence; autonomous vehicles (AVs); pedestrian behaviour; technology acceptance model (TAM); pedestrian behaviour questionnaire (PBQ); mixed-effects ordered logistic regression.

1. INTRODUCTION

The rapid advancement of AVs has significantly transformed urban transportation systems globally. Wuhan, the capital of Hubei Province and a major transportation hub in central China, was selected as the empirical setting for this study due to its pioneering role in AV deployment. As of 2024, Wuhan emerged as the world's largest AV operational area, operating nearly 500 AVs covering 3,378 kilometres of public roads, serving over 900,000 passengers in 2023 alone (China Daily, 2024). This large-scale implementation provides a realistic and technologically advanced urban environment to examine AV-pedestrian interaction patterns.

AV technology, driven by artificial intelligence (AI), offers considerable potential to improve road safety and traffic efficiency by reducing human errors [1, 2]. However, effective interaction between AVs and vulnerable road users, especially older pedestrians, remains challenging [3].

In this study, older pedestrians are defined as individuals aged 60 years or older, consistent with prior research [4]. Older pedestrians often experience age-related physical, sensory and cognitive declines, which impair their ability to make timely decisions and safely interact with AVs [5, 6]. Additionally, older adults typically have lower digital competence, hindering their interpretation of AV signals and digital interfaces [7, 8]. Digital competence, encompassing skills required for effective interaction with digital technologies, is increasingly essential for pedestrian safety in modern traffic environments [9]. However, the impact of digital competence on older pedestrians' interaction with AVs has received limited attention in the existing literature [10, 11].

While prior research has focused on a broad range of AV-related topics, the majority of studies have centred on younger or more digitally literate populations. These studies primarily explore how AVs can interact with pedestrians in general, without a specific focus on the challenges faced by older pedestrians. For instance, research by [12, 13] highlights how AVs can communicate with pedestrians through visual and auditory signals, but does not address how older pedestrians, who may face cognitive and sensory challenges, interpret these signals. In contrast, the current study explicitly targets older pedestrians, examining how their lower levels of digital competence affect their ability to safely interact with AVs.

Moreover, while digital competence has been studied in general technology adoption contexts [14, 15], few studies have specifically examined its role in the safety of older pedestrians in AV environments. Most studies on digital competence focus on younger populations or assess technology acceptance broadly without linking it to pedestrian behaviour [14-16]. This study builds on these earlier works by using IRT to measure digital competence in older pedestrians and investigating how varying levels of competence impact their perceptions and behaviours towards AVs. The present research also integrates the TAM and the PBQ, a combination not found in previous studies, to gain a multidimensional understanding of AV-pedestrian interactions.

Furthermore, Wuhan is experiencing a rapid demographic shift characterised by accelerated population ageing. The convergence of widespread AV deployment and a high density of older residents makes Wuhan an especially relevant and strategic location for investigating how digital competence shapes older pedestrians' perceptions and behaviours toward AVs. Its comprehensive AV infrastructure and sociotechnical complexity offer an ideal context for exploring the inclusivity, usability and safety of smart mobility systems in ageing societies.

Therefore, this research seeks to address these gaps by analysing the influence of digital competence on older pedestrians' behaviours when interacting with AVs, employing IRT for digital competence measurement and the PBQ for behaviour assessment.

The primary objective of this study is to investigate how digital competence impacts older pedestrians' behaviours and attitudes toward AVs. Specifically, the study aims to:

1) Assess digital competence among older pedestrians using IRT methods.
2) Examine how digital competence influences older pedestrians' perceptions (perceived usefulness, perceived ease of use), attitudes and behavioural intentions toward AVs based on TAM.
3) Analyse older pedestrians' behaviours (violations, errors, lapses and positive behaviours) toward AV interactions using the PBQ framework.

By achieving these objectives, this study aims to offer new insights into how digital competence influences older pedestrians' interaction with AVs, particularly in urban mobility contexts shaped by emerging technologies.

Unlike most prior research that centres on younger or general populations, this study focuses specifically on older pedestrians and their unique interaction challenges in AV environments. Moreover, by employing a multidimensional methodological approach that integrates IRT, the TAM and the PBQ, this research provides a novel framework for understanding how digital skills shape both perceptual and behavioural responses to AV technology.

2. LITERATURE REVIEW

2.1 Older pedestrians and AV interactions

Older pedestrians face distinct challenges when interacting with AVs, primarily due to age-related declines in cognitive, sensory and physical abilities [17, 18]. They often experience slower reaction times, difficulties accurately judging vehicle speeds and higher uncertainty when interpreting AV signals, increasing accident risks [6, 19]. Previous studies highlighted that older pedestrians show greater hesitation and anxiety toward AV technology, often resulting in overly cautious behaviour [20, 21].

Despite growing attention on pedestrian-AV interactions, research has predominantly focused on younger pedestrians, with limited attention to older adults [22, 23]. Furthermore, studies on AV interfaces (e.g. visual and auditory signals) have rarely accounted for older pedestrians' cognitive and sensory limitations [23-25]. To ensure the safety benefits of AVs are inclusive, it is essential to address these knowledge gaps, particularly examining how older pedestrians interpret AV signals and how their digital competence affects these interactions [26].

Research suggests that older adults often prioritise safety and explicit communication when interacting with AVs. For instance, Billings et al. emphasise that external human-machine interfaces (eHMIs) can enhance perceived safety by clearly communicating vehicle intentions to pedestrians [27]. This form of interaction is essential for older adults, who may have slower reaction times and require additional cues to feel secure in their interactions with AVs. In fact, researchers have found that different communication modalities are necessary to ensure that AVs do not only rely on conventional signals but also incorporate user-friendly eHMIs that resonate with older populations [28, 29].

2.2 Digital competence among older adults

Digital competence, defined as the ability to effectively utilise digital technologies, is crucial for navigating increasingly digitised urban environments [30]. Older adults often have lower digital literacy levels due to limited exposure, cognitive decline and physical impairments, resulting in potential digital exclusion [31]. This limited digital competence could negatively impact their interactions with digitally driven AV systems [32, 33].

IRT has proven effective in measuring digital competence, capturing diverse competencies across individuals [34, 35]. For instance, studies by Hämäläinen et al. [36] and Helsper and Eynon [37] highlighted that higher digital competence correlates positively with greater technology acceptance among older adults. Thus, using IRT can provide precise, individualised insights into older pedestrians' digital literacy levels, essential for understanding AV interactions.

2.3 Research on TAM

The TAM is a widely used theoretical framework that helps explain how users come to accept and use new technologies. Originally proposed by Davis (1989) [38], TAM posits that two key factors, PU and PEU, influence an individual's attitude towards using a new technology, which in turn affects their behavioural intention (BIU) to use the technology. TAM has proven effective in predicting technology adoption across diverse domains, including transportation systems, healthcare and education [39, 40]. PU is defined as the extent to which an individual believes that using a particular technology will enhance their performance or yield desirable outcomes in a specific context [41]. PEU refers to the degree to which an individual believes that using a particular technology will be free of effort [38]. An individual's attitude towards using a new technology is shaped by their perceptions of PU and PEU and reflects their positive or negative feelings about engaging with that technology [42]. Behavioural intention (BI) refers to an individual's intention to use or interact with a technology in the future [43].

TAM is particularly effective in explaining older adults' adoption and acceptance of transportation technologies [44, 45]. For older pedestrians, PU reflects beliefs that AVs enhance safety and mobility, while PEU represents the ease of interpreting and responding to AV signals [46, 47]. Positive perceptions of PU and PEU lead to favourable attitudes and stronger behavioural intentions toward AV usage, significantly influencing older pedestrians' safety behaviours [48, 49]. Therefore, investigating older pedestrians' PU and PEU regarding AVs is vital for enhancing their safety and acceptance in AV contexts [48, 54]. Integrating insights from TAM with behavioural studies can further enrich the understanding of older pedestrians' interactions with AVs. Examining psychological factors such as trust and perceived risk in correlation with the constructs of TAM can elucidate why older adults may be hesitant to embrace such technologies. Awareness and proactive measures to address these psychological barriers are pivotal in encouraging acceptance and promoting safe interactions with AVs [50].

2.4 Research on PBQ

The PBQ, introduced by Granié [51], classifies pedestrian behaviours into violations, errors, lapses, aggressive behaviours and positive behaviours. Violations include intentional rule-breaking, while errors involve unintentional mistakes, both increasing AV-pedestrian conflict risks [52, 53]. Lapses, such as distractions, also heighten accident risk, especially among older pedestrians who are vulnerable to attention deficits [51, 54]. Aggressive behaviours, though rare among older pedestrians, pose challenges for AV predictability [51, 55, 56]. Positive behaviours (e.g. adherence to signals) facilitate safer interactions. Understanding these behaviours through PBQ allows targeted improvements in AV design, communication systems and safety interventions specific to older pedestrians.

3. THEORETICAL FRAMEWORK AND HYPOTHESES

3.1 Measurement of digital competence using IRT

IRT was employed to precisely assess older pedestrians' digital competence, a latent trait reflecting their ability to effectively use digital technologies [57]. Five key items measuring engagement with smart devices, internet communication, online entertainment, economic transactions and digital learning were selected based on literature recommendations [58-61]. The IRT model generated individual digital competence scores (theta, θ), subsequently classified into three levels (high, medium, low) according to a percentile-based method [62]. This facilitated analysing the relationship between digital competence and pedestrian behaviour, particularly in AV interactions [63-65].

3.2 Integration of TAM and PBQ frameworks

The TAM was applied to evaluate older pedestrians' perceptions of AV technology, specifically PU and PEU, along with ATT and behavioural intention (BI) as mediating variables [38]. The behavioural indicators were derived from the established PBQ, which evaluates respondents' general traffic behaviour in everyday pedestrian contexts. These include violations (VIO), errors (ERR), lapses (LAP), aggressive behaviours (AGG) and positive behaviours (POS) [51].

Based on TAM and PBQ, the following streamlined hypotheses were proposed:

TAM-based hypotheses:

H1: PEU positively influences PU [66, 67].

H2: PU positively influences ATT [68].

H3: PEU positively influences ATT [68].

H4: ATT positively influences BIU [69].

H5: PU positively influences BIU [69].

PBQ-based hypotheses:

H6: Frequent violations reduce willingness to interact with AVs [51].

H7: Frequent errors negatively affect AV interaction acceptance [51].

H8: Lapses/distractions reduce willingness for AV interactions [51].

H9: Aggressive behaviours lower AV acceptance [55].

H10: Positive behaviours increase safe AV interaction willingness [70].

3.3 Mixed-effects ordered logistic regression (meologit)

A mixed-effects ordered logistic regression (meologit) model was selected for data analysis, suitable for modelling ordered outcomes like willingness to share roads with AVs (measured on a 5-point Likert scale). The model structure integrates fixed effects (PU, PEU, ATT, BI, POS, AGG, VIO, ERR and LAP) and random intercepts to account for individual-level variability related to digital competence [71]. The general model structure is:

$$log\frac{P(Y \leq j)}{(P(Y > j)} = \beta 0 + \beta_1 X_1 + \beta_2 X_2 \cdots + u_i \quad (1)$$

where:

τ_j are the threshold parameters (cut-points) for the ordinal categories,

Y represents the ordered pedestrian behaviour outcome for individual i,

j is the threshold for each category in the ordinal outcome,

X_i is a vector of fixed-effect predictors (including PU, PEU, ATT, BIU, POS, AGG, VIO, ERR, LAP and sociodemographic covariates),

$\beta_1, \beta_2, \cdots$ are the estimated coefficients for each fixed effect,

$u_i \sim N(0, \sigma_u^2)$ is the participant-specific random intercept, capturing unobserved heterogeneity across individuals.

The random effect u_i is modelled as a function of digital competence, which is treated as a latent variable estimated through the IRT framework. By including random intercepts, the model accounts for the variability in pedestrian behaviours that can be attributed to differences in individual digital competence beyond the influence of other fixed effects, such as attitudes or behavioural intentions. This random effect structure is critical for capturing how individual-level digital competence influences pedestrian behaviour in non-linear ways, allowing for personalised inferences regarding pedestrian safety in AV environments.

3.4 Summary of variables, measurement frameworks and sources

To enhance methodological transparency, *Table 1* summarises the latent variables, corresponding theoretical frameworks, analytical methods, conceptual definitions and literature sources from which items were adapted.

Table 1 – Summary of variables, methods, conceptual definitions and sources

Framework	Variable / Construct	Method used	Conceptual definition	Source
IRT	Digital competence (θ score)	2PL IRT Model	Individual's ability to use digital tools (smartphone, internet, e-commerce, digital learning)	Aesaert et al., 2014; Tennant & Conaghan, 2007 [35, 62]
TAM	PEU	SEM, Meologit	The degree to which a person believes using AVs would be free of effort	Davis, 1989 [72]
TAM	PU	SEM, Meologit	The degree to which a person believes using AVs would enhance their mobility or safety	Davis, 1989 [72]
TAM	Attitude toward use (ATT)	SEM	Affective evaluation of using AVs in real-world settings	Ajzen, 1991; Davis, 1989 [72, 73]
TAM	BIU	SEM, Meologit	The likelihood that a person will choose to share roads with AVs	Venkatesh & Davis, 2000 [39]
PBQ	Violations (VIO)	SEM, Meologit	Intentional rule-breaking pedestrian behaviour	Granié, 2009 [51]
PBQ	Errors (ERR)	SEM, Meologit	Unintentional mistakes made during road crossing (e.g. misjudging vehicle speed)	Granié, 2009 [51]
PBQ	Lapses (LAP)	SEM, Meologit	Distractions or memory failures during pedestrian activity	Granié, 2009 [51]
PBQ	Aggressive behaviours (AGG)	SEM, Meologit	Hostile or impatient behaviour toward traffic	Yadav et al., 2023 [55]
PBQ	Positive behaviours (POS)	SEM, Meologit	Rule-following, careful, and proactive pedestrian actions	Ma et al., 2013 [70]
Sociodemographics	Gender, age, education, income, job status, car ownership, traffic accident history	Meologit (control variables)	Personal and household background characteristics that may affect AV interaction willingness	Modelled after standard sociodemographic control variables in behavioural transport studies

4. METHODOLOGY

4.1 Research design

This study integrates IRT, TAM and PBQ into a unified research framework to evaluate how digital competence affects older pedestrians' behaviour towards AVs. Using IRT, we measured digital competence through five key indicators covering device usage, online communication, entertainment, economic activities and digital learning [58-60]. Digital competence scores (θ values) were categorised into high, medium and low levels based on a percentile-based classification of theta scores [62].

The TAM framework assessed PU, PEU, attitudes (ATT) and behavioural intentions (BI) toward AV technology [38]. PBQ captured pedestrian behaviours, including violations, errors, lapses/distractions, aggressive behaviours and positive behaviours [51]. Combining these models provides a holistic analysis linking cognitive factors to actual pedestrian behaviours. In addition to the basic AV interaction scenario, the study also involved an external human-machine interface (eHMI) scenario. The eHMI system provided real-time visual and auditory cues to facilitate communication between the vehicle and pedestrians. This scenario aimed to assess whether the presence of such an interface would enhance older pedestrians' willingness to engage with AVs. The structured survey questionnaire used in this study is provided in **Appendix A**, including all items related to digital competence, pedestrian behaviour and AV interaction.

4.2 Data collection

A structured questionnaire was administered to 750 older pedestrians (aged ≥60 years) in Wuhan, China, between 1 June 2024 and 30 July 2024. The structured questionnaire presented two distinct AV interaction scenarios: one where participants were asked to evaluate their willingness to share the road with AVs without an eHMI system, and another where they were asked to evaluate AVs with an eHMI system. The questions pertaining to these scenarios measured perceived ease of use, perceived usefulness and their willingness to share the road with AVs in both conditions. The eHMI system was introduced to assess its potential role in improving communication and safety for older pedestrians. Stratified random sampling was employed using administrative districts and age groups to ensure representativeness across socioeconomic and geographic strata. Data collection was conducted in urban and suburban areas with a high prevalence of older pedestrians, such as community centres, parks, public transportation hubs and senior living facilities. The two-month data collection period was designed to capture potential seasonal variations in pedestrian behaviour.

To accommodate different levels of digital competence, both paper-based and tablet-assisted questionnaires were utilised. Trained survey administrators were present to assist participants with reading difficulties, thereby ensuring accessibility and response accuracy. All procedures strictly adhered to ethical standards, with informed consent obtained from each participant prior to participation. To ensure the inclusion of cognitively capable individuals, we used a screening question in the survey to identify participants who might have significant cognitive impairments (e.g. dementia). Participants were asked about their ability to independently complete the survey, with assistance provided if necessary. Individuals who self-reported significant cognitive impairments, or who were identified by survey administrators as unable to complete the questionnaire meaningfully, were excluded from the study.

The questionnaire comprised four main sections:

1) *Socioeconomic information*: This section collected demographic and socioeconomic data, including age, gender, education level, household income, employment status, car ownership and past experience with pedestrian traffic incidents.
2) *Digital competence assessment*: Digital competence was assessed using an IRT-based framework, evaluating participants' ability to use smart devices, engage in online communication, participate in digital economic activities and acquire digital learning. This section aims to capture various facets of digital literacy pertinent to interacting with AVs.
3) *Latent variables*: Latent variables from the TAM and the PBQ were measured using a five-point Likert scale. These variables included perceived usefulness (PU), perceived ease of use (PEU), attitude (ATT), behavioural intention (BIU) and violations (VIO), errors (ERR), lapses (LAP), aggressive behaviour (AGG) and positive behaviour (POS). Detailed measurement items are provided in *Table 1*.
4) *Willingness to share roads with AVs*: This section assessed participants' willingness to share the road with AVs under scenarios both with and without an eHMI system. A five-point Likert scale ranging from "strongly disagree" to "strongly agree" was used to capture participants' responses.

Eligible participants were required to be aged 60 years or older, capable of independent walking, and able to respond to the questionnaire independently or with minimal assistance. Importantly, participants were screened using an explicit survey question to confirm that they had personally encountered or interacted with autonomous vehicles during their regular pedestrian activities. Respondents without any direct exposure to AVs were excluded from the final sample to ensure the validity of measuring their PU and PEU based on direct experiences, as required by the TAM. Additionally, individuals with significant cognitive impairments that could hinder meaningful engagement with the survey were excluded. All survey administrators received training to standardise the data collection process and provide necessary assistance to participants.

4.3 Descriptive statistics

This section presents the demographic and socio-economic characteristics of the sample, along with the distribution of digital competence among the respondents. The sample consisted of 750 older pedestrians, with key characteristics summarised in *Table 2*. The descriptive statistics provide an overview of the socio-demographic profile of the older participants, which includes gender distribution, age, educational attainment, household income, employment status, household size, car ownership and traffic accident history.

The gender distribution is relatively balanced, with 48.80% male and 51.20% female participants. The majority of participants are aged between 60-65 years (41.33%), followed by 28.93% in the 66-70 age group, 19.33% aged 71-75 and 10.40% aged 76 or above. Educational attainment shows a skew towards lower levels, with 57.07% of the participants having completed elementary school or below, while 30.00% have completed middle school, and only 1.60% have attained a university-level education or higher. Household income distribution reveals that 66.93% earn CNY 3,000 or below, and 30.00% earn between CNY 3,001-5,000 per month, indicating relatively low-income levels among the sample.

Regarding employment status, 83.73% of respondents are retired, with only 1.73% engaged in full-time work and 1.33% in part-time employment. Household size primarily consists of three-member households (37.73%), followed by two-member (17.33%) and four-member households (32.80%). A significant proportion (72.27%) of respondents report owning a car, while 88.40% possess IC cards for public transportation.

In terms of traffic accident history, 66.93% of participants have never been involved in an accident, while 18.13% report having experienced 1-2 traffic incidents. Digital engagement is relatively low, with 31.47% owning and using smart devices, 28.53% using the internet for communication, 32.53% for entertainment, 35.47% for economic activities and 34.80% for learning professional knowledge. These findings underscore the socio-economic challenges and limited digital engagement prevalent among this older population, which may influence their interaction with technology, including AVs.

Table 2 – Sample distribution of socio-demographics (N = 750).

Variable	Level	Frequency	Ratio (%)
Gender	Male	366	48.80%
	Female	384	51.20%
Age	60-65 years	310	41.33%
	66-70 years	217	28.93%
	71-75 years	145	19.33%
	76 years and above	78	10.40%
Education level	Elementary school or below	428	57.07%
	Middle school	225	30.00%
	High school or vocational school	85	11.33%
	University or higher	12	1.60%
Household monthly income (CNY)	3,000 or below	502	66.93%
	3,001-5,000	225	30.00%
	5,001-10,000	14	1.87%
	10,001-20,000	6	0.80%
	20,001 or above	3	0.40%

Variable	Level	Frequency	Ratio (%)
Employment status	Full-time	13	1.73%
	Part-time	10	1.33%
	Retired	628	83.73%
	Unemployed	99	13.20%
Car ownership (car)	Yes	542	72.27%
	No	408	54.40%
Possession of identification card (ICard)	Yes	663	88.40%
	No	87	11.60%
Involvement in traffic incidents (last 2 years)	0	502	66.93%
	1-2	136	18.13%
	3-4	70	9.33%
	5 or more	42	5.60%
Ownership and use of smart devices	Yes	236	31.47%
	No	514	68.53%
Use of the internet for communication	Yes	214	28.53%
	No	536	71.47%
Use of the internet for entertainment	Yes	244	32.53%
	No	506	67.47%
Use of the internet for economic activities	Yes	266	35.47%
	No	484	64.53%
Use of the internet for learning professional knowledge	Yes	261	34.80%
	No	489	65.20%

4.4 Reliability and validity analysis

To ensure the reliability and validity of the constructs used in this study, we conducted reliability analysis using Cronbach's alpha (α) and composite reliability (CR), while convergent and discriminant validity were assessed using average variance extracted (AVE) and Fornell-Larcker criterion. The findings are summarised in *Tables 3* and *4*.

Reliability analysis

Reliability was assessed using Cronbach's alpha and CR. All constructs exceeded the recommended threshold of 0.70 for Cronbach's alpha, indicating good internal consistency among the items. For example, Cronbach's alpha for "positive behaviours" was 0.9068, while for "perceived ease of use" it was 0.815, demonstrating strong reliability across constructs. CR values for all latent variables also exceeded 0.70, confirming adequate reliability [74].

Convergent validity

Convergent validity was evaluated by examining the AVE values for each construct. An AVE greater than 0.50 indicates that the construct explains more than half of the variance of its indicators. As shown in *Table 3*, all constructs had AVE values above the 0.50 threshold, ensuring convergent validity [75]. For instance, "attitude" had an AVE of 0.574, while "behavioural intention" had an AVE of 0.606, supporting the constructs' validity.

Table 3 – Reliability and convergent validity of constructs

Latent variables	Code	Means	SD	Standardised factor loading	Cronbach's	CR	AVE
Violations (VIO)	vio1	2.2707	1.1298	0.7808	0.8509	0.837	0.562
	vio2	2.2120	1.1163	0.7468			
	vio3	2.3627	1.1043	0.7628			
	vio4	2.2960	1.1240	0.7071			
Errors (ERR)	err1	2.0893	1.0944	0.7662	0.8615	0.848	0.583
	err2	2.0667	1.0670	0.7616			
	err3	2.1653	1.0922	0.7583			
	err4	2.2413	1.1562	0.767			
Lapses (LAP)	lap1	2.0453	1.0441	0.7664	0.8616	0.849	0.585
	lap2	1.9933	1.0393	0.7753			
	lap3	2.1493	1.0957	0.7508			
	lap4	2.1853	1.1114	0.766			
Aggressive behaviours (AGG)	agg1	2.1333	1.1111	0.8097	0.8604	0.848	0.583
	agg2	2.0320	1.0847	0.7761			
	agg3	2.1280	1.0874	0.7015			
	agg4	2.2480	1.1461	0.7633			
Positive behaviours (PB)	pb1	2.6573	1.3280	0.8193	0.9068	0.898	0.688
	pb2	2.7040	1.3417	0.832			
	pb3	2.7667	1.3226	0.8304			
	pb4	2.6893	1.2608	0.836			
PU	pu1	3.7760	1.1441	0.7851	0.8286	0.799	0.57
	pu2	3.7960	1.1344	0.7563			
	pu3	3.6573	1.1339	0.7231			
Perceived ease of use (PEU)	peu1	3.7653	1.0917	0.7584	0.815	0.783	0.546
	peu2	3.8080	1.0891	0.7298			
	peu3	3.6467	1.1258	0.7272			
Attitude (ATT)	att1	3.8227	1.1151	0.7672	0.8308	0.802	0.574
	att2	3.8267	1.1389	0.7808			
	att3	3.7280	1.1265	0.7243			
Behavioural intention (BIU)	biu1	3.6440	1.1692	0.7834	0.8478	0.822	0.606
	biu2	3.8693	1.0871	0.7921			
	biu3	3.6467	1.1388	0.7591			

Discriminant validity

Discriminant validity was assessed using the Fornell-Larcker criterion, which compares the square root of the AVE for each construct with its correlations with other constructs. The results are presented in *Table 4*. The diagonal elements represent the square root of the AVE, and they are consistently greater than the off-diagonal correlations, indicating that each construct is distinct from the others. For example, the square root of the AVE for "behavioural intention" (0.778) is greater than its correlations with other constructs, confirming discriminant validity [76].

Table 4 – Results of the discriminant validity test

Constructs	1	2	3	4	5	6	7	8	9
Violations	0.750								
Errors	0.487	0.764							
Lapses	0.453	0.425	0.765						
Aggressive behaviours	0.417	0.406	0.366	0.764					
Positive behaviours	0.056	0.114	-0.021	0.009	0.829				
Perceived usefulness	-0.156	-0.117	-0.140	-0.098	-0.059	0.755			
Perceived ease of use	-0.381	-0.286	-0.343	-0.240	0.409	0.739	0.546		
Attitude	-0.174	-0.130	-0.156	-0.109	0.437	0.456	0.758	0.574	
Behavioural intention	-0.213	-0.190	-0.170	-0.186	0.336	0.287	0.456	0.386	0.778

5. RESULTS

5.1 Results of the IRT model

The two-parameter logistic (2PL) model was applied to assess the digital competence of 750 older individuals based on five key variables: ownership and use of smartphones (“iphone”), internet use for communication (“ichat”), internet use for entertainment (“ivideo”), internet use for economic activities (“ienco”) and internet use for learning professional knowledge (“ilearn”). The IRT model provides estimates for two main parameters: the discrimination parameter (Discrim) and the difficulty parameter (Diff). The discrimination parameter reflects how effectively each item differentiates between individuals with varying levels of digital competence, while the difficulty parameter indicates the level of digital competence required to answer each question affirmatively.

The results from the IRT 2PL model (*Table 5*) indicate that all five items had statistically significant discrimination and difficulty parameters ($p < 0.001$), suggesting that each item effectively differentiates individuals by their level of digital competence.

The “iphone” variable, representing smartphone use, had the highest discrimination value (Discrim = 4.689, $z = 7.22$, $p < 0.001$), indicating that this variable strongly differentiated individuals based on their digital skills. Its difficulty parameter (Diff = 0.507, $z = 11.53$, $p < 0.001$) shows that individuals needed a moderately high level of digital competence to report smartphone ownership and use.

“ichat”, which measures internet use for communication, had a lower discrimination value (Discrim = 3.053, $z = 9.04$, $p < 0.001$) compared to “iphone”, suggesting it was somewhat less effective at distinguishing between individuals with different levels of digital competence. The difficulty parameter for “ichat” was higher (Diff = 0.654, $z = 12.03$, $p < 0.001$), indicating that individuals required a higher level of competence for online communication than for smartphone use.

The variable “ivideo”, reflecting internet use for entertainment, also had a high discrimination value (Discrim = 4.127, $z = 7.73$, $p < 0.001$) and a moderate difficulty parameter (Diff = 0.489, $z = 10.89$, $p < 0.001$). This implies that digital competence plays a significant role in whether older individuals use the internet for entertainment.

“ienco”, which refers to internet use for economic activities, had a discrimination value of 3.799 ($z = 7.97$, $p < 0.001$) and a difficulty value of 0.415 ($z = 9.40$, $p < 0.001$), showing moderate difficulty and effective discrimination.

Finally, “ilearn”, which captures internet use for learning professional knowledge, had a discrimination parameter of 3.512 ($z = 8.32$, $p < 0.001$) and a difficulty parameter of 0.441 ($z = 9.62$, $p < 0.001$). This item was slightly easier than the others, indicating that learning online was accessible even to those with lower digital competence.

Table 5 – Two-parameter logistic model results

Variable	Discrimination (SE)	z-score	p-value	Difficulty (SE)	z-score	p-value
iphone	4.689 (0.649)	7.22	0.000	0.507 (0.044)	11.53	0.000
ichat	3.054 (0.338)	9.04	0.000	0.654 (0.054)	12.03	0.000
ivideo	4.128 (0.534)	7.73	0.000	0.489 (0.045)	10.89	0.000
ienco	3.799 (0.477)	7.97	0.000	0.415 (0.044)	9.40	0.000
ilearn	3.512 (0.422)	8.32	0.000	0.441 (0.046)	9.62	0.000

Following the IRT model, individual digital competence levels (theta values) were estimated. The mean estimated digital competence (theta) was 0.028 (SD = 0.830), with a range from -0.760 to 1.436. To classify participants' digital competence levels, we adopted a percentile-based method based on their theta scores (estimated using item response theory). Participants were categorised into three levels: low digital competence (bottom 25th percentile), moderate digital competence (26th to 75th percentile) and high digital competence (top 25th percentile). Thus, approximately 25% of the respondents, who predominantly reported minimal or no usage of smart devices and internet-based activities, were classified into the low digital competence group. This percentile-based method accurately captures the range of digital abilities within the older population, ensuring representation of individuals with varying digital literacy levels. The IRT results provide a robust framework for understanding the varying levels of digital competence among older populations. Smartphone usage and internet-based activities emerged as significant indicators of digital skills. These insights contribute to a broader understanding of digital inclusion among older individuals and serve as a foundation for future interventions aimed at improving digital literacy in this demographic.

5.2 Structural equation model (SEM) results

The structural equation model (SEM) was employed to explore the relationships between key latent variables, including PU, PEU, ATT, BIU, positive behaviours (POS), aggressive behaviours (AGG), violations (VIO), errors (ERR) and lapses (LAP). The model's fit was evaluated through multiple indices, all of which indicated a satisfactory fit. The chi-square test yielded a significant result ($\chi^2(439) = 831.308$, $p < .001$), suggesting that the model provided a significantly better fit compared to the baseline model. The root mean squared error of approximation (RMSEA) was 0.035, with a 90% confidence interval of 0.031 to 0.038, and a probability (pclose) of 1.000, indicating good model fit [77, 78] (Hu & Bentler, 1999). The comparative fit index (CFI) and Tucker-Lewis index (TLI) were 0.967 and 0.963, respectively, both exceeding the recommended threshold of 0.90, suggesting a strong model fit [79] (Bentler, 1990). Additionally, the standardised root mean squared residual (SRMR) was 0.066, within the acceptable range (below 0.08) [78] (Hu & Bentler, 1999). Lastly, the Akaike information criterion (AIC) and Bayesian information criterion (BIC) were 62689.823 and 63248.852, respectively, providing values for model comparison, where lower values suggest a better fit.

The parameter estimation results of the structural equation model, shown in *Table 6* and *Figure 1*, indicate that solid lines represent significant causal relationships at the 5% level, while dashed lines indicate non-significant causal relationships at the 5% level. PEU significantly and positively influenced PU ($\beta = 0.446$, $z = 9.09$, $p < .001$), indicating that when older pedestrians find autonomous vehicles (AVs) easy to use, they are more likely to consider them beneficial. PU also positively affected ATT ($\beta = 0.284$, $z = 6.53$, $p < .001$), supporting the notion that the perceived utility of AVs fosters positive attitudes. Furthermore, PEU significantly influenced ATT ($\beta = 0.343$, $z = 7.01$, $p < .001$), implying that user-friendly AV technology encourages positive attitudes among older pedestrians. Both PU and ATT had positive effects on BIU, with coefficients of 0.182 ($z = 3.72$, $p < .001$) and 0.278 ($z = 5.49$, $p < .001$), respectively, indicating that positive perceptions of AVs contribute to a greater willingness to engage with them.

Interestingly, positive behaviours (POS) had a negative effect on BIU ($\beta = -0.163$, $z = -4.83$, $p < .001$), suggesting that older pedestrians who exhibit cautious pedestrian behaviours may still show reluctance toward adopting new technologies like AVs. One possible explanation for this negative relationship is that older pedestrians who exhibit positive behaviours, such as strict adherence to traffic rules and careful navigation, may be more safety-conscious. These individuals could view AVs with scepticism, especially in the early stages of AV integration. They might prefer traditional modes of transportation where they have greater control over their safety, leading to lower willingness to engage with AVs, even though they exhibit positive pedestrian behaviours. Aggressive behaviours (AGG) demonstrated a marginally significant negative influence on BIU (β = -0.088, z = -1.87, p = 0.061), while violations (VIO), errors (ERR) and lapses (LAP) did not have significant effects, implying that these factors might not directly affect older pedestrians' willingness to share roads with AVs.

Table 6 – Structural model results

Hypothesis	Path	Coefficient	Std. err.	z	p-value	95% conf. interval
H1	PU ← PEU	0.446	0.049	9.09	0.000	0.350 to 0.542
H2	ATT ← PU	0.284	0.043	6.53	0.000	0.198 to 0.369
H3	ATT ← PEU	0.343	0.049	7.01	0.000	0.247 to 0.438
H4	BIU ← ATT	0.278	0.051	5.49	0.000	0.179 to 0.377
H5	BIU ← PU	0.182	0.049	3.72	0.000	0.086 to 0.277
H6	BIU ← VIO	-0.062	0.053	-1.17	0.241	-0.167 to 0.042
H7	BIU ← ERR	-0.038	0.055	-0.69	0.492	-0.145 to 0.070
H8	BIU ← LAP	-0.038	0.055	-0.69	0.492	-0.146 to 0.070
H9	BIU ← AGG	-0.088	0.047	-1.87	0.061	-0.180 to 0.004
H10	BIU ← POS	-0.163	0.034	-4.83	0.000	-0.229 to -0.097

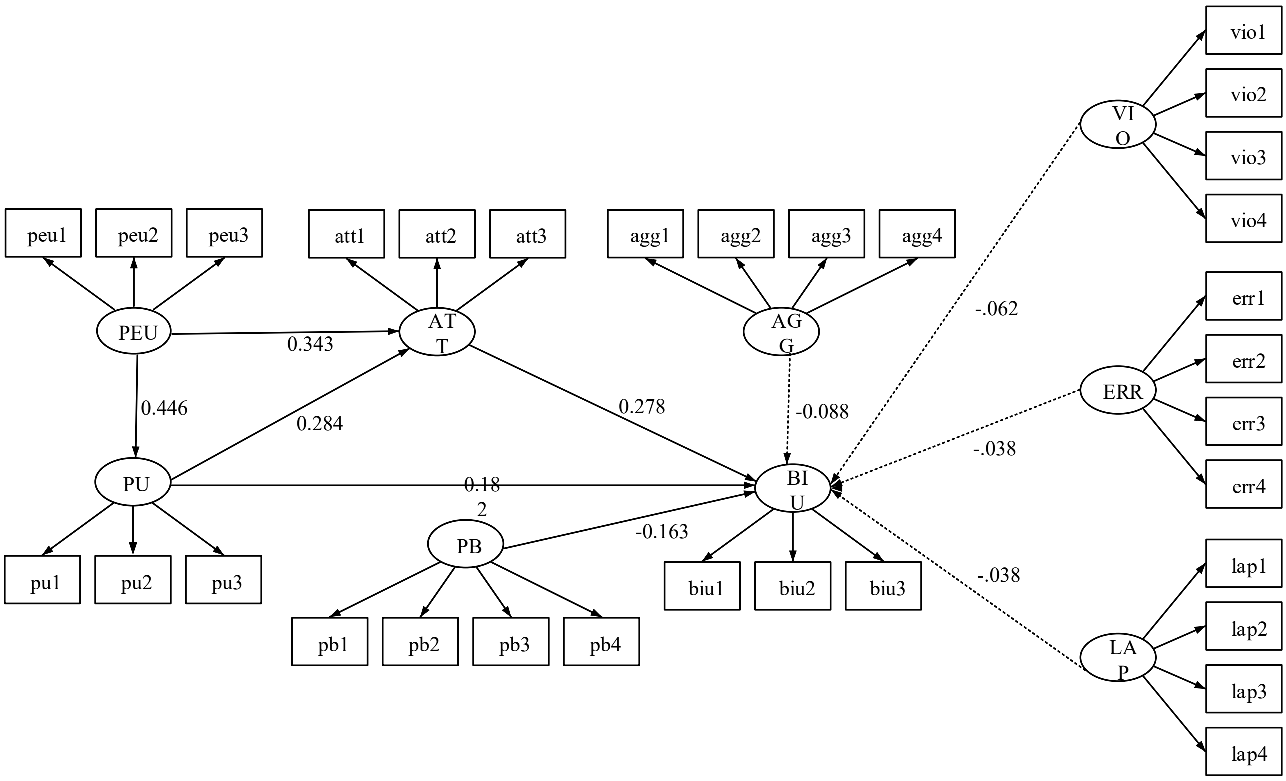

Figure 1 – Parameter estimation results of the structural equation model

The SEM analysis provides robust support for the theoretical framework, confirming that PEU significantly influences PU and ATT. Both PU and ATT were found to be strong predictors of older pedestrians' behavioural intentions to share roads with AVs. Interestingly, positive pedestrian behaviours (POS) were inversely related to behavioural intention, highlighting potential caution or risk aversion among older individuals exhibiting safe pedestrian behaviours.

5.3 Mixed-effects ordered logistic regression results

This section presents the results from the mixed-effects ordered logistic regression models, which analyse older pedestrians' willingness to share roads with AVs under two distinct conditions: without an eHMI system and with an eHMI system. The models consider various factors, including digital competence, PU, PEU, BIU, attitudes (ATT) and pedestrian behaviours such as violations (VIO), errors (ERR), lapses (LAP), aggressive behaviours (AGG) and positive behaviours (POS). Additionally, demographic variables like age, gender, education level, income, employment status, car ownership and accident history were included. Digital competence was modelled as a random effect to understand individual-level variability in its influence on AV acceptance.

Model without eHMI system

In this section, we present the results of the mixed-effects ordered logistic regression model (meologit) to analyse older pedestrians' willingness to share roads with AVs in the absence of an eHMI system. The model incorporates both fixed and random effects, including various behavioural and demographic factors, as well as digital competence levels, to assess their influence on AV acceptance. The results of the mixed-effects ordered logistic regression model for the scenario without an eHMI system are presented in *Table 7*.

Positive behaviours (POS): The results show a significant positive relationship between positive pedestrian behaviours (e.g. following traffic rules and signals) and the willingness to share roads with AVs ($\beta = 0.160$, $p = 0.035$). Older pedestrians who exhibited safer and more cautious road behaviours were more likely to accept the presence of AVs, suggesting that safety-conscious individuals are more open to interacting with AV technology.

Errors (ERR): The variable representing errors, which includes unintentional pedestrian mistakes such as misjudging vehicle speed, was also found to significantly influence AV acceptance ($\beta = 0.246$, $p = 0.032$). This implies that pedestrians who recognise their potential for errors may perceive AVs as a safer alternative, possibly due to the belief that AVs can help reduce human-induced traffic risks.

PEU: The variable PEU, which measures the ease with which individuals believe they can use AV technology, showed a significant positive effect on AV acceptance ($\beta = 0.237$, $p = 0.043$). This result underscores the importance of designing AV systems that are easy to use and understand, particularly for older pedestrians who may have limited familiarity with new technology.

Income level (5,001-10,000 CNY): Individuals in the income bracket of 5,001-10,000 CNY demonstrated a significant negative association with AV acceptance ($\beta = -1.389$, $p = 0.008$). This suggests that older pedestrians with moderate income may have lower AV acceptance, potentially due to limited access to technology or financial constraints that hinder exposure to AV systems.

Traffic incident history: A history of traffic incidents had a significant impact on AV acceptance. Participants with no history of traffic incidents were significantly more likely to accept AVs ($\beta = 0.441$, $p = 0.001$), while those who had experienced 1-2 incidents were less likely to embrace AVs ($\beta = -0.312$, $p = 0.043$). This suggests that prior experiences with road safety may shape pedestrians' perceptions of AV technology, with some viewing AVs as a safer alternative, while others exhibit greater caution.

Gender: Gender showed a marginal effect on AV acceptance, with males ($\beta = 0.117$, $p = 0.1$) being slightly more inclined to share roads with AVs. However, this effect did not reach statistical significance, suggesting that gender may not be a primary determinant of AV acceptance in this context.

The model's overall fit was evaluated using the likelihood ratio (LR) test, which compares the mixed-effects ordered logistic regression model against a standard ordered logit model. The test statistic for the LR test was significant (chibar2(01) = 61.32, $p < 0.0000$), indicating that the mixed-effects model provides a significantly better fit than the basic ordered logit model. This demonstrates the utility of incorporating random effects (i.e. digital competence levels) to account for individual-level variability in AV acceptance.

Table 7 – Ordered logit model results without eHMI system

Variable	Coefficient	Std. error	z-score	p-value
POS	0.160	0.076	2.11	0.035
AGG	-0.096	0.098	-0.99	0.325
VIO	0.107	0.113	0.95	0.344
ERR	0.246	0.115	2.15	0.032
LAP	0.024	0.118	0.21	0.836
PU	0.149	0.105	1.42	0.154
PEU	0.237	0.117	2.02	0.043
ATT	0.127	0.112	1.13	0.257
BIU	0.149	0.100	1.5	0.134
Gender	0.117	0.071	1.64	0.1
60-65 years	-0.048	0.116	-0.41	0.679
66-70 years	-0.084	0.123	-0.68	0.494
71-75 years	-0.160	0.139	-1.15	0.249
Elementary school and below	0.084	0.248	0.34	0.734
Middle school	0.303	0.254	1.19	0.234
High school or technical school	-0.105	0.264	-0.4	0.691
≤ 3,000 CNY	-0.375	0.440	-0.85	0.395
3,001-5,000 CNY	-0.113	0.441	-0.26	0.797
5,001-10,000 CNY	-1.389	0.521	-2.67	0.008
10,001-20,000 CNY	0.494	0.914	0.54	0.589
Full-time job	-0.442	0.445	-0.99	0.321
Part-time job	0.007	0.466	0.01	0.988
Retired	0.295	0.231	1.28	0.202
Car	-0.007	0.087	-0.08	0.939
ICard	0.009	0.117	0.08	0.939
0 Traffic incident	0.441	0.135	3.25	0.001
1-2 Traffic incidents	-0.312	0.154	-2.03	0.043
3-4 Traffic incidents	-0.313	0.193	-1.62	0.104
Threshold 1	-3.374	0.602		
Threshold 2	-1.835	0.581		
Threshold 3	-0.580	0.576		
Threshold 4	0.893	0.577		
Digital competence levels	0.577	0.492		

LR test vs. ologit model: chibar2(01) = 61.32   Prob >= chibar2 = 0.0000

Model with eHMI system

In this section, we present the results of the mixed-effects ordered logistic regression model (meologit) for older pedestrians' willingness to share roads with AVs in the presence of an eHMI system. *Table 8* presents the results for the scenario involving an eHMI system, highlighting key differences from the non-eHMI scenario.

PU: The coefficient for PU was significantly positive (β = 0.253, p = 0.013), indicating that older pedestrians who perceive AVs as useful are more likely to accept sharing roads with AVs when an eHMI is present. This finding emphasises the importance of highlighting the practical benefits of AV technology, such as safety and convenience, in fostering acceptance among older pedestrians.

Positive behaviours (POS): The coefficient for POS was negative (β = -0.152, p = 0.031), suggesting that older pedestrians who exhibit positive, safety-conscious behaviours, such as following traffic signals and adhering to road rules, were less likely to accept AVs in the presence of eHMI systems. This could be due to increased cautiousness, where older pedestrians who typically exhibit safe behaviour may perceive AVs, particularly in eHMI contexts, as introducing additional uncertainties or complexities.

Part-time employment (job2): Interestingly, part-time employment was negatively associated with AV acceptance (β = -0.922, p = 0.042), suggesting that older individuals engaged in part-time employment are less likely to accept AVs with an eHMI system. This could be attributed to limited exposure to AV technology or a lack of perceived relevance of AVs to their daily routines.

Middle school education level (edu2): Older pedestrians with a middle school education were more likely to accept AVs (β = 0.688, p = 0.003), suggesting that individuals with basic education levels may find eHMI systems more understandable and accessible. This highlights the potential role of education in facilitating technology acceptance among older adults.

Traffic incident history (acci2): Traffic incident history continued to play a significant role in shaping AV acceptance. Older pedestrians who had been involved in 1-2 traffic incidents were less likely to accept AVs with eHMI systems (β = -0.346, p = 0.027). This finding suggests that individuals with prior traffic incident experience may exhibit greater caution, even when an eHMI system is present, possibly due to concerns over reliability and trust in the system.

Other demographic variables: Age, gender, car ownership and the possession of an ID card did not have significant effects on AV acceptance with eHMI in this model. However, the trend for car ownership was marginally positive (β = 0.162, p = 0.057), suggesting that individuals who own cars may be slightly more open to AV technologies.

The mixed-effects ordered logistic regression model provided a robust fit to the data, as indicated by the Wald chi-squared value (31.34, p < 0.0000) and the log-likelihood of -927.69107. The model's fit was further validated by the significant likelihood ratio (LR) test comparing the mixed-effects model to the standard ordered logit (ologit) model, confirming the adequacy of the model in capturing the variability in AV acceptance due to individual digital competence levels and other predictors.

Table 8 – Ordered logit model results with eHMI system

Variable	Coefficient	Std. error	z-score	p-value
POS	-0.152	0.070	-2.16	0.031
AGG	-0.071	0.096	-0.74	0.462
VIO	0.044	0.111	0.4	0.691
ERR	0.049	0.111	0.44	0.661
LAP	-0.021	0.116	-0.19	0.853
PU	0.253	0.102	2.49	0.013
PEU	0.013	0.114	0.11	0.912
ATT	0.088	0.112	0.79	0.432
BIU	-0.060	0.097	-0.62	0.535
Gender	-0.041	0.069	-0.59	0.555
60-65 years	0.014	0.113	0.12	0.902
66-70 years	-0.041	0.118	-0.35	0.728
71-75 years	0.055	0.138	0.4	0.688
Elementary school and below	0.334	0.225	1.49	0.137
Middle school	0.688	0.233	2.96	0.003
High school or technical school	0.180	0.244	0.74	0.462

Variable	Coefficient	Std. error	z-score	p-value
≤ 3,000 CNY	-0.071	0.401	-0.18	0.86
3,001-5,000 CNY	-0.006	0.404	-0.02	0.988
5,001-10,000 CNY	0.260	0.502	0.52	0.604
10,001-20,000 CNY	0.143	0.833	0.17	0.863
Full-time job	-0.089	0.435	-0.2	0.838
Part-time job	-0.922	0.454	-2.03	0.042
Retired	0.446	0.226	1.98	0.048
Car	0.162	0.085	1.9	0.057
ICard	-0.103	0.119	-0.86	0.388
0 Traffic incident	0.184	0.137	1.35	0.178
1-2 Traffic incidents	-0.346	0.157	-2.21	0.027
3-4 Traffic incidents	-0.037	0.196	-0.19	0.85
Threshold 1	-2.961	0.503		
Threshold 2	-1.298	0.470		
Threshold 3	0.113	0.466		
Threshold 4	1.900	0.469		
Digital competence levels	0.292	0.259		

LR test vs. ologit model: chibar2(01) = 31.34 Prob >= chibar2 = 0.0000

6. DISCUSSION

6.1 Interpretation of key findings

This study offers important insights into the relationship between older pedestrians' digital competence and their willingness to share roads with autonomous vehicles (AVs). A key finding is that older pedestrians with higher levels of digital competence are more likely to accept AVs, both in scenarios with and without external human-machine interface (eHMI) systems. This result supports the growing recognition of digital competence as an essential factor in understanding older adults' engagement with technology [80]. Specifically, the higher the PEU and PU of AV technology, the more positively older pedestrians viewed interacting with AVs. These findings are consistent with the TAM, which emphasises that ease of use and perceived utility are critical to technology acceptance [81].

Another important factor influencing AV acceptance among older pedestrians is their behavioural disposition, particularly regarding compliance with traffic rules. In the scenario without an eHMI system, positive pedestrian behaviours, such as rule adherence and cautious crossing, were associated with greater willingness to accept AVs. However, when an eHMI system was introduced, this relationship reversed. However, the presence of an eHMI system shifted this relationship, with the coefficient for positive behaviours becoming negative. This finding suggests that while eHMI systems can provide additional information, they might also introduce complexity or uncertainty that deters safety-conscious individuals from embracing AVs. This aligns with the view that the effectiveness of new technology, including AVs and eHMI systems, depends on its design and its ability to communicate clear, intuitive information to users [82, 83].

Participants' prior traffic incident history also emerged as a significant determinant of AV acceptance. Those who had never experienced a traffic accident were more receptive to AVs, particularly in the eHMI scenario, whereas those with prior incident experience exhibited increased caution. This finding suggests that individuals without previous negative experiences with traffic are more open to the perceived safety benefits of AVs. Conversely, those who had experienced traffic incidents exhibited greater caution, even with an eHMI system in place, possibly due to lingering concerns about reliability and trust in the system. This echoes the findings of Habibovic et al. [84], who found that prior traffic incident experiences shape pedestrians' perceptions of AV technology, especially concerning safety and trust.

Socioeconomic status, particularly income level, was also found to affect older pedestrians' acceptance of AVs. Interestingly, individuals in the middle-income range (5,001–10,000 CNY) were less likely to accept AVs compared to those at lower or higher income levels. This finding suggests that income may act as a barrier to the adoption of AV technology, as individuals with moderate income levels may have limited access to such technologies. Previous research has highlighted similar barriers related to income, showing that lower socioeconomic status often correlates with lower levels of technology adoption [85]. Thus, addressing these barriers could improve AV accessibility for a broader demographic.

6.2 Theoretical contributions

This study contributes significantly to the theoretical understanding of AV acceptance and the role of digital competence in shaping pedestrian-AV interactions, particularly among older adults. It integrates three frameworks: the TAM, the PBQ and IRT, offering a multidimensional perspective on AV adoption.

One key innovation lies in the modelling of digital competence as a latent variable using IRT. This allowed for a more precise and individualised assessment of older adults' digital literacy and its moderating role in AV interaction. The inclusion of random effects for digital competence provides new insights into the heterogeneity of older pedestrians' attitudes and behaviours toward AV technology. This methodological approach enhances our understanding of how digital competence influences technology acceptance in ageing populations, an area that has been underexplored in previous research.

By applying the PBQ framework, this study also extends our understanding of pedestrian behaviour by including not only positive behaviours but also violations, errors, lapses and aggressive actions. This framework allows for a better understanding of the specific challenges that older adults face when interacting with AVs, thus contributing to the literature on vulnerable road users.

While previous research has largely focused on younger, digitally literate populations, this study emphasises the unique challenges that older pedestrians face when interacting with AVs. It provides a nuanced understanding of how digital competence, along with behavioural factors, influences older adults' willingness to engage with AVs. The findings highlight the need to consider digital literacy when studying the adoption of new technologies, particularly for older populations who may face cognitive, sensory and mobility challenges.

6.3 Practical implications

The findings of this study have several important practical implications for policymakers, technology developers and urban planners, particularly as AVs continue to be integrated into urban environments.

To facilitate AV adoption among older pedestrians, eHMI systems must be designed with simplicity and user-friendliness as core principles. The negative association between positive pedestrian behaviours and AV acceptance in the eHMI condition suggests that current designs may inadvertently overwhelm cautious users. To address this, eHMIs should employ clear, standardised and multimodal cues, such as green LED walk signals, verbal prompts and anthropomorphic features like animated eyes or gestures, that are cognitively accessible and socially intuitive for older adults. This supports previous research suggesting that clear and simple communication between AVs and pedestrians is essential for fostering trust and reducing anxiety among older adults [86, 87].

Improving digital literacy is also essential for increasing AV acceptance. The study confirms that digital competence significantly shapes how older pedestrians evaluate and respond to AV technologies. Community-based educational programs and training sessions could focus on enhancing older adults' ability to interact with AV technologies and eHMI systems, thereby improving their comfort and safety in AV environments. Such interventions are crucial for bridging the digital divide and promoting inclusivity in the adoption of new technologies [88].

Given the role of economic constraints in shaping AV acceptance, policy and industry responses should aim to improve the accessibility of AV technology for diverse income groups. This might include subsidies, low-cost trials or public access programs that expose older individuals, particularly those in the middle-income range, to AVs in a familiar and controlled environment.

Building public trust in AV safety mechanisms is another important strategy to promote wider acceptance. Given that prior traffic incidents reduce willingness to accept AVs, safety messaging and demonstration of AV reliability, especially in reducing human error, can play a pivotal role in alleviating scepticism. Public awareness campaigns and transparent safety metrics may be effective tools in this regard.

7. CONCLUSION

This study investigates the impact of digital competence on older pedestrians' behaviours and attitudes toward AVs, utilising IRT, the TAM and the PBQ frameworks. The findings reveal critical insights into how varying levels of digital competence influence older pedestrians' willingness to share the road with AVs, as well as the significant role of both behavioural factors and digital skills in shaping AV acceptance. This section summarises the key findings, discusses the limitations of the study and provides recommendations for future research.

7.1 Summary of findings

The primary aim of this study was to explore the role of digital competence in shaping older pedestrians' willingness to engage with AV technology. Key findings include the following.

Digital competence emerged as a key predictor of AV acceptance. This highlights the importance of digital skills in enabling older adults to interact effectively with AV technology. The relationship between PEU and PU of AVs supports the TAM, which suggests that older adults' perceptions of AV technology's utility and ease of use are central to their adoption decisions [80].

Older pedestrians who exhibit positive safety behaviours, such as adherence to traffic rules, were more likely to accept AVs, particularly in scenarios without eHMI systems. However, the introduction of an eHMI system appeared to complicate this relationship, with safety-conscious individuals becoming less likely to embrace AVs. This finding underscores the complexity of integrating eHMI systems into AV environments and the need for intuitive designs that minimise cognitive load for older adults [82, 83].

Another key determinant of AV acceptance was prior experience with traffic incidents. This supports the findings of Habibovic et al. (2019), which suggest that trust in AV technology is shaped by previous safety experiences [84].

The study also highlighted socioeconomic disparities, particularly among middle-income older adults, who were less likely to express acceptance of AVs. This finding aligns with previous studies on the barriers to technology adoption, which emphasise the role of income in determining access to innovative technologies [85].

While eHMI systems are designed to enhance pedestrian-AV communication, they may inadvertently complicate decision-making processes for older adults. This finding suggests that eHMI systems need to be designed with simplicity and clarity in mind to effectively support AV adoption among older pedestrians [86, 87].

7.2 Limitations of the study

While this study provides valuable insights into the relationship between digital competence and older pedestrians' interaction with autonomous vehicles (AVs), several limitations should be acknowledged.

First, although the sample of 750 older pedestrians in Wuhan is sizable and demographically diverse within the urban context, it may not fully represent the heterogeneity of older adults across different cultural and geographic settings. Wuhan's unique environment, characterised by rapid AV deployment and concentrated urban infrastructure, may shape user perceptions in ways that differ from those in rural areas or less technologically developed regions. To enhance the generalisability of future findings, subsequent research should seek to incorporate samples from both urban and rural areas, as well as cross-national comparisons.

Second, the study employed a cross-sectional design, which restricts the ability to infer causal relationships. While statistical associations between digital competence and AV acceptance were observed, longitudinal data would provide a more robust framework for evaluating how digital literacy evolves over time and how these changes influence technology-related attitudes and behaviours among older adults.

Third, the measurement of digital competence, although strengthened by the use of item response theory (IRT), relied on binary self-report indicators such as smartphone ownership or participation in internet-based activities. These indicators may oversimplify the actual breadth and depth of digital skills. For example, merely owning a smartphone does not equate to proficiency in navigating complex digital interfaces or performing multi-step online tasks. Similarly, acknowledging participation in digital entertainment or economic activities does not capture the frequency, complexity or autonomy of such behaviours. This lack of granularity may lead to an underestimation of individual differences in digital competence and limit the precision of psychometric modelling.

Lastly, while the study incorporated behavioural variables such as violations, errors, lapses and positive behaviours, other important psychological and contextual factors were not directly measured. Constructs such as perceived trust in AV systems, previous experience with automated vehicles, cognitive load and risk perception may also significantly shape older pedestrians' technology acceptance. Integrating these variables in future studies would offer a more comprehensive understanding of the underlying psychological mechanisms influencing AV interaction.

7.3 Recommendations for future research

Building on the findings and acknowledging the limitations of the present study, several avenues for future research are proposed to advance the understanding of older pedestrians' interactions with autonomous vehicles (AVs) in the context of digital competence.

First, longitudinal studies are essential to establish causality between digital competence and AV acceptance. Unlike cross-sectional analyses, longitudinal designs can capture temporal changes in digital literacy and their evolving influence on attitudes, trust and behavioural intentions toward AVs. Such studies would offer more dynamic insights into how digital adaptation over time mediates technology acceptance among ageing populations.

Second, future research should incorporate a broader range of behavioural and psychological determinants. Variables such as perceived risk, trust in AV systems, prior exposure to automation, cognitive load and emotional responses (e.g. anxiety or curiosity) may significantly shape how older adults evaluate and respond to AV technology. Including these constructs would provide a more holistic framework for interpreting AV acceptance behaviour beyond observable pedestrian actions.

Third, conducting cross-cultural and international comparative studies could reveal important contextual differences in AV perception. Factors such as national infrastructure readiness, cultural norms around technology, societal trust in automated systems and varying levels of digital literacy may result in different patterns of acceptance. Comparative research across countries or regions would improve the external validity of existing models and support the development of culturally sensitive AV integration strategies.

Fourth, given the critical role of external human–machine interfaces (eHMIs) in AV–pedestrian communication, design-focused studies are warranted. Future research should evaluate the usability, effectiveness and cognitive demands of different eHMI modalities, visual (e.g. LED strips, icons), auditory (e.g. spoken cues, tones) and tactile feedback. Experimental and user-centred design methods, particularly involving older adults, would help identify interface features that improve clarity, reduce cognitive burden and enhance perceived safety and trust.

Fifth, it is important to address socioeconomic disparities in AV acceptance. Research should explore how factors such as income, education and access to digital infrastructure constrain individuals' opportunities to learn about or interact with AV technology. Evaluations of policy interventions (e.g. digital literacy programs, public AV trials, financial subsidies) would be particularly valuable in promoting inclusive and equitable access to emerging mobility technologies.

Lastly, future studies should aim to enhance the granularity and validity of digital competence assessment. The current reliance on binary indicators (e.g. device ownership, activity participation) may overlook important nuances in skill level. More refined instruments, such as validated digital literacy scales (e.g. DigComp), task-based performance evaluations or scenario simulations, can better distinguish between superficial exposure and meaningful, skilful engagement. Such methodological advancements will yield a more accurate understanding of how digital proficiency shapes older pedestrians' interaction with AV systems.

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INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects involved in the study.

DATA AVAILABILITY STATEMENT

The data presented in this study are available on request from the corresponding author due to the need to protect individual privacy.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Zhiwei Liu: writing–review & editing, writing – original draft, validation, supervision, methodology. Wenli Ouyang: resources, investigation, data curation. Jie Wu: writing–review & editing, writing – original draft, validation, supervision, methodology.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX A: SURVEY ON DIGITAL COMPETENCE AND INTERACTION WITH AUTONOMOUS VEHICLES AMONG OLDER PEDESTRIANS

Preface & informed consent

Dear Participant,

This survey is part of an academic study investigating how older adults interact with autonomous vehicles (AVs), and how their digital competence (skills in using digital tools like smartphones and the internet) influences such interactions. The findings will help improve smart transportation systems and enhance pedestrian safety, especially for senior citizens.

Please read the instructions carefully and answer truthfully based on your experiences. There are no right or wrong answers.

— Estimated time: 10–15 minutes
— Participation is voluntary and all responses are anonymous and confidential
— You may stop at any time without any consequences

Have you ever directly encountered or interacted with autonomous vehicles (AVs) during your daily pedestrian activities in Wuhan?

☐ Yes, I have encountered or interacted directly with AVs.

☐ No, I have never encountered or interacted with AVs. *(If selected, the respondent was excluded from the study.)*

Consent:

☐ I understand the purpose of this study and voluntarily agree to participate.

☐ I do not wish to participate. (Please stop here.)

Section 1: Socio-demographic information

1. Gender

☐ Male

☐ Female

2. Age

☐ 60–65 years

☐ 66–70 years

☐ 71–75 years

☐ 76 years or above

3. Education level

☐ Elementary school or below

☐ Middle school

☐ High school / vocational

☐ University or higher

4. Household monthly income (CNY)

☐ ≤3,000

☐ 3,001–5,000

☐ 5,001–10,000

☐ 10,001–20,000

☐ ≥20,001

5. Employment status

☐ Full-time

☐ Part-time

☐ Retired

☐ Unemployed

6. Do you own a private car?
   ☐ Yes
   ☐ No
7. Do you possess a public transport smart card (e.g. IC card)?
   ☐ Yes
   ☐ No
8. Have you been involved in a pedestrian traffic accident in the past two years?
   ☐ No
   ☐ 1–2 times
   ☐ 3–4
   ☐ ≥5

Section 2: Digital competence (past week activity)

9. I own and use a smart device (e.g. smartphone or tablet).
   ☐ Yes
   ☐ No
10. I used the internet to communicate with friends/family.
   ☐ Yes
   ☐ No
11. I used the internet for entertainment (videos, music, news, games).
   ☐ Yes
   ☐ No
12. I performed economic activities online (shopping, banking, ticket booking).
   ☐ Yes
   ☐ No
13. I learned new information online (e.g. health, finance, technology).
   ☐ Yes
   ☐ No

Section 3: Pedestrian behaviour

Please indicate how frequently you engage in the following behaviours while walking. Use a 5-point Likert scale where: 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Often, 5 = Always.

Violations

1. I cross at red lights.
   ☐1 ☐2 ☐3 ☐4 ☐5
2. I jaywalk to save time.
   ☐1 ☐2 ☐3 ☐4 ☐5
3. I cross outside marked crosswalks.
   ☐1 ☐2 ☐3 ☐4 ☐5
4. I use restricted pedestrian zones.
   ☐1 ☐2 ☐3 ☐4 ☐5

Errors

5. I cross between stopped vehicles.
   ☐1 ☐2 ☐3 ☐4 ☐5
6. I assume cars will stop for me.
   ☐1 ☐2 ☐3 ☐4 ☐5

7. I walk in bike lanes.
☐1 ☐2 ☐3 ☐4 ☐5
8. I dash across streets without checking traffic.
☐1 ☐2 ☐3 ☐4 ☐5

Lapses
9. I cross without paying attention.
☐1 ☐2 ☐3 ☐4 ☐5
10. I am distracted while crossing.
☐1 ☐2 ☐3 ☐4 ☐5
11. I talk to others while crossing unsafely.
☐1 ☐2 ☐3 ☐4 ☐5
12. I cross without checking traffic because I'm meeting someone.
☐1 ☐2 ☐3 ☐4 ☐5

Aggressive behaviours
13. I yell at other road users.
☐1 ☐2 ☐3 ☐4 ☐5
14. I delay drivers intentionally.
☐1 ☐2 ☐3 ☐4 ☐5
15. I use rude gestures at drivers.
☐1 ☐2 ☐3 ☐4 ☐5
16. I physically hit a vehicle.
☐1 ☐2 ☐3 ☐4 ☐5

Positive behaviours
17. I thank drivers who yield.
☐1 ☐2 ☐3 ☐4 ☐5
18. I walk in a single file on narrow sidewalks.
☐1 ☐2 ☐3 ☐4 ☐5
19. I keep to the right of the walkway.
☐1 ☐2 ☐3 ☐4 ☐5
20. I yield to vehicles when safe to do so.
☐1 ☐2 ☐3 ☐4 ☐5

Section 4: Technology acceptance of autonomous vehicles (AVs)
Scale: 1 = Strongly disagree 2 = Disagree 3 = Neutral 4 = Agree 5 = Strongly agree

Perceived usefulness (PU)
1. Sharing roads with AVs can improve the efficiency of the transportation system.
☐1 ☐2 ☐3 ☐4 ☐5
2. Sharing roads with AVs can meet individual travel needs.
☐1 ☐2 ☐3 ☐4 ☐5
3. Sharing roads with AVs can reduce traffic accidents.
☐1 ☐2 ☐3 ☐4 ☐5

Perceived ease of use (PEU)
4. It is easy for me to interact with AVs while walking.
☐1 ☐2 ☐3 ☐4 ☐5
5. The interaction with AVs is clear and understandable to me.
☐1 ☐2 ☐3 ☐4 ☐5

6. I can easily become proficient at interacting with AVs while walking.
☐1 ☐2 ☐3 ☐4 ☐5

Attitude toward AVs (ATT)

7. I enjoy walking on roads where AVs are present.
☐1 ☐2 ☐3 ☐4 ☐5
8. Walking on roads shared with AVs is a positive experience for me.
☐1 ☐2 ☐3 ☐4 ☐5
9. I look forward to walking on roads shared with AVs.
☐1 ☐2 ☐3 ☐4 ☐5

Behavioural intention (BIU)

10. I would try walking on roads where AVs are operating.
☐1 ☐2 ☐3 ☐4 ☐5
11. I plan to walk on AV-operated roads in the future.
☐1 ☐2 ☐3 ☐4 ☐5
12. I would recommend walking on AV roads to my family and friends.
☐1 ☐2 ☐3 ☐4 ☐5

Section 5: Scenario-based AV interaction

Scenario 1: General road sharing

Q: How willing are you to **walk on urban roads where autonomous vehicles (AVs) are operating**?

☐ Strongly disagree

☐ Disagree

☐ Neutral

☐ Agree

☐ Strongly agree

Scenario 2: External human-machine interface (eHMI)

What is eHMI?

AVs have no human driver, which removes traditional cues like eye contact. To restore communication, AVs now use external human-machine interfaces (eHMI) such as LED signs, light signals or projected messages like:

- “Slowing down”
- “Stopping”
- “Please cross”
- “Turning left”

These messages are displayed on the front of the vehicle to help pedestrians understand the vehicle’s behaviour.

[Visual cue card with eHMI examples will be provided by the interviewer.]

Q: If an AV uses a clear and understandable eHMI, how willing are you to **walk on urban roads where autonomous vehicles (AVs) are operating**?

☐ Strongly disagree

☐ Disagree

☐ Neutral

☐ Agree

☐ Strongly agree