

The Influence of Familiarity and Exposure on Comfort in and Around Autonomous Vehicles

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STRUCTURED ABSTRACT

Objectives: Autonomous vehicles (AVs) are increasingly prevalent, yet public comfort remains limited and varies by exposure and travel role. Much prior work contrasts riders with non-riders or focuses on passenger acceptance. This study examines whether stated AV comfort varies across exposure and experience levels and across passenger and road-user roles.

Methods: The analysis uses Wave 2 of the Transportation Heartbeat of America survey. AV exposure is coded as a cumulative four-stage ladder: Not aware; Aware, not seen; Seen, not ridden; and Ridden. Comfort is measured for riding alone, riding with strangers, driving near an AV, and walking or cycling near an AV. A Generalized Heterogeneous Data Model jointly relates these ordered outcomes to individual, household, and travel attributes, local AV service availability, and three latent constructs: multimodal lifestyle, safety sensitivity, and technology enthusiasm.

Findings: Exposure stages are not interchangeable. Awareness alone is associated with lower comfort across passenger roles and comfort around AVs. Seeing an AV enhances comfort around AVs, whereas riding experience positively enhances all four comfort outcomes very strongly. Comfort remains lowest for riding with strangers even among those who have ridden AVs. Technology enthusiasm has the strongest positive latent association with comfort, while safety sensitivity is negatively associated with comfort across roles. Multimodal lifestyle is positively associated with exposure, riding with strangers, and walking or cycling near an AV. Local AV supply and household resources relate more clearly to exposure levels than to uniformly higher comfort.

Novelty: The study jointly models a staged AV exposure ladder and role-specific comfort outcomes for a national sample, distinguishing awareness, observation, and riding – rather than collapsing non-riders into one category.

Practical Applications: Deployment and engagement strategies should treat observation and riding as distinct experiences and address passenger, shared-ride, and road-user comfort separately rather than relying on a single acceptance metric.

1. INTRODUCTION AND MOTIVATION

Autonomous vehicles (AVs) are rapidly moving from experimentation into the mainstream transportation landscape. Commercial robotaxi services, public-road testing programs, and automated shuttles are exposing a growing share of the public to vehicles operating with limited or no direct human control. Waymo has expanded fully autonomous ride-hailing across several U.S. metropolitan areas (Waymo 2026). Tesla has initiated limited Robotaxi operations in selected markets (Reuters 2026), while Zoox has begun offering rides in its purpose-built autonomous vehicle (Zoox 2026). Internationally, Baidu Apollo Go, WeRide, and other firms are expanding autonomous ride-hailing in China, the Middle East, and other markets (Baidu 2026). These deployments differ in scale and operating design, but they demonstrate that AVs are becoming real usable transportation services.

The implications of widespread AV adoption extend well beyond replacing human driving with automated driving. AVs could affect vehicle ownership, mode choice, trip frequency, travel distance, vehicle occupancy, and the organization of daily activities (Batur et al. 2026). They may expand independent mobility for people unable or unwilling to drive (Wu et al. 2021). They may also generate empty vehicle travel, increase roadway demand, draw riders from public transportation, and reshape parking and infrastructure needs (Narayanan et al. 2020). Their effects on safety, accessibility, energy use, emissions, equity, and autonomy will depend on deployment and adoption pathways (Makahleh et al. 2024).

Public adoption and market penetration are therefore central to understanding the transportation system impacts of AVs. Planning agencies and travel demand modelers increasingly examine AV scenarios when evaluating future roadway demand, transit use, parking needs, and infrastructure investments (McAslan et al. 2021). These scenarios require assumptions about who will adopt AVs, how quickly adoption will occur, and how travel behavior may change. Yet the AV environment is evolving rapidly, and assumptions derived from older surveys or highly hypothetical settings may become outdated quickly. Recent evidence on familiarity, exposure, experience, and comfort can help ground such scenarios in contemporary behavioral data. Although stated perceptions cannot definitively forecast adoption, they can support more credible scenario assumptions and planning (Saeed et al. 2020).

Adoption requires more than awareness of AV technology or recognition of its potential benefits. People must feel sufficiently comfortable riding in AVs and interacting with them in shared transportation environments. Comfort reflects perceived safety, trust in automated decision-making, confidence in vehicle reliability, and willingness to relinquish control. National evidence continues to reveal substantial skepticism. Nair and Bhat (2021), for example, found that 72.9 percent of respondents considered sharing the road with an autonomous passenger vehicle to be only somewhat safe or not too safe. More recent surveys similarly indicate that trust in riding in a self-driving vehicle remains limited (Farias et al. 2026).

Comfort is not a single, context-independent attitude. Riding alone requires surrendering control to an AV, riding with strangers raises concerns about personal security and privacy, and interacting with AVs as a driver, pedestrian, or cyclist requires confidence that they will behave predictably. Tennant et al. (2019) found that discomfort differed between using a driverless vehicle and driving alongside one. Long et al. (2025) similarly reported differences across passenger, driver, and pedestrian roles. Even after a successful ride, some passengers remain uneasy about traveling without onboard personnel (Fonzone et al. 2025). A single measure of AV acceptance cannot capture these distinct concerns.

Familiarity, exposure, and direct experience may be especially important in shaping perceptions. Individuals generally encounter AVs through a progression of stages: some are unaware that AVs operate on public roads; others are aware but have never seen one; a smaller group has observed AVs in traffic; and an even smaller group has actually taken a ride in one. These stages are cumulative, but they are not interchangeable. Awareness provides conceptual familiarity. Seeing an AV operate in mixed traffic reveals how it interacts with other road users. Riding in one provides firsthand information about vehicle behavior, ride quality, perceived safety, and traveling without a human driver.

Existing research generally suggests that direct riding experience is associated with greater trust, perceived safety, and willingness to use AVs. First-time rides have produced meaningful increases in trust and performance expectations (Schwindt-Drews et al. 2024; Wang et al. 2024). Direct experience has also shifted initially ambivalent participants toward more favorable positions and improved safety perceptions following automated shuttle pilots (Kutela et al. 2024; Liu and Xu 2020). Satisfaction with the ride experience is associated with subsequent use intentions (Dai et al. 2021). These gains are not universal. Some participants report no change or less favorable safety opinions after riding (Li et al. 2024), while abrupt braking can undermine perceived ride comfort (Fonzone et al. 2025). Repeated experience may also produce diminishing returns as users become familiar with service limitations (Guo et al. 2026; Xie et al. 2025).

The intermediate stages between unfamiliarity and direct riding remain less clearly understood. Awareness may improve perceptions when it conveys meaningful knowledge (Nair and Bhat 2021), but superficial familiarity may do little to resolve safety concerns. Modest knowledge has been associated with greater interest and trust, although more extensive self-reported knowledge does not necessarily produce more favorable views (Othman 2023). Residents of AV pilot communities have reported greater awareness and more positive attitudes than residents elsewhere (Jiang et al. 2022), while repeated observation has been associated with improved perceived safety (Colley et al. 2024). Awareness, observation, and riding should therefore not be collapsed into a simple distinction between users and non-users. Each stage may resolve a different form of uncertainty and may shape comfort differently across travel roles and contexts.

This study uses Wave 2 of the Transportation Heartbeat of America Survey, a national survey of 8,567 U.S. adults, to model the influence of AV familiarity and experience on comfort across passenger and road-user roles. Familiarity and experience are represented through a four-stage exposure ladder ranging from no awareness to direct riding. The analysis jointly considers comfort riding alone, riding with strangers, driving near an AV, and walking or cycling near an AV. A Generalized Heterogeneous Data Model relates these outcomes to individual and household attributes, mobility characteristics, local AV availability, and three latent constructs that capture technology enthusiasm, safety sensitivity, and multimodal lifestyle orientation.

The central thesis is that AV comfort develops through a staged and role-dependent process. Awareness may shape general understanding without resolving uncertainty about vehicle behavior. Observation may be especially relevant to comfort interacting with AVs as a driver, pedestrian, or cyclist. Direct riding experience is expected to have the strongest influence on passenger comfort and perceptions of safety around AVs. Experience may not, however, eliminate the distinct discomfort associated with sharing an AV with strangers. By distinguishing familiarity, observation, and firsthand experience across travel roles, the study provides evidence to inform AV adoption scenarios, public engagement, service design, and deployment strategies.

The remainder of this paper is organized as follows. Section 2 describes the survey data, analysis sample, endogenous outcomes, and latent constructs. Section 3 presents the modeling framework. Section 4 discusses the model estimation results and section 5 presents average treatment effects. Section 6 summarizes the major findings, discusses policy and planning implications, and identifies directions for future research.

2. DATA DESCRIPTION

This section describes the data used in the analysis. It first presents the survey design, sampling approach, and socio-economic and demographic composition of the analysis sample. It then describes the AV exposure measure, the four role-specific comfort outcomes, and the attitudinal indicators used to define the latent constructs included in the model.

2.1. Survey Overview and Sample Characteristics

Data for this study are drawn from Wave 2 of the Transportation Heartbeat of America (THA) Survey, a national survey conducted between February and March 2026. The survey was administered through an online panel assembled by a commercial survey firm and was open to adults aged 18 years or older residing in the United States. Quotas were imposed across several socio-economic and geographic dimensions, including gender, age, race, ethnicity, educational attainment, household income, urban or rural residence, and Census division. This sampling strategy was designed to ensure adequate representation across different population groups and to capture the broad variation in characteristics observed nationally. Multiple attention checks and data-quality controls were embedded in the survey instrument to identify inattentive or inconsistent responses.

The THA Survey collected detailed information on transportation attitudes and behavior, including current travel patterns, mode use, commute and telework arrangements, safety perceptions, delivery and online activity participation, transportation investment preferences, and views concerning emerging transportation technologies. The present analysis focuses on respondents' familiarity and experience with autonomous vehicles, together with their stated comfort riding in and interacting around AVs. Survey records were also supplemented with built-environment attributes from the U.S. Environmental Protection Agency Smart Location Database, including population density, employment density, roadway network density, and transit accessibility at the residential ZIP-code level (Chapman et al. 2021).

After removing records with missing information or clearly erroneous responses and appending the built environment measures, the final analysis sample includes 8,567 respondents. Table 1 presents the socio-economic and demographic composition of the sample alongside corresponding benchmarks from the 2024 American Community Survey. The sample is broadly similar to national benchmarks on several dimensions. Women constitute 52.9 percent of the sample, compared with 51.0 percent nationally, while Hispanic respondents account for 19.3 percent, compared with 18.1 percent in the ACS. The racial composition is also generally comparable, although Black respondents are somewhat overrepresented at 16.0 percent relative to 11.8 percent nationally.

TABLE 1 Socio-Economic and Demographic Characteristics of the Sample

<i>Individual Characteristics (N=8,567)</i>			<i>Household Characteristics (N=8,567)</i>		
Variable	Sample (%)	ACS (%)	Variable	Sample (%)	ACS (%)
Gender			Annual household income		
Female	52.9	51.0	Less than \$25,000	18.9	14.4
Male	47.1	49.0	\$25,000 to \$49,999	20.3	16.2
Age category			\$50,000 to \$99,999	26.6	28.2
18 to 24 years	11.4	11.7	\$100,000 to \$149,999	19.7	17.8
25 to 34 years	10.6	17.3	\$150,000 to \$199,999	9.5	9.7
35 to 44 years	21.0	17.2	\$200,000 or more	5.0	13.7
45 to 54 years	16.1	15.3	Household size		
55 to 64 years	13.6	15.6	One	21.2	28.9
65 years or older	27.4	22.9	Two	34.1	34.2
Employment status			Three or more	44.7	37.0
Full-time worker	40.3	44.4	Housing unit type		
Part-time worker	9.3	21.9	Stand-alone home	68.0	61.1
Non-worker	50.4	33.7	Attached home/apartment	26.8	33.4
Educational attainment			Other	5.2	5.5
High school or less	32.2	37.4	Homeownership status		
Some college or technical school	32.5	28.5	Own	61.2	65.3
Bachelor's degree(s)	17.2	21.0	Rent	33.8	34.7
Graduate degree(s)	18.1	13.1	Other	5.0	0.0
Race			Vehicle ownership		
Asian or Pacific Islander	6.7	6.7	Zero	10.7	8.5
Black	16.0	11.8	One	44.0	33.2
White	63.3	62.1	Two	33.1	36.3
Other	14.0	19.4	Three or more	12.2	22.0
Ethnicity			Location*		
Hispanic	19.3	18.1	Urban	75.6	80.0
Non-Hispanic	80.7	81.9	Rural	24.4	20.0

Note: (*) The location values reported in the ACS column are drawn from the 2020 Decennial Census (Table P2).

Some differences are evident across age, employment, household composition, and vehicle ownership. Respondents aged 65 years or older account for 27.4 percent of the sample, compared with 22.9 percent in the ACS, while adults aged 25-34 years are underrepresented. Non-workers comprise 50.4 percent of the sample, compared with 33.7 percent nationally, and part-time workers are correspondingly underrepresented. The sample also includes larger shares of respondents with graduate degrees and households with three or more members. Zero- and one-vehicle households are more prevalent than in the ACS, while households owning three or more vehicles are less common. Urban residents constitute 75.6 percent of the sample, compared with 80.0 percent nationally. Overall, the dataset provides substantial variation across demographic, household, mobility, and geographic attributes, making it well suited for examining heterogeneity in AV exposure and role-specific comfort.

2.2. Endogenous Outcomes

The study examines two related dimensions of public response to autonomous vehicles, namely, the extent of prior AV exposure and the degree of stated comfort in different travel roles. Exposure was measured through a sequence of three yes-or-no questions. Respondents were first asked whether they were aware that rides in autonomous vehicles were already being offered by ride-hailing services and operating on public roads in parts of the United States. Those who reported

awareness were then asked whether they had seen an AV operating on the road, and respondents who had seen one were subsequently asked whether they had ridden in an AV.

Responses to these questions were used to construct a cumulative four-level ordered exposure measure: Not aware, Aware-not seen, Seen-not ridden, and Ridden. Respondents who were unaware that AVs were operating on public roads were assigned to the first category. Those who were aware but had not seen an AV were assigned to the second category, those who had seen but not ridden in one were assigned to the third category, and those with direct riding experience were assigned to the fourth category. As shown in Figure 1(a), 19.6 percent of respondents were not aware of AV operations, while 53.7 percent were aware but had not seen an AV. Another 20.0 percent had seen an AV but had not ridden in one, and 6.7 percent reported direct riding experience. Thus, nearly three-quarters of the sample had no visual or firsthand exposure, while fewer than one in fourteen respondents had ridden in an AV.

Role-specific comfort was measured by asking respondents how comfortable they would feel in four situations: riding alone in an AV, riding with strangers in an AV, driving near an AV, and walking or cycling near an AV. Respondents were instructed to base their answers on either their expectations or, where applicable, their previous AV experience. Each item was recorded on a five-point scale ranging from very uncomfortable to very comfortable, with neither comfortable nor uncomfortable as the midpoint. The four items are treated as ordered endogenous outcomes in the modeling framework.

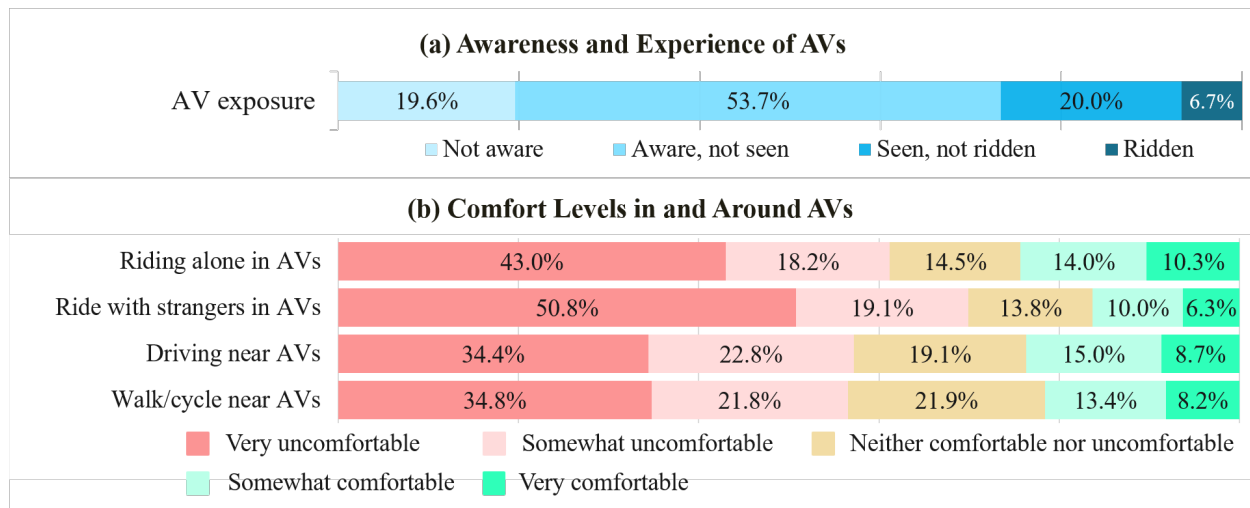


Figure 1 AV Exposure Stages and Comfort Levels in and Around AVs (N=8,567)

Figure 1(b) shows that stated comfort is generally low across all four situations. Discomfort is greatest for riding with strangers, with 69.9 percent reporting that they would be somewhat or very uncomfortable. Riding alone also evokes considerable unease, with 61.2 percent expressing discomfort. Outside-the-vehicle interactions are viewed somewhat more favorably, although discomfort remains widespread; 57.2 percent would be uncomfortable driving near an AV, and 56.6 percent would be uncomfortable walking or cycling near one. The share reporting that they would be somewhat or very comfortable ranges from only 16.3 percent for riding with strangers to 24.3 percent for riding alone. These distributions indicate that discomfort is not limited to occupying an AV; it also extends to sharing the roadway with the technology.

Figure 2 further illustrates how comfort varies across the four exposure stages. The relationship is not strictly monotonic at the earliest stages. Respondents who were aware of AVs

but had not seen one were, in several instances, as uncomfortable or more uncomfortable than those who were not aware. More pronounced differences emerge once respondents have seen or ridden in an AV. Among those who had seen but not ridden in one, the shares reporting that they were somewhat or very comfortable were 35.7 percent for riding alone, 22.6 percent for riding with strangers, 36.2 percent for driving near an AV, and 32.2 percent for walking or cycling near one. Comfort is substantially higher among respondents with direct riding experience. Within this group, 77.2 percent were comfortable riding alone, 60.2 percent were comfortable riding with strangers, 70.9 percent were comfortable driving near an AV, and 67.3 percent were comfortable walking or cycling near one.

The descriptive patterns suggest that the stages of AV exposure are substantively distinct. Awareness alone does not correspond to greater comfort, whereas seeing an AV is associated with more favorable perceptions, particularly for interactions outside the vehicle. Direct riding experience is associated with the highest comfort across every travel role. At the same time, riding with strangers remains the least comfortable setting even among respondents who have ridden in an AV, indicating that concerns associated with shared travel may persist beyond comfort with the vehicle technology itself.

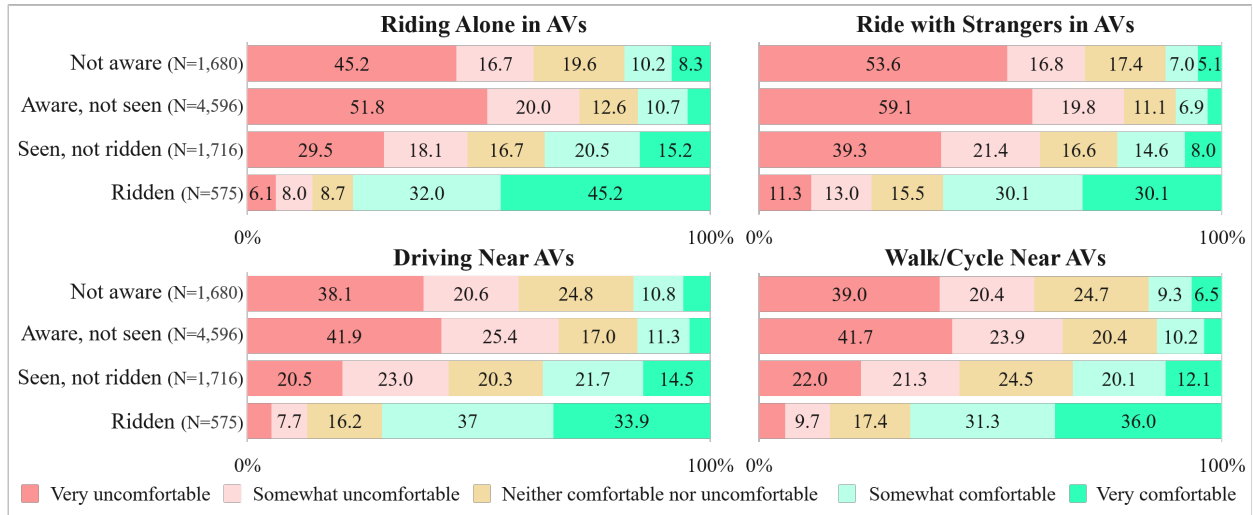


Figure 2 Comfort Levels in and Around AVs by AV Exposure (N=8,567)

2.3. Stochastic Latent Constructs

The survey included a broad set of attitudinal statements capturing respondents' transportation preferences, safety priorities, and receptiveness to emerging technologies. Three stochastic latent constructs were specified for this study: Technology Enthusiasm, Safety Sensitivity, and Multimodal Lifestyle. Each construct is represented by three attitudinal indicators, as shown in Figure 3. Responses were recorded on a five-point Likert scale ranging from "Strongly disagree" to "Strongly agree." These constructs provide a means of accounting for underlying orientations that may jointly shape AV exposure and comfort, but cannot be captured adequately by observed socio-economic characteristics alone.

Technology Enthusiasm captures openness to emerging technologies and AI-enabled travel tools. Its indicators reflect a preference for being among the first to acquire new technology, interest in AI learning personal travel habits and recommending alternatives, and expectations that AI assistants will become part of future travel planning. Responses indicate considerable caution

toward technology-enabled mobility. Only 36.9 percent agreed that they liked being among the first to have the latest technology, while 43.8 percent disagreed. Agreement was similarly limited for AI learning travel habits and suggesting better travel options, at 32.1 percent, and for the anticipated use of AI assistants in travel planning, at 34.6 percent. The construct therefore distinguishes respondents who are especially receptive to technology-intensive transportation innovations from those who remain hesitant or uncertain.

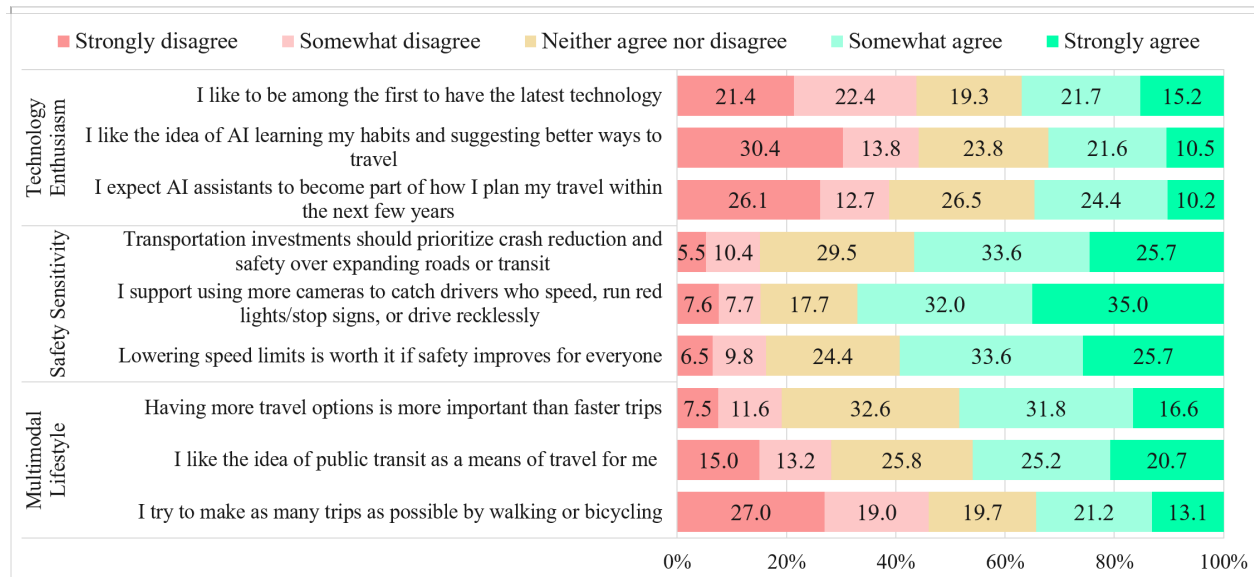


Figure 3 Agreement with Attitudinal Indicators Defining Latent Constructs (N=8,567)

Safety Sensitivity reflects the priority respondents place on crash reduction and safety-oriented transportation policies. The three indicators capture support for prioritizing safety over transportation system expansion, using cameras to identify unsafe driving behavior, and lowering speed limits when doing so improves safety. Support for these principles is generally strong. About 59 percent agreed that transportation investments should prioritize crash reduction and safety and that lower speed limits are worthwhile when they improve safety. Support was even higher for camera-based enforcement, with 67.0 percent expressing agreement. The construct is therefore best interpreted as a general safety-prioritizing orientation rather than as a direct measure of fear or anxiety regarding AVs. Such an orientation may be particularly relevant when individuals evaluate the safety of riding in or sharing the road with an AV.

Multimodal Lifestyle captures affinity for non-automobile travel and the value placed on having multiple transportation options. Its indicators reflect a preference for travel-option variety over faster trips, interest in using public transportation, and efforts to walk or bicycle for as many trips as possible. Nearly one-half of respondents agreed that having more travel options is more important than making faster trips, while 45.9 percent viewed public transportation favorably as a personal travel option. Support for walking or bicycling was lower; 34.3 percent agreed that they try to make as many trips as possible by these modes, while 46.0 percent disagreed. This pattern suggests that many respondents value transportation alternatives even when active travel is not a regular component of their current mobility. The construct is included to capture whether broader openness to modal variety is also associated with greater comfort with AVs as an emerging mobility option.

3. MODELING FRAMEWORK

The study utilizes the Generalized Heterogeneous Data Model (GHDM) framework developed by Bhat (2015). The GHDM provides a flexible structure for jointly modeling multiple interrelated outcomes while incorporating stochastic latent constructs that represent unobserved attitudes and preferences. In the present study, all five endogenous outcomes are ordinal. The four-stage AV exposure measure is modeled together with the five-level comfort measures corresponding to riding alone in an AV, riding with strangers in an AV, driving near an AV, and walking or cycling near an AV. Each outcome is represented through an underlying continuous propensity that is mapped to its observed ordered categories through estimated threshold parameters.

Figure 4 provides a conceptual representation of the model system. The individual- and household-level explanatory variables appear on the left side of the figure. These include socio-demographic characteristics, household attributes, travel and mobility characteristics, built-environment measures, and indicators of residence in metropolitan areas with robotaxi or related AV deployments. These observed factors may influence the endogenous outcomes directly. They may also exert indirect influences through the three stochastic latent constructs shown at the center of the figure: Technology Enthusiasm, Safety Sensitivity, and Multimodal Lifestyle. Each latent construct is defined through the attitudinal indicators presented in the previous section.

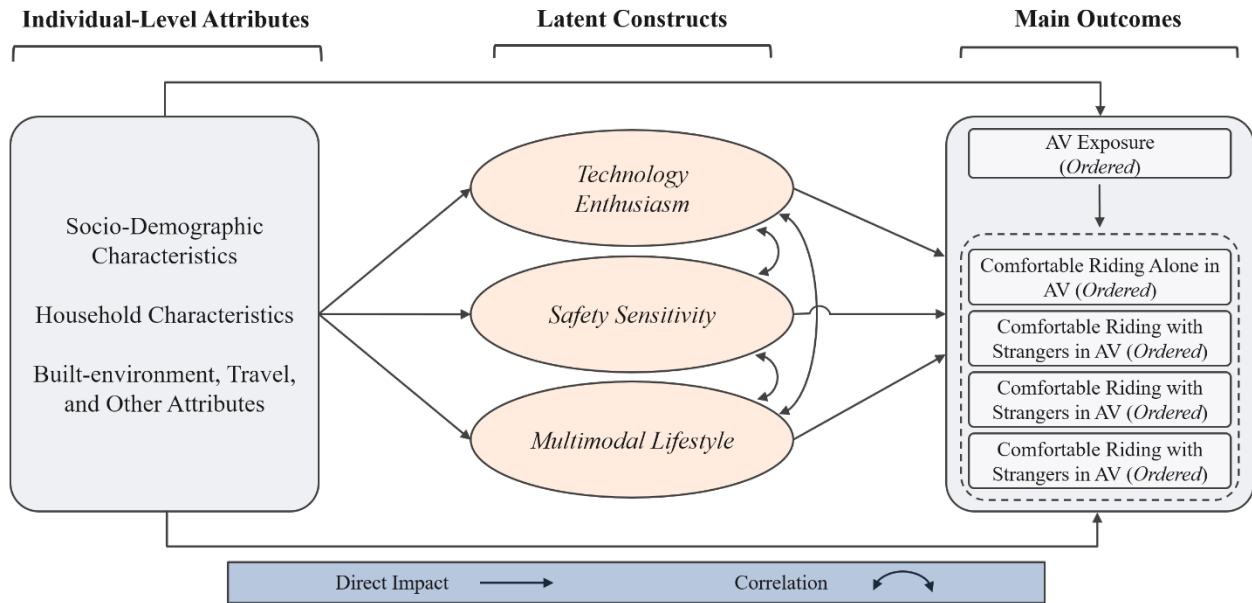


Figure 4 Model Framework

The framework is especially useful for this study because AV exposure and comfort are unlikely to be independent behavioral phenomena. Individuals who are more receptive to emerging technologies may be more likely to encounter or seek opportunities to ride in AVs and may also report greater comfort across multiple travel roles. Similarly, respondents with stronger safety-oriented attitudes may evaluate riding in an AV differently from interacting with one as a driver, pedestrian, or cyclist. By modeling the latent constructs as correlated stochastic factors, the framework accounts for shared attitudinal orientations that may generate systematic associations across exposure and comfort outcomes.

The model also incorporates a direct relationship between AV exposure and each role-specific comfort measure. The four exposure stages are entered into the comfort equations to

examine whether comfort differs among respondents who are unaware of AV operations, aware but have not seen an AV, have seen but not ridden in one, and have ridden in an AV. This recursive structure is central to the study because it allows the intermediate stages of familiarity and observation to be distinguished from direct riding experience. The joint estimation further engenders correlations across the comfort outcomes (through correlations among the stochastic latent constructs) that may arise from unobserved factors not fully captured by the observed variables or latent constructs. Thus, the model recognizes that an individual's comfort riding in an AV may be related to that same individual's comfort driving, walking, or cycling near one.

The resulting framework captures three pathways through which observed characteristics may be associated with AV exposure and comfort: direct effects on the ordered outcomes, indirect effects operating through the latent constructs, and exposure-related differences in the comfort propensities. The model is intended to identify how familiarity, exposure, personal characteristics, and underlying attitudes jointly shape comfort in and around AVs. The complete mathematical formulation and estimation procedure are lengthy and notation intensive and are therefore omitted in the interest of brevity. Detailed documentation of the GHDM formulation may be found in Bhat (2015).

4. MODEL ESTIMATION RESULTS

This section presents the model estimation results in detail. The discussion begins with the latent construct component, which relates individual, household, mobility, and residential characteristics to the three underlying orientations – Technology Enthusiasm, Safety Sensitivity, and Multimodal Lifestyle – and reports the corresponding factor loadings for the attitudinal indicators. The discussion then turns to the ordered AV exposure outcome and the four role-specific comfort outcomes, focusing on the direct effects of observed characteristics, the influence of the latent constructs, and the extent to which progressively greater familiarity and experience are associated with comfort riding in and interacting around autonomous vehicles.

4.1. Latent Constructs

Table 2 presents the estimation results for the three stochastic latent constructs – Technology Enthusiasm, Safety Sensitivity, and Multimodal Lifestyle. The upper portion reports the effects of individual, household, and residential characteristics on each construct, while the lower portion presents the factor loadings linking the constructs to their observed attitudinal indicators. Correlations among the constructs are also reported. The measurement equation results in the bottom half of the table support the latent construct specification. All factor loadings are positive and statistically significant, with directions consistent with the intended meaning of each construct.

In the structural equations model component, systematic differences are evident across individual characteristics. Female respondents exhibit lower Technology Enthusiasm and Multimodal Lifestyle propensities. Their Safety Sensitivity score is modestly higher, although only marginally significant. Age differences are particularly pronounced. Respondents aged 18-44 have higher scores on all three constructs than the omitted middle-age categories. In contrast, those aged 65-74 and especially those aged 75 years or older have substantially lower Technology Enthusiasm and Multimodal Lifestyle scores (Batur et al. 2023; Lavieri et al. 2017). Respondents aged 75 years or older also exhibit higher Safety Sensitivity (Mizenko et al. 2015). Thus, younger adults are more receptive to emerging technology and multimodal travel, while the oldest adults place greater emphasis on safety-related considerations.

Educational attainment is positively associated with all three constructs. Respondents with at least a bachelor's degree have higher Technology Enthusiasm, Safety Sensitivity, and Multimodal Lifestyle scores. Black respondents also exhibit higher scores on all three constructs. Hispanic respondents have a notably higher Multimodal Lifestyle score, while the positive association with Technology Enthusiasm is smaller and only marginally significant. Full-time workers have higher scores on all three constructs, whereas part-time workers exhibit a higher Multimodal Lifestyle score. These findings are generally consistent with expectations and behaviorally intuitive.

Household circumstances also matter, although the patterns differ across constructs. Respondents in households earning less than \$35,000 have a substantially higher Multimodal Lifestyle score. Households earning at least \$100,000 exhibit slightly greater Technology Enthusiasm, while those earning at least \$150,000 have a lower Multimodal Lifestyle score. One-person households show modestly higher scores across all three constructs, whereas households with three or more members exhibit higher Safety Sensitivity. The presence of children is strongly associated with Technology Enthusiasm and weakly associated with greater Safety Sensitivity, but negatively associated with Multimodal Lifestyle at a marginal level of significance. Once again, these findings are consistent with expectations and aligned with mode use patterns reported in the literature among different population subgroups. Urban residence is positively associated with all three latent orientations. This finding is consistent with the greater availability and visibility of multiple transportation modes and emerging mobility services in urban settings (Ardeshiri and Vij 2019).

The estimated correlations show that the constructs are related but distinct. Technology Enthusiasm is negatively correlated with Safety Sensitivity and positively correlated with Multimodal Lifestyle. The strongest correlation is between Safety Sensitivity and Multimodal Lifestyle indicating that respondents who value transportation alternatives also tend to place greater emphasis on safety.

Overall, the latent construct results reveal substantial heterogeneity in technology receptiveness, safety orientation, and multimodal preferences. These constructs capture attitudinal dimensions not fully represented by observed socio-economic characteristics and provide important pathways through which individual and household attributes are associated with AV exposure and role-specific comfort.

TABLE 2 Determinants of Latent Variables and Loadings on Indicators (N = 8,567)

Explanatory Variables (base category)		Structural Equations Model Component					
		Technology Enthusiasm		Safety Sensitivity		Multimodal Lifestyle	
		Coef.	t-stat	Coef.	t-stat	Coef.	t-stat
Individual characteristics							
Gender (male)	Female	-0.34	-5.48	0.13	1.59	-0.19	-2.13
Age (*)	18 to 44 years	0.11	1.99	0.15	2.06	0.16	2.48
	65 to 74 years	-0.33	-7.11	0.08	1.67	-0.36	-4.15
	75 years or older	-0.54	-10.78	0.20	3.51	-0.67	-5.77
Education (<bachelor's degree)	≥ Bachelor's degree	0.25	3.46	0.07	2.03	0.23	3.33
Race (not Black)	Black	0.08	2.01	0.14	2.13	0.16	2.28
Ethnicity (not Hispanic)	Hispanic	0.04	1.72	—	—	0.27	4.65
Employment (*)	Full-time worker	0.15	3.09	0.09	1.99	0.17	3.84
	Part-time worker	—	—	—	—	0.17	4.47
Household attributes							
Household income (*)	< \$35,000	—	—	—	—	0.39	4.70
	≥ \$100,000	0.07	1.97	—	—	—	—
	≥ \$150,000	—	—	—	—	-0.21	-4.70
Household size (*)	One	0.06	2.16	0.12	1.85	0.09	1.89
	Three or more	—	—	0.18	3.03	—	—
Child presence (none)	At least one child	0.29	7.77	0.08	1.80	-0.12	-1.66
Location (suburbs/small town/rural)	Urban	0.29	4.31	0.35	5.79	0.49	4.29
Correlations Between Latent Constructs							
Technology enthusiasm		1.00	—	-0.17	-2.71	0.15	2.14
Safety sensitivity				1.00	—	0.36	5.25
Attitudinal Indicators[^]		Loadings of Latent Variables on Indicators (Measurement Equations Model Component)					
I like to be among the first to have the latest technology		0.39	10.44	—	—	—	—
I like the idea of AI learning my habits and suggesting better ways to travel		0.42	11.61	—	—	—	—
I expect AI assistants to become part of how I plan my travel within the next few years		0.57	22.21	—	—	—	—
Transportation investments should prioritize crash reduction and safety over expanding roads or transit		—	—	0.41	20.71	—	—
I support using more cameras to catch drivers who speed, run red lights/stop signs, or drive recklessly		—	—	0.32	16.80	—	—
Lowering speed limits is worth it if safety improves for everyone		—	—	0.36	21.37	—	—
I like the idea of public transit as a means of travel for me		—	—	—	—	0.48	22.72
I try to make as many trips as possible by walking or bicycling		—	—	—	—	0.45	20.70
Having more travel options is more important than faster trips		—	—	—	—	0.48	21.64

Note: Coef. = coefficient; “—” = not applicable; (*) Base category is not identical across the model equations and corresponds to all omitted categories. (^) Some attitudinal statements have been slightly re-worded for presentation purposes while preserving their intended meaning.

4.2. Estimation Results for the Main Outcomes Model

Table 3 presents the estimation results for the ordered AV exposure outcome and the four role-specific comfort outcomes. Positive coefficients in the exposure equation indicate a greater latent propensity to occupy a higher stage of the exposure ladder, progressing from no awareness toward observation and direct riding experience. Positive coefficients in the comfort equations indicate a greater propensity to report a higher level of comfort, whereas negative coefficients indicate a greater inclination toward lower comfort categories. These estimates reflect changes in underlying

ordered propensities rather than direct changes in category probabilities and should therefore be interpreted accordingly, even if the wording may not explicitly say so.

4.2.1. Exogenous Variable Effects

The exogenous variable results reveal systematic differences in both AV exposure and role-specific comfort. Gender exhibits one of the most consistent patterns. The main female coefficient is negative in the exposure equation and across all four comfort equations, with the largest negative association appearing for riding with strangers. This pattern is consistent with prior evidence that women report greater concern regarding AV safety and lower willingness to use shared automated mobility services (Nair and Bhat 2021).

The positive gender-age interactions, however, show that this relationship is not uniform across the life course. The negative associations with passenger comfort are substantially attenuated among women aged 18-44 years, while younger women exhibit relatively greater comfort driving, walking, or cycling near AVs. These findings underscore the importance of accounting for heterogeneity within broad demographic groups rather than treating gender differences as uniform across all age categories.

Age is also associated with exposure and comfort in distinct ways. Respondents aged 45-64 years exhibit a lower propensity to occupy a higher exposure stage, while adults aged 25-44 report greater comfort driving and walking or cycling near AVs. Respondents aged 18-24 are also more comfortable walking or cycling near AVs. In contrast, adults aged 65 years or older exhibit lower comfort riding alone, riding with strangers, and driving near an AV. The interaction terms provide an important qualification: older adults who do not drive are more comfortable in the two passenger contexts (riding alone or riding with others) than older adults who continue to drive. For individuals who face limitations on independent driving, AVs may be seen as a potentially valuable mobility option (Wu et al. 2021).

Education is positively associated with progressing to a higher AV exposure stage, and respondents with at least a bachelor's degree are also somewhat more comfortable riding alone. Current students exhibit greater comfort riding alone as well. These results may reflect greater familiarity with emerging technologies, more frequent exposure to innovation, or greater access to information about AV capabilities (Nair and Bhat 2021). Race effects are comparatively limited. Asian respondents exhibit lower AV exposure, while Blacks report slightly lower comfort driving near AVs. The absence of broad, consistent race effects suggests that the more prominent sources of variation in this specification arise from exposure, mobility experience, and latent attitudes.

Household resources are associated more consistently with AV exposure than with comfort. Respondents in households owning two or more vehicles exhibit greater exposure, as do those with household incomes of at least \$100,000. Conversely, respondents in households earning less than \$35,000 have a substantially lower propensity to occupy a higher exposure level. Higher-income respondents also report greater comfort riding alone, driving near an AV, and walking or cycling near one (but not in riding with others). These patterns suggest that opportunities to encounter or experience AVs may be distributed unevenly. Early exposure may be more accessible to individuals with greater financial resources, broader travel activity, and stronger connections to markets in which AV services are deployed (Jiang et al. 2022).

Existing mobility behavior provides additional insight into AV familiarity and comfort. Air travelers exhibit a considerably greater propensity for AV exposure, possibly reflecting greater overall travel intensity or more frequent encounters with emerging mobility services. Public transit users are more comfortable riding with strangers in an AV, but no corresponding association

appears for the other outcomes. This selective effect is behaviorally plausible because transit users are already accustomed to sharing vehicles with unfamiliar passengers (Magassy et al. 2024).

Ride-hailing use produces the most consistent mobility-related pattern. Users exhibit greater AV exposure and substantially greater comfort across all four roles. The association is especially strong for riding alone, but it also extends to riding with strangers and interacting with AVs as a driver, pedestrian, or cyclist. Ride-hailing users may be more familiar with app-based mobility, less attached to personally operating a vehicle, and more comfortable obtaining transportation from an unfamiliar service provider. Existing ride-hailing experience may therefore provide a behavioral bridge between conventional mobility and future automated services (Magassy et al. 2024).

Residential geography is associated primarily with opportunities for exposure. Urban residence has modest positive associations with exposure and all four comfort outcomes. Much stronger exposure effects appear for respondents residing in metropolitan areas identified in the model as Waymo-serving cities. Phoenix and San Francisco exhibit the largest coefficients, followed by Austin, Las Vegas, Los Angeles, and Atlanta. The longer history and greater visibility of AV operations in some of these markets likely increase opportunities to see or ride in an AV (Jiang et al. 2022).

The comfort effects of local deployment are considerably less uniform. Residence in Phoenix, San Francisco, and Los Angeles is associated with greater comfort riding alone, but most city indicators are not significant in the other comfort equations. Phoenix residents also exhibit lower comfort riding with strangers. Thus, living in a market where AVs are visible is strongly associated with exposure, but local availability alone does not generate broad comfort across all travel roles.

4.2.2. Endogenous Variable Effects

The estimated effects of AV exposure on comfort provide the clearest evidence that the stages of familiarity and experience are substantively different. Relative to respondents who are unaware that AVs are operating on public roads, those who are aware but have not seen one exhibit lower comfort across all four outcomes. Awareness by itself therefore does not correspond to increased comfort in using the technology. It may expose individuals to unresolved questions, media reports, or highly salient safety incidents without providing direct information about how AVs actually operate. These associations should not be interpreted as awareness causing discomfort; rather, they indicate that conceptual familiarity alone does not overcome apprehension.

Seeing an AV without having ridden in one produces a markedly different pattern. Respondents at this exposure stage exhibit greater comfort riding alone, driving near an AV, and walking or cycling near one. The largest coefficient appears for driving near an AV, followed by walking or cycling nearby. No significant association is found for riding with strangers. Observation therefore appears most relevant to comfort outside the vehicle. Seeing an AV move through traffic may provide information about whether it stops, yields, navigates, and responds predictably. However, visual exposure offers limited insight into the passenger experience and does not address concerns associated with sharing an enclosed vehicle with strangers (Aasvik et al. 2025; Long et al. 2025).

Direct riding experience is the strongest positive exposure correlate in every comfort equation. Respondents who have ridden in an AV exhibit substantially greater comfort riding alone, riding with strangers, driving near an AV, and walking or cycling near one. Direct experience therefore appears to shape not only passenger comfort but also perceptions of how AVs

interact with surrounding road users. A successful ride allows individuals to observe vehicle behavior from inside the system and to evaluate acceleration, braking, navigation, yielding, and responsiveness firsthand. This finding is consistent with experimental and demonstration-based research showing that direct experience is more strongly associated with trust and acceptance than general awareness alone (Farias et al. 2026; Paddeu et al. 2020).

The smaller coefficient for riding with strangers remains substantively important. Experience with the automated driving system may reduce uncertainty regarding vehicle performance without fully addressing concerns about privacy, personal security, and shared travel. Overall, the endogenous effects support a staged and role-specific interpretation of AV comfort. Awareness introduces the technology, observation provides evidence about roadway behavior, and direct riding experience provides the most comprehensive basis for evaluating comfort and safety.

4.2.3. Latent Construct Effects

The three latent constructs exhibit distinct and substantively meaningful associations with AV exposure and comfort. Technology Enthusiasm is positively associated with occupying a higher exposure stage and with comfort across all four travel roles. Respondents who are receptive to emerging technologies and AI-enabled travel tools are therefore not only more likely to have encountered AVs but are also more comfortable riding in and interacting around them. This result reinforces the importance of accounting for pre-existing technology orientation when evaluating the relationship between experience and comfort. Individuals who seek AV experiences may already be more positively disposed toward emerging technology use (Nair and Bhat 2021).

Safety Sensitivity exhibits the opposite pattern. Although it has no significant influence on AV exposure level, it is strongly and negatively associated with all four comfort outcomes. Respondents who place greater emphasis on crash reduction, enforcement, and safety-oriented policy are thus more cautious about AVs - regardless of the role in which they imagine encountering them. This does not imply opposition to AV technology. Rather, safety-sensitive respondents may require stronger evidence that AVs can operate reliably without compromising the safety of passengers or surrounding road users before they feel comfortable adopting the technology (Li et al. 2024).

The interaction terms show that the relationship between Safety Sensitivity and comfort is conditional. Its interactions with direct riding experience are positive for riding alone and riding with strangers. Direct experience therefore attenuates, but does not eliminate, the negative association between safety orientation and comfort. This finding is particularly important from a deployment perspective; carefully managed riding experiences may help reassure safety-conscious individuals, provided that the vehicles operate smoothly, predictably, and without incident.

Educational attainment also moderates the effect of Safety Sensitivity. The positive interactions between Safety Sensitivity and having at least a bachelor's degree appear in the exposure equation and across all four comfort equations. In the comfort models, these interaction effects offset much of the negative main effect of Safety Sensitivity. More highly educated respondents may be better positioned to evaluate technological risk, distinguish between system limitations and generalized apprehension, and interpret available safety information (Li et al. 2024; Nair and Bhat 2021).

TABLE 3 Estimation Results for Main Outcome Variables (N = 8,567)

Explanatory Variables (base category)		AV Exposure		Ride Alone		Ride with Strangers		Drive Near AVs		Walk/Cycle Near AVs	
		Ordinal (4-level)		Ordinal (5-level)							
		Coef.	t-stat	Coef.	t-stat	Coef.	t-stat	Coef.	t-stat	Coef.	t-stat
Endogenous Variable Effects											
AV exposure (not aware)	Aware, not seen	—		-0.35	-5.26	-0.30	-5.31	-0.26	-6.30	-0.27	-6.73
	Seen, not ridden	—		0.11	2.12	—		0.27	4.97	0.18	3.49
	Ridden in an AV	—		0.73	5.15	0.59	7.60	0.77	9.31	0.78	9.87
Latent Constructs											
Technology enthusiasm		0.14	3.33	0.60	10.60	0.57	10.16	0.57	10.12	0.64	10.65
Safety sensitivity		—		-0.48	-9.55	-0.49	-11.07	-0.49	-8.71	-0.51	-9.38
Safety sensitivity × Ridden in AV		—		0.30	7.05	0.24	5.72	—		—	
Safety sensitivity × ≥ Bachelor’s degree		0.20	8.75	0.40	15.88	0.40	8.51	0.38	13.82	0.39	14.39
Multimodal lifestyle		0.16	2.89	—		0.22	3.93	—		0.22	3.33
Individual Characteristics											
Gender (male)	Female	-0.19	-2.85	-0.32	-2.36	-0.39	-3.24	-0.18	-2.39	-0.16	-2.12
Age (*)	18 to 24 years	—		—		—		—		0.15	2.04
	25 to 44 years	—		—		—		0.18	3.28	0.19	3.41
	45 to 64 years	-0.10	-2.92	—		—		—		—	
	65 years or older	—		-0.18	-1.70	-0.06	-1.81	-0.11	-1.91	—	
Race (*)	Asian	-0.11	-2.47	—		—		—		—	
	Black	—		—		—		-0.06	-2.12	—	
Education (< bachelor’s)	≥ Bachelor’s degree	0.16	4.28	0.05	2.88	—		—		—	
Current student (no)	Yes	—		0.17	5.94	—		—		—	
Household Characteristics											
Vehicle ownership (< 2)	Two or more	0.11	4.50	—		—		—		—	
Household income (*)	< \$35,000	-0.23	-5.69	—		—		—		—	
	≥ \$100,000	0.10	3.02	0.13	2.81	—		0.13	2.89	0.13	2.91
Mode Use Attributes											
Air travel (non-user)	User	0.23	8.51	—		—		—		—	
Public transit (non-user)	User	—		—		0.23	8.06	—		—	
Ridehailing (non-user)	User	0.20	7.35	0.33	12.15	0.27	9.47	0.27	9.40	0.26	9.22
Residential Geography											
Location (all others)	Urban	0.09	1.78	0.10	1.83	0.06	1.73	0.11	1.72	0.06	1.79
Waymo serving city (*)	Phoenix	1.18	21.34	0.27	3.24	-0.31	-4.06	—		—	
	San Francisco	1.02	9.67	0.29	2.83	—		—		—	
	Los Angeles	0.56	10.51	0.24	3.95	—		—		—	
	Atlanta	0.53	5.99	—		—		—		—	
	Austin	0.76	6.57	—		—		—		—	
	Las Vegas	0.69	6.32	—		—		—		—	
Interaction Terms (*)											
Female × 18 to 24 years		—		—		—		0.21	2.71	0.17	2.30
Female × 18 to 44 years		—		0.23	4.79	0.26	5.71	—		—	
65 years or older × Does not drive		—		0.17	2.15	0.20	2.64	—		—	
Thresholds											
1 2		-0.70	-21.68	-0.47	-8.79	-0.17	-3.52	-0.70	-12.40	-0.63	-11.56
2 3		0.93	28.17	0.33	6.15	0.63	12.42	0.27	4.98	0.28	5.31
3 4		1.98	54.53	1.04	18.61	1.37	25.13	1.16	20.35	1.29	22.65
4 5		—		2.03	33.54	2.27	38.96	2.24	35.08	2.29	35.87
Correlations											
AV Exposure		1.00		0.05		0.08		0.05		0.08	
Ride Alone		—		1.00		0.37		0.38		0.39	

Ride with Strangers	—	—	1.00	0.36	0.40
Drive Near Avs	—	—	—	1.00	0.39
Walk/Cycle Near AVs	—	—	—	—	1.00
Data Fit Measure	GHDM		Independent Model		
Predictive log-likelihood at convergence	-49440.41		-50154.70		
Predictive log-likelihood at constants	-59796.98		-59796.98		
Number of parameters	185.00		162.00		
Adjusted likelihood ratio index	0.17		0.16		
Bayesian information criterion	50278.06		50888.21		
Non-nested likelihood ratio test			-38.44		

Note: Coef. = coefficient: “—” = not applicable; (*) Base category is not identical across the model equations and corresponds to all omitted categories.

Multimodal Lifestyle has a more selective influence. It is positively associated with AV exposure and with comfort riding with strangers and walking or cycling near an AV. No significant association is found for riding alone or driving near one. The shared-riding result is consistent as individuals who value transit and multiple transportation options are more accustomed to collective travel and more receptive to pooled AV services (Magassy et al. 2024). The positive association with walking or cycling near AVs may similarly reflect greater familiarity with navigating multimodal transportation environments.

Overall, the latent construct results demonstrate that AV comfort reflects more than the influence of observed demographic or household characteristics. Technology receptiveness strongly promotes exposure and comfort, safety orientation constrains comfort unless moderated by experience and education, and multimodal preferences are associated especially with shared and active-mode contexts. These attitudinal pathways help explain why individuals with otherwise similar characteristics may feel very differently about AV technology.

4.2.4. Correlations and Goodness-of-Fit

The estimated correlations indicate that the four comfort outcomes share common unobserved traits. Correlations among comfort riding alone, riding with strangers, driving near AVs, and walking or cycling near AVs range from 0.36 to 0.40. Thus, individuals who are more comfortable with AVs in one travel role also tend to exhibit greater comfort in the other roles, even after accounting for observed characteristics and latent attitudes. By comparison, the correlations between AV exposure and the comfort outcomes are small, ranging from 0.05 to 0.08. This pattern suggests that exposure and comfort are strongly related through the direct effect incorporated in the model specification with little residual shared unobserved effects, while the different forms of comfort are more closely connected through shared unobserved influences.

The GHDM provides a better statistical fit than a corresponding independent model where each outcome is specified and estimated separately. The predictive log-likelihood at convergence improves from -50,154.70 for the independent specification to -49,440.41 for the GHDM, while the adjusted likelihood ratio index increases from 0.16 to 0.17. Despite estimating 23 additional parameters, the GHDM also yields a substantially lower Bayesian Information Criterion (BIC), 50,278.06 compared with 50,888.21, indicating that the improvement in fit more than offsets the added model complexity. Overall, the predictive log-likelihood and BIC provide clear evidence in favor of the joint GHDM specification.

5. AVERAGE TREATMENT EFFECTS

Ordered probit coefficients describe changes in underlying latent propensities and therefore do not translate directly into changes in the probability of reporting comfort. Table 4 consequently presents average treatment effects (ATEs) for each pair of AV exposure categories. For every respondent, the model is used to predict the probability of being *somewhat or very comfortable* under a designated base exposure category and an alternative exposure category, while holding all other observed characteristics and latent constructs constant. The difference between these probabilities is then averaged across the sample. The percentage average treatment effect (PATE) expresses the ATE relative to the average predicted probability under the base category. Thus, an ATE of 0.10 represents a 10-percentage-point change, whereas the corresponding PATE indicates how large that change is relative to the initial comfort probability. Additional details on the computation of such probability effects are provided by Bhat and Eluru (2009). Because exposure is not randomly assigned and the data are cross-sectional, the terms *base* and *treatment* describe model-implied exposure scenarios rather than causal interventions.

The results reinforce the conclusion that awareness, observation, and direct riding experience represent substantively different stages of exposure. Moving from being unaware of AV operations to being aware but not having seen an AV is associated with lower comfort across all four settings. The estimated declines range from 4.6 to 6.5 percentage points, equivalent to reductions of roughly 23 to 29 percent relative to the predicted comfort levels of respondents who were unaware. Awareness alone may therefore introduce the technology without resolving uncertainty regarding its performance or safety. This result should not be interpreted as evidence that information itself causes discomfort; rather, it indicates that abstract awareness, in the absence of direct observation or experience, does not necessarily bring about greater comfort.

Visual exposure produces a more favorable but role-specific pattern. Relative to being unaware, having seen but not ridden in an AV is associated with modest increases in comfort riding alone, driving near an AV, and walking or cycling near one. The largest increase appears for driving near AVs, while no change is estimated for riding with strangers. Seeing an AV operate may provide useful information about how it moves through traffic, yields, stops, and responds to surrounding road users. Such observation appears less effective in addressing concerns about the onboard experience and offers little reassurance regarding the additional social and personal-security considerations associated with riding alongside strangers.

Direct riding experience generates the largest positive changes across every comfort dimension. Relative to being unaware, moving to the ridden category increases the probability of comfort by nearly 12 percentage points for riding with strangers and by approximately 18 percentage points for the other three contexts. These changes correspond to relative increases of about 69 to 92 percent. The result is especially important because the benefits of direct experience extend beyond passenger comfort. Respondents, when assigned to the ridden scenario, are also substantially more likely to feel comfortable driving, walking, or cycling near AVs, suggesting that firsthand experience may provide broader reassurance regarding vehicle behavior and safety.

The largest contrasts arise when direct riding experience is compared with awareness without visual exposure. Moving from the aware-not seen category to the ridden category raises comfort by 16.6 to 24.2 percentage points across the four settings. Because predicted comfort is particularly low under the awareness-only scenario, these changes represent relative increases exceeding 130 percent in every case. Direct riding experience also adds considerably beyond visual observation. Relative to respondents who have seen but not ridden in an AV, assignment to the ridden category increases comfort by approximately 12-15 percentage points, or about 50 to

69 percent. Direct experience therefore provides information and reassurance that neither awareness nor observation appears able to supply fully.

TABLE 4 Average Treatment Effects (ATEs) Comfort Dimensions by AV Exposure

Base	Treatment	Ride Alone		Ride with Strangers		Drive Near AVs		Walk/Cycle Near AVs	
		ATE	PATE (%)	ATE	PATE (%)	ATE	PATE (%)	ATE	PATE (%)
Not aware of AVs	Aware, not seen	-0.065	-28.5	-0.046	-26.9	-0.047	-23.4	-0.048	-22.7
	Seen, not ridden	0.024	10.3	0.000	0.0	0.057	28.4	0.037	17.7
	Ridden in an AV	0.177	77.5	0.119	69.2	0.186	92.3	0.182	86.1
Aware, not seen	Not aware	0.065	39.8	0.046	36.8	0.047	30.5	0.048	29.4
	Seen, not ridden	0.089	54.2	0.046	36.8	0.104	67.5	0.085	52.3
	Ridden in an AV	0.242	148.1	0.166	131.4	0.233	150.9	0.230	140.8
Seen, not ridden	Not aware	-0.024	-9.4	0.000	0.0	-0.057	-22.1	-0.037	-15.0
	Aware, not seen	-0.089	-35.2	-0.046	-26.9	-0.104	-40.3	-0.085	-34.3
	Ridden in an AV	0.154	60.9	0.119	69.2	0.129	49.8	0.145	58.1
Ridden in an AV	Not aware	-0.177	-43.7	-0.119	-40.9	-0.186	-48.0	-0.182	-46.3
	Aware, not seen	-0.242	-59.7	-0.166	-56.8	-0.233	-60.2	-0.230	-58.5
	Seen, not ridden	-0.154	-37.8	-0.119	-40.9	-0.129	-33.2	-0.145	-36.8

The results for riding with strangers remain distinctive. Visual exposure alone produces no increase in this outcome, and the gains associated with direct riding are generally smaller in absolute terms than those observed for riding alone or interacting with AVs from outside the vehicle. This pattern is consistent with the view that shared AV comfort involves two separate judgments, namely, confidence in the automated driving system and willingness to occupy a confined vehicle with strangers. Experience with the vehicle may improve the first judgment without fully resolving concerns related to personal security, privacy, or shared travel.

Overall, the ATE results provide a clear probability-scale interpretation of the model findings. Awareness without observation is associated with lower comfort, visual exposure yields modest and primarily outside-vehicle gains, and direct riding experience produces substantial increases across all four contexts. The results strongly support the study's central proposition that familiarity matters, observation matters, and direct experience matters most in shaping comfort in and around autonomous vehicles.

6. DISCUSSION AND CONCLUSIONS

This study examined how familiarity, observation, and direct experience with autonomous vehicles (AVs) are associated with comfort in four distinct travel situations: riding in an AV alone, riding in an AV with strangers, driving near an AV, and walking or cycling near an AV. Data were drawn from Wave 2 of the Transportation Heartbeat of America Survey, comprising 8,567 adults from across the United States. A four-stage exposure ladder – not aware, aware but not seen, seen but not ridden, and ridden – was jointly modeled with the four comfort outcomes using a Generalized Heterogeneous Data Model. The framework accounted for observed individual, household, mobility, and geographic characteristics, as well as latent factors representing technology enthusiasm, safety sensitivity, and multimodal lifestyle orientation. The analysis was motivated by the notion that people encounter AVs through progressively more direct forms of exposure, and each stage may shape comfort differently.

The descriptive evidence reveals the magnitude of the adoption challenge. Only 6.7 percent of respondents had ridden in an AV, while 53.7 percent were aware of AV operations but had

never seen one. Discomfort was widespread across all four scenarios. About 61 percent were uncomfortable riding alone, 70 percent when riding with strangers, 57 percent when driving near an AV, and 57 percent when walking or cycling near one. These findings show that public unease is not confined to surrendering control as a passenger. It extends to the broader transportation environment in which drivers, pedestrians, and cyclists must interact with vehicles whose intentions and capabilities may not yet be fully understood.

The results strongly demonstrate that the stages of AV exposure matter. Awareness is an important first step, but awareness alone does not create comfort. Respondents who were aware of AVs but had not seen one were no more comfortable than those who were unaware. General knowledge may introduce people to the promise of AVs, but it may also expose them to uncertainty, negative news, or safety concerns without providing tangible evidence regarding how the vehicles actually perform. Seeing an AV operate was associated more clearly with comfort outside the vehicle, particularly when driving, walking, or cycling nearby. Observation appears to provide useful information about how AVs move, stop, yield, and interact with other road users, but does not necessarily substitute for passenger experience.

Direct riding experience stands apart as the most consequential exposure stage. Having ridden in an AV exhibited the largest positive association in every comfort scenario. Across the four scenarios considered, the model-implied probability of being somewhat or very comfortable was 11.9 to 18.6 percentage points higher for respondents who had ridden in an AV than for those who were unaware, representing relative increases of approximately 69 to 92 percent. The descriptive distributions are equally striking. Among respondents with direct experience, 77.2 percent were comfortable riding alone, 60.2 percent riding with strangers, 70.9 percent driving near an AV, and 67.3 percent walking or cycling near one. The central message that direct experience matters greatly is therefore unmistakable. People may learn about AVs through information campaigns and become accustomed to their presence through observation, but firsthand riding provides a qualitatively different basis for evaluating safety, reliability, ride quality, and the experience of relinquishing control.

Comfort nevertheless remains role specific. Even among those who had ridden in an AV, comfort riding with strangers was lower than comfort riding alone or interacting with AVs from outside the vehicle. Shared riding combines considerations of confidence in the automated driving system with concerns about personal security, privacy, and occupying an enclosed space with unknown passengers. Consistent with this interpretation, multimodal lifestyle orientation was most strongly associated with comfort riding with strangers, suggesting that people accustomed to transit and shared mobility may be more receptive to this service model. AV adoption strategies should therefore avoid treating willingness to ride alone and willingness to share a vehicle as manifestations of the same underlying attitude.

The safety findings carry especially important implications. Safety sensitivity was negatively associated with comfort in every context and most strongly with comfort riding with strangers. At the same time, its negative association with comfort riding alone was less pronounced among respondents who had ridden in an AV. This pattern suggests that direct experience may help address the concerns of safety-conscious individuals, but only when that experience is demonstrably safe, predictable, and well managed. A poor encounter, highly publicized failure, or unexplained vehicle behavior may reinforce skepticism rather than overcome it. Public acceptance cannot be built through exposure alone; it must be built through exposure to systems that perform safely and consistently.

Accordingly, pilots and public demonstrations can play a major role in accelerating informed adoption, but they must operate within strong safety guardrails. Programs should be introduced through phased deployment, clearly defined operating conditions, rigorous pre-deployment testing, continuous performance monitoring, transparent incident reporting, and credible procedures for responding when the automated system encounters conditions beyond its capabilities. Independent safety review and clear communication regarding system limitations are essential to public confidence. Demonstrations should offer meaningful firsthand experience to a broad cross-section of the population, including older adults, women, safety-sensitive individuals, people with disabilities, and other groups that may have distinct concerns or stand to benefit substantially from automated mobility. They should also expose drivers, pedestrians, and cyclists to AV operations in controlled and carefully monitored settings. Piloting should represent disciplined learning under enforceable safeguards – not an open-ended experiment conducted on public roads.

Overall, this study shows that familiarity matters, observation matters, and direct experience matters most. Yet experience will accelerate adoption only when it demonstrates that AVs can operate safely, predictably, and responsibly. The pathway to public acceptance is therefore neither unrestricted experimentation nor promotion alone. It is the deliberate combination of rigorous safety assurance, transparent governance, controlled exposure, and successful firsthand experience. Encouraging the use of shared AV services will require a concerted effort to offset concerns about personal safety, security, privacy, and inconvenience. Meaningful fare discounts, minimal route deviation and added travel time, and reliable matching and service standards should be coupled with robust safeguards, including verified rider identities, easily accessible emergency call buttons, real-time assistance, and onboard video monitoring governed by clear privacy and data-protection protocols.

AI STATEMENT

Artificial intelligence tools – ChatGPT and Claude – were used to support the preparation of this manuscript, assisting with formatting content and refining language. All AI-assisted output was critically reviewed, revised, and validated by the authors. The study design, analysis, interpretation of results, and conclusions reflect the authors’ academic and professional judgment. AI tools improved efficiency and communication but did not substitute for engineering judgment, technical review, or responsibility for the final content. The authors are solely responsible for all content, including any errors or omissions.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: F. Alfawzan, I. Batur, C.R. Bhat, R.M. Pendyala; data collection: D. Robbennolt, I. Batur, C.R. Bhat, R.M. Pendyala; analysis and interpretation of results: F. Alfawzan, I. Batur, F. Yu, M. Rodriguez Ocana, D. Robbennolt, C.R. Bhat, R.M. Pendyala; draft manuscript preparation: F. Alfawzan, D. Robbennolt, F. Yu, M. Rodriguez Ocana, C.R. Bhat, R.M. Pendyala. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

- Aasvik, Ole, Marjan P. Hagenzieker, Pål Ulleberg, and Torkel Bjørnskau. 2025. "How testing impacts willingness to use and share autonomous shuttles with strangers: the mediating effects of trust and optimism." *International Journal of Human-Computer Interaction* 41 (6): 3783–98.
- Ardehshiri, Ali, and Akshay Vij. 2019. "Lifestyles, residential location, and transport mode use: A hierarchical latent class choice model." *Transportation Research Part A: Policy and Practice* 126: 342–59.
- Baidu, Inc. 2026. "Baidu announces first quarter 2026 results." Press release, May 18, 2026. <https://ir.baidu.com/news-releases/news-release-details/baidu-announces-first-quarter-2026-results/>.
- Batur, Irfan, Katherine E. Asmussen, Aupal Mondal, Sara Khoeini, Tassio B. Magassy, Ram M. Pendyala, and Chandra R. Bhat. 2023. "Understanding interest in personal ownership and use of autonomous vehicles for running errands: An exploration using a joint model incorporating attitudinal constructs." *Transportation Research Record* 2677 (2): 541–54.
- Batur, Irfan, Aupal Mondal, Victor O. Alhassan, Katherine E. Asmussen, Chandra R. Bhat, and Ram M. Pendyala. 2026. "The induced demand implications of alternative adoption modalities of automated vehicles." *Transport Policy* 175: 103879.
- Bhat, Chandra R. 2015. "A new generalized heterogeneous data model (GHDM) to jointly model mixed types of dependent variables." *Transportation Research Part B* 79: 50–77.
- Bhat, Chandra R., and Naveen Eluru. 2009. "A copula-based approach to accommodate residential self-selection effects in travel behavior modeling." *Transportation Research Part B* 43 (7): 749–65.
- Chapman, Jim, Eric H. Fox, William Bachman, Lawrence D. Frank, John Thomas, and Alexis Rourk Reyes. 2021. *Smart Location Database Technical Documentation and User Guide*. Version 3.0. Washington, DC: U.S. Environmental Protection Agency.
- Colley, Mark, Daniel Kornmüller, Debargha Dey, Wendy Ju, and Enrico Rukzio. 2024. "Longitudinal effects of external communication of automated vehicles in the USA and Germany: A comparative study in virtual reality and via a browser." *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 8 (4): Article 176, 1–33.
- Dai, Jingchen, Ruimin Li, and Zhiyong Liu. 2021. "Does initial experience affect consumers' intention to use autonomous vehicles? Evidence from a field experiment in Beijing." *Accident Analysis & Prevention* 149.
- Farias, Adriana Valentina, Shanjiaang Zhu, and Ying Liu. 2026. "Tracking longitudinal changes in awareness, usage, and trust in autonomous vehicles: Evidence from large-scale, nationally representative U.S. surveys, 2023–2025." *Transport Policy* 184: 104191.
- Fonzone, Achille, Grigorios Fountas, Lucy Downey, and Adebola Olowosegun. 2025. "How autonomous bus trials affect passengers' views: Exploring the gap between pre-ride expectations and real-world experience." *Transportation Research Part F* 115: 103311.
- Guo, Jia, Xiao yan Kang, Yusak Susilo, Constantinos Antoniou, and Anna Pernestål. 2026. "Changes in the service evaluations of automated buses over time: A one-year, three-wave panel study in Stockholm." *Journal of Urban Technology* 33 (1): 1–21.
- Jiang, Zhiqiu, Max Zheng, and Andrew Mondschein. 2022. "Acceptance of driverless shuttles in pilot and non-pilot cities." *Journal of Public Transportation* 24: 100018.

- Kutela, Boniphace, Norris Novat, Panick Kalambay, Oscar Oviedo-Trespalacios, and Angela E. Kitali. 2024. "What drives the change in safety perception and willingness to re-ride shared automated passenger shuttles?" *Transportation Research Part F* 106: 1–13.
- Lavieri, Patrícia S., Venu M. Garikapati, Chandra R. Bhat, Ram M. Pendyala, Sebastian Astroza, and Felipe F. Dias. 2017. "Modeling individual preferences for ownership and sharing of autonomous vehicle technologies." *Transportation Research Record* 2665 (1): 1–10.
- Li, Yang, Xiaowei Shi, and Xiaopeng Li. 2024. "Effect of riding experience on changing opinions toward connected and autonomous vehicle safety: Evidence from field experiments." *Transportation Research Part F* 105: 491–504.
- Liu, Peng, and Zhigang Xu. 2020. "Public attitude toward self-driving vehicles on public roads: Direct experience changed ambivalent people to be more positive." *Technological Forecasting and Social Change* 151: 119827.
- Long, Keke, Xiaowei Shi, Yang Li, Zhiwei Chen, Yuan Wang, and Xiaopeng Li. 2025. "Before and after riding: Changing comfort attitude toward autonomous shuttles from perspectives as riders, drivers, and pedestrians." *Transportation Research Part A* 199: 104613.
- Magassy, Tassio B., Irfan Batur, Aupal Mondal, Katherine E. Asmussen, Chandra R. Bhat, and Ram M. Pendyala. 2024. "Multidimensional analysis of willingness to share rides in a future of autonomous vehicles." *Transportation Research Record* 2678 (6): 865–80.
- Makahleh, Hisham Y., Emma Jayne Sakamoto Ferranti, and Dilum Dissanayake. 2024. "Assessing the role of autonomous vehicles in urban areas: A systematic review of literature." *Future Transportation* 4 (2): 321–348.
- McAslan, Devon, Max Gabriele, and Thaddeus R. Miller. 2021. "Planning and policy directions for autonomous vehicles in metropolitan planning organizations (MPOs) in the United States." *Journal of Urban Technology* 28 (3–4): 175–201.
- Mizenko, Alexander J., Brian C. Tefft, Lindsay S. Arnold, and Jurek G. Grabowski. 2015. "The relationship between age and driving attitudes and behaviors among older Americans." *Injury Epidemiology* 2 (1).
- Nair, Gopindra S., and Chandra R. Bhat. 2021. "Sharing the road with autonomous vehicles: Perceived safety and regulatory preferences." *Transportation Research Part C* 122: 102885.
- Narayanan, Santhanakrishnan, Emmanouil Chaniotakis, and Constantinos Antoniou. 2020. "Shared autonomous vehicle services: A comprehensive review." *Transportation Research Part C* 111: 255–293.
- Othman, Kareem. 2023. "A microscopic analysis of the relationship between prior knowledge about self-driving cars and public acceptance: A survey in the US." *Transport and Telecommunication Journal* 24 (2): 128–42.
- Paddeu, Daniela, Graham Parkhurst, and Ian Shergold. 2020. "Passenger comfort and trust on first-time use of a shared autonomous shuttle vehicle." *Transportation Research Part C* 115: 102604.
- Reuters. 2026. "Tesla's once-bullish tone on robotaxis shifts." *Reuters*, July 23, 2026. <https://www.reuters.com/business/autos-transportation/teslas-once-bullish-tone-robotaxis-shifts-2026-07-23/>
- Saeed, Tariq Usman, Mark W. Burris, Samuel Labi, and Kumares C. Sinha. 2020. "An empirical discourse on forecasting the use of autonomous vehicles using consumers' preferences." *Technological Forecasting and Social Change* 158: 120130.

- Schwindt-Drews, Sarah, Kai Storms, Steven Peters, and Bettina Abendroth. 2024. "Acceptance and trust: Drivers' first contact with released automated vehicles in naturalistic traffic." *IEEE Transactions on Intelligent Transportation Systems* 25 (11): 18601–10.
- Tennant, Chris, Sally Stares, and Susan Howard. 2019. "Public discomfort at the prospect of autonomous vehicles: Building on previous surveys to measure attitudes in 11 countries." *Transportation Research Part F* 64: 98–118.
- Wang, Zhenyu, Haolong Hu, Meng Sun, and Dengbo He. 2024. "An exploration of users' trust in and willingness to pay for fully driverless vehicles after their first ride." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 68 (1): 861–65.
- Waymo. 2026. "From the road — May 13, 2026." Waypoint (blog), May 13, 2026. <https://waymo.com/blog/shorts/growing-to-1400-sqm/>.
- Wu, Xinyi, Jason Cao, and Frank Douma. 2021. "The impacts of vehicle automation on transport-disadvantaged people." *Transportation Research Interdisciplinary Perspectives* 11: 100447.
- Xie, Weiyin, Zhenyu Wang, and Dengbo He. 2025. "Effect of riding experience and HMI on users' trust and riding comfort in fully driverless autonomous vehicles: An on-road study." *Applied Ergonomics* 129: 104580.
- Zoox, Inc. 2026. "The Zoox robotaxi rolls into Miami." Zoox Journal, April 23, 2026. <https://zoox.com/journal/zoox-robotaxi-in-miami>.