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Abstract

Urban congestion in large metropolitan areas persists despite continuous expansion of surface road infrastructure, reflecting structural spatial constraints rather than temporary capacity shortages. In this context, underground expressways represent a major reconfiguration of urban transport systems and raise key policy questions regarding user acceptance, toll feasibility, and performance.

This study analyzes commuter choice behavior and willingness to pay for underground expressways using a stated choice experiment in the Seoul metropolitan area. The analysis incorporates travel time savings, toll levels, underground-space effects, and enhanced safety and environmental attributes. Multinomial logit and panel mixed logit models are estimated to capture repeated choices and preference heterogeneity.

Results reveal a significant underground-space penalty that cannot be explained by travel time or tolls alone. On average, commuters require about ten minutes of additional travel time savings to offset this disutility. The penalty varies systematically with perceptions of policy necessity, safety, and reliability. Preferences for premium underground expressways are driven mainly by improved safety and environmental features rather than additional time savings.

Scenario simulations show that toll acceptability depends strongly on realized performance. When expected travel time savings are achieved, demand remains stable under moderate tolls. However, performance shortfalls lead to sharp demand declines even at low toll levels. These findings highlight that the viability of underground expressways depends more on credible performance delivery than on toll levels, emphasizing the importance of performance-linked and adaptive tolling strategies.

Keywords: underground expressway; user acceptance; willingness to pay; stated choice experiment; tolling; Seoul metropolitan area

1. Introduction

In large metropolitan areas such as the Seoul metropolitan region, persistent growth in travel demand combined with severe constraints on surface space has fundamentally limited the effectiveness of expanding surface road capacity as a long-term response to recurring congestion. Peak-period congestion not only increases average travel times but also undermines travel time reliability, reducing schedule predictability and commuter welfare. Recent studies indicate that urban congestion is not a temporary phenomenon but a structurally persistent condition that propagates across metropolitan networks and recurs systematically during peak periods (Jung and Eom 2023; Mystakidis, et al. 2025).

Under these conditions, underground expressways that utilize subsurface urban space have emerged as a potential policy alternative for improving capacity and travel time reliability in space-constrained urban corridors. In Korea, the inclusion of roadway undergrounding projects in selected corridors under the Second National Expressway Construction Plan reflects a shift from conceptual discussion toward active policy consideration. Figure 1 shows the study area and the locations of the planned underground expressway corridors in the Seoul metropolitan area that motivate the empirical analysis.

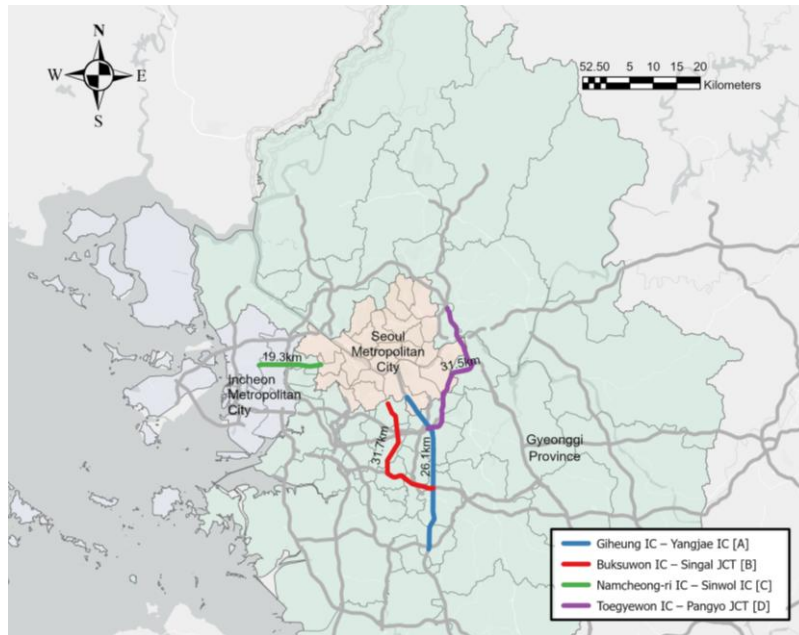


Figure 1. Study Area and Locations of the Planned Underground Expressway Corridors in the Seoul Metropolitan Area

However, underground expressways differ fundamentally from conventional surface facilities in both their operating environment and cost structure. Extensive safety and environmental systems—such as ventilation, fire protection, and emergency evacuation infrastructure—substantially increase construction and operating costs. As a result, user acceptance may depend not only on travel time savings but also on perceived safety, psychological discomfort associated with enclosed environments, and tolerance for additional toll payments.

Underground expressways may influence user choice through multiple behavioral and perceptual channels. On the one hand, they may generate positive utility through reduced travel time, improved travel time reliability, and protection from surface-level disruption. On the other hand, they may generate negative utility through psychological discomfort associated with enclosed space, perceived safety risk, unfamiliar driving environments, and concerns about emergency response conditions. In addition, users may respond differently to underground expressways depending on whether enhanced safety and environmental facilities are provided. Accordingly, the acceptance of underground expressways should be understood as the net outcome of time-related benefits, monetary costs, and non-time perceptual factors associated with underground travel.

Because underground expressways are highly likely to be operated as tolled facilities, their policy feasibility hinges on a critical question: under what conditions can tolls be implemented without eroding user acceptance, particularly when planned performance is uncertain? For high-cost urban road infrastructure, even moderate deviations between planned and realized travel time savings can have disproportionate effects on public acceptance and demand, making toll acceptability closely linked to the credibility of performance delivery.

Despite its policy relevance, existing transportation research has largely examined toll acceptance while treating road or tunnel usage as an exogenous condition. Most willingness-to-pay studies focus on trade-offs between travel time and tolls, providing limited empirical evidence on how users value the introduction of underground road infrastructure itself. In particular, the intrinsic disutility associated with underground space has rarely been quantified explicitly within tolling frameworks. This study addresses this gap by empirically examining how travel time savings, toll levels, perceptions of underground space, and the provision of premium safety and environmental facilities jointly shape commuter choice behavior and willingness to pay for underground expressways. Using a stated choice experiment conducted among commuters in the Seoul metropolitan area, multinomial logit and panel mixed logit models are estimated to account for repeated choices and preference heterogeneity.

In addition, policy simulations are performed to evaluate underground expressway usage under alternative toll levels and under scenarios in which realized travel time savings fall short of planned targets. By doing so, this study makes three policy-relevant contributions: it demonstrates that toll acceptability depends primarily on realized performance rather than toll levels alone; it quantifies the disutility associated with underground road use as a key acceptance risk; and it provides empirical support for adaptive, performance-linked tolling strategies for high-cost urban road infrastructure.

The remainder of this paper is organized as follows. Section 2 reviews prior studies on willingness to pay and stated choice methods. Section 3 presents the analytical framework and model specifications. Sections 4 and 5 describe the survey design and respondent characteristics. Sections 6 and 7 report the estimation results and willingness-to-pay analysis. Section 8 presents the simulation results, and Section 9 discusses the main findings and policy implications.

2. Literature review

2.1. Willingness-to-Pay Studies in the Transportation Sector

In the transportation field, users' willingness to pay (WTP) has been widely employed as a key indicator providing an economic basis for pricing policies and transport service-related decision-making. Recent studies have predominantly relied on stated preference (SP)-based discrete choice models to analyze trade-offs between costs and service attributes (Bwambale, et al. 2023; Hoen, et al. 2023; Wang, et al. 2021), as this approach allows for the quantitative estimation of user-perceived utility associated with changes in multiple transport service attributes.

More recently, a limited but growing body of studies has begun to examine public willingness to pay for newly introduced transport infrastructures and services, particularly those involving substantial upfront investment and uncertainty regarding future performance and usage (Hyun, et al. 2025; Ko, et al. 2026). These studies suggest that user acceptance of such systems may depend not only on expected travel-time benefits but also on non-time attributes related to service characteristics and perceived reliability.

Recent WTP research in transportation has otherwise primarily focused on user acceptance of additional or modified service attributes within existing transport systems, such as waiting time for electric vehicle charging, safety and hygiene measures, convenience, and operational changes (Bwambale, et al. 2023; Hoen, et al. 2023). These studies empirically demonstrate that users exhibit significant willingness to pay not only for reductions in travel time and monetary costs, but also for experiential aspects of travel, including waiting, uncertainty, and perceived safety.

By contrast, studies that directly examine willingness to pay for new road infrastructure itself—namely, the impact of introducing new road types or spatial configurations on user utility—remain relatively limited in the mainstream literature. Most existing studies focus on changes in service attributes or operational conditions under the assumption of established infrastructure, which constrains their ability to independently quantify non-temporal and psychological utility components arising from changes in spatial structure.

2.2. Travel Time and Toll Evaluation Using Stated Choice Experiments

Research on users' willingness to pay for tolls in the transportation sector has evolved as a major research stream providing an economic rationale for road pricing policies and demand management strategies. Early studies, primarily focusing on highways and toll roads, analyzed users' willingness to pay by examining trade-offs between travel time savings and toll charges under given road facilities and pricing schemes (Jou, et al. 2012; Jou and Huang 2014).

Subsequent research expanded this framework to congestion pricing and high-occupancy toll (HOT) lanes as demand management instruments. These studies retained the same analytical structure,

estimating the toll levels users are willing to accept in exchange for attributes such as travel time reduction, congestion avoidance, and improved reliability, while holding lane or facility types constant (Burris, et al. 2012; Ma, et al. 2024).

Studies on tunnel tolls share this analytical framework. (Yusuf, et al. 2014) demonstrated that willingness to pay for tunnel tolls may be influenced not only by travel time savings but also by non-temporal factors such as trust in government, community perceptions, and political or environmental attitudes. Nevertheless, the primary focus remained on users' acceptance of toll levels for tunnel usage. More recent studies have applied advanced discrete choice models, including mixed logit and scale heterogeneity models, to estimate tunnel toll WTP more precisely. (Lu, et al. 2021), using a tolled tunnel in Copenhagen as a case study, provided refined estimates of heterogeneity in toll willingness to pay and demonstrated the applicability of advanced discrete choice models to real-world tolling contexts.

This analytical framework has largely persisted in recent studies. Research published in 2024 on congestion pricing and toll policies continues to focus on user acceptance of toll levels and associated socioeconomic and behavioral factors (Gunjo, et al. 2024; Lin, et al. 2024), without explicitly separating road, lane, or tunnel types as distinct utility components.

In summary, existing toll and tunnel WTP studies have generally treated spatial facility types as fixed conditions and focused on estimating willingness to pay for toll levels associated with facility usage. In contrast, studies that explicitly estimate incremental willingness to pay arising from changes in spatial structure under otherwise identical travel conditions remain relatively scarce. This limitation is particularly consequential for transport policy, as high-cost underground road projects involve irreversible investment decisions under substantial demand and performance uncertainty.

2.3. Conceptual Framework and Contribution of This Study

Figure 2 presents the conceptual framework underlying this study. As illustrated in the figure, commuter choice for underground expressways is understood as the outcome of interactions among underground expressway attributes, perceived benefits and perceived costs, and heterogeneous user characteristics. In this framework, travel time savings and premium safety and environmental facilities may increase utility through faster travel, improved travel time reliability, and enhanced service quality, whereas additional tolls and underground travel environments may reduce utility through monetary burden, psychological discomfort, perceived safety risk, and concerns about emergency response conditions. These effects are further moderated by user attitudes, trust, and travel conditions, including perceived policy necessity and justification, willingness to pay for time savings, the perceived importance of safety and environmental facilities, travel time reliability perception, and socio-demographic and trip characteristics.

Building on this conceptualization, this study contributes by explicitly examining willingness to pay for underground expressways as a spatial transformation rather than as a marginal modification of existing road facilities. Unlike prior toll and tunnel studies that estimate toll acceptance while treating

road or facility type as an exogenous condition, this study incorporates the distinction between surface and underground expressways directly into the utility function under otherwise identical travel conditions. By separating travel time effects from an underground-space effect, the analysis provides empirical estimates of incremental willingness to pay associated with roadway undergrounding that cannot be explained by conventional time–cost trade-offs alone. In doing so, the study extends stated choice-based toll evaluation frameworks and offers policy-relevant evidence to inform toll design and performance-based operation strategies for future underground expressway projects. In particular, the study highlights that willingness to pay for underground expressways is shaped not only by toll levels but also by uncertainty in realized performance. This conceptual framework therefore motivates the empirical separation of travel time, toll, underground-space, and premium-service effects in the utility specification.

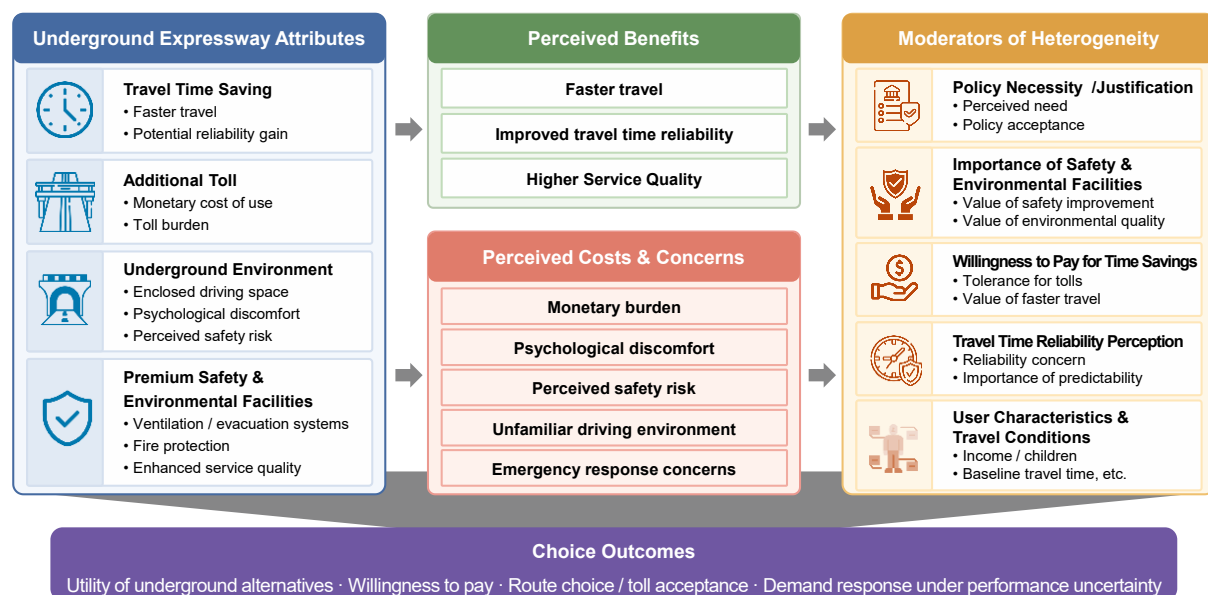


Figure 2. Conceptual framework of commuter choice for underground expressways

3. Methodology

3.1. Elicitation Methods for Willingness to Pay

Survey-based approaches to estimating willingness to pay (WTP) are commonly classified into direct and indirect methods, among which the contingent valuation method (CVM) and choice experiments (CE) are most widely used. CVM directly elicits respondents' maximum WTP for a specified policy or service improvement and has been extensively applied in the valuation of public goods (Mitchell and Carson 2013). However, CVM is subject to well-documented methodological limitations, including starting-point bias and hypothetical bias (Bateman and Großbritannien 2002; Diamond and Hausman 1994).

Choice experiments infer preferences from repeated choices among alternatives described by multiple attributes and levels, allowing simultaneous estimation of marginal utilities and marginal WTP for individual attributes (Adamowicz, et al. 1994; Hanley, et al. 2001). When a monetary attribute is included, CE provides a flexible framework for policy evaluation and cost–benefit analysis. Despite increased cognitive burden due to repeated choice tasks, CE has been widely adopted in transportation research because it closely reflects real-world decision-making processes. Accordingly, this study employs a choice experiment to examine how travel time savings, toll levels, underground-space characteristics, and safety and environmental facilities jointly influence user choice behavior and willingness to pay for underground expressways.

3.2. Choice Model Specification

The choice experiment data are analyzed using a multinomial logit (MNL) model and a panel mixed logit (MXL) model. The MNL model serves as a baseline specification to identify the average effects of key attributes, such as travel time savings and toll levels. However, the MNL framework is limited in accounting for repeated choices by the same individual and unobserved preference heterogeneity. To address these limitations, a panel mixed logit model is estimated, allowing selected coefficients to vary across individuals. This specification jointly captures unobserved preference heterogeneity and correlation across repeated choice observations.

3.2.1. Random Utility Theory

Choice behavior is modeled within the random utility framework (Train 2009). Individuals are assumed to choose the alternative that yields the highest utility, which is decomposed into a systematic component and a random error term:

$$U_{njt} = V_{njt} + \varepsilon_{njt}$$

The systematic utility component is specified as a function of observed attributes, including travel time savings, tolls, and underground-road characteristics. Alternative-specific constants are included to capture systematic effects not explained by observed variables (Hensher, et al. 2015).

3.2.2. Multinomial Logit Model

Under the assumption that the error terms are independently and identically distributed with a Type I extreme value distribution, the choice probability that individual n selects alternative j in choice situation t is given by the multinomial logit (MNL) formulation (Ben-Akiva, et al. 1997; Li 2011; Train 2009):

$$P_{njt} = \frac{\exp V_{njt}}{\sum_k \exp V_{nkt}}$$

Although computationally convenient, the MNL model relies on the independence of irrelevant alternatives (IIA) assumption, which may be restrictive when alternatives share unobserved components (Li 2011). In this study, underground expressways are differentiated into basic and

premium types, potentially inducing correlation across underground alternatives and motivating the use of a more flexible modeling framework.

3.2.3. Panel Mixed Logit Model

The panel mixed logit model relaxes the IIA assumption by allowing preference parameters to vary across individuals (Hensher, et al. 2015; Train 2009). Utility is specified as:

$$U_{njt} = \beta_n^T x_{njt} + \varepsilon_{njt}, \quad \beta_n = \bar{\beta} + \eta_n, \quad \eta_n \sim f(\eta | \Omega)$$

where $f(\bullet)$ denotes a distribution such as normal or log-normal, and Ω is the variance–covariance matrix. For panel data, repeated choices by the same individual may be correlated; therefore, the individual-level choice probability is defined as the product of conditional choice probabilities across choice situations, integrated over the distribution of β_n . As this integral has no closed-form solution, model parameters are estimated using simulated maximum likelihood methods (Hensher, et al. 2015; Train 2009)

3.2.4. Utility Function Specification

The baseline utility specification includes travel time savings, additional tolls, a common underground-space effect, and a premium service effect. To disentangle the physical characteristics of underground expressways from qualitative differences associated with premium services, the underground effect and the premium effect are specified separately.

Travel time savings (DT_{njt}) and tolls ($Price_{njt}$) are defined as continuous variables. A common underground dummy (UG_{njt}) equals 1 for both basic and premium underground expressways and 0 otherwise, capturing the structural effect of underground space itself. A premium dummy ($Premium_{njt}$) equals 1 for the premium underground alternative and 0 otherwise, capturing additional preferences for enhanced safety and environmental facilities.

In the multinomial logit (MNL) model, all coefficients are assumed to be homogeneous across individuals, and the systematic utility is specified as:

$$V_{njt} = \theta_{dt} \cdot DT_{njt} + \theta_{price} \cdot Price_{njt} + \theta_{UG} \cdot UG_{njt} + \theta_p \cdot Premium_{njt}$$

To account for preference heterogeneity and the panel structure of the data, a panel mixed logit (MXL) model is additionally estimated. In the mixed logit specification, coefficients associated with travel time savings and premium services are treated as random parameters, while the toll coefficient is fixed to ensure stable willingness-to-pay estimation. The underground-space effect is also specified as fixed, as it reflects an average structural disutility rather than individual-specific taste variation. Importantly, the underground-space coefficient should not be interpreted as a purely physical or engineering attribute. Rather, it is intended to capture the composite average effect of unobserved perceptions associated with underground travel environments after controlling for

observed travel time, toll, and premium service attributes. This specification therefore provides a reduced-form measure of the net residual utility associated with underground road use, rather than a fully separable structural estimate of each underlying psychological mechanism.

3.2.5. Interaction Effects

To account for heterogeneity in sensitivity to travel time savings, tolls, and premium services across individuals, key coefficients are specified as functions of respondent characteristics and attitudes. This interaction structure is applied in both the MNL and MXL models, with the latter additionally capturing unobserved heterogeneity through random parameters. The interaction variables were selected to reflect theoretically plausible channels identified in the conceptual framework and prior stated preference research. In particular, variables related to policy acceptance, psychological discomfort, reliability perception, safety valuation, and price tolerance were included because these dimensions were considered most directly relevant to underground expressway choice in the Seoul metropolitan commuting context. The interaction structure was therefore designed to capture heterogeneity in both time–cost trade-offs and non-time perceptions associated with underground travel.

Accordingly, individual-specific coefficients are defined as

$$\begin{aligned}\theta_{dt}(n) &= \theta_{dt} + \sum_k \gamma_k X_{n,k}^{(dt)} + \zeta_{dt,n} \\ \theta_{price}(n) &= \theta_{price} + \sum_m \delta_m X_{n,m}^{(price)} \\ \theta_{UG}(n) &= \theta_{UG} + \zeta_{UG,n} \\ \theta_p(n) &= \theta_p + \sum_h \eta_h X_{n,h}^{(P)} + \zeta_{p,n} \\ (\zeta_{dt,n}, \zeta_{price,n}, \zeta_{p,n})^T &\sim N(0, \Sigma)\end{aligned}$$

where θ_{dt} , θ_{price} and θ_p represent mean sensitivities to travel time, cost, and premium services, respectively. The parameters γ_k , δ_m and η_h capture interaction effects between individual characteristics or attitudes and the corresponding sensitivities. The random terms ζ represent individual-specific deviations, assumed to follow a multivariate normal distribution with variance–covariance matrix Σ . The underground dummy is specified as a fixed coefficient to capture the average effect of the underground environment itself. Definitions and measurements of interaction variables are provided in the survey and variable description section.

4. Survey and Choice Experiment Design

4.1. Target Population and Survey Structure

To analyze stated preferences under the hypothetical introduction of underground expressways, this study conducted an online survey targeting adult commuters residing in the Seoul metropolitan area who commute at least twice per week. Commuters were selected because they constitute the most regular and policy-relevant user group for evaluating repeated exposure to tolls, travel time savings, and underground travel conditions during peak-period travel. Compared with occasional users, commuters are more likely to make systematic trade-offs between time, cost, reliability, and route conditions. Freight and commercial vehicle operators were not included because their route choices are shaped by additional operational constraints, regulatory considerations, and business-related cost structures that fall outside the scope of this study.

The survey was administered by a professional online survey firm using screening questions to verify respondents' place of residence, commuting frequency, and relevant travel experience. The main survey was conducted online from October 16 to October 24, 2025. The final sample consisted of 500 respondents, each of whom completed eight stated choice tasks. This yielded a panel dataset suitable for discrete choice analysis of repeated decisions under hypothetical but policy-relevant commuting scenarios.

The target sample size was determined to balance statistical efficiency, subgroup heterogeneity, and respondent burden in a repeated stated choice design. Given that each respondent completed multiple choice tasks and that the analysis employed both multinomial logit and panel mixed logit models with interaction effects, a sample of 500 respondents was considered adequate to support stable estimation. Prior to the main survey, pilot surveys with transportation experts and general users were conducted to assess attribute realism, scenario comprehension, and respondent fatigue.

4.2. Choice Experiment Scenarios and Personalized Design

The choice experiment presented respondents with a comparison between their current commuting option and underground expressway alternatives. The underground alternative was further differentiated into a basic type and a premium type to reflect differences in service quality. While the basic alternative represents standard underground expressway functionality, the premium alternative incorporates enhanced safety and environmental facilities, such as improved evacuation systems, to convey higher perceived safety and comfort.

Each respondent completed eight choice tasks, consisting of four morning (commuting) and four

evening (return) trips. In each task, travel time savings and additional tolls associated with underground expressway use were jointly presented. Choice tasks were personalized based on respondents' self-reported baseline travel conditions to ensure realistic and context-relevant decision-making, while maintaining a consistent attribute framework across respondents. The attribute structure and level design used to generate these personalized scenarios are described in the following subsection.

4.3. Attributes and Level Design

Attributes and levels for the choice experiment were selected to balance statistical identification, behavioral realism, and respondent burden. Key attributes include travel time savings, additional tolls, and service type (basic versus premium underground expressway). Attribute levels were defined within ranges that respondents could plausibly perceive as realistic, informed by pilot survey results and previous empirical evidence.

For the premium alternative, an additional surcharge was introduced to reflect qualitative improvements in safety and environmental facilities beyond travel time savings. This design allows the analysis to distinguish preferences for pure time savings from those for enhanced service quality associated with premium underground expressways.

Detailed definitions of attribute levels, personalized level construction, and calculation rules are provided in Appendix A.

5. Descriptive Statistics

5.1. Socio-demographic and Travel Characteristics

Table 1 summarizes the socio-demographic characteristics and travel patterns of the survey respondents. Among the 500 respondents, 332 were male (66.4%) and 168 were female (33.6%), indicating a relatively higher proportion of male commuters. The mean age was 47.4 years (standard deviation: 10.6), suggesting that the sample is largely composed of middle-aged commuters who are actively engaged in economic activities.

In terms of marital status, 371 respondents (74.2%) were married. The average household size was 3.0 persons (standard deviation: 1.1). Households with preschool-aged children accounted for 10.6% of the sample, representing a subgroup that may exhibit heightened sensitivity to travel time

reliability and safety.

Regarding monthly personal income, the largest shares were observed in the 3–4 million KRW range (20.8%) and the 4–5 million KRW range (17.8%). In addition, high-income respondents earning 5 million KRW or more per month accounted for approximately 41% of the sample. This distribution indicates sufficient income heterogeneity for analyzing willingness to pay for travel time savings.

With respect to travel characteristics, the average commuting time was 56.16 minutes (standard deviation: 24.34) for morning trips and 62.89 minutes (standard deviation: 28.81) for evening trips, with return trips being longer and more variable on average. The mean toll payments were 802 KRW for morning trips and 785 KRW for evening trips, accompanied by relatively large standard deviations, reflecting substantial variation in individual travel environments.

In terms of commuting frequency, the majority of respondents (80.8%) reported commuting five days per week or more. This indicates that the sample consists predominantly of regular commuters rather than occasional travelers, supporting the realism of the hypothetical scenarios presented in the choice experiment.

Perceptions of travel time reliability differed markedly between morning and evening commutes. For morning trips, 66.8% of respondents reported that travel time was “mostly reliable” or “very reliable,” whereas the corresponding share for evening trips was 46.4%. This suggests that perceived travel time variability is greater for return trips, highlighting systematic differences in reliability perceptions between peak periods.

Table 1 Socio-demographic Characteristics and Travel Attributes of Respondents

Category	Variable	Category / Statistic	Frequency (n)	Percentage (%)
Socio-demographic characteristics	Gender	Male	332	66.4
		Female	168	33.6
	Age	Mean (SD)	47.4 (10.6)	—
	Marital status	Married	371	74.2
		Unmarried	129	25.8
	Household size	Mean (SD)	3.0 (1.1)	—
	Preschool children	Yes	53	10.6
	Monthly personal income (KRW)	< 2 million	19	3.8
		2–3 million	62	12.4
		3–4 million	104	20.8

		4–5 million	89	17.8
		5–6 million	56	11.2
		6–7 million	50	10.0
		7–8 million	40	8.0
		8–9 million	27	5.4
		9–10 million	18	3.6
		≥ 10 million	35	7.0
Travel perception characteristics	Morning travel time (min)	Mean (SD)	56.16 (24.34)	—
	Evening travel time (min)	Mean (SD)	62.89 (28.81)	—
	Morning toll (KRW)	Mean (SD)	802.22 (1,388.83)	—
	Evening toll (KRW)	Mean (SD)	785.04 (1,398.84)	—
	Commuting frequency	2 days/week	27	5.4
		3–4 days/week	69	13.8
		≥ 5 days/week	404	80.8
	Morning travel time reliability	Very unreliable	22	4.4
		Somewhat unreliable	87	17.4
		Neutral	69	13.8
		Mostly reliable	291	58.2
		Very reliable	43	8.6
	Evening travel time reliability	Very unreliable	82	16.4
		Somewhat unreliable	92	18.4
		Neutral	134	26.8
		Mostly reliable	213	42.6
		Very reliable	19	3.8
	Incheon terminal trip	Non-Incheon trips	356	71.2
		Incheon trips	144	28.8

Notes: SD = standard deviation. Percentages may not sum to 100 due to rounding.

Travel time reliability is based on respondents' subjective assessments.

5.2. Perceptions and Attitudinal Characteristics

Table 2 reports descriptive statistics for respondents' perceptions and attitudes toward transportation conditions, underground expressways, and tolling policies. The mean score for the perceived necessity and justification of introducing underground expressways was 3.284, indicating an overall neutral-to-positive stance. Perceived stress from traffic congestion was relatively high (mean = 3.824), suggesting latent demand for time-saving transport infrastructure.

Psychological discomfort associated with driving through long underground road sections exhibited a mean score of 3.016, indicating substantial heterogeneity across respondents. By contrast, the statement that willingness to use underground expressways would increase if safety and environmental facilities were sufficiently provided received a higher mean score of 3.456, highlighting the importance of facility standards in shaping user acceptance.

Willingness to pay additional costs for travel time savings and for safety and environmental improvements showed mean scores of 3.392 and 3.248, respectively. Agreement with the concept that paying more enables faster travel also yielded a relatively high mean score of 3.414. Together, these results suggest a moderate level of acceptance for differentiated pricing and premium service schemes.

Attitudes toward congestion-based pricing and environmentally differentiated tolls differed by policy type, with mean scores of 2.982 and 3.454, respectively. The importance of travel time reliability for commuting was rated very highly (mean = 3.872), and trust in smart transportation services—such as electronic toll collection and real-time route or pricing information—was also high (mean = 3.814).

Table 2 Attitudes Toward Underground Expressways and Tolling Policies

Item	Variable	Median	Mean	SD
1) Introducing underground expressways and tolling them is necessary and justified	Attitude toward underground expressway introduction	3.0	3.284	0.956
2) I experience substantial inconvenience and stress due to traffic congestion	Congestion-related stress	4.0	3.824	0.909
3) I feel psychological discomfort when driving through long underground roads (enclosed tunnels)	Psychological discomfort in underground roads	3.0	3.016	1.104
4) My willingness to use underground	Importance of safety and	4.0	3.456	0.852

roads increases if ventilation, evacuation, and communication facilities are sufficient	environmental facilities			
5) I am willing to pay additional costs to save travel time	Willingness to pay for time savings	4.0	3.392	0.959
6) I am willing to pay additional costs for safety and environmental improvements	Willingness to pay for safety and environmental improvements	3.0	3.248	0.888
7) I agree with the idea that paying more allows faster travel (e.g., fast-track or priority access services)	Acceptance of time–money trade-off	4.0	3.414	1.010
8) Charging higher tolls during congested periods is necessary	Acceptance of congestion-based pricing	3.0	2.982	1.099
9) Differentiating tolls based on vehicle environmental performance is necessary	Acceptance of environmental pricing	4.0	3.454	0.960
10) I trust the government to manage toll revenues transparently and fairly	Trust in toll revenue management	3.0	2.940	0.924
11) Travel time reliability (predictability) is very important for my commuting trips	Importance of travel time reliability	4.0	3.872	0.823
12) I frequently use smart transport services due to trust in them (e.g., ETC, real-time route or pricing information)	Trust in smart transport services	4.0	3.814	0.815
13) My commuting route can be easily switched among multiple alternatives depending on traffic conditions	Ease of switching alternative routes	4.0	3.422	0.924

Notes: Responses were measured on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree). SD = standard deviation.

6. Results of Underground Expressway Choice Model Estimation

6.1. Baseline Model Results

Table 3 reports the estimation results of the baseline MNL and MXL models. The two specifications show consistent coefficient signs: the toll price coefficient (θ_{price}) is negative, the travel time saving

coefficient (θ_{dt}) is positive, and the underground-space common effect (θ_{UG}) is negative, indicating reduced usage with higher tolls, increased usage with greater time savings, and an average disutility associated with underground road use.

Model fit statistics—including log-likelihood, AIC, BIC, and pseudo- R^2 —improve substantially in the MXL_basic specification, demonstrating that the mixed logit model, which accounts for panel structure and preference heterogeneity, provides a markedly better representation of commuters' choice behavior. Moreover, the larger absolute magnitudes of key coefficients and the statistical significance of the standard deviations of random parameters indicate substantial heterogeneity in preferences for underground expressways across individuals. These findings motivate the subsequent extension to interaction models.

Table 3 Estimation Results of the Baseline Multinomial Logit and Panel Mixed Logit Models

Category	Variable	MNL_basic	MXL_basic
Mean coefficients	Travel time saving, (θ_{dt})	0.14115***	0.348165***
	Toll price, (θ_{price})	−0.0007168***	−0.00232682***
	Underground space, (θ_{UG})	−1.964***	−3.5297***
	Premium alternative, (θ_p)	0.1699**	−0.47847**
Standard deviations	σ_{dt}	—	0.2741***
	σ_{UG}	—	3.9844***
	σ_p	—	2.3242***
Covariances	cov(θ_{dt} , θ_{UG})	—	−1.7197***
	cov(θ_{dt} , θ_p)	—	−0.1705 ($p \approx 0.13$)
	cov(θ_{UG} , θ_p)	—	0.6842***
Goodness of fit	Log Likelihood	−3,418.368	−2,256.952
	AIC	6,844.735	4,533.903
	BIC	6,869.912	4,596.844
	pseudo- R^2	0.0291	0.3569

Note: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, · $p < 0.10$.

Coefficients without symbols are not statistically significant.

6.2. Specification of Interaction Effects

To account for preference heterogeneity associated with respondents' characteristics and attitudes, models incorporating interaction terms are estimated. Table 4 summarizes the interaction structure used in the empirical models by linking each interaction target to its corresponding explanatory

variable and behavioral interpretation. In particular, the table shows how sensitivity to travel time savings, tolls, premium services, and underground-space effects is expected to vary with respondents' travel conditions, attitudes, and perceptions, thereby providing the conceptual basis for the reduced-model estimates reported later.

Table 4 Integrated Structure of Interaction Effects

Interaction target (parameter)	Interaction variable	Interpretation
Travel time saving sensitivity (θ_{dt})	Congestion-related stress	Greater perceived congestion stress increases sensitivity to travel time savings
	Ease of switching alternative routes	Easy access to alternative routes reduces sensitivity to travel time savings
	Number of preschool children	Higher childcare burden increases sensitivity to travel time savings
	Morning commute (AM)	Sensitivity to travel time savings is higher during morning commutes
	Current travel time reliability	Higher existing reliability reduces marginal sensitivity to time savings
	Importance of travel time reliability	Stronger emphasis on reliability increases sensitivity to time savings
	Baseline travel time	Longer baseline travel times increase sensitivity to time savings
Toll price sensitivity (θ_{price})	Willingness to pay for time savings	Greater stated willingness to pay reduces price sensitivity
	Acceptance of time–money trade-off	Higher acceptance of paying for speed reduces price sensitivity
	Trust in toll revenue management	Greater trust lowers resistance to toll increases
	Monthly income	Higher income reduces price sensitivity
	Age	Price sensitivity varies across age groups
	Gender	Gender-related differences in price sensitivity
	Acceptance of congestion-based	Higher acceptance lowers price sensitivity

	pricing	
	Incheon terminal trips	Regular Incheon-related trips are associated with different price sensitivity
	Baseline toll payment	Higher existing tolls increase sensitivity to further toll increases
Premium preference (θ_p)	Importance of safety and environmental facilities	Greater emphasis increases preference for the premium alternative
	Willingness to pay for safety and environmental improvements	Higher willingness increases acceptance of premium surcharges
	Trust in smart transport services	Greater trust increases premium preference
	Acceptance of environmental pricing	Higher acceptance increases premium preference
Underground-space effect (θ_{UG})	Attitude toward underground expressway introduction	Greater policy acceptance increases utility of underground expressways
	Psychological discomfort in underground roads	Greater discomfort reduces utility associated with underground road use

6.3. Estimation Results with Interaction Effects

Table 5 compares model fit across the baseline, full-interaction, and reduced-interaction specifications. To account for preference heterogeneity, multinomial logit (MNL) and panel mixed logit (MXL) models including all previously defined interaction terms were first estimated, and the final specifications were then obtained through a stepwise elimination procedure. Interaction terms that were statistically insignificant in both models (p -value > 0.1) were sequentially removed.

Because the initial full specification included a relatively large number of interaction terms, model reduction was undertaken to limit the risk of overfitting and to improve interpretability. The final reduced model was selected based on joint consideration of theoretical plausibility, parameter stability, and information criteria.

Comparisons between the reduced specifications and the full interaction models indicate no substantial deterioration in model performance. Specifically, the reduced models exhibit lower AIC and BIC values than the full models, while McFadden's pseudo- R^2 remains virtually unchanged. These results suggest that eliminating statistically insignificant interaction terms improves interpretability and model parsimony while preserving overall explanatory power.

Table 5 Model Fit Statistics across Specifications

Specification	Model	LogLik	K_par	AIC	BIC	McFadden's pseudo- R^2
Baseline	MNL	-3418.368	4	6844.735	6869.912	0.029149
	MXL	-2256.952	10	4533.903	4596.844	0.356915
Full interactions	MNL	-3030.439	26	6112.877	6276.522	0.132955
	MXL	-2176.758	32	4417.516	4618.926	0.373423
Reduced interactions	MNL	-3033.199	21	6108.398	6240.573	0.13359
	MXL	-2176.906	27	4407.813	4577.752	0.3748

Notes: Lower AIC and BIC values indicate better model fit, while higher log-likelihood and McFadden's pseudo- R^2 values indicate improved explanatory performance.

6.3.1. Interpretation of the Baseline Utility Structure

Table 6 reports the estimated coefficients of the reduced multinomial logit and panel mixed logit

models. The signs of the coefficients for travel time saving (θ_{dt}), toll price (θ_{price}), and the underground-space common effect (θ_{UG}) are consistent across the reduced specifications. The coefficient on travel time saving is positive, indicating increased usage with greater time reductions, whereas the toll price coefficient is negative, reflecting reduced usage as tolls increase. The underground-space effect is also negative, capturing an average disutility associated with underground road use.

These results indicate that commuters in the Seoul metropolitan area are highly sensitive to both travel time reductions and monetary costs, while a general aversion to underground travel environments persists on average. Importantly, the magnitude of the underground-space effect suggests that a non-trivial level of travel time saving is required to offset this average disutility, implying that underground expressways must deliver sufficiently large performance gains to achieve user acceptance.

The absolute magnitudes of the mean coefficients are generally larger in the mixed logit model than in the multinomial logit model. This reflects the ability of the mixed logit specification to account explicitly for individual-level preference heterogeneity and repeated choices, thereby reducing attenuation caused by preference averaging. Differences in statistical significance between the MNL and MXL specifications for some variables may likewise be attributed to the panel structure and the inclusion of random parameters, whereby part of the variation is absorbed by coefficient dispersion rather than by mean effects alone.

6.3.2. Interpretation of Interaction Effects

Table 6 also reports the retained interaction terms in the reduced MNL and MXL models, allowing direct interpretation of observable heterogeneity in time sensitivity, toll sensitivity, underground-space effects, and premium-service preferences. Overall, the results indicate that underground expressway choice is shaped not only by average time–cost trade-offs but also by systematic differences in user attitudes, travel conditions, and perceived service attributes.

With respect to travel time sensitivity, the marginal utility of travel time saving is significantly higher for morning (AM) commutes, indicating stronger time sensitivity during work-bound trips. In the mixed logit specification, variables such as ease of switching alternative routes, the number of preschool children, and baseline travel time also contribute positively to time sensitivity, suggesting that commuters facing tighter time constraints or greater schedule rigidity place higher value on travel time savings. By contrast, the effects of current travel time reliability and the stated importance of reliability weaken once unobserved heterogeneity is accounted for in the mixed logit model.

Turning to toll sensitivity, respondents with a higher willingness to pay for time savings or higher income levels exhibit lower sensitivity to toll increases, whereas commuters whose regular trips originate or terminate in Incheon display significantly higher sensitivity to additional tolls. These results suggest that tolerance for toll increases is shaped both by economic capacity and by the structure of existing travel conditions. The effect of trust in toll revenue management is weaker, but still points to the possibility that institutional trust can moderate price resistance.

Regarding the underground-space effect, perceived necessity and justification for introducing underground expressways exert a positive and significant influence in both models, indicating that policy acceptance mitigates the average disutility associated with underground travel. Psychological discomfort related to long or enclosed underground facilities also reduces underground preference, although this effect weakens once broader unobserved heterogeneity is explicitly modeled. This pattern is consistent with the interpretation of the underground-space coefficient as a reduced-form composite effect reflecting multiple non-time perceptions associated with underground travel.

Finally, for the premium alternative, the importance attached to safety and environmental facilities and the willingness to pay for such improvements exhibit strong positive effects, confirming that premium preferences are driven primarily by perceived service quality rather than by time savings alone. By contrast, trust in smart transport services and acceptance of environmentally differentiated pricing are associated with lower premium preference, suggesting that users may view bundled premium services as substitutable, at least in part, with other mechanisms for improving transport system performance or environmental outcomes.

6.3.3. Interpretation of Standard Deviations and Covariance Structure

The reduced mixed logit specification further provides evidence of substantial heterogeneity in preferences across individuals. As shown in Table 6, the standard deviations of the coefficients for travel time saving, the underground-space effect, and premium preference are all statistically significant, indicating that commuters differ meaningfully not only in the strength but also in the direction of some preferences related to underground expressway use.

The estimated covariance structure provides additional insight into how these preferences are related. In particular, the travel time saving coefficient is negatively correlated with both underground-space preference and premium preference. This suggests that commuters who place a particularly high value on time savings do not necessarily prefer underground facilities or higher-

priced premium services. Rather, time-oriented users and premium-oriented users may represent distinct behavioral segments with different priorities.

From a policy perspective, this pattern highlights the multidimensional nature of underground expressway preferences. User acceptance is not determined by a single trade-off between time and money, but by the interaction of time valuation, perceived underground disutility, and the value attached to enhanced safety and environmental services. This finding supports the view that uniform tolling and service strategies may be insufficient to address heterogeneous user responses in the context of underground expressway planning and operation.

Table 6 Estimation Results of the Reduced Multinomial Logit and Panel Mixed Logit Models

Variable	MNL_red	MXL_red
Travel time saving (θ_{dt})	0.1784***	0.3460***
Travel time interactions		
Morning commute (AM)	0.0179**	0.0249*
Current travel time reliability	-0.0171***	-0.00154 (ns)
Importance of reliability	-0.0131**	-0.00208 (ns)
Ease of switching alternative routes	0.00575 (ns)	0.0193**
Number of preschool children	0.0183·	0.0727***
Baseline travel time	-4.97e-05 (ns)	0.000571**
Toll price (θ_{price})	-0.001341***	-0.003236***
Price interactions		
Willingness to pay for time savings	0.000635***	0.001272***
Acceptance of congestion pricing	7.64e-05**	6.40e-05 (ns)
Trip origin/destination in Incheon	-0.000263***	-0.000640***
Trust in government toll policy	-1.19e-05 (ns)	-0.000104·
Monthly income	4.21e-07 (ns)	6.17e-05**
Underground-space effect (θ_{UG})	-1.9437***	-3.3628***
Underground-space interactions		
Perceived justification for underground expressways	0.2065***	0.6852***
Psychological discomfort with underground roads	-0.1244***	-0.0918 (ns)
Premium alternative constant (θ_p)	0.0164 (ns)	-0.4456*

Premium interactions		
Importance of safety and environmental facilities	0.2559***	0.5536***
Willingness to pay for safety/environmental improvements	0.3553***	0.6132***
Trust in smart transport services	-0.1219·	-0.2508*
Acceptance of environmental pricing	-0.1088·	-0.2704**
Standard deviations (random parameters)		
σ_{dt}	–	0.2820***
σ_{UG}	–	3.2156***
σ_p	–	2.3604***
Covariances		
$\text{cov}(\theta_{dt}, \theta_{UG})$	–	-2.0295***
$\text{cov}(\theta_{dt}, \theta_p)$	–	-0.2920*
$\text{cov}(\theta_{UG}, \theta_p)$	–	0.1199 (ns)
Goodness of fit		
Log-likelihood	-3,033.199	-2,176.906
AIC	6,108.398	4,407.813
BIC	6,240.573	4,577.752
McFadden pseudo-(R ²)	0.1336	0.3748

Note: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, · $p < 0.10$.

Coefficients without symbols are not statistically significant.

6.4. Policy Implications of the Model Estimates

Table 7 summarizes the time- and cost-equivalent interpretation of key parameters from the final panel mixed logit model. By translating coefficient estimates into minutes and percentage changes, the table provides more intuitive thresholds for policy interpretation.

To provide an intuitive interpretation of the conditions under which commuters switch from existing travel alternatives to underground expressways, the estimated coefficients were translated into time- and cost-equivalent measures. Using parameter estimates from the final panel mixed logit model, the level of travel time saving required to offset the average disutility associated with underground expressway use was calculated in minutes. In addition, the monetary burden of additional tolls was converted into equivalent changes in travel time, allowing direct comparison between time and cost effects. Interaction effects related to time and price were further summarized in proportional terms to illustrate how time valuation and price sensitivity vary across user groups. This approach moves beyond coefficient comparison and provides concrete thresholds at which choice switching is likely to occur.

The results indicate that approximately 10 minutes of travel time saving are required, on average, to compensate for the negative utility associated with underground expressway use. This estimate reflects the conversion of the underground-space disutility into time units and suggests that the underground attribute itself exerts a substantial influence on choice behavior, such that marginal time savings alone are insufficient to induce switching.

When the toll coefficient is expressed in time units, an additional charge of KRW 1,000 (approximately USD 0.67) is perceived as equivalent to approximately 9–10 minutes of increased travel time for the average respondent. However, substantial heterogeneity exists. For individuals with a stronger willingness to pay for time savings, price sensitivity declines markedly, with a one-point increase on the Likert scale associated with an estimated reduction in price sensitivity of about 40%. This finding implies that identical toll increases may be accepted with relatively little resistance by certain user segments.

By contrast, commuters whose trips originate or terminate in Incheon exhibit approximately 20% higher price sensitivity than the sample average, indicating a more cautious response to additional tolls for underground expressways.

The valuation of travel time savings also varies systematically across user characteristics. An increase of one preschool child in the household raises the travel time coefficient by more than 20%, indicating that households with childcare responsibilities assign high utility even to modest time savings. Morning (AM) commuters likewise value time savings more highly than average, with an

estimated increase of approximately 7%, although this effect is smaller than that associated with childcare burdens.

Attitudinal factors related to underground infrastructure also play a key moderating role. A higher perceived necessity and justification for introducing underground expressways significantly mitigates the underground-space penalty. A one-point increase in perceived justification reduces the underground disutility by the equivalent of approximately 2 minutes of travel time. Under a scenario in which perceived justification rises from a very low to a moderate level, a substantial portion of the underground penalty is offset, such that time savings of only 4–5 minutes may suffice for underground alternatives to become competitive.

Taken together, these results suggest that underground expressway acceptance is governed not only by average willingness to pay, but also by threshold effects and heterogeneous sensitivities across user groups. From a policy perspective, this implies that toll design should be interpreted in relation to expected time savings, perceived justification, and user trust, rather than as a stand-alone pricing question.

Table 7 Time- and cost-equivalent effects of key parameters estimated from the panel mixed logit model

Category	Time-equivalent effect (minutes)	Change in price or time sensitivity (%)
Underground-space disutility (θ_{UG})	Approximately 9.7 minutes required	–
Additional toll of KRW 1,000 (θ_{price})	Equivalent to ~9.3 minutes	–
One-point increase in willingness to pay for time savings	–	Price sensitivity ↓ ~40%
Incheon-based commute (origin or destination)	–	Price sensitivity ↑ ~20%
One additional preschool child in household	–	Time coefficient ↑ ~21%
Morning (AM) commute	–	Time coefficient ↑ ~7%
One-point increase in perceived justification for underground expressways	~2 minutes offset ($\approx 20\%$ reduction in disutility)	–

Note: Monetary values are reported in KRW. For international reference, KRW 1,000 is approximately equivalent to USD 0.67.

7. Willingness-to-Pay Estimates

Table 8 reports willingness-to-pay estimates for a 10-minute travel time saving across key respondent subgroups. The table highlights the extent of heterogeneity in time valuation by willingness to pay for time savings and income level.

Willingness to pay (WTP) was derived from the final panel mixed logit model (MXL_red) using the ratio of the estimated coefficients on travel time saving and toll price. In the choice model, the toll price coefficient represents the marginal utility loss associated with an increase in tolls, while the travel time saving coefficient captures the marginal utility gain from a one-minute reduction in travel time. Accordingly, WTP—defined as the additional monetary amount an individual is willing to pay for a one-minute reduction in travel time—is calculated as the negative ratio of the travel time coefficient to the toll coefficient. This measure serves as a key indicator of how commuters value travel time savings on underground expressways.

Building on this basic formulation, individual-specific WTP measures were estimated by incorporating interaction terms reflecting attitudes, travel experience, and commuting characteristics. The results indicate that the average WTP for a 10-minute reduction in travel time is approximately KRW 1,722, with a median of KRW 1,251. The distribution is right-skewed, reflecting substantial heterogeneity across respondents and the influence of a subset of individuals with particularly high valuations of time savings.

Notably, respondents reporting a stronger willingness to pay for time savings exhibit WTP levels approximately two to three times higher than those of other groups. This finding suggests that time-saving services targeted at commuters who place a high premium on punctuality and efficiency can secure a relatively stable willingness-to-pay base. In addition, income-related differences are pronounced: the value of travel time for high-income commuters is estimated to be roughly 40–50% higher than that for low-income commuters.

These findings indicate that willingness to pay for underground expressway use is not evenly distributed across the commuting population. Rather, it varies systematically with both attitudinal and socioeconomic characteristics, implying that a single toll level may generate substantially different perceptions of burden and value across user groups. From a policy standpoint, this reinforces the importance of recognizing heterogeneity when considering toll design, service differentiation, and communication strategies for future underground expressway projects.

Table 8 Willingness to pay for a 10-minute travel time saving by subgroup (KRW per 10 minutes)

Category	Sample size	Mean	Minimum	1st quartile	Median	3rd quartile	Maximum
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Total	500	1,721.6	487.1	937.8	1,250.6	1,758.7	25,046.7
Willingness to pay for time saving							
Low	82	688.4	487.1	627.5	690.0	750.8	928.6
Medium	165	1,033.6	740.4	935.4	1,028.1	1,115.7	1,430.1
High	253	2,505.1	1,007.8	1,505.5	1,749.7	2,148.0	25,046.7
Income level							
Low income	185	1,375.8	487.1	867.2	1,177.3	1,632.2	6,230.9
Middle income	195	1,435.7	588.6	928.7	1,188.6	1,699.3	5,903.1
High income	120	2,719.1	504.2	1,096.2	1,792.0	2,269.2	25,046.7

Note: Monetary values are reported in KRW. For international reference, KRW 1,000 is approximately equivalent to USD 0.67.

8. Scenario-Based Demand Responses under Alternative Toll and Performance Conditions

Table 9 presents scenario-based demand responses for the planned underground expressway corridors under alternative toll and performance conditions. The table illustrates how predicted usage changes when realized travel time savings fall short of planned targets.

Given the high construction and operating costs and the long-term demand uncertainty associated with underground expressways, it is essential to assess in advance how usage levels may respond to different toll levels and service performance assumptions during the planning stage. Travel time savings and toll levels are key determinants of user choice, and evaluating the sensitivity of demand to changes in these factors is critical for assessing both toll design and overall project feasibility.

Accordingly, this study conducted usage simulations for two planned underground expressway corridors—Giheung IC–Yangjae IC [A] and Namcheongni IC–Sinwol IC [B]—using the panel mixed logit model. Corridor-specific baseline travel times and planned travel time savings were incorporated, and toll levels were simulated over a range from KRW 0 to KRW 8,000. For ease of interpretation and policy-oriented presentation, simulation results are reported at KRW 1,000 intervals. To account for the possibility that realized performance may fall short of planned targets, an additional scenario was evaluated in which only 50% of the planned travel time savings are

achieved.

The simulation results indicate that when the planned level of travel time savings is fully realized, usage of underground expressways remains relatively stable across both corridors. Under the assumption of 100% realization of time savings, the predicted share of underground expressway use remains above 50% even as tolls increase to approximately KRW 2,500–3,000. This pattern is particularly pronounced in corridors with planned travel time reductions of around 30 minutes, where substantial usage is maintained even under moderate to relatively high toll levels. These findings confirm that travel time savings play a central role in supporting toll acceptability.

By contrast, when realized travel time savings fall short of planned targets, user responses become considerably more sensitive to toll changes, leading to a rapid decline in predicted usage. Under the 50% realization scenario, even moderate toll increases result in a pronounced reduction in underground expressway demand. This pattern suggests that travel time savings function as a critical buffer against toll resistance and that user acceptance deteriorates sharply when expected performance is not delivered.

From a policy perspective, these results indicate that the feasibility of underground expressway projects depends less on the toll level per se than on the credibility and reliability of delivered performance. Toll levels that are acceptable under fully realized travel time savings may become unsustainable if operational performance deteriorates. Accordingly, toll design and demand forecasting for underground expressways should explicitly account for performance uncertainty and consider performance-linked pricing mechanisms, such as performance-contingent toll caps or adaptive pricing during early operation phases. Emphasizing credible and sustained travel time savings is therefore essential for maintaining user acceptance and long-term demand stability.

The simulation results should be interpreted as partial-equilibrium demand responses derived from stated individual choice behavior rather than as full network-equilibrium forecasts. The analysis does not explicitly model congestion feedback, route reallocation across the broader network, or induced demand effects that may arise after the introduction of underground expressways. Accordingly, the simulated usage rates are best understood as indicative behavioral responses to toll and performance conditions rather than precise traffic assignment outcomes.

Table 9 Predicted Usage Rates of Planned Underground Expressway Corridors

Toll increase relative to existing route	Time saving 100%		Time saving 50%	
	[A] (≈30 min)	[B] (≈23 min)	[A] (≈15 min)	[B] (≈11.5 min)

(KRW)				
0	100%	99%	87%	70%
1000	95%	78%	39%	22%
2000	68%	43%	15%	8%
3000	42%	21%	8%	5%
4000	25%	12%	6%	4%
5000	14%	8%	4%	3%
6000	10%	7%	3%	2%

Note: Monetary values are reported in KRW. For international reference, KRW 1,000 is approximately equivalent to USD 0.67.

9. Conclusion

This study analyzed user acceptance and willingness to pay for underground expressways using stated choice experiment data and a panel mixed logit framework. The results confirm that travel time savings are the dominant determinant of underground expressway choice, while also identifying a substantial intrinsic disutility associated with underground road use that cannot be fully explained by time savings or toll costs alone.

On average, commuters require approximately ten minutes of additional travel time savings to offset this underground-space penalty. Importantly, this disutility is not uniform across individuals. It is significantly attenuated among users who perceive stronger policy necessity and justification for underground expressways and who exhibit higher trust in safety and travel time reliability. These findings indicate that acceptance of underground expressways is shaped not only by physical service performance but also by policy trust and risk perception.

Preferences for premium underground expressways are driven primarily by perceived improvements in safety and environmental facilities rather than by additional travel time savings. This suggests that differentiated pricing based on service quality is feasible, but only if safety enhancements and service standards are communicated clearly and credibly to users.

Simulation results highlight the central role of performance realization in toll acceptance. When planned travel time savings are not fully delivered, underground expressway demand declines sharply even at relatively low toll levels. By contrast, when performance targets are consistently met, usage remains relatively stable under higher toll scenarios. This asymmetric response implies that underground expressway pricing should be designed as a flexible, performance-linked mechanism

rather than as a fixed toll structure.

From a transport policy perspective, underground expressways should be regarded as high-cost, policy-sensitive urban infrastructure whose viability depends less on toll levels per se than on credible and sustained performance delivery. Performance-linked tolling, early-phase toll moderation, and transparent communication of safety and reliability outcomes may therefore be more effective than static pricing schemes in maintaining public acceptance.

Several limitations should be noted. First, the analysis is based on stated choice data rather than revealed behavior, and the estimated preferences may differ from actual post-opening responses. Second, the underground-space coefficient represents a reduced-form composite effect and does not fully disentangle all underlying psychological and perceptual mechanisms associated with underground travel. Third, the policy simulations are partial-equilibrium exercises that do not incorporate broader network congestion feedback or traffic reassignment effects. Future research should therefore combine post-opening revealed preference data, richer measurement of perceptual channels, and network-based demand modeling to strengthen external validity.

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Appendix A. Choice Experiment Design and Implementation

A.1. Attribute Selection and Level Definition

Attributes and levels for the choice experiment were selected to ensure statistical identification, behavioral realism, and manageable respondent burden. Attribute selection was informed by a review of previous transportation stated preference studies, pilot survey feedback, and policy relevance to underground expressway pricing.

Travel time savings were specified as proportional reductions relative to respondents' reported baseline travel time. Two sets of reduction rates were employed to capture sensitivity to both marginal and substantial time savings. Smaller reductions were designed to identify responses to incremental improvements, while larger reductions were included to capture nonlinear valuation effects under more pronounced travel time savings.

Toll levels were constructed based on the value of travel time and adjusted to reflect realistic pricing conditions observed in urban expressway systems. To capture heterogeneity in cost sensitivity, a proportional scaling factor was introduced, allowing toll increases to vary across respondents while preserving consistent trade-offs between time savings and monetary costs. For the premium underground alternative, an additional surcharge was introduced to reflect qualitative improvements in safety and environmental facilities beyond travel time savings. Pilot survey results confirmed that the selected surcharge levels were perceived as realistic and interpretable by respondents.

A.2. Personalized Choice Card Generation Procedure

The choice experiment adopted a personalized design in which choice cards were generated based on respondents' self-reported baseline travel conditions. Specifically, respondents reported their current commuting travel time and toll payments, which were used as reference values for constructing hypothetical alternatives.

Each respondent was presented with eight choice tasks, consisting of four morning and four evening trips. While the attribute framework remained identical across respondents, attribute levels were individualized to ensure that the presented scenarios closely reflected respondents' actual commuting contexts.

To reduce cognitive burden and enhance realism, toll amounts presented in the choice cards were rounded to the nearest 100 KRW. This rounding procedure is consistent with common toll presentation practices and reduces decision fatigue associated with overly precise monetary values.

A.3. Travel Time and Toll Calculation Rules

Travel time savings for underground expressway alternatives were calculated as proportional reductions from respondents' reported baseline commuting travel time. Let t_0 denote the baseline travel time. Travel time savings for the basic and premium underground alternatives were defined as:

$$\Delta t_{\text{basic}} = t_0 \times r_{\text{basic}}$$

$$\Delta t_{\text{prem}} = t_0 \times r_{\text{prem}}$$

Where r_{basic} and r_{prem} represent the travel time reduction rates assigned to the basic and premium alternatives, respectively.

Toll increments were derived by converting travel time savings into monetary values using the value of travel time and an individual-specific cost sensitivity factor. Specifically, toll increments were calculated as:

$$\Delta p_{\text{basic}} = k \times v \times \Delta t_{\text{basic}}$$

$$\Delta p_{\text{prem}} = k \times v \times \Delta t_{\text{prem}} + s \times \Delta t_{\text{prem}}$$

where k is a proportional factor capturing individual differences in perceived cost sensitivity, v denotes the value of travel time (KRW per minute), and s represents the premium surcharge applied to the premium alternative. A summary of attribute levels and calculation rules used in the choice experiment is provided Table A 1.

Table A 1 Attribute Levels and Calculation Rules Used in the Choice Experiment

Attribute	Symbol	Levels	Unit	Description
Baseline travel time	t_0	Respondent-specific	minutes	Self-reported current travel time for commuting trips, used as the reference value for personalized choice card generation
Travel time reduction rate	r_{basic} r_{prem}	10%, 12%, 14% 10%, 20%, 30%	%	Proportional reduction applied to baseline travel time. Reduction rates are assigned asymmetrically across the basic and premium underground alternatives to generate trade-offs
Value of travel time	v	100, 115, 130	KRW/min	Monetary value of travel time used to convert time savings into toll increments
Cost sensitivity factor	k	0.7, 0.9, 1.1	–	Proportional factor capturing heterogeneity in perceived cost sensitivity across respondents
Premium surcharge	s	10, 30, 50	KRW/min	Additional per-minute surcharge reflecting qualitative improvements in

				safety and environmental facilities for the premium alternative
Toll increment	Δp	Derived	KRW	Toll increase calculated based on travel time savings, value of travel time, and cost sensitivity factor. For the premium alternative, an additional surcharge reflecting enhanced safety and environmental services is included

A.4 Orthogonal Array Design

Given the predefined attributes, levels, and personalized construction rules, an orthogonal array (OA) design was employed to generate the choice tasks. The OA design minimizes correlation among attributes while maintaining statistical efficiency, enabling reliable estimation of attribute effects with a limited number of choice tasks (Hensher, et al. 2015).

The OA design was applied to the attribute-level combinations prior to personalization, ensuring that the experimental design retained orthogonality while allowing individual-specific scaling of attribute levels. This approach balances design efficiency with behavioral realism in the context of personalized stated preference experiments.

A.5. Dominance and Consistency Constraints

To prevent the emergence of dominant alternatives, design constraints were imposed to ensure that the premium underground alternative was not simultaneously associated with both shorter travel time and lower tolls than the basic alternative. When such combinations arose during the choice card generation process, an automatic adjustment rule was applied to increase the premium toll relative to the basic alternative.

This procedure was implemented to reduce estimation bias and coefficient instability in the multinomial logit and panel mixed logit models, ensuring that observed choices reflected meaningful trade-offs rather than trivial dominance.

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