Empirical Insights into Rural Bicycle Facility Design: A User-Centered Approach to Define Level of Traffic Stress Criteria

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Short summary

Bicycle level of traffic stress (LTS) establishes criteria to evaluate how comfortable or stressful a cycling facility is for riders, and this framework is used to assess cycling suitability across different cyclist types. Most prior studies have relied on literature reviews and expert opinions, with limited attention given to rural highways. Further, they follow a pre-defined segmentation of cyclists and, therefore, are subject to the bias of self-reporting on that scale. This study addresses these gaps by presenting an empirical approach to developing LTS criteria specific to rural contexts using the entire distribution of taste parameters.

To understand when cycling conditions are unsuitable, were gathered responses from 982 participants via an online survey. Using vignette-based experiments, respondents identified preferred cycling conditions, enabling the derivation of individual-level parameters for each roadway attribute. The analysis revealed that self-reported cyclist classifications inadequately captured the variability in preferences in the rural context.
Keywords: Cycling Behavior, Cycling Design, Traffic Stress.

1 Introduction

Since the mid-1980s, researchers and practitioners have explored the impact of roadway design and traffic characteristics on cyclists' perceptions of comfort, safety, and the overall quality of cycling, along with the determinants of their route selection. Different approaches have developed concurrently, from level of service concepts (Transportation Research Board, 2010; Oregon Department of Transportation, 2020) to bikeability (San Francisco Department of Public Health, 2010) and level of traffic stress (Mekuria et al., 2012; Oregon Department of Transportation, 2020).

In recent years, the level of traffic stress has garnered increased attention and emerged as a central framework for addressing bicycle facility selection in the US for rural highways (Massachusetts Department of Transportation Transportation, 2015; Onta, 2018; Schultheiss et al., 2019; Oregon Department of Transportation, 2020; Colorado Department of Transportation, 2023). Accessible look-up tables present the preferred bicycle facility (shared lanes, paved shoulders, or separated shared-use pathway) for the design user in a given context. In rural contexts, they use automobile speed and volume as main attributes, and the design users are confident. Most guidelines follow the same principles: considering a higher level of bikeway accommodation with increased traffic speeds and volumes. However, current thresholds vary broadly, as do cyclist segmentations. For example, for a daily volume over 7,000 vpd and 40 mph speed limit, the FHWA (Schultheiss et al., 2019), Colorado Department of Transportation (2023), and Oregon Department of Transportation (2020) guidelines recommend a 8-feet, or 0 to 4-feet shoulder to accommodate "somewhat confident" or "enthused and confident" cyclists, respectively.

This approach faces some challenges. Firstly, the design criteria for rural contexts are based on expert opinion and literature review and have not been validated with user perception, although is validated with urban cyclists (Dill & McNeil, 2013, 2016; Ferenchak & Marshall, 2020). Secondly, design users are based on the first cyclist segmentation by Geller for Portland, OR (Geller, 2006) based on expert knowledge. Geller (2006) and later refined using the rule-based method developed by Dill & McNeil (2013). Geller distinguished four classes of cyclists ordered by their comfort level and intent to cycle: "no way, no how", "interested but concerned", "enthused and confident" and "strong and fearless" and identified "interested but concerned" as the target design cyclist user for urban contexts to increase bicycle modal share. In the rural context, design users are among the most confident types: either "somewhat confident" (Schultheiss et al., 2019; Colorado Department of Transportation, 2023) or "enthused and confident" (Oregon Department of Transportation, 2020). However, this segmentation is prone to the bias of self-reporting on these scales, and it is not driven by their choice to cycle on a given facility. Researchers found that the rule-based method provided groups with high heterogeneous responses to their perceived level of comfort, and they suggested a data-driven segmentation for urban cyclists (Cabral & Kim, 2020) and rural leisure cyclists (Cai & Moreno, 2024).

2 Methodology

Stated preference survey

The study expands upon an online survey created by Moreno et al. (2024) and utilized by Cai & Moreno (2024) to categorize rural leisure cyclists. The survey aimed to identify key highway attributes influencing the likelihood of cycling on rural highways. Conducted via LimeSurvey from November 2022 to January 2023, it gathered 982 complete responses out of 1,650 participants. The survey consisted of five parts: an introduction explaining its purpose, cyclist segmentation questions, choice experiments involving images of cycling conditions, user-specific questions about leisure and typical cycling experiences, and demographic and attitudinal questions.

To gather their preferences, we used a series of choice experiments with different cycling facilities (context classification, speed limit, shoulder presence/width, traffic volume, pavement quality, and grade). Fractional design was used to reduce from 324 possible combinations to 16 representative configurations. Each respondent completed four choice sets with four alternatives, which were presented randomly. The choice sets were constructed using still images based on real-world images from rural routes captured from Mapillary, and speed limit signs, automobile traffic volume, and pavement conditions were edited on them. Table 1 summarizes their roadway conditions.

Table 1: Choice set images: roadway conditions

Choice set	Roadway conditions					
image	Context	Shoulder width	Pavement	Traffic volume	Speed limit	Terrain
1	Rural	Narrow	Good	Low volume	Low	Rolling
2	Rural	No shoulder	Good	High volume	Low	Rolling
3	Rural	Wide	Acceptable	No vehicles	Low	Level
4	Rural	No shoulder	Acceptable	Low volume	High	Level
5	Rural	Wide	Deteriorated	High volume	High	Rolling
6	Rural	Narrow	Deteriorated	High volume	Low	Level
7	Rural Town	Narrow	Good	No vehicles	High	Level
8	Rural Town	Wide	Good	High volume	High	Level
9	Rural Town	No shoulder	Acceptable	No vehicles	Low	Level
10	Rural Town	Wide	Acceptable	High volume	Low	Rolling
11	Rural Town	No shoulder	Deteriorated	Low volume	High	Rolling
12	Rural Town	Narrow	Deteriorated	Low volume	Low	Rolling
13	Suburban	No shoulder	Good	No vehicles	Low	Rolling
14	Suburban	Wide	Good	Low volume	Low	Level
15	Suburban	No shoulder	Acceptable	High volume	High	Rolling
16	Suburban	No shoulder	Good	High volume	Low	Level

Modeling framework

Different approaches can be used to model heterogeneous tastes of alternative attributes in the choice model, depending on the assumption made on the distribution of taste parameters (Kim, 2023). We selected a model with continuous taste parameters (e.g., random parameters model) to present the randomness of the taste among the population by fitting a parameterized distribution. The Bayes theorem is used to derive the taste parameters for the design attributes of individuals conditional on their observed choices from a mixed logit model, referred to as individual-level parameters (Revelt & Train, 2000). This approach allows for the individual parameter to be drawn from the estimated distribution of the random taste parameters over the population, and we could use their observed choices to better infer their taste parameters.

In a mixed logit model with the prior of normally distributed taste parameters for design attributes, the utility that individual i obtains from alternative scenarios $j = 1, ..., 17$ (17 is the opt-out option) is obtained in Equation 1.

$$U_{ij} = \alpha + X_j^{'}\beta_i + \epsilon_{ij} \tag{1}$$

Where α is the constant term for 16 highway scenarios except the opt-out option; X_j is the vector of design attributes of alternative j; $\beta_i \sim N(\mu, \Omega)$ is the vector of normally distributed taste parameters of individual i; $\epsilon_{ij} \sim Gumbel(0, 1)$ is the random error term.

Let Y_i denote the chosen alternatives of individual i for the presented choice tasks, X_i denote the attributes of the alternatives presented to individual i, and $\theta = \{\alpha, \mu, \Omega\}$ denote the collection of estimated parameters. The probability of choosing the alternatives presented to individual i can be calculated using Equation 2 (since β_i is unknown).

$$P(Y_i|X_i, \theta) = \int P(Y_i|X_i, \beta)f(\beta|\theta)d\beta \tag{2}$$

Where $f(\beta|\theta)$ is the distribution of taste parameters for the population; $P(Y_i|X_i, \beta)$ is the kernel of the choice model when β is known. Based on the Bayes theorem, we can then derive the distribution of taste parameters for the individual i (Equation 3).

$$h(\beta|Y_i, X_i, \theta) = \frac{P(Y_i|X_i, \beta)f(\beta|\theta)}{P(Y_i|X_i, \theta)} = \frac{P(Y_i|X_i, \beta)f(\beta|\theta)}{\int P(Y_i|X_i, \beta)f(\beta|\theta)d\beta} \tag{3}$$

The individual-level parameters are then evaluated as the expected value of this distribution using Equation 4.

$$\bar{\beta}_i = \int \beta h(\beta|Y_i, X_i, \theta)d\beta = \frac{\int \beta P(Y_i|X_i, \beta)f(\beta|\theta)d\beta}{\int P(Y_i|X_i, \beta)f(\beta|\theta)d\beta} \tag{4}$$

The mixed logit model and the individual-level parameters were estimated using Markov Chain Monte Carlo (MCMC) method (Bansal et al., 2020) in Biogeme.

3 Results and discussion

Descriptive sample

The survey received 1,650 responses, with 982 complete responses from US residents across all 50 states and the District of Columbia. Most respondents were male (68%), with a significant portion in midlife (43% aged 31-59) and older (50% over 60), and had medium-high household incomes. When asked about their cycling type, 70% identified as “Enthused and confident,” 20% as “Interested but concerned,” and 8% as “Strong and fearless.” This distribution aligns with the preferred user types for rural highways, emphasizing more confident male cyclists, as opposed to urban cycling studies, and the tendency that females usually have less confidence (Dill & McNeil, 2013). A notable 20% of respondents were “Interested but concerned” cyclists, reflecting those who may rely on a bike for transportation.

Model estimation

Table 2 presents the estimation results of $\theta = \{\alpha, \mu, \Omega\}$. The estimated population mean taste parameters β is very close to the mean value of posterior individual-level parameters $\bar{\beta}_i$, which implies a correctly specified and constantly estimated model. $\hat{R} \approx 1.0$ indicates a good convergence of MCMC method.

Table 2: Estimation results of mixed logit model

Parameters	Mean (α, μ)	Std error	$\hat{R}$	Standard deviation (Ω)	Std error	$\hat{R}$
Constant	-2.505					
Context classification: rural (reference)						
Context classification: rural town	0.917	0.075	1.037	1.290	0.088	1.037
Context classification: suburban	1.046	0.117	1.015	2.204	0.117	1.021
Shoulder: no (reference)						
Shoulder: narrow	1.438	0.131	1.012	2.203	0.125	1.018
Shoulder: wide	4.696	0.136	1.011	1.820	0.101	1.028
Pavement conditions: deteriorated (reference)						
Pavement conditions: acceptable	0.222	0.116	1.015	1.736	0.105	1.026
Pavement conditions: good	1.735	0.092	1.024	1.300	0.089	1.035
Traffic volume: none (reference)						
Traffic volume: low	-0.621	0.085	1.029	0.777	0.119	1.020
Traffic volume: high	-1.512	0.090	1.026	1.356	0.094	1.032
Speed limit: low (reference)						
Speed limit: high	-1.248	0.098	1.022	1.521	0.099	1.029
Terrain: level (reference)						
Terrain: rolling	0.874	0.076	1.035	1.412	0.078	1.047
Sample size	982					
Number of simulation draws	500000					
Number of iterations	400000					
Final log likelihood	-8400.42					
$\bar{R}^2$ for the constant only model	0.331					

Note: $\hat{R} < 1.1$ indicates that Markov Chain Monte Carlo (MCMC) chains have likely converged

On average, wide shoulders have the most significant positive impact on cycling preferences, followed by good pavement conditions and narrow shoulders. High speed limits and increased traffic volume negatively affect the likelihood of choosing to cycle, as expected. Cyclists prefer more urbanized contexts, with a slight difference between rural town and suburban contexts, compared to the difference between rural and rural town contexts. Rolling terrain is favored over flat terrain, likely due to a more enjoyable ride. This is a main distinction with urban contexts, where more challenging terrain is usually associated with a negative utility, as the main driver for route selection is reduced energy consumption for utilitarian purposes. In rural contexts, preferences for more pleasant/fun rides for leisure cycling may emerge. The variability in preferences for narrow shoulders and suburban contexts is higher than for other categories, as noted by a higher standard deviation of the random taste parameters.

Distribution of individual preferences to attributes

After estimating the population distribution of taste parameters using the mixed logit model, we simulated individual parameters based on this distribution and observed choices. Figure 1 shows the individual parameter distributions by cyclist type, allowing us to examine potential differences among cyclist types. The distributions overlapped for some attributes, such as low traffic volume or rural town contexts, showing no significant variations across cyclist types. However, for other attributes, certain cyclist types shared similar preferences although the overlapping groups vary. For example, “Interested but concerned” and “Enthused and confident” cyclists favored high traffic volume, suburban contexts, wide shoulders, and good pavement, while “Enthused and confident” and “Strong and fearless” cyclists preferred high speed limits and rural town contexts. Distinct preferences were observed for attributes like narrow shoulders and pavement conditions, with “Interested but concerned” cyclists preferring acceptable pavement, “Enthused and confident” cyclists being indifferent, and “Strong and fearless” cyclists preferring acceptable pavement. Some cyclists, particularly "Interested but concerned” and “Enthused and confident,” preferred no shoulder over a narrow shoulder, a preference not seen in "Strong and fearless” cyclists.

The results suggest that self-reported confidence levels do not adequately capture systematic variability, as some distributions overlap and others show multiple peaks rather than bell-shaped curves.

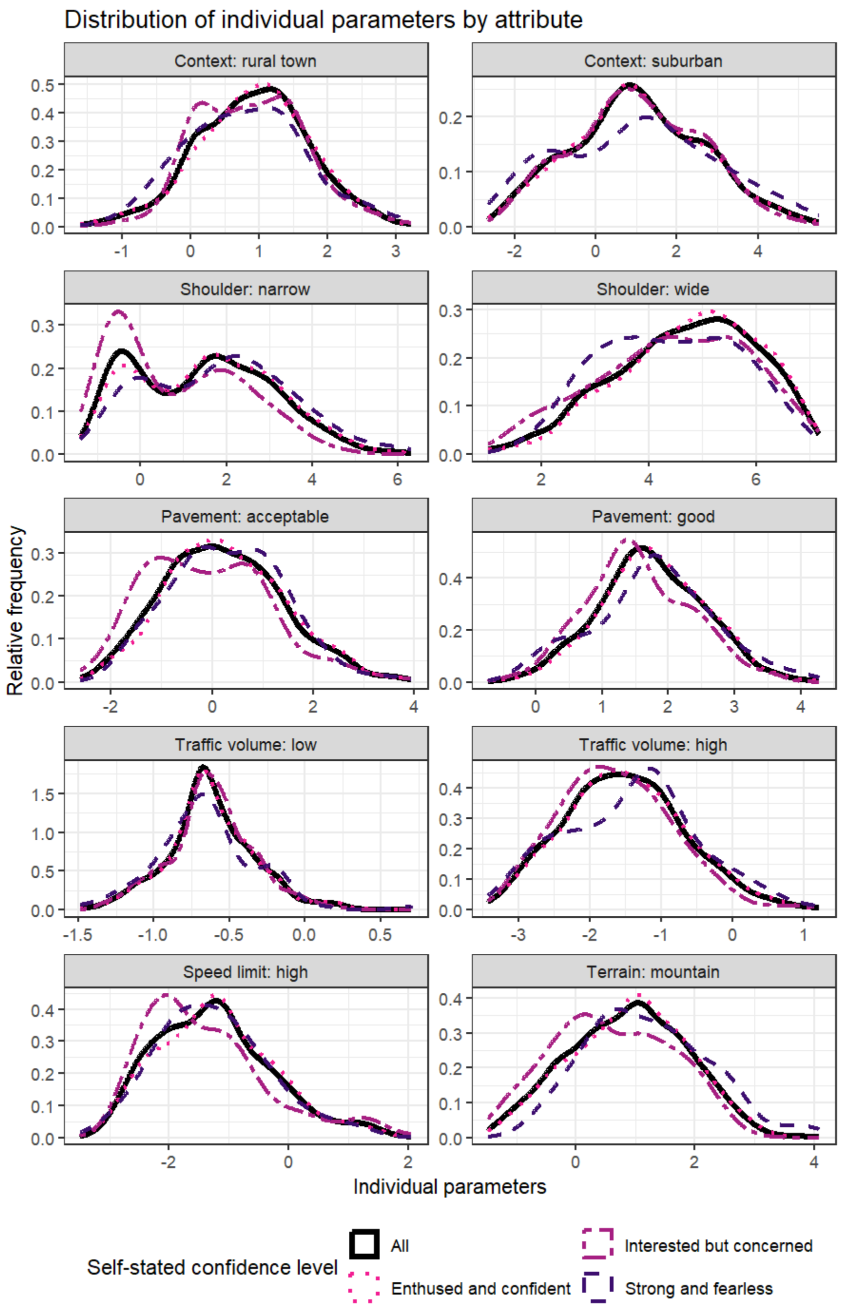

Figure 1: Distributions of parameters by attribute and self-stated confidence levels

Deriving recommendation criteria

To derive recommendation criteria, we synthesized the bicycle facility recommendations from the literature (Schultheiss et al., 2019; Colorado Department of Transportation, 2023; Minnesota Department of Transportation, 2020; Oregon Department of Transportation, 2020; Onta, 2018) for given context class, speed limit, and traffic volume. Then, we used the mixed logit model to calculate the propensity to cycle of survey participants under those conditions. With the cumulative frequency distribution of the propensity to cycle, we determined thresholds to derive recommendation criteria. The thresholds are based on two anchoring points that represent most adults and advanced cyclists. For most adults, we selected the first quartile (Q1), which splits off the lowest 25% of data from the highest 75%. The third quantile (Q3) can be a good indicator of conditions that are comfortable only for the most advanced cyclists, as splits off the highest 25% of data. We also selected a set of propensity to cycle values to represent preferable ($\geq 75\%$), acceptable ($\geq 50\%$), not preferable ($\geq 25\%$), and unsuitable conditions ($< 25\%$).

Specifically, we set the following thresholds:

1. **Cycling is recommended for all users**: roadway conditions preferable for cycling to most adults. Considering that the 25% percentile represents most adults, we set that the propensity to cycle at Q1 must be at least 75% ($Q1 \geq 75\%$).
2. **Cycling is recommended for advanced users**: roadway conditions acceptable for cycling to advanced cyclists. Advanced cyclists are considered the top 25% of the distribution (Q3), and we set that the propensity to cycle at Q3 must be at least 50% ($Q3 \geq 50\%$).
3. **Cycling is not recommended**: roadway conditions less preferable for advanced cyclists, but still a significant share of advanced cyclists would select to cycle. We set that the propensity to cycle at Q3 must be between 25 and 50% ($25Q3 < 50\%$).
4. **Cycling is not suitable and shared use path is required**: roadway conditions not preferable for even advanced cyclists. We set that the propensity to cycle at Q3 is lower than 25% ($Q3 < 25\%$).

Table 3 summarizes the recommendations for bicycle facilities from the literature and according to our framework.

Table 3: Comparison of bicycle facility recommendations

Conditions				Guidelines				Propensity to cycle			
Context class	Speed limit	Traffic volume	Shoulder width	FHWA 2019 CDOT 2023	MnDOT 2020	ODOT 2020	AASHTO 2018	Q1	Q2	Q3	Recommendation
			No	Y	-	YY	-	5.7	9.8	15.9	-
Rural town	30 mph	< 1500 vpd	Narrow	Y	Y	YY	Y	8.8	35.1	65.4	Y
			Wide	Y	Y	YY	Y	78.1	93.6	97.9	YY
			No	-	-	Y	-	1.8	5.5	16.1	-
Rural town	30 mph	> 7000 vpd	Narrow	-	-	Y	Y	3.8	22.2	61.6	Y
			Wide	-	Y	Y	Y	56.0	88.3	97.4	Y
			No	-	-	Y	-	2.2	4.9	10.6	-
Rural	40 mph	< 1500 vpd	Narrow	-	-	Y	Y	3.8	20.2	53.9	Y
			Wide	Y	Y	Y	Y	66.2	88.1	96.1	Y
			No	-	-	Y	-	0.8	2.3	5.6	-
Rural	40 mph	> 7000 vpd	Narrow	-	-	Y	Y	1.5	9.7	35.5	N
			Wide	Y	Y	Y	Y	40.0	74.6	92.1	Y
			No	-	-	Y	-	0.8	2.3	5.6	-
Rural	50 mph	< 1500 vpd	Narrow	-	-	Y	Y	0.8	6.8	29.7	N
			Wide	Y	Y	Y	Y	28.0	70.8	89.9	Y
			No	-	-	-	-	0.2	0.6	2.0	-
Rural	50 mph	> 7000 vpd	Narrow	-	-	-	-	0.4	3.2	17.0	-
			Wide	Y	Y	Y	Y	12.5	48.9	81.1	Y

Note. Q1, Q2, and Q3 refers to 25%, 50%, and 75% percentile of the distribution
Note. YY: cycling is recommended in the facility for all users
Y: cycling is recommended in the facility for advanced cyclists
N: cycling is not recommended in the facility
-: cycling is not suitable, separate bike lane or shared use path is required

FHWA (Schultheiss et al., 2019), Colorado Department of Transportation (2023), and Minnesota Department of Transportation (2020) provide the most conservative criteria, allowing cycling only with wide shoulders when speed limits exceed 35 mph or on low-speed, low-traffic roads. AASHTO (Onta, 2018) permits cycling on wide shoulders under all conditions and narrow shoulders except with high speed and traffic volumes. Oregon Department of Transportation (2020) allows cycling in most conditions, except narrow/no shoulders with high speed and traffic.

Model results show a low propensity to cycle without shoulders (2-16%), suggesting that such conditions should be classified as unsuitable and separate bike lanes or shared paths are required. Wide shoulders are preferable for cycling for all speed-volume pairs for advanced cyclists, and therefore cycling is recommended. Wide shoulders on low-volume rural roads are also recommended for all cyclists. Narrow shoulders are acceptable for advanced cyclists on low-speed, low-traffic roads but not when speeds and volumes increase. Under such conditions, separate paths are required.

4 Conclusions

This study used an online survey to empirically derive recommendations for bicycle facilities in rural contexts, with 982 participants selecting their preferred cycling conditions. A total of 7,856 individual choices were analyzed using a mixed-logit model that accounts for individual-level parameters, offering a more robust approach compared to previous studies relying on mean parameters for cyclist subgroups. Our sample closely aligns with the target user groups in rural contexts as defined by AASHTO, FHWA, and state DOTs.

The main conclusions of the study are:

- Providing wide shoulders resulted in preferable conditions for advanced cyclists regardless of speed limits, traffic volumes, and context classes. Roadways without shoulders, on the other hand, had a little propensity to cycle even in the most favorable traffic conditions.
- The interaction of speed limits and traffic volumes is important, as captured in the current design guidelines. The analyses revealed that higher speeds are tolerated when traffic volumes are low, and vice versa.
- Segmentation by cyclist type revealed inconsistencies in responses, suggesting that using percentiles of the distribution of taste parameters is more representative than using self-reported confidence levels.
- Recommendations based on user preferences can be derived using the propensity to cycle distribution. The anchoring points could be flexibly set by agencies and/or researchers, so that more/less conservative criteria are defined. The proposed recommendations using empirical data are closer to the AASHTO preliminary guideline (Onta, 2018), less conservative than FHWA (Schultheiss et al., 2019) and MnDOT (Minnesota Department of Transportation, 2020), and more conservative than ODOT (Oregon Department of Transportation, 2020).

The study proposes recommendations for bicycle facilities based on individual preferences, emphasizing the importance of capturing the full distribution of preferences rather than relying on mean values of pre-defined segmentations. Limitations include the potential impact of environmental variables and the inherent challenge of interpreting ambiguous data from simulated images. Further, there could be sample biases towards more confident cyclists, as they were targeted in the survey distribution. Additional individual weights, if available among all rural cyclists or the overall population, would make the taste distribution more representative. Future research should address these issues and further refine the segmentation model for rural cyclists.

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