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Research Article

Safety over all? How European riders evaluate advanced cyclist assistance systems (ACAS) and their features☆

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A B S T R A C T

As cycling gains traction as a sustainable transport mode, enhancing cyclists' safety has become a key priority within European policy. Among the various developments introduced, Advanced Cyclist Assistance Systems (ACAS) stand out as a promising technological innovation. However, research on their perceived value and adoption remains limited, particularly regarding user preferences and demographic differences.

Aim: This study aimed to examine European cyclists' evaluation of five ACAS types and their core functional features, as well as to explore demographic differences, particularly in relation to cyclists' gender and age.

Method: This study used the data provided by 6167 cyclists (47.4% females; 51.5% males; 1.1% others) from 19 European countries. Participants provided self-reported evaluations of five ACAS types (environmental monitoring, rider visibility enhancement, real-time information, crash prevention-assistance, and post-crash appliances) along with key features (safety contribution, reliability, ease of use, novelty, and everyday need).

Results: Among ACAS types, visibility-enhancing systems (designed to increase cyclists' conspicuity) and environmental monitoring technologies received the highest valuations, while real-time information systems were rated the lowest. Safety contribution was the most highly valued attribute across all ACAS features. Additionally, gender differences were observed, with female cyclists prioritizing visibility and safety-related aspects. In contrast, male cyclists –while also favoring visibility-improving ACAS– placed greater emphasis on ease of use as a core feature.

Conclusion: These findings highlight the importance of user-centered ACAS design and suggest that broader adoption may depend on improving system reliability, regulatory frameworks, and alignment with cyclists' needs and attitudinal factors. Future research should explore real-world ACAS implementation and long-term adoption trends to support safer and more technologically integrated cycling environments.

1. Introduction

Cycling has become an increasingly popular mode of transportation and recreation worldwide, offering numerous health and environmental benefits. However, as more people take to the roads on bicycles, ensuring cyclist safety has become a growing concern for policymakers, urban planners, and public health officials [1]. While overall road fatalities and serious injuries in the European Union declined by 23% between 2010 and 2019, the proportion of cycling crashes resulting in death or serious injury increased from 7% to 9% over the same period

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[2]. In response, various interventions and technological advancements have emerged in recent years, with cyclist assistance systems standing out as a key development. Given that these represent relatively new and pioneering efforts, the present study aims to provide insights into European cyclists' perspectives on such innovations, specifically addressing the case of Advanced Cyclist Assistance Systems (ACAS).

From a conceptual standpoint, ACAS, named in alignment with Advanced Driver Assistance Systems (ADAS), encompass a range of technological solutions designed to enhance cyclists' safety, improve situational awareness, and mitigate crash risks, becoming increasingly recognized as a valuable tool for enhancing rider safety and confidence on the road [3,4]. Indeed, emerging factors such as advancements in sensor technology, the increasingly widespread adoption of electric bikes (e-bikes), and rising public interest in cycling safety have led recent studies to forecast that, sooner rather than later, Advanced Cyclist Assistance Systems might experience several advancements in the next few years [5,6].

However, while automotive ADAS keep gaining ground in the industry, and most new vehicles include a certain number of them, the development and market permeation of their equivalent for bicycles (ACAS, or ADAS-B) lags behind, growing at a very low speed [5,7]. The attributable causes for this constrained growth include forecasted high costs, a fragmented manufacturing market, potential users' lack of confidence, and cultural and behavioral aspects influencing the perceived need and acceptance of ACAS systems among cyclists and other road users [8–10].

In this regard, and despite the limited knowledge about the user perspective of ACAS, it is worth noting that research on bicycle assistance systems is still at a very early stage, although it is expected to represent a relevant contribution to riders' safety [11]. Thus, understanding the evaluation of ACAS and their features by potential users, apart from a pending challenge, represents a currently critical step toward the accurate and human-centered development, promotion, and a faster adoption of safety-enhancing systems for bicycles [6,8].

1.1. Advanced cyclists' assistance systems: features and types

Unlike the well-established framework for ADAS in automobiles, which has seen continuous advancements despite some persistent limitations [9,12,13], the classification and typification of ACAS remain underdeveloped and lack a universally recognized standard. This highlights the need for exploratory and integrative efforts to address cyclists' specific requirements, considering their ergonomic characteristics and user-related differences compared to motor vehicle drivers [7,14].

In the case of motor vehicles, assistance systems are commonly categorized based on their functionalities, such as collision avoidance, parking assistance, lane keeping, and adaptive cruise control [9,15]. Alternative classifications based on ergonomic features have also been proposed to enhance user-centered design and system evaluation [16,17]. In contrast, ACAS remain in an early stage of development, with features typically described in terms of specific applications rather than organized into broader functional categories. This disparity highlights the need for a more systematic and structured framework, akin to those established in automotive contexts, to support the development and broader adoption of ACAS technologies.

Regarding previous insights on ACAS, a preliminary review of the state-of-the-art reveals their limited penetration into global markets despite increasing interest in cycling safety [18]. Emerging systems, such as proximity radars, automated lighting, and emergency response tools, mark initial steps toward integrating ACAS into cycling usage patterns but remain minimally commercialized, remaining limited to a segment within the e-bike industry. However, these advancements are often fragmented, lacking comprehensive frameworks for interoperability or scalability, as remarked in recent reviews such as [6,15,18]. Moreover, the scarcity of studies validating ACAS' ergonomic benefits and safety-enhancing potential has led to debate, further emphasizing the need for foundational research to address these gaps.

On the other hand, preliminary evidence suggests that the integration of sensor-based technologies and machine learning algorithms has the potential to gradually revolutionize cyclist safety by enabling real-time hazard detection and adaptive feedback mechanisms [19–21]. However, the large-scale application of such devices remains limited by technological and economic barriers in addition to user-related issues such as low perceived ease of use and personal security concerns [6,22,23]. Additionally, other recent studies such as Kapousizis et al. [8] emphasize the fragmented nature of ACAS development globally, with most innovations remaining at the prototype stage or limited to region-specific implementations rather than achieving a broader adoption. This is particularly critical given that cycling crashes and their impacts remain a widespread issue globally, while technological advancements for bicycles remain largely underutilized [24–26].

1.2. ACAS state of knowledge

While evidence on the acceptance of ACAS remains relatively limited from a scientific standpoint, there are some recent studies that highlight diverse approaches to their development, evaluation, and adoption. Overall, the findings suggest that aligning ACAS development with user preferences could foster broader acceptance.

Among these pioneering efforts, applied studies integrating both ACAS and user-based data stand out. For instance, in a recent experiment conducted in Europe, Wang et al. [4] implemented and evaluated a set of pre-collision warning systems, including adaptive cruise control and lane-keeping, using a motion-based bicycle simulator. The preliminary findings of their study show that while adaptive cruise control enhanced user experience and safety, lane-keeping assistance showed limited acceptance despite its functional stability. This outcome stresses the pressing need to adapt automotive technologies effectively to the unique contexts and requirements of cyclists.

From a legislative and standardization perspective, the absence of technical standards or regulatory frameworks poses critical challenges for ACAS deployment. In contrast to automotive ADAS, which benefit from well-defined safety regulations and performance benchmarks, ACAS remain loosely governed. Preliminary discussions on the inclusion of ACAS-related provisions in broader cycling policies are gaining traction, particularly in European countries where cycling is more widespread [27–29]. However, critical issues such as data privacy, liability, and system compatibility with different bicycle types remain largely unaddressed. Significant legislative gaps persist in most countries, limiting the broader acceptance and implementation of these systems [5,30].

Regarding user-related aspects, recent research has offered scarce but valuable insights into cyclists' perceptions and the potential impact of ACAS on cycling behavior. For instance, Haufe et al. [11] suggest that cyclists tend to prioritize features aimed at enhancing visibility and situational awareness – and thus providing simple cycling experience improvements –, such as automated lighting and environmental monitoring systems, over more complex technologies like crash-prevention assistance. At a theoretical level, it could be hypothesized that this preference for 'simpler systems and solutions' could be influenced by users' perceived usefulness and short-term satisfaction [31]. On the other hand, ACAS perceived as 'complex' or 'not user-friendly' may create reluctance, as highlighted in studies of drivers' supporting systems [13,32].

In the field of cycling, preliminary evidence highlights the role of e-bikes as a catalyst for ACAS adoption, as their increased use aligns with the technological sophistication required to integrate assistance systems. Research involving e-bike users –who often represent the primary adopters of ACAS technologies– has highlighted that, beyond their potential to enhance safety, the successful adoption of ACAS may largely depend on aligning system design with user needs and expectations, also suggesting potential demographic differences (e.g., gender and age) that may modulate their technology adoption patterns [23,33–35]. For instance, some prior studies suggest that women, being generally more safety-oriented, may have a greater acceptance of safety-focused technological devices and developments than their male counterparts [11,36].

Also, the real-world applicability of many ACAS systems remains limited due to their prototypical nature and lack of standardization. Still, additional research is necessary to understand long-term adoption trends and the systems' impact on cycling safety and behavior [6,34,37], suggesting that future ACAS research should also focus on refining both users' perceptional and technological features, i.e., integrating technological innovations into scalable, user-centric solutions to enhance safety and promote adoption.

1.3. ACAS in Europe: more prospects than realities?

In Europe, the development of ACAS is a growing yet fragmented field, with prospects for widespread adoption receiving political endorsement despite remaining in an early development phase [27,28]. The continent's strong commitment to sustainable transportation, reflected in cycling-focused policies such as the European Cycling Strategy, provides a favorable foundation for integrating ACAS into urban mobility (see [29]).

However, current progress remains hindered by technical and legislative barriers. For instance, and similar to what happens in other regions, while ADAS are governed by unified European Union (EU) safety standards, such as the General Safety Regulation (EU) 2019/2144, no equivalent framework currently exists for ACAS, leaving the design and deployment of these systems inconsistently regulated across member states [38]. At a practical level, this regulatory gap limits innovation and cross-border compatibility, despite increasing calls for standardized technical and safety requirements [39].

Several promising trends highlight the potential for ACAS growth in Europe. The rising popularity of e-bikes, particularly in countries like the Netherlands and Germany, offers an opportunity for integrating ACAS functionalities, as e-bike users are more likely to adopt technologies that enhance riding safety and convenience [8]. However, market penetration of technology-assisted bicycles remains low, as ACAS are often perceived as cost-prohibitive or unnecessary by a significant portion of the cycling population [6]. Additionally, some studies have suggested that cultural differences in cycling behavior (e.g., those between highly cycling-oriented regions and emerging cycling areas in Europe) may influence user acceptance of ACAS. In particular, safety-focused features tend to be prioritized in countries where cycling is perceived as riskier [11].

Despite these challenges, pilot initiatives and research are paving the way for greater integration of ACAS. For example, simulation studies have demonstrated the feasibility of incorporating lane-keeping and adaptive cruise control into bicycles, albeit with varying levels of user acceptance among specific user profiles (see [4,21]). Furthermore, discussions within EU-funded projects, such as Horizon Europe's urban mobility initiatives, increasingly emphasize the need for cyclist-centered safety technologies to complement broader sustainable mobility strategies, motivating the development of the present research. Moreover, to the best of our knowledge, this is the first applied study addressing these relevant issues regarding ACAS in Europe.

In this article we take a prior step toward adoption analyses by mapping cyclists' differential evaluations of ACAS types and core features at scale. Our focus is comparative prioritization rather than willingness to pay or cost–benefit estimation. This scope sets the stage for subsequent work that will integrate user valuation with implementation costs and policy instruments.

1.4. ACAS and technology acceptance models

Advanced Cyclist Assistance Systems (ACAS) are technological tools that can influence everyday mobility dynamics, from perceived safety and reliability to routine route choices, and their adoption can be appraised from a theoretical standpoint. In acceptance research, the Technology Acceptance Model (TAM) proposes two core appraisals (perceived usefulness and perceived ease of use) that help explain how people evaluate and ultimately adopt new systems [40]. Extensions such as TAM2 specify social influence and cognitive instrumental processes that shape perceived usefulness over time. In this study, these constructs serve as a lens to organize the evaluation space of ACAS features, particularly those linked to performance benefits or effort costs in daily cycling. In line with prior work, acceptance models are used here to motivate what to measure and how to label core dimensions, not to impose a structural model test on data designed for large-scale comparative evaluations across technology types and features (single-item ratings, no intention or use indicators) [41,42].

A complementary framework is the Unified Theory of Acceptance and Use of Technology (UTAUT). It synthesizes prior models and posits four main determinants of intention and use: performance expectancy, effort expectancy, social influence, and facilitating conditions, with moderators such as age and gender. UTAUT2, its latest version used in research, adapts this view to consumer contexts by adding hedonic motivation, price value, and habit, factors that become relevant when technologies are discretionary and personally purchased [43]. For ACAS, these frameworks indicate which perceptions plausibly connect to intentions and subsequent use as infrastructure, device availability, and user experience evolve. Consistent with our design, we draw on UTAUT and UTAUT2 to first define feature families and to interpret, compare, and understand observed patterns as descriptive evidence rather than as a formal test of acceptance pathways [40,44].

1.5. Study aims and hypotheses

The aim of this study was to assess European cyclists' evaluation of five different types and features of ACAS technologies, as well as to identify potential demographic differences (i.e., by gender and age) in the relative importance attributed to them. In this context, two hypotheses were formulated based on a review of the literature and the anticipated study outcomes:

Firstly, drawing on insights from previous studies on ADAS and ACAS [8,16,20] it was hypothesized that features related to safety contribution and reliability would receive greater valuation compared to those emphasizing novelty, ease of use, or expected frequency of use by cyclists.

Secondly, it was expected that demographic differences between cyclists would influence the rating of ACAS types and features. Specifically, significant differences were anticipated based on key demographic factors, such as age and gender, which could shape cyclists' evaluations of these technologies.

2. Methods

2.1. Participants

This study analyzed data from a sample of 6167 European cyclists from 19 countries, with a mean age of 34.04 years (s = 16.93), ranging from 16 to 81 years. Among the participants, 47.4% (n = 2924) were female riders, 51.5% (n = 3178) were male, and 1.1% (n = 65) identified as non-binary/other.

Regarding cycling-related information, participants reported a mean weekly cycling intensity of 4.98 h (s = 4.89), and the average duration of their most frequent cycling trips was 39.82 min (s = 38.94). Further details on participants' demographic and cycling-related variables are presented in Table 1.

Table 1
Basic demographic data and cycling patterns of the study sample.

Variable	Category	Total n	Total %
Gender	Female	2924	47.4%
	Male	3178	51.5%
	Non-binary/other	65	1.1%
	Total	6167	100%
Age range	<25 years	2499	40.52%
	25–44	1874	30.38%
	45–65	1489	24.14%
	>65 years	294	4.77%
	Prefer not to say	11	0.21%
	Total	6167	100%
Educational attainment	Primary school or lower	51	0.8%
	Secondary school/ high school	1237	20.1%
	Technical-intermediate training	765	12.4%
	Undergraduate University Degree	3052	49.5%
	Postgraduate University Degree	730	11.8%
	Prefer not to say	332	5.4%
	Total	6167	100%
Cycling weekly intensity	< 1 h	1003	16.3%
	1–2 h	1697	27.5%
	3–5 h	1462	23.7%
	6–10 h	1440	23.3%
	> 10 h	534	8.7%
	Prefer not to say	31	0.5%
	Total	6167	100%
Main reason(s) for cycling [1]	Daily commuting/Work	2332	37.8%
	Sport/fitness	3176	51.5%
	Leisure	4835	78.4%

Notes for the Table: [1] Participants were allowed to select multiple responses, resulting in relative frequencies that collectively exceed 100%.

2.2. Procedure

For this cross-sectional study, participants completed an online survey that gathered information on cycling habits, riding safety, cycling trends, and emerging phenomena such as ACAS and technology use patterns. The data were collected as part of the Bike-Barometer II project, which explores emerging factors and phenomena that relate to the safety and well-being of urban cyclists. The survey was conducted between the years 2023 and 2024. It is important to note that this paper constitutes the full-length version of the presentation of the preliminary study results, available in [45]. This corresponds to the preliminary abstract presented at the International Cycling Safety Conference (ICSC) 2024 (Imabari, Japan). The present article is the complete version with expanded methods, analyses, and discussion.

Data were collected via a multi-country online questionnaire. Recruitment channels differed by country (for example, national cycling federations, institutional lists, social media, online panels). Table 2 reports, for each country, the female/male share, original language, institutional list usage, and whether incentives were offered. Quality controls included screening for incomplete or inconsistent responses, checks against duplicate entries, and a minimum completion time.

Recruitment strategies included social media advertisements, questionnaire distribution in educational settings, the use of institutional and preexisting mailing lists of the collaborating research-centers, online-panels of market research companies, and partnerships with national cycling federations. Overall, participants did not receive any financial compensation for their involvement in the electronic survey.

2.3. Measures

The survey measured various variables and scales, including socio-demographic characteristics such as age, gender, and educational level, which were utilized for descriptive and statistical control purposes. However, the gender category 'non-binary/other', representing about 1% of the sample, was used exclusively for descriptive purposes due to its low share. Therefore only 'female vs. male' comparative analyses were conducted. All non-English versions were produced via forward translation by a native speaker with domain knowledge, independent back-translation into English, bilingual adjudication, and a brief pilot check to ensure semantic equivalence with the English canonical wording.

Bearing in mind the currently available types and features of cyclists' assisting technologies, the questionnaire measured two ACAS-related sets of factors: the types (five categories) and the five principal features of current onboard assistance systems that contribute to improving the cycling experience. Both sets were assessed using a Likert-type (1 to 5) scale, where larger values represent a greater valuation of the assessed ACAS types or features. Item examples (English wording) are provided here for transparency. *Type rating:* "How do you rate the overall value of the following ACAS type for your everyday cycling"? (1 = Very low, 2 = Low, 3 = Moderate, 4 = High, 5 = Very high). *Feature rating:* "How do you rate the feature 'Safety contribution' (in each ACAS) for your everyday cycling"? (same 1–5 Likert). Evaluations were global

Table 2
Summary of European countries involved in the data collection process.

Country	Frequency	Percent	Gender M:F:O Ratio [a]	Language	Institutional lists	Incentives
Bosnia and Herzegovina	169	2.7%	1:0.54:0.0	Bosnian	Yes	No
Croatia	148	2.4%	1:0.99:0.01	Croatian	Yes	No
Finland	345	5.6%	1:0.74:0.07	Finnish	Yes	No
France	139	2.3%	1:4.48:0.08	French	Yes	No
Germany	507	8.2%	1:1.47:0.03	German	Yes	No
Greece	833	13.5%	1:0.62:0.01	Greek	Yes	No
Italy	157	2.5%	1:0.41:0.01	Italian	Yes	No
Latvia	299	4.9%	1:0.72:0.01	Latvian	Yes	No
Norway	311	5%	1:1.88:0.0	Norwegian	Yes	No
Poland	76	1.2%	1:0.85:0.0	Polish	Yes	No
Portugal	43	0.7%	1:0.3:0.0	Portuguese	Yes	No
Romania	297	4.8%	1:0.32:0.01	Romanian	Yes	No
Russia	404	6.6%	1:0.58:0.0	Russian	Yes	No
Serbia	294	4.8%	1:0.75:0.01	Serbian	Yes	No
Slovakia	225	3.7%	1:0.74:0.02	Slovak	Yes	No
Spain	560	9.1%	1:1.49:0.01	Spanish	Yes	No
Sweden	392	6.4%	1:1.51:0.06	Swedish	Yes	No
Switzerland	535	8.7%	1:1.48:0.0	Swiss German	Yes	No
Ukraine	430	7%	1:0.8:0.02	Ukrainian	Yes	No

Notes for the Table: [a] Gender Ratio (Male:Female:Other).

and not scenario-based. We asked respondents to provide overall ratings across ACAS types and features rather than situational judgments, based on their visual exemplification. The full wording and all response options shown to participants are listed in Appendix I.

2.3.1. Types of ACAS

Firstly, a set of five different types of ACAS was evaluated, categorized based on their core functionalities, as outlined in Table 3. This classification was derived from a comprehensive literature review on existing ACAS, and a synthesis of core systems developed for automobiles, with consideration of their potential adaptation and applicability to bicycles.

2.3.2. ACAS features

To characterize and comparatively assess cyclists' perceptions on specific technical features commonly implied by driving assistance systems, ACAS features were assessed using five criteria (see Fig. 1). These were based on an extended version of the technology acceptance model [18,40], including several dimensions of performance expectancy (safety contribution, reliability), ease of use and extended the model with the features of everyday need and novelty.

At a methodological level, the analysis focuses on comparative prioritization across ACAS types and features, using TAM/UTAUT as a grounding frame to motivate the selection of feature dimensions (performance expectancy, ease of use, everyday need, novelty), having shown theoretical consistency in previous studies conducted with two-wheeled users regarding technology adoption affairs (see [43,46]). The present design is large-scale and comparative, relying on single-item feature ratings and lacking multi-item intention or use measures. We therefore do not estimate a structural TAM here (that analysis requires a different instrument), even though we outline this as a pathway for future work.

2.4. Data analysis

After preparing the dataset, including removing incomplete and unreliable responses, basic descriptive analyses were conducted to score the scales used and key statistical measures, including means, standard deviations, and standard errors for the study scales. In addition to full-sample descriptives, gender-specific descriptive statistics, including 95% confidence intervals, were computed to enhance measurement precision, minimize potential errors, and facilitate meaningful comparisons between female and male cyclists. Given their low representation in the sample (about 1%), and as this makes it impossible to conduct statistical contrasts under parameters of reliability and rigor, other gender categories were dismissed for all comparative purposes.

To account for sample characteristics, such as gender distribution, the data were probability-weighted. This is an analytical step based on adjusting the relative importance of each case in statistical analyses, useful to correct for over- or under-representation of certain characteristics. Specifically, we used post-stratification (raking) by gender and age bands (<25, 25–44, 45–65, >65) to align sample margins to balanced targets at the pooled European level. We trimmed extreme weights to limit variance inflation (weight bounds set between 0.50 and 2.00). Key results were robust under both unweighted and weighted analyses.

Regarding comparative analyses, an Analysis of Covariance (ANCOVA) was conducted to examine gender differences (fixed factor) in the study variables, using participants' age and weekly cycling hours as covariates, which addresses residual imbalance at the covariate level. ANCOVA was selected for its ability to assess multiple dependent variables (e.g., ACAS feature evaluations) simultaneously while controlling for confounding factors (e.g., cyclists' age), allowing for a more precise examination of group differences across key self-reported outcomes. Additionally, a tabular representation of the results was included to provide a clear visualization of gender-specific differences and trends, alongside the aggregated results for the full sample.

Moreover, we conducted exploratory ANCOVAs to examine whether ACAS valuations differed by cycling motives. For these analyses, commuting/work, leisure, and sport/fitness were entered as binary factors (0/1), and age, gender, and weekly cycling hours were included as covariates. For each dependent variable, we also report covariate statistics (F, p, partial η^2) for age and weekly cycling hours, alongside group effects. All the statistical analyses were conducted using IBM SPSS Statistics, version 29.0 (Armonk, NY, United States).

Table 3
ACAS types measured in the study.

Type of ACAS	Description	Common ACAS applications
Environmental monitoring	Devices that monitor the surrounding environment of the bicycle, such as detecting nearby vehicles, pedestrians, or obstacles, to enhance situational awareness and safety.	Proximity radars, rear-view displays
Rider visibility	Aimed at improving the visibility of the cyclist to other road users (especially drivers).	Automated lighting systems, turn signaling devices
Real-time information	Provide cyclists with immediate, up-to-date information about their trip settings (i.e., speed, inclination, wind, body measurements) or potential hazards, often through visual or auditory feedback.	Navigation displays, on-board control center
Crash prevention-assistance	Help to prevent falls or collisions by alerting cyclists to potential dangers, automatically applying brakes, or assisting in evasive maneuvers	Automated/enhanced braking systems, balance/turning assistance systems
Post-crash appliances	Focused on providing assistance or support to cyclists in the aftermath of a crash or other type of emergency.	Emergency notification systems, pre-crash data storage, or automated response mechanisms

2.5. Ethics

The procedures for this study were reviewed and approved by the Research Ethics Committee at the Research Institute on Traffic and Road Safety (IRB approval number HE0001291022), ensuring full compliance with the principles outlined in the Declaration of Helsinki and the General Data Protection Regulation (GDPR). The research protocol was deemed to pose very low risk to participants, as only basic demographic information, cycling habits, and questionnaire-based self-reported data were collected, with no sensitive personal data involved.

Additionally, to preserve anonymity, all unnecessary details, such as participants' names, addresses, or contact numbers, were not recorded. Also, as standardized for its European framework, this study specifically focused on adult cyclists, used an informed consent form to explain participants 'rights and duties' – especially the voluntary and merely scientific character of the participation, and ensured participants' confidentiality throughout the data collection process.

3. Results

3.1. Descriptive outcomes

Descriptive analyses suggest the existence of differential trends in the evaluation of ACAS based on both their typology/function and core features. Specifically, among the five ACAS types assessed, systems aimed at enhancing cyclist visibility received the highest average valuation ($\mu = 3.67$; $\sigma = 0.87$). These systems, which include features such as

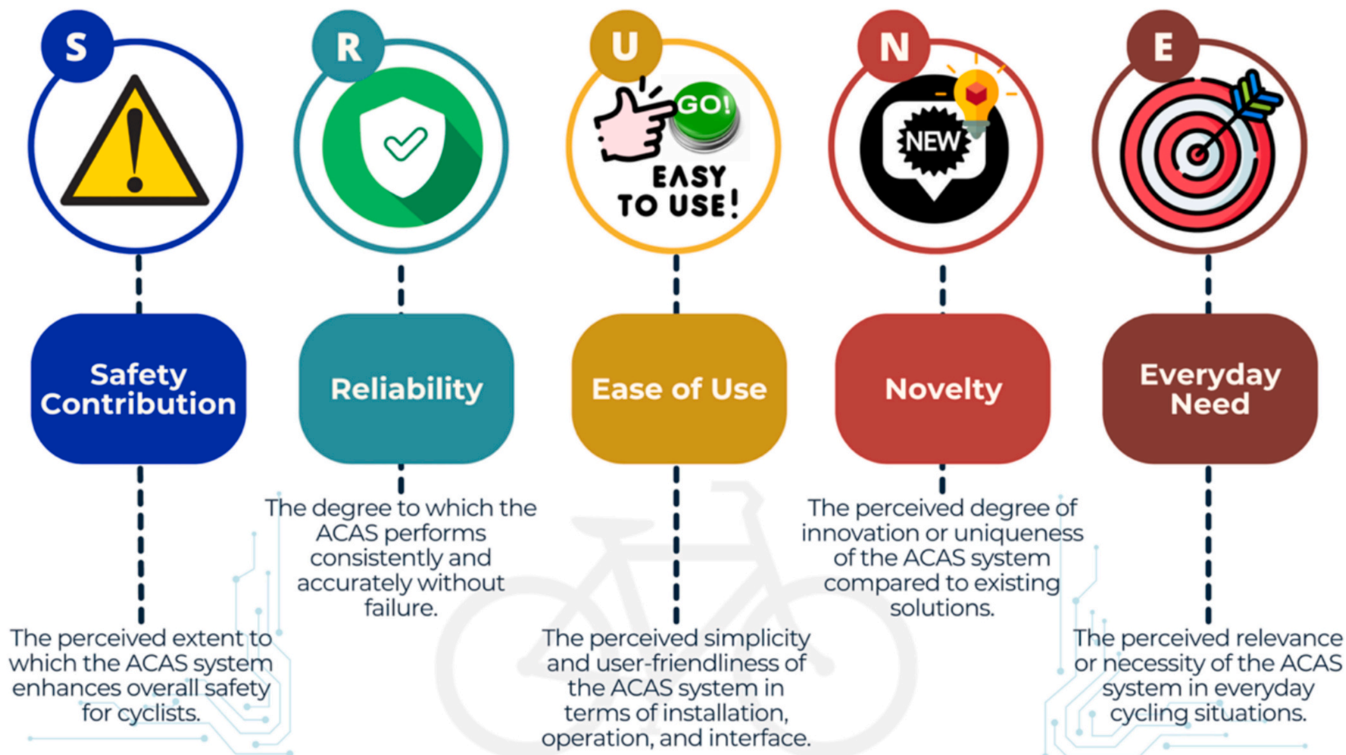

Fig. 1. From safety to everyday need: ACAS features addressed in the research.

automated lighting and turn signaling, were recognized for their immediate and practical contribution to safety in traffic-dense environments. Similarly, environmental monitoring systems, designed to improve situational awareness, received relatively strong support among the participants ($\mu = 3.39$; $\sigma = 0.88$), suggesting a considerable perceived utility in preventing potential collisions or hazards, as shown in Table 4.

Other ACAS types, such as crash prevention-assistance ($\mu = 3.12$; $\sigma = 1.01$) and post-crash appliances ($\mu = 3.13$; $\sigma = 1.00$), were rated moderately, suggesting that while their importance is acknowledged, their practical adoption might depend on further technological development or user familiarity. Real-time information systems, which provide riders with immediate data on trip settings or potential hazards, received the lowest valuation ($\mu = 3.06$; $\sigma = 0.98$), potentially due to their perceived complexity or lesser relevance for everyday cycling scenarios.

In terms of ACAS features, safety contribution was the most highly rated feature across all those presented to participants ($\mu = 3.51$; $\sigma = 0.86$), reinforcing the importance of safety as a core driver of ACAS adoption. Reliability ($\mu = 3.39$; $\sigma = 0.84$) and ease of use ($\mu = 3.50$; $\sigma = 0.84$) were also positively appraised, reflecting the emphasis placed on user-friendly and dependable systems. Meanwhile, novelty ($\mu = 3.43$; $\sigma = 0.94$) and everyday need ($\mu = 3.08$; $\sigma = 0.95$) received slightly lower ratings. In descriptive terms, this may indicate that cyclists might prioritize practical benefits over innovative or less immediately applicable features.

3.2. Mean comparisons: gender differences

After ensuring the adequacy of statistical assumptions and controlling for key covariates (age and cycling intensity), ANCOVA tests were conducted to compare the key variables across the weighted groups of

Table 4
European cyclists' evaluation of ACAS types and features (full sample).

Study Variable	Scale	Mean	σ	SE	95% CI[a]		Comparative Tests		
					Lower	Upper	T[b]	Cohen[c]	Sig.[d]
ACAS types									
Environmental monitoring		3.39	0.88	0.01	3.37	3.41	298.16	3.84	***
Rider visibility		3.67	0.87	0.01	3.65	3.69	327.52	4.22	***
Real-time information	[1–5]	3.06	0.98	0.01	3.04	3.09	242.89	3.13	***
Crash prevention-assistance		3.12	1.01	0.01	3.09	3.15	240.08	3.09	***
Post-crash appliances		3.13	1.00	0.01	3.10	3.15	241.03	3.11	***
ACAS features									
Safety contribution		3.51	0.86	0.01	3.49	3.54	315.74	4.06	***
Reliability		3.39	0.84	0.01	3.37	3.41	313.69	4.04	***
Ease of use	[1–5]	3.50	0.84	0.01	3.48	3.52	322.09	4.15	***
Novelty		3.43	0.94	0.01	3.41	3.45	282.67	3.64	***
Everyday need		3.08	0.95	0.01	3.06	3.11	253.61	3.20	***

Notes for the table: σ = Standard Deviation; SE = Standard Error; Cohen = *Cohen's d* – variable effect size estimator (standardized); [a] Confidence Interval at the level 95%; [b] One-sample test value; [c] Estimated based on the fixed-effect model; [d] Significance levels: *** ≤0.001; ** ≤0.010.

female and male cyclists. The descriptive statistics, including means, standard deviations, standard errors, and confidence intervals (at the level 95%) for each group of cyclists, are shown in the left columns of Table 5, split by gender-specific and full sample scores, and graphically shown in Fig. 2 using standardized scores for better illustrating these differential scores.

In order to avoid age-related bias, gender group comparisons were estimated with ANCOVAs controlling for age and weekly cycling hours.

Among the significant ANCOVA results, gender-based differences exist both in terms of ACAS types and features. Regarding ACAS types, systems designed to enhance rider visibility were significantly more valued by female ($\mu = 3.78$; $\sigma = 0.83$) than by male cyclists ($\mu = 3.58$; $\sigma = 0.88$; $p < .001$). This trend aligns with findings emphasizing the prioritization of visibility enhancements among female riders (see second set of rows of Table 4), possibly reflecting heightened safety concerns in traffic-dense environments. Similarly, environmental monitoring systems received slightly higher valuations among women ($\mu = 3.44$; $\sigma = 0.85$) compared to men ($\mu = 3.35$; $\sigma = 0.90$; $p < .001$), descriptively indicating a consistent preference for features that improve situational awareness among female cyclists.

On the other hand, when evaluating ACAS features, safety contribution emerged as the most highly rated attribute among both genders. However, female cyclists rated this feature significantly higher ($\mu = 3.59$; $\sigma = 0.47$) compared to male cyclists ($\mu = 3.45$; $\sigma = 0.54$; $p < .001$). Additional differences were observed for features such as ease of use and novelty, with women attributing higher importance to these aspects ($p < .050$).

Interestingly, no significant gender-based differences were found for crash prevention-assistance systems or post-crash appliances. Overall, and considering that age was included as a control variable, these findings suggest that gender may influence the perceived value of certain ACAS functionalities, even though other systems such as real-time information, crash prevention-assistance, and post-crash appliances were similarly valued by cyclists regardless of these demographic factors.

3.3. Mean comparisons: cycling motives

In addition to gender, we explored whether self-reported reasons for cycling were associated with differences in the valuation of ACAS types and features. As reported in Table 1, most cyclists indicated more than one reason for riding, with leisure being the most frequently selected (78.4%), followed by sport or fitness (51.8%) and daily commuting or work-related trips (37.8%). Given this overlap, motives were treated as binary indicators (0 = not reported, 1 = reported) rather than forcing a single "primary" category.

For each of the three main motives, we computed overall indices of ACAS types and ACAS features and estimated ANCOVAs with the motive as fixed factor and age, weekly cycling hours, and gender as covariates. As summarized in Table 6, overall valuations are relatively similar across the three motive groups. Mean scores for ACAS types range from 3.12 among cyclists who report commuting or work-related trips to 3.29 and 3.31 among those who report leisure and sport or fitness, respectively. A comparable pattern appears for ACAS features, where mean values vary between 3.23 for commuters and 3.40–3.42 for leisure and sport or fitness riders.

ANCOVAs including age, gender, and weekly cycling hours as covariates showed statistically significant but small effects for cycling motives on both indices, with partial η^2 in the low range (Table 6). Covariate effects, when significant, were also small and did not alter the relative ordering of motives. Overall, cyclists who report leisure or sport and fitness as reasons for riding show slightly higher valuations than those who ride for commuting or work, but these differences are modest in absolute terms.

Effect sizes for the motive factor are small, with partial η^2 values between 0.002 and 0.023, indicating that, once age, gender, and cycling intensity are controlled for, cycling motives account for a limited share of variance in overall ACAS valuation. Descriptively, cyclists who ride for leisure or sport and fitness tend to show slightly higher ACAS valuations than those who ride for commuting or work, but these differences are modest in absolute terms. Importantly, the general ordering of ACAS types and features remains stable across motive groups, with visibility enhancement and environmental monitoring leading among types and safety contribution emerging as the most highly rated feature.

4. Discussion

The aim of this study was to evaluate European cyclists' perceptions of five types and key features of Advanced Cyclist Assistance Systems (ACAS), and to identify potential demographic differences in the valuation attributed to them. In interpreting these patterns, the design emphasizes comparative prioritization across ACAS types and feature families, privileging a scalable map of perceived value.

Set against the acceptance literature, this comparative lens reads cyclists' evaluations through well-known appraisals of performance and effort (especially TAM, UTAUT), while keeping the analysis scalable and directly interpretable for policy and design. In other words, the study provides a ranked map of perceived value rather than a structural test, which is the level of evidence most useful at early stages of ACAS development and roll-outs [40–42,44]. At a practical level, focusing on comparative prioritization provides a policy-relevant ordering of what ACAS features and contributions cyclists may value most, which can guide early development choices, communication, and staged deployments.

Overall, the results support the view that ACAS technologies receive different appraisals depending on both their core types and features. To present the key findings and situate them within the existing literature, the discussion is organized around the two preliminary study hypotheses.

4.1. Do all ACAS 'count the same' for cyclists?

The first hypothesis of this study proposed that certain features would be valued more highly than others. Drawing on insights from previous studies on ADAS and ACAS [9,15,16,18], it was anticipated that features related to safety contribution and reliability would receive greater valuation compared to those emphasizing novelty, ease of use, or forecasted frequency of use by potentially adopting cyclists.

In a first analytic step, i.e., using the full sample before controlling for cyclists' demographic features, our findings show significant differences in how cyclists value various types and features of Advanced Cyclist Assistance Systems (ACAS). Specifically, ACAS designed to enhance visibility were the most highly rated, followed closely by environmental monitoring technologies.

At a literature-based standpoint, and although it should be kept in mind that these are still few in number, prior studies align with our results, which consistently emphasize the importance of, beyond inclusive infrastructural improvements [47], situational awareness for cyclist safety in challenging environments [48,49]. By contrast, real-time information systems, which offer advanced functionalities such as navigation or hazard notifications, received the lowest valuation. One possibly suitable interpretation could be that it occurs due to their perceived complexity or reduced practical relevance for everyday cycling [8,18].

Moreover, the prioritization of visibility and safety-enhancing systems highlights the fundamental importance of core safety functions to cyclists. For instance, features such as automated lighting and turn signaling are not only practical but also directly address some of the most pressing risks faced by cyclists, including low visibility during nighttime or adverse weather conditions [6,21]. Similarly, environmental monitoring systems, such as proximity radars, provide relevant situational awareness by alerting cyclists to nearby vehicles or obstacles,

Table 5
Descriptive gender-based outcomes and comparative (Analysis of Covariance) test data for the study variables, including covariates' effects.

Factor	Group	Mean	SD	SE	95% CI[a]		Comparative Tests		Gender Effects			Age Effects			Intensity Effects		
					Lower	Upper	Test value[c]	Sig.[d]	*F*	Sig.	η^2p	*F*	Sig.	η^2p	*F*	Sig.	η^2p
ACAS Types																	
	Female	3.44	0.85	0.02	3.41	3.48											
Environmental monitoring	Male	3.35	0.90	0.02	3.32	3.39	15.866	***	26.15	***	0.009	8.73	**	0.002	4.78	*	0.001
	Total	3.39	0.88	0.01	3.37	3.42											
	Female	3.78	0.83	0.02	3.75	3.81											
Rider visibility	Male	3.58	0.88	0.02	3.55	3.61	82.518	***	59.83	***	0.021	0.492	0.483	0.000	12.83	**	0.002
	Total	3.67	0.86	0.01	3.66	3.70											
	Female	3.08	0.95	0.02	3.04	3.11											
Real-time information	Male	3.07	0.99	0.02	3.04	3.11	0.008	0.927	16.65	***	0.006	67.77	***	0.012	10.08	**	0.002
	Total	3.07	0.97	0.01	3.05	3.10											
	Female	3.15	0.98	0.02	3.11	3.19											
Crash prevention-assistance	Male	3.11	1.02	0.02	3.07	3.15	2.174	0.140	6.45	**	0.002	37.59	***	0.007	32.92	***	0.006
	Total	3.13	1.01	0.01	3.10	3.15											
	Female	3.15	0.98	0.02	3.11	3.19											
Post-crash appliances	Male	3.12	1.01	0.02	3.09	3.16	1.056	0.304	11.82	***	0.004	53.10	***	0.009	0.094	0.759	0.000
	Total	3.13	1.00	0.01	3.11	3.16											
ACAS Features																	
	Female	3.59	0.468	0.02	3.57	3.63											
Safety contribution	Male	3.45	0.543	0.02	3.43	3.49	37.991	***	36.14	***	0.013	31.04	***	0.005	8.89	**	0.002
	Total	3.52	0.521	0.01	3.50	3.55											
	Female	3.43	0.547	0.02	3.41	3.47											
Reliability	Male	3.36	0.594	0.02	3.34	3.40	10.710	**	14.01	***	0.007	15.96	***	0.003	1.07	0.301	0.000
	Total	3.40	0.581	0.01	3.38	3.42											
	Female	3.53	0.990	0.02	3.51	3.57											
Ease of use	Male	3.48	0.855	0.02	3.46	3.52	4.950	*	17.34	***	0.006	85.01	***	0.015	4.03	*	0.001
	Total	3.51	0.901	0.01	3.49	3.53											
	Female	3.51	0.787	0.02	3.48	3.54											
Novelty	Male	3.37	0.710	0.02	3.34	3.41	31.956	***	32.23	***	0.011	0.013	0.910	0.000	13.24	***	0.002
	Total	3.43	0.736	0.01	3.42	3.46											
	Female	3.09	1.196	0.02	3.06	3.13											
Everyday need	Male	3.08	0.973	0.02	3.06	3.12	0.106	0.744	11.86	***	0.004	30.05	***	0.005	0.185	0.667	0.000
	Total	3.09	1.053	0.01	3.07	3.12											

Notes for the Table: SD = Standard Deviation; SE = Standard Error; [a] Confidence Interval at the level 95%; [b] Estimated based on the fixed-effect model; [c] Test value - Controlling for age and cycling intensity; [d] Significance levels: *** ≤0.001; ** ≤0.010; η^2 = Eta-squared (Fixed-effect).

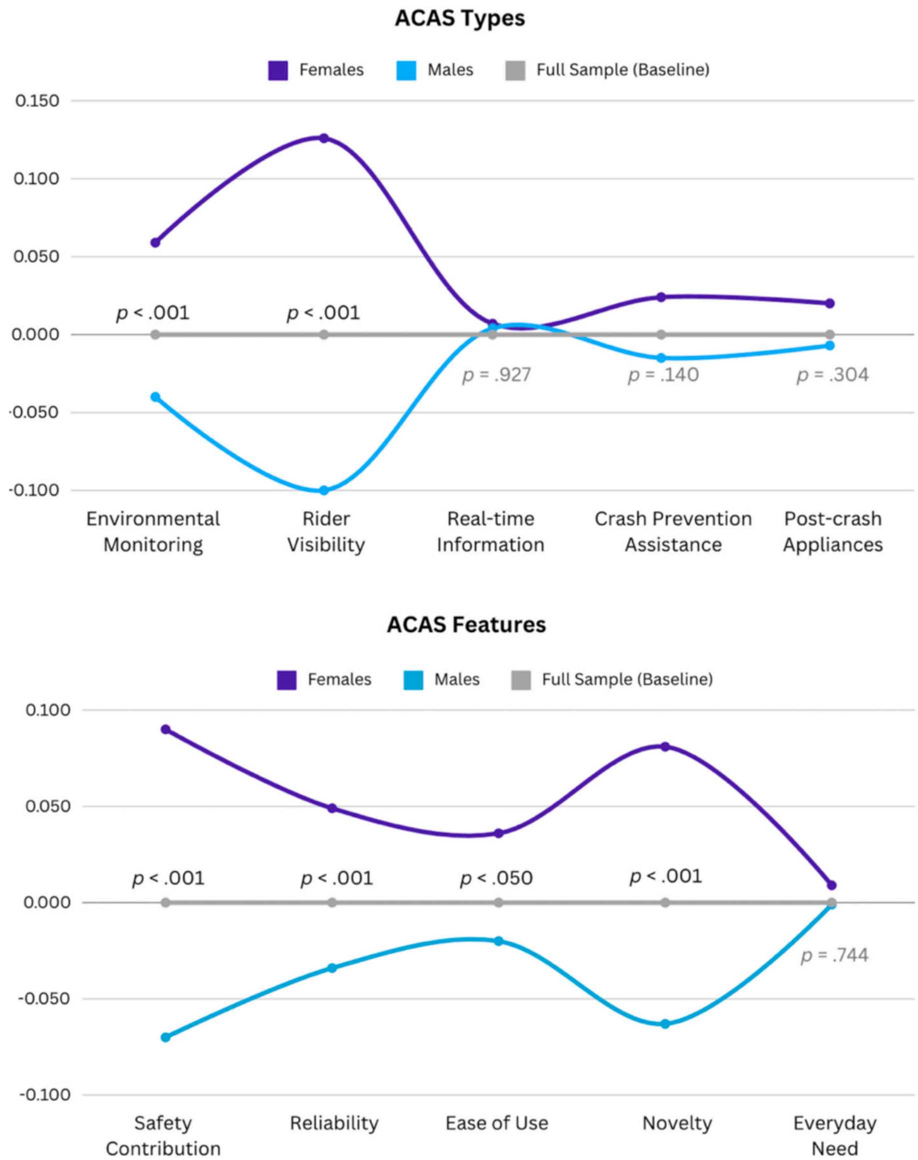

Fig. 2. Gender differences in the evaluation of ACAS types and features. *Notes:* [1] Axis Y (left column) is graphically scaled in terms of standardized (Z) scores to favor fair comparability; Axis X (0.0) represents the full sample average; [2] Controlling for cyclists' age and intensity.

Table 6
Mean valuation of ACAS types and features by self-reported cycling motives (code = 1).

Motive	Percent (code=1)	Valuation of ACAS types			Valuation of ACAS features		
		Mean	SD	η^2	Mean	SD	η^2
Commuting	37.8%	3.12	0.79	0.023	3.23	0.80	0.022
Leisure	78.4%	3.29	0.79	0.002	3.40	0.80	0.002
Sport / fitness	51.8%	3.31	0.80	0.003	3.42	0.80	0.002

Notes: Values refer to respondents who reported each motive, coded as binary indicators (0 = motive not reported, 1 = motive reported). Mean scores refer to respondents who reported each motive (code = 1). Partial η^2 values correspond to the motive effect in ANCOVAs controlling for age, weekly cycling hours, and gender.

thus suggesting that cyclists may be more inclined to value technologies with immediate and clear safety benefits, supporting the conclusions of previous research indicating that user acceptance is closely tied to perceived usefulness and reliability [17,20].

On the other hand, there were some systems with considerably low valuations. For instance, the lower scoring of crash prevention-assistance and post-crash appliances, despite their potential utility, reflects an interesting discrepancy. One possible explanation is that these systems may be perceived as more relevant to high-risk or professional cycling scenarios, making them less appealing to everyday cyclists. Furthermore, the current state-of-affairs, stressed in the introduction of this paper, must be acknowledged; the limited market penetration and prototypical nature of such systems likely contribute to reduced familiarity and perceived utility among users [5,32,37]. These findings echo broader trends in ADAS adoption for motor vehicles, where features offering immediate and recognizable benefits tend to achieve higher acceptance [13,16].

From a theoretical standpoint, this pattern is consistent with acceptance frameworks in which performance gains and effort costs shape early evaluations. In both TAM and UTAUT2 models, features that deliver clear, near-term utility tend to receive higher appraisals than functions that are rarer or harder to experience in everyday use. Read this way, the lower ratings for crash prevention and post-crash tools align with the idea that perceived usefulness and ease of use anchor initial acceptance, especially when familiarity is limited [20,43].

This divergence in valuation across ACAS types also highlights the need for user-centered design approaches in their development. Aligning systems with cyclists' priorities (i.e., primarily safety and ease of use) may not only enhance adoption rates but also maximize their potential to improve cycling safety. Future studies should explore how cyclists' familiarity and usage contexts influence their preferences, as well as the potential role of education campaigns in increasing awareness of underappreciated ACAS features (something timely remarked in [8]). Still, the safety contributions of ACAS remain valued over all other possible contributions of these systems. At a practical level, the present findings provide a comparative map of perceived value across ACAS types and features (at scale and across user segments). This positioning is intentional. Cost–benefit and willingness-to-pay analyses require specific designs and data (for example, stated-preference experiments), which we outline as a next step.

4.2. Does gender 'matter' for ACAS valuation? What differences do exist?

Regarding our second hypothesis, it was expected that variations in cyclists' profiles would influence the valuation of ACAS types and features. Specifically, significant differences were anticipated based on key demographic factors, such as age and gender, which could shape preferences and perceptions of these technologies. For this purpose, the comparative analyses were structured according to European cyclists' gender and controlled for age values in all cases.

Regarding the results of these comparisons, two essential conclusions could be drawn: first, that key differences exist, although not in all ACAS categories; and second, that the existing ones highlight notable differences in the valuation of ACAS, across cyclists' genders. Specifically, it stands out that female cyclists consistently rated visibility-enhancing systems, such as automated lighting and signaling, higher than male cyclists. This difference, while very preliminary, suggests a gender-based divergence in perceived importance, which may stem from variations in exposure to safety-related risks or differing cycling behaviors.

At a theoretical level, this finding aligns with research suggesting that women may prioritize features addressing visibility and perceived vulnerability in road environments, where safety concerns are heightened [11,34]. In contrast, male cyclists tended to attribute comparable importance to other ACAS types, such as real-time information and crash prevention-assistance, reflecting potentially differing risk perceptions and usage preferences.

Intriguingly, beyond their specific types –among which significant differences were observed in environmental monitoring and rider visibility ACAS–, these gender-based discrepancies extend to the perceived contributions or 'features' of these systems. Specifically, female cyclists placed a higher value on safety contributions and ease of use, whereas male cyclists showed a more balanced evaluation across various attributes. This outcome aligns with prior studies in transportation technology, where gender differences frequently emerge in the valuation of safety-enhancing features, with women emphasizing intuitive and user-friendly designs [7,17,45]. Such differences may reflect broader psychological and behavioral patterns in risk perception and decision-making between genders, as highlighted in the safety, technology, and ergonomics literature [16,33,50].

Age-related differences, while less pronounced, also warrant attention. Older cyclists were more likely to value reliability and safety contributions, while younger riders showed greater interest in novel and technology-driven features. These findings resonate with existing literature on technology acceptance [51,52], which suggests that younger users are often more inclined toward innovation, while older users prioritize dependability and proven benefits [11,18,21]. Such variations, while only descriptively addressed in the current study, deserve attention, given the importance of considering the existence of different demographic groups that could keep different levels of perceived need, affinity for technological advances for cycling, and economic capacity, ensuring inclusivity in design and development.

Furthermore, the differences found also suggest that a one-size-fits-all approach to ACAS, something very prevalent in the collective imaginary, may fail to address the nuanced needs of different groups of riders. Gender- and age-specific preferences highlight the need for adaptive systems capable of catering to diverse user profiles [43,53]. This pattern also appeared stable across cycling motives. Even though leisure and sport or fitness riders tended to show slightly higher valuations than commuters, exploratory ANCOVAs with age, gender, and weekly cycling hours as covariates indicated that motive effects were small and did not change the ranking of ACAS types and features (see Table 6; section 3.3).

Overall, the present comparative map provides an actionable baseline for design and policy: it indicates where to start, for whom, and which feature bundles merit early investment. Read operationally, it supports priority setting and sequencing that can be adapted across countries and rider segments, with performance and everyday usefulness leading early iterations and ease of use guiding interface simplification and onboarding [8,41,43]. Future model-based work can build on this baseline by incorporating multi-item measures of intentions and use, allowing formal tests of acceptance pathways and monitoring how valuations evolve as ACAS availability and user experience grow over time [44,53].

4.3. Limitations of the study and further research

While this study provides valuable insights into European cyclists' perceptions of ACAS using a wide multinational sample, and the questionnaire was comprehensive and produced consistent results, several limitations should be acknowledged and considered when interpreting the findings.

First, the cross-sectional nature of this study limits the ability to establish causality or examine longitudinal trends in the valuation and adoption of ACAS technologies. Future studies could benefit from longitudinal designs to assess how perceptions and usage evolve over time, particularly as new technologies are developed and introduced to the market, as anticipated by recent studies [20]. Moreover, this study did not estimate willingness to pay or implementation costs. Adoption depends on both perceived value and cost structures, which call for dedicated designs (for example, stated-preference or WTP studies) and market data. We include a short guidance note in the Discussion on combining the present valuations with cost information or cost matrices to prioritize functions for development and policy.

Second, although the sample size was robust and diverse, the reliance on self-reported data may have introduced biases, such as social desirability or recall effects [54,55]. While efforts were made to enhance data quality (for example, we carefully dismissed incomplete or inconsistent responses), future research could incorporate more objective measures, including behavioral tracking or experimental designs, to validate self-reported ACAS-related attitudes and consumer behaviors. For instance, because no scenarios were presented, future work should test whether evaluations vary under distinct traffic contexts (for instance, night-time riding or high-traffic corridors). In addition, future research could explore how these differences evolve with increased ACAS adoption and whether tailored design strategies can enhance user satisfaction and safety outcomes.

Third, demographic categories, particularly those beyond male and female genders, were underrepresented, precluding in-depth comparative analyses for non-binary participants. Thus, we believe that expanding future studies to include more diverse demographic groups would provide a broader understanding of user-specific preferences and needs, improving inclusivity in ACAS design. Similarly, cultural and regional differences among cyclists from different European countries were not explicitly analyzed, despite their potential influence on ACAS perceptions. Also relevantly, while we used post-stratification and ANCOVAs controlling for age and weekly cycling intensity, residual confounding by unmeasured factors (for example, income, cycling tenure, local infrastructure) may remain. Results should be interpreted with this caveat in mind.

Moreover, as shown by various comparative studies previously developed by the authors (see [45] for an illustrative figure), conducting cross-country analyses across diverse cycling cultures and policy contexts may yield additional evidence on regional variation in ACAS evaluations and, potentially, on cycling-related behavioral correlates. A further related limitation is that, while the analysis focuses on comparative prioritization across ACAS types and features, a structural TAM/UTAUT analysis was not feasible with the present single-item feature measures and the absence of intention or use indicators. Therefore, future studies should employ multi-item scales and model-based approaches to test acceptance pathways.

Finally, the study primarily focused on attitudinal evaluations, leaving actual usage and real-world effectiveness of ACAS largely unexplored. In this regard, future research should prioritize field studies and pilot implementations to assess the practical impact of ACAS technologies on cycling safety and behavior [5,37]. At a practical level, this could include evaluating how cyclists interact with ACAS in real-world conditions and examining the role of contextual factors, such as traffic density or road infrastructure.

Despite these limitations, the findings of this study lay a strong foundation for advancing research on ACAS. Precisely, this is an implicit value of this study: it is possible that, by addressing these gaps, upcoming studies can contribute to the development of more user-centered, effective, and inclusive technologies that enhance the safety and well-being of cyclists.

5. Conclusions

Overall, the findings of this study indicate that European cyclists exhibit differential preferences for specific typologies and features of Advanced Cyclist Assistance Systems (ACAS).

Among the five function-based types of ACAS examined in the study, the most highly valued are those designed to enhance the visibility and recognizability of cyclists by other road users, followed by systems that enable cyclists to enhance real-time monitoring of their traffic environment.

Regarding the different features of Advanced Cyclist Assistance Systems addressed, the most valued of all is their contribution to safety. While aspects such as novelty and reliability are also valued, their value for preventing road crashes while riding represents the most highly valued characteristic of ACAS among our participants.

There are user-based (e.g., age and gender) differences that may influence the acceptance of ACAS and their functions. Specifically, women tend to value those that increase their visibility on the road more than men. Regarding types of Advanced Cyclist Assistance Systems, and after controlling for riders' age, female cyclists also value the safety and novelty of these systems to a significantly higher degree than their male counterparts.

CRediT authorship contribution statement

Sergio A. Useche: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Steve O'Hern:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation. **Francisco Alonso:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Dorothea Schaffner:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Javier Gene-Morales:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Milad Mehdizadeh:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Mette Møller:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Trond Nordfjærn:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Felix W. Siebert:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Nora Studer:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Oscar Oviedo-Trespalacios:** Writing – review & editing, Writing – original draft, Validation.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.iatssr.2026.05.002.

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