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Are alternative fuels considered a game changer? Benefit and barrier perceptions and the acceptance of alternative fuels for road transport

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Abstract

Background Replacing diesel and gasoline in combustion engines with fuels from renewable resources can reduce emissions in the transport sector. This study investigated public perceptions of alternative fuels to reveal potential adoption drivers and barriers for a successful introduction in road transport.

Results The findings point towards a high acceptance of alternative fuels in road transport. Benefits for the environment and drivers were acknowledged, whereas barrier perceptions were comparably low. The acceptance of alternative fuels was affected by perceived environmental benefits and environment-related attitudes. Higher environmental awareness and perceived responsibility for environmental problems were related to higher acceptance, higher benefit perceptions, and lower barrier ratings.

Conclusions Considering the key finding that environment-related attitudes and the perception of environmental benefits were factors positively impacting the acceptance of alternative fuels, communication concepts should be designed to inform transparently and comprehensibly about the environmental effects of alternative fuels. Where applicable and possible, fuel design should reduce user-perceived barriers—such as high costs and infrastructure incompatibility. Policy making should furthermore support planning security via long-term framework design in order to enable heightened fuel adoption and positive climatic impacts of alternative fuels.

Keywords Social acceptance, Benefit perception, Barrier perception, Risk perception, User diversity, Alternative fuels

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Background

Our society's reliance on fossil fuels continues to harm the climate and environment by contributing to global warming through continuous emission of carbon dioxide (CO₂). The transport sector was responsible for 37% of global emissions in 2021 [1]. For this reason, continuous work is being done on the development and introduction of approaches that separate emitted CO₂ from the atmosphere (e.g., via Direct Air Carbon Capture and Storage) as well as alternative propulsion options that can, for example, cover the fuel demand in the transport sector by means of more climate-friendly alternatives. Alternative fuels, e.g., in the form of bio- or e-fuels, are potential technological advancements that among other approaches may foster the defossilization of high-emission sectors [2].

Even if developments such as alternative fuels are associated with benefits in terms of climate protection for today's society and future generations, this does not mean that public acceptance can be expected from the beginning. On the contrary, acceptance for innovations is often accompanied by lively public discussions, and sometimes resistance, as is the case in Germany [3]. The previous implementation of energy technologies shows that public perception and acceptance is a crucial prerequisite to the successful integration of technologies in existing energy infrastructures and systems. The introduction of the ethanol-blend E10 in Germany is one example of how a lack of public support and willingness to use can slow down the integration of a more climate-friendly propulsion alternative [4]. Therefore, a thorough analysis of public acceptance and potential acceptance-influencing factors as early as possible during the roll-out process is advised.

Alternative fuels in road transport

In the literature, different definitions of the term "alternative fuels" exist [5]. Here, we define alternative fuels based on definitions from previous literature as all liquid and gaseous fuels [6] that can replace conventional gasoline and diesel in combustion engines [5] and that are produced from renewable raw materials such as biomass or CO₂, water, and green electricity [7, 8]. Thus, alternative fuels are distinguished from electric powertrains [6]. Basically, there are two production routes for renewable alternative fuels: the biofuel and the e-fuel pathway. Bio-fuels are made from biomass (e.g., from lignocellulose), whereas e-fuels are produced from CO₂ and hydrogen [6, 8]. The required hydrogen is obtained by water electrolysis using renewable energy or biomass gasification and the CO₂ is either captured from industrial sources (flue gas) or the atmosphere via Direct Air Capture [8]. Both production routes can also be combined in the production of biohybrid fuels [9].

The motivation behind developing these alternative fuels are the defossilization of transport by replacing fossil fuels through renewable resources and energy [5, 10], an optimization of engine efficiency [5], and/or the reduction of CO₂ and pollutant emissions [5, 7]. An important prerequisite for a defossilizing and emission-reducing effect is that renewable electricity is used in the production [6]. As alternative fuels have different properties, their advantages and disadvantages are specific to the fuel in question. In addition to the potential reduction in CO₂ and pollutant emissions, alternative fuels have several advantages over electric vehicles. For instance, they have an improved energy density [11] and are compatible with conventional engines and infrastructure [6]. However, some alternative fuels require a retrofit of the vehicle or can only be used in specific engines [12]. Furthermore, e-fuels provide a means to store surplus renewable energy, thereby balancing the fluctuating supply and demand of electricity [11, 13]. Disadvantages of alternative fuels are high costs [5] – although these are expected to decrease once their diffusion progresses [8] – and a lower energy efficiency compared to electric vehicles, which results in an increased energy demand [8, 10]. Furthermore, alternative fuels that are incompatible with current infrastructure require the roll-out of new supply infrastructure. Therefore, fuels that are highly compatible with existing engines and infrastructure should preferably be selected [5].

Public perception and social acceptance of alternative fuels

Apart from the development and potential through emission reduction or engine compatibility of alternative fuels, the public perception and acceptance are two aspects that are increasingly investigated in social science research. They can play a crucial role in the implementation of a novel technology or consumer good, such as alternative fuels. In the past, the implementation of novel technologies or products has in some cases been hindered by a lack of acceptance by the public, resulting in protests or the non-adoption of, for example, climate-friendly innovations [14, 15]. That is why technology perceptions and acceptance by all involved stakeholder groups should be assessed as early as the development phase. By iteratively revisiting (public) perception and acceptance, (mis-)conceptions can be identified and – in case of unfounded negative evaluation due to false assumptions – counteracted in the case of early consideration. This strategy is not to be misunderstood as forcing acceptance or preventing protest at the end of the development phase or even before the new product enters the market. Rather, it is intended to enable each involved stakeholder to make an informed decision about whether to accept the technology, based on verifiable information,

and to ensure that their perspectives, concerns, and requirements are sufficiently considered in technology development.

Public perception refers to cognitive evaluations that people can associate with a technology, such as perceived benefits, barriers or risks [16]. For technology acceptance, there is no commonly held definition in literature. In this study, we define *acceptance* as the act of active or passive approval of a technology or product, referring to its development, implementation, and usage [17]. It can be characterized as a process in which participating stakeholders (such as the general public) dynamically revisit and re-evaluate their attitudes toward a technology or a product [18]. Public perception and acceptance are closely linked, since the former impacts the latter: Previous acceptance research in the field of energy technologies links perceived benefits and risks to a person's attitude, which impacts their intention to accept a technology [19]. Wüstenhagen et al. [20] identify three dimensions of acceptance in the context of sustainable energy: socio-political, community, and market acceptance. Socio-political acceptance refers to general acceptance on a broader level by e.g., the public, policy makers, or other involved stakeholders. The concept of community acceptance addresses approval for local (energy) projects, highlighting relevant factors such as trust and procedural justice. Finally, market acceptance by consumers or investors refers to market adoption, i.e., to an adoption of a technology in the form of large-scale distribution [20]. While all three dimensions play a key role for the successful roll-out of a technology, this study focuses on market acceptance of alternative fuels by potential fuel consumers.

In recent years, research into the public perception and acceptance of alternative fuels has increased. For e-fuels, a *perceived benefit* that has been identified is the positive impact on the climate [21]. Similarly, for biofuels, an interview study with users in the freight transport sector found that biogas was perceived as environmentally and sustainably beneficial in terms of access and production, as well as circularity and emissions. In direct comparison with electric vehicles, driving range was perceived to be another advantage, as well as engine compatibility [22]. Additionally, Dallendörfer et al. [23] identified people's perception of economic benefits of biofuels to impact support for biofuels as a potential bioeconomy measure. As for the influence of benefit perceptions on the acceptance of alternative fuels, perceived usefulness and efficiency, as well as price, were identified as predictors of acceptance of CO₂-based fuels [24].

With regard to *perceived barriers*, Björner Brauer & Khan [22] observed that the number and siting of fuel infrastructure pose a barrier to use biofuel. Furthermore, they found that from a freight transport perspective, a

lack of regulatory and policy measures can lead to investment hesitancy due to uncertainty in planning. The lack of refueling infrastructure was also discovered to be the main perceived barrier in case of hydrogen fueled vehicles, alongside the perception of generating hydrogen via electrolysis of water as inefficient [25]. Price was identified as an additional potential barrier for certain user segments of alternative fuel vehicles. For individuals with a preference for alternative fuels, price was of lesser importance, while it was identified to be the most decisive factor in other user groups [26].

A study on *risk perception* of e-fuel found that it was assessed by laypeople to be less risky in comparison to conventional fuel [27]. However, there still are risk perceptions linked to alternative fuel (use), e.g., risks posed by biofuels for the environment and humans [28, 29]. Similarly, environmental and human health-related threats are also feared in connection with the production of e-fuels as well as potential leakage of transported CO₂ [30, 31]. Mohammed et al. [32] observed that perceived technological, operational, and financial risks may influence the decision of stakeholders, such as companies with a transportation fleet, to opt for alternative fueled transport. Regarding the relationship between risk perceptions and the acceptance or adoption of alternative fuels, Linzenich et al. [24] found that, in case of e-fuels, perceived risks and feared environmental effects are key predictors of acceptance.

Finally, regarding the topic of *acceptance of alternative fuels*, research found generally high levels of acceptance for alternative fuels [21]. Additionally, there are findings on the influences on acceptance by both user factors and perceptions of alternative fuels. For user factors, knowledge was identified as a predictor with the potential to increase acceptance – although knowledge is usually low among laypeople [33–35] – and there have been results that support the assumption that political attitudes affect people's acceptance [36]. Trust (e.g., in key stakeholders involved in implementation processes) was found to influence people's barrier and benefit perceptions and acceptance of alternative fuel options [37, 38].

Furthermore, Yaghoubi et al. [39] detected the influence of personal (moral) norms on people's intention to use biofuels. Perceived fairness additionally can impact a person's evaluation in the context of land-use in biomass production [40]. Aside from user factors, perceptions related to alternative fuels can substantially affect the acceptance and intention to use them. In a study on hydrogen fuel cell vehicles, Kar et al. [41] demonstrated that perceived benefits, awareness of the technology, and policy interventions positively influenced respondents' usage intentions, while risk perception negatively influenced the intention to use hydrogen fuel cell cars. Furthermore, risk perceptions play a mediating role in

the effects of benefit perception, technology awareness, and policy interventions. The influence of barrier and benefit perceptions was also confirmed by Simons et al. [21]. They found that perceptions of both the end-product (e-fuel) and the underlying technological approach impact product acceptance. In case of e-fuels, studies furthermore revealed fuel being the preferred production route option compared to, for example, the production of fertilizers or mattresses [42].

Defining the research goals

The current study has two goals (Fig. 1):

1. Quantifying the social acceptance and the perceived benefits and barriers of alternative fuels.

We aim at observing the acceptance of alternative fuel and are specifically concentrating on the context of road traffic. The reason for this is that this usage context can be directly experienced by laypeople, e.g., through refueling processes of passenger cars, in contrast to other applications of alternative fuels. Previous studies have focused on specific applications, e.g., in the aviation sector [21, 43]. By focusing on perceptions of the benefits, barriers, and risks of alternative fuels, as well as their acceptance and use in road traffic, we complement the scope of past research on aviation (a mode of transport that is usually less frequently used by laypeople, where passengers do not actively decide to use alternative fuels), by considering its opposite: a frequently used mode of transport where drivers actively choose to use a fuel. As these applications represent two poles of the application spectrum for alternative fuels, it is reasonable to conclude that they cover a wide range of acceptance factors that are also relevant to other transport sectors within this spectrum.

2. Understanding the relation between user factors, perceptions, and acceptance.

As has been established in the literature review, user factors and perceptions may impact a person's acceptance and willingness to use an alternative fuel. That is why we test their relationships for the context of road traffic.

Methods

In the following section, the research approach and methodical procedure are described.

Focus of the study and questionnaire

Figure 1 illustrates the research focus. Pursuing the two research aims defined in the previous section, we investigated benefit, barrier, and risk perceptions and their relationship with acceptance in a study with $n = 151$ German laypeople. On top of that, we analyzed user diversity to reveal how perceptions and acceptance change with person-related characteristics and whether personality explains additional variance in acceptance compared to perceptions.

Matching the research focus, the online questionnaire used in the survey contained three parts covering the three levels (user factors, perceptions, acceptance) in Fig. 1. The structure of the questionnaire is depicted in Fig. 2 (see Table A.1 in the Appendix for survey materials).

In the first part of the questionnaire, user factors (i.e., person-related characteristics) were assessed. This included demographics (age, gender, education). Also, attitudinal variables were measured to analyze whether alternative fuel perceptions and acceptance are related to a person's general attitude towards environmental problems, the use of technology to solve problems, and the value that driving a car has for an individual.

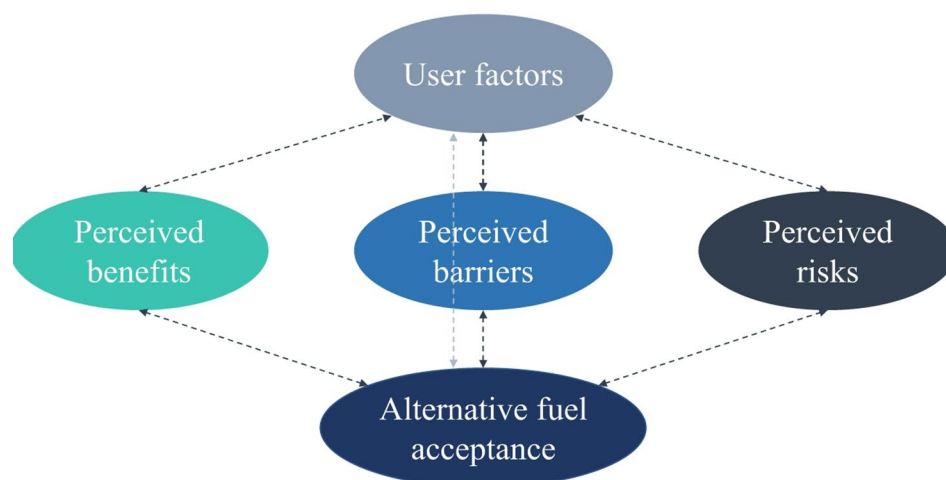


Fig. 1 Research focus of the study

Participants (n = 151)				
USER FACTORS	Demographics	• Age	• Gender	• Education
	Personality	• Attitude towards car use (ATC)	• Technical self-efficacy (TSE)	• Attitude towards environment (ATE)
		• Morality regarding car use (MCU)	• Alternative fuel knowledge (KAF)	
ALTERNATIVE FUELS	Perceptions	• Perceived benefits	• Perceived barriers	• Perceived risks
	Acceptance	• Attitude	• Usage intention	• Preference

Fig. 2 Structure of the questionnaire

Attitude towards car use (ATC, Cronbach's alpha = 0.81) was measured with six items by Steg [44] that related to the perception of driving either as a necessary means or as a pleasant activity and symbol of self-expression.

Technical self-efficacy (TSE, Cronbach's alpha = 0.89) refers to a person's confidence in their ability to get along with and use technology successfully to solve problems. TSE was assessed with four items from Beier [45].

As further measure for technology-related attitudes, the *personal innovativeness* (PI, Cronbach's alpha = 0.88), defined as interest and openness towards technical innovations, was captured by four items from Fazel [46].

The general *attitude towards environment and climate* (ATE, Cronbach's alpha = 0.86) was assessed as awareness for current environmental and climate-related problems and the relevance attributed to them. The scale for ATE contained four single items from Spence and Pidgeon [47], Dunlap et al. [48], Eurobarometer [49], and Preisdörfer [50].

In addition to ATE, also the *morality regarding car use* (MCU, Cronbach's alpha = 0.63) was measured using three items by Bask et al. [51] and De Groot & Steg [52]. This was done to understand whether laypeople perceive their mobility behavior as being responsible for environmental problems, and if they would be willing to change their lifestyle for the sake of the environment.

In addition to general attitudes, the *self-assessed knowledge about alternative fuels* (KAF, Cronbach's alpha = 0.89) was measured with two items from Engelmann et al. [27] to check whether the perceived familiarity with alternative fuels is related to acceptance. All attitudinal variables were answered on a six-point scale (min = 1, max = 6).

The second part of the questionnaire focused on *perceptions of alternative fuels*. Respondents were asked to indicate their agreement to perceived benefits, barriers, and risks of alternative fuels on a six-point scale (min = 1, max = 6). The assessed benefits, barriers, and risks were not selected due to their relevance from a technical perspective but from a social science perspective based on interview pre-studies with laypeople and experts and on previous acceptance research in similar technology contexts. For example, some of the assessed benefits and barriers were already identified as acceptance-relevant in the context of Carbon Capture and Utilization (CCU), which also refers to an alternative feedstock technology. Thus, items from Arning et al. [53] on perceived benefits and barriers of CCU were adapted to the context of alternative fuels.

For *risk perception*, not only specific risks associated with alternative fuels in the pre-studies (a higher flammability and a risk of explosion) were included, but also risk dimensions that have been revealed as integral to lay risk judgments for a set of different hazards in risk perception research (e.g., [54, 55]). This includes, for example, perceived uncontrollability and unfamiliarity of risks, as well as the target affected by a risk such as human health or the environment.

An overview of the assessed benefits, barriers, and risks can be found in Figs. 3 and 4. The corresponding items measuring perceptions of alternative fuels are included in Table A.2 in the Appendix.

The third and last part of the questionnaire measured *acceptance of alternative fuels*. General acceptance of alternative fuels in individual transport (Cronbach's alpha = 0.88), which contained both the general attitude towards the use of alternative fuels and one's willingness

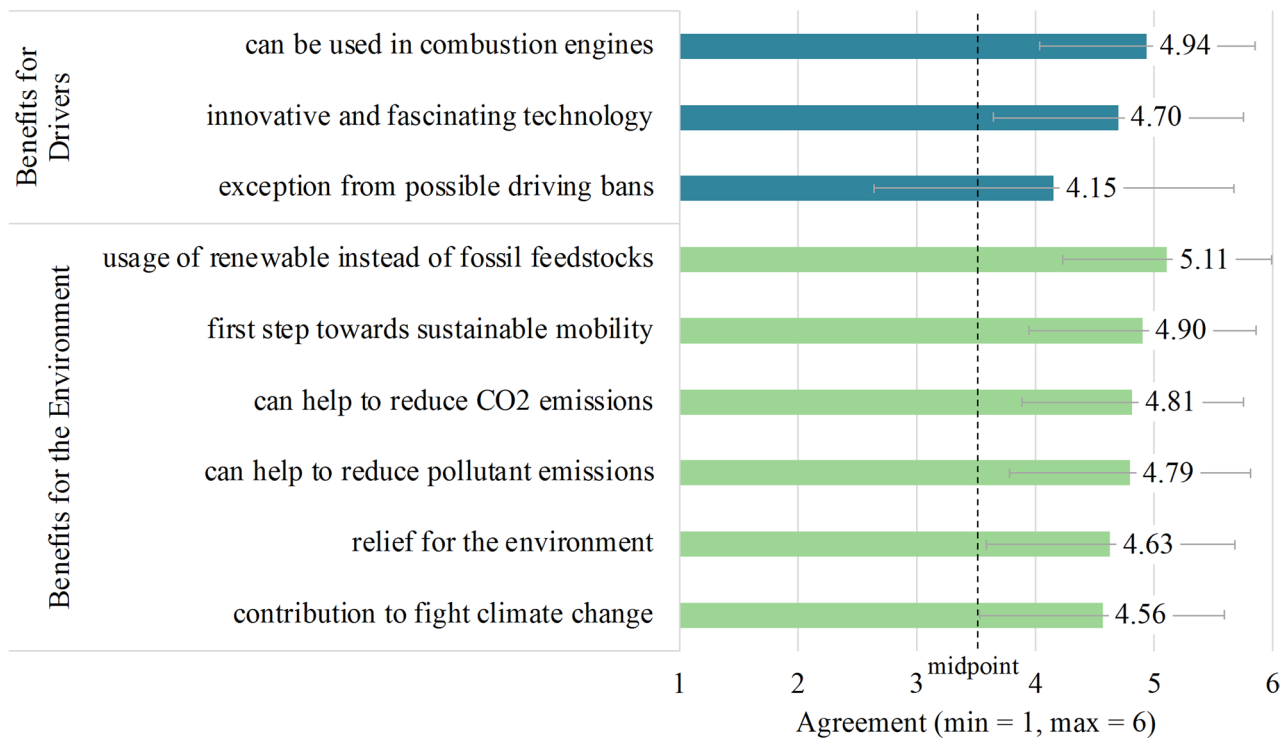


Fig. 3 Perceived benefits of alternative fuels ($n = 151$). Perceived benefits are grouped by topic and affected target

to drive with alternative fuels, was measured with five items from Engelmann et al. [27] and Linzenich et al. [56].

Data analysis

Table 1 summarizes the research aims and the analyses conducted for the two research aims.

Survey sample

In the study, we targeted laypeople who drive at least seldomly. Thus, individuals with expertise in the field of fuel research and combustion engines and individuals who never drove by car were excluded by filtering questions in the survey. In total, 249 respondents fitting the target group participated in the study. A quality control for detecting speeders, cheaters, and incomplete data sets resulted in 151 data sets for further analysis.

The participants (64.2% female, 35.8% male) were aged between 18 and 83 years ($M = 33.6$ years, $SD = 15.8$ years). The sample had a high formal education with 43.0% having achieved at least a university degree, 15.9% having completed vocational training, and 35.1% reporting a university entrance certificate as the highest educational achievement. Respondents came from both the countryside (41.1%) and urban areas (29.8% lived in the city center and 29.1% in a suburb or the outskirts of a city).

Most participants owned a car (68.9%). In addition, 23.8% reported using the car of family members or friends, 7.9% drove a company car, and 6.0% used car

sharing or a rented car. Attitude towards driving was rather negative ($M = 2.59$, $SD = 0.97$), meaning that driving a car was seen as a necessity rather than a source of fun. By contrast, attitude towards the environment, measuring participants' awareness for environmental and climate problems, was highly positive ($M = 5.01$, $SD = 0.96$). However, morality regarding car use, measuring the perceived responsibility for environmental problems and the readiness to change one's mobility behavior, was rather moderate ($M = 3.74$, $SD = 0.98$).

The sample reported a high confidence in their ability to use technology successfully (technical self-efficacy, $M = 4.04$, $SD = 1.24$). Still, the personal innovativeness (as measure for the interest in innovative technologies) was moderate ($M = 3.53$, $SD = 1.18$) and self-assessed knowledge about alternative fuels was rather low ($M = 2.82$, $SD = 1.15$).

Results

In this section, acceptance, perceived benefits, barriers, and risks of alternative fuels are quantified and the structure of factors underlying these perceptions is explored. Furthermore, the relationship between perceptions and acceptance is analyzed. Here, user diversity is included to reveal if and how perceptions and acceptance change for different groups of people.

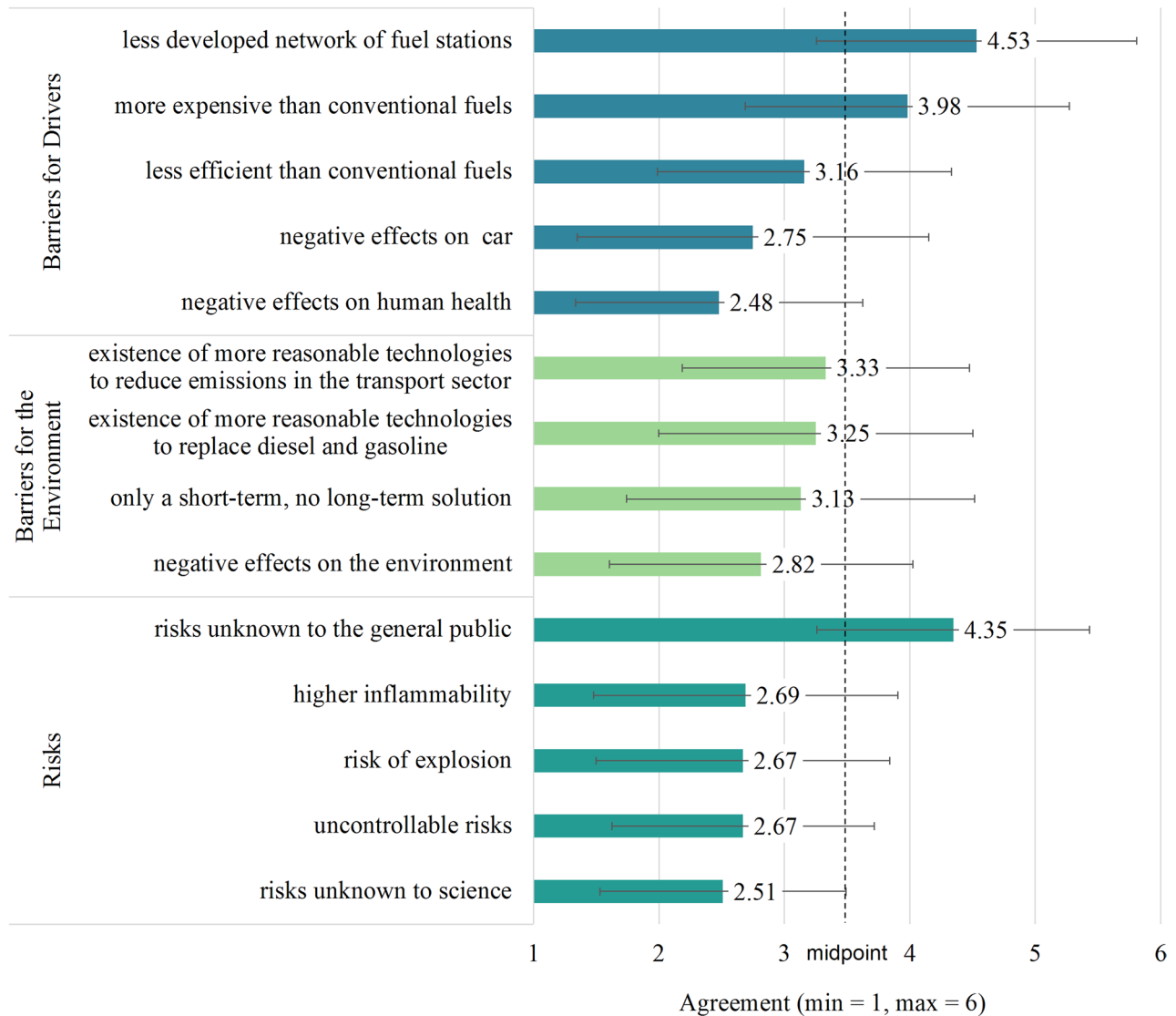


Fig. 4 Perceived barriers and risks of alternative fuels (n = 151). Perceived barriers and risks are grouped by topic and affected target

Table 1 Data analysis procedure for the two research aims

Research aim	Methodical procedure
1. Quantification of acceptance, perceived benefits, barriers, and risks of alternative fuels	<ul style="list-style-type: none"> • Calculation of mean values for acceptance of alternative fuels and benefit, barrier, and risk perceptions • Analysis of underlying factor structure of perceptions by principal component analysis • Analysis of significant differences between the obtained factors by t-tests
2. Analysis of the relationship between user factors, perceptions, and acceptance	<ul style="list-style-type: none"> • Performance of correlation analyses between user factors and perceptions and acceptance • Performance of a hierarchical regression (enter method) for ... <p>1. step: the impact of perceptions on acceptance 2. step: the impact of perceptions and user factors (only those that showed significant correlations with acceptance) on acceptance</p>

Quantifying social acceptance and public perceptions of alternative fuels

Despite the low familiarity with alternative fuels, the general initial acceptance of alternative fuels was high (M = 4.99, SD = 0.89). When asked about their willingness to use alternative fuels when driving, 94.0% of respondents said they were willing to do so, and 83.4% said they would prefer alternative fuels to conventional fuels (relative frequencies of answering options ‘rather agree,’ ‘agree,’ and ‘fully agree’).

The agreement for perceived benefits for drivers and the environment is illustrated in Fig. 3. All benefits were (rather) agreed to, indicating that laypeople expected alternative fuels to provide advantages for the environment but also for the people using these fuels.

Compared to benefits, barriers and risks of alternative fuels were evaluated more heterogeneously, as Fig. 4

shows. Out of all the disadvantages and risks considered, only three barriers evoked concern: low availability, high costs, and unknown risks to the general public. By contrast, neither negative effects on the environment and human health nor sustainability concerns or specific risks were expected by laypeople.

Principal component analysis to better understand the structure of perceived benefits, barriers, and risks

To check for an underlying factor structure of the considered perceptions, a principal component analysis (PCA) using varimax rotation with Kaiser normalization was conducted. Only items with a factor loading of ≥ 0.45 were considered due to the sample size of $n = 151$ [57]. The PCA revealed five factors (Table A.2 in the Appendix contains all items entered in the PCA and their factor loadings):

1. *Perceived benefits* (Cronbach's $\alpha = 0.89$): This factor comprises all perceived positive aspects of alternative fuels for humans and the environment.
2. *Perceived barriers for the environment and human health* (Cronbach's $\alpha = 0.83$): This factor refers to perceived negative effects of alternative fuels, such as a lack of sustainability and effectiveness in tackling environmental problems, as well as perceived negative consequences for human health.
3. *Perceived accident risks* (Cronbach's $\alpha = 0.79$): This factor refers to perceived specific risks from alternative fuels such as explosion risks and higher inflammability that could lead to accidents.
4. *Perceived usage barriers for drivers* (Cronbach's $\alpha = 0.65$): This factor encompasses perceived disadvantages for drivers who choose to use alternative fuels in their cars such as a lack of

availability and effectiveness of the fuel, higher fuel costs, and negative effects on the vehicle.

5. *Perceived unknown and uncontrollable risks* (Cronbach's $\alpha = 0.53$): This factor is related to a perceived lack of controllability of risks and a lack of knowledge about risks among the public and science.

In the following, the identified factors and their impact on the acceptance of alternative fuels are examined.

As the distinction of barrier perception into several underlying factors shows that laypeople distinguished between environment- and driver-related aspects, we decided to also structure the benefit perceptions into two variables (one for driver-related and one for environment-related benefits) for consistency and to assure a better comparability of the effects of benefits and barriers on acceptance. Therefore, the perceived benefits were divided into environmental benefits (Factor 1a, Cronbach's $\alpha = 0.90$) and driver-related benefits (Factor 1b, Cronbach's $\alpha = 0.67$) as displayed in Fig. 3.

Figure 5 displays the mean values of the perception factors. As can be seen, perceived benefits for the environment were significantly higher than perceived benefits for drivers ($p < 0.001$, see Table A.3 in the Appendix). Of the perceived barriers and risks, the barriers for drivers were rated highest, but were significantly less associated with alternative fuels than the two benefit aspects (both $p < 0.001$). The perceived barriers for drivers, however, were significantly higher than the other perceived barriers and risks ($p < 0.001$), which were rather low.

Understanding the relationship between user factors, perceptions, and acceptance

Considering user diversity: How are user factors linked to perceptions and acceptance? Correlation analyses were

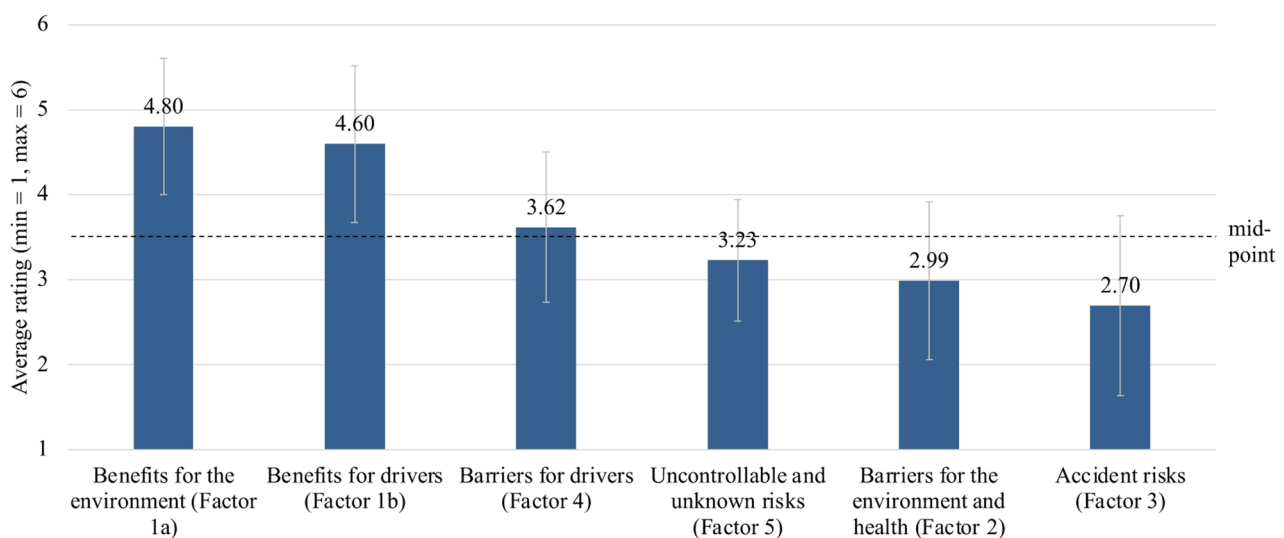


Fig. 5 Perception factors from PCA ($n = 151$)

Table 2 Results of correlation analysis between user factors and perceptions and acceptance

	Acceptance	Benefits for environment	Benefits for drivers	Barriers for environment and health	Barriers for drivers	Accident risks	Uncontrollable, unknown risks
Age		-0.225**					
Gender		0.178*		-0.170*			0.181*
Education ^a		-0.181*		0.207*			
ATC							
TSE							
PI							-0.207*
ATE	0.544***	0.453***	0.248**		-0.294***		-0.207*
MCU	0.364***	0.212**		-0.172*	-0.266***		
KAF							-0.309***

Only significant correlations are displayed with * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

ATC Attitude towards car use, TSE Technical self-efficacy, PI Personal innovativeness, ATE Attitude towards the environment, MCU Morality regarding car use, KAF Knowledge about alternative fuels

^aFor correlation analyses, formal education was grouped into three categories ("low," "medium," and "high" education) according to the ISCED 11 [58] with:

Low lower secondary education, Medium vocational training or university entrance certificate, High university degree or PhD

run to investigate relations between user factors (demographics and personality) and alternative fuel perceptions (see Table 2) to examine whether perceptions change for different groups of people.

Acceptance of alternative fuels was positively correlated with environmental attitudes: The higher the awareness for environmental problems (ATE = attitude towards the environment) and the higher the perceived obligation and readiness to change one’s mobility behavior for the environment (MCU = morality regarding car use), the higher the acceptance of alternative fuels was.

Whereas perceived benefits and barriers for the environment were correlated with both demographics and personality factors, perceived benefits and barriers for drivers had significant correlations with fewer user factors. Female gender, a lower formal education, and a higher morality regarding car use were by tendency linked to higher benefit perceptions for the environment and lower barrier perceptions for environment and health. Perceived environmental benefits were also correlated with age and attitude towards the environment: The younger participants were and the more positive their attitude towards the environment, the higher was the environmental benefit perception.

Environment-related attitudinal variables were the only user factors which showed a significant correlation with driving-related benefit and barrier perceptions: The more positive the attitude towards the environment, the higher were the perceived benefits and the lower the perceived barriers for drivers. Furthermore, the lower the perceived barriers for drivers, the higher the morality regarding car use was.

Perceived risks showed rather weak correlations with user factors. For accident risk perceptions, no significant relationships with the assessed user factors were

Table 3 Results of hierarchical regression for the impact of user factors and perceptions on acceptance (only factors with significant impact are listed)

	B	SEB	β	t	p
Step 1: Perceptions ($R^2 = 0.43$; $\Delta R^2 = 0.43$; $F(6,144) = 18.00$, $p < 0.001$)					
Constant	2.48	0.73		3.40	0.001
Benefits for environment	0.61	0.11	0.55	5.54	0.000
Barriers for drivers	-0.16	0.07	-0.16	-2.24	0.027
Step 2: Perceptions + User Factors ($R^2 = 0.51$; $\Delta R^2 = 0.08$; $F(8,142) = 18.65$, $p < 0.001$)					
Constant	1.52	0.71		2.15	0.033
Benefits for environment	0.37	0.11	0.34	3.27	0.001
ATE	0.22	0.07	0.24	3.01	0.003
MCU	0.14	0.06	0.15	2.18	0.031

ATE Attitude towards the environment, MCU Morality regarding car use

revealed. Perceptions of unknown, uncontrollable risks showed the highest correlation with self-assessed knowledge about alternative fuels. Additionally, the greater the self-assessed knowledge of alternative fuels, the higher the personal level of innovativeness, and the more positive the attitude towards the environment, the lower was a person’s risk perception. Also, a male gender was by tendency linked to a lower perceived unknown, uncontrollable risk.

How do user factors and perceptions impact the acceptance of alternative fuels?

A two-stage hierarchical regression (using the enter method) was conducted. In step 1, the PCA Factors were included, while step 2 added the user factors ATE and MCU – to analyze how much variance user factors explain in addition to perceptions – which were significantly correlated with acceptance (see Table 2). Results are presented in Table 3.

VIF factors were <10 , showing that multicollinearity could be ruled out.

The regression model in step 1, investigating the impact of perception factors on alternative fuel acceptance, explained 42.9% of variance in acceptance. Perceived benefits for the environment were found to increase acceptance, whereas perceived barriers for drivers decreased acceptance (see Table 3). All other included perception factors did not have a significant impact.

After the inclusion of ATE and MCU in step 2 it was found that user factors added significantly to explaining the variance in acceptance ($\Delta R^2 = 0.08$; $\Delta F(2,142) = 12.19$, $p < 0.001$). In addition to fuel perceptions, ATE and MCU explained an additional 8.4% of variance in alternative fuel acceptance. Both factors exerted a positive impact on acceptance: A higher ATE and MCU increased acceptance (see Table 3). Interestingly, perceived barriers for drivers no longer had a significant effect on acceptance in the second model but the effect of perceived benefits for the environment remained significant. This indicates that the initial effect of barrier perceptions for drivers on acceptance (and partially the effect of perceived benefits for the environment) in step 1 was due to differences in environmental awareness, which shape both barrier perceptions and, in consequence, acceptance of alternative fuels.

Discussion

In the following, we discuss the findings in greater detail while acknowledging potentials for future research and outlining recommendations for fuel design, policy making, and communication.

Insights on the acceptance and perceptions of alternative fuels

In addition to large scale efforts to lower emissions in the atmosphere, e.g., via negative emission technologies, the development of alternative fuels holds the potential to help decarbonize the transport sector. According to our findings, the high initial acceptance of alternative fuels with benefits being acknowledged and barrier and risk perceptions being rather low indicates that alternative fuels are not expected to be directly rejected by the public. This is in line with previous research, e.g., [21, 27]. It was revealed that positive environmental effects could act as an enabler of alternative fuel adoption, but restrictions for drivers could hinder the successful implementation of these fuels. This finding is consistent with those of a previous study [22].

As a potential early adopter group for alternative fuels, people with high environmental awareness and a high morality regarding car use were identified, as positive environmental attitudes were found to lead to higher acceptance and perceived benefits, and lower perceived

barriers. Interestingly, we find that perceived barriers for the environment have a stronger impact of a person's acceptance of alternative fuels: The perception of benefits for drivers was only linked to the attitude towards car use and the influence of perceived benefits for potential drivers of alternatively fueled vehicles became insignificant after the inclusion of additional user factors in the regression analysis. Nevertheless, the distinction between different kinds of benefits indicates that there are different motives underlying people's perception that stem from a practical (benefits for drivers) vs. moral/biocentric (benefits for the environment) standpoint. Based on this finding, future studies should analyze if there are diverse segments in society that support (or oppose) alternative fuel use and development because of diverse underlying motivations, which could potentially be transferred into user specific communication about the topic of alternative fuels.

For perceived risk of alternative fuels, a link with familiarity with alternative fuels was found. An inverse relationship between risk perceptions and self-reported knowledge has also been previously revealed in other contexts, e.g., energy storage [59] and CCU [60]. Although specific risks were rather not attributed to alternative fuels, and it was believed that the risks were known to science, the risks were largely unknown for laypeople. This highlights an important gap to be addressed in both policy design and communication concepts accompanying the market diffusion of alternative fuels. The results furthermore allow for recommendations for fuel design.

Recommendations for fuel design

Based on the key findings summarized previously, fuel design should consider the following aspects for the selection of socially accepted fuel candidates. As a prominent role of both the perception of environmental compatibility and the impact of people's environmental awareness for acceptance have been established, there should be an emphasis on optimizing environmental effects in fuel design. Furthermore, as can be derived from the perceptions related to the drivers potentially using alternative fuel candidates, a decrease of barriers for drivers should be aimed at, for example by choosing fuels that are compatible with current engines and current refueling infrastructure. By doing so, hurdles to adoption by potential consumers can more likely be circumvented. A third recommendation concerns costs. A reduction in costs is an approach that can be derived on the basis of the results obtained. This can entail both the price of fuel as well as indirect costs, e.g., potential cost reductions by retrofitting current fuel production plants instead of having to build new plants. This can make fuels

not only more attractive for individual traffic but also for fleets [22].

Recommendations for policy decision-making and communication

Next to guidelines for fuel design, the key results also revealed focal points for policy decision-making and communication concepts for the development and diffusion of alternative fuels.

Based on the findings, it can be concluded that it is important to inform both car drivers as potential users as well as the general public about the environmental benefits of alternative fuels. Explaining under which conditions the use of alternative fuels can contribute to defossilizing the transport sector, alongside electric vehicles, and how it complements other approaches to emission reduction (such as active removal of emissions via Direct Air Carbon Capture and Storage), can foster an understanding of the relative strengths of alternative fuels. This enables laypeople to understand and assess the suitability of alternative fuels for different applications and allows them to make informed decisions. Furthermore, the public should comprehensibly and accessibly be informed about potential risks in order to address the concerns about risks presumed to be unknown to the public that were investigated in this study. This is supported by findings that underlined that an increase in knowledge goes hand in hand with an increase of support for the technology or fuel (e.g., [33–35]).

There should furthermore be endeavors to foster the roll-out of alternative fuels by committing to long-term policy measures in an attempt to enable users (laypeople and their vehicles but also enterprises with their fleets) to invest in vehicles. This would result in a more robust planning certainty for users [22] and could mitigate the identified concerns about high costs and insufficient availability. As European policy stipulates that from 2035 onwards new vehicles must not emit CO₂¹, alternatives such as e-fuel or battery driven vehicles are playing an increasingly important role. This is reflected in the respondents' moderate agreement with the perceived benefit that alternative fuels (such as e-fuels) provide a possibility to avoid being affected by driving bans. Transparently communicating the (long-term) effects of policies for both the environment but also for drivers allows the public to make informed decisions. This applies to drivers and their decisions when buying or renting vehicles but also to the general public in their decisions as representatives of the various roles they can hold in a society as members of societal organizations, as investors

or as voting citizens supporting or opposing policy making [61]. Our findings emphasize that there is public awareness of the benefits of alternative fuels for the environment and their potential to move away from fossil resources and to significantly reduce CO₂ emissions. Therefore, we identify the need to design (and communicate) policies that enable sustainable mobility at a reasonable level of impact for drivers.

When it comes to communication, strategies should be tailored to different target groups. In this study, people that are more environmentally aware were found to have a more pronounced benefit perception and a lessened barrier perception for impacts for drivers and the environment. Therefore, for people who are less environmentally aware, communication about alternative fuels should be framed in the context of the relevance of current environmental problems and the contribution that alternative fuels can have to solve these problems. A general appeal to ecological responsibility can be particularly effective with less engaged audiences. Additionally, as demographic characteristics such as age were found to impact acceptance of alternative fuels, a focus should be placed on identifying consumer groups and designing information material and output in a consumer adequate way.

Since the perceived risk was linked to self-assessed knowledge, communication concepts should raise awareness and provide a basic understanding of alternative fuels. This does not refer to the delivery of purely technical facts that are considered relevant from an expert's perspective. Rather, it refers to the adaptation of information to what laypeople really want to know [61] and to facilitating dialogue [62]. Especially when integrating public perceptions in early phases of technology development, technical innovations in general, but also alternative fuels for road [63] and in particular aviation transport [64], can be supported by timely information and communication activities. Previous research reports that the utilization of digital platforms and social media worked as effective communicative measures as well as the organization of local workshops in case of localized community efforts. Implementing such communicative measures was found to increase awareness and behavioral changes in the context of a variety of sustainable behaviors [62]. Furthermore, potential consumers of sustainable alternatives such as fuels need to be educated in a transparent fashion. As Durmus Senyapar et al. underline, outcomes of sustainable consumption options should be verifiable, as the public is more aware of environmental issues and practices of for example greenwashing [63].

Limitations and future research

The study revealed factors that enable or inhibit the acceptance of alternative fuels among laypeople.

¹ <https://www.europarl.europa.eu/topics/en/article/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained> retrieved 28.07.2025.

Although it is based on a small sample in which women and people of young age and high formal education were overrepresented, the study offers a first exploration and identification of acceptance-relevant benefit and barrier perceptions for alternative fuels in road transport. However, future research should assess acceptance and perceptions in a larger, more representative sample of the German population to validate the results. Research indicates that younger people are more environmentally aware than older generations [64], which is why the results obtained in this study would need to be compared to a sample that is more diverse in terms of key factors such as demographic and attitudinal variables. Future research should also include the perspectives of other stakeholder groups such as companies with vehicle fleets (e.g., car rental companies, freight companies, and companies providing their employees with company cars). This is important because the diffusion of alternative fuels in traffic will also depend on the acceptance of these fleet operators, a topic that should be explored in future research. Given Germany's long-lasting relationship with cars and its rich automotive history², the German perspective on cars in general could influence the discussion on alternative fuels for road transport [65]. Research should therefore be extended to the perceptions in other countries in order to validate the findings. Another line of research is to broaden the focus to different transport sectors. While it was reasonable to consider individual transport in a first step, as this is an easily imaginable scenario for laypeople, and because using alternative fuels in individual traffic requires drivers to actively decide to use these fuels, subsequent studies should aim for a direct comparison of different transport sectors, e.g., heavy-duty transport, public transport, and shipping. By doing so, it is possible to elicit which application area is most favorable from a social acceptance perspective and if the most accepted application is also the most technically reasonable (e.g., which application would be most feasible and allow for the greatest emission reductions).

Another addendum that should be considered in follow-up research is the inclusion of a broader selection of evaluation facets beyond environmental and driving-related aspects, such as the relevance and preferences regarding energy and fuel security, and independence from imports from other countries.

Conclusions

The present study quantified perceptions and acceptance of alternative fuels and identified enablers and inhibitors of alternative fuel adoption. Although acceptance of alternative fuels was high, the uptake of such fuels could be inhibited by perceived barriers for drivers, e.g., high costs and insufficient availability. In contrast, the existence and acknowledgment of favorable environmental effects such as emission reductions can increase acceptance and thus act as an enabler for the adoption of alternative fuels. Attitudes towards the environment, climate, and one's own contribution to environmental problems were identified as vital factors affecting perceptions and acceptance of alternative fuels. In addition, perceived knowledge about alternative fuels was found to be inversely related to risk perceptions. This shows that familiarity with alternative fuels is linked to lower concerns about unknown and uncontrollable risks. Our findings contribute to the understanding of the rather positive public evaluation of alternative fuels, which hold the potential to decarbonize the transport sector alongside other complementary efforts to reach climate goals. With regard to policy design, we furthermore conclude that efforts are necessary for the promotion of stability in times of change for society in general but also consumers and drivers of cars in particular. The study highlights the need for communication – by policy makers but also other stakeholders involved in the development and implementation of alternative fuels. As two prominent areas of benefit and barrier perceptions were discussed, we conclude that emphasizing beneficial effects for the global climate due to the implementation of policies affecting mobility should be communicated to the public, while also acknowledging outcomes for drivers and considering public perceptions of uncertainty and unknown risks. It is advisable to address this knowledge-risk gap by providing accessible and relevant information to laypeople and to tailor messages to diverse groups in society that can vary in their communicative needs and preferences. Future research can build on these findings by expanding the scope to different transport sectors, e.g., aviation and maritime as hard-to-abate emission sectors, and stakeholder groups to foster a sustainable and socially accepted introduction of alternative fuels in transport.

Appendix

See Tables 4, 5 and 6.

² <https://www.dw.com/en/germanys-love-affair-with-the-car/a-37917377>. retrieved 30.10.2023.

Table 4 English translation of German instructional material and items used in the survey study. Agreement with items was indicated on a scale from 1 = do not agree at all to 6 = strongly agree

Constructs and items	References
<p>[Info text at the beginning of the survey]</p> <p>Many vehicles in Germany today run on petrol or diesel, the combustion of which releases CO₂ emissions. In this context, the transport sector accounted for 19% of climate-damaging greenhouse gas emissions in 2018. Pollutant emissions, especially from diesel vehicles, are also increasingly the subject of public debate: in 2018, almost 43% of nitrogen oxide emissions in Germany were caused by transport. Pollutant emissions can have a negative impact on people and the environment.</p> <p>Alternative fuels can help to reduce CO₂ and pollutant emissions as they are used in combustion engines and can therefore replace conventional fuels made from fossil fuels such as petrol and diesel. They also have the potential for cleaner combustion. Unlike diesel and petrol, alternative fuels are produced from renewable raw materials, for example CO₂, water and renewable electricity or biomass.</p>	[44]
<p><i>Attitude towards car use</i></p> <p>For me, the car has instrumental functions only.</p> <p>A car provides status and prestige.</p> <p>My car shows who and what I am.</p> <p>I like to drive just for the fun.</p> <p>I only have a car to travel from A to B.</p> <p>I love driving.</p>	[44]
<p><i>Technical self-efficacy</i></p> <p>Because I could cope well with technical problems so far, I am optimistic about future technical problems.</p> <p>I can solve many of the technical problems I am confronted with on my own.</p> <p>I really enjoy solving technical problems.</p> <p>I feel so helpless when interacting with technical devices that I rather keep my hands off them.</p>	[65]
<p><i>Personal innovativeness</i></p> <p>I regularly look out for new products.</p> <p>I often search for information about new technologies and products that could be of interest to me.</p> <p>Most often, I am the first of my friends to test new products.</p> <p>I find it interesting to test new products.</p>	[46]
<p><i>Self-assessed knowledge about alternative fuels</i></p> <p>I feel well informed about alternative fuels.</p> <p>I feel well informed about the production of alternative fuels.</p>	[27]
<p><i>Attitude towards environment and climate</i></p> <p>If we carry on like before, we are heading towards an environmental catastrophe.</p> <p>I think that CO₂ emissions have a strong influence on climate change.</p> <p>I consider the effects of climate change to be minor.</p> <p>In my opinion, the environmental problem is greatly exaggerated by the media and politicians.</p>	[47–50]
<p><i>Morality regarding car use</i></p> <p>I don't feel guilty when I use the car, even though there are more environmentally friendly alternatives.</p> <p>I am prepared to change my way of life in order to protect the environment.</p> <p>My vehicle use contributes to environmental and climate problems.</p> <p>I am prepared to change my mobility behavior in order to protect the environment and the climate.</p>	[51, 52]
<p>[Info text]</p> <p>The following is about your attitude towards new fuels as an alternative to diesel and petrol. As described at the beginning of the survey, these alternative fuels are produced from renewable raw materials. These can be CO₂, water and renewable electricity or biomass, for example. Alternative fuels are used in combustion engines, i.e. electromobility is not included.</p>	[53]
<p><i>Perceived benefits</i></p> <p>By using alternative fuels, an innovative and fascinating technology is used.</p> <p>I believe that alternative fuels bring relief for the environment.</p> <p>I think it is good that renewable raw materials are used instead of finite fossil resources in the production of alternative fuels.</p> <p>I believe that alternative fuels can help to reduce CO₂ emissions in the transport sector.</p> <p>I think that alternative fuels are a first step towards a sustainable mobility.</p> <p>I believe alternative fuels contribute to combating climate change.</p> <p>It would be an advantage for me if I was exempted from possible driving bans in cities by using alternative fuels.</p> <p>I believe that alternative fuels can help to reduce pollutant emissions in the transport sector.</p> <p>I think it is good that alternative fuels can be used in combustion engines.</p>	[53]
<p><i>Perceived barriers</i></p> <p>Alternative fuels are only a short-term, no long-term solution for a sustainable road transport.</p>	[53]

Table 4 (continued)

Constructs and items	References
I believe that alternative fuels have a less well-developed fuel station network than conventional fuels like diesel or gasoline.	
I believe that alternative fuels are less efficient than conventional fuels like diesel and gasoline.	
There are more reasonable technologies to reduce emissions in the transport sector than alternative fuels.	
I believe that alternative fuels are more expensive than conventional fuels like diesel and gasoline.	
There are more reasonable technologies to replace diesel and gasoline than using alternative fuels.	
I fear that the use of alternative fuels could have negative effects on my car.	
<i>Perceived risks</i>	
I fear that alternative fuels pose a risk for explosion.	
I fear that alternative fuels could be more flammable than conventional fuels.	
I fear that alternative fuels could have negative effects on human health.	
I find the risks of using alternative fuels controllable.	
I fear that alternative fuels could have negative effects on the environment.	
I think that the risks of alternative fuels are known to the general public.	
I think that the risks of alternative fuels are known to science.	
<i>Acceptance of alternative fuels</i>	[27, 56]
Ich möchte keine alternativen Kraftstoffe beim Autofahren nutzen.	
Ich würde alternative gegenüber herkömmlichen Kraftstoffen beim Autofahren bevorzugen.	
Ich halte den Einsatz von alternativen Kraftstoffen im Straßenverkehr für eine schlechte Idee.	
Ich bin bereit, alternative Kraftstoffe zu tanken.	
Ich finde es gut, wenn alternative Kraftstoffe im Autoverkehr eingesetzt werden.	

Table 5 Results of the principal component analysis for alternative fuel perceptions

Items	Factor 1: Perceived benefits	Factor 2: Perceived barriers for environment and human health	Factor 3: Perceived accident risks	Factor 4: Perceived usage barriers for drivers	Factor 5: Perceived unknown and uncontrollable risks
I think it is good that renewable raw materials are used instead of finite fossil resources in the production of alternative fuels.	0.804				
By using alternative fuels, an innovative and fascinating technology is used.	0.772				
I think it is good that alternative fuels can be used in combustion engines.	0.759				
I believe that alternative fuels can help to reduce CO ₂ emissions in the transport sector.	0.731				
I believe alternative fuels contribute to combating climate change.	0.728				
I believe that alternative fuels can help to reduce pollutant emissions in the transport sector.	0.699				
I think that alternative fuels are a first step towards a sustainable mobility.	0.679				
I believe that alternative fuels bring relief for the environment.	0.667				
It would be an advantage for me if I was exempted from possible driving bans in cities by using alternative fuels.	0.532				
There are more reasonable technologies to replace diesel and gasoline than using alternative fuels.		0.774			
There are more reasonable technologies to reduce emissions in the transport sector than alternative fuels.		0.730			
I fear that alternative fuels could have negative effects on the environment.		0.673			
Alternative fuels are only a short-term, no long-term solution for a sustainable road transport.		0.631			
I fear that alternative fuels could have negative effects on human health.		0.606			
I fear that alternative fuels pose a risk for explosion.			0.887		
I fear that alternative fuels could be more flammable than conventional fuels.			0.733		
I believe that alternative fuels are more expensive than conventional fuels like diesel and gasoline.				0.728	
I believe that alternative fuels are less efficient than conventional fuels like diesel and gasoline.				0.654	
I believe that alternative fuels have a less well-developed fuel station network than conventional fuels like diesel or gasoline.				0.654	
I fear that the use of alternative fuels could have negative effects on my car.				0.573	
I think that the risks of alternative fuels are known to the general public (reverse coded).					0.715
I think that the risks of alternative fuels are known to science (reverse coded).					0.678
I find the risks of using alternative fuels controllable (reverse coded).					0.601

Only items with a factor loading of ≥ 0.45 were considered due to sample size $n = 151$ [57]

A high sampling adequacy was given with $KMO = 0.848$

Bartlett's test of sphericity was significant ($p < 0.001$)

Item Sources: Arning et al. [53], Fischhoff et al. [54], and interview pre-studies conducted prior to this study

Table 6 Results of t-tests for differences between perception factors

Compared factors	t(150)	p	d
Benefits for the environment – Benefits for drivers	3.58	< 0.001	0.29
Benefits for the environment – Barriers for drivers	11.14	< 0.001	0.91
Benefits for the environment – Uncontrollable and unknown risks	15.91	< 0.001	1.29
Benefits for the environment – Barriers for environment and health	14.32	< 0.001	1.17
Benefits for the environment – Accident risks	18.99	< 0.001	1.55
Benefits for drivers – Barriers for drivers	8.73	< 0.001	0.71
Benefits for drivers – Uncontrollable and unknown risks	12.90	< 0.001	1.05
Benefits for drivers – Barriers for environment and health	12.57	< 0.001	1.02
Benefits for drivers – Accident risks	16.03	< 0.001	1.30
Barriers for drivers – Uncontrollable and unknown risks	4.66	< 0.001	0.38
Barriers for drivers – Barriers for environment and health	7.50	< 0.001	0.61
Barriers for drivers – Accident risks	9.92	< 0.001	0.81
Uncontrollable and unknown risks – Barriers for environment and health		n.s.	
Uncontrollable and unknown risks – Accident risks	5.41	< 0.001	0.44
Barriers for environment and health – Accident risks		n.s.	

Bonferroni-adjusted significance level: $p < 0.003$; n.s. = not significant

t = t-test statistic, p = significance level, d = Cohen's d (effect size)

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Author contributions

All listed authors of this publication made substantial, direct and intellectual contributions to the work, and approved it for publication. Conceptualization: [AL, LE, MZ]; methodology: [AL, LE, MZ]; formal analysis and investigation: [AL]; writing—original draft preparation: [AL, LE, MZ]; writing—review and editing: [AL, LE, MZ]; funding acquisition: [MZ]; resources: [MZ]; supervision: [MZ].

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Data availability

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Declarations

Ethics approval and consent to participate

Because this study falls in the category where no institutional review board approval is required in Germany according to the guidelines of the German

Psychological Association (Deutsche Gesellschaft für Psychologie, 2018),³ we did not seek ethical approval from the ethics committee. All of the respondents were of legal age and consented to participate in the study. The respondents were not reimbursed for their participation. At the beginning of the questionnaire, the participants were transparently informed about the purpose of the study and that it is of vital relevance to understand free opinions and attitudes towards alternative fuels. While we expressed that we would be glad if the participants shared their perspective with us, we emphasized that their participation was entirely voluntary and that they could quit the questionnaire at any time. We assured a high standard privacy protection and informed the respondents that none of the questionnaire answers can be referred to them as individuals.

Consent for publication

The raw data provided by the participants was stored in anonymized/ aggregated form, which prevents the possibility of inferring details of individuals. The raw, anonymized/ aggregated data can be made available on request for the purpose of further research by the authors or the Chair of Communication Science at RWTH Aachen University. The respondents were informed that the survey data was intended to be analyzed for scientific purposes solely by the Chair of Communication Science at RWTH Aachen University. Moreover, they were informed that the questionnaire answers could not be referred to them as individuals because of the high standard privacy protection. The present manuscript does not contain any individual details, videos, or images of individuals.

Competing interests

The authors declare no competing interests.

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