What fuels the adoption of alternative fuels? Examining preferences of German car drivers for fuel innovations

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ABSTRACT

In the search for sustainable transport solutions, fuel production from renewable resources has received significant attention. Some proposed synthetic fuels have favorable combustion properties compared to existing fuels, e.g., significant reductions in pollutant formation. However, penetration of such fuels requires a favorable social acceptance, as demonstrated by the consumer boycott of the ethanol-blend fuel with 10% ethanol and 90% gasoline (E10) in Germany. Therefore, the consumer perspective and their preferences regarding alternative fuels should be considered in the fuel design. We use conjoint methodology to analyze the preferences of German car drivers for alternative fuels. This aims at understanding which criteria determine consumer preferences and usage decisions. Among the five considered fuel attributes (fuel availability, driving range, pollutant emissions, fuel costs, and usage requirements to enable the use of alternative fuels), fuel costs had the highest decision impact for alternative fuel preferences, followed by fuel availability and usage requirements. Pollutant emissions had the lowest impact on alternative fuel choices. A market simulation of conventional diesel and alternative fuels (dimethyl ether (DME) and a blend of diesel with oxymethylene dimethyl ethers (OME)) revealed that currently a large majority of car drivers would prefer conventional fossil fuel options, indicating a currently low consumer demand for alternative fuels. Thus, the findings demonstrate the importance of integrating social acceptance as an objective function in the design of novel fuels and production processes.

Nomenclature

Abbreviation

AFV	alternative fuel vehicle
CA	conjoint analysis
CBC	choice-based conjoint
CI	compression ignition
CNG	compressed natural gas
CO_2	carbon dioxide
ct/l	cent/liter
DME	dimethyl ether
E10	ethanol-blend fuel with 10% ethanol and 90% gasoline
EV	electric vehicle
GHG	greenhouse gas
H_2	hydrogen
HB	Hierarchical Bayes
LPG	liquefied petroleum gas
NO_x	nitrogen oxides
O35	blend of diesel with 35 vol.-% oxymethylene dimethyl ethers
OME	oxymethylene dimethyl ether
PM	particulate matter
PV	photovoltaics
R&D	research and development
RFC	Randomized First Choice
RLH	root likelihood
SI	spark ignition

Roman

M	mean
n	sample size
p	test significance
SD	standard deviation
t	t-test statistic

Greek

Cronbach's $\propto$	scale reliability
η^2	effect size

1. Introduction

Greenhouse gas (GHG) emissions are accepted as the major driver of climate change [1]. The European Union aims at expanding the infrastructure for alternative (renewable) fuels in order to increase their market share to 10% and reduce the GHG emissions caused by transport by 60% till 2050 [2]. This implies the need for novel, alternative fuels with drastically lower GHG emissions than fossil fuels. Simultaneously, it is necessary to reduce pollutant emissions, in particular NOx and soot. Biofuels made from biomass, electricity-based fuels (e-fuels, produced from CO_2, water, and renewable electricity), as well as the combination of these approaches (termed biohybrid fuels), have the potential to reduce GHG and pollutant emissions and can overcome the range issues of electric vehicles (EV) in long-distance transport [3]. For example, the alternative fuels methanol and methane can each reduce NOx emissions by 30-50% and total hydrocarbon emissions by 15-30% compared to gasoline. Also, some alternative fuels for compression ignition engines can drastically reduce particulate matter (PM) emissions, e.g., in case of dimethyl ether (DME) by more than 95% compared to diesel fuel [4]. Some of these alternative fuels can even be used in conventional vehicles, requiring no retrofit of the infrastructure, car or engines [5]. The pollutant emissions from individual transport have a high environmental impact and might also affect our driving behavior in the near future: As a consequence of the “Dieselgate” scandal [6], possible driving bans for diesel-powered vehicles in highly polluted urban areas are currently under consideration in Germany to reduce urban air pollution [7,8]. Such discussions further strengthen the need for alternative fuels.

The market penetration of alternative fuels is not exclusively determined by technical, economic, legal, and environmental parameters. Car drivers have a choice of fuels, in particular whether to use an alternative fuel. This impacts the market success of new fuels [9], as the consumer boycott of ethanol-blend fuel E10 (10% ethanol, 90% gasoline) in Germany showed [10]. Often, technical developments inadequately include users' demands and requirements, possibly resulting in innovative products that are rejected once they enter the market (as highlighted in studies on biofuels [11] and climate-smart agriculture technologies [12]). This highlights the importance of enhancing the techno-economic and ecological perspective on alternative fuels by integrating the perspective of car drivers in early stages of fuel design.

Although alternative fuels and their technical feasibility have been intensively researched, some pending research questions, including social acceptance issues, remain. First, previous studies on consumer preferences for alternative fuels (e.g., [9]) mostly considered alternative fuel vehicles as a whole, including the propulsion technology, fueling/loading infrastructure, etc., but did not exclusively focus on the alternative fuel candidate and its acceptance-relevant characteristics. This leads to a second knowledge gap: Although using some alternative propulsion technologies (such as electric vehicles and fuel cells) requires the purchase of a new vehicle, some alternative fuels could be used in conventional CI or SI engines after a moderate retrofit of the engine or without adjustments. These retrofit / no-adjustment cases and their perception by consumers are not adequately covered by studies on AFVs so far. However, understanding which criteria and configurations are related to alternative fuel preferences is highly valuable for a sustainable and socially accepted fuel design and a positive market adoption.

The present conjoint study investigates the market acceptance of alternative fuels [13]. It aims at identifying, quantifying, and weighting the decision criteria and preferences of car drivers for alternative fuels. Moreover, by conducting a market simulation of specific alternative fuel types, more specifically dimethyl ether (DME) and a blend of diesel with oxymethylene dimethyl ethers (OME), versus conventional diesel, the study offers insights into the consumer demand for alternative fuels.

The paper is structured as follows: First (in Section 2), we give an overview of alternative fuels in individual transport and of the current state of research on their social acceptance. Afterwards (Section 3), we describe the experimental design and empirical procedure of the conjoint study. We report results on decision criteria and preferences for alternative fuels in Section 4 (including a market simulation of existing fossil and alternative fuel types). In Section 5, we discuss the findings and derive implications for fuel design, policy-making, and communication and information strategies for alternative fuels. A concluding summary is provided in Section 6.

2. Alternative fuels in transport and their social acceptance

2.1 Alternative fuels – technical background

We use the term *alternative fuels* to denote any gaseous or liquid transportation fuel for light-duty vehicles other than gasoline or diesel. Alternative fuels thus include fuels produced from oil (e.g., liquefied petroleum gas (LPG)) or natural gas (e.g., compressed natural gas (CNG), or DME), but also biofuels (e.g., bio-ethanol), e-fuels (e.g., methane produced from water, CO_2, and electricity) and biohybrids. Such alternative fuels can have vastly different properties regarding production processes and raw materials, handling for fuel distribution and fueling, but also vehicle performance.

There has been a large amount of research over the past decades on various alternative fuels, considering both the production processes and the engines. One major motivation for alternative fuels is their potential to reduce GHG emissions, either through reduced carbon content (e.g., CNG), improved engine efficiency, or the use of renewable raw materials and energy sources. The latter option also addresses the limited availability of fossil energy sources. Additionally, several alternative fuels have the potential to substantially reduce formation of pollutants such as nitrogen oxides (NO_x), soot, carbon monoxide, and unburned hydrocarbons compared to gasoline and diesel (cf., e.g., [14]).

A major challenge in the development and deployment of alternative fuels is cost competitiveness to gasoline and diesel. Fossil-based alternative fuels like CNG or LPG are currently offered in Germany at lower prices (on an energy basis) than Gasoline or Diesel thanks to their rather low production cost and reduced fuel taxes. In contrast, production cost and total price of biofuels [15] or e-fuels [16] has so far often been higher than that of established fuels. An additional barrier is that most alternative fuels are not fully compatible with today's vehicle fleet as well as infrastructure for fuel distribution and fueling. Thus, their penetration would require changes within these systems. Finally, many alternative fuels have lower volumetric energy densities than gasoline and diesel, either because they are oxygenated (e.g., ethanol) or because they are gaseous at feasible storage conditions (e.g., CNG).

DME is currently predominantly being used as a cooking and heating fuel added to LPG [17]. Since the 1990's, it is also considered as an alternative diesel fuel [18] and there have been fleet tests of heavy-duty trucks operating on bio-based DME [19]. DME is a gas at ambient conditions, but it can be liquified at moderate pressures and hence handled in a way similar to LPG [20]. Its main advantage as an alternative diesel fuel is the dramatic reduction in soot formation due to the absence of carbon-carbon bonds, which also allows to reduce NO_x by adapting the engine calibration [21]. To date, DME is produced from methanol, which in turn is derived from natural gas or coal [22,23]. However, alternative production processes have been suggested that enable DME production as biofuels [17] or e-fuels [4] with good efficiencies compared to other fuel candidates.

Oxymethylene dimethyl ethers (OMEs) have attracted interest as alternative diesel fuels or blend components [24]. OMEs enable strong reductions in pollutant emissions, even when blended with fossil diesel [25,26]. Compared to DME, the advantage of OMEs is that they are liquid at ambient conditions and miscible with conventional diesel fuel and could hence serve either as blend component or as neat fuel [25]. Compared to DME, interest in OMEs has only increased much more recently, and hence there is less experience in vehicle applications. Currently, OMEs are mainly produced in China from coal-based methanol in rather complex processes [27]. However, numerous novel production processes have been developed to improve efficiency and reduce production cost (e.g., [28,29]). Furthermore, by switching to different methanol sources, OMEs can also be produced as biofuels [30] or e-fuels [31,32]. In this case, they can also have a favorable carbon footprint compared to conventional diesel [33,34].

Even before considering consumer acceptance, evaluation of alternative fuels from a technical perspective can include a large number of factors (cf., e.g., [4]). Regarding fuel production, the most typical performance measures are related to conversion efficiencies (e.g., raw material consumption or energy efficiency) as well as economic (e.g., production cost per fuel energy) and environmental (e.g., GHG emissions) considerations. Furthermore, fuels may differ regarding the types of raw materials that can be used for their production. Regarding vehicle application, fuels are often assessed based on resulting engine efficiencies, emissions of noise, pollutants, and tailpipe CO_2, requirements regarding exhaust gas treatment systems, tanks, or fuel pumps, and many more technical aspects. Finally, regarding handling, alternative fuels are sometimes assessed by their state at ambient conditions and the extent to which they are compatible with established infrastructure.

2.2 Social acceptance of alternative fuels

The failed market introduction of E10 [10] and the reluctant market adoption of CNG [35] in Germany showed that a favorable acceptance of alternative fuels and their refueling infrastructure is a decisive factor for the market adoption of alternative fuels. Social acceptance includes an attitude-related component (i.e., a favorable attitude towards a technology) and a behavior-related component (either the active use and/or passive tolerance [36] of this technology) [37].

In the renewable energy context, Wüstenhagen et al. [13] revealed three (interdependent) dimensions of social acceptance, which impact the successful rollout of energy technologies:

1) *socio-political acceptance* referring to the general acceptance of energy technologies and energy strategies in the public and among political and industrial actors,
2) *community acceptance* denoting the local acceptance of specific energy infrastructure projects (such as wind farms or biorefineries) by residents and municipal authorities, and
3) *market acceptance* encompassing the market adoption of innovative energy technologies by consumers and investors. Market acceptance is specifically relevant in case of small-scale energy or product technologies that involve

direct interaction with the end-user, such as smart-grid technologies, domestic PV systems, or alternative fuels.

We focus on the dimension of market acceptance and investigate the demand of consumers for alternative fuels. We use the term “consumer” from a social acceptance perspective, which differs from the economic perspective: Whereas consumer requirements are considered in economic analysis as a prerequisite for worthwhile, *economically sustainable* innovations (as an element in supply and demand), acceptance research aims at identifying parameters for a *socially accepted* innovation and enabling novices to participate in the innovation process. A favorable market acceptance of alternative fuels requires a positive purchase decision (consumption) by car drivers. If car drivers are not willing to purchase alternative fuels, resulting in a low market demand, they cannot be produced in an economically viable way and will consequently fail on a free market.

Previous studies have come to mixed results for acceptance of alternative fuels and consumers’ intention to use them. In some surveys, alternative fuels (biofuels in particular) and the willingness to use them were positively evaluated (e.g., [38]) and consumers were on average willing to pay an extra charge of 7-8 cents/liter for using biofuels compared to their conventional fuel [39,40]. In contrast, several studies have revealed low preferences for alternative fuel vehicles compared to conventional vehicles (e.g., [41]).

2.3 Consumer preferences for alternative fuels

Conjoint studies can demonstrate the characteristics of a socially accepted alternative fuel and the factors car drivers consider when deciding among fuels. They allow for a realistic decision scenario, in which respondents evaluate whole product scenarios (for more details on the conjoint method see Section 3.1). A number of empirical studies investigated consumer preferences for alternative fuel vehicles (AFVs) based on the conjoint measurement approach to analyze acceptance-relevant evaluation criteria and identify the optimal configuration of AFVs from the consumer perspective (e.g., [42,43]).

Preferences for alternative fuel vehicles have been researched as early as the 1970s motivated by the global oil crisis [44]. Table 1 presents an overview of selected recent conjoint studies on AFV[1] preferences. The listed studies were selected on the basis of their fit to the research focus and the investigated attributes of this paper.

As shown in Table 1, evaluation criteria frequently investigated in previous research on consumers' choice decisions for AFVs were: 1) cost-related factors (e.g., fuel costs and vehicle purchase costs); 2) infrastructure-related factors (e.g., fuel availability); 3) parameters concerning the technical performance of the vehicle and vehicle options (e.g., vehicle or fuel type, driving range); 4) policy incentives (e.g., tax reductions, free parking); 5) environmental effects (CO_2 and pollutant emissions).

In many studies, financial costs (above all vehicle- and fuel price) were identified as highly relevant for consumers' hypothetical choices for or against an alternative fuel vehicle (e.g., [45]), in some cases outweighing factors like emissions and range (e.g., [46]). Alongside costs, fuel availability was a crucial parameter affecting consumers'

[1] Because studies on AFV preferences also include investigations of electric vehicles, it would be more accurate to use the term "alternative propulsion technologies," but "alternative fuel vehicles" is the widely used "umbrella term" for vehicles powered by alternative propulsion technologies in acceptance research.

choice decisions (e.g., [47]). Especially for EVs but also for AFVs in general, driving range played an important role (e.g., [48]). Mixed results were found for policy incentives: Whereas in a study by Hackbarth & Madlener [41] policy incentives were highly important for consumer preferences, compared to factors such as range and additional detour time for refueling they were only of limited relevance to respondents in the study by Koetse & Hoen [49].

Likewise, research has come to divergent results for the importance of emissions. A number of studies looked into the effects of CO_2 emissions on AFV preferences (e.g., [47]) and while some found a considerable impact of CO_2 output on choices and willingness to pay for AFVs (e.g., [50]), its effect was low in e.g., Caulfield et al. [51]. Moreover, environmental awareness was identified as an important factor influencing the role CO_2 emissions play in choice decisions on AFVs [47]. So far, pollutant emissions were rarely considered in research on AFV acceptance. Exceptions include Bunch et al. [52] and the study by Hidrue et al. [44], which focused exclusively on electric vehicles. In contrast to the results of Bunch et al. [52], who found pollutant emissions to considerably impact choice decisions, pollution was the least important attribute in the study by Hidrue et al. [44].

Table 1
Overview of selected conjoint studies on AFV preferences.

	Financial costs			Infra-structure	Technical performance and vehicle options				Policy	Emissions	
Study	Fuel costs	Purchase price	Taxes and/or maintenance costs	Fuel availability	Vehicle or fuel type	Car models	Engine Perfor-mance[a]	Driving range	Incentives[b]	CO_2	Pollutants
Bunch et al. 1993 [52]	X	X		X	X		X	X			X
Caulfield et al. 2010 [51]	X		X							X	
Hidrue et al. 2011[c,e] [44]	X	X					X	X			X
Achtnicht 2012 [53]	X	X		X	X		X			X	
Achtnicht et al. 2012 [47]	X	X		X	X		X			X	
Ziegler 2012 [50]	X	X		X	X		X			X	
Hackbarth & Madlener 2013[d,e] [41]	X	X		X	(X)[d]			X	X	X	
Khachatryan et al. 2013 [54]	X			X						X	
Hoen & Koetse 2014[e,f] [42]		X	X	X[f]	X	X		X	X		
Koetse & Hoen 2014[e,f] [49]		X	X	X[f]	X	X		X	X		
Hackbarth & Madlener 2016[d,e] [9]	X	X		X	(X)[d]			X	X	X	
Byun et al. 2018[e] [43]		X	X	X	X					X	
Soto et al. 2018 [45]	X	X	X	X	(X)[d]			X			

[a] E.g., engine power or acceleration.
[b] E.g., tax reductions, access to bus lanes, free parking.
[c] Exclusive focus on electric vehicles (EV).
[d] Fuel type indirectly included (not as attribute but as scenario comprising a set of attribute levels).
[e] Also, refilling and charging time was included as attribute in these studies but was omitted for a better overview in this list.
[f] Fuel availability was modeled as additional detour time for refueling in these studies.

Only a small number of studies so far has specifically focused on preferences for alternative fuels. The study by Winden et al. [55] had a main focus on production characteristics: Examined attributes included environmental effects, consumption of resources, and human health risks related to biofuel production. In contrast, the research by Khachatryan et al. [54] investigated usage-related attributes for biofuels (fuel costs and availability) and CO_2 emissions. Thus, insights into consumer preferences for alternative fuels as products and the acceptance-impact of specific AFV-characteristics are still scarce.

Using the conjoint methodology, we aim at quantifying and weighting the decision criteria and preferences of car drivers for alternative fuels (exemplified as biofuels and e-fuels) and deriving implications for a socially accepted fuel design. Moreover, we aim to identify focal points for stimulating the consumer demand for DME and a blend of diesel with OME.

3. Methods and materials

In order to investigate the decision criteria and preferences of car drivers for alternative fuels, we conducted a *choice-based conjoint study* (CBC) in Germany in February 2018. In the following, we describe the basics of conjoint methodology are presented, and the experimental design and concept of empirical procedure used.

3.1 Conjoint analysis

We apply the conjoint analysis approach (CA) for empirical data assessment of fuel design preferences. Conjoint analysis (CA) is an established method in social-, environmental-, and medical science (e.g., [56]), which allows individual preference measurement, trade-off-analysis, group segmentation, and the simulation of preferences for novel products or scenarios [57]. Compared to survey methods, CA represents an experimental approach with a high external validity: Selected factors (validated in earlier research) are varied and the interaction of factors as well as their contribution to the overall preference rating can be exactly defined. In addition, CA closely mimics real-life decisions, where more than one attribute influences the final decision, because participants evaluate complete scenarios rather than isolated features. CA is a decompositional method of preference measurement, in which the individual preference judgment (the “utility”) is assumed to be linearly additive from partial utility values. This allows to determine the relative contribution of individual features to the overall evaluation. More precisely we apply CBC (choice-based conjoint), a special type of CA where participants select the most attractive alternative in different choice tasks. Based on the stated choices of respondents, we develop a choice probability model, based on a multinomial logit or probit model [57].

3.2 Selected attributes and experimental design

We selected relevant impact criteria on the preferences of car drivers for alternative fuels for the CBC study based on interviews with novices and experts in the field of fuel design. We then asked the participants in the conjoint study to evaluate different alternative fuels with substantial differences in the following five attributes: usage requirements, pollutant emissions, fuel availability at conventional filling stations, fuel costs, and driving range. For each attribute, we allowed three levels, based on the properties of existing alternative fuels. An overview of the attributes and levels as well as the attribute definitions are provided in Table 2.

Table 2
Attributes and levels used in the conjoint study.

Attribute	Definition	Number of levels	Levels
Usage requirements	car adjustments required for alternative fuel use	3	no requirements, retrofitting, purchase
Pollutant emissions	pollutant emission reductions compared to diesel	3	-10%, -30%, -60% compared to diesel
Fuel availability	share of conventional filling stations in the near vicinity offering the alternative fuel	3	10%, 50%, 100% of filling stations
Fuel costs[2]	extra charge compared to diesel price	3	+0, +10, + 20 euro cents/liter compared to diesel
Driving range	driving range reached by a tank filling of the alternative fuel (reference: range is 1000 km for a tank filling of diesel)	3	400 km, 700 km, 1000 km

The attribute *usage requirements* measures the actions required by a conventional car owner to be able to use an alternative fuel. The attribute levels span the entire range from alternative fuels designed to be fully compatible with today's vehicles (e.g., E10 or Fischer-Tropsch gasoline or diesel [5]), those requiring retrofitting measures (e.g., enabling a gasoline car to run on CNG [58]), to those likely to require the purchase of a new car (e.g., biomass-derived designer fuels [59]). Note that for some fuels, e.g., OME, it is not entirely clear yet to what extent changes to the vehicle are necessary.

In the attribute *pollutant emissions*, several simplifications were necessary to keep the description concise and comprehensible for novices without expert knowledge. First, we made no distinction in the description between pollutant formation (i.e., raw emissions) and tailpipe emissions because in the pre-study interviews we found that novices did not and/or were not able to distinguish between them. In the selection of the levels, we considered raw emissions that are more closely linked to the fuel itself, although technically a reduction in raw emissions could translate either

[2] Total fuel cost with taxes.

into reduced tailpipe emissions or into simplified exhaust gas treatment at similar tailpipe emissions. Second, we made no distinction between different types of pollutants (e.g., NO_x, soot, or carbon monoxide), although the emission characteristics with respect to different pollutants may well differ between alternative fuels. Third, we chose diesel as the single reference point to measure pollutant reduction, although it is known that pollutant comparisons are challenging even within a given engine class (e.g., compression ignition vs. spark ignition) because of their dependence on engine design, operating conditions and the like [12]. We thus chose the levels qualitatively to range from moderate reduction (-10%) to significant reductions (-60%). We selected relative emission reductions rather than absolute emission values because previous studies found that absolute emission values are difficult for novices to understand and make sense of (e.g., [60]).

Fuel availability was modeled as the share of filling stations offering a certain fuel, with levels ranging from rather low (10%) to perfect (100%) availability. While novel fuels will inherently start with a very low availability, the speed at which availability can be increased likely depends on the compatibility with today's fueling (and distribution) infrastructure. Therefore, fuels like OME-diesel blends or methanol can be expected to allow for a faster expansion than, for example, hydrogen (H_2).

For *fuel costs*, we considered final purchase costs including all taxes. We give fuel costs as extra charge compared to diesel (in ct/l) to facilitate the evaluation for novices. The levels comprised the optimistic case of cost-competitive production (±0 ct/l) and two cases with moderate cost increases (up to 20 ct/l), allowing for a range that appeared reasonable based on responses in the pre-studies.

For *driving range*, we chose the levels to cover the entire span of performance expected for alternative fuels. For instance, 400 km corresponds to some current H_2

fuel cell vehicles [61], and 1000 km corresponds to a vehicle running on Fischer Tropsch diesel with a 60 l tank and a fuel consumption of 6 l per 100 km.

In each choice task, respondents had to select their preferred fuel scenario out of three randomly generated fuel options varying on the five attributes (no "none"-option). Since a fully orthogonal design (participants evaluating all possible combinations of attribute levels) would have resulted in $3^5 = 243$ scenarios, we reduced the number of stimuli. Altogether, respondents had to complete 10 choice tasks (6 random plus 4 fixed tasks). On the basis of the completed choice tasks, we calculated the preferences for the other possible combinations of attribute levels by Lighthouse Studio using Hierarchical Bayes estimation (HB).

We evaluated the HB model's goodness of fit the root likelihood (RLH). For the current CBC design with three selectable scenarios per choice task, the calculated RLH for the present CBC design was 0.67.

3.3 Questionnaire

The questionnaire was structured in four parts. The concept of empirical procedure is displayed in Fig. 1. For an overview of the questionnaire items see Appendix A.

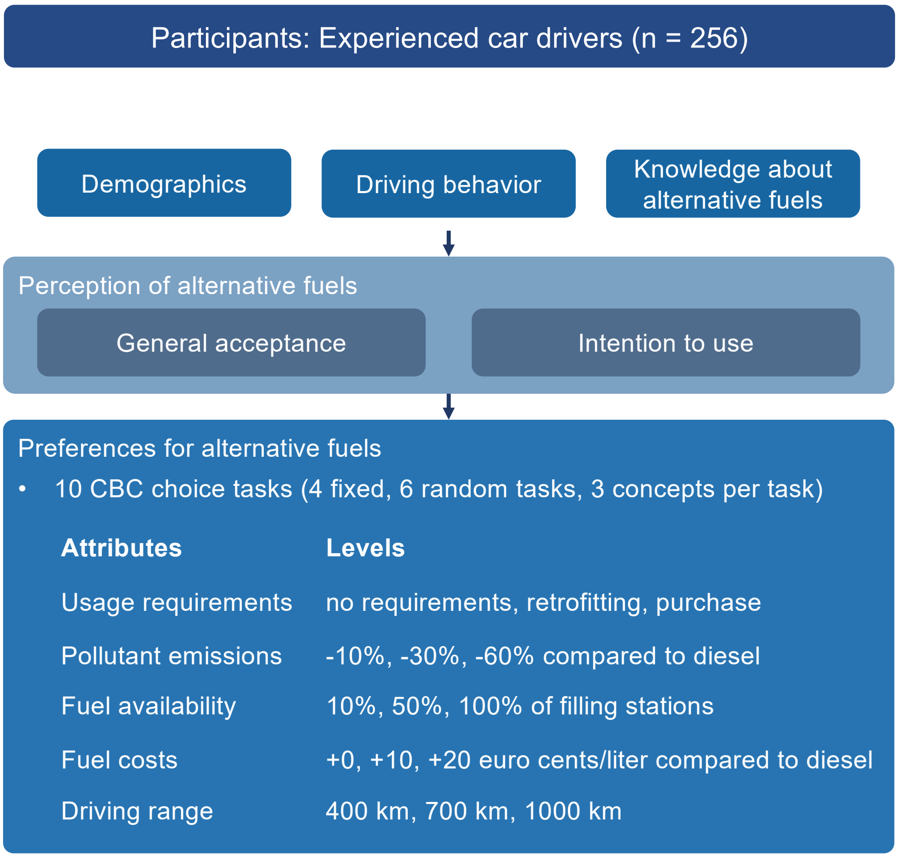

Fig. 1. Concept of empirical procedure.

At the beginning, a short introductory text on the topic of alternative fuels was presented to participants, in which alternative fuels were introduced as a possible replacement for conventional fossil fuels to tackle the environmental challenges of CO_2 and pollutant emissions caused by individual transport. Also, the relevance of integrating consumers' requirements and wishes in the design of alternative fuels was highlighted. In the second part of the questionnaire, respondents' demographic characteristics (age, gender, education, place of residence), driving behavior, and self-reported knowledge about alternative fuels were assessed. Variables used to characterize participants' driving behavior were car ownership (*own car, company car, carsharing, privately borrowed car*), vehicle type (*gasoline, diesel, electric, hydrogen, gas, hybrid*), annual mileage (measured in steps of 5,000 km from $\leq$ *5,000 km* to > *20,000 km*) and driving frequency (*daily, several times per week / per month / per year,* *never*). Respondents' self-reported knowledge was assessed using three items specifically developed to measure awareness of alternative fuels (Cronbach's $\propto$ = 0.93, see Appendix A, Table A.1).

The third part of the questionnaire captured perceptions and acceptance of alternative fuels. General acceptance of alternative fuels was measured by the item "I find alternative fuels acceptable." Respondents were additionally asked to report their intention to use alternative fuels. They had to indicate their level of agreement to four items dealing with the willingness to switch to alternative fuels and to retrofit one's car for this purpose (Cronbach's $\propto$ = 0.81, see Appendix A, Table A.1). All items on awareness and perceptions of alternative fuels had to be answered on six-point Likert scales (1=do not agree at all, 6=fully agree) and were specifically developed for this study since preexisting scales did not accurately fit the innovative topic of alternative fuels. The items used had been tested and validated in pre-studies.

The last part of the study contained the conjoint task, in which respondents were instructed to imagine that they intended to switch to alternative fuels within the next five years and were asked to choose their preferred fuel scenario out of three options varying on the five attributes defined in Section 3.2. This task was repeated ten times for each participant (4 fixed tasks with predefined configurations and 6 random tasks, in which attribute levels were randomly varied). An example of the choice tasks presented to the participants is shown in Fig. 2.

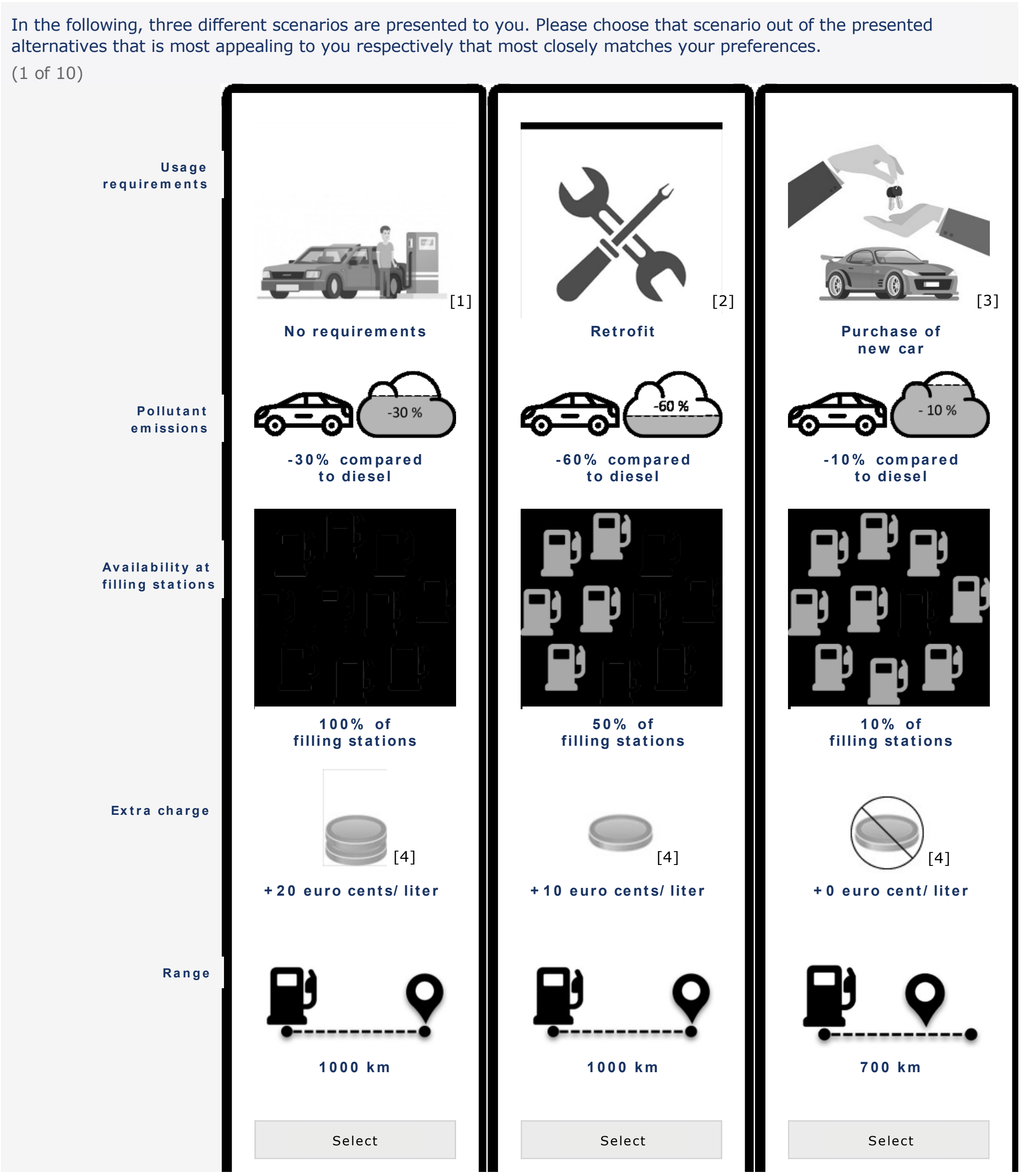

Fig. 2. Example for a choice task in the conjoint study (For picture sources, see Appendix, Table A.2).

3.4 Sample

We collected data via an online survey conducted in February 2018. Aiming for a sample representative for the German population in terms of age, gender, and education, an external market research institute recruited and financially rewarded the participants.

A total of 336 driver's license holders participated in the study. We included only participants with a minimum of driving experience (at least several times a year with an annual mileage of at least 5,000 km) in our analysis, to ensure that valid statements regarding the study topic were captured. We further excluded incomplete data sets, speeders (respondents with a response time below 65% of the median), and cheaters (respondents who gave wrong answers to attention tests included in the survey). This procedure resulted in 256 data sets.

The analyzed sample consisted of 43.8% women and 56.3% men from all regions of Germany (details on demographic characteristics and driving behavior of the sample are given in Table 3). The mean age was 44.2 years (*SD* = 13.0; Range: 18-78 years). Ratings on self-assessed knowledge about alternative fuels (min = 1, max = 6) revealed that the sample felt rather not knowledgeable about this topic (*M* = 2.9, *SD* = 1.3). 67.6% of respondents reported a (rather) low knowledge (score < 3.5), whereas 32.4% felt (rather) informed about alternative fuels in transport (score ≥ 3.5).

Table 3
Demographic characteristics and driving behavior (*n* = 256).

Demographic characteristics		Percentage of sample
Gender	female	43.8%
	male	56.3%
Age	young (18-35 years)	26.6%
	middle (36-55 years)	56.6%
	old (56-78 years)	16.8%
Education level	university degree	29.3%
	high school degree	26.6%
	primary, secondary, or middle school	44.1%
Region of Germany	Northern Germany (Bremen, Hamburg, Lower Saxony, Mecklenburg-Western Pomerania, Schleswig-Holstein)	21.1%
	Western Germany (North Rhine-Westphalia, Rhineland-Palatinate, Saarland)	26.6%
	Eastern Germany (Berlin, Brandenburg, Saxony, Saxony-Anhalt)	12.8%
	Central Germany (Hesse, Thuringia)	9.0%
	Southern Germany (Baden-Württemberg, Bavaria)	30.5%
Area of living	city center	21.5%

	city outskirts / suburb	38.7%
	rural area / village	39.8%
Car engine type	gasoline	68.0%
	diesel	27.0%
	hybrid	2.7%
	gas	2.0%
	electric	0.4%
Driving frequency	every day	58.2%
	several times per week	37.9%
	several times per month	3.5%
	several times per year	0.4%
Annual mileage	5,001-10,000 km	34.8%
	10,001-15,000 km	27.0%
	15,001-20,000 km	19.5%
	> 20,000 km	18.8%

3.5 Data analysis

We conducted the estimation of part-worth utilities and preference simulations using Sawtooth Software (Lighthouse Studio [62]). We estimated part-worth utilities and relative importance scores based on HB. Part-worth utilities indicate how a specific level of an attribute contributes positively or negatively to the overall preference for a scenario. Using zero-centered diffs (i.e., re-scaling part-worth utilities so that they amount to zero within each attribute when added together) allows for comparing part-worth utilities within an attribute [63].

We calculated the relative importance score of an attribute from the relative range between the maximum and minimum part-worth-utility of the attribute levels. It serves as a measure for the attribute's contribution to the overall preference of a scenario. More specifically, the higher the relative importance score of an attribute (the higher the range between part-worth utilities of the attribute levels), the more involved is the attribute in the choice decision for a scenario [63].

A limitation of conjoint analysis is that part-worth utility values can only be compared to each other within a single attribute but not across different attributes since “part-worths are scaled to an arbitrary additive constant within each attribute” (Orme [63], p. 78). Likewise, relative importance scores are tied to the set of attributes analyzed in the study (because the score is calculated relatively to the other attributes considered) and therefore cannot be transferred to other sets of attributes.

Further, based on respondents’ conjoint judgements, we conducted preference simulations using the Sawtooth Choice Simulator® [64]. The Choice Simulator®[3] allows for defining hypothetical products, which then compete against each other in a hypothetical market scenario. The results from this market simulation are *shares of preference* [63]. Preference shares are not equivalent to actual market shares because the market scenarios used in the simulation are always limited to the set of considered attributes. Sensitivity simulations show how consumers’ preference shares change when certain attribute levels are varied in a product scenario while all others are kept constant. The choice simulator can also be used in a more specific way to estimate how a new product performs compared with products already available on the market (e.g., the leading product on the market) in terms of consumer preferences [63]. Thus, in a last step, we defined product scenarios that matched one of three fuels: DME, an OME-diesel blend with 35 vol.-% OME as suggested by Omari et al. [26] (denoted as "O35" in the following), and conventional diesel most closely. We thus simulated the hypothetical market demand for the alternative fuel types compared to diesel and analyzed which properties can *and* need to be adjusted to improve preferences for DME and O35.

4. Results

[3] Choice Simulator® is the original term used by Sawtooth Software.

4.1 General acceptance of and intention to use alternative fuels

To evaluate the sample's general acceptance of and intention to use alternative fuels, we calculated mean scores for the two scales (Fig. 3, for an overview of the items included in the scales, see Appendix A, Table A.1). The sample reported a positive general acceptance of alternative fuels (*M* = 4.1, *SD* = 1.1), but the intention to use alternative fuels was lower and rather neutral (*M* = 3.7, *SD* = 1.1). The difference between acceptance and usage intention was statistically significant ($t(255) = 5.97$, $p < 0.001$, $\eta^2 = .12$).

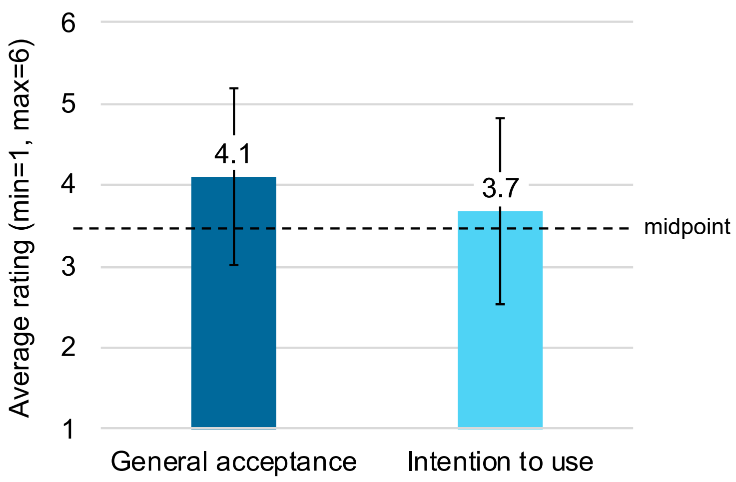

Fig. 3. Acceptance ratings for alternative fuels (*n* = 256). Mean values on top of the bars, error bars indicate standard deviations.

4.2 Decision criteria and preferences for alternative fuels

The importance scores (shown in Fig. 4) revealed that fuel costs and availability had the highest influence on preferences for alternative fuels: The extra charge payable for alternative fuels reached the highest importance score (27.3%), followed by the availability of the fuel at conventional filling stations in the near vicinity (21.4%). Usage requirements were of medium importance among the five attributes (20.7%). Driving range (17.8%) and pollutant emissions (12.7%) had the lowest decision-relevance.

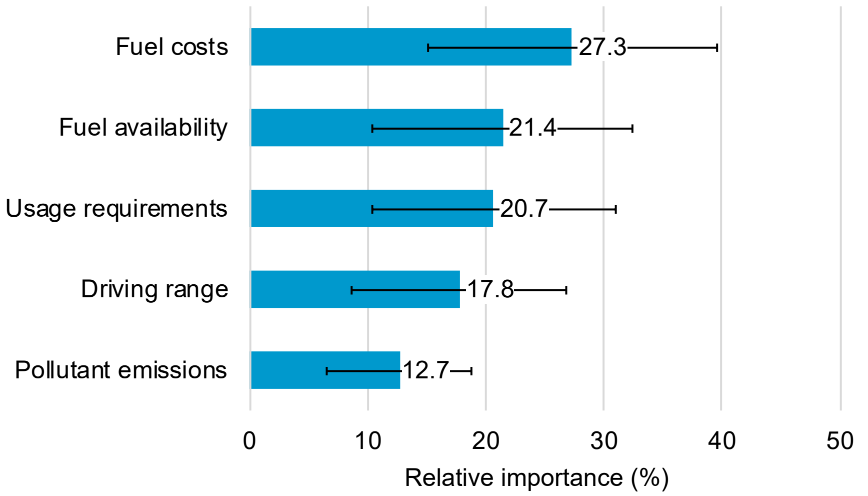

Fig. 4. Relative importance scores for alternative fuel attributes (*n* = 256). Mean values on top of the bars, error bars indicate standard deviations.

Fig. 5 displays the average part-worth utilities for all attribute levels. Respondents preferred the best performance on each fuel characteristic coupled with least efforts required from consumers' side: The highest part-worth utilities were found for maximum availability (at 100% of conventional filling stations), the highest possible range of 1000 km, and maximum emission reductions (-60% compared to diesel). At the same time participants opted for a fuel that requires no extra charge compared to diesel and that can be used in their current car without any needs for adjustments. In contrast, highest fuel costs (+ 20 cents/liter), lowest availability (10%), shortest driving range (400 km), minimum emission reductions (-10%), and the required purchase of a new car were most rejected.

However, the intermediate levels of fuel availability and driving range (availability at 50% of filling stations and a range of 700 km) still represented acceptable fuel design options.

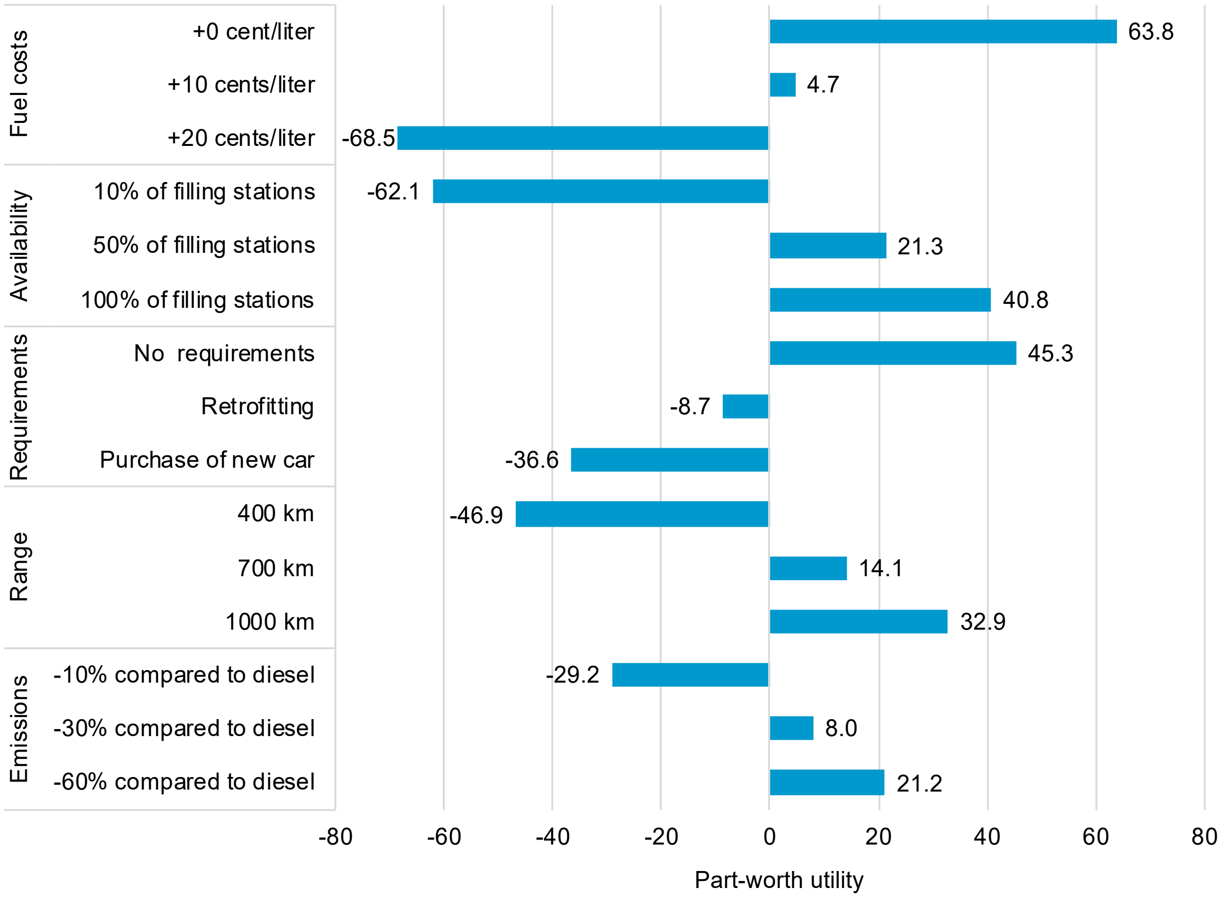

Fig. 5. Part-worth utility values (zero-centered diffs) for alternative fuel attributes and their respective levels (n = 256).

4.3 Sensitivity simulations for alternative fuel design scenarios

We simulated the sensitivity using the Randomized First Choice model (RFC), which calculates preference shares. This is based on the assumption that every participant selects the fuel option that possesses the maximum utility and also accounts for the degree of error inherent in choice decisions due to random influences, for example, one fuel option being temporarily unavailable on the market [65]. In the scenario “alternative fuel usage requirements” we examined changes in preferences for different usage requirement conditions (no requirement vs. retrofitting vs. purchase of a new car), since some alternative fuels are compatible with existing engines while others are not. Starting from the best-case configuration (a fuel option consisting of the most preferred levels for each attribute, see Section 4.2) for the four attributes pollutant emissions, fuel availability, fuel costs, and driving range, we analyzed the impact of different usage requirement conditions on preferences: The preference share for the *no requirement scenario* was highest (58.8%), followed by the *retrofitting scenario* (24.1%) and the *new car scenario* (17.1%).

In the sensitivity analysis, we kept the usage requirement conditions constant while varying the levels of the other four attributes (pollutant emissions, fuel availability, fuel costs, and driving range). Results are displayed in Fig. 6. For all single attribute levels, the relative preference for the *no requirement scenario* was higher than for the other two scenarios. Even when deteriorating emission reduction or driving range in the *no requirement scenario*, it was still preferred over *retrofitting* or the *purchase of a new car* even though these options offered maximum driving range and highest emission reductions. For fuel availability, preference shares of the *no requirement* scenario and the *retrofitting scenario* approached more closely if the *no requirement scenario* was linked to a decrease in availability (10% of filling stations) and the *retrofitting option* provided an availability at 100% of filling stations. However, even in this case, the preference for *no requirement* was higher (27.0%) than for the *retrofitting case* (24.1%). The only configuration which resulted in a shift of preferences was the *no requirement scenario* in combination with a high surcharge (+20 cents/liter) versus the *retrofitting scenario* without surcharge (+0 cent/liter): In this configuration the *retrofitting scenario* was more preferred (24.1%) than the *no requirement option* (17.5%).

Overall, results of the sensitivity analysis for different usage requirements show that the differences in preference shares were higher between the *no requirement scenario* and the *retrofitting scenario* than between *retrofitting* and *purchase of a new* *car*. For some fuel configurations (e.g., a fuel surcharge of +20 cents/liter or an availability at 10% of filling stations), the difference in relative preferences between *retrofitting* and *purchase* was only marginal.

Fig. 6 shows that for each attribute decreases in preferences were always lower between the most preferred and the middle level than between the middle and the least-preferred level (which is indicated by the differences in slopes of the trend lines). The only exception was the fuel cost attribute: here, the decrease in preferences was even higher between the most preferred (+0 cent/liter) and the middle level (+10 cents/liter). Moreover, the range between the highest and lowest preference shares for each usage requirement scenario was highest for the fuel cost attribute, which reflects the large relative importance of costs.

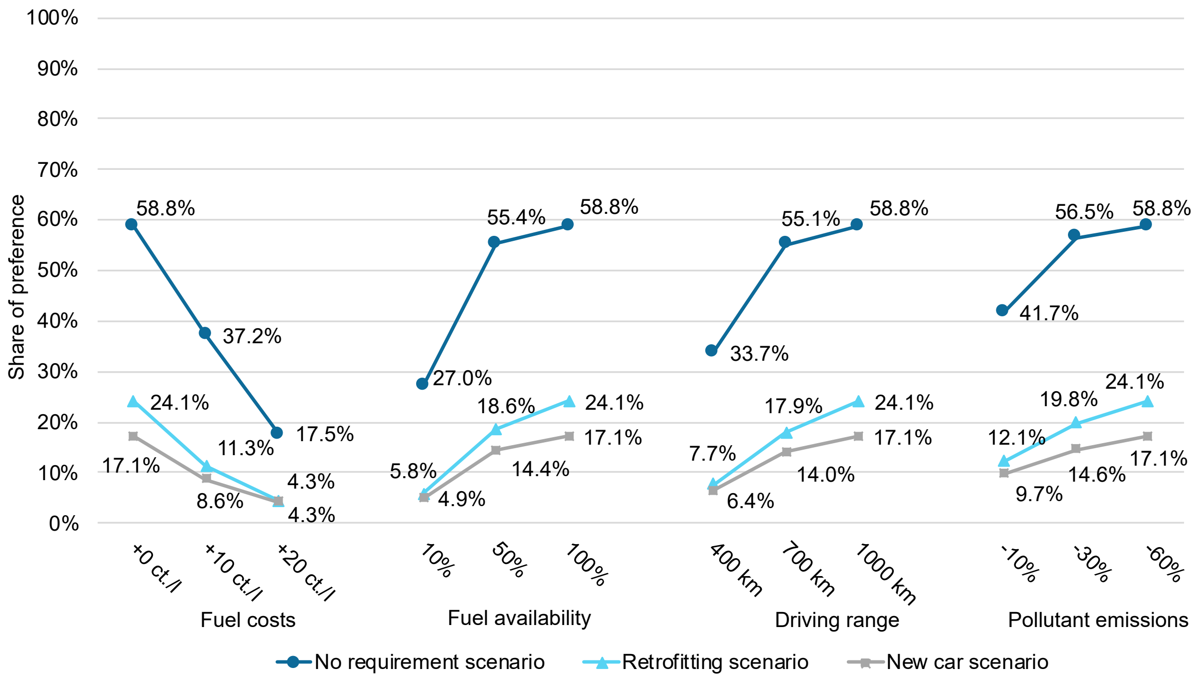

Fig. 6. Sensitivity analysis with constant usage requirement levels (*n* = 256).

4.4 Simulating the fuel market: Analyzing preferences for CI fuels (OME-diesel blend, DME, diesel)

OME and DME are two promising alternative fuels for CI engines but they are still in the development stage and it is unknown if they would be accepted by the public. To simulate their market demand in comparison to conventional diesel (within the scope of the five attributes), we defined product scenarios to closely match the properties of the three fuel types: the *O35 scenario* (a blend of 35 vol.-% OME in diesel [26]), the *DME scenario*, and the *diesel scenario* (see Table 4). As the attribute levels were predefined in the conjoint study and could not be adjusted post-hoc, we always took the level that matched each fuel best (even if not 100% accurate).

Table 4
Fuel scenarios used in the market simulator.[a]

Fuel type	Usage requirements	Pollutant emissions	Fuel availability	Fuel costs	Driving range
O35 (OME)	retrofitting	-60%	10%	+20 ct./liter	1000 km
DME	retrofitting	-60%	10%	+20 ct./liter	700 km
Diesel	no requirements	-10%	100%	+0 ct./liter	1000 km

[a] As the attribute levels were predefined, we always took the level that matched best (even if not 100% accurate).

The diesel scenario requires no changes to the vehicle, has no pollutant emission reductions by definition (hence the selection of the lowest possible level, -10%), perfect fuel availability in Germany, no difference in fuel cost by definition, and the highest range. For both DME and O35, we assumed that retrofitting of diesel vehicles was possible and necessary. For DME, this will include a pressurized tank as well as a modified injection system [21], while O35 might require changing seals and possibly the tank system (in case of OME_1) [25]. Since both fuels enable dramatic reductions in soot formation and by extension (through suitable engine calibration) also NO_x [21,26], we selected the strongest pollutant reduction level. Since neither of the two is currently available, fuel availability was set to the lowest possible value. Fuel costs were set to the highest value, since we assumed production from renewable resources. For driving range, O35 was left at 1000 km because its energy density is only about 15% lower than that of diesel and its engine efficiency is slightly higher [26]. DME can also enable slightly higher engine efficiencies than diesel [4], but on the other hand it has about 40-50% lower energy density than diesel and hence we selected 700 km as range.

Results revealed a far higher preference share for diesel (97.5%), whereas preference shares for O35 (1.7%) and DME (0.9%) were only marginal. To investigate if there are options for improving the low product attractiveness of the OME blend O35 and DME for car drivers, we performed a sensitivity analysis for the three fuel types. Table 5 provides an overview of the level variation used in the analysis.

Table 5
Level variation in the sensitivity analysis for CI fuels.

Fuel type	Usage requirements	Pollutant emissions	Fuel availability	Fuel costs	Driving range
O35 (OME)	freely varied[a] (base case: retrofitting)	-60%(X)[b]	freely varied (base case: 10%)	freely varied (base case: +20 ct./liter)	1000 km(X)
DME	varied between retrofitting and purchase[c] (base case: retrofitting)	-60%(X)	freely varied (base case: 10%)	freely varied (base case: +20 ct./liter)	700 km(X)
Diesel	no requirements(X)	-10%(X)	100%(X)	+0 ct./liter(X)	1000 km(X)

[a] "Freely varied" means all three levels were varied in the sensitivity analysis starting from the given base case (see Table 4).
[b] An (X) behind a level means that the level was kept fixed and was not varied in the sensitivity analysis.
[c] For DME, only retrofitting and purchase were varied as "no requirements" was not considered technically feasible.

As diesel is an established fuel with a high market penetration, we kept the levels for diesel (utilizing diesel as a benchmark for comparison with the DME and O35 options). We varied O35 and DME levels according to the current scientific knowledge of their technical feasibility. We took the initial scenario definitions in Table 4 as baseline (starting point) for the simulation. For O35, we varied the *usage requirements* since to our knowledge there is no consensus yet to what extent OME-diesel blends are directly compatible with today's diesel engines, whether retrofitting is necessary and feasible, or whether it requires completely new engines. For DME, we considered only retrofitting and new purchase since the characteristics of DME are too different from diesel to allow for direct application (e.g., it needs a pressurized tank because of its high vapor pressure). We varied *fuel availability* to examine the case where the fuels have been introduced and expanded to a significant share of filling stations. We varied f*uel cost* in the entire range to investigate the impact of improvements in fuel production processes resulting in lower cost. We did not vary d*riving range* since it is closely linked to the energy density of the fuels, which is essentially fixed. We also kept the levels for *pollutant emissions* constant because the reported reductions are so strong that we saw no reason to consider worse performance.

As seen in the sensitivity results in Fig. 7, preference shares for DME and O35 only slightly changed under the different conditions. For every fuel configuration, O35 and DME were vastly outperformed by diesel. The (relatively) highest preference shares for DME (10.6%) and O35 (15.4%) were obtained in case of no extra charge compared to diesel. Furthermore, Fig. 7 shows that preference shares were marginal and only changed slightly for the three usage requirement conditions, indicating that usage requirements hardly affected preferences for O35 and DME.

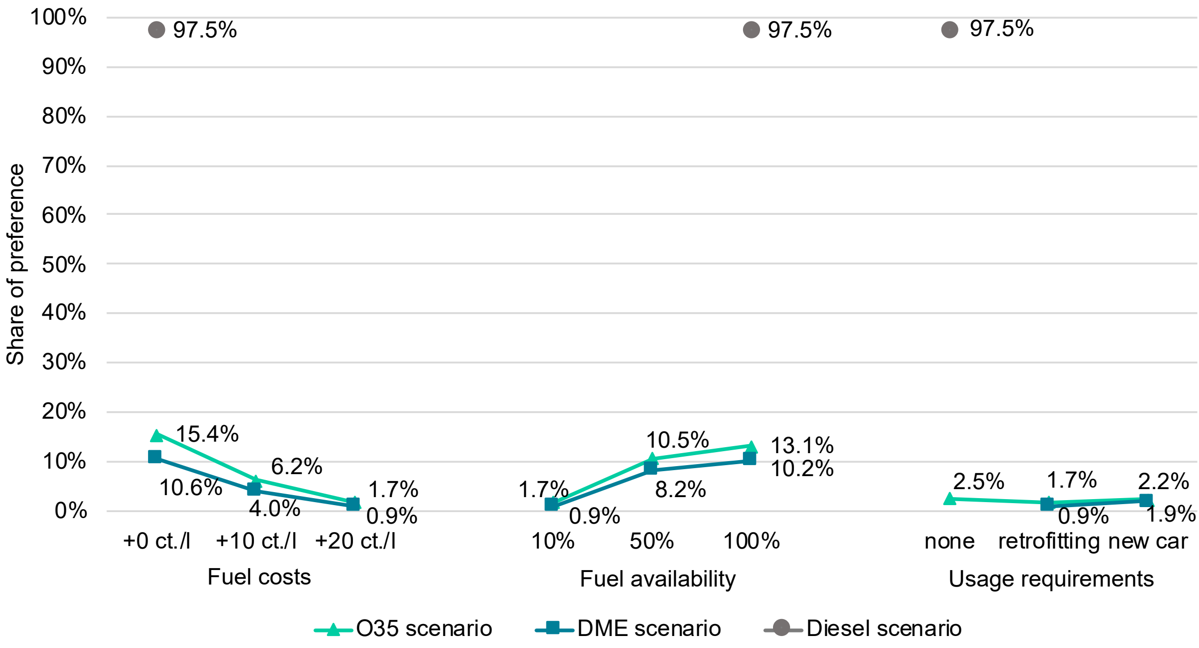

Fig. 7. Sensitivity analysis for O35 (OME blend), DME, and diesel (n = 256).

5. Discussion

By applying conjoint analysis, we investigated how alternative fuels are evaluated and perceived by customers. The results can be used to inform research, developers, and industry about how to develop acceptable and preferable alternative fuels.

5.1 Acceptance, evaluation criteria, and consumer demand for alternative fuels

Costs and the *availability* of alternative fuels were most relevant for alternative fuel preferences. This mirrors findings from previous research on alternative fuel vehicles (e.g., for fuel costs: [45], for availability: [47]). But alongside costs and availability, *usage requirements* such as adjustments vs. the purchase of a new car also influenced the evaluation of alternative fuels. Due to the fact that past research has mainly focused on preferences for alternative fuel vehicles (AFVs) and less on the fuel itself, this factor has received low attention so far. Consumers are not willing to purchase a new car to be able to use alternative fuels. In comparison, retrofitting of one's car had a slightly higher preference share, but it was shown that the majority of respondents would neither retrofit nor buy a new car to use alternative fuels. Results for the purchase of a new car corroborate findings from previous studies (e.g., [41]). However, in the present study the attribute *usage requirement* was deliberately not limited to financial costs for retrofitting and car purchase because it is unclear yet whether car drivers only consider financial costs in their evaluations of this attribute or also other dimensions (e.g., effort or time spent to retrofit or buy a car).

Surprisingly, the comparison between the three usage requirements showed that preference shares for the *no requirement scenario* were not 100%. Thus, although all other characteristics were the same, some people would rather buy a new car or retrofit their car than use a fuel compatible with their current vehicle. This finding might be explained by the influence of random factors (e.g., one fuel option being currently unavailable on the market), which were considered in the used simulation model. However, another explanation could be that some respondents thought that using an alternative fuel in their current car might be less effective or have negative effects on the engine compared to using a car that was specifically developed or retrofitted for the use of alternative fuels.

In contrast, *driving range* and *pollutant emissions* were the least important attributes in the current study. It should be noted here that the given range levels (400-1000 km) were already quite high compared to alternative propulsion technologies such as battery electric vehicles. In other studies, a higher decision-relevance of driving range was found (e.g., [48]). Although highly relevant for researchers developing novel fuels and engines and from a public health perspective, pollutant emissions were of very low decision-relevance to car drivers. Since some studies found CO_2 emissions to considerably impact preferences for AFVs (e.g., [50]), this could indicate that consumers value reductions of CO_2 emissions higher than that of pollutant emissions. On the other hand, a low relevance of CO_2 emissions was also found (e.g., [51]) and one should bear in mind that results obtained in conjoint studies are always relative to the set of attributes considered and can therefore not easily be compared. Consequently, further research should aim at a direct comparison of CO_2 and pollutant emissions within a single study (see Section 5.3). Moreover, the low importance of emissions does not necessarily imply that respondents did not value environmental effects. Apparently, respondents felt that their individual contribution to pollutant emissions was too marginal to affect air pollution and so they did not feel an urge to reduce the emission output of their car.

The market simulation of the OME-diesel blend O35 and DME against conventional diesel revealed that consumer preferences for both alternative fuel candidates were very low, indicating a low market demand for alternative fuels. This corroborates findings from past studies, which uncovered negative preferences for AFVs compared to conventional vehicles (e.g., [41]). Still, price and availability were revealed as possible starting points for positively affecting acceptance for alternative fuels. But these alone cannot compensate all drawbacks associated with alternative fuel use. Therefore, it is even more important to come to an understanding how to remove adoption barriers for alternative fuels and to develop appropriate steps of action to facilitate the socially accepted transition to alternative fuels in transport.

5.2 Application potential: Implications for fuel design and policy

In the following, we discuss how the study findings can be used to recommend actions for different stakeholder groups (fuel scientists, policy-makers, communication experts) on how to promote the socially accepted transition to alternative fuels in individual transport.

Fuel design: The high importance of fuel cost for fuel costumers confirms the role of fuel production cost as one of the primary objectives in the design of novel fuel production processes. In fact, in combination with the low relative importance of pollutant emissions found in the present study, the results also suggest that customers will not be willing to pay a premium for a cleaner fuel.

While availability at filling stations is inherently low for new fuels entering the market, its high relative importance suggests that it is worth emphasizing the search for fuels that are compatible with existing infrastructure or enable rapid expansion (e.g., because they only require minor changes).

The low relative importance of range, in particular in contrast to the findings of other studies including battery electric vehicles (cf. Section 5.1), suggests that reduced energy density of an alternative fuel might not be as large a drawback from a customer perspective as it is sometimes considered in technical discussions. This implies that it is possible to increase the search space for fuel design to include fuels that have elicited concern because of their energy density but perform well in other metrics.

The low relative importance of pollutant formation as well as the low preference shares for DME and O35 in the market simulation may seem daunting for fuel developers, who have mostly been focusing on environmental aspects. It should, however, be considered that we restricted the evaluation to pollutants and did not consider CO_2 emissions (and, by extension, explicit use of renewable raw materials and energy sources). Moreover, perception might change once pollutant formation gets linked to specific usage restrictions (e.g., diesel driving bans). Both of these points require further research (cf. Section 5.3). Insufficient consideration of pollutant and CO_2 emissions in purchase decisions would then ultimately mean that such factors needed to be left to legislation, unless improvements in engine and fuel production process design enable alternative fuels that are competitive to established options with respect to cost, availability, and range as well.

Policy: We identified price and availability as promising starting points for positively affecting acceptance for alternative fuels. Financial incentives could stimulate demand for alternative fuels, for example by tax cuts or exemptions to lower fuel prices as it is currently the case for diesel compared to gasoline. Also, subsidies for retrofitting or the purchase of a new car could promote the adoption of alternative fuels [45].

Further policy measures should aim at improving the availability of alternative fuels, e.g., by expanding the infrastructure for alternative fuels that are incompatible with existing refueling infrastructure (such as methane, hydrogen, and DME), to accelerate the market diffusion of these fuels.

Since the expansion of refueling infrastructure is linked to significant costs, the threshold or minimum requirement of gas stations offering alternative fuel needs to be identified for a positive market adoption. According to the present results, 50% of filling stations would suffice to meet consumers' requirements. Further studies should be conducted to determine if this availability threshold applies for all consumers or if it is influenced by further characteristics (e.g., urban or rural areas, driving distance to the next gas station). Nevertheless, expansion of refueling infrastructure for electric vehicles, hydrogen, and methane will take certain time, making these fuel types less attractive as short-term solutions. To achieve a transition to a sustainable mobility sector, also more immediate strategies are needed which are targeted at alternative fuels compatible with existing engines and fuel infrastructure, since the adoption of these could be more easily realized in the short-term. For example, current research aims at clarifying to what extent OME-diesel blends are compatible with today's engines and infrastructure, which would make these fuels a promising option.

Communication and information concepts: Information and communication concepts for alternative fuels should be directed at providing comprehensive and neutral information to the public to enable an informed decision for car drivers which fuel to use. Information should be provided by different stakeholders, such as the government, the fuel industry (e.g., fuel companies, filling station owners), but also by research (universities, research institutes).

The following guidelines for information concepts can be derived: The public and consumers need to be informed about the price and the availability of alternative fuels (e.g., filling station networks), since both aspects affect preferences the most. Otherwise car users might refrain from retrofitting or buying a new car if they fear a lack of refueling facilities. Also, car drivers might be unable to compare fuel prices because alternative fuels are given in different units than conventional fuels (e.g., price per kg instead of liter for natural gas), for which they have no reference frame [35].

Even though pollution reduction was only of minor decision-relevance for consumers, this environmentally-relevant message should also be highlighted, since past research identified health- and environmental aspects as acceptance-relevant aspects in the context of eco-innovations, especially for novices [66]. Alongside environmental information also the personal benefits of alternative fuel use and the related pollution reduction (e.g., being exempted from diesel driving bans) should be emphasized because these might be a considerable incentive for switching to alternative fuels.

Moreover, information concepts on alternative fuels should not only transport factual knowledge, but – especially when it comes from industry sources – also trust-enhancing content [67]. Finally, information and communication campaigns should be timely launched because they are especially effective in early phases of technology diffusion [68] and can at this stage reduce the emergence of misconceptions and concerns due to insufficient information provision as it was the case for E10 in Germany.

5.3 Proposed future studies on alternative fuel acceptance

The results and limitations of the present study point to some unresolved issues which should be investigated in future research to broaden the perspective on alternative fuel acceptance and timely integrate acceptance as an objective function in the design of alternative fuels.

We considered pollutant emissions but not CO_2 emissions. Since CO_2 emissions from transport and their relevance for climate change are highly topical in the public debate, they should be integrated into future studies alongside pollutant emissions to compare which environmental effect is more relevant for consumers. Further, we framed pollutant emissions in terms of environmental effects but not with respect to possible health effects due to air pollution and possible diesel driving bans in urban areas that are currently publicly discussed in Germany. It should be examined in a subsequent study if information provision (framing) has an effect on preferences of alternative fuels: Does the pollutant emissions attribute gain in importance if it is associated with personal consequences for driving behavior?

The current study should be replicated at a later point in time since social acceptance is time-dependent. Alternative fuel acceptance is constantly impacted by media coverage, policy and public debates, the current stage of development and experience with a new technology, etc. and might therefore change over time. Future research efforts should also investigate the effect of user diversity on preferences for alternative fuels to identify different consumer groups and develop target-group-specific information strategies. Moreover, research efforts should perform a cross-country comparison of alternative fuel acceptance and preferences to consider different political and R&D roadmaps for sustainable transport, different mobility behavior, e.g., higher share of natural gas and electric vehicles in other countries.

As we identified fuel costs as the most decision-relevant attribute as well as a low willingness to pay an extra charge for alternative fuels, future research should investigate if there are other preferred characteristics of alternative fuel production that consumers value and weigh off against increased fuel costs. These could include an improved carbon footprint, local production of alternative fuels vs. imports, local creation of jobs. This would help to shape the pathway to a socially accepted and sustainable fuel production.

Also, further studies should not only capture the driving behavior of respondents (driving frequency, mileage, and engine type) but additionally examine the refueling behavior to distinguish different types of car users.

Furthermore, future acceptance studies on alternative fuels should expand the market acceptance perspective (end-product perspective) and consider two currently neglected acceptance dimensions: socio-political and community acceptance. Future studies should also examine the acceptance of the whole fuel life-cycle, including infrastructure needed for fuel production, distribution, and refueling, e.g., biorefineries and filling stations.

Finally, the limited scope of the current study (focus on individual transport and the chosen single-country approach) needs to be addressed.

In this study, we decided to focus on individual transport because in this context, car drivers actively choose which fuel they want to use. However, research has found alternative fuels to be especially suitable in long-distance transport [3], shipping [69], and aviation [70], since battery electric solutions suffer from range issues in these long-distance applications and these sectors cause high pollutant and GHG emissions. Thus, future studies should investigate the acceptance of alternative fuels in various applications to identify stakeholder and policy requirements for the different transport sectors.

A further limitation refers to the chosen single-country approach: Only car drivers in Germany were surveyed. Due to country-specific differences, e.g., related to policy-making in the energy and transport sector, to the previous experience with alternative fuels (such as the reluctant market adoption of E10 in Germany [10]), and to cultural value concepts regarding environment and mobility, a single-country approach is methodologically sound. However, as our sample characteristics covered a broad group of car drivers (all ages, different educational levels, different geographical regions, different socioeconomic conditions), we can assume that preference ratings also apply to other comparable driver segments in other countries. Still, this needs to be shown in further research. As a consequence, future studies should aim for a comparison of acceptance patterns and consumer groups in different countries to examine the effects of social and cultural value concepts on technology acceptance [71].

6. Conclusion

The present conjoint study investigated the decision criteria and preferences of car drivers for alternative fuels to derive recommendations for an acceptance-optimized fuel design. Fuel costs had the highest relevance for car drivers' fuel choice decisions, followed by fuel availability and usage requirements. Interestingly, pollutant emissions only marginally affected preferences for alternative fuels although they are a crucial factor in fuel design. We found that neither improvements in fuel availability and driving range nor lower usage requirements could offset the decrease in preferences caused by higher fuel costs. This underlines fuel costs as decisive barrier for the adoption of alternative fuels. The results of a market simulation including the alternative fuels O35 (an OME-diesel blend with 35 vol% OME) and DME as well as conventional diesel indicated a low market demand for alternative fuels within the scope of the considered attributes. Based on our findings, we derive the following recommendations for a fuel design aiming at socially accepted alternative fuels that will stimulate market demand for alternative fuels:

1. Alternative fuels need to be affordable. Ideally, there should be no or only a marginal extra charge compared to conventional diesel. This could be achieved by tax reductions or subsidies in addition to sustained research efforts to reduce the production cost of alternative fuels.
2. A sufficient refueling infrastructure should be established: respondents expect the fuel to be available at 50-100% of filling stations. To achieve this quickly,

alternative fuels should be compatible with existing refueling infrastructure or require only minor adjustments.

3. Research and development of alternative fuels should focus more on fuels that can be easily provided at a higher number of (conventional) filling stations rather than on maximizing driving range since car drivers seem to be more willing to accept drawbacks in range than in availability.
4. Alternative fuels should be compatible with existing engines since car drivers' willingness to retrofit their car or buy a new vehicle to use such fuels are limited.

Future research should identify how to directly integrate social acceptance as an objective function in the screening of possible fuel candidates or even in the optimization-based fuel design in order to minimize the risk of an early failure of alternative fuels on the market.

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Appendix A

Table A.1
Items used to measure self-reported knowledge and perceptions of alternative fuels.[a]

Self-reported knowledge about alternative fuels	Cronbach’s ∝ = 0.93
I feel well informed about alternative fuels.	
I know a lot about alternative fuels.	
I know more about alternative fuels than my friends and acquaintances.	
General acceptance of alternative fuels	
I find alternative fuels acceptable.	
Intention to use alternative fuels	Cronbach’s ∝ = 0.81
I don’t want to use alternative fuels.[b]	
I would be willing to retrofit my car to use alternative fuels.	
I can well imagine switching to alternative fuels.	
A retrofit of my car is not an option for me.[b]	

[a] All items had to be answered on six-point Likert scales (1 do not agree at all – 6 fully agree).
[b] Negatively worded items were recoded for calculating scale mean values.

Table A.2
Picture sources used in the conjoint tasks.

[1]	Man refuelling his car at petrol station” (https://www.freepik.com/free-vector/man-refuelling-his-car-at-petrol-station_1311090.htm#term=refuelling&page=1&position=0) by Iconicbestiary – Freepik (https://www.freepik.com/iconicbestiary).
[2]	“Black and white car repair icons” (https://www.freepik.com/free-vector/black-and-white-car-repair-icons_1011161.htm#term=black%20white%20iconic%20car&page=1&position=10) by Macrovector – Freepik (https://www.freepik.com/macrovector).
[3]	“Buying, renting a new or used speedy sports car” (https://www.freepik.com/free-vector/buying-renting-a-new-or-used-speedy-sports-car_1311573.htm#term=buy%20rent%20car&page=1&position=0) by Iconicbestiary – Freepik (https://www.freepik.com/iconicbestiary).
[4]	“Coin Money Kopek” (https://pixabay.com/en/coin-money-kopek-1873955/) by 1264187 – Pixabay (https://pixabay.com/en/users/1264187-1264187/), licensed under CC0.

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