Reverse Engineering of Stakeholder Preferences – A Multi-Criteria Assessment of the German Passenger Car Sector

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Abstract: Germany is a frontrunner in setting frameworks for the transition to a low-carbon system. The mobility sector plays a significant role in this shift, affecting different people and groups on multiple levels. Without acceptance from these stakeholders, emission targets are out of reach. This research analyzes how the heterogeneous preferences of various stakeholders align with the transformation of the mobility sector, looking at the extent to which the German transformation paths are supported and where stakeholders are located.
Under the research objective of comparing stakeholders' preferences to identify which car segments require additional support for a successful climate transition, a status quo of stakeholders and car performance criteria is the foundation for the analysis. Stakeholders' hidden preferences hinder the derivation of criteria weightings from stakeholders; therefore, a ranking from observed preferences is used. This study's inverse multi-criteria decision analysis means that weightings can be predicted and used together with a recalibrated performance matrix to explore future preferences toward car segments.
Results show that stakeholders prefer medium-sized cars, with the trend pointing towards the increased potential for alternative propulsion technologies and electrified vehicles. These insights can guide the improved targeting of policy supporting the energy and mobility transformation. Additionally, the method proposed in this work can fully handle subjective approaches while incorporating a priori information. A software implementation of the proposed method completes this work and is made publicly available.

Highlights:

- Deriving systematic weightings from a ranking of options reveals preferences.
- Policies supporting the mobility transition should be place-based.
- Medium-sized battery electric vehicles will gain market share.
- Heterogeneity of stakeholders will shape the mobility transition.

Keywords: Mobility Transition, E-Mobility, Preference Assessment, Multi-Criteria Decision Analysis, Regionalization

Wordcount: 7346

Abbreviations:
MCDA: Multi-criteria decision analysis
ICE: Internal combustion engine
HEV: Hybrid electric vehicle
BEV: Battery electric vehicle
SUV: Sports utility vehicle

1 Introduction

In response to the Paris Agreement adopted in 2015 and the most recent Intergovernmental Panel on Climate Change's reports, more than 100 countries have committed to reducing their greenhouse gas emissions to zero over the coming decades [1]. Currently, the mobility sector accounts for 24% of direct global CO_2 emissions [2]. Hence, the so-called Net Zero targets require significant changes from this sector, including changes in the transport mix and technological changes.

The following observations guide the analysis. Concerning car purchases, stated preferences and empirical observations do not necessarily match due to hypothetical bias. When respondents face hypothetical scenarios in surveys of unknown situations, the recorded outcome deviates from actual behavior [3, 4]. Conducting Multi-criteria decision analysis (MCDA) to assess car purchasing criteria supports the observation that surveyed information on preferences does not always correspond to actual preferences [5]. Hence, there is a need to develop and employ an approach that enables the identification of hidden priorities.

Secondly, policy measures will be easier to implement if stakeholders support the efforts. The "yellow vests" protests in France showed that a transformation of the transport system requires consideration of the heterogeneous attitudes of the public. Since the attitudes of car manufacturers could foster or hamper the transformation of the transport sector, it is necessary to take a closer look at their attitudes. In the past, car manufacturers partially showed resistance to e-mobility, citing low demand, which resulted in limited activities in developing and marketing e-vehicles. Car manufacturers, to a large part, still rely on producing cars with internal combustion engines (ICE). In some instances, only expect a decline in this technology as late as 2050, suggesting synthetic fuels as an alternative [6].

Thirdly, the development of car technologies' characteristics is linked with uncertainties. Information on car purchasing criteria can help assess possible attitudes toward car technologies. In the context of sensitivity analyses of energy scenarios, fuel prices and costs for fuel cell cars or electric cars, as well as charging time and charging infrastructure, are factors that are often adjusted. Assessing the impacts of the modifications in these factors requires information on their importance in the purchase decision. Thus, reliable information on purchasing criteria is necessary. This information could help assess the direction that strategies in the transport sector should be developed to increase their acceptance [7].

In this study, a modified MCDA approach is applied to the example of car purchases in Germany. Instead of relying on further surveys to obtain criteria weightings, we derive weighting factors systematically, reflecting differing attitudes towards car characteristics based on empirically observed or claimed rankings of options. Our method does not require extensive empirical work with humans or stated preferences. Additionally, heterogeneity within the group of car purchasers and vehicle manufacturers is explicitly considered. Based on this and information on technological developments, conclusions can be drawn about attitudes toward future car technologies and car segments likely to be preferred in the long term. Moreover, the approach can be used for spatial analysis. The overarching research question concerns the extent to which different transformation pathways for the mobility sector enjoy support from German society.

Research emphasizes the impact of socio-demographic factors on car purchasing decisions. Other research tests several household criteria, with gender, age, occupation, political views, education, household income, car ownership, and kilometers traveled daily by car, included in a survey analysis, see, e.g., the study on electric mobility in Scandinavian countries by Sovacool et al. [8]. A person's age can affect their need and preference for mobility, meaning that young and older people travel less than middle-aged people. This phenomenon is even more apparent if these household types also have children [9]. Many conflicting studies exist that elaborate on different characteristics of households that should be considered aside from income and size. Excluding these additional criteria can lead to financial burdens for families and impair the fairness of policies. These policies must avoid lock-ins and supporting end-of-pipe technologies, but they may have unintended consequences. If policy measures like taxes are implemented, they could influence households differently based on their characteristics, which could generate an unfair burden [9].

In Norway, another study compares battery electric vehicles (BEVs) to conventional cars with a diesel or gasoline ICE. It investigates whether diverging household characteristics play a role in the adoption decision. The socio-demographic profiles of drivers vary according to the type of car they own and also influence general mobility decisions. BEV drivers are younger, have a higher income, and have more children than conventional car owners. The more a person's characteristics diverge from this profile, the lower the probability of owning a BEV. Thus, personal factors must be considered while planning a mobility transition [10].

Further research confirms that the spatial context affects mobility decisions distinguishing between rural and urban contexts, refers to spatial aspects, and mentions age as an influencing factor [11, 12]. Different household characteristics must be considered to properly assess the participation of the stakeholders in the mobility transition.

Since decisions in the mobility sectors are determined by factors that differ in terms of their units and dimensions, approaches are needed which can deal with this challenge [13]. A widespread approach to address complex decisions resulting from heterogenous sets of relevant criteria is MCDA (see, e.g., [14, 15]). MCDA focuses on the ranking of options by stakeholders taking the options’ characteristics and their weightings by the stakeholders into consideration.

MCDA has proven its strengths and applicability in many studies (e.g., [15, 16]). Its power, in contrast to other approaches, allows a ranking of decision options based on heterogeneous factors. It neither requires a monetarization of factors (see, e.g., [17] as an example for cost benefit analysis) nor a complex and computationally intensive analysis (see, e.g., [18] for examples for multi-objective optimization models).

Concerning mobility, MCDA has been applied to decision problems around preferences for urban public transport options [19-21], investing in transport infrastructure [22, 23], or for the evaluation of energy and environmental efficiency of different transport modes [24]. Most of these studies focus on specific projects, such as appraising investment options for the Baltic rail network [22] or evaluating transport policy alternatives within particular cities.

Some studies combine MCDA with other tools, for instance, to employ MCDA to supplement cost-benefit analysis [22]. MCDA can be applied to non-monetary criteria and combined with a cost-benefit analysis to derive a single measure of attractiveness for an option. In this context, it also targets criteria that are difficult to quantify [22]. Other MCDA methods, e.g., the Data Envelopment Analysis (DEA) method, can be combined with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to obtain a ranking of options defined as efficient [19, 24].

Many methods exist for finding weightings in the context of decision making using MCDA. They can be grouped into subjective and objective methods [25]. Subjective methods are based on surveys, e.g., [19], or on expert knowledge or assessments (see, e.g., [14, 26]). Therefore, they may be prone to bias and, in the case of surveys, to inconsistent statements from stakeholders.

As an objective method for multi-criteria assessment and selection of BEVs for transportation applications, SECA [25] can be employed [27]. Objective methods, as in [28], provide weightings for a robust decision in the context of decision-making, using characteristics alone. As they cannot exploit the outcome of a decision as a priori information, they are not suitable for deriving weightings from observed actions or stated preferences.

	Subjective	Objective	Inverse MCDA
Short description	Information gained by conducting surveys or by expert judgments	Application of mathematical methods for decision-making (without explicit stakeholder consideration, e.g., multi-objective optimization)	Identification of weightings that fit a given ranking, explicit stakeholder consideration
Examples	[19, 26]	[25, 27]	
Required inputs	Information on stakeholders' preferences	Objective information	Ranking of options
Challenges	Relatively costly/time-consuming (depending on the size of the survey or on the number of experts) Risk of hidden preferences	Identification of artificial factors ("free of personal thoughts and preferences") Differentiation according to stakeholders impossible	Calculated/artificial weightings
Advantage	Use of primary data	No subjective bias	Fast, moderate data requirement Exploitation of observed behavior

Table 1: Methodological performance of different weighting approaches compared. Own illustration.

Table 1 compares the two major MCDA approaches to this work's inverse MCDA method.

Monte-Carlo simulations or fuzzy approaches have also been used to assess impacts resulting from weighting factors' uncertainties (e.g., [15, 26]). These approaches require information on probability distributions that are often unavailable or linked with uncertainties.

The literature review supports the conclusion that an assessment of future mobility requires a consideration of heterogenous stakeholders' individual preferences. MCDA is an appropriate approach for considering factors that differ in units and scales. However, the specification of reliable weightings is still challenging, and there is a gap concerning assessing weighting factors based on an observed ranking of options.

Based on these findings, this study aims to provide an inverse MCDA approach that enables to draw conclusions on the weightings of car characteristics based on rankings of heterogeneous stakeholders. It allows the identification of low-emission car segments that need further policy support to reach the market share necessary for meeting emission reduction goals. Additionally, a python software implementation of the executed method is created and made publicly available [29].

The study is organized as follows. The method is described in section 2, the results are discussed in section 3, and the conclusion is in section 4.

2 Materials and methods

Figure 1 shows the process used to find stakeholders' attitudes. Since it is expected that the stakeholders do not always reveal their actual preferences, it is necessary to employ an approach that can help identify hidden preferences. In addition, the process must be flexible concerning changes in the characteristics of cars and attitudes.

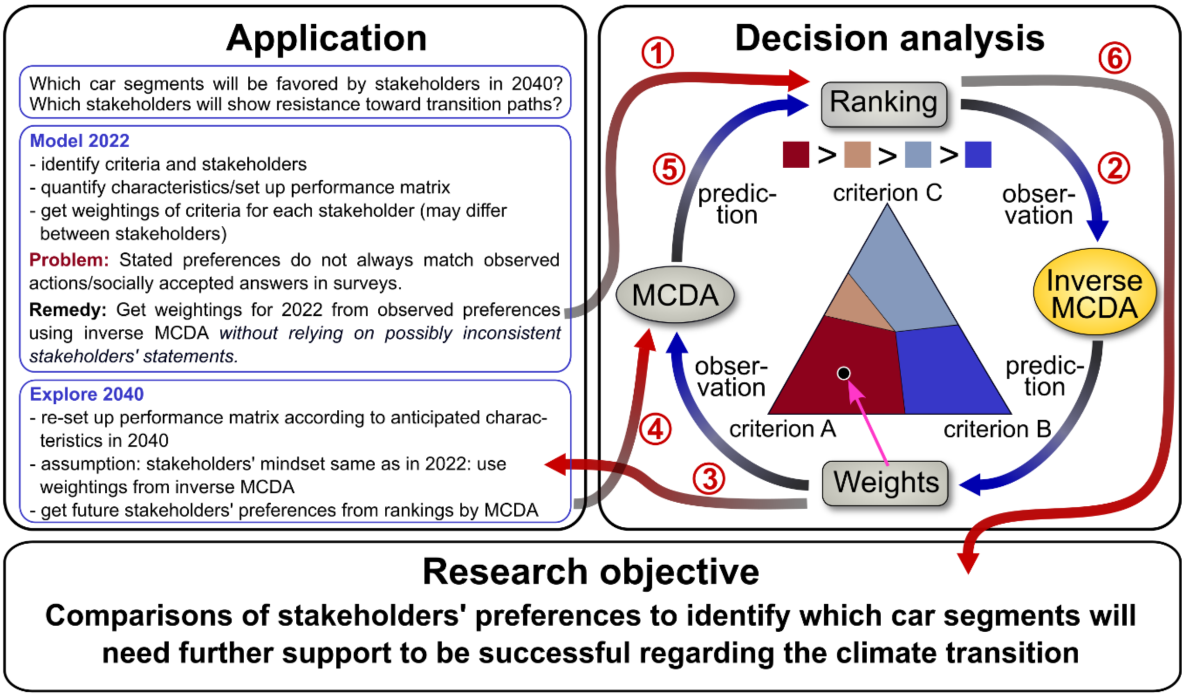

Figure 1: Overview. Own illustration.

The inverse MCDA approach, which fulfills these requirements, is detailed in the following sections.

2.1 General assessment procedure

MCDA is a structured way of approaching complex decision problems in which the decision-maker must assess conflicting criteria when deciding between alternatives [30, 31]. Approaches fall into two broad categories: outranking methods and methods based on multi-attribute utility theory [32]. The concept of 'dominance' underlies outranking approaches, whereby an alternative dominates another if it shows superior performance on a sufficient number of essential indicators without a substantially inferior performance on any of them [33]. Multi-attribute utility theory is based on utility functions that express the preferences of alternatives from the decision maker's point of view; marginal utility functions relating to each indicator are aggregated to form one overall function [34]. MCDA techniques are typically used to rank different decision alternatives from the decision maker's preferences. They are employed in this study to assess the desirability of the German mobility sector car segments from the stakeholders' point of view.

Common approaches belonging to the outranking family include ELECTRE [35] and PROMETHEE [36]. Under PROMETHEE, positive preference flows, where an alternative performs better than another on a particular criterion, are compared with negative preference flows, where an option performs worse on a specific criterion [36]. These flows are then compared across all criteria to form a net preference flow that ranks the alternatives from best to worst [37]. For interpreting the results of PROMETHEE, it is valuable to set thresholds defining the point after which a superior performance on a criterion leads to the alternative becoming preferred from the decision maker's point of view [38].

Various MCDA methods, including PROMETHEE, require evaluating each alternative for each criterion. First, the aggregated preference index π is calculated. It corresponds to the pairwise difference in the alternatives' performance scores on each criterion multiplied by the weightings allocated to those criteria by each stakeholder [36]. For this work's method for determining the weightings w from observed preferences, see section 2.3.

While MCDA often assumes a single stakeholder, many decision problems require considering multiple stakeholders [39, 40]. A successful energy system transformation depends on stakeholders' support, but the implications of transformation pathways differ for each stakeholder. Therefore, stakeholder-specific benefits and costs of each path must be considered.

2.1.1 Individual perspectives

The literature often treats households as a single fixed stakeholder alongside others, like industry, rather than as a set of actors with differing characteristics [41]. As consumers of energy and mobility, households must be the focus of attention when developing successful transition paths toward sustainability [8]. Therefore, a comprehensive set of all relevant socio-technical aspects is necessary, including technology options, policy measures, the simulation of diverging transition paths, and cultural and behavioral insights [42]. Social factors are crucial because understanding the acceptance and perception of different transition paths is essential for incentivizing sustainable behavior. Social factors account for the actions of stakeholders and their decision-making. The household actor's age, if they have children, their gender, or their working conditions are suitable characteristics to approximate these decisions and, thus, can be related to behavior and, lastly, the acceptance of the transition [43].

Households' perspectives influence their preferences, which shapes their behavior. If a particular household actor prefers a consumption choice, its acceptance is likely higher. Households effectively represent the population and, thus, constitute a significant stakeholder affected by the energy and mobility transition, in which they actively participate as consumers. They are differentiated by age, family type, net household income, and population size of the area in which they live. The selection of the stakeholders and their specification is based on a cluster analysis of data by VuMA Touchpoints [16] on car purchase decisions of private households.

The factor representing age is modeled by dividing the households into two groups – those where the head of the household is between 15 and 39, covering young households, and those between 40 and 99, representing the older population. According to the literature, the mobility needs of younger and older households differ [8, 44]. Very young or very old households are responsible for few GHG emissions, mobility included. Still, the effects of age on mobility are not clear-cut and often conflicting [9]. Households are also differentiated according to whether there are children under 14 or no children. Families with children naturally have a larger household size, which can be used as a proxy and points to a relatively higher potential effect on mobility.

Another factor for characterizing households is their net household income. Households are divided into two groups, those with less and those with more than 2000 Euros net income. Income is a characteristic commonly used to differentiate households [45]. Overall household emissions rise with increasing income, while emissions from transport decline but are lower than emissions in other areas of living [9].

Furthermore, the place of residence is considered by dividing households in cities with fewer and more than 500.000 inhabitants, which reflects the significant difference between the infrastructure in highly urbanized and less urban areas. In agglomerated densely populated regions, fewer households need to own cars as they can use public transport as an alternative [44]. Furthermore, if households own cars, they are often not as dependent on vehicles with a high range, as distances traveled are, on average, shorter than in rural regions. Where the population density is sparse, households often have no choice but to rely on individual mobility [11].

The primary data for the household characteristics are obtained from the income and consumption survey ("Einkommens- und Verbrauchsstichprobe") issued by the statistical office. It contains information about the living conditions of private households in Germany, such as income, place of residence, or consumption. About 60,000 households of all social groups are included in a quota sampling process, meaning it is representative of almost the entire population in Germany [46]. The criteria are filtered according to income, age, children, and size of the area in which they live and then extrapolated with factors provided by the survey to obtain information about the entire population in Germany. There exist differences in the specific features of cars the households value most, depending on their individual needs derived from their age, family status, income, and place of residence. A study by Aral [47] is used to select the range of motivations of consumers that influence a possible purchasing decision for a car. Decision criteria are disaggregated for different car segments. They contain, e.g., price-performance ratio, comfort, safety, design, price, and environmental friendliness.

The future of the mobility sector depends not only on the development of attitudes on the demand side but also on the support of technology by car producers. A glance at the big vehicle manufacturers shows that they concentrate on different car categories. Peugeot, for instance, focuses on small cars, whereas Mercedes and Tesla produce mainly medium and large cars. Tesla and Toyota are examples of vehicle manufacturers strongly prioritizing the production of cars with low or no greenhouse gas emissions [48, 49]. The range of manufacturers' product portfolios indicates no single decision criterion. Instead, multiple criteria may be relevant for decisions on the portfolio of cars.

One criterion is short-term profit maximization. As an indicator, we use car categories' specific profit rates. A further criterion is the current market share of the individual car categories in Germany, reflecting the manufacturers' attitudes towards mass or premium markets.

Rogers [50] stresses the importance of compatibility with existing structures for innovation processes. Hence, ‘compatibility with existing structures’ and ‘degree of novelty’ are criteria. Research also identifies dependency on foreign suppliers as relevant for manufacturers (see, e.g., [51]), motivating the criterion ‘import dependency’. The criterion ‘potential market share in 2050’ indicates the long-term perspectives of some car producers and identifies the criteria ‘image,’ ‘production cost,’ and ‘CO_2 emissions’ as relevant for vehicle manufacturers. ‘Image’ aims to incorporate the attitude towards vehicle manufacturers like Porsche and Mercedes, and ‘production cost’ helps to explain attitudes towards mini and small cars[1]. ‘CO_2 emissions’ are included since environmental constraints affect car portfolios [52].

2.1.2 Technological options

Ambitious emission reduction targets set on a national and a European level will change the future of the mobility sector. The set of possible options for the transformation of the mobility sectors includes, e.g., increases in the use of public transport systems, reducing the transport of goods by road or by trains, as well as reducing mobility generally (see, e.g., [53, 54]). This study focuses on another critical option, namely switching to more environmentally-friendly car technologies. The actors' attitudes towards different car technologies are analyzed, and the extent of support for new technologies is assessed.

The MIT Energy Initiative [54] in the technology options is followed, and attitudes toward BEVs, hybrid vehicles, cars equipped with hydrogen fuel cells, and advanced ICE vehicles are assessed. Research highlights that car size matters (e.g., [55]). Hence, the categories are sub-classified into small, medium, and large cars.

Assessing the different car segments requires information on the car characteristics relevant to the actors. These characteristics include prices, resale value, comfort, family friendliness, and image (compare Table A. 1, Table A. 2, and section 2.1.1). The latter characteristics are challenging to assess, so research often focuses on quantitative factors. For an appropriate assessment of attitudes, qualitative aspects are essential, and this research exploits information on existing car technologies and extrapolates future technologies' characteristics. Data published by the German Automobile Association, ADAC, is used, one of Europe's most significant motoring associations, which regularly tests cars based on more than 300 criteria [56].

[1] E.g., the market share of premium cars is not as high as the share of medium-sized cars.

These are graded using a scale from one to five (with additional markups and markdowns resulting in 0.6 (best) to 5.6 (worst)) and grouped into critical characteristics. These data are a unique source for assessing cars, collected autonomously by an independent association using a standardized list of parameters.

This study considers ‘sample cars’ for each car segment and propulsion type, where three standard cars of each segment/propulsion technology are selected. Then ranges are developed for the criteria manifestation. For example, a VW eGolf in the medium-sized car segment of BEVs was chosen as standard, and its characteristics were adjusted for variation with data on the same criteria as the BMWi3 and the Hyundai IONIQ Elektro [57]. Data on the development of prices and specific exhaust of CO_2 emissions [57] were extracted. It is assumed that, in principle, the qualitative characteristics of the car segments will remain unchanged for cars sold in 2040, except for the driving range and charging time of BEVs, where the current trends are anticipated to continue.

The characteristics relevant for vehicle manufacturers are based on information on market shares of specific car segments in Germany [58] and expected market share in 2040 [59] (Table A. 3 and Table A. 4). By using the information on profitability and investment activities of vehicle manufacturers, which differ for their car portfolios, EBIT (earnings before interest and taxes) margins published for VW, Daimler, Ford, Nissan, PSA, Renault, Toyota, and Tesla can be used as a first approximation to profit rates [60, 61]. Information on car segment-specific research and development expenditure is extracted from annual reports of vehicle manufacturers.

2.2 Consideration of spatial aspects

Socio-technical systems are heterogeneous in their composition and differ across the local, regional, national or global scale. These geographical divergences, not sufficiently covered by the literature, can lead to problems when trying to understand the transition of systems (e.g., [11, 62]). Geography and proximity should be explicitly considered in the transition analysis of the mobility sector, which is essential in contributing to global sustainability [11]. The development of socio-technical networks is often related to the spatial agglomeration context, where networks, such as the road network, allow the economy to develop and accelerate mobility for the population [63].

Furthermore, highly agglomerated regions, like large cities, offer good possibilities for a modal split, with an increase in the share of public transportation, reducing the need for residents to own cars, as they can rely on alternative mobility options for traveling short distances. The higher the level of urbanization in housing and industry, the greater the population density, which then stimulates mobility [63]. A dispersion of activity results in more sparsely populated regions, where private car use is expected to increase as the supply of public transportation is often reduced [63]. The distinction between urban and rural regions is usually included in research about transitions, as this covers a significant part of the spatial variation in the need for mobility. This work applies the division of actors across the German Bundesländer and a criterion for large/small cities.

Several studies consider electric mobility in a spatial context (e.g., [64, 65]). Looking at the expected adopters, less than a quarter live in larger cities, making the more rural regions central in terms of the majority of adopters [66]. In less dense areas with sparse infrastructure, a need for higher individual mobility underlines the value BEVs could have in suburban and rural areas [67]. The technology of BEVs depends, to an extent, on the spatial dimension, as different transition systems are needed for seamless adoption and a successful transition [68].

There exist spatial differences between the areas in household type concentration, underlining the need to consider the transition as regionally differentiated (compare Figure A. 1). Still, there does not seem to be a significant difference in spatial allocation patterns based on whether a household has children or not, or if it is a relatively younger or older household, ceteris paribus. In contrast, the most considerable differences between the households and federal states concern household income and the size of the city where the household resides [69].

The automotive industry is distributed across all federal states except for Schleswig-Holstein and Mecklenburg-Vorpommern. The most prominent sites for the automotive industry are in the South of Lower Saxony, in the center of Germany, and the South, e.g., in Wolfsburg, Emden, Dresden, and Stuttgart (compare Figure A. 2) [70].

2.3 Preference-derived weightings

Usually, information on the weighting of characteristics is gained by conducting surveys (e.g., [71]). Conducting a bespoke survey featuring the classifications of elements and actors used in this research was not practical here. Vögele et al. [5] developed a new approach to analyzing weightings; this work introduces a considerably more advanced version of this approach, which provides an integrated robustness analysis. It offers a systematic way to derive the weightings in the absence of data from, i.e., focus groups and surveys, and avoids relying on respondents' stated priorities. It assumes that, for every stakeholder, a ranking of options is available. From the database VuMA Touchpoints [16], information is retrieved on the car segments desirable to actors for their next car purchase. These categories are ranked based on their frequency of stated preferences. The order of most desirable car segments yields an incomplete ranking r for any actor (Table A. 5).

Weightings $w = (w_1, \cdots, w_c)^T$ are objectively obtained from r, where "$(\cdot)^T$" stands for a transposed vector. As r does not determine w uniquely, it is necessary to search for a w representing all possible w leading to r. Any w fulfilling the side conditions are called feasible. It is well known that the set of feasible weightings is the standard simplex S in $\mathbb{R}^c$ [72]. $m(w)$ denotes the ranking obtained by given w and by W_r the set of all admissible weightings leading to r,

$$W_r = \{w = (w_1, \cdots, w_c)^T \mid m(w) \rightleftarrows r\},$$

where "$\rightleftarrows$" symbolizes that the first entries of $m(w)$ are equal to r, i.e., the stakeholder ranks the most desirable alternatives from his point of view and considers all other options inferior without ranking them explicitly. While $m(w)$ is a complete ranking, r may be incomplete, a full ranking being a special case.

The geometric properties of W_r for PROMETHEE II are now investigated. A straightforward rearrangement of the preference index and the net flows reveals that it is possible to compute the values of the alternatives as a matrix-vector product: $\varphi = \Pi w$ with

$$\Pi_{ij} = \frac{1}{a-1} \sum_{k=1}^{a} \left(f_j(\tilde{P}_{ij} - \tilde{P}_{kj}) - f_j(\tilde{P}_{kj} - \tilde{P}_{ij}) \right), \tag{1}$$

where Π has the same dimension as the performance matrix $\tilde{P}$ and consists of rows $p_1, \cdots, p_a$. In the analysis, the ideas outlined in [73] are followed. For two vectors $x = (x_1, \cdots, x_c)^T$ and $y = (y_1, \cdots y_c)^T$, let be $x \cdot y = x_1 y_1 + \cdots + x_c y_c$ their standard scalar product.

Then,

$$\varphi(k) = p_k \cdot w. \tag{2}$$

From two alternatives k and l, an actor considers k, iff $\varphi(k) \geq \varphi(l)$. Inserting (1) yields

$$p_k \cdot w \geq p_l \cdot w \Leftrightarrow (p_l - p_k) \cdot w \leq 0\,. \tag{3}$$

With $n_{kl} = p_l - p_k$, (2) defines a half-space $\{w \in \mathbb{R}^c \mid n_{kl} \cdot w \leq 0\} \subset \mathbb{R}^c$. For $r = (r_1, \cdots, r_n)^T$, the $n-1$ conditions $\left(p_{r_{j+1}} - p_{r_j}\right) \cdot w \leq 0, 1 \leq j < n \leq a$ must be fulfilled simultaneously. The alternatives not included in r are considered inferior to all included ones, leading to the $a - n - 1$ conditions $\left(p_{r_n} - p_{r_l}\right) \cdot w \leq 0$ for any such alternative l.

The side condition $w_k \geq 0$ translates into $-e_k \cdot w \leq 0$ with the k-th standard unit vector e_k. Thus, enforcing non-negativity for all weightings corresponds to intersecting with c additional half-spaces. It remains the normalization condition $w_1 + \cdots + w_c = 1$. With $\mathbb{I} = (1, \cdots, 1)^T \in \mathbb{R}^c$, this is equivalent to $\mathbb{I} \cdot w \leq 1$ and $-\mathbb{I} \cdot w \leq -1$ holding simultaneously, which corresponds to intersecting with two additional half-spaces. As all conditions on W_r have been expressed as intersections with half-spaces, it is an intersection of finitely many half-spaces and bounded due to $0 \leq w_j \leq 1$. To sum up, for arbitrary r, the corresponding set of compatible weightings W_r are characterized as a polytope [52]. Moreover, convex is an intersection of convex sets (half-spaces are convex). Therefore, finding representative weightings for a given ranking translates into finding a point representing a convex bounded polytope.

For that purpose, choosing the center of gravity and approximating its coordinates using Monte-Carlo methods is proposed [72, 73]. Error bounds for the approximation depend on the number of samples. However, Monte-Carlo methods require uniformly sampling on W_r. Without the availability of structural information on W_r, it is straightforward to uniformly sample on S and to reject all samples not leading to r. If, however, the volume of W_r is small compared to that of the standard simplex, the chance to hit W_r is low, such that sampling on W_r can be very cumbersome due to the large fraction of rejected samples. This effect is particularly pronounced for a large number of criteria. Moreover, choosing the center of gravity is mainly motivated by physical and practical reasons and less by economic ones.

Another common notion of a center of a convex polytope is the Chebyshev center [74], the center of a volume-maximal sphere inscribed to W_r. This corresponds to a maximum minimum margin approach due to largest possible radius of that sphere, which is, at the same time, the distance of its center to the boundary of W_r. As the Chebyshev center is not unique in general, the volume-maximal inscribed ellipsoid as a generalization is and can be computed by solving a convex optimization problem [75]. Its center $\overline{w}$ is chosen as representative for W_r.

The c-dimensional volume - the Lebesgue measure of S in $\mathbb{R}^c$ and all measurable subsets like W_r - is zero, which makes maximizing volume meaningless at first glance. Still, S can be embedded into $\mathbb{R}^{c-1}$ by an orthogonal mapping. The $c-1$-dimensional volume of that image is positive, and the same holds for a non-degenerated W_r. This approach, therefore, maximizes in $\mathbb{R}^{c-1}$ and maps the results back to W_r afterward. A python implementation of the proposed method is publicly available [29].

The manufacturers' weightings are assessed the same way. The necessary rankings are derived assuming that the number of sold cars in Germany in the different segments reflects the attitudes of vehicle manufacturers (Table A. 6), and the car segments are, therefore, ranked according to their sales numbers. Based on statistics on car sales in Germany in 2019, the most critical vehicle manufacturers [58] are selected. Together, these manufacturers had more than 78% of the overall sales.

The robustness of the decisions to variations in the weightings is assessed by providing the radius ρ_r of the maximal sphere around a weighting inscribed in the respective W_r. Any weighting with Euclidean distance to the given weightings smaller than ρ_r leads to ranking r . Therefore, these radii can be interpreted as margins of variation of the weights given.

3 Results and Discussion

3.1 Weightings

The weightings are calculated employing the inverse MCDA approach by using information on rankings of car segments by actor groups.

Figure 2 shows that the weightings derived support the expected heterogeneity between the different groups of households (16 groups numbered 1-16). As all weightings sum up to one for each stakeholder, increasing one weighting implies scaling down others. For households with lower income, ‘price’ is essential; for families with children, ‘family friendliness’ is relatively relevant. ‘Comfort’ seems less relevant as a purchasing factor for households under 40 years, whereas ‘space’ is more important for households with children than those without children.

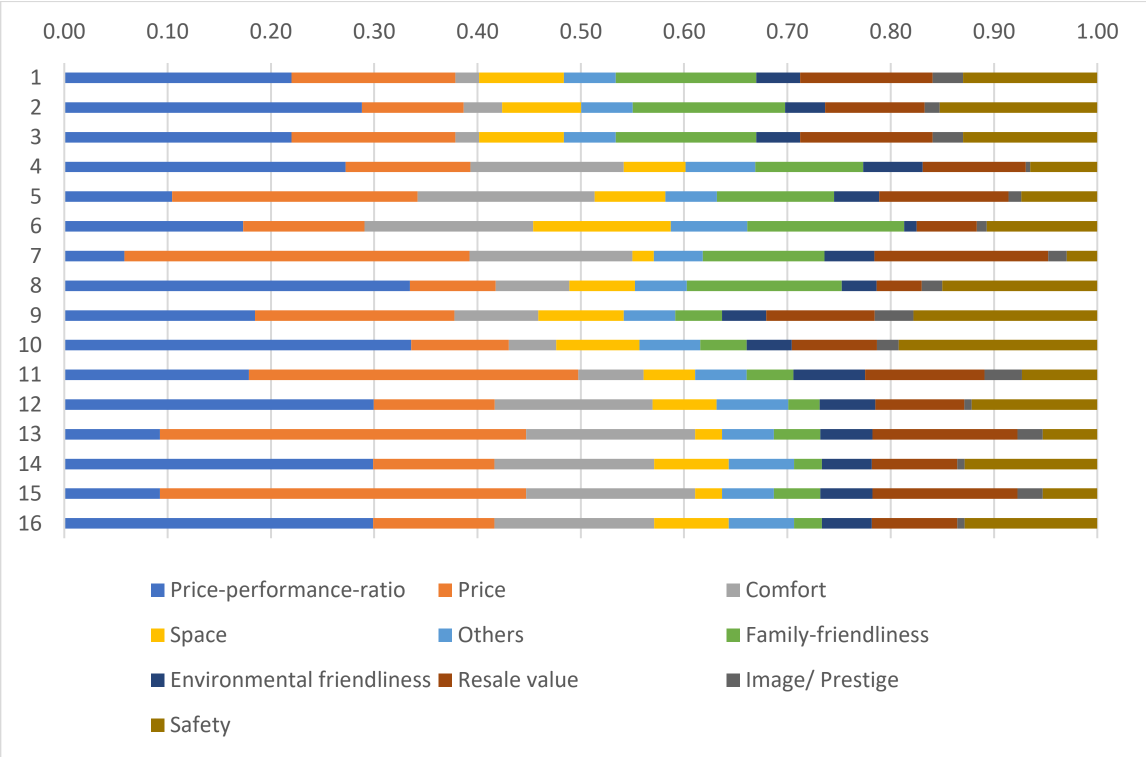

Figure 2: Weightings of car characteristics by households (in rows numbered 1-16, all weights add up to 1) and corresponding margins of variation ρ_r: 1: 0.0072, 2: 0.0035, M3: 0.0072, 4: 0.0029, 5: 0.0059, 6: 0.0088, 7: 0.0185, 8: 0.0067, 9: 0.0114, 10: 0.0079, 11: 0.0173, 12: 0.0036, 13: 0.0154, 14: 0.0046, 15: 0.0154, 16: 0.0046. Source: own calculation.

It turns out that, for some stakeholders, the margins ρ_r shown in Figure 2 are relatively low, so their decision does not seem very robust. This corresponds to the stated preferences of car segments from which the rankings were generated and where, in some cases, a vehicle class had received only a bare majority of mentions. Then, the aggregation of rankings appears to be a considerable simplification which will be addressed in a forthcoming study.

Figure 3 shows that the weightings calculated for the vehicle manufacturers are as heterogeneous as for the households. For Seat, the production cost is highly relevant. Audi focuses strongly on 'image'. Mercedes and BMW emphasize 'compatibility' with existing structures. Volkswagen weighs the factors more evenly than others but focuses highly on 'current market share'.

The results show that, based on the selected indicators, it is possible to draw conclusions about the attitudes of vehicle manufacturers. However, since the assessment of attitudes of vehicle manufacturers is based on static information from one year for Germany and neither on a time series nor data for the world car market, the results should be interpreted carefully.

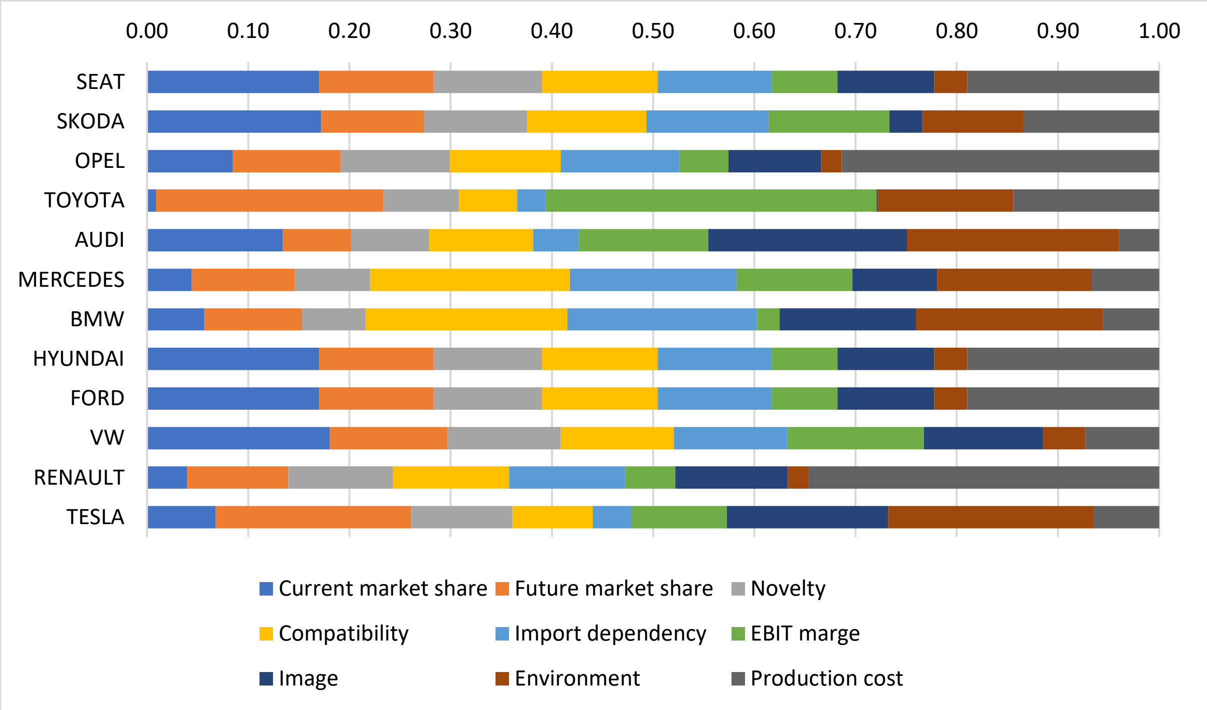

Figure 3: Vehicle manufacturers' weightings of car segments. All weights add up to 1. Source: own calculation.

3.2 Preference ranking

The calculated weightings are employed to forecast possible changes in the attitudes towards individual car segments. Table 2 displays the car segments preferred by households for 2020 and 2040, respectively. It is anticipated that the ranking of car segments will shift from ICE vehicles to BEVs, which is strongly driven by the assumed price changes for the cars. For actors 1, 2, and 3, results indicate a shift to another type of propulsion technology and another car segment. The attitudes towards ICE vehicles of actors 6, 7, and 8 seem more robust than those of other groups. Hence, it may take additional measures to convince them to buy BEVs.

Household 1		Household 2		Household 3		Household 4	
2020	2040	2020	2040	2020	2040	2020	2040
ICE Small	ICE Small	ICE Medium	BEV Medium	ICE Small	ICE Small	ICE Medium	ICE Medium
ICE Medium	BEV Medium	ICE Large	ICE Medium	ICE Medium	BEV Medium	ICE Large	BEV Medium
ICE Large	ICE Medium	ICE Small	BEV Large	ICE Large	ICE Medium	ICE Small	HEV Large

Household 5		Household 6		Household 7		Household 8	
2020	2040	2020	2040	2020	2040	2020	2040
ICE Medium	BEV Medium	ICE Large	ICE Large	ICE Small	ICE Small	ICE Medium	BEV Large
ICE Small	ICE Medium	ICE Medium	BEV Large	ICE Medium	ICE Mini	ICE Large	ICE Medium
ICE Large	BEV Large	ICE Minivans	HEV Large	ICE Mini	BEV Medium	ICE SUVs	HEV Large
Household 9		**Household 10**		**Household 11**		**Household 12**	
2020	2040	2020	2040	2020	2040	2020	2040
ICE Medium	BEV Medium	ICE Medium	BEV Medium	ICE Small	ICE Small	ICE Medium	ICE Medium
ICE Small	ICE Medium	ICE Small	ICE Medium	ICE Medium	BEV Medium	ICE Small	BEV Medium
ICE Large	ICE Small	ICE Large	BEV Large	ICE Mini	HEV Small	ICE Large	HEV Large
Household 13		**Household 14**		**Household 15**		**Household 16**	
2020	2040	2020	2040	2020	2040	2020	2040
ICE Small	ICE Small	ICE Medium	ICE Medium	ICE Small	ICE Small	ICE Medium	ICE Medium
ICE Medium	BEV Medium	ICE Large	BEV Medium	ICE Medium	BEV Medium	ICE Large	BEV Medium
ICE Mini	ICE Mini	ICE Small	HEV Large	ICE Mini	ICE Mini	ICE Small	HEV Large

Table 2: Preferred car segments by group of households. Abbreviations: Vehicle propulsion types: With internal combustion engine (ICE); Hybrid electric vehicle (HEV), battery electric vehicle (BEV); vehicle class: Sports Utility Vehicle (SUV). Source: own calculations.

The vehicle manufacturers shift toward medium-sized BEVs, as shown in Figure 4. Results indicate vehicle manufacturers are not primarily interested in environmental aspects, and innovative technologies will follow the frontrunner in the long term due to expected changes in demand and, thus, market share. Like the results for the household actors, some vehicle manufacturers will not only have a higher preference for BEVs but also will aim to sell larger cars.

2020

	Seat	Skoda	Opel	Toyota	Audi	Mercedes	BMW	Hyundai	Ford	Volkswagen	Renault	Tesla
ICE Mini cars	0.16	0.17	0.24	0.12	-0.07	0.12	0.07	0.16	0.16	0.06	0.25	-0.09
ICE Small cars	0.23	0.24	0.27	0.12	-0.04	0.12	0.07	0.23	0.23	0.15	0.25	-0.09
ICE Medium cars	0.28	0.28	0.26	0.12	0.10	0.17	0.14	0.28	0.28	0.24	0.24	0.01
ICE Large cars	0.17	0.15	0.11	0.03	0.10	0.14	0.13	0.17	0.17	0.20	0.10	0.00
ICE Executive cars	0.02	0.04	-0.01	0.09	0.04	0.13	0.08	0.02	0.02	0.11	0.00	-0.03
ICE Luxury cars	-0.07	-0.05	-0.15	0.07	0.08	0.13	0.08	-0.07	-0.07	0.10	-0.14	-0.02
ICE SUVs	0.30	0.22	0.29	-0.02	0.07	0.11	0.12	0.30	0.30	0.26	0.27	-0.03
ICE Off-road vehicles	0.18	0.12	0.14	-0.06	0.08	0.11	0.13	0.18	0.18	0.19	0.13	-0.01
ICE Mini vans	-0.02	-0.04	0.01	-0.05	-0.18	0.01	-0.03	-0.02	-0.02	-0.04	0.03	-0.20
HEV small	-0.06	-0.04	0.05	0.12	-0.17	-0.10	-0.18	-0.06	-0.06	-0.15	0.08	-0.12
HEV medium	-0.08	-0.02	-0.08	0.13	0.03	-0.02	-0.07	-0.08	-0.08	-0.06	-0.08	0.03
HEV large	-0.04	-0.01	-0.06	0.12	0.14	0.02	0.00	-0.04	-0.04	0.00	-0.05	0.10
BEV small	-0.08	-0.08	0.01	0.06	-0.13	-0.12	-0.11	-0.08	-0.08	-0.20	0.02	0.06
BEV medium	-0.07	-0.08	-0.01	0.09	-0.04	-0.12	-0.08	-0.07	-0.07	-0.13	-0.01	0.18
BEV large	-0.20	-0.20	-0.23	-0.11	0.01	-0.16	-0.09	-0.20	-0.20	-0.17	-0.23	0.14
H2 small	-0.21	-0.21	-0.23	-0.25	-0.01	-0.16	-0.08	-0.21	-0.21	-0.19	-0.23	0.03
H2 medium	-0.28	-0.25	-0.34	-0.30	-0.03	-0.18	-0.09	-0.28	-0.28	-0.21	-0.35	0.01
H2 large	-0.24	-0.23	-0.29	-0.28	0.01	-0.18	-0.08	-0.24	-0.24	-0.18	-0.29	0.05

2040

	Seat	Skoda	Opel	Toyota	Audi	Mercedes	BMW	Hyundai	Ford	Volkswagen	Renault	Tesla
ICE Mini cars	0.04	0.03	0.15	0.05	-0.17	-0.02	-0.07	0.04	0.04	-0.08	0.17	-0.15
ICE Small cars	0.03	0.02	0.14	0.04	-0.20	-0.04	-0.10	0.03	0.03	-0.07	0.16	-0.18
ICE Medium cars	0.03	0.02	0.11	0.03	-0.10	0.00	-0.04	0.03	0.03	-0.02	0.13	-0.10
ICE Large cars	-0.02	-0.05	-0.02	-0.04	-0.04	-0.01	-0.03	-0.02	-0.02	0.00	-0.01	-0.08
ICE Executive cars	-0.05	-0.04	-0.08	0.06	0.00	0.02	-0.03	-0.05	-0.05	0.04	-0.07	-0.06
ICE Luxury cars	-0.09	-0.08	-0.19	0.06	0.08	0.04	-0.02	-0.09	-0.09	0.08	-0.19	-0.02
ICE SUVs	0.05	-0.05	0.13	-0.12	-0.12	-0.06	-0.06	0.05	0.05	-0.01	0.16	-0.14
ICE Off-road vehicles	-0.01	-0.09	0.01	-0.15	-0.06	-0.04	-0.02	-0.01	-0.01	-0.01	0.03	-0.10
ICE Mini vans	-0.08	-0.10	-0.05	-0.12	-0.22	-0.11	-0.14	-0.08	-0.08	-0.10	-0.04	-0.23
HEV small	0.04	0.08	0.14	0.12	-0.05	0.06	0.03	0.04	0.04	-0.06	0.15	-0.03
HEV medium	-0.03	0.03	-0.03	0.07	0.03	0.07	0.06	-0.03	-0.03	-0.02	-0.02	0.02
HEV large	0.00	0.03	0.00	0.08	0.14	0.11	0.12	0.00	0.00	0.03	0.01	0.10
BEV small	0.25	0.29	0.24	0.34	0.14	0.12	0.09	0.25	0.25	0.19	0.21	0.24
BEV medium	0.33	0.36	0.26	0.40	0.29	0.19	0.18	0.33	0.33	0.33	0.20	0.38
BEV large	0.13	0.18	0.02	0.24	0.31	0.15	0.16	0.13	0.13	0.23	-0.03	0.33
H2 small	-0.18	-0.18	-0.21	-0.32	-0.02	-0.15	-0.04	-0.18	-0.18	-0.17	-0.22	0.00
H2 medium	-0.24	-0.23	-0.33	-0.36	-0.03	-0.17	-0.06	-0.24	-0.24	-0.19	-0.35	-0.01

Figure 4: Vehicle manufacturers' preferred car segments. Remarks: PROMETHEE performance values, Green: preferred car segment, Red: car segment the actor is less interested in. The numbers correspond to the preferences and lie between -1 (minimum) and 1 (maximum). Abbreviations: Vehicle propulsion types: with internal combustion engine (ICE), Hybrid electric vehicle (HEV), battery electric vehicle (BEV), hydrogen-powered vehicle (H2); vehicle class: Sports Utility Vehicle (SUV). Source: own calculations.

3.3 Spatial distribution of attitudes

Generally, the states in the East seem to diverge from the West and South-West concerning their preferences, which could be explained by differences in income and urbanization structures of these states, as income alone does not suffice to explain discrepancies. In Thuringia and Bavaria, differences exist that cannot be fully accounted for by relatively lower average household income per month alone. Among the states where hybrid vehicles or BEVs are preferred, besides income or urbanization (which also vary across states), there also seem to be other factors influencing these decisions that are subject to investigation in a future study.

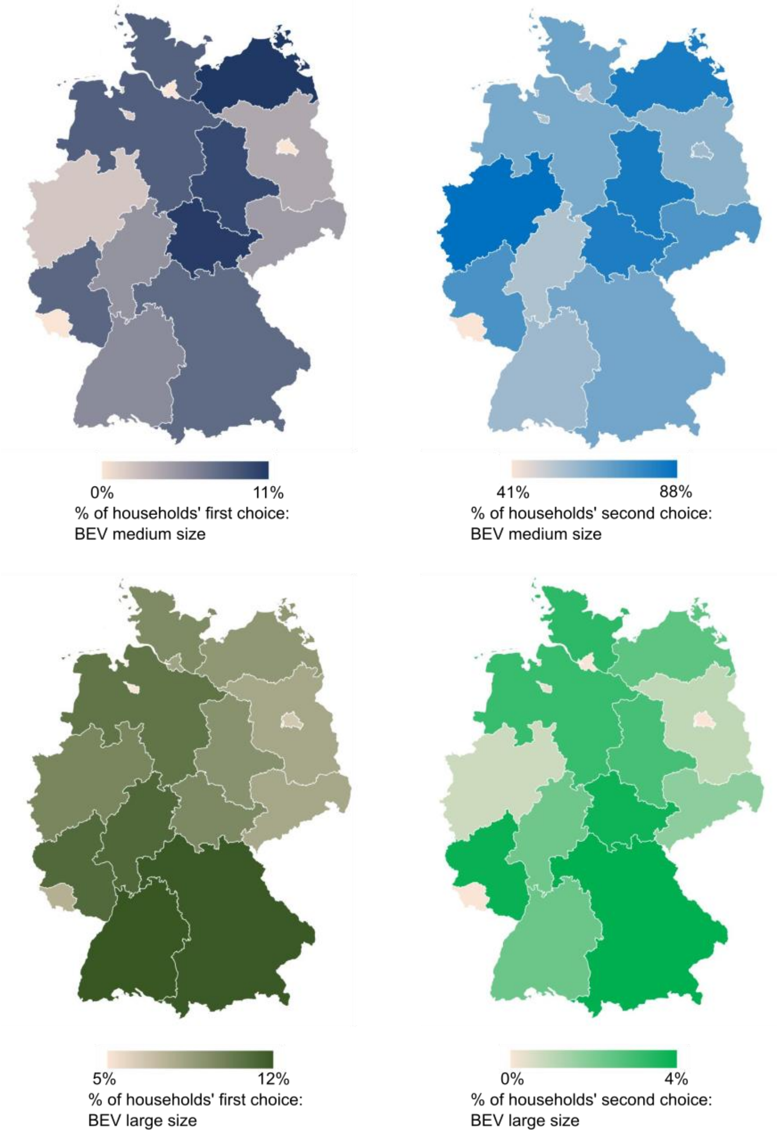

Figure 5: Regionalized preferences for BEVs in 2040 according to household type distribution based on average monthly household income. Upper row: Car segment "Medium Sized Vehicle", lower row: Segment "Large Sized Vehicle". Source: Own illustration.

Figure 5 illustrates the regional dispersion of the preferences for the two overall most preferred car segments in 2040, namely medium and BEVs. Depicted are the shares of households that select these two segments either as their most preferred vehicle in 2040 (first choice) or as their second preferred option (second choice). In most states, medium BEVs are the second preferred option, except for the Saarland, where they rank third, and small ICE cars second. The latter model type ranks third overall, with exceptions in Rhineland-Palatinate and Baden-

Wuerttemberg. The preferences are not uniform across all states but are much more uniform for specific vehicle types.

The resulting geographically disaggregated preferences illustrate, depending on households' possibilities (e.g., financially) and the area in which they live (in urban or rural areas), that different options are preferred and, thus, feasible to implement on a larger scale.

In line with [8] and [10], this study's results show that income and household type are essential in determining preferences. However, it is shown how these variations in income and household type affect choices across regions, which is also found by [11] and [12].

3.4 Combined assessment

There is a need to consider stakeholders' characteristics as differentiated. Aside from other inherent stakeholder characteristics, the spatial dimension can provide a solution that facilitates the successful consideration of relevant features without resulting in high transaction costs. Another main contribution of this study is that the perspective of the vehicle manufacturers towards the mobility transition is considered. Crucially, a willingness to shift towards BEVs is identified, accompanied by a trend toward selling larger BEVs in 2040. However, a group of three manufacturers more resistant to alternative powertrains remains, having a more significant commitment to ICE cars. Manufacturers have different preferences and require different kinds of support in the mobility transition. By 2050, it is estimated that the number of electric vehicles in Germany will increase by 20% [76].

Regarding the life cycle of the production of BEVs compared to ICEs, BEVs had substantial negative impacts on climate change (increased emissions from fossil-fuel-based electricity generation mix), human toxicity, and metal depletion (due to the production phase, including battery production) in 2015. These effects are bound to decrease over time [77]. Still, compared to fuel-cell electric vehicles, medium-sized BEVs are eco-friendlier overall. While this depends partly on costs and taxes, fuel supply, and share of renewables used for electricity generation, the range and use patterns for cars are also important [78].

However, the analyses reflect two more or less static viewpoints, as they do not include dynamic changes among the actors but investigate the situation as of 2020 and 2040. Any resulting uncertainty could be modeled by widening the range of the criteria preferences.

Furthermore, the interpretation of the results is made under the following assumptions. In households with children under 14, 'family friendliness' is valued more highly than in households with no or older children. In households with a lower average monthly income of 2000 Euros, 'price' is more critical than in those with higher income. In households where the head is older than 40, 'comfort' and 'space' are valued higher than in households where this condition is not met. These assumptions influence the weighting and, subsequently, the preference order of options.

The availability of data impacts the reliability of the results. For the existing database, a sufficient number of observations was available for each stakeholder group, but further increasing the resolution of the subdivision into groups, the number of observations per group may become too small to be statistically significant. The uncertainty in the characteristics of the car segments, which partially arises from considering prototypical car models in each segment, is currently neglected. This may impact the accuracy of the weights derived using inverse MCDA and, subsequently, the predictive power of implications for a future mobility sector.

Moreover, the inverse MCDA approach is based on a consistent and clear ranking of the three most favored car segments. Sensitivity analyses show that considering two or even one favorite car segment can only result in inconclusive weightings, whereas increasing the number of favored segments decreases the reliability of the results.

4 Conclusion and Outlook

With the tightening of climate policy targets, pressure is increasing on the mobility sector. Numerous studies have investigated factors influencing buyers to purchase or use lower-emission vehicles. So far, information has been obtained mainly through surveys and experiments, which are time-consuming and expensive. In addition, one must deal with possible discrepancies between stated and actual preferences. This study applies an alternative approach to drawing inferences about attitudes toward vehicle characteristics from aggregate information without human intervention. The approach is highly flexible concerning various features and stakeholders and can be used to explain the behavior of vehicle manufacturers. Compared to surveys, this method reduces assessment costs while providing helpful guidance in shaping a successful mobility and energy transition.

The results indicate that under the assumption of decreasing costs for BEVs and expanding charging infrastructure, medium-sized BEVs will gain importance. It is anticipated that, due to increasing profit rates in combination with changes in market share, vehicle manufacturers still hesitant about BEVs today will increasingly move in this direction.

Stakeholders are dispersed across the country, and so is the allocation of their characteristics. Determining these characteristics, like income or urbanization, the differing strategies of industry, and the consequences of these strategies will shape the mobility side of the energy transition, which can benefit from policies tailored to these differences.

The scope of future research will focus on further applications of the methods presented here and comparisons with insights gained from, e.g., surveys. Uncertainties in the parameters and associated consequences for the robustness of the performances will be discussed in much more detail in future work. Additionally, analysis with more actors or on a more disaggregated level could prove insightful. Data limitations and information needed for prioritizing choices of actors can hinder the application of the method used in this study.

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6 Appendix

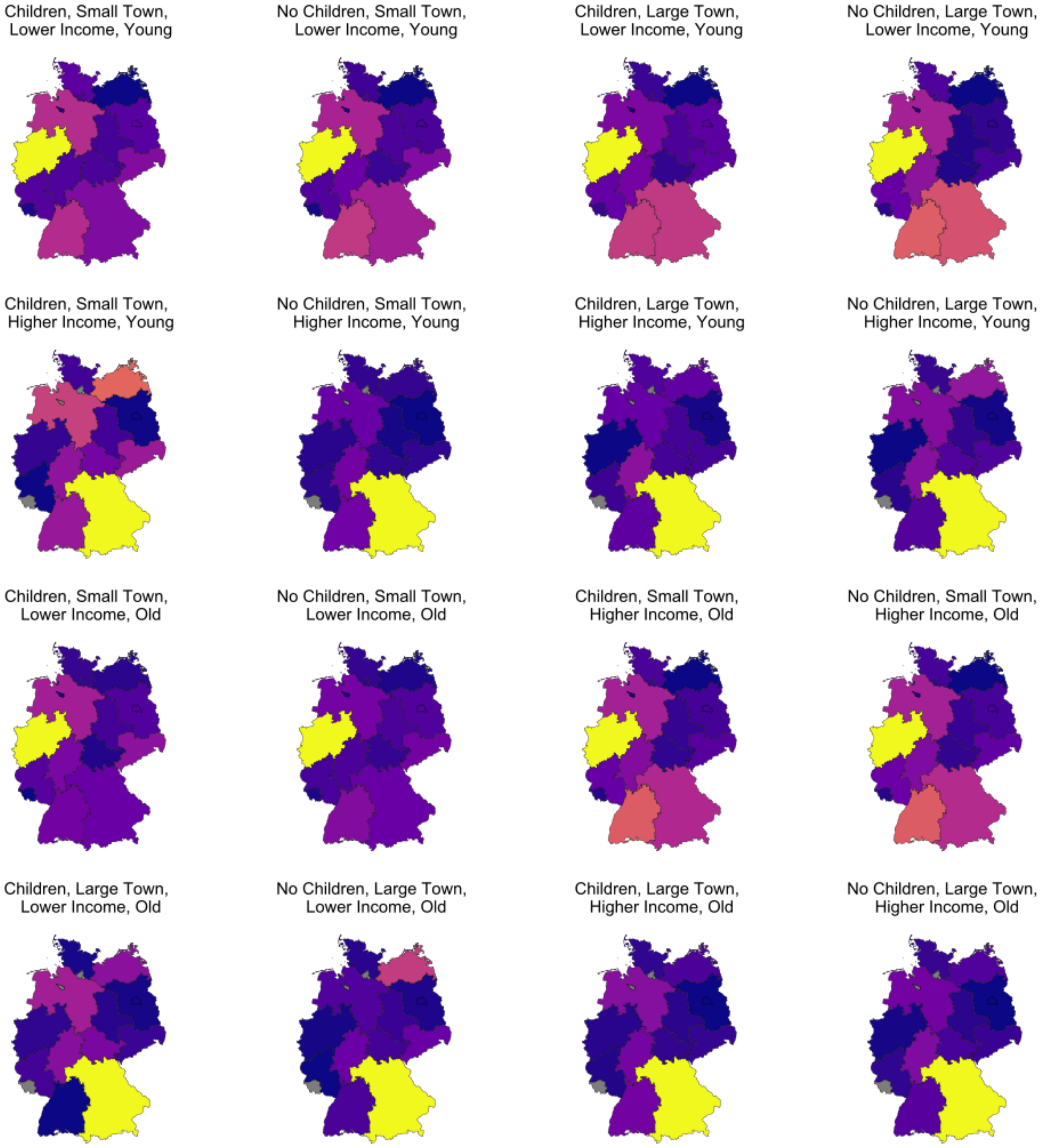

Figure A. 1: Distribution of household types in Germany, differentiated by family status (children or no children in household), urbanity (living in urbanized cities or more rural areas), household income (less than 2000€ per month or more than 2000€ per month), and age (younger or older than 40). Source: own illustration [46].

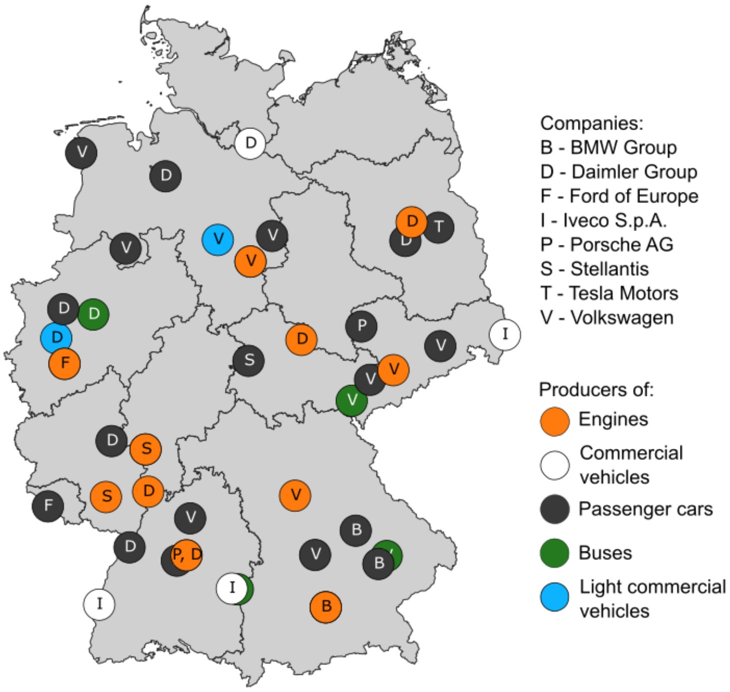

Figure A. 2: Automotive industry locations in Germany differentiated by the type of producer. Own illustration [70].

	2020																	
Propulsion type	Internal Combustion Engine (gasoline)									Hybrid electric			Electric (battery)			Hydrogen		
	Mini cars	Small cars	Medium cars	Large cars	Executive cars	Luxury cars	Sports Utility Vehicles	Off-road vehicles	Mini vans	Mini/Small cars	Medium cars	Large cars	Mini/Small cars	Medium cars	Large cars	Mini/Small cars	Medium cars	Large cars
Examples for car types	VW up	VW Polo	VW Golf 1.5 TSI	VW Passat Variant 2.0 TSI	VW Arteon	Audi A8	VW T-ROC	VW Tiguan	VW Sharan	Toyota Yaris Hybrid	Hyundai Ioniq	VW Passat Variant GTE	VW e-up	VW e-Golf	Tesla Model 3	Imaginary Hundai H2_i10	Toyota Mirai	Hyundai Nexo
Price-performance-ratio	3.9	4.0	3.9	3.5	3.1	3.2	3.9	3.8	3.0	3.9	3.7	3.5	3.9	3.9	3.5	1.9	2.1	3.3
Price	5.0	4.9	4.3	3.2	2.7	1.3	4.1	3.4	3.5	4.7	3.3	3.1	4.3	3.7	2.2	2.2	1.0	1.6
Comfort	2.6	2.8	3.8	3.9	3.9	4.4	3.5	3.7	3.2	2.6	3.7	3.9	2.6	3.5	3.9	2.6	3.6	3.5
Space	1.0	1.0	2.0	5.0	3.1	2.3	1.9	2.2	4.8	1.0	1.0	3.1	1.0	1.6	3.8	1.0	1.8	2.9
Availability of charging/filling infrastructure (example 1000 km trip)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.5	4.5	4.0	2.0	2.0	2.0	1.0	1.0	1.0
Family-friendliness	2.3	2.8	3.1	3.6	3.3	3.3	3.5	3.4	3.5	2.3	3.0	3.5	2.3	2.8	3.5	2.3	3.0	3.0
Environmental friendliness	2.9	2.5	2.6	2.0	2.0	1.7	1.0	1.6	1.4	3.5	4.3	4.2	5.0	5.0	5.0	1.3	5.0	5.0
Resale value	3.2	3.1	2.5	1.0	1.9	5.0	1.9	2.7	4.5	3.2	2.5	1.0	3.2	2.5	1.0	3.1	2.5	1.0
Image/Prestige	1.0	1.0	2.0	3.0	3.0	4.0	3.0	3.0	2.0	1.0	2.0	3.0	1.0	2.0	3.0	3.0	3.0	3.5
Safety	2.5	3.9	3.9	4.1	4.4	4.3	3.8	3.9	4.1	2.5	3.9	4.1	2.5	3.9	4.1	2.5	3.6	3.7

Table A. 1: Characteristics of car segments relevant for private car purchasers in 2020. Source: Own compilation based on [47, 57].

2040																			
Propulsion type	Internal Combustion Engine (gasoline)									Hybrid electric			Electric (battery)			Hydrogen			
	Mini cars	Small cars	Medium cars	Large cars	Executive cars	Luxury cars	Sports Utility Vehicles	Off-road vehicles	Mini vans	Mini/Small cars	Medium cars	Large cars	Mini/Small cars	Medium cars	Large cars	Mini/Small cars	Medium cars	Large cars
Examples for car types	VW up	VW Polo	VW Golf 1.5 TSI	VW Passat Variant 2.0 TSI	VW Arteon	Audi A8	VW T-ROC	VW Tiguan	VW Sharan	Toyota Yaris Hybrid	Hyundai Ioniq	VW Passat Variant GTE	VW e-up	VW e-Golf	Tesla Model 3	Imaginary Hundai H2_i10	Toyota Mirai	Hyundai Nexo
Price-performance-ratio	3.8	3.9	3.8	3.4	3.0	3.1	3.8	3.7	2.9	4.0	3.7	3.5	4.1	4.0	3.6	2.0	2.2	3.5
Price	5.0	4.8	4.2	3.0	2.5	1.0	4.1	3.2	3.3	4.8	3.4	3.2	4.7	4.3	3.2	3.8	2.9	3.3
Comfort	2.6	2.8	3.8	3.9	3.9	4.4	3.5	3.7	3.2	2.6	3.7	3.9	2.6	3.5	3.9	2.6	3.6	3.5
Space	1.0	1.0	2.0	5.0	3.1	2.3	1.9	2.2	4.8	1.0	1.0	3.1	1.0	1.6	3.8	1.0	1.8	2.9
Availability of charging/filling infrastructure (example 1000 km trip)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.0	5.0	5.0	5.0	4.0	4.0	4.0	3.0	3.0	3.0
Family-friendliness	2.3	2.8	3.1	3.6	3.3	3.3	3.5	3.4	3.5	2.3	3.0	3.5	2.3	2.8	3.5	2.3	3.0	3.0
Environmental friendliness	2.9	2.5	2.6	2.0	2.0	1.7	1.0	1.6	1.4	3.5	4.3	4.2	5.0	5.0	5.0	1.3	5.0	5.0
Resale value	3.2	3.1	2.5	1.0	1.9	5.0	1.9	2.7	4.5	3.2	2.5	1.0	3.2	2.5	1.0	3.1	2.5	1.0
Image/Prestige	1.0	1.0	2.0	3.0	3.0	4.0	3.0	3.0	2.0	1.0	2.0	3.0	1.0	2.0	3.0	3.0	3.0	3.5
Safety	2.5	3.9	3.9	4.1	4.4	4.3	3.8	3.9	4.1	2.5	3.9	4.1	2.5	3.9	4.1	2.5	3.6	3.7

Table A. 2: Characteristics of car segments relevant for private car purchasers in 2040. Source: Own calculations [47, 57].

	2020																	
Propulsion type	**Internal combustion engine (gasoline)**									**Hybrid electric**			**Electric (battery)**			**Hydrogen**		
Characteristics	**Mini cars**	**Small cars**	**Me-dium cars**	**Large cars**	**Execu-tive cars**	**Lux-ury cars**	**Sports Utility Vehi-cles**	**Off-road vehi-cles**	**Mini vans**	**Mini cars**	**Me-dium cars**	**Large cars**	**Mini cars**	**Me-dium cars**	**Large cars**	**Mini cars**	**Me-dium cars**	**Large cars**
Current market share	2.2	3.6	4.9	3.0	1.7	1.2	5.0	2.9	1.4	1.1	1.7	1.7	1.2	1.2	1.03	1.0	1.0	1.0
Future market share	1.1	1.2	1.2	1.1	1.0	1.0	1.2	1.1	1.0	1.1	1.4	1.1	2.5	5.0	2.2	1.1	1.2	1.1
Degree of novelty	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	2.0	2.0	2.3	3.0	3.0	4.0	4.0	5.0
Compatibility with existing structures	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.0	4.0	4.0	3.8	3.0	3.0	2.0	2.0	1.0
Import depend-ency	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	2.6	2.6	2.6	1.0	1.0	1.0	3.4	3.4	3.4
EBIT marge	3.0	3.2	3.4	3.6	4.3	5.0	2.76	2.83	3.1	3.0	3.4	3.6	1.0	1.0	1.0	1.0	1.0	1.0
Prestige	1.0	1.0	2.0	3.0	3.0	4.0	3.0	3.0	2.0	1.0	2.0	3.0	1.0	2.0	3.0	3.0	3.0	3.5
CO2	2.9	2.5	2.6	2.0	2.0	1.7	1.0	1.6	1.4	3.5	4.3	4.2	5.0	5.0	5.0	5.0	5.0	5.0
Production cost	5.0	4.9	4.3	3.2	2.7	1.3	4.2	3.4	3.5	4.7	3.3	3.1	4.3	3.7	2.2	2.2	1.0	1.6

Table A. 3: Characteristics of car segments relevant for vehicle manufacturers in 2020. Source: Own calculations, [50-52, 58, 59][49-51, 57, 58][49-51, 57, 58][49-51, 57, 58][49-51, 57, 58][49-51, 57, 58][49-51, 57, 58][49-51, 57, 58][49-51, 57, 58].

	2040																	
Propulsion type	**Internal combustion engine (gasoline)**									**Hybrid electric**			**Electric (battery)**			**Hydrogen**		
Characteristics	**Mini cars**	**Small cars**	**Me-dium cars**	**Large cars**	**Execu-tive cars**	**Lux-ury cars**	**Sports Utility Vehi-cles**	**Off-road vehi-cles**	**Mini vans**	**Mini cars**	**Me-dium cars**	**Large cars**	**Mini cars**	**Me-dium cars**	**Large cars**	**Mini cars**	**Me-dium cars**	**Large cars**
Current market share	1.1	1.2	1.2	1.1	1.0	1.0	1.2	1.1	1.0	1.1	1.4	1.1	2.5	5.0	2.2	1.1	1.2	1.1
Future market share	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.1	2.5	5.0	2.2	1.1	1.3	1.1
Degree of novelty	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	2.0	2.0	2.0	2.0	2.0
Compatibility with existing structures	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.0	4.0	4.0	3.0	3.0	3.0
Import depend-ency	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.8	4.8	4.8	4.6	4.6	4.6	5.0	5.0	5.0
EBIT marge	3.0	3.2	3.4	3.6	4.3	5.0	2.8	2.8	3.1	3.0	3.4	3.6	3.0	3.4	3.6	1.0	1.0	1.0
Prestige	1.0	1.0	2.0	3.0	3.0	4.0	3.0	3.0	2.0	1.0	2.0	3.0	1.0	2.0	3.0	3.0	3.0	3.5
CO2 emissions	2.9	2.5	2.6	2.0	2.0	1.7	1.0	1.6	1.4	4.4	4.3	4.2	5.0	5.0	5.0	5.0	5.0	5.0
Production cost	5.0	4.8	4.2	3.0	2.5	1.0	4.1	3.2	3.3	4.7	3.3	3.1	4.3	3.7	2.2	2.2	1.0	1.6

Table A. 4: Characteristics of car segments relevant for vehicle manufacturers in 2040. Source: Own calculations [50-52, 58, 59].

Characteristics	With children under 14 years								No children							
	Under 40 years				40 and older				Under 40 years				40 and older			
	<500T		>=500T		<500T		>=500T		<500T		>=500T		<500T		>=500T	
	<2000 Euro	>=2000	<2000	>=2000	<2000	>=2000	<2000	>=2000	<2000	>=2000	<2000	>=2000	<2000	>=2000	<2000	>=2000
Household Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
First preference	ICE Small cars	ICE Medium cars	ICE Small cars	ICE Medium cars	ICE Medium cars	ICE Large cars	ICE Small cars	ICE Medium cars	ICE Medium cars	ICE Medium cars	ICE Small cars	ICE Medium cars	ICE Small cars	ICE Medium cars	ICE Small cars	ICE Medium cars
Second preference	ICE Medium cars	ICE Large cars	ICE Medium cars	ICE Large cars	ICE Small cars	ICE Medium cars	ICE Medium cars	ICE Large cars	ICE Small cars	ICE Small cars	ICE Medium cars	ICE Small cars	ICE Medium cars	ICE Large cars	ICE Medium cars	ICE Large cars
Third preference	ICE Large cars	ICE Small cars	ICE Large cars	ICE Small cars	ICE Large cars	ICE Minivans	ICE Mini cars	ICE SUVs	ICE Large cars	ICE Large cars	ICE Mini cars	ICE Large cars	ICE Mini cars	ICE Small cars	ICE Mini cars	ICE Small cars

Table A. 5: Ranking of car segments by household type (1-16) according to Vuma, 2020. Abbreviations: Vehicle propulsion types: With internal combustion engine (ICE); vehicle class: Sports Utility Vehicle (SUV). Source: Own calculations [16].

	Manufacturers											
	SEAT	**SKODA**	**OPEL**	**TOYOTA**	**AUDI**	**MERCEDES**	**BMW**	**HYUNDAI**	**FORD**	**VW**	**RENAULT**	**TESLA**
First preference	ICE SUVs	ICE Medium cars	ICE SUVs	HEV Medium cars	HEV Large cars	ICE Large cars	ICE Medium cars	ICE SUVs	ICE SUVs	ICE Medium cars	ICE SUVs	BEV Medium cars
Second preference	ICE Medium cars	ICE Small cars	ICE Small cars	ICE Mini cars	ICE Large cars	ICE Medium cars	ICE Off-road vehicles	ICE Medium cars	ICE Medium cars	ICE Off-road vehicles	ICE Small cars	BEV Large cars
Third preference	ICE Small cars	ICE SUVs	ICE Medium cars	ICE Small cars	ICE Medium cars	ICE Executive cars	ICE Large cars	ICE Small cars	ICE Small cars	ICE SUVs	ICE Mini cars	

Table A. 6: Vehicle manufacturers'ranking of car segments, 2020. Abbreviations: Vehicle propulsion types: With internal combustion engine (ICE), hybrid electric vehicle (HEV), battery electric vehicle (BEV); vehicle class: Sports Utility Vehicle (SUV). Source: Own calculations.