Electric vehicle ownership dynamics at household level: A stated adaptation experiment on the effects of pricing and incentive policies

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Abstract

A reduction of vehicles and a shift from to electric vehicles (EV) is crucial for transport decarbonisation. This transition requires effective policies. In a stated adaptation experiment, 444 respondents were faced with four scenarios presenting hypothetical pricing values concerning EV purchase subsidies, fuel and electricity prices, and public transport (PT) fares. Respondents were asked to adapt their actual household fleet in response to the scenarios. They could remove current or add new vehicles or PT passes, while being supported by a live cost calculation. The effects of the pricing strategies on changes in vehicle ownership were modelled in an integrated choice and latent variable (ICLV) model. Results suggest that the removing a conventional vehicle and/or replacing it with an EV can be promoted by increasing fuel prices, lowering electricity prices, and lowering PT fares. EV purchase subsidy was found to be ineffective.

Keywords: *electric vehicles, EV, ICLV model, hybrid choice, stated adaptation, attitudes*

1. Introduction

The transport sector is one of the largest sources of total greenhouse gas emissions, with road transport being the largest contributor (Buysse et al., 2021; EU, 2018; IEA, 2023). Both battery electric vehicles (BEV) and plug-in hybrid vehicles (PHEV) have a noteworthy potential to reduce emissions, and governments around the world are implementing policies to accelerate their diffusion (Hardman et al., 2017). This paper focuses on economic mechanisms that can be implemented by governments in the short and medium term. The consensus in previous research is that operating costs negatively affect vehicle preference (see e.g. Jensen et al., 2021, 2020; Jia and Chen, 2021; Li et al., 2020). Moreover, research agrees that such economic pull factors as free or reduced electricity prices (Ghasri et al., 2019; Langbroek et al., 2016) and providing purchase subsidies (Bjerkan et al., 2016; Ghasri et al., 2019; Higgins et al., 2017) but also push factors as increasing fuel prices (Jäggi et al., 2012; Lebeau et al., 2012) can effectively promote the uptake of EVs. However, the majority of these studies focusses merely on factors effective in EV promotion. Our study contributes to existing research by examining the impact of pricing and incentive strategies (fuel prices, electricity prices, EV purchase subsidies, and public transport (PT) fares) in a more complex framework by considering not only the impact on EV adoption but also the associated changes in a household's mobility tool ownership. In particular, we aim to understand what strategies households adopt when considering buying an EV. Do they see this as a substitute for an existing internal combustion engine (ICE) vehicle or as an addition? And what is the effect of a reduction in PT fares? Would households consider giving up one of their ICE vehicles?
Moreover, this study aims to explain the decisions and sensitivities of different people at more detail. As changes in vehicle ownership usually require a great involvement and deliberation, socio-psychological theories considering antecedents of a behaviour can help to gain understanding (Lehman et al., 2017; Steg & Gifford, 2017). Therefore, within a discrete choice model framework, we apply an integrated choice and latent variable (ICLV) model to account for the effects of socio-psychological constructs such as attitudes and perceptions (Abou-Zeid & Ben-Akiva, 2014; Walker & Ben-Akiva, 2011). With reference to the theory of planned behaviour (Ajzen, 1991), the latent behavioural predictor

"intention to buy an EV", as well as "environmental concern" will be incorporated into the ICLV model. This abstract is a short summary of a submitted journal article. Interested readers are encouraged to read the full preprint (Gutjar et al., 2024).

2. Methods

2.1 Data

This study analyses survey data, which were obtained as part of a project in "Electric City Russelsheim" initiated by the German government to equip Russelsheim am Main, a medium-sized city in South-Western Germany, with dense charging infrastructure. A marketing company was engaged to draw a random sample of contacts for persons aged 18 years or older. The institute provided a contact list of 6,107 people/households. These people were contacted via an invitation letter and a follow-up recruitment phone call in the period. Data were collected between January to December 2020 in computer-assisted personal interviews. The survey started as face-to-face interviews (January-March) but continued via an online video-based communication tool (May-December) due to COVID-19. Additional recruitment was carried out by approaching Russelsheim citizens in person in parking lots (September-November). An incentive of 20€ was offered to every respondent. A total sample of n=466 respondents was achieved. Data from 444 respondents will be considered after data cleaning.

2.2 Study design

The study focuses on vehicle ownership dynamics within households. Respondents provided information on their household (e.g., household income, housing type), and on the sociodemographic characteristics of every household member. Additionally, the socio-psychological constructs "intention to buy an EV" and "environmental concern" were assessed for the respondent. To answer the research question regarding adaptation of vehicle ownership within the household, a two-stage process was created:

1) In the first stage, revealed preferences data was collected on the mobility tools in the household fleet. Respondents provided detailed information on all vehicles (e.g., vehicle type, engine type, annual VKM travelled), motorcycles, and PT subscriptions.
2) Next, a stated adaptation experiment (Lee-Gosselin, 1996) was employed to assess the effect of pricing strategies and incentives on changes in the household fleet. Stated adaptation experiments present respondents with predefined attributes and choice alternatives, but respondents have more flexibility in their decisions than in a standard stated preferences (SP) experiment. In our stated adaptation experiment, the attributes of interest are predefined to depict scenarios with hypothetical pricing policies. The respondents can entirely redefine their household fleet. Choice tasks were defined by presenting hypothetical scenarios with different pricing and incentive strategies for fuel price (€/l), CO_2 surcharge (€/litre fuel), electricity price (€/100km), purchase subsidy for EVs (€), and PT fares relative to today (%).

Figure 1 visualises the two-stage study design and presents the pricing and incentive attributes along with the variation of the levels. Based on the attributes and variation levels, an experimental design was created in Ngene (Rose et al., 2018) to define the levels for every price attribute for the scenarios to be presented to the respondents. The experimental design included twenty scenarios divided into five blocks. Every respondent received one randomly assigned block with a total of four choice tasks in randomised order. A choice task example for a fictive household is presented in Figure 2. The respondent was asked to adapt the household fleet under a given pricing scenario (in blue). Employing the data on mobility tools in the household, the survey program initially calculated the actual household fleet costs. This allowed us to present changes in monthly and annual costs (in orange) for the actual household fleet as a consequence of the hypothetical economic regulations given in the scenario. This is a dynamic cost calculation in dependence on respondents' every single adaptation during the task. Namely, respondents were asked to react to the hypothetic regulation scenario by adapting the current household fleet (in green). They could e.g., remove a current and/or add a new vehicle(s), a motorcycle(s), and PT subscriptions as well as adjust the annual VKM. Figure 2 presents all possible options for the adaptation of mobility tools.

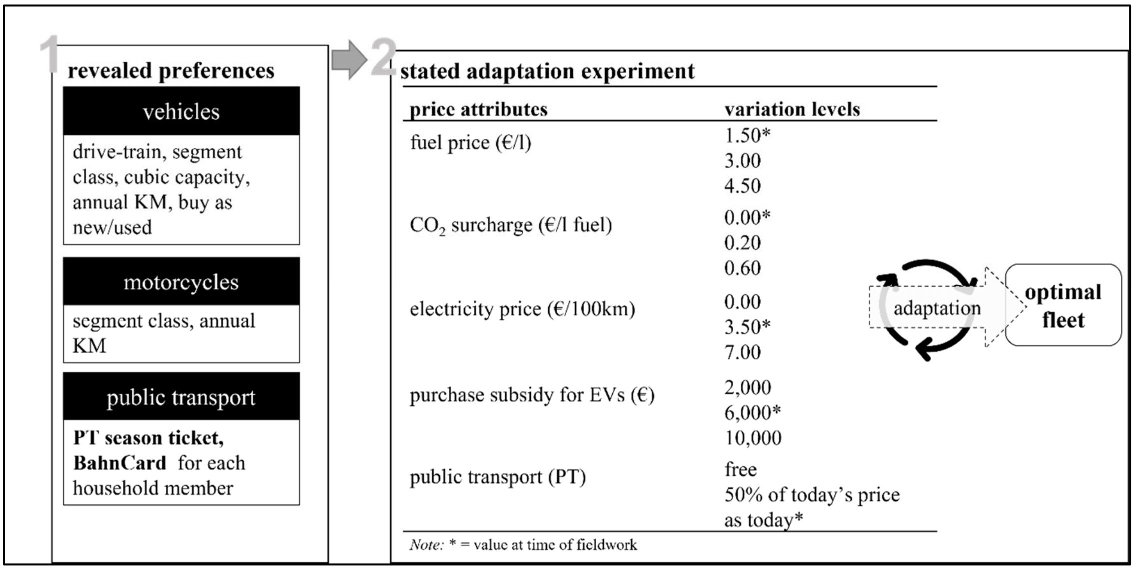
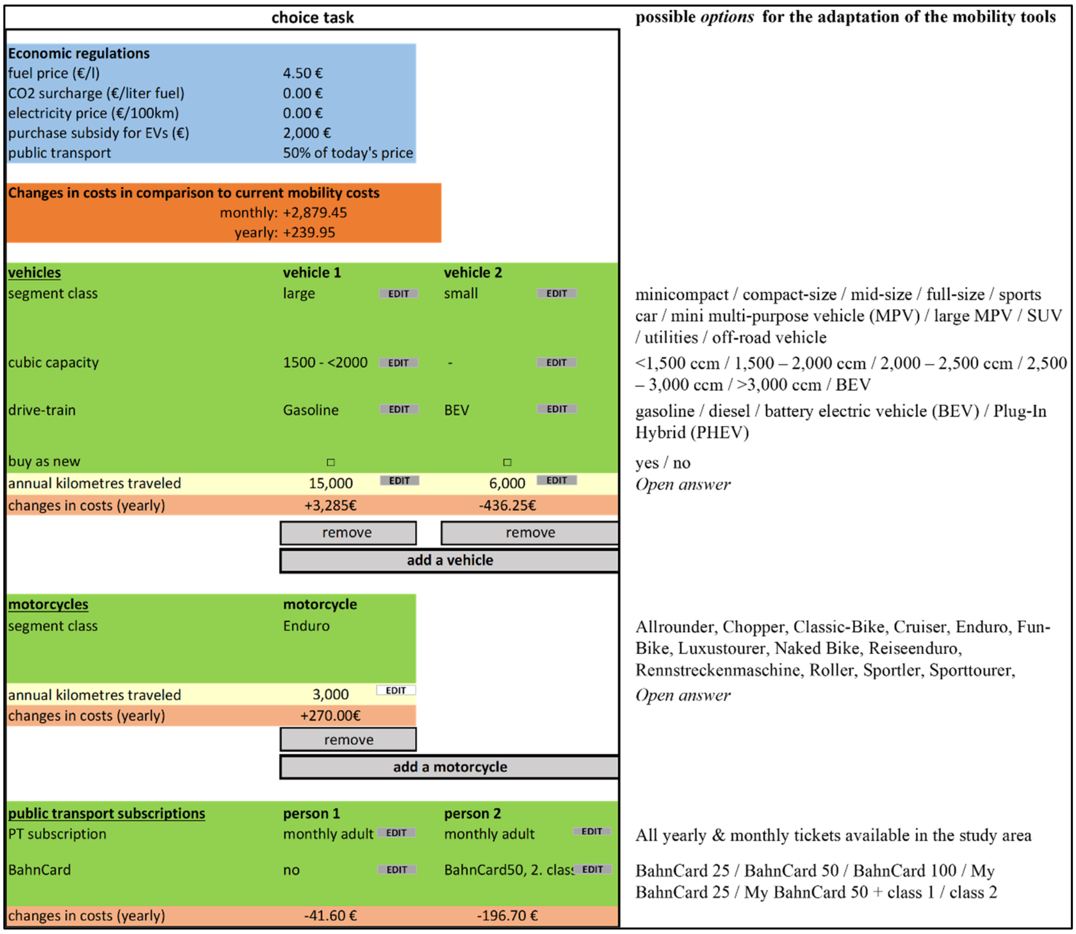


Figure 1. Two-stage study design along with attributes and variation levels



choice task			possible *options* for the adaptation of the mobility tools
Economic regulations			
fuel price (€/l)	4.50 €		
CO2 surcharge (€/liter fuel)	0.00 €		
electricity price (€/100km)	0.00 €		
purchase subsidy for EVs (€)	2,000 €		
public transport	50% of today's price		
Changes in costs in comparison to current mobility costs			
monthly: +2,879.45			
yearly: +239.95			
vehicles	**vehicle 1**	**vehicle 2**	
segment class	large EDIT	small EDIT	minicompact / compact-size / mid-size / full-size / sports car / mini multi-purpose vehicle (MPV) / large MPV / SUV / utilities / off-road vehicle
cubic capacity	1500 - <2000 EDIT	- EDIT	<1,500 ccm / 1,500 – 2,000 ccm / 2,000 – 2,500 ccm / 2,500 – 3,000 ccm / >3,000 ccm / BEV
drive-train	Gasoline EDIT	BEV EDIT	gasoline / diesel / battery electric vehicle (BEV) / Plug-In Hybrid (PHEV)
buy as new	☐	☐	yes / no
annual kilometres traveled	15,000 EDIT	6,000 EDIT	*Open answer*
changes in costs (yearly)	+3,285€	-436.25€	
	remove	remove	
	add a vehicle		
motorcycles	**motorcycle**		
segment class	Enduro		Allrounder, Chopper, Classic-Bike, Cruiser, Enduro, Fun-Bike, Luxustourer, Naked Bike, Reiseenduro, Rennstreckenmaschine, Roller, Sportler, Sporttourer,
annual kilometres traveled	3,000 EDIT		*Open answer*
changes in costs (yearly)	+270.00€		
	remove		
	add a motorcycle		
public transport subscriptions	**person 1**	**person 2**	
PT subscription	monthly adult EDIT	monthly adult EDIT	All yearly & monthly tickets available in the study area
BahnCard	no EDIT	BahnCard50, 2. clas EDIT	BahnCard 25 / BahnCard 50 / BahnCard 100 / My BahnCard 25 / My BahnCard 50 + class 1 / class 2
changes in costs (yearly)	-41.60 €	-196.70 €	

Figure 2. Choice task example (translated from German)

2.3 Analytical procedure and model specification

The study aims to model the likelihood of changes in household vehicle ownership in response to the hypothetical price regulations presented in a stated adaptation experiment. Due to a limited number of observations, BEVs and PHEVs vehicles were aggregated into a single EV category, while petrol and diesel vehicles were grouped as ICE vehicles. After data cleaning, n=1,737 observations from 444 individuals were included in the analysis. Table 2 shows the household fleet changes considered in the analysis and the availability of such options to different households.

Table 1. Changes to household fleet

alternative	**explanation**	**available to households**
adding an EV	an EV is adopted as an additional vehicle to the household fleet →increased number of vehicles	all
removing an ICE	at least one existing ICE is removed and no new vehicles are acquired →decreased number of vehicles	owning at least one ICE
replacing an ICE with an EV	an ICE was removed from the household fleet and an EV was acquired →no changes in the number of vehicles	owning at least one ICE
removing two and replacing an ICE	Two or more ICEs were removed from the household fleet and a smaller number of EVs were acquired instead →decreased number of vehicles	owning at least two ICEs

The outcomes listed above represent discrete and mutually exclusive alternatives. An appropriate methodological tool to model such choices is the multinomial logit model (MNL) (Hensher et al., 2015; Louviere et al., 2000; Train, 2009). The structural equation represents an indirect utility U_{nj} an individual *n* associates with alternative *j*:

$$U_{nj} = x'_{nj}\beta + \varepsilon_{nj} \quad (1)$$

where U_{nj} is not observed, where x'_{nj} is a vector of observed variables relating to the attributes of alternative *j* and respondent *n*, β is a vector of coefficients to be estimated; ε_{nj} is a random component. While the effect of changes in fuel price (together with CO_2 surcharge) will be modelled as a continuous variable, changes in the electricity price, purchase subsidies, and PT fares will be modelled as categorical/dummy variables and interpreted as the utility differences to the omitted reference category, i.e. no changes in price (Louviere et al., 2000; Mariel et al., 2021).

To account for taste heterogeneity, the sensitivity to the economic attributes interacts with the total annual VKM travelled with ICEs (in thousands of km) and monthly equivalised disposable income (eurostat, 2021) (in thousands of €). For the taste heterogeneity in fuel price, which is treated as a continuous variable, a continuous interaction was specified (Hess et al., 2007):

$$U = \dots + \beta_{fuel}\left(\frac{VKM}{\overline{VKM}}\right)^{\lambda_{VKM,fuel}} fuel + \dots \quad (2)$$

where $\lambda_{\text{VKM,fuel}}$ indicates the sensitivity towards fuel price with increasing VKM.

Our "best" MNL model was extended to an ICLV model to additionally explain people's taste sensitivities to pricing and incentive strategies throughout latent variables a) intention to buy an EV and b) environmental concerns. Only significant and behaviourally meaningful interactions will be presented in the results section, while all previous models are available upon request.

Figure 3 illustrates the relationships modelled in the ICLV framework for the dynamics of vehicle ownership as a reaction to hypothetical pricing and incentive strategies. Due to space restrictions, readers are encouraged to read the methodological papers on ICLV estimation (e.g.,: Abou-Zeid & Ben-Akiva, 2014; Ben-Akiva, Walker, et al., 2002).

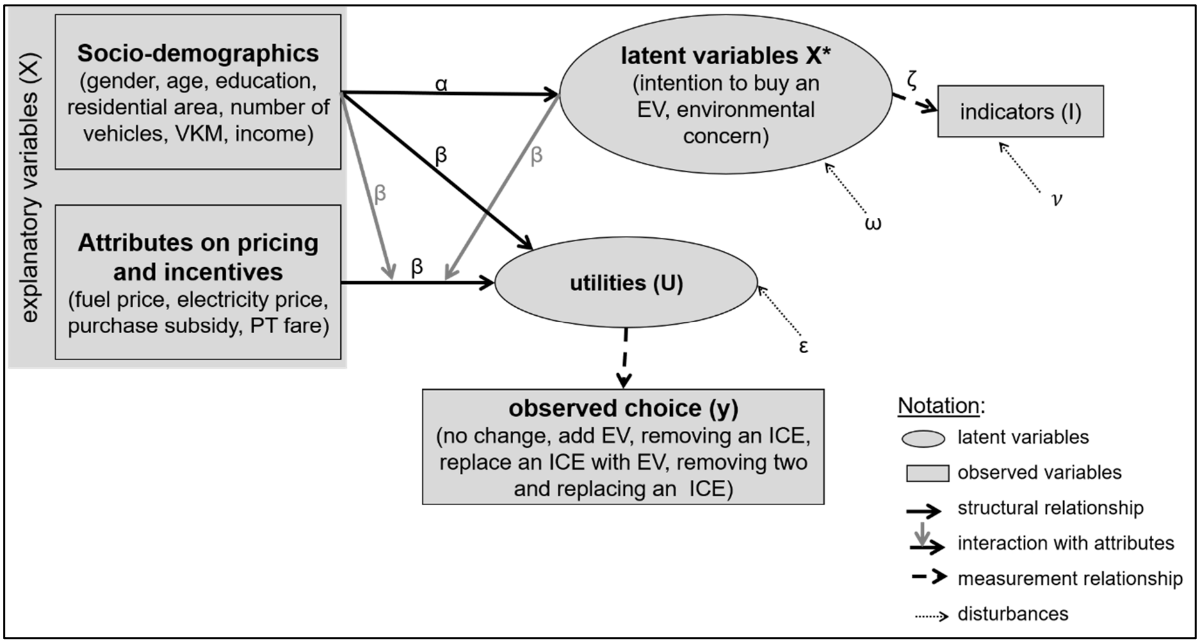


Figure 3. Application of the ICLV framework for dynamics in vehicle ownership (illustration of an ICLV framework adopted and modified from Walker and Ben-Akiva (2002))

3. Main results and discussion on policy implications

All data analyses were performed with R using the package *apollo* (Hess & Palma, 2019; R Core Team, 2020). 2,000 Halton draws were used for the ICLV model.

An increase in **fuel prices** is effective in motivating people to replace an existing ICE vehicle with an EV, and the effect becomes stronger with more VKM travelled. Rising fuel prices also have a positive effect on the likelihood of removing an ICE vehicle completely in environmentally concerned households (see positive interaction parameter). Thus, this push measure is highly recommended to achieve the decarbonisation of road transport. The resulting revenue needs then to be invested in pull strategies.

Free **electricity** encourages individuals to shift from an ICE to an EV, especially those with greater intention to buy an EV. However, this policy implication needs to be taken with caution. Namely, results also show that free electricity prices cause unintended effects for wealthy households, who become attracted to buy an EV as an additional vehicle. Moreover, according to studies in behavioural economics, free products gain in value (Shampanier et al., 2007) and thus free operating costs might induce even more traffic. Moreover, providing free electricity needs great governmental investment. Therefore, further research on the effects of reduced prices and rebates on the likelihood of replacing an ICE with an EV is needed.

The results indicate that an increase in **purchase subsidy** does not have an effect on achieving the switch to EVs and was fixed to zero. At the same time, the reduction of purchase subsidy is effective in preventing households from buying an EV as an additional vehicle, although wealthier households and people with greater intention to buy an EV are less sensitive towards the reduction. This indicates that they are less monetary-driven. In general, the negative main effect is in line with behavioural economics assumptions that a reduction in price does not add to the associated value of a product (Shampanier et al., 2007). Moreover, previous studies showed that the sensitivity to fuel costs is stronger than to purchase price (Hess et al., 2012), which confirms the recommendation to increase fuel prices and to stop providing purchase subsidies for the broader public. Thus, instead of spending the budget on purchase subsidies, policymakers are encouraged to better invest the budget in providing other pull measures and investing in further effective interventions e.g. charging infrastructure (Brückmann et al., 2021; Buchmann et al., 2021; Chandra, 2022; Jia & Chen, 2021). However, when fuel prices become very high, while the purchase of EVs is still expensive, it is still important to provide purchase subsidies to households with low equivalised income to avoid mobility discrimination. As shown in a simulation study by Xing et al. (2021) income-dependent subsidies increase EV sales as well, while savings are mainly coming from households who would buy an EV also with the absence of subsidies. Further, to avoid the risk that households would buy an EV as an additional vehicle, policymakers might consider providing the purchase incentive only on the condition that a currently existing ICE vehicle will be sold. Although the effects are statistically not significant, the results suggest that free PT motivates highly environmentally concerned households to remove an ICE. Further, free PT might be needed to compensate for increasing fuel prices. As in the case of fare-free PT in Tallinn, PT usage increases especially among price-sensitive groups (young, elderly, very low income, and people out of employment/education) resulting in greater mobility and accessibility (Cats et al., 2017). However, it is important to note that free PT might induce travel demand without leading to a large reduction in vehicle usage, as only by 10% in Tallinn (Cats et al., 2017). Furthermore, subsidising completely free PT would be very costly for the government. It is, therefore, necessary to further investigate how similar results can be achieved while generating revenue.

The application of the ICLV model including interaction effects of the pricing and incentive attributes with unobserved latent variables "intention to buy an EV" and "environmental concern" provides important insights into the complexities of the decision-making process. The results demonstrated that pricing schemes aimed at encouraging the removal of internal combustion engine (ICE) vehicles — such as increased fuel prices and free public transport — are only effective for individuals with a strong environmental concern. At the same time, people with greater intention to buy an EV are less monetary-driven than those with low intention and are more likely to switch to EVs even in the absence of policies for EV promotion such as purchase subsidies. These findings underscore the importance other interventions such as information campaigns (Steinmetz et al., 2008) targeting people's attitudes and perceptions, which can motivate changes in their household fleets on voluntary basis (Steg & Gifford, 2017).

Table 2. Estimation results of the final ICLV model

change	attribute	est.	r. t-val.
	price attributes		
removing an ICE	**fuel price**	-4.007	-2.52
	λ(income, fuel)	-0.135	-0.60
	λ(VKM, fuel)	0.210	1.70
	X env. concern	1.147	4.26
replace ICE	**fuel price**	0.537	1.96
	λ(VKM, fuel)	0.127	1.18
	X intention	0.467	4.44
remove & replace ICE	**fuel price**	0.507	1.62
	λ(income, fuel)	-0.392	-1.56
	λ(VKM, fuel)	0.400	1.65
	X intention	0.464	2.77
adding EV	**electricity price** (Ref: no change)		
	minus 3.50€	-0.347	-0.54
	X income	0.373	2.27
	plus 3.50€	-0.004	-0.01
	X VKM	-0.059	-1.96
replace ICE	**electricity price** (Ref: no change)		
	minus 3.50€	0.793	1.35
	X intention	0.979	3.43
	plus 3.50€	-1.369	-1.51
	X intention	1.471	3.80
remove & ...	**electricity price** (Ref: no change)		

change	attribute	est.	r. t-val.
	minus 3.50€	2.173	2.67
	X income	-0.333	-1.58
	X intention	0.796	1.62
	plus 3.50€	*fixed*	
adding EV	**purchase subsidy** (Ref: no change)		
	minus 4,000€ (2k)	-1.930	-1.97
	X income	0.443	2.03
	X intention	1.061	5.04
	plus 4,000€ (10k)	*fixed*	
replace ICE	**purchase subsidy** (Ref: no change)		
	minus 4,000€ (2k)	*fixed*	
	plus 4,000€ (10k)	0.477	1.44
	X intention	-0.412	-1.50
remove & replace ICE	**purchase subsidy** (Ref: no change)		
	minus 4,000€ (2k)	-0.565	-1.54
	plus 4,000€ (10k)	*fixed*	
removing an ICE	**PT** (Ref: no change)		
	minus 50%	*fixed*	
	minus 100%	-5.390	-1.46
	X VKM	-0.034	-1.44
	X env. concern	1.547	1.86
remove & replace ICE	**PT** (Ref: no change)		
	minus 50%	*fixed*	
	minus 100%	0.402	1.08
	ASCs & socio-demographics		
no	ASC	*fixed*	
adding EV	ASC	-0.427	-0.46
	age	-0.019	-1.47
	education (ref: low)		
	middle - high	-0.549	-1.29
	urban (Ref: suburban/rural)	-0.879	-2.44
	more vehicles or equal than drivers (Ref: less)	-0.621	-1.78
removing an ICE	ASC	-1.002	-0.46
	age	-0.049	-0.57
	age2	0.000	0.17
	education (ref: low)		
	middle	*fixed*	
	high	0.016	0.03
	more vehicles or equal than drivers (Ref: less)	0.504	1.04
	female (Ref: male)	-2.285	-2.82
replace ICE	ASC	-3.619	-3.25
	age	0.050	1.14
	age2	-0.001	-1.37

change	attribute	est.	r. t-val.
remove & replace ICE	education (ref: low)		
	middle		
	high	0.252	1.03
	urban (Ref: suburban/rural)	-0.297	-1.26
	more vehicles or equal than drivers (Ref: less)	0.200	0.89
	ASC	-3.456	-2.80
	age	-0.021	-0.93
	education (ref: low)		
	middle		
	high	0.583	0.98
Latent variable components not presented due to space restrictions			
Model fit			
draws		2000 Halton	
n individuals		444	
n choices		1737	
n estimated parameters		86	
log-likelihood choice		-1279.24	
log-likelihood overall		-4034.91	
adjusted rho-square		0.3536	
AIC		8241.82	
BIC		8594.06	

Note: est = estimate; r.t-val. = robust t-value; X = interaction; AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion

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