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External costs of electric vehicles

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Abstract

Electric vehicles (EV) are often considered a promising technology to decrease external costs of road transport. Therefore, main external cost components are estimated for EV and internal combustion engine vehicles (ICEV). These include costs of accidents, air pollu-tion, climate change, noise, and congestion. All components are estimated over the product lifetime and, where appropriate, differentiated according to fuel type, vehicle size as well as emission location and time. The advantage of this differentiation is, however, compen-sated by high uncertainties of most cost estimates. Overall, the external costs of EV and ICEV do not differ significantly. Only for climate change, local air pollutants in congested inner-cities, and noise some advantageous effects can be observed for EV. The advantages depend strongly on the national electricity power plant portfolio and potentially also on the charging strategy. Controlled charging might allow for higher emission reductions than uncontrolled charging of EV.

Keywords: External costs; Environmental impact; Electric vehicle; Passenger car; Internal combustion engine vehicle

Introduction

In 2012, almost the entire (99.8%) global vehicle stock was still based on internal combustion engine vehicles (ICEV) using petroleum-based fuels (Clean Energy Ministerial et al., 2013). Europe is highly dependent on these fuels imported mainly from the Middle East and Russia (IEA, 2012a) and road transport induces several environmental problems (e.g. acidification and eutrophication, ozone alarm, particulate matter, noise nuisance, etc.). Hence, road transport is a key sector in the context of environmental protection and energy security.

Currently, climate change is in the focus of politics, public, and scientific literature. In the European Union (EU-27), the emissions of the most relevant greenhouse gas (GHG), carbon dioxide (CO2), were reduced by almost 12% between 1990 and 2010, whereas the transport sector increased its CO2 emissions by 20.6% during the same period. In the new EU member states this increase even reached 58.5% versus a decrease in overall CO2 emissions by 29.5% (Eurostat, 2013). These trends are expected to continue, although somewhat weakened (JRC, 2008). In view of these trends, high technical CO2 abatement costs, and the expected change of conduct, many studies came to the conclusion that transport will be among the last sectors to bring its emissions down below current levels (e.g. Stern, 2006, Annex 7c and Skinner et al., 2010). On the global scale, the situation is even more severe. The World Business Council on Sustainable Development (WBCSD, 2004) expects the global vehicle fleet1 to more than double until 2050. This is supported by several other studies (cf. Gomez-Vilchez et al., 2013).

Electric vehicles (EV) might help to master some of those challenges (e.g. Anable et al., 2012). Even though this idea is not new (cf. Hamilton, 1980), the electrification of the road transport sector is said to be an ecologically promising pathway. Some studies show that the marginal abatement costs for GHG emissions are lower compared to ICEV (Hacker et al., 2009, and TNO et al., 2006). Needless to say, EV have considerable external costs which highly depend on the electricity generation during the EV's lifetime and for the construction of the vehicle and battery (e.g. Bickert and Kuckshinrichs, 2011). Besides the impact on GHG emissions there are several other influences on the environment and the society, which are not jet explicitely considered in the users' utility - and are therefore extrenal costs. Economic concepts for measuring and internalising external costs seem convenient to identify these effects (cf. Proost and Van Dender, 2012). We therefore apply this concept in the following and compare the external costs from EV with those from ICEV.

Even though EV have been existing as long as ICEV, they were rather insignificant during the last century and gained relevance in recent years only. This recovery was mainly driven by the pressure of rising GHG emissions and high fuel dependency of industrialised countries as well as by strong breakthroughs in battery development (cf. Nykvist and Nilsson, 2015). To date, a number of studies have dealt with the environmental impacts of EV – most of them focusing on CO2 emissions (e.g. a broad literature overview by Hacker et al., 2009). In addition, first in-depth studies (e.g. Torchio and Santarelli, 2010) were published, with some even using life cycle assessment (LCA) approaches (cf. Hawkins et al., 2012a,b; Messagie et al., 2010; Lane, 2006). For Germany, e.g. Helms et al. (2013), Zimmer et al. (2011), and Peters et al. (2012) provide first analyses. However, current literature remains at the level of average driving cycles, averaging urban and rural travel. In the discussion on charging vehicles according to their local and temporal impact, as promoted by the European Commission's vision of marginal social cost pricing (MSCP) for all transport modes, more disaggregated figures of the external costs of EV in comparison to ICEV are needed. The present paper aims at shedding some light on this issue taking into account the transport and energy sectors.

We are well aware that environmental and climate issues are important challenges for the transport sector Creutzig et al. (2015), but do not capture completely the social burden of transport. Current policies and visions on sustainable transport try to get cars completely out of the city centers (cf. Anas and Lindsey, 2011) – a place where EV have their main environmental advantage over traditionally powered cars. We also pay attention to safety and congestion issues. Space consumption and the separation of cities by busy roads will be discussed qualitatively. Furthermore, our analysis will focus on pure battery electric vehicles (BEV) even though other EV, such as plug-in hybrid electric vehicles (PHEV) or range-extended electric vehicles (REEV), will probably have a much higher market potential (Kay et al., 2013). Their emissions, however, are somewhere between the ICEV and the BEV.

The structure of this paper is as follows: We give a short introduction to external costs in the next section, before outlining current external costs of ICEV (i.e. external costs of accidents, air pollution, climate change, noise, congestion as well as other external costs) in chapter three. As the market share of EV seems to be rather low before 2030 and as vehicle technology as well as electricity consumption will improve until then, we give an outlook on external costs until 2030. Then, in chapter four, the current and future external costs of EV are given. A comparison of the external costs of ICEV and EV completes this paper.

External costs

Overview

Challenges associated with measuring external costs of transport are serious (cf. Verhoef, 1994). However, in order to compare the environmental sustainability of different modes and technologies, the concept of external costs is hardly evitable. Their (uniform) assessment is claimed to be necessary for reasons of equity and international comparisons (e.g. CE Delft et al., 2008). The challenges in assessing external costs are mainly based on the different impacts due to individual local conditions (e.g. different vulnerability or population density) or complex interdependencies of the emission and its impact (e.g. the statistically proven impact of noise emissions on life time or the evaluation of long-term impacts of climate change) (cf. Jochem and Rothengatter, 2011).

In the past, approaches to measuring external costs temporarily prevailed. However, methods for willingness to pay and willingness to accept concepts, such as stated or revealed preference approaches, were criticised strongly throughout the 1990s (e.g. by Rosenthal and Nelson, 1995; Hausman, 1993; Diamond and Hausman, 1994). Even the more recent contingent valuation approach is increasingly criticised (e.g. Hausman, 2012). The development of new methods (e.g. with the help of data envelopment analysis) is continuing (Kuosmanen and Kortelainen, 2007). However, emergence of an all-convincing approach remains highly unlikely.

Besides these challenges in the evaluation methodology, the considered time horizon (cf. Fouquet, 2011), system boundaries, technical measurement, cost category (e.g. marginal vs. average), equity, handling of subjective evaluations, etc. are highly contentious issues when assessing external costs. They may be obstacles when comparing different results. Notwithstanding the concept of external costs serves as a basis for many environmental policies. Therefore, comprehensive best practice approaches for different cost categories (e.g. from CE Delft et al., 2008:8) have been used so far to cope with this contradiction and to give sound estimates for their internalization (e.g. in Maibach et al., 2008; UBA, 2012; Korzhenevych et al., 2014). Despite these uncertainties, we compare the external costs of ICEV with those of EV and try to indicate the corresponding uncertainties in the following sections. We consider (where possible) the product lifetime of the vehicle by

LCA and of the fuel by comprehensive well-to-wheel (WTW) analysis data. Hence, the following LCA includes the emissions caused by well-to-tank (WTT) activities and tank-to-wheel (TTW) emissions during vehicle use as well as the emissions associated with vehicle production, maintenance, and disposal.

We focus our analysis on Europe, because – according our literature review – only for European road transport comprehensive cost factors in high resolution are available. Only a few values are found for other countries, however, often restricted to certain areas or situations. There is a focus on developing countries, mainly for Asia and Latin America, where the problem of urban air quality is most evident (e.g. Sen et al., 2010, quantify main externalities for Dehli, Cravioto et al., 2013, adopt European approaches to Mexico or Tseng et al., 2014, relate the development of external costs to the introduction of road tolls in Taiwan). For North America Delucchi and McCubbin (2010) compile national estimates of transport externalities in the United States and Litman (2014) broadens the methodology and evidence for assessing the social costs and benefits of transport and urban development for Canada and the United States.

Methodology

The assessment makes use of latest European research relating to external costs. We concentrate on European, and more precisely on German assessments, as in particular for EV external impacts are closely related to power generation and national power plant fleets are very heterogeneous in Europe. Transferring our external cost estimates to other countries seems highly inappropriate.

Before we determine the specific cost estimates we specify main categories. First, we consider the following four main external impacts (on both ICEV and EV):

- *Accident consequences:* We value the loss of human lives or impairment of health according to the degree of severity.
- *Air pollution:* The impact from air pollution considers emissions of nitrogen oxides (NO_X), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC) as well as of particles below 10 µm (PM_{10}) and below 2.5 µm ($PM_{2.5}$).
- *Climate change:* We consider all emissions of GHG expressed in CO_2equivalents.
- *Noise exposure:* We mainly distinguish between persistent exposure above 55 dB(A) night/65 dB(A) day and above 70 dB(A) day and night with the corresponding health impacts.

Other external impacts, such as further impacts of vehicle production (costs of up- and downstream processes), percep-tion and use of soil and groundwater pollution, costs of energy dependency, the deterioration of nature, landscape, natural habitats, and urban fabric by the road infrastructure as well as the financial burden of public households resulting from the construction and maintenance (which is partly internalized) of roads, are neglected, as they hardly contribute to the total external costs and do not differ considerably between ICEV and EV.

Second, most cost estimates are differentiated with respect to the following characteristics

- *Fuel type* (gasoline, diesel, and electricity): For ICEV we focus on gasoline (and values for diesel added where appropriate). Other fossil fuels (such as LPG or CNG), biofuels, hydrogen, and different forms of hybrid fuels are not considered here.
- *Vehicle size* (small and medium): We assume a trend towards smaller vehicles and assume that large cars (>2 l engine displacement) will not be in the focus of manufacturers of BEV in the beginning of market penetration (Peters et al., 2012 and Mock et al., 2009). We do not consider light vehicles, such as bicycles, scooters, and motor cycles, and delivery vehicles – even though EV have already reached considerable market shares in these segments in some countries.
- *Emission location* (urban, rural): This differentiation is mainly due to the corresponding population density: Local pollutants (e.g. air pollutants, noise) should be valued according to the number of potential victims. Furthermore, the difference in the driving cycle may affect the amount of emissions, too. Consequently, also global emissions (e.g. CO_2emissions) are affected by this differentiation.

• *Time of day of emission* (day peak, day off-peak, night): This distinction is particularly relevant to congestion and noise impacts. Also accident rates and the exposure of residents to air pollutants may vary over the day. However, these variations are not investigated in detail in current literature and, hence, excluded. Furthermore, the electricity mix might differ between day and night time.

With regard to the people's willingness-to-pay, other cost items, population density, and geographical structures, we refer to the German conditions in the reference year of 2010 and our forecast for 2030.

External costs of ICEV

External costs of ICEV in 2010

The latest study ''External Costs of Transport in Europe" conducted by CE Delft et al. (2011) on behalf of the International Union of Railways (UIC) and the initial issue of the European Commission's Handbook on the Estimation of the External Costs of Transport (Maibach et al., 2008) are considered highly valuable bases for the estimation of the external costs of transport for ICEV. Recently, the methodology was developed further by the German Federal Environmental Agency (UBA, 2012). The differentiated average cost values reported for the year 2008 in the study are transferred to 2010 values for Germany in order to make them comparable to latest estimates for EV. The cost values of the studies are given for the years 2000 (Maibach et al., 2008) and 2008 (CE Delft et al., 2011) for Europe. From these, we extract cost figures for Germany, apply the given country adjustment factor of 1.16 to average European values, and finally deflate them to the year 2010 using price indices of 16.7% from 2000 to 2010 and 0.5% from 2008 to 2010 (according CE Delft et al., 2011). The subsequent sections report on the valuation principles and results by cost category, followed by summary tables.

Accidents

The non-monetized consequences of traffic accidents make up the largest share in external costs of road passenger trans-port. Among these, the value attached by the society to preserving human health and life is the most expensive component by far. This so-called ''value of statistical life" (VSL) includes utility losses for the victim as well as suffering and grief of relatives and friends (CE Delft et al., 2011). When adapting the VSL of 1.5 million € proposed by CE Delft et al. (2008) to 2010 values in terms of price inflation and PPP adjustment according to CE Delft et al. (2011), a European value of 1.67 million € results.

With a PPP adjustment for Germany, a German VSL of 2 million € is obtained for 2010. For severe injuries, 13% (230,000 euros) and for slight injuries 1% (20,000 euros) of the VSL is used according to Maibach et al. (2008).

The marginal cost principle, however, goes beyond the counting and assessment of incidents and the allocation of costs to user groups: It measures the impact of an additional vehicle entering the road on total accident costs. Two very different outcomes may result. On the one hand, an increasing number of vehicles leads to a rising number of accidents (i.e. higher total accident costs) due to the increase in mutual interferences. On the other hand, increasing traffic density implies lower speeds and, thus, reduces the severity of crashes and, consequently, the number of fatal injuries. We argue that for a very empty infrastructure the first principle outweighs the second and vice versa.

The UNITE project (Nash, 2003) studied the interrelationship between traffic density and accident costs using data from Switzerland. The results reveal that the net effect of additional vehicle kilometres (vkm) on accident costs is positive, but that the resulting marginal costs for all road categories (15.6 €/1000 vkm) are well below the corresponding average accident costs (43.9 € per 1000 vkm) (i.e. the corresponding cost function is concave). Table 1 presents the highly diverging results of CE Delft et al. (2011), updated to 2010 by road class.

Table 1 Marginal external accident costs by road class 2008 ($€_{2010}$ per 1000 vkm) for Germany.
Source: CE Delft et al. (2011), Table 33, inflated to 2010 with consumer price index according toDeStatis (2013).

Road type	Marginal accident costs
Motorways	4.16
Rural roads	21.7
Urban roads	55.1
All roads	15.8

Air pollution

Air pollutants affect health and cause cardiovascular and respiratory diseases. These can be valued by the loss of healthy life years based on epidemiological studies and dose–response relationships derived from them. Further impacts are building and material damages, crop losses, impacts on biodiversity and ecosystems (CE Delft et al., 2011). The most relevant substances are particulate matter (PM), nitrogen oxides (NO_X), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOC). Particulate matter appears in different particle diameters: PM_{10} includes all particles smaller than 10 µm mainly due to tire abrasion and re-suspension, while $PM_{2.5}$ denotes particles below 2.5 µm mainly stemming from fuel combustion. The share of $PM_{2.5}$ in the PM_{10} cocktail from ICEV is estimated to be 70% by UBA (2012).

The damage potential of air pollutants – as well as of GHG – can be determined by two approaches: The impact pathway approach as developed by the ExternE in the mid-1990s (Friedrich, 2005) or the eco-inventories or LCA approach (Guinée et al., 2011). While the impact pathway method is well suited for tracking emission, dispersion, re-formation, and absorption of pollutants from the source to people or objects affected at different times and under varying topographical and climate conditions, the LCA aims at analysing the composition of materials and their environmental damage potential. Hence, the impact pathway approach is typically applied to TTW emissions (e.g. Jensen et al., 2008), whereas the LCA approach is better suited for the vehicle production and WTT emissions (e.g. Hawkins et al., 2012a,b).

WTT and TTW (and, hence, WTW) emissions are directly linked to the usage of the vehicle and, thus, count when estimating the marginal external costs of transport. Production and disposal are mainly one-off emissions and, hence, considered only when computing the average external costs of transport. However, a vehicle with a longer lifetime usually has lower average costs (except if comprehensive investments are necessary).

Tank-to-wheel emissions of ICEV

The TTW emissions of ICEV are mainly dependent on the fuel-type, the combustion engine, and the filter technologies. The corresponding monetized impact is determined mainly by an assumption of cost factors and number of affected persons. Therefore, the cost factors for metropolitan areas are significantly higher than for non-urban areas (cf. Jensen et al., 2008). However, the uncertainty is high. For Germany, the latest assessment (by the impact pathway approach) is provided by the update of the methodological convention on estimating the external costs of energy use by the Federal Environmental Agency in UBA (2012). The study only provides local differentiations for PM emissions, which are valued three times higher in urban areas than in inter-urban transport for both particle sizes (i.e. PM_{10} and $PM_{2.5}$).

The corresponding cost estimates for particulate matter significantly differ from other studies, such as for example CE Delft et al. (2011) (cf. Table 2). This difference is non-systematic: The German values from UBA (2012) are significantly higher for $PM_{2.5}$, but lower for PM_{10}. As for other pollutants, the differences are minor and more systematic, indicating that the definition of $PM_{10}$is not the same across the studies. It either denotes the mix of all particles smaller than 10 µm or only those from 2.5 to 10 µm. In addition, the studies are based on varying assumptions regarding population density and/or the value of a healthy life year lost.

Table 2 Assessment of air pollutants by transport (€$_{2010}$ per t).

Sources: UBA (2012) and CE Delft et al. (2011), Table 7, values for Germany, transformed to 2010 values using the DeStatis (2013) consumer price index.

Pollutant	CE Delft et al. (2011)			UBA (2012)	
	Metropolitan	Urban	Non-urban	Urban	Inter-urban
$PM_{2.5}$	436,410	140,771	85,091	364,100	122,800
PM_{10}	174,544	56,288	34,077	33,700	11,000
NO_X	14,310			15,400	
NMVOC	1420			1700	
SO_2	11,318			13,200	
NH_3	–			26,800	

We quantify the emissions released per vkm for vehicle compliant with the Euro-5 standard in order to ensure fair comparison of new electric and gasoline or diesel cars. According to the regulations of the European Commission (EC, 2007), the maximum permissible local emissions from passenger cars in the New European Driving Cycle (NEDC) differ neither in vehicle size nor in weight. Although smaller cars usually emit fewer pollutants, this simplification is maintained. When restricting the analysis to the tailpipe emissions regulated by the Euro emission standards, we neglect the important category of particles re-suspended from the pavement and from brakes and tires. However, this is less problematic, since these emissions are mostly independent of the propulsion system.

Well-to-tank emissions of ICEV

The emissions of drilling, transporting, and processing of crude oil occur globally, mainly outside of populated areas. We use the unit costs per ton of pollutant given for the category ''industry world" in UBA (2012). Emission factors are taken from IFEU (2011) for fossil energy production. Finally, we take fuel consumption rates by size class and fuel type from the Handbook Emission Factors for Road Transport (HBEFA) vehicle emission database (INFRAS, 2010). With these data, we calculate the average WTT emissions per vkm. Table 3 shows the results by vehicle and settlement category for both direct (TTW) and upstream (WTT) emissions.

Table 3 Marginal external air pollution costs for Euro-5 ICEV (€$_{2010}$ per 1000 vkm).

Source: Own calculations based on different sources.

Vehicle size and fuel (Euro 5)	Metropolitan		Other urban		Rural	
	WTT	TTW	WTT	TTW	WTT	TTW
Small gasoline	2.35	2.92	2.18	1.61	1.68	1.36
Small diesel	1.78	3.19	1.63	1.88	1.18	1.63
Medium gasoline	2.85	2.92	2.68	1.61	2.18	1.36
Medium diesel	2.22	3.19	2.07	1.88	1.63	1.63
Average values	2.30	3.06	2.14	1.75	1.67	1.50
Average values (WTW)	5.36		3.89		3.16	

These values from 1.36 up to 3.19 € per 1000 vkm are significantly lower than the marginal costs of gasoline cars across all size classes and emission standards reported in CE Delft et al. (2011) of 148 €/1000 vkm in metropolitan areas and 49 €/1000 vkm on rural roads. The discrepancy can be explained by the great uncertainty of the local impacts of air pollution at the location of fossil fuel extraction and production. In case drilling and refinery take place close to settlement areas, as e.g. in Nigeria, the impacts on people's health are enormous. By contrast, as long as no major accidents occur, off-shore drilling causes only little impacts on people.

Climate change

The impacts of GHG emissions from road vehicles on global warming are independent of their timing and location. More-over, the emission standard of vehicles, i.e. filtering of exhaust fumes in the tailpipe, does not affect the GHG emissions directly. However, fuel efficiency and (adding) biofuels may decrease GHG emissions considerably – even if these measures seem to be limited today. Hence, for assessing the global warming impact of ICEV, two parameters are relevant: Fuel consumption and GHG content (including WTT emissions) of the fuel. The analysis of the GHG content can be limited to the global warming potential of CO2 (i.e. neglecting other GHG and focusing on the carbon content of the fuel, which reacts to CO2 during the combustion process), as the share in the global warming potential of non-CO2 GHG emissions amounts to 0.3% only for delivery vans and to 1.2% for passenger cars (Peters et al., 2012). However, the monetization of the global warming potential is crucial (cf. Jochem and Rothengatter, 2011).

For internalizing the economic impact of GHG emissions, the damage cost approach seems to be more appropriate at first. However, due to the long persistence of CO2 in the atmosphere (about 90 years), the multitude of impacts all over the globe, and potential reaction mechanisms of human societies and nature, reliable estimations are hardly possible. Moreover, internalization is associated with the problem of using the ''right'' discount rate (inter-generational equity) and the ''right'' valuation of damages in all affected continents (intra-generational equity) (cf. Jochem and Rothengatter, 2011). For these long time horizons, the discount rate has a very significant impact on the corresponding monetary values (cf. Stern, 2006 and Nordhaus, 2007). Consequently, the right discount rate no longer is an economic question, but rather a question of inter-generational equity (Stirling, 1997) and, hence, an ethical question (Nordhaus, 2007), for which a consensus on the ''right'' discount rate seems to be impossible. Furthermore, the forecasted impact on countries differs significantly (e.g. Anthoff et al., 2009), which affects the intra-generational equity.

For these reasons, a unique external cost for GHG emissions is highly unlikely and we should rather calculate with a range of probable estimates. We use the recommendations made by the German Environmental Agency for CO2 emissions (UBA, 2012) (cf. Table 4). These are somewhat below the value recommended by CE Delft et al. (2011:49). Due to the underlying risks (high uncertainty of high costs) confirmed by the recent IPCC report (IPCC, 2013) and the responsibility we should have for future generations, we use the still rather high prices of 120 €/t CO_2.

Table 4 Marginal external costs of CO_2 emissions ($€_{2010}$ per ton of CO_2).
Source: UBA (2012).

	Short run	Medium run	Long run
	2010	2030	2050
Lower value	40	70	130
Medium value	80	145	260
Upper value	120	215	390

As already mentioned, GHG emissions of fossil fuels during vehicle usage (TTW) are a direct function of fuel consumption. The CO_2 emissions, however, vary slightly among the fuel types. Fuel consumption is mainly determined by the engine efficiency and driving patterns. Here, we assume that in metropolitan and urban peak traffic fuel consumption rates are 20% above urban off-peak values, while for rural driving patterns consumption rates are 20% lower.

For the CO2 emissions of the WTT processes, the values from Peters et al. (2012) are used. The study reports the ratio of WTT to TTW emissions to be 17% for gasoline and 19% for diesel cars. Multiplying these values by the monetary factor of 120 € per ton from UBA (2012), we obtain the costs of GHG emissions by vehicle category, fuel concept, and traffic condition (cf. Table 5).

Table 5 Marginal external costs of climate change for ICEV (€$_{2010}$ per 1000 vkm).

Source: Own compilations based on different sources.

Car size and	Urban peak		Urban off-peak		Rural peak & off-peak	
Fuel	WTT	TTW	WTT	TTW	WTT	TTW
Mini gasoline	2.59	15.26	2.16	12.72	1.73	10.18
Mini diesel	2.51	13.15	2.09	10.96	1.67	8.76
Comp. gasoline	4.08	23.92	3.40	19.93	2.72	15.95
Comp. diesel	3.72	19.40	3.10	16.16	2.48	12.93
Average values	3.23	17.93	2.69	14.94	2.15	11.96
Average values (WTW)	21.16		17.63		14.11	

Noise

Constant exposure to high levels of environmental noise leads to disturbance and, thus, to a decrease in the perceived quality of life as well as to physical health impacts. The stress impact of noise pollution can be quantified by stated or revealed preference surveys, e.g. by the observation of prices of real estates exposed to different noise levels (cf. Bickel and Friedrich, 2005 or CE Delft et al., 2011). According to the World Health Organisation (WHO and JRC, 2011), this includes cardiovascular diseases, cognitive impairment, sleep disturbance, and tinnitus. The quantification of these ‘‘environmental burdens of disease" (EBD) requires estimating noise emission levels, the number of affected people, and appropriate dose–response functions.

The level of annoyance and health impacts on a particular person exposed to high sound volumes depend on the noise level in decibels (dB), its frequency spectrum, its dynamics, the time of day, and the physical and psychological condition of the person affected. Exposure–response functions for transportation noise show that people are annoyed by noise at levels below 55 dB (Miedema and Vos, 1998, 1999 and Finegold et al., 1994; Brandt and Maennig, 2011) and that elimination of noise annoyance occurs at 37–40 dB (and theoretically even lower). In practice other noise sources, e.g. noise from neigh-bours, may dominate road noise. The German Environmental Agency recommends target levels of 55 dB(A) at daytime and 45 dB(A) at night, while in the long run 50 and 40 dB(A) should be reached (UBA, 2012). The lower value for night-time is based on the significant higher sensitivity especially for areas with a high population density (Tobías et al., 2015).

With threshold levels of 55 and 45 dB(A), CE Delft et al. (2011) calculate 1.55 billion € of annual noise costs for Germany in 2008, of which 671 million € are caused by passenger cars.

This corresponds to an average of 0.8 € per 1000 passenger kilometres or 1.2 € per 1000 vkm. According to the procedure proposed by CE Delft et al. (2008), the study derived marginal costs by applying the German transport noise model to typical traffic situations. Table 6 presents the updated values from CE Delft et al. (2011) – even if the local impact can significantly differ depending on the local conditions (cf. Bickel et al., 2003). Due to the strongly non-linear perception of noise by the human ear, the recognised loudness of a vehicle strongly depends on the prevailing background noise. In other words: The higher the traffic density is, the less disturbing is an additional car. Accordingly, by far the highest marginal noise costs are obtained in night time where traffic density is low and the people's sensitivity is high.

Table 6 Marginal external noise costs for ICEV (€$_{2010}$ per 1000 vkm).

Source: Own compilation based on CE Delft et al. (2011), Table 37; costs adjusted from European average 2008 to Germany 2010 by PPP-adjusted GDP/capita and consumer price index.

	Urban	Suburban	Rural
Day peak	10.5	0.6	0.1
Day off-peak	25.5	1.6	0.2
Night (off-peak)	46.5	3.0	0.5

Congestion

External costs of congestion occur when users plan their mobility individually but the required resource, the infrastructure, is (temporary) too scarce to fulfil this mobility demand. Even though the initiator bears already a share of these costs (own delay), she or he contributes to this congestion and therefore impose costs to other traffic participants (intra-sectoral external costs) and simultaneously to the society (the transport system becomes more inefficient, which leads to welfare losses) (cf. Rothengatter et al., 2015). The basic principle of the external costs of congestion was formulated by Pigou (1920) a century ago in the form of the famous ''Pigou problem" of traffic assignment on two routes between origin and destination. The congestion externality is caused by involuntary interactions among road users and the fact that they do not take into account the impacts of their route choices on other users. Main cost elements in this case are time losses and their economic value, plus speed-dependent fuel costs. The value of travel time strongly varies with the travel purpose. CE Delft et al. (2011) suggest values of time between 7 € per hour for leisure travel and commuting and up to 20 € per hour for business trips. Other additional costs, i.e. environmental costs, traffic accident costs, and fuel consumption costs, are negligible (Qingyu et al., 2007). Increasing fuel costs due to stop-and-go conditions usually amount to some 10 € of time costs.

Nonetheless, the internalization remains challenging. As shown by CE Delft et al. (2008), the velocity in congestions might be strongly non-linear and in cases of complete breakdown, the corresponding marginal costs per vehicle kilometre increase to infinity. Thus, it seems hardly possible to identify reasonable and empirical marginal congestion costs. Therefore, CE Delft et al. (2011) derive the corresponding estimates by meta-studies comparing area-wide model applications. These values in peak times may range between more than 2 € per vkm in central urban areas to 0.3 € per vkm in small towns and 0.1 € in rural areas (Maibach et al., 2008; CE Delft et al., 2011) (cf. Table 7).

Table 7 Marginal external congestion costs for ICEV (€$_{2000}$ per vkm).

Source: CE Delft et al. (2011:108), Table 38.

	Large urban areas	Medium urban areas	Rural areas
Motorway	0.5	0.25	0.1
Collectors	0.5	0.3	–
Local street/trunk road	0.75–2	0.3	0.05
Average values	0.79	0.28	0.08

Summary of cost estimates for internal combustion engine vehicles

So far, all cost estimates have been subject to uncertainties resulting from different market situations, differences in spatial circumstances, and the chosen internalization method. Even though the magnitudes differ widely, we can state that the main cost components of external effects of passenger cars are congestion, accidents, noise and air pollution costs. Climate change costs (in spite of the huge specific costs assumed) reach a minor share only. Fig. 1 gives cost estimates for all cost components on the logarithmic scale.

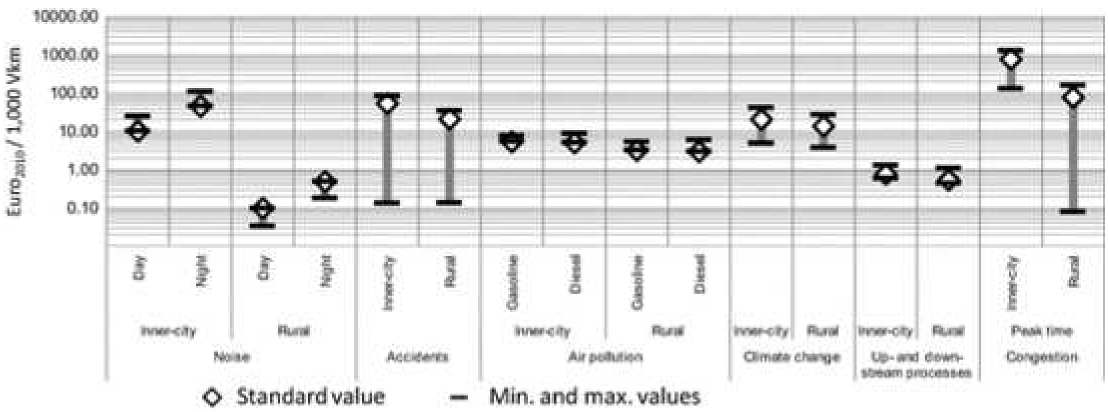

Fig. 1 Maximum, minimum, and standard external costs of ICEV in €$_{2010}$ per 1.000 vkm.

In order to compare the two technologies, we aggregate the average of the marginal external cost values for ICEV. For this, we need assumptions of the total mileage of the vehicle, i.e.

200,000 km, and of the share of inner-city mileage as well as daytime. According to a German mobility survey, 26% of average mileage is driven in cities and 8% during night time (from 9 p.m. to 6 a.m.) (Infas and DLR, 2010: 46). Therefore, the external costs for a life-cycle of a vehicle amount to about 65,000 € for ICEV for standard values (cf. Fig. 2 below). The most significant shares in these external costs per vehicle are congestion (67%), vehicle production (16%), and accidents (10%).

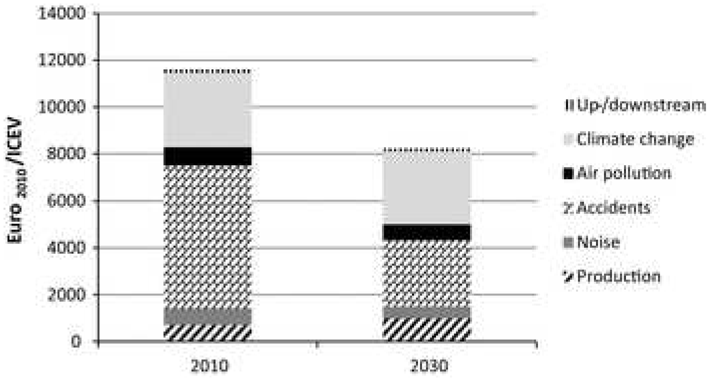

Fig. 2 External costs per ICEV in 2010 and 2030 (own calculation).

Extrapolation of external costs of ICEV to 2030

For analysing the potential of EV to reduce the social and environmental burden of road transport, we estimate external costs of ICEV in 2030. The corresponding forecast for EV will be made in the subsequent section.

The forecast is considering ceteris paribus conditions, i.e. as many as possible of the determinants of external costs, which are not linked to the vehicle propulsion system, are kept constant. Furthermore, we do not expect breaking innovations in the field of passenger cars before 2030. These are in particular driving cycles, vehicle stock, population densities, willingness-to-pay values, etc. We then express the cost change per vehicle based on the following assumptions:

- *Traffic safety:* According to new vehicle technologies and the European safety vision of zero fatalities in transport by 2050 (EC, 2011), we assume for 2030 50% less fatalities and, hence, a reduction of external accident costs by the same magnitude.
- *Air pollution:* Our values for 2010 refer to Euro-5 vehicles. As the external costs are already low and as further reduction by technology seems to be limited, we assume a deceleration of Euro standards and, hence, only marginal decreasing in external costs by 10% until 2030.
- *Climate change:* Even though we assume – forced by legislation – a further increase of fuel efficiency of about 40% (from about 6 to 3.5 litres gasoline per 100 km (40- 67 MPG)), the increase in unit costs per ton of CO_2 from 120 to 200 € is balancing the effect. Therefore, the external costs of climate change remain stable until 2030. However, a potential breakthrough in bio-fuels might change this value significantly.

- *Noise:* As engine and tire technology will continue to result in more silent cars, we assume a further decrease of noise emissions and correspondingly of external costs of noise by 10% until 2030.
- *Vehicle production:* We assume a further decrease of CO_2 emissions during vehicle production (mainly due to a decrease of emissions for electricity generation) from currently 6 to 5 tons per vehicle in 2030. However, the assumed increase of CO_2 prices to 200 € leads to an increase in external costs of 1.000 € per vehicle.
- *Congestion:* For congestion we assume a heterogeneous development. Whereas the values in cities will decline by 10% due to better public transport systems, other alternatives, better communication systems, and more restrictive regulations for ICEV, we assume a slight increase of external costs in rural areas of 10% until 2030.
- *Rural vs. inner-city:* Furthermore, we assume a decreasing share of trips within the city from 0.26 to 0.2.
- *Up- and downstream processes:* We assume a small decrease of costs by 10% due to an increasing awareness of these issues.

Even though all our assumptions are rather vague, the following tendencies can be derived: The improvements in congestion costs (from about 53,000 to 49,000 € per vehicle – not illustrated in Fig. 2) and in accident costs contribute to decreasing external costs in passenger road transport. All other improvements are comparatively marginal (cf. Fig. 2). The overall external costs per vehicle decrease only from about 65,000 (11,600) to 57,000 (8200) € per vehicle (without external costs of congestion).

External costs of electric vehicles

Despite the long history of EV, the estimation of their external costs is rather unknown. Due to the technology's recent revival, the interest in this issue increased again (e.g. Bickert and Kuckshinrichs, 2011). Comprehensive studies of external effects in the field of electricity generation, which contribute the most during the EV life cycle, were accomplished during the ExternE project (e.g. Friedrich, 2005; Krewitt, 2002 and Krewitt and Schlomann, 2006; Sundqvist, 2004). In the following sections, we refer mainly to those contributions.

External costs of electric vehicles in 2010

Accidents and congestion

The external costs of EV in the two cost categories of accidents and congestion do not significantly differ from those of ICEV. On the one hand some authors argue that the number of accidents at low speed (below 25 km/h; 15 mph) might rise due to the silent rolling of EV (e.g. Stelling-Kon´czak et al., 2015) – even though the problem seems to be marginal (Cocron et al., 2011; Dudenhöffer et al., 2011). On the other hand, the maximum speed of EV might be lower (or drivers avoid high speed due to inefficiencies), which could decrease the severity of accidents at high speeds. Safety issues relating to the drivers of serial EV are comparable to ICEV (Paine, 2011). We therefore argue for equal external cost factors for EV and ICEV.

Air pollution

External costs of air pollution by EV include several pollutants emitted during electricity generation, i.e. WTT. TTW emissions are negligible – only some particles from tire abrasion or from the brakes can be measured (Garg et al., 2000) – and are reduced by recuperation processes. The WTT emissions of EV differ as a function of the time and location of the analysed charging process. This is usually advantageous for EV, as the emissions of air pollutants take place when the people stay at home and notably in less densely populated areas, which has a huge effect on external costs, as the impact especially from PM emissions is of very local character (Funk and Rabl, 1999). For other secondary pollutants (e.g. nitrate and sulphate aero-sol particles), this effect is somewhat limited, as their formation takes some time and occurs over distances of tens to hundreds of kilometres (Funk and Rabl, 1999).

For measuring the additional emissions through the increased electricity demand of EV, four assessment principles can be distinguished (Jochem et al.,2015):

1. *Annual average mix:* A straightforward method would be to multiply the average annual emissions per energy unit (e.g. gram of NO_X per kWh) by the electricity demand from EV (in kW h).
2. *Weighted average mix:* As the energy mix might change during the day, it might be reasonable to integrate a weighting of the energy mix according to the amount of electricity demand from EV.
3. *Marginal electricity mix:* The additional electricity demand of EV leads to an increase of local air pollutants from electricity generation. This marginal electricity mix is based on different power plant typs with different specific emission factors.
4. *Balancing a sugar-coated energy mix*: It is ensured that the sum of the additional electricity demand of EV is generated by clean energy generation (e.g. from renewable energy sources). In times of expensive electrical storage systems, this only seems to be possible by a hypothetical balancing of energy.

The resulting emissions may differ considerably, as the emissions from the underlying technologies as well as their distance from settlement areas differ, too. Furthermore, the factors relevant for monetizeing might differ with respect to population density, national specifications, time, etc.

In Germany, emissions depend strongly on the charging time. The main impact on national emissions over time is caused by the share of electricity generation by renewable energy resoures (cf. Fig. 5). Most charging processes would mainly proceed in the early evening hours when most vehicles arrive (infas and DLR, 2010) and the conventional electricity demand is already high. This would increase the share of peak-load power plants. A charging process automatically postponed to the night could lead to a decrease of emissions (e.g. by increasing the feed-in of electricity from renewable energy ressources (cf.Jochem et al., 2015).

When multiplying the volumes of electricity generation during all charging processes by the corresponding electricity consumption and the fuel-specific external cost values given by Sundqvist (2004), we obtain the corresponding external effects during the vehicle use phase. Sundqvist (2004) highlights the uncertainty of these factors due to different method-ologies applied (cf. e.g. Schleisner, 2000) and differences in local or regional costs (cf. e.g. Owen, 2006, and Stirling, 1997). However, Sundqvist's cost estimations do not consider recent power plant technology, but refer to literature from the 90ties. Our approach neglects additional emission through ramp-up and ramp-down processes – which might increase in the future German energy system due to an increasingly volatile electricity generation by wind and photovoltaic.

Therefore, the formula for estimating the external costs of air pollutants and climate change during the usage phase of the EV ($EC^{EV,use}$) is as follows:

$$\mathrm{EC}^{\mathrm{EV},use} = \sum_{t\in T}\sum_{i\in I} \alpha_{i,t} \cdot \mathrm{cf}_{i,t} \cdot \mathrm{ed}_t^{\mathrm{EV}} \quad \textbf{(1)}$$

where $\alpha_{i,t}$ is the share of electricity generation at time $t \in T$ from fuel $i \in I$=*{natural gas, lignite, hard coal, nuclear, wind, …}*, $cf_{i,t}$ is the specific internalization factor for the fuel *i* at time *t*, and ed_t^{EV} is the electricity demand by the EV at time t. Hence, the overall external costs of an average EV in Germany can be estimated by assuming an expected electricity demand of an EV of about 40 MWh (200,000 km times 0.2 kWh/km) during its lifetime and multiplying this by the external cost estimates for air pollutants of an average German electricity generation mix of about 5 €-ct per kWh (obtained from the median emission values for electricity generation technologies given by Sundqvist, 2004, and the average electricity generation given by ENTSO-E, 2013). This results to 1.836 € per vehicle. Hence, the kilometer-specific values amount to about 8 € per 1.000 vkm in Germany, excluding GHG emissions. As the energy efficiency of EV is higher in urban than in rural areas (Hacker et al., 2009:37), we assume for Germany external costs of air pollution for EV of 7.2 € in urban and 9.9 € per 1.000 vkm in rural areas. In other countries (especially with a lower share of fossil fuel power plants) the corresponding costs are significantly lower.

Climate change

As the air pollutants, GHG emissions are strongly dependent on the current electricity mix (cf. Fig. 5, Jochem et al., 2015). We refer in the following to the average electricity mix and neglect the marginal consideration or interactions with the cur-rent EU-ETS cap although we know about their momentousness (cf. Jochem et al., 2015 and Heinrichs et al., 2014). These average electricity mixes differ strongly between countries. In Europe, for instance, the specific CO2 emissions range from 0.03 (Sweden) to 0.78 kg CO2 per kWh (cf. Table 8). This corresponds to specific CO2 emissions of 6–156 g of CO2 per vkm. The marginal external costs of CO2 of 120 € per ton (see above) lead to 1 up to 19 € per 1000 vkm. The German values are somewhere in the middle and correspond to external costs of about 11 € per 1000 vkm. Together with the more efficient use in urban areas (see above), we assume 14.8 € for rural and 9.8 € per 1000 vkm for urban areas.

Table 8 Specific CO_2 emissions by EV in different European countries in 2010.

Source: IEA (2012b), Assumption: Electricity consumption of EV is 0.2 kW h per km. Values above the current European regulation (130 g CO_2 per km) are shown in bold.

	Average CO_2 emissions in	
Country	kg CO_2/kW h_{el}	g CO_2/km
Austria	0.19	38
Belgium	0.22	44
Denmark	0.36	72
Finland	0.23	46
France	0.08	16
Germany	0.46	92
Greece	0.72	**144**
Ireland	0.46	92
Italy	0.41	82
Netherlands	0.42	84
Poland	0.78	**156**
Portugal	0.26	52
Spain	0.24	48
Sweden	0.03	6
UK	0.46	92

	Average CO_2 emissions in	
Country	kg CO_2/kW h_{el}	g CO_2/km
EU-27	0.43	86

GHG emissions from vehicle production seem to differ for EV and ICEV. Hawkins et al. (2012a,b) show that the higher CO_2 emissions for EV production indicated in some studies (e.g. Held and Baumann, 2011) cannot be confirmed by the majority of the studies. Furthermore, they find decreasing emissions for EV production and point out that EV may have significantly lower overall CO_2emissions during their whole life time than ICEV when "clean" electricity is used. Currently, literature gives about 6 t of CO_2 emissions for the production of ICEV, about 7 tons for HEV and PHEV, about 8 to 9 tons for REEV, and between 9 to 11 tons of CO_2 for BEV (Kay et al., 2013 and Helms et al., 2013). These values amount to about 20 t CO_2 over the life cycle with a decreasing tendency for all vehicles until 2020 – even though the decrease for ICEV seems to be somewhat smaller than for EV (Kay et al., 2013; Helmers and Marx, 2012, and Held and Baumann, 2011).

Taking the marginal costs of 120 € per ton of CO_2 into account and using an average vehicle mileage of 200,000 km, the marginal cost for climate change increases from 3.6 € per 1.000 vkm for ICEV to 6.6 € for EV due to vehicle production.

Noise

As depicted above, the marginal costs of noise per vehicle are highly dependent on the noise level of other cars (i.e. back-ground noise level) and the traffic density (cf. Haling and Cohen, 2007). As the share of noise by the engine is marginal, if the velocity of the vehicle exceeds 40 km/h (25 mph) and the noise by tires and by the aerodynamic shape of the vehicle dominates the noise produced (cf. Fig. 3), EV do not differ from ICEV in the usual traffic, except for urban traffic during night at low speed. In this particular situation, the people's noise perception is highest, which is expressed by a 10 dB(A) lower noise target level during light time compared to daytime limits. This positive effect could be even more significant, if extreme conditions, such as e.g. ICEV with high motor speed, are considered.

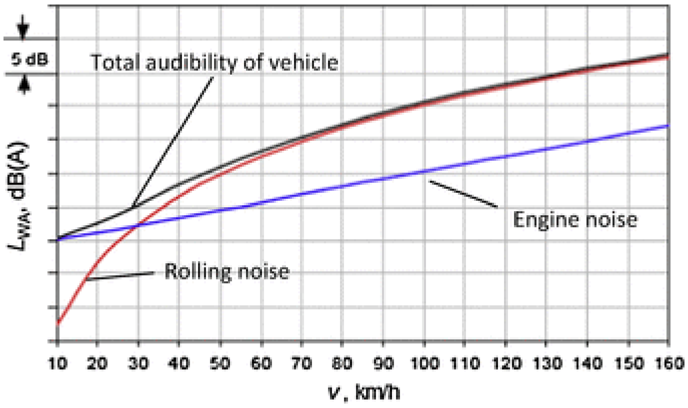

Fig. 3 Audibility of passenger cars (L_{WA}) vs. velocity of the vehicle.

Source: Beckenbauer (2011).

We therefore assume benefits (halving of costs) during nighttime in urban areas (where speed is low and individual vehi-cles are noticed) and marginal benefits (0.1 € per 1000 vkm) in rural areas (cf. Table 9). Other external costs of EV have been treated in the section of ICEV above.

Table 9 Marginal external noise costs for EV (€$_{2010}$ per 1000 vkm).

	Urban	Rural
Day peak	10.5	0.1
Night (off-peak)	23.25	0.4

Summary of cost estimates for electric vehicles

The external costs of EV mainly differ in air pollutants and climate change. These two components are highly dependent on the measuring approach and the underlying power plant portfolio as well as the charging time of the EV. This increases the uncertainty range of the cost estimates. Another difference is noise disturbance during nights, especially for inner-city transport. Fig. 4 gives an overview of cost estimates for all cost components of EV on the logarithmic scale. In analogy to the procedure chosen for ICEV, the future development of cost components for EV until 2030 is outlined.

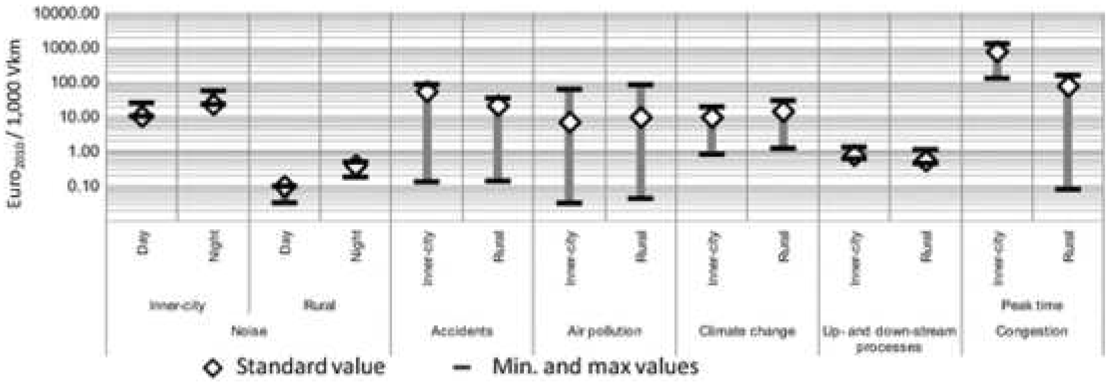

Fig. 4 Maximum, minimum, and standard external costs of EV in €$_{2010}$ per 1.000 vkm.

Extrapolation of external costs of EV to 2030

For comparability reasons, we assume the same development of most considered external cost components for EV as for the ICEV (see above). This applies to the external cost components of traffic safety, noise, vehicle production, and congestion. Furthermore, in analogy to the scenario for the ICEV, we assume a decreasing share of trips within the city from 0.26 to 0.2 and decreasing costs for up- and downstream processes by 10%.

Only the cost components of air pollution and climate change are based on the development of the underlying power plant portfolio. As carbon intensity declines in most countries (cf. IEA, 2012a:183), the specific carbon emissions of electricity will decrease, too. The German target for the future energy system is ambitious and refers mainly to the electricity generation (known as the German Energy Transition). The political target for electricity generation from renewable energy sources amounts to 50% (80%) of gross electricity consumption until 2030 (2050). Together with an assumed increase of electricity from natural gas and a decreasing share of lignite and hard coal, this would lead to an average decrease of specific CO_2emissions by about 30% between 2010 and 2030 (Jochem et al., 2015). This emission reduction corresponds to the development for ICEV (see above). Due to the high costs for CO2 emissions, we assume again constant cost components for climate change for EV. As regards the air pollutants, however, the change in electricity generation leads to decreasing costs. Even though the European directive 2010/75/EU will lead to decreasing specific emissions of air pollutants for most fossil power plants, we neglect this development, as the exact improvement for the heterogeneous power plant portfolio can hardly be predicted. Therefore, we take conservatively constant specific cost factors from the 90ties provided by Sundqvist (2004) for each fuel and consider the change in the composition of energy generation only. This leads to decreasing specific external costs of about 32% compared to the 2010 values.

Looking at the German electricity mix in 2030 over time we still see a considerable share of electricity generation by hard coal and lignite (cf. Fig. 5). However, due to the increased capacity of wind turbines, the volatile electricity generation by wind power plants has a significant impact on the time dependent specific CO2 emissions: during hours with a high share on wind generated electricity the emissions are nearly negligible, whereas during some nights, the specific emissions are still high (cf. Jochem et al., 2015). The relevance of charging time is, therefore, increased.

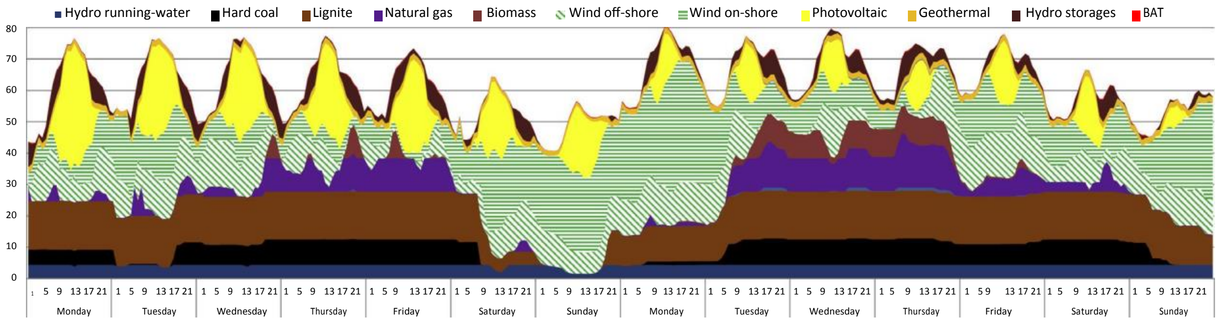

Fig. 5 Example electricity mix over two weeks in 2030 (based on Jochem et al., 2015).

The corresponding cost components lead to an external cost structure similar to that of ICEV (cf. Figs. 6 and 2). The improvements in congestion costs (see above) and in accident costs (by about 3000 €) contribute to a decrease of external costs in passenger road transport. All other improvements are comparatively marginal (cf. Fig. 2). The overall external costs per vehicle decrease similarly to the ICEV from about 65,000 (12,000) to 57,000 (8400) € per vehicle (without external costs of congestion).

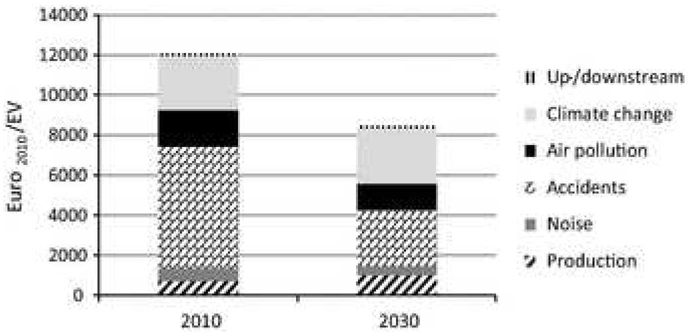

Fig. 6 External costs per EV in 2010 and 2030 in Germany (own calculation).

Comparison of external costs for EV and ICEV

When comparing all cost components for Germany, the main differences between external costs of EV and ICEV are found for climate change, air pollutants, and noise (cf. Fig. 7). Whereas EV seem to have an advantage in climate change (especially in inner-city areas) and noise (especially during the night), the external costs for air pollutants are on the national level still somewhat higher than for ICEV. Overall, the external costs of congestion are still dominating. Consequently, an increased market share of EV will not provide a significant relief for our current external effects in transport.

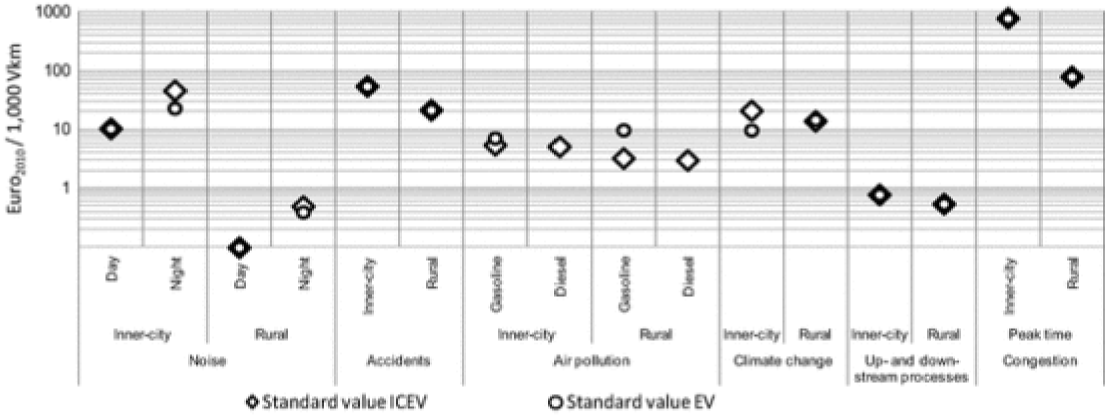

Fig. 7 Differences of standard external costs of ICEV and EV in 2010 in €$_{2010}$ per 1.000 vkm.

The broad literature overview of the impact on GHG emissions, air pollutants, and noise given by Hacker et al. (2009) con-firms our results for GHG emissions and noise impacts. However, they expect a lower impact from air pollutants for EV and argue that emissions are relocated to rural areas. Our analysis shows, by contrast, that the overall costs from local air emis-sions are higher from EV (based on conservative assumptions of the German power plant portfolio) than from ICEV. In other countries (with a higher or lower share of fossil fuels), this value might differ significantly. Furthermore, optimised charging strategies (e.g. with the objective to integrate as much photovoltaic electricity generation as possible) could decrease those values considerably (e.g. Jochem et al., 2015) and air quality of congested inner-cities could be improved by EV.

Due to our conservative assumptions of external costs from air pollution costs from power plants, EV seem to score worse than ICEV in Germany until 2030. The overall amounts as well as the cost structures of external costs of vehicles are very similar for both technologies (cf. Figs. 2 and 6). This confirms the result obtained by Torchio and Santarelli (2010) or Wietschel and Doll (2009). Only the 'Balancing a sugar-coated energy mix' approach ('EVsugar') seems to lead to a significant external cost advantage for EV (cf. Fig. 8). However, when congestion costs are included, the effect on the overall external costs is limited, as the share of external costs of climate change and air pollutants amounts to about 7.4% only (cf. Table 10). The corresponding cost savings (of 4500 €) result in overall external costs per vehicle of 53,000 €. Measures leading to fewer vehicles (i.e. vehicle usage) seem to be more appropriate to significantly cut external costs in passenger road transport.

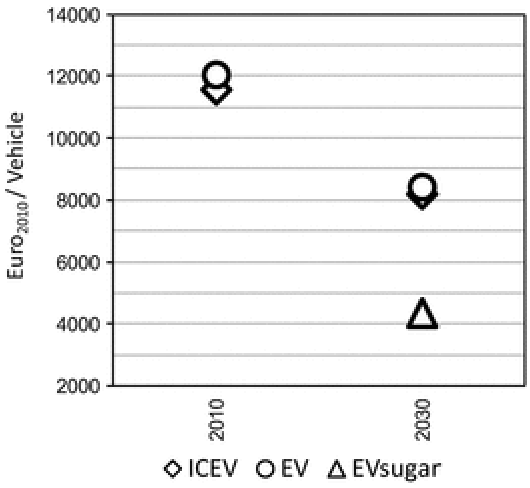

Fig. 8 Differences of external costs of EV and ICEV in 2030 over lifetime (own calculation).

Table 10 Shares of external costs for ICEV and EV in 2010 and 2030 (own calculation).

	EV		ICEV	
	2010	2030	2010	2030
Production (%)	1.1	1.7	1.1	1.8
Noise (%)	0.9	0.8	1.1	0.9
Accidents (%)	9.3	4.9	9.4	5.0
Air pollution (%)	2.8	2.6	1.2	1.2
Climate change (%)	4.2	4.8	4.9	5.4
Up-/downstream (%)	0.2	0.2	0.2	0.2
Congestion (%)	81.4	85.0	82.0	85.6

Critical appraisal

The uncertainty of the cost components limits our results. This is especially true for our estimated values in 2030. The assumed decrease of overall external costs – including congestion effects – by 10% is lower than the uncertainty of external costs estimates for congestion alone. However, this uncertainty is not only related to methodological issues, but reflects the strong dependency of transport externalities on the technology and spatial settings. Although other unit cost values will lead to other results, we consider the tendency of our findings to remain valid.

We neglected external costs of land use as well as other up- and downstream processes. According to literature, these effects seem to be of minor importance – especially with respect to differences between ICEV and EV. Additionally, we neglected a potential increase in efficiency of EV (cf. e.g. Karplus et al., 2010) and decreasing emissions of air pollutants from fossil power plants. Espeially power plant technology improved considerably during the last years (de Gouw et al., 2014).

Furthermore, our assumptions regarding the development until 2030 (cf. Sections 'Extrapolation of external costs of ICEV to 2030' and 'Extrapolation of external costs of EV to 2030') describe the right tendencies – their concrete values might, how-ever, be somewhat arbitrary.

Conclusions

The electric vehicle (EV) is often considered a promising technology for coping with future challenges in road transport. We analysed the differences between EV and internal combustion engine vehicles (ICEV) from an environmental and economic point of view and compared the external costs of both alternatives. Even though we are aware of the high uncertain-ties of cost estimates in specific situations, we differentiated the analysis by fuel type, vehicle size as well as by emission location and time of day. This differentiation provides indications regarding specific discrepancies in some special applications. Our calculations indicate that locally emission-free and silent driving of EV in inner-cities may contribute to meeting urban environmental challenges.

However, we find that the external costs of EV and ICEV in Germany do not differ significantly. Only for oil dependency, climate change, local air pollutants in congested inner-cities, and noise, some advantages of EV over ICEV can be found. These are strongly dependent on the electricity mix and potentially also on the charging strategy of vehicle users. Other countries with strongly diverging power generation technologies might face very different results. Nevertheless, EV are far from solving our main challenges in motorised individual transport and external costs of congestion still dominate the external costs in transport. A decreasing motorisation rate and the replacement of car trips by active mobility, i.e. walking, cycling, and use of public transport means, will be much more effective in improving the quality of life in our cities (Creutzig et al., 2012). Stronger efforts in mitigating air pollutants and GHG from power plants would certainly contribute to a stronger advantage of EV.

References

Anable, J., Brand, C., Tran, M., Eyre, N., 2012. Modelling transport energy demand: a socio-technical approach. Energy Policy 41, 125–138.

Anas, A., Lindsey, R., 2011. Reducing urban road transportation externalities: road pricing in theory and in practice. Rev. Environ. Econ. Policy 5 (1), 66–88.

Anthoff, D., Hepburn, C., Tol, R.S.J., 2009. Equity weighting and the marginal damage costs of climate change. Ecol. Econ. 68 (3), 836–849.

Beckenbauer, T., 2011. Lärmminderungspotentiale im Straßenverkehr durch Elektromobilität, 5. DEGA-Symposium, 21.10.2011, Stuttgart, Germany.

Bickel, P., Friedrich, R. (Eds.), 2005. ExternE, Externalities of Energy, Methodology 2005 Update, Luxemburg.

Bickel, P., Schmid, S., Tervonen, J., Hämekoski, K., Otterström, T., Anton, P., Enei, R., Leone, G., van Donselaar, P., Carmigchelt, H., 2003. Environmental Marginal Cost Case Studies, Project report within UNITE, Stuttgart, Germany. <http://www.its.leeds.ac.uk/projects/unite/downloads/D11> (accessed 25.05.15).

Bickert, S., Kuckshinrichs, W., 2011. Electro-mobility as a technical concept in an ecological mobility sector? An analysis of costs. In: 9th International Conference of the European Society for Ecological Economics, Istanbul, Turkey, 14–17.06.2011.

Brandt, S., Maennig, W., 2011. Road noise exposure and residential property prices: evidence from Hamburg. Transport. Res. Part D: Transport Environ. 16 (1), 23–30.

CE Delft, INFRAS, Fraunhofer ISI, 2011. External Costs of Transport in Europe. Update Study. International Union of Railways (UIC), Delft, The Netherlands. CE Delft, INFRAS, Fraunhofer ISI, University of Gdansk, 2008. Internalisation Measures and Policies for All External Cost of Transport (IMPACT), Project Report, Delft, The Netherlands.

Clean Energy Ministerial, EVI (Electric Vehicles Initiative), IEA (International Energy Agency), 2013. Global EV Outlook, Paris, France.

Cocron, P., Bühler, F., Franke, T., Neumann, I., Krems, J.F., 2011. The Silence of Electric Vehicles – Blessing or Curse?, TRB 2011, Washington, DC. Cravioto, J., Yamasue, E., Okumura, H., Ishihara, K.N., 2013. Road transport externalities in Mexico: estimates and international comparisons. Transp. Policy 30, 63–76.

Creutzig, F., Jochem, P., Edelenbosch, O.Y., Mattauch, L., Vuuren, D.P.v., McCollum, D., Minx, J., 2015. Transport – a roadblock to climate change mitigation? Science (Policy Forum) 350 (6263), 911–912.

Creutzig, F., Mühlhoff, R., Römer, J., 2012. Decarbonizing urban transport in European cities: four cases show possibly high co-benefits. Environ. Res. Lett. 7, 044042.

Delucchi, M., McCubbin, D., 2010. External costs of transport in the United States. In: de Palma, A., Lindsey, R., Quinet, E., Vickerman, R. (Eds.), A Handbook of Transport Economics. Wiley Peridicals, Hoboken, NJ, pp. 341–368.

DeStatis, 2013. Preise, Verbraucherpreisindizes für Deutschland, lange Reihe ab 1948. Statistisches Bundesamt, Wiesbaden, Germany.

Diamond, P.A., Hausman, J.A., 1994. Contingent valuation: is some number better than no number. J. Econ. Perspect. 8 (4), 45–64.

Dudenhöffer, K., Dudenhöffer, F., Hause, L., 2011. Gefahrenpotential leises Elektroauto? Internationales Verkehrswesen 63 (5), 71–72.

EC (European Commission), 2011. White Paper: Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System, Brussels, Belgium.
EC (European Commission), 2011. White Paper: Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System, Brussels, Belgium.
ENTSO-E (European Network of Transmission System Operators for Electricity), 2013. Statistical Yearbook 2011, Brussels, Belgium.

Eurostat, 2013. Statistics database, Brussels, <http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database> (accessed 25.05.15). Finegold, L.S., Harris, C.S., von Gierke, H.E., 1994. Community annoyance and sleep disturbance: updated criteria for assessment of the general transportation noise on people. Noise Control Eng. J. 42 (1), 25–30.

Fouquet, R., 2011. Long run trends in energy-related external costs. Ecol. Econ. 70, 2380–2389.

Friedrich, R., 2005. ExternE: Methodology and Results, ExternE Workshop, Brussels, 9 December 2005, <http://www.externe.info/externe_d7/sites/ default/files/br0900.pdf> (accessed 25.05.15).

Funk, K., Rabl, A., 1999. Electric versus conventional vehicles: social costs and benefits in France. Transp. Res. Part D 4, 397–411.

Garg, B.D., Cadle, S.H., Mulawa, P.A., Groblicki, P.J., Laroo, C., Parr, G.A., 2000. Brake wear particulate matter emissions. Environ. Sci. Technol. 34 (21), 4463– 4469. http://dx.doi.org/10.1021/es001108h.

Gomez-Vilchez, J.J., Jochem, P., Fichtner, W., 2013. The impact of electric vehicles on the global oil demand and CO_2 emissions. In: Proceedings of World Conference of Transport Research Society, Rio de Janeiro.

de Gouw, J.A., Parrish, D.D., Frost, G.J., Trainer, M., 2014. Reduced emissions of CO_2, NO_X, and SO_2 from U.S. power plants owing to switch from coal to natural gas with combined cycle technology. Earth’s Future, 75–82. http://dx.doi.org/10.1002/2013ef000196.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle assessment: past, present, and future. Environ. Sci. Technol. 45 (1), 90–96. http://dx.doi.org/10.1021/es101316v.

Hacker, F., Harthan, R., Matthes, F., Zimmer, W., 2009. Environmental Impacts and Impact on the Electricity Market of a Large Scale Introduction of Electric Cars in Europe, Berlin, <http://acm.eionet.europa.eu/docs/ETCACC_TP_2009_4_electromobility.pdf> (accessed 25.05.15).

Haling, D., Cohen, H., 2007. Residential noise damage costs caused by motor vehicles. Transport Res. Rec. 1559, 84–93.

Hamilton, J., 1980. Energy use of electric vehicles. Transport. Res. A 14A, 415–421.

Hausman, J.A., 2012. Contingent valuation: from dubious to hopeless. J. Econ. Perspect. 26 (4), 43–56.

Hausman, J.A., 1993. Contingent Valuation: A Critical Assessment. North-Holland, NY.

Hawkins, T.R., Gausen, O.M., Strømman, A.H., 2012a. Environmental impacts of hybrid and electric vehicles – a review. J. Life Cycle Assess. 17, 997–1014. http://dx.doi.org/10.1007/s11367-012-0440-9.

Hawkins, T.R., Singh, B., Majeau-Betez, G., Strømman, H., 2012b. Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. 17 (1), 53–64. http://dx.doi.org/10.1111/j.1530-9290.2012.00532.x.

Heinrichs, H., Jochem, P., Fichtner, W., 2014. Modelling implications of an extended EU-ETS on the German energy and transport sector. Energy 69, 708–720. http://dx.doi.org/10.1016/j.energy.2014.03.061.

Held, M., Baumann, M., 2011. Assessment of the environmental impacts of electric vehicle concepts. In: Finkbeiner, M. (Ed.), Towards Life Cycle Sustainability Management, Berlin, pp. 535–546, http://dx.doi.org/10.1007/978-94-007-1899-9_52.

Helmers, E., Marx, P., 2012. Electric cars: technical characteristics and environmental impacts. Environ. Sci. Europe 24, 14. http://dx.doi.org/10.1186/2190-4715-24-14.

Helms, H., Jöhrens, J., Lambrecht, U., 2013. Umweltwirkungen alternativer Antriebe. In: Jochem, P., Poganietz, W.-R., Grunwald, A., Fichtner, W. (Eds.), Alternative Antriebskonzepte bei sich wandelnden Mobilitätsstilen, Karlsruhe, Germany, pp. 123–146.

IEA (International Energy Agency), 2012a. World Energy Outlook 2012, Paris.

IEA (International Energy Agency), 2012b. CO_2 Emissions from Fuel Combustion, Paris. <http://www.iea.org/co2highlights/co2highlights.pdf> (accessed 25.05.15).

IFEU (Institut für Energie- und Umweltforschung), 2011. UmweltMobilCheck. Scientific background report to Deutschen Bahn AG, Heidelberg, Germany. Infas (Institute for Applied Social Sciences), DLR (German Aerospace Center), 2010. Mobilität in Deutschland 2008, Berlin, <http://www.mobilitaet-in-deutschland.de/pdf/MiD2008_Abschlussbericht_I.pdf> (accessed 25.05.15).

INFRAS, 2010. HBEFA – Handbook Emission Factors for Road Transport: Database provided to the German Federal Environmental Agency (UBA). Zurich, <http://www.hbefa.net/e> (accessed 25.05.15).

IPCC (Intergovernmental Panel on Climate Change), 2013. Fifth Assessment Report Climate Change 2013: The Physical Science Basis, Working Group I Contribution, Geneva, Switzerland.

Jensen, S.S., Willumsen, E., Brandt, J., Kristensen, N.B., 2008. Evaluation of exposure factors applied in marginal external cost analysis of transportation related air pollution. Transport. Res. Part D: Transport Environ. 13 (4), 255–273.

Jochem, P., Babrowski, S., Fichtner, W., 2015. Assessing CO_2 Emissions of Electric Vehicles in Germany in 2030. Transport. Res. A-Pol. 78, 68–83. http://dx.doi.org/10.1016/j.tra.2015.05.007.

Jochem, P., Rothengatter, W., 2011. Internalizing external costs of transport with a focus on climate change. In: Rothengatter, W., Hayashi, Y., Schade, W. (Eds.), Transport Moving to Climate Intelligence. New Chances for Controlling Climate Impacts of Transport after the Economic Crisis. Springer, New York, pp. 187–207.

JRC (EU Joint Research Centre), 2008. Backcasting Approach for susTainable Mobility, Luxembourg.

Karplus, V.J., Paltsev, S., Reilly, J.M., 2010. Prospects for plug-in hybrid electric vehicles in the United States and Japan: a general equilibrium analysis. Transp. Res. Part A 44 (8), 620–641.

Kay, D., Hill, N., Newman, D., 2013. Powering Ahead – The Future of Low-Carbon Cars and Fuels, London, UK. <http://www.theengineer.co.uk/Journals/2013/04/22/i/k/h/powering_ahead-kay_et_al-apr2013-embargoed_copy.pdf> (accessed 30.11.13).

Korzhenevych, A., Dehnen, N., Bröcker, J., Holtkamp, M., Meier, H., Gibson, G., Varma, A., Cox, V., 2014. Update of the Handbook on External Costs of Transport. Final Report to the European Commission, DG-MOVE. London, UK.

Krewitt, W., 2002. External costs of energy – do the answers match the questions? Looking back at 10 years of ExternE. Energy Policy 30, 839–848. http://dx.doi.org/10.1016/S0301-4215(01)00140-9.

Krewitt, W., Schlomann, B., 2006. Externe Kosten der Stromerzeugung aus erneuerbaren Energien im Vergleich zur Stromerzeugung aus fossilen Energieträgern, Karlsruhe, Germany.

Kuosmanen, T., Kortelainen, M., 2007. Valuing environmental factors in cost-benefit analysis using data envelopment analysis. Ecol. Econ. 62, 56–65. http://dx.doi.org/10.1016/j.ecolecon.2007.01.004.

Lane, B., 2006. Life Cycle Assessment of Vehicle Fuels and Technologies, Final Report, London, UK.

Litman, T., 2014. Transportation Costs and Benefits – Resources for Measureing Transportation Costs and Benefits. TDM Encyclopedia, Victoria Transport Policy Institute, Victoria, Canada. <http://www.vtpi.org/tdm/tdm66.htm> (accessed 22.05.15).

Maibach, M., Schreyer, C., Sutter, D., van Essen, H.P., Boon, B.H., Smokers, R., Schroten, A., Doll, C., Pawlowsk, B., Bak, M., 2008. Handbook on Estimation of External Costs in the Transport Sector, Delft, the Netherlands.

Messagie, M., Boureima, F., Matheys, J., Sergeant, N., Turcksin, L., Macharis, C., Van Mierlo, J., 2010. Life Cycle Assessment of conventional and alternative small passenger vehicles in Belgium. In: Proceedings of Vehicle Power and Propulsion Conference (VPPC), Lille, France.

Miedema, H.M.E., Vos, H., 1999. Demographic and attitudinal factors that modify annoyance from transportation noise. J. Acoust. Soc. Am. 105, 3336.

Miedema, H.M.E., Vos, H., 1998. Exposure-response relationships for transportation noise. J. Acoust. Soc. Am. 104, 3432–3445.

Mock, P., Hülsebusch, D., Ungethüm, J., Schmid, S., 2009. Electric vehicles – A model based assessment of future market prospects and environmental impacts. In: Proceedings of EVS24, Stavanger, Norway.

Nash, C., 2003. UNITE (Unification of Accounts and Marginal Costs for Transport Efficiency), Report funded by the European Commission, 5th Framework-Transport RTD, Institute for Transport Studies, University of Leeds, Leeds, UK.

Nordhaus, W., 2007. The Stern Review on the Economics of Climate Change. Yale, New Haven.

Nykvist, B., Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nature Climate Change 5, 329–332. http://dx.doi.org/10.1038/ nclimate2564.

Owen, A.D., 2006. Renewable energy: externality costs as market barriers. Energy Policy 34 (5), 632–642. http://dx.doi.org/10.1016/j.enpol.2005.11.017.

Paine, M., 2011. Safety Requirements for small motorised alternative vehicles. In: Proceedings of the Conference on the Enhanced Safety of Vehicles (ESV), June 13–16, Washington, DC, <http://www-nrd.nhtsa.dot.gov/pdf/esv/esv22/22ESV-000108.pdf> (accessed 30.11.13).

Peters, A., Wietschel, M., Doll, C., Schade, W., Tielmann, A., et al, 2012. Konzepte der Elektromobilität und deren Bedeutung für Wirtschaft, Gesellschaft und Umwelt. Fraunhofer ISI on behalf of Buero fuer Technikfolgenabschaetzung (TAB). Deutscher Bundestag, Karlsruhe, Berlin.

Pigou, A.C., 1920. The Economics of Welfare. Macmillan, London, UK.

Proost, S., Van Dender, K., 2012. Energy and environment challenges in the transport sector. Econ. Transport. 1, 77–87. http://dx.doi.org/10.1016/j.ecotra.2012.11.001.

Qingyu, L., Zhicai, J., Baofeng, S., Hongfei, J., 2007. Method research on measuring the external costs of urban traffic congestion. J. Transport. Syst. Eng.

Inform. Technol. 7 (5), 9–12. http://dx.doi.org/10.1016/S1570-6672(07)60035-X.
Rosenthal, D.H., Nelson, R.H., 1995. Why existence value should not be used in cost-benefit analysis. J. Policy Anal. Manage. 11 (1), 116–122. http://dx.doi.org/10.1002/pam.4050110109.
Rothengatter, W., Hayashi, Y., Fujisaki, K., Kato, H., Okuda, T., Shibahara, N., 2015. Climate change impacts of intercity transport in the context of external costs and their internalisation. In: Hayashi, Y., Morichi, S., Oum, T.H., Rothengatter, W. (Eds.), Intercity Transport and Climate Change. Springer, Berlin, pp. 89–175. http://dx.doi.org/10.1007/978-3-319-06523-6_3.
Schleisner, L., 2000. Comparison of methodologies for externality assessment. Energy Policy 28, 1127–1136. http://dx.doi.org/10.1016/S0301-4215(00) 00084-7.
Sen, A.K., Tawari, G., Upadhyay, V., 2010. Estimating marginal external costs of transport in Delhi. Transp. Policy 17 (1), 27–37.
Skinner, I., van Essen, H., Smokers, R., Hill, N., 2010. Towards the Decarbonisation of EU's Transport Sector by 2050, Project Report, London, UK. Stelling-Kon´czak, A., Hagenzieker, M., van Wee, B., 2015. Traffic sounds and cycling safety: the use of electronic devices by cyclists and the quietness of hybrid and electric cars. Transport Rev., 1–23
Stern, N., 2006. Stern Review on the Economics of Climate Change. HMSO, London, UK.
Stirling, A., 1997. Limits to the value of external costs. Energy Policy 25 (5), 517–540. http://dx.doi.org/10.1016/S0301-4215(97)00041-4.
Sundqvist, T., 2004. What causes the disparity of electric externality estimates? Energy Policy 32, 1753–1766. http://dx.doi.org/10.1016/S0301-4215(03) 00165-4.
TNO, IEEP (Institute for European Environmental Policy), LAT (Laboratory of Applied Thermodynamics), 2006. Review and Analysis of the Reduction Potential and Costs of Technological and Other Measures to Reduce CO_2 Emissions from Passenger Cars, Project Report, Delft, the Netherlands.
Tobías, A., Recio, A., Díaz, J., Linares, C., 2015. Health impact assessment of traffic noise in Madrid (Spain). Environ. Res. 137, 136–140. http://dx.doi.org/10.1016/j.envres.2014.12.011.
Torchio, M.F., Santarelli, M.G., 2010. Energy, environmental and economic comparison of different powertrain/fuel options using well-to-wheels assessment, energy and external costs – European market analysis. Energy 35 (10), 4156–4171. http://dx.doi.org/10.1016/j.energy.2010.06.037.
Tseng, P.-H., Lin, D.-Y., Chien, S., 2014. Investigating the impact of highway electronic toll collection to the external cost: a case study in Taiwan. Technol. Forecast. Soc. Chang. 86, 265–272.
UBA (German Federal Environmental Agency) (Ed.), 2012. Ökonomische Bewertung von Umweltschäden. Methodenkonvention 2.0 zur Schätzung von Umweltkosten. Umweltbundesamt (UBA), Dessau, Germany.
Verhoef, E., 1994. External effects and social costs of road transport. Transport Res. A 28 (4), 273–287. http://dx.doi.org/10.1016/0965-8564(94)90003-5. WBCSD (World Business Council on Sustainable Development), 2004. Mobility 2030: Meeting the Challenges to Sustainability, Geneva, Switzerland. WHO (World Health Organisation), JRC (Joint Research Centre), 2011. Burden of Disease from Environmental Noise. Quantification of Healthy Life Years Lost in Europe. Copenhagen, Denmark. <http://www.euro.who.int/__data/assets/pdf_file/0008/136466/e94888.pdf> (accessed 30.11.13).

Wietschel, M., Doll, C., 2009. Sustainable transport visions: The role of hydrogen and fuel-cell vehicle technologies. In: Ball, M., Wietschel, M. (Eds.), The Hydrogen Economy: Opportunities and Challenges. Cambridge University Press, UK, pp. 563–598.

Zimmer, W., Buchert, M., Dittrich, M., Hacker, F., Harthan, R., Hermann, H., Jenseit, W., Kasten, P., Loreck, C., Götz, K., Sunderer, G., Birzle-Harder, B., Deffner, J., 2011. OPTUM: Optimierung der Umweltentlastungspotenziale von Elektrofahrzeugen – Integrierte Betrachtung von Fahrzeugnutzung und Energiewirtschaft. Final report to the Federal Ministry for Environment, Nature Preservation and Nuclear Safety (BMU), Frankfurt a. M., Germany.