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ISBN 978-82-326-4532-9 (printed version)
ISBN 978-82-326-4533-6 (electronic version)
ISSN 1503-8181

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Thesis for the degree of Philosophiae Doctor

Trondheim, April 2020

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Printed by Skipnes Kommunikasjon as

To Olea Fiore

Abstract

Car electronics form an extensive yet untapped source for secondary critical raw materials. The complexity and time variability of car electronics pose a challenge for estimating the potentials for recycling and for adapting recycling systems in a timely fashion. The aim of this thesis is to inform end-of-life management of car electronics in light of the potential recovery of critical metals (CMs). The particular focus is on informing the revision of the Swiss regulation for electronic waste recycling in which a framework for mandatory pre-shredding dismantling of selected car electric and electronic (EE) devices is being established based on three criteria: (i) CM content, (ii) environmental benefits, and (iii) economic feasibility. This thesis addresses questions related to the first criterion for including EE devices in the regulation, i.e. characterizing the physical system and CM content of car EE devices. Additionally, it presents methodological developments to facilitate the modelling of stocks and flows of CMs in car electronics. The central methods used were material and substance flow analysis (MFA and SFA), which were complemented by chemical analysis of EE components and shredder output fractions, as well as by statistical analysis of car electronics trends.

The results confirmed that car electronics are a large potential source of secondary CMs. Compared to other sources of secondary CMs such as waste electrical and electronic equipment (WEEE), car electronics constitute an extensive stock of CMs. The Nd stock in car electronics in Switzerland in 2014 was estimated to be higher than that in WEEE categories 3 & 4 (IT, communication and consumer equipment), while the Au stock in car electronics was one fifth of the Au stock in WEEE categories 3 & 4. The end-of-life (EoL) flows of CMs in car electronics however tend to be one order of magnitude smaller than those in WEEE categories 3&4, mainly due to the long lifetime of cars compared to consumer electronics. However, given the higher inflow of car electronics, the EoL flows are likely to grow substantially in the future.

Dismantling car electronics can substantially increase the mass fraction of CMs, and thereby facilitate subsequent recovery. It was found that four EE devices accounted for more than 50% of the Ag and Au mass in new cars, cars in use, and ELVs in 2014: Fuse box, radio, navigation system and engine controller. Five EE devices contained more than 50% of the La and Nd mass: Alternator, electronic power steering motor, drive motor/generator, nickel metal hydride (NiMH) battery and speakers. Considering their high CM mass content, as well as their high contribution to the total stocks and flows of CMs in cars, these devices were identified as promising candidates to include in the amended Swiss regulation for electronic waste recycling. The environmental and economic aspects of recycling-oriented dismantling are still to be determined before a final list of mandatory EE devices to dismantle can be defined.

An analysis of the historical penetration and unit-mass trends of representative car EE devices indicated that these trends are characterized by s-shaped curves. Contrary to the case of WEEE, where trends of decreasing unit mass have led to a decrease in the total mass flow of EE devices and related CMs, the examples analysed in this thesis show that, even though there has been a strong decrease in the unit mass of individual automobile EE devices (downsizing), their historical mass inflows have increased and flattened over time. This is mainly due to the increased penetration of multifunctional EE devices in heavier car types. The more cost-effective opportunities for a recycling-oriented dismantling of car electronics seem to lie at the beginning of penetration, when downsizing potentials have not been fully realized.

Chemical analysis of shredder output fractions indicated a considerable accumulation of CMs in the automobile shredder residue (ASR), which represents an opportunity for recovering CMs from this waste stream, but also a challenge for finding downstream processes that can recovery the highly mixed CMs. The optimal recovery of CMs from car electronics may require a combination of interventions, including, among others, pre-shredding dismantling of EE devices and post-shredder treatment of ASR, rather than just one intervention alone.

Monitoring trends for car electronics at the car inflow can inform the timely adjustment of dismantling targets and related financing mechanisms, helping to guarantee the long-term effectiveness of recycling-oriented dismantling strategies. The longer average lifetime of cars compared to consumer electronics allows for a more robust forecasting of EoL flows for a time range of 10-20 years, providing more time to adjust strategies, technologies, and practices to recover CMs from electronics in ELVs. MFA could serve as the backbone in a potential monitoring system for CMs in car electronics by enabling the accounting of all physical flows and stocks of materials that are necessary in further energetic, environmental and economic assessments. Combined efforts from all actors in the passenger car system are required for collecting, structuring and reporting data and to ensure the success of such monitoring system.

Acknowledgements

This work is part of the project Recycling Electronics from ELVs (EVA by its German acronym) and was funded by the following institutions: Swiss Federal Office for the Environment (FOEN), Swiss association of automobile importers (Auto-Schweiz), Office of Waste, Water, Energy, and Air of the Canton of Zurich (AWEL), Foundation Auto Recycling Switzerland (SARS), Association of the Official Car Collection Point Proprietors of Switzerland and the Principality of Liechtenstein (VASSO), and Swiss Association of Automobile Recyclers and Exporters (VAREX). The following institutions kindly provided access to databases used in this work: Swiss Federal Roads Office (FEDRO) and Auto-i-Dat AG. The work was primarily carried out at the Critical Materials and Resource Efficiency Group (CARE) of the Technology and Society Laboratory (TSL) at Empa – Swiss Federal Laboratories for Materials Science and Technology. Important parts of this work were also conducted during a one-year stay at and several visits to the Industrial Ecology Programme (IndEcol), Department of Energy and Process Engineering, at the Norwegian University of Science and Technology (NTNU). I thank all institutions and their representatives for their financial and in-kind support.

Thank you to supervisor Prof. Dr. Daniel B. Müller, particularly for his guidance with finding the broader significance of my work. Thank you to co-supervisor Dr. Patrick Wäger and mentor Mr. Rolf Widmer, particularly for laying the foundations that enabled this research. I am sincerely thankful to co-authors Xiaoyue Du, Amund N. Løvik, Radek Lonka and Olaf Haag for their valuable contributions. I consulted with a variety of experts that helped clarify concepts and assumptions; they are acknowledged in the appended papers and here I reiterate my appreciation. Thank you to all the colleagues both at Empa and NTNU for their collegiality and inspiring discussions during my years of work.

Additional thanks to Amund N. Løvik for his unconditional support and thank you to all family, friends and day-care personnel for their invaluable assistance while I was conducting this research.

Table of Contents

List of Appended Papers and Author's Contributions

Paper no.	Tittle and authors	Contribution by Eliette Restrepo
I	*Scarce metals in conventional passenger vehicles and end-of-life vehicle shredder output* Widmer R, Du X, Haag O, **Restrepo E**, and Wäger P, in *Environmental Science and Technology*, 2015, DOI: 10.1021/es505414d *The order of co-authors after the main author is alphabetical	Dismantling electronic devices, analysis of laboratory results, visualization, model development, writing, co-preparation of samples, and co-design of research.
II	*Quantifying the distribution of critical metals in conventional passenger vehicles using input-driven and output-driven approaches: a comparative study* Du X, **Restrepo E**, Widmer R, and Wäger P, in *Journal of Material Cycles and Waste Management*, 2015, DOI: 10.1007/s10163-015-0353-3	Co-design of research, half of: data collection, analysis and writing
III	*Stocks, flows and distribution of critical metals in embedded electronics in passenger vehicles* **Restrepo E**, Løvik AN, Wäger P, Widmer R, Lonka R, and Müller DB, in *Environmental Science and Technology*, 2015, DOI: 10.1021/acs.est.6b05743	Research design, data collection, analysis, visualization, modelling and writing
IV	*Historical penetration patterns of automobile electronic control systems and implications for critical raw materials recycling* **Restrepo E**, Løvik AN, Widmer R, Wäger P, and Müller DB, in *Resources*, 2019, DOI: 10.3390/resources8020058	Research design, data collection, analysis, visualization, modelling and writing
V	*Effects of car electronics penetration, integration and downsizing on their recycling potentials* **Restrepo E**, Løvik AN, Widmer R, Wäger P, Müller DB, in *Resources, Conservation and Recycling: X, 2020*. DOI: 10.1016/j.rcrx.2020.100032	Research design, data collection, analysis, visualization, modelling and writing

1 Introduction

1.1 Critical metals

The vast majority of the chemical elements that constitute all matter in our planet, including *us*, originated millions of years ago during the explosion, merging, and dying of stars (1,2). Supernovae explosions, liberating around 10^{44} joules of energy (the total energy produced by our sun over its 10 billion year existence) (3,4), are responsible for the creation of more than half of the elements in the periodic table (5,6). The colossal amounts of energy needed to produce these chemical elements are well out of reach to humans and represent the fundamental physical limit that defines them as non-renewable resources. We will never be able to "replant" gold, neodymium, or cobalt. What there is, is what we have.

These elements have deposited at various relative abundances in our planet and are unevenly distributed across the globe (7). Our contest for getting a hold of these resources to sustain our living standards shapes the definition of *material criticality,* which changes across regions and in time to reflect the potential of a restricted access to essential raw materials (8–13). For example, since 2010, the European Union has defined three different lists of *critical raw materials*, considering aspects such as the economic importance and the supply risk of materials that are essential to Europe's economy (8,9,11). Two lists of critical raw materials have also been defined for the US since 2010 (12,13). In 2015, Graedel and colleagues (10) reflected on the subjectivity and time variability of the definition of material criticality and proposed a method to comprehensively assess material criticality considering three main factors: i) Vulnerability to supply restriction, ii) supply risk and iii) environmental implications derived from its production. As a result of these assessments, approximately 20 metals and metalloids have been identified as critical at a global level (10). For the EU, the list of critical raw materials in 2016 covers more than 20 different materials (11).

In general, metals have higher criticality scores than any other material; rare earth elements (REE) have one of the highest criticality scores in most criticality assessments (8–12,14–16). This mainly reflects three aspects (8–13): i) the indispensability of REE for technologies that play a key role in our transition to a carbon-neutral society; for example electric cars and wind turbines, ii) their current primary production being highly concentrated in a single country (China), and iii) their current lack of substitutes. Gold and other precious metals are also considered highly critical, mainly due to the environmental implications associated with their production (10).

As the demand for CMs, particularly to be used in low-carbon technologies, soars quickly, recycling emerges as a key strategy to ensure future availability (8–11). This also lines up with circular economy strategies, aiming at a long-term sustainable management of resources. In a circular economy, "the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimized" (17). For CMs, circular economy strategies in which EoL recycling plays a major role may ensure that metals that have already been extracted and processed, with high energy inputs, are further used in new products. If we consider that the natural deposits from which the metals have been extracted can never be created again(18) – recall the immense amounts of energy necessary to form them, recycling would enable an extension of the *expiring date* of these non-renewable resources and thus their availability for many more generations to come.

1.2 Car electronics and their relevance for the future availability of critical metals

Due to their unique physical and chemical properties, CMs are extensively used in electronic applications (10,19–22). Neodymium and dysprosium are indispensable in high-performance permanent magnets used in electric motors (23) and a printed wiring board can contain up to 44 different elements, most of which are considered critical (10). Simultaneously, electronics are penetrating all aspects of our lives, with cars being one of their most prominent application (24–28). As an example, automotive electronics represent the second largest application for neodymium-iron-boron (NdFeB) permanent magnets (26) and currently, electronics account for one third of a car's cost (27). With the shift towards electricity-powered vehicles and autonomous driving, the percentage cost of electronics in cars is expected to increase to half of the car cost by 2030 (27). Due to this electrification development, the mass fractions of CMs in cars can be expected to increase dramatically in the coming years.

In the meantime, the number of cars sold worldwide is expected to increase from approximately 80 million in 2018 to around 120 million in 2040 (29,30). Piled up, the expected global inflow of cars in 2040 would make approximately 200 000 kilometres (assuming a height of 1.7 meters per car); enough to cover half the distance from the Earth to the Moon (31). Considering the growing penetration of car electronics containing CMs in the substantial number of cars being sold, car-embedded electronics represent a large potential source of CMs for recycling in the future.

1.3 Problem statement and motivation

Despite the above recycling potentials, the current end-of-life (EoL) recovery of CMs is virtually non-existent (32,33). Car recycling is still centred on shredding and sorting for recovering iron and aluminium scrap while little pre-shredding dismantling of the ELVs is carried out (34). The lack of recycling-oriented dismantling of ELVs also translates into "contaminated" scrap metal fractions of lower quality (35,36). Improving the end-of-life treatment of car electronics and obtaining higher quality ELV metal scrap are two sides of the same challenge – the optimal treatment of end-of-life vehicles.

The complexity and time variability of car electronics pose a challenge when assessing the potential CM quantities for recycling and the definition of recycling targets, for example regarding which EE devices to dismantle, is not straightforward. The car fleet is composed by a large variety of car types, from different cohorts and diverse configurations, and electronics change over time, for example, by becoming smaller and integrating more functions (37).

Legal efforts to adjust ELV recycling to the changing material composition of cars are happening at the Swiss and the European levels. The Swiss regulation for electronic waste recycling (VREG by its German acronym) (38) is currently being revised to set the framework for a mandatory pre-shredding dismantling and subsequent recycling of selected car EE devices based on three criteria: i) CM mass content in EE devices, ii) economic viability of dismantling and iii) environmental benefits of dismantling (39). Parallel to this, the European ELV Directive is under review until 2020; one key aspect is the introduction of material-specific recycling targets that could potentially lead to an increased pre-shredding dismantling of car EE devices (40). For the final implementation of these regulations, it is imperative to estimate the mass of CMs in the car stocks and flows as well as the distribution of these metals' mass among the embedded EE devices. To guarantee the long-term effectiveness of the regulations, it is also essential to understand the effects that changes in penetration, unit mass and CM content of car electronics have on the number and volumes of EE devices reaching end of life. For example, does a decrease in unit mass of EE devices outweigh penetration trends, thus making the recovery of CMs from EoL car electronics less attractive in the future? Such questions are still to be answered; the potential EE devices for mandatory dismantling as well as the material recycling targets are still to be defined for both regulations.

1.4 State of the art and research gaps

The topic of cars as a possible source of CMs recycling has gained interest in the past years. Ten available studies are relevant for the state of the art on critical metals in car electronics to date: four Japanese studies (41–44), three North-American studies (45–47), two Swedish studies (32,48), and one Swiss study (49). Due to the almost complete lack of knowledge about CM content, seven of the studies focused on generating new data about the presence and mass content of CMs in cars (41–46,48). Five of the studies also included estimations of mass flows and stocks of CMs in the entire vehicle fleet and/or the ELV treatment system (32,43,44,47,49). An overview of the available literature is presented below, followed by a summary of the most important findings, limitations and research gaps.

All of the seven studies generating new data assessed conventional passenger vehicles powered by internal combustion (IC) engines using gasoline or diesel fuel (41–46,48), five of them (41,43–45,47) also considered electric and hybrid cars (powered by both an IC engine and an electric motor). Most of the studies generating new data provided the CM mass content only at an aggregated level of one car or in selected car subsystems. The amount of detail data on CM mass distribution among the embedded EE devices is scarce, with values being available only for selected EE devices of less than ten car types from the following brands: Volvo (48), Toyota (41–44), Suzuki (44), Nissan (44) and Ford (45,46).

For estimating the occurrence and mass of CMs in cars, two of the three North-American studies and the two Swedish studies (32,45,46,48) relied on data from the International Material Data System (IMDS) database, which is compiled by the original equipment manufacturers (OEMs). Chemical analyses of EE components were carried out by three of the four Japanese studies (41,43,44); the remaining Japanese study carried out chemical analysis of car shredder output fractions (42).

In terms of stocks and flows (S&F) estimations, five of the available studies used material and substance flow analysis in their assessments. For S&F estimations spanning several accounting years only the Swiss study used an agent-based model, while the remaining three studies used a stock-driven dynamic material flow analysis (MFA) model. Most studies considered the use phase of cars (car stock) as the central process in their S&F estimations, evaluating CM content mainly in this stock and the associated inflow and outflow of cars. The CM content in waste flows was estimated only by three of the available studies (32,43,44). In these three studies the processes of the passenger car system (lifecycle stages) varied slightly, but they all included: car registration, use (stock), ELV treatment, reuse/recycling of materials and components, waste treatment and waste disposal. All of the studies assumed that the available values for CM mass fraction were representative for the entire vehicle fleet and scaled them up to calculate CM S&F without considering the associated uncertainties related to, for example, the high variability of the few available values for CM mass fraction per car. For analysing S&F developments over time, the studies considered changes in car electronics penetration, while assuming constant numbers and unit mass of EE devices.

Four important insights can be drawn from the available studies:

i) Rare earth elements were the focus in nine of the ten available studies, indicating that they are highly important for automotive electronic applications (32,41–43,45–49).
ii) The mass fraction of gold in cars can be between approx. 1 g/t (46) and approx. 6 g/t (44,48). This is similar to the average ore grade in gold mines worldwide, which is around 1g/t (50).
iii) By 2050, the neodymium stock in alternative energy vehicles (for example hybrid and electric) in the U.S. can grow to be half of the 2017 in-ground reserves in the country (47). Half of the neodymium demand for the production of new Japanese cars in 2030 could potentially be covered from neodymium recovered from ELVs (43).
iv) Out of the CMs investigated, only platinum from catalytic converters is functionally recycled in current ELV treatment systems (32). Functionally recycled means that the properties of the metal are utilized in the new application (33,51). Contrary to this definition, virtually all of the CMs found in ELVs are currently either transferred to waste fractions or end up as impurities in scrap-metal fractions after EoL treatment.

The most important limitations and research gaps are:

i) Heterogeneous definitions of vehicle subsystems and lack of detailed data on CM mass distribution among car components: Each of the studies considered different car components and classified them under different vehicle subsystems. For example, the exhaust subsystem was considered to be part of three different systems by three different studies: The engine system (48), the functional mechanical system (41) and the fuel and exhaust system (45). The heterogeneity in the classification of components under vehicle subsystems prevents the comparison of results and reduces the usability of the studies to determine hotspots, for example for the identification of those EE devices that contain most of the CM mass in a car and that are therefore the best candidates to include in a mandatory dismantling scheme. Only four of the ten available studies reported the CM mass distribution among the EE devices considered (41,43,44,46), while the remaining ones reported aggregated results by vehicle subsystem, by car or as total stocks and flows.

ii) High variability of values for CM mass fraction and no account of parameter uncertainties in S&F estimations: The CM mass fraction values reported by the available studies originate from less than ten car types of five specific car brands: Volvo, Toyota, Suzuki, Nissan and Ford. There are large variations in the mass of CMs per car and per EE device. For example, the mass of Nd in conventional passenger cars has been estimated to be as low as approximately 1 g/car (41) and as high as almost 300 g/car (45). The poor type and cohort specification for the investigated cars hinders a clear explanation for the variability of the results. Additionally, the poor type and cohort differentiation severely limits the identification of associations between car characteristics and the presence of electronics (car electrification level), which would be necessary when determining car types in S&F estimations involving the whole vehicle fleet. The few cars investigated might also not be representative of the entire car fleet. For example, the most common car brands registered in Switzerland over the past 30 years have been VW, Opel and Skoda (52), none of which have been investigated so far. The effects of using a few scattered CM mass values in S&F estimations covering the whole vehicle fleet have also not been examined.

iii) Lack of independent primary data: Only the four Japanese studies reported direct measurements of CM mass fractions by means of chemical analysis (41–44), while the rest of the studies relied on confidential industry data.

iv) Poor understanding of the fate of CMs in the entire passenger car system: Only three of the available studies considered the S&F of CMs beyond car use (32,43,44). The estimations of S&F of critical metals in the ELV treatment and waste management processes derive mostly from mass balance calculations based on transfer coefficients obtained from expert consultation. There is little knowledge about the fate of CMs in processes such as car shredding, spare-part replacement, waste incineration and metal smelting. The spare-part replacement process, including related flows, is of particular importance for understanding the reuse and recycling rates of CMs in car electronics and remains unanalyzed in this context: There is currently no comprehensive information about S&F of EE spare parts, either new or second hand. There is also lack of information about the age of exported cars, which would be necessary to determine the type and number of EE devices they contain as well as their CM content. Other waste types treated in car shredders also remain uncharacterized.

v) No explicit consideration of car electronics integration and unit mass trends: Three of the four studies assessing the S&F of CMs over time have considered only penetration trends while assuming constant unit mass of the embedded EE devices (44,47,49). Only one of the studies (43) considered unit mass changes over time for selected EE components, however the potential phase-out of EE devices embedded due to integration was not considered. Neglecting integration and unit mass reduction trends for EE devices can lead to overestimation of the S&F of CMs. As the trends have not been explicitly considered, it also remains unclear how integration and unit mass reduction would affect the potential for recycling car electronics. In general, there is still a lack of time series data, particularly for unit mass of the embedded EE devices and their corresponding CM mass fractions.

Besides answering the main research questions below, the five papers appended in this thesis tackle the following research gaps: heterogeneity in definition of vehicle subsystems: in papers II, III and IV; CM mass distribution per car: in papers I, II and III; uncertainty accounting: in paper III; independent primary data provision: in paper II; understanding of the fate of CMs in the passenger car system: in papers III and V; and explicit consideration of car electronics trends: in papers IV and V.

1.5 Goal, scope, research questions and structure of the thesis

The main goal of this thesis is to inform end-of-life management of car electronics in light of the potential recovery of critical metals. The particular focus is on informing the revision of the Swiss regulation for electronic waste recycling in which a mandatory dismantling of car electronics is being considered. The following two research questions guide the overall research:

1. Which automotive EE devices from Swiss ELVs are potentially attractive candidates for dismantling from a critical metal mass content perspective?
2. How can the stocks and flows of critical metals in car electronics be modelled in a socio-economic metabolism framework and how could a monitoring of these stocks and flows most effectively support public and industry decision making on recycling critical metals from automotive EE devices?

This thesis refers to critical metals (CMs) as characterized by Graedel et al., 2015 (10) at the global level for the 2008 epoch. In this sense, the term "critical metals" or "CMs" refers to metals with medium to high criticality scores in either of the criticality dimensions (vulnerability to supply restriction, supply risk, and environmental implications derived from its production) at the global level in 2008. There is some overlap with the lists of CMs defined at the regional level for the EU in 2010, 2014 and 2016 (8,9,11) and at the national level for the US in 2010 and 2011 (12,13). For example, REE have been identified as critical in all of these assessments.

Considering the lifetime of cars, the knowledge of past developments at the car inflow is important for understanding the waste flows in the future. A historical perspective is therefore taken, considering a time span of 40 years between 1975 and 2015. Since end-of-life flows in the medium term will be largely composed by conventional passenger cars (powered by an internal combustion engine), these are the main target. The research questions are addressed in the five papers appended. Papers III and V present, respectively, a quasi-stationary and a dynamic MFA of cars, components, materials and critical metals in the Swiss passenger car system. Papers I, II and IV generated parameter data to feed the models in papers III and V. Figure 1 illustrates how the papers fill out formerly missing pieces of the passenger car system puzzle in relation to critical metals. The grey arrows in the figure indicate the focus of each paper. However, each of them as summarized in section 3 below addresses a larger range of aspects.

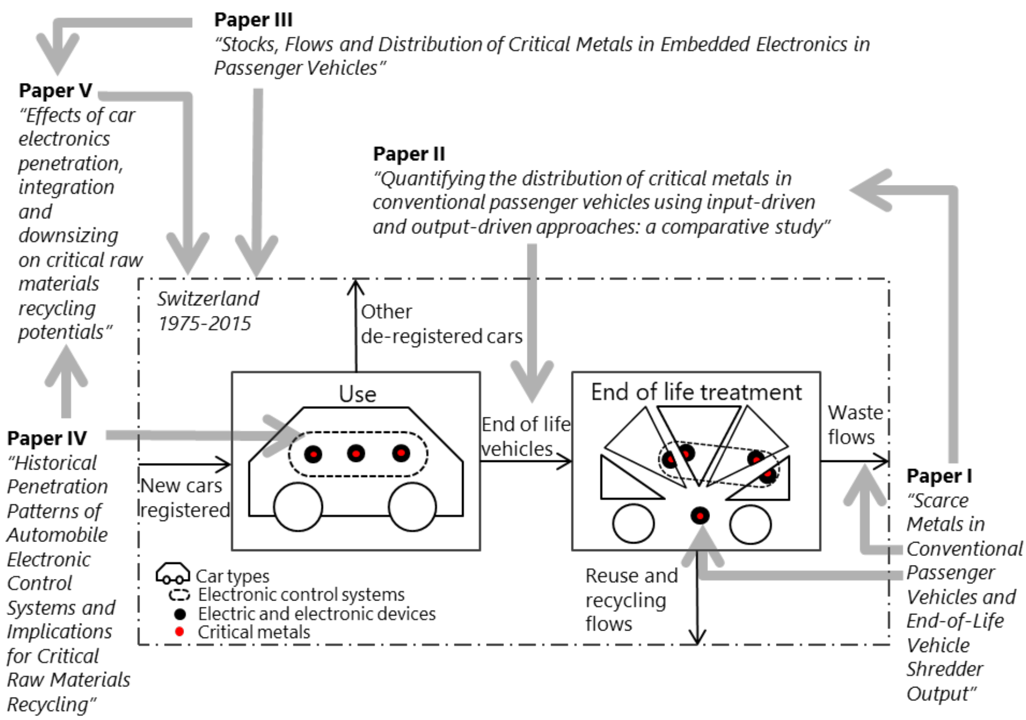

Figure 1. Simplified Swiss passenger car system and overview of main aspects considered in this thesis. The grey arrows indicate the focus of each paper. A simplified structure of car electronics is presented in the car use phase: Critical metals exist within electric and electronic devices (EE devices) which are found in automobile electronic control systems (AECS) in a variety of car types.

The subsequent chapters in this thesis are organized as follows: Chapter 2 outlines the methods used, Chapter 3 provides a summary of the papers and main findings, and Chapter 4 presents a discussion with respect to the research questions as well as the conclusions and outlook. The five papers are appended at the end.

2 Materials and methods

In the process of answering the above research questions, this thesis covered a range of aspects related to the estimation of mass stocks and flows of CMs in car electronics, from *micro-level* aspects such as CM mass fraction measurements in car EE components, to *macro-level* aspects such as estimations of the total stocks and flows of CMs in the car fleet. To answer the above research questions the first step was to identify which CMs occurred in cars and in what amounts (masses per car). To establish which were most relevant for a subsequent dismantling, the distribution of the CMs among the embedded EE devices and components was investigated. To determine the impact of dismantling specific EE devices and the significance of car electronics in general, the amounts of CMs in the total vehicle fleet were estimated. In a final step, trends in penetration and downsizing of EE devices were analysed to determine the impact of such trends on future EoL flows.

The central methods used were material and substance flow analysis (MFA and SFA) (53,54). For S&F estimations spanning several accounting years, a stock-driven dynamic material flow analysis (MFA) model was used (35,55–57). To identify the occurrence and mass fraction of CMs in EE components and in ELV shredder outputs, the following analytical chemistry techniques were used: X-ray fluorescence (XRF) spectrometry, inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma optical emission spectrometry (ICP-OES). Elements of control systems theory (58) were used for modelling car electronics as goods and substances in an MFA framework. Uncertainty propagation by means of Monte Carlo Simulation (59) was carried out to account for parameter uncertainties in the S&F estimations.

Data from three large databases were used: The Swiss vehicle registration database (MOFIS database) from the Swiss Federal Roads Office (FEDRO) (60), the Autohandel database from Auto-i-DAT AG (61) and the End-of-life vehicle de-registration database ("ELV database") compiled by the Foundation Auto Recycling Switzerland (SARS) (62).

To extract and analyse the relevant data, various statistical learning tools were used: Pareto analysis (63) random forest (64,65) and logistic generalized additive models (GAM) (64). Several software tools were used to handle data and implement the models: MySQL (66) was used to extract and combine information from the databases, R (67) was used for the statistical analyses, and MATLAB (68) was used to program the MFA, SFA and dynamic MFA models.

3 Summary of the papers and main findings

Paper I presented measurements of mass fractions, by means of chemical analysis, of 31 metals (Ag, Au ,Be, Ce, Co, Dy, Ga, Gd, Ge, In, La, Li, Mo, Nb, Nd, Pd, Pr, Pt, Rb, Re, Ru, Sb, Sm, Sn, Sr, Ta, Tb, Te, W, Y and Zr) in selected EE components from 119 car EE devices and in six out of the seven output fractions generated by shredding 100 ELVs at a Swiss car shredder in 2012. The results of the chemical analysis were later used to carry out a mass balance between a modelled shredder input and output. The cars from which the EE devices were obtained were selected to be as similar as possible as the shredded ELVs and to represent average "young" Swiss ELVs at the time of the experiment in 2012: four-door middle class passenger vehicles of cohorts between 2003 and 2008. The reason for this selection was to obtain information about the material content of average Swiss ELVs in the near future. Examples of EE devices considered are: radio, starter motor and engine control unit, which respectively contain EE components such as printed wiring boards (PWBs), magnets and contacts. The input to the shredder was modelled by assuming that the shredded ELVs contained an average number of EE devices found in four-door middle class passenger cars of the cohorts considered; for example one radio, one airbag controller and one lambda probe. The mass of CMs in these devices was obtained by multiplying the measured mass fraction in EE components times their mass in the respective EE devices. The mass of CMs in the shredder outputs was estimated by multiplying the mass fraction of CMs measured by chemical analysis times the total mass of the respective shredder output.

The results of the chemical analyses show that Co, Sn, Sr, Ta, Y, and Zr had the highest mass fractions in the EE components, with values higher than 20 000 g/t. The mass fractions of Ag, Ga, Mo, Sb, Sn, Sr, and Zr were dominant in the analysed shredder fractions, with values higher than 50 g/t. In the EE components, the metals were found in a wide range of mass fractions; from 0.4 g/t for Dy in Liquid Crystal Display (LCD) screens to 380 000 g/t for Zr in lambda probe sensor elements. As the unit mass of a lambda probe is only 13 g on average, the total mass of Zr in a car is however not as high. After the lambda probe, magnets and populated printed wiring boards (PWBs) contained the highest mass fractions of, respectively, rare earth elements such as La and Nd, and precious metals such as Ag and Au. For example, magnets contained approximately 7 200 g/t of La and 480 g/t of Nd; PWBs contained approximately 410 g/t of Ag and 120 g/t of Au. The mass fractions in PWBs are at least three orders of magnitude higher than in the Earth's Crust (53).

The mass fractions of the measured metals in the shredder output fractions were however several orders of magnitude lower than in the investigated EE components. For example, the highest mass fraction of Sn in shredder outputs was approx. 1 400 g/t, while in PWBs it was approx. 21 000 g/t. Among the shredder output fractions, the automobile shredder residue (ASR) was found to contain the vast majority of the analysed metals, by number and mass.

Based on these results, it can be inferred that: i) EE devices are important carriers of CMs in cars, ii) EE devices containing magnets and PWBs, such as electric motors and controllers, represent better candidates for a mandatory dismantling than sensors, because their unit mass is higher, iii) the shredding process *mixes* and *dilutes* the metals originally found in EE components, which may reduce opportunities for recycling, and iv) most CMs tend to accumulate in the ASR, which implies that they are currently not recovered, because the ASR is incinerated and subsequently landfilled. This is confirmed by a Swedish study in which only Pt from catalytic convertors was found to be functionally recycled in the Swedish ELV treatment system (32). Even though the accumulation of CMs in the ASR may represent an opportunity for recovering CMs after shredding in the future, the mixing of CMs within this large mass of heterogeneous waste materials may represent a challenge when finding downstream processes able to separate and ultimately recover these CMs (69). The optimal recovery of CMs from ELVs may require a combination of interventions, such as pre-shredding dismantling, post-shredding treatment of ASR, and/or incineration and smelting, instead of just one intervention alone. An assessment of the downstream recovery yields of CMs, and associated thermodynamic and environmental implications can help define the optimal combination of interventions. Approaches such as design-for-disassembly and design-for-recycling can also facilitate the establishment of optimal EoL treatment of car electronics and subsequent recovery of CMs (17,70).

Figure 2 presents an example of the shredder mass balance for the case of gold. The modelled shredder input and output flows of Sr, Au and Nd balanced relatively well, while there were large mass imbalances for the remaining 28 metals analysed. The mass outflow of 23 of the metals was larger than the estimated inflow, implying that these metals might occur mainly in other car components, such as alloys of the body-in-white (containing Co), which were not analysed in the study. The estimated mass inflow of La, In and Pt was larger than the outflow, indicating output flows for these metals that were not analysed in the study, such as EE devices dismantled as second-hand parts prior to shredding as well as a shredder output known as "meatballs" in which pieces of electric motors can be found.

This study also revealed several challenges related to the measurement of elements at low mass fractions in heterogeneous material streams. Sampling and measurement errors may have added to the observed mass imbalances. The study illustrated that sampling and chemical analysis methods customized to large and heterogeneous material streams are needed for a better understanding of the CM content in car shredder output fractions and EE components.

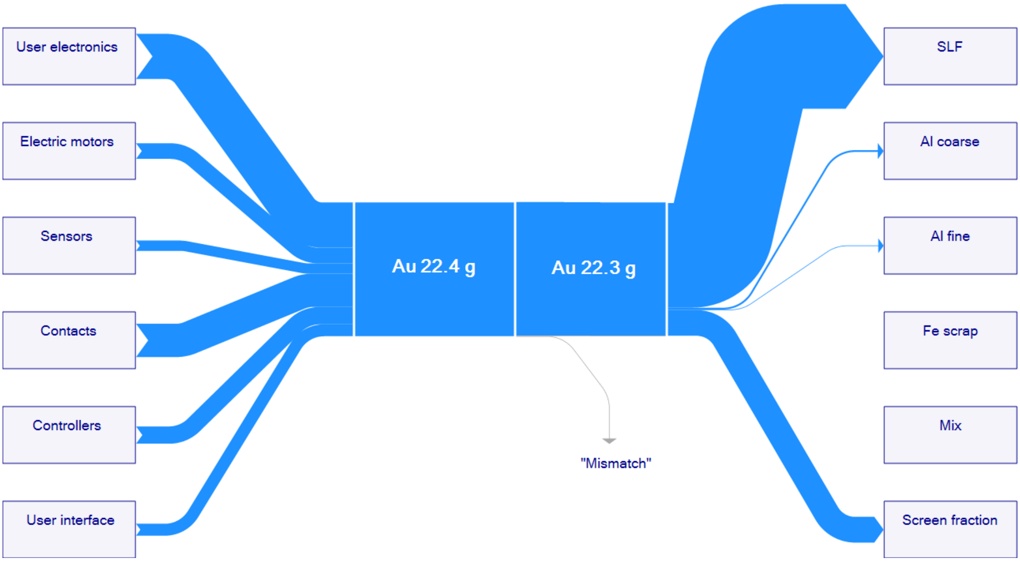

Figure 2. Estimated mass balance of gold in 100 shredded ELVs in 2012. The left-hand side shows the mass distribution in the embedded EE components and the right-hand side shows the mass distribution in the shredder output fractions. SLF: Shredder light fraction. The Automobile shredder residue (ASR) is composed by the SLF and the screen fraction. Source: Paper I.

Paper II presents a compilation and comparison of the results of five studies regarding the occurrence and mass of 25 CMs (Ag, Au, Ce, Co, Cu, Dy, Ga, Gd, In, La, Mn, Mo, Nb, Nd, Pd, Pr, Pt, Sb, Sm, Sr, Ta, Tb, W, Y and Zr) in conventional passenger cars until 2014, including the results from paper I above. Variations in estimation methods and results were also discussed in the paper. The results of the comparison show that CMs in cars occur in a wide range of *small* mass fractions, Figure 3. Out of the 25 CMs investigated in the five studies, only four were found to have median masses higher than 40 g/car (Cu, Mn, Nd and Sr), Figure 3(A). Eight CMs (Nb, Zr, Co, La, Mo, Nd, Ce and Ag) had median masses around or below 10 g/car, Figure 3(B), and the median masses of 13 CMs (Pd, Ta, Pr, Ga, Sm, Y, W, Au, Gd, Dy, In, Pt and Tb) were less than 1 g/car, Figure 3(C). The results per metal and per car among the five studies were highly scattered. Due to lack of reported detail about characteristics such as cohort and mass of the investigated cars, the reasons for the scattered values remain unclear, but it is likely a combination of different factors, including differences in type and cohort of the investigated cars as well as different methodologies (e.g. data from manufacturers vs. data from sampling and analysis). As the studies used different definitions of vehicle subsystems, allocated parts differently, and presented results in an aggregated form, it was also not possible to identify which EE devices contained the largest mass of CMs in each assessment. Two approaches to estimate CM mass per car were identified among the five studies: an input-oriented approach and an output-oriented approach. In the input-oriented approach, the mass of the CMs per car was estimated from data about CM mass in EE devices, which was obtained either from OEM databases or by means of chemical analysis. In the output-oriented approach, the mass of CMs per car was estimated from measurement of CM mass fractions in car shredder outputs by means of chemical analysis. The input-oriented approach represents an advantage when identifying hotspots for CMs; disadvantages arise due to data confidentiality by OEMs and accessibility to EE devices for chemical analysis. To improve the usability of future input-driven assessments of CM mass per car, while complying with confidentiality, a homogeneous definition of vehicle subsystems and a comprehensive structure of car electronics need to be developed and adopted. The output-oriented approach represents a reality check; the experimental analysis is however costly and challenging, and therefore has limited capacity to produce comprehensive data.

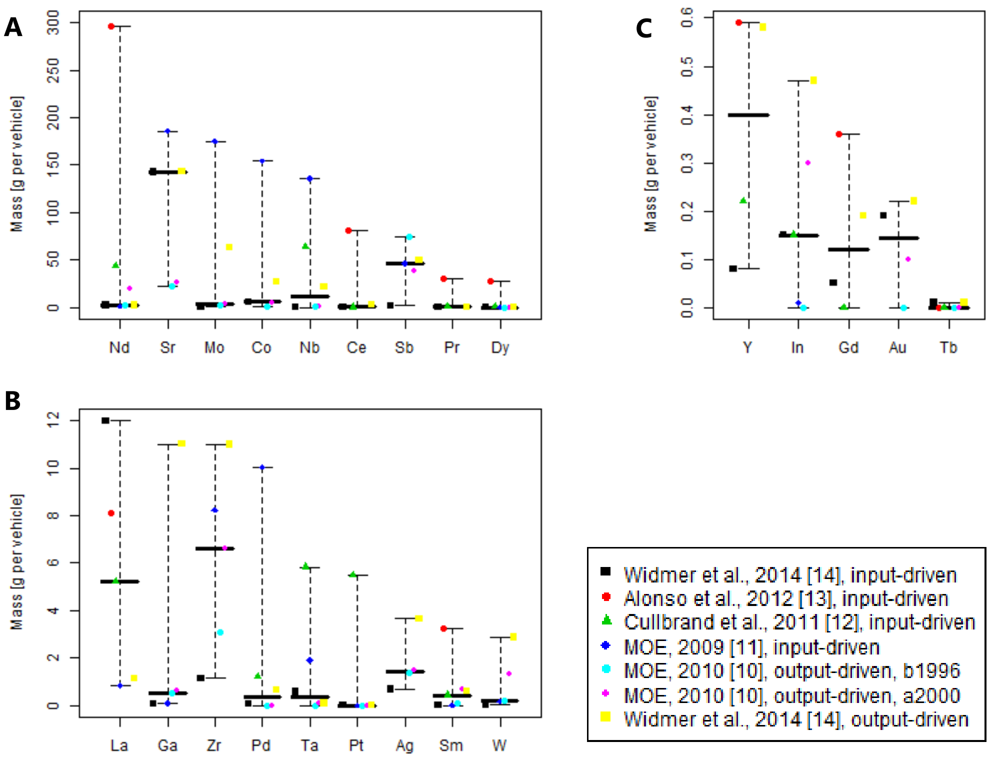

Figure 3 (A) (B) (C). The mass of 23 metals (except Cu and Mn) in one conventional passenger vehicle (g per vehicle). The results of mass per vehicle from the five reviewed studies are shown as the individual data points in different markers. The thick black bars are the medians of the results from the five studies. The upper and lower whiskers indicate the maximum and minimum results from the five studies. Source: Paper II.

Paper III presents an estimation of the stocks and flows (S&F) of eight CMs in the Swiss passenger car system in 2014: Ag, Au, Pd, Ru, Dy, La, Nd and Co. Following the identification of problems related to classification of vehicle subsystems and devices in Paper II, a methodological objective of Paper III was to develop a more universally applicable system for accounting for car electronics. A nested hierarchical structure of car electronics based on elements of control theory was developed, Figure 4. In this structure, all car-embedded EE devices were classified as sensors, controllers or actuators, depending on their function in specific automobile electronic control systems (AECS). Public and private databases containing detailed characteristics of the cars imported, in use and shredded in the country as well as information about the standard embedded AECS in these cars were used. Parameter uncertainties were accounted for and propagated to quantified system variables by means of Monte Carlo simulation.

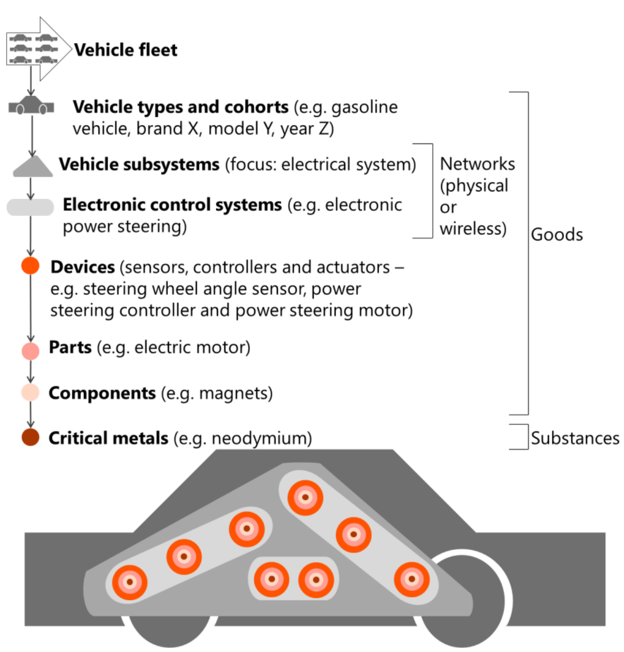

Figure 4. Nested hierarchical structure of car electronics. Automobile electronic control systems (AECS) are a sublayer of goods within passenger vehicles and represent the network structure in which embedded EE devices interact. EE devices, EE parts and EE components are subsequent layers of goods in which CMs (substances) are found. Source: Paper III.

The results show that, automotive electronics constitute a significant stock of CMs when compared to the stock of IT & communication equipment and consumer equipment (categories 3 & 4 in the EU waste electrical and electronic equipment –WEEE regulation (71)). The Nd in Swiss car electronics in 2014, estimated to be 70^{+30}_{-30}, was higher than the stock of Nd in the combined stock of WEEE categories 3&4 in the same year, which was approximately 40 t (72) (updated value compared to the reported in paper III). In the case of Au, the stock in car electronics in 2014 was estimated to be approximately 20% of the Au stock in WEEE categories 3&4 in the same year (72). The total estimated CM masses in the inflow of cars were more than five times higher than in the ELV flow. For example, it was calculated that there were 25^{+8}_{-6} t/a REE in the car inflow in 2014, while there were only 3^{+2}_{-1} t/a REE in the ELV flow. About half of the mass increase (2.5 times more CM mass) in the car inflow can be explained by the larger number of cars: There were three times more imported cars than there were ELVs treated in Switzerland in 2014, due to a growth of the vehicle fleet and a net export of cars that are not treated as ELVs in Switzerland. The remaining difference can be attributed to a higher CM mass per car, regarded to either an increased penetration or an increased unit mass of the embedded EE devices in new cars. Given today's number and composition of new cars sold, it can be expected that the flows of CMs ELVs will increase by at least a factor of two in the coming 15 – 20 years (average lifetime of cars).

The CM flows in ELVs tend to be smaller than those in WEEE categories 3&4. In 2014, the estimated Nd and Au content in ELVs, was, respectively, only 8% and 6% of the Nd and Au content in WEEE in the same year (72). An important reason for the difference in relevance of car electronics for the stock and the EoL flow of CMs is that cars tend to have longer lifetimes than IT & communication equipment and consumer equipment. However, as the number of cars and their CM content is expected to increase in the future, the relevance of EoL car electronics in comparison to WEEE can also be expected to increase. Considering similarities in their vehicle fleet and number of cars per capita (73), similar results regarding the contribution of car electronics to the national stocks of Nd and Au may be expected in most west-European countries.

The nested structure of car electronics defined in this paper allowed a comprehensive accounting of the number of EE devices embedded in all car types, as well as an identification of the hotspots for each CM considered. By combining data on the composition of individual devices with data on the occurrence of these devices in cars (i.e. the frequency at which they are employed in cars) it was found that the fuse box, radio, navigation system and engine controller contain more than 50% of the Ag and Au mass in new cars, cars in use, and ELVs, Figure 5. The alternator, electronic power steering motor, drive motor/generator, nickel metal hydride (NiMH) battery and speakers contain more than 50% of the La and Nd mass. By dismantling the fuse box, the radio and the navigation system from ELVs, the mass fraction of gold can be increased from an average of 1 g/t in cars to 400 g/t in dismantled EE devices (increase by two orders of magnitude). By dismantling the electronic power steering motor, the electric drive motor and the NiMH battery the mass fraction of Nd could be increased 20 times. Considering their high CM mass content, as well as their high contribution to the total S&F of CMs in cars, these devices were identified as potential candidates to include in the amended Swiss regulation for electronic waste recycling. However, changes in penetration, unit mass and CM content may affect the potential for recovering CMs in the future. As their material composition is similar to that of consumer electronics, the inclusion of EE devices such as the radio and the navigation system in the current WEEE recycling system to recover precious metals seems straightforward (74). Even though some industrial recycling of EoL magnets has been developed in Japan (75) and it is operational at small scales in the U.S. (76), the recovery of REE from EoL electronics is currently not well established (77). The potential for recovering CMs such as Nd and Dy after dismantling electric motors is therefore still unclear and will depend on the establishment of appropriate processes for recovering rare earths from WEEE.

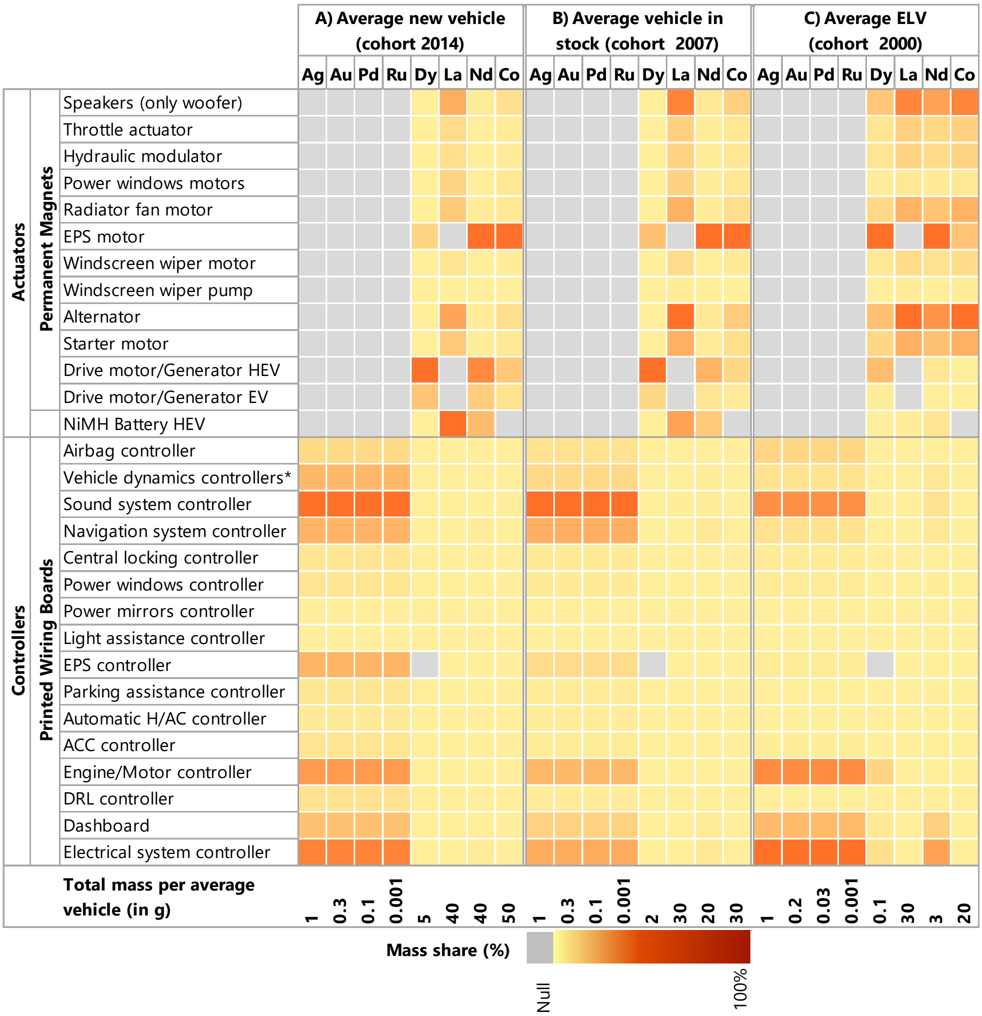

Figure 5. Distribution of CM mass in EE devices in an average (A) new vehicle, (B) vehicle in stock, and (C) ELV. The figure reads by element (columns): for each element, the colour scale corresponds to the share of total element mass (in percentage) that is contained in a specific EE device per average vehicle. For example, in an average ELV, La is found mainly in the alternator, while in an average new vehicle it is found mainly in the NiMH battery of hybrid electric vehicles. *Vehicle dynamics controllers include: ABS, ESP, EBD, HHC, DSR, TCS, and CBC. Acronyms are provided in the supplementary information file of paper III, section 1. Source: Paper III.

Paper IV presents an analysis of the historical penetration of four representative automobile electronic control systems (AECS) in more than 65 000 car models sold in Switzerland between 2001 and 2015 by means of statistical learning. The results show that the historical penetration of AECS tends to follow s-shaped curves, however with substantial variations in penetration speed and saturation level, Figure 6. Although there is evidence of a fast increase in electronic functions in cars, comfort-related AECS, such as the cruise control system, remained below 40% penetration even after 14 years on the market. In contrast, the penetration of safety-related AECS, such as the electronic stability control (ESC), increased rapidly to almost 100% penetration, mainly due to the implementation of safety regulations that make the ESC mandatory for all car types. Stronger safety standards for cars may push penetration of related electronics in the future. Environmental emission regulations seem to indirectly affect the penetration of related AECS, such as the stop-start system, to a medium penetration level, for example reaching 60% penetration after six years on the market. It was identified that unifunctional AECS such as the anti-lock braking system (ABS) are being integrated into new, multifunctional ones, such as the ESC. An additional measure to ensure the long-term effectiveness of the amended Swiss electronic waste recycling regulation would therefore be to define the list of mandatory car electronics to dismantle at the level of AECS instead of at the level of specific EE devices. For example by mandating the dismantling of “controllers related to vehicle dynamics”, rather than the dismantling of “ABS controllers”, because, as shown in this paper, unifunctional AECS such as the ABS are phasing out.

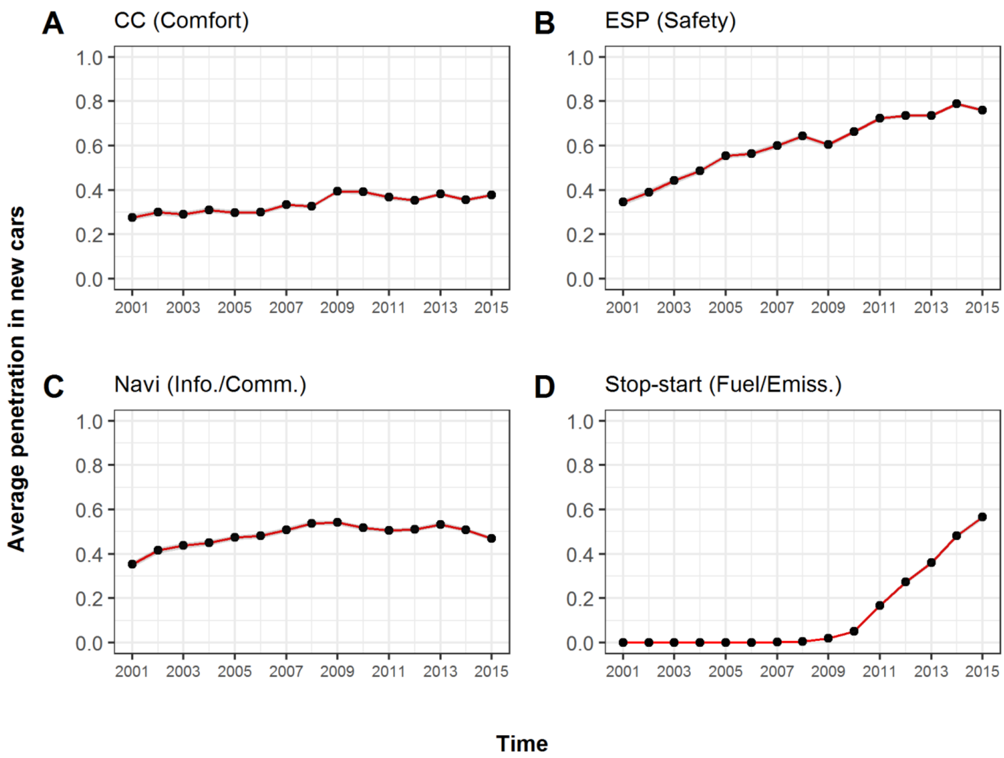

Figure 6. Average historical penetration of established AECS in new cars: (A) cruise control (CC)– representing comfort AECS, (B) electronic stability program (ESP)– also known as electronic stability control and representing safety AECS, (C) navigation system (Navi) –representing information/communication AECS, and (D) stop-start system – representing fuel efficiency/emission control AECS. The curves are accompanied by a grey ribbon corresponding to the 95% confidence interval (CI) of the mean. In this case, the grey ribbon is almost invisible, due to the CI being very narrow. Source: Paper IV.

Statistical learning tools helped understand associations between car characteristics and the presence of car electronics, which is valuable knowledge when developing models to estimate S&F of EE devices and their related materials in the entire vehicle fleet. For example, by means of a random forest model, it was identified that, among 14 different car characteristics, the following four were the ones that were more strongly associated with the presence of the AECS considered: price, mass, engine displacement (or power), and cohort. To be useful for estimations of S&F of materials in car electronics, car statistics should ideally employ car classification systems based on these four characteristics. Swiss public statistics on the in-use stock of cars currently includes engine displacement, power and cohort, but misses the two most important characteristics: price and mass(78). Public EU statistics on the in-use stock in member states includes mass categories and some cohort groups (5-10 year intervals), but not power or price (79).

Statistical learning models can also be useful for making short-term inferences about the developments in car electronics. For example, from the results of a generalized additive model, it can be inferred that in the short term, preferences towards larger cars (high mass, high engine displacement) may be associated with an increased use of embedded car electronics. Long-term penetration of car electronics is however influenced by the interaction of external drivers, such as regulatory framework and technological maturity. As car electronics are such a complex system, statistical learning tools cannot be used for long-term projections. Assessments of future developments of electronics in new cars in the long-term would require other tools such as scenario analysis (80).

Paper V presents a historical estimation of the S&F of two representative EE devices: The anti-lock braking system (ABS) and electronic stability control (ESC) actuator assemblies, in the inflow, stock and EoL flow of Swiss cars between 1975 and 2015 by means of a dynamic MFA combined with comprehensive time-series for penetration and unit mass of the EE devices. An analysis of the effects of penetration and unit mass trends on the numbers and volumes of EE devices reaching EoL was included.

The results show that the penetration of ABS and ESC control systems coincided with an integration of the ABS function into the ESC and a unit-mass decrease for both EE devices (downsizing). Both penetration and downsizing are s-shaped; their periods of strongest changes in new cars coincided in the 1990s, and they have flattened since the 2000s. The impacts of penetration on mass flows outweighed the impacts of integration and downsizing, resulting in an increase in the total mass flows of the EE devices, Figure 7. Contrary to the case of consumer electronics, where integration and downsizing trends have led to a decrease in the total mass flow of EE devices and related CMs (37), the example of the ABS and ESC actuator assemblies shows that, even though integration and downsizing have been strong for individual EE devices, their historical mass inflows have increased and flattened over time. This is mainly due to the increased penetration of multifunctional EE devices (heavier than unifunctional ones) in heavier car types. In 2015, the EoL flow trends of ABS and ESC actuator assemblies were still pointing sharply upwards. Since the penetration of these devices saturated by 2008, we can expect the EoL flows to grow further but at a slower pace between 2015 and 2025 (depending on the lifetime of cars), with remaining growth being driven mainly by the switch to the multifunctional ESC, the switch to heavier car types and an increasing number of ELVs.

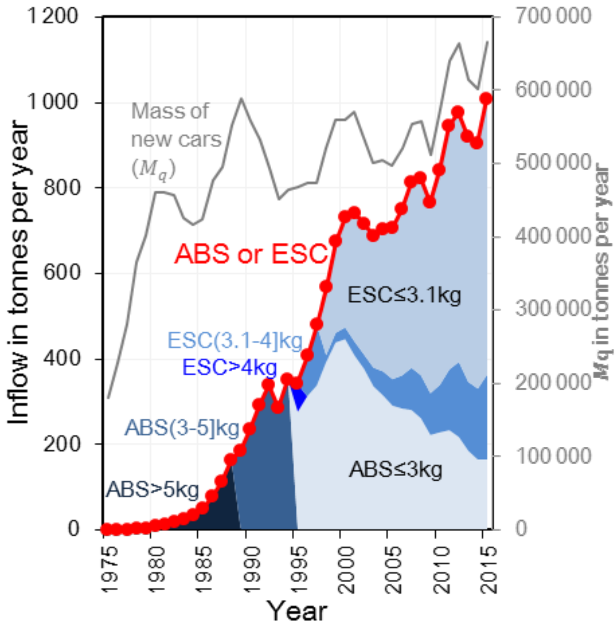

Figure 7. Mass inflow of ABS and ESC actuator assemblies, Switzerland 1975-2015. The red-dotted line represents the combined inflow of actuator assemblies and the blue wedges represent the inflow of different generations of actuator assemblies; values are provided on the left-hand axis. The total mass inflow of cars is represented by the grey line; values are provided in the right-hand y-axis. Source: Paper V.

The results also show further downsizing potentials for the ABS and ESC actuator assemblies in new cars. If these are realized, the mass flow of the EE devices may decline in the future. Similarly, the EoL mass flows could fade-out if the ABS and ESC functions are integrated in new EE devices. Due to the long lifetime of cars, the increased penetration and strong downsizing of the EE devices is still evident at the end-of-life, which can cause the dismantling costs per kilogram to increase. However, as these trends can be expected to settle between 2015 and 2025, more cost-effective opportunities for dismantling car EE devices for material recovery may arise in the future. A dismantling experiment showed that the reuse-oriented dismantling rate of the actuator assemblies was approximately 10% in 2015; it is presumed that the dismantled assemblies are reused as spare parts, but the percentage is unknown. In general, the spare-part replacement process and related flows remain unexplored; the lifetime of EE devices has so far been assumed to be equal to that of cars and it also remains to be more accurately determined. The remaining 90% of the assemblies ended up being shredded with the ELVs.

If the mandatory dismantling strategy is implemented, additional environmental benefits in the form of reduced resource consumption for producing new spare parts can be expected, as a result of the potential increased availability of second-hand spare-parts dismantled. Considering similarities in their car fleet, comparable patterns for EoL flows, with similar implications for recycling, can be expected in most west-European countries. Similar patterns for other EE devices in cars that have penetrated in the past 30 years, especially when they include actuator assemblies with electric motors, can be expected. This study demonstrated that by monitoring the penetration, unit mass and CM content of EE devices at the car inflow, in combination with a dynamic MFA, future changes in the EoL flows of car electronics can be foreseen 10 to 20 years before they occur. This can timely inform dismantling policies regarding which EE devices to include in a mandatory dismantling strategy, as well as the necessary financing mechanisms at different stages of penetration and downsizing. For this monitoring to succeed, easier access to data about penetration, unit mass and CM content of new car EE devices is crucial.

4 Discussion, conclusions and outlook

4.1 Question 1: Which automotive EE devices from Swiss ELVs are potentially attractive candidates for dismantling from a critical metal mass content perspective?

The main motivation for this work is the upcoming changes in the Swiss electronic waste recycling regulation and the potential inclusion of specific car EE devices in a mandatory recycling scheme. The apparently simple question of which devices to include in such a scheme opens up a number of more specific questions, such as "which metals occur in car electronics?", "in what quantities"?, "which electronics contain the largest amounts of metals"?, "what are the environmental benefits of recycling car electronics?", "what are the costs of recycling-oriented dismantling of car electronics?", "are there unintended economic consequences of a mandatory dismantling”?, etc. Some of these questions, specifically those that relate to characterizing the physical system of car EE devices and the CMs contained in these, were addressed in this work. The reason for focusing on this physical system is that this lays the foundation for answering other questions related to economics or environmental impacts as well. For example, to determine the economic and environmental benefits of recycling-oriented dismantling, the content of various metals that can be recovered in a given EE device needs to be known. To establish the total costs and therefore the impact on the dismantling business in general, the total mass flows of the specific devices needs to be known. The results of this work point out potential EE devices to include in the amended regulation, based on their individual CM content and their contribution to the total CM stocks and flows. For a final list of mandatory EE devices to include in the amended regulation, the environmental and economic aspects of recycling-oriented dismantling need to be determined.

The results of this thesis have demonstrated the importance of car electronics as a potential source of secondary CMs: A large number of CMs occur in car electronics, in many devices and components at mass fractions that are much higher than typical mass fractions in natural ores. Compared to other sources of secondary CMs such as WEEE, car electronics constitute an extensive stock of CMs. The Nd stock in car electronics was estimated to be higher than that in WEEE categories 3 & 4 (IT, communication and consumer equipment), while the Au stock in car electronics is one fifth of the Au stock in WEEE categories 3 & 4. The mass flows of CMs in EoL car electronics is nevertheless much smaller than that of WEEE, mainly due to the long lifetime of cars compared to consumer electronics. However, as the number of cars in use and the number of embedded car electronics have been increasing steadily over the past years, the amounts of CMs in ELVs are likely to grow significantly in the future. Considering that there is already an established system for recycling non-car electronics, and that many metals are recovered from devices with lower or similar mass fractions as in many car electronics devices, there is clearly a potential for establishing such a recycling route also for electronics embedded in cars.

It has been established that the majority of CM mass contained in EoL car electronics is lost in the current treatment system. Some devices are dismantled for reuse, but based on the example of the ABS and ESC actuator assemblies in this thesis it can be presumed that the reuse-oriented dismantling only removes approximately 10% of the total embedded devices before shredding. The remaining 90% of the devices remain in the car and are shredded. Additionally, some devices that are dismantled for reuse may never be sold for this purpose and end up in to-date unknown recycling systems instead. The results of the shredder experiment in paper I show a considerable accumulation of CMs in the ASR. Although it is difficult to investigate the individual behaviour of single devices in the shredder, by the mass of CMs in ASR it can be assumed that the materials from a large number of EE devices are systematically concentrated in this fraction.

Given the demonstrated importance of car electronics as a potential source of secondary CMs, as well as the limitations of the current treatment system, the questions of whether to implement mandatory dismantling and if so, which devices to dismantle, appears highly relevant. It was found through sampling and chemical analyses that sensors, controllers and actuators contain high mass fractions of specific CMs and are therefore all relevant candidates to consider. Sensors contain remarkably high mass fractions of metals, but due to their small unit mass and low occurrence in cars, their contribution to the total CM mass per car is currently low. To determine whether a device is a good candidate to include in the regulations, it is not enough to know that it contains high mass fractions of CMs: Specific devices may be extremely rich in CMs, but at the same time rarely embedded in cars. Frequently embedded devices can have a strong influence on the total flow of CMs even if their single CM content is not as high. The impact of including such frequently embedded devices versus the impact of including *rare* CM-rich devices in the regulation should be further assessed.

Quantification of the stocks and flows of specific devices and their CM contents revealed that the EE devices that contain most of the CM mass in cars (new, in-use and ELVs) seem to be electric motors, batteries, and control units, in which REE and precious metals can be found. Furthermore, it was found that a relatively small number of devices are responsible for the majority of the mass stocks and flows of important CMs in car electronics. The fuse box, radio, navigation system and engine controller contain more than 50% of the Ag and Au mass in cars, while the alternator, electronic power steering motor, drive motor/generator, nickel metal hydride (NiMH) battery and speakers contain more than 50% of the La and Nd mass. These devices were therefore identified as promising candidates to include in a mandatory dismantling strategy. It should be noted that the dismantling of the NiMH battery from hybrid-electric vehicles is already mandatory for safety reasons.

Beyond the identification of candidate devices and metals, the work revealed the complexity of the system and highlighted several potential challenges or obstacles related to a mandatory recycling strategy. It was found that the majority of CMs in car electronics currently end up in the ASR. Currently, this mostly represents a loss for most CMs, because the ASR is incinerated and mostly landfilled, but it could also represent an opportunity in the future if post-shredder treatment of ASR is established broadly.

One municipal solid waste incineration plant in Switzerland where ASR is also incinerated has developed a new process to recover precious metals from incineration outputs (81). This plant currently receives around 20% of the ASR generated in Switzerland (82). Given the establishment of such recovery routes, there are interests to keep precious metals in this waste flow. However, as the mass fractions of CMs in EE devices are much higher than in ASR, it can also be expected that a mandatory dismantling scheme with subsequent recycling could achieve better recovery rates than the post-shredder treatment of ASR. The dismantling strategy also has a potential additional environmental benefit if the dismantled parts are in condition to be reused. Nevertheless, high dismantling rates may render the new post-incineration recovery of CMs uneconomic. An overall system optimization, considering environmental and economic constraints of a combination of interventions is needed.

An additional consideration before determining a specific list of mandatory EE devices to dismantle is the fact that penetration, unit mass and CM content of these devices changes over time. Integration and downsizing trends have negatively influenced the flow of precious metals in WEEE. With the example of the ABS and ESC actuator assemblies, this thesis shows that in the case of cars, the increased penetration of EE devices in heavier car types has pushed the total flows upwards. The flows flatten once full saturation is achieved and with the levelling-off of downsizing. The results also demonstrate that a possible mandatory dismantling of car EE devices may be challenged by increasing costs per kilogram of material dismantled, resulting from the progressive decrease in the unit mass of some EE devices. However, as downsizing levels-off, so will the dismantling costs, showing future opportunities for recycling-oriented dismantling. Based on these results, it can be inferred that recycling-oriented dismantling may be more cost-efficient at the initial penetration stage, before substantial downsizing has taken place. Financing mechanisms can be timely adjusted according to such changes in penetration and downsizing if an appropriate monitoring system is established.

The analysis of historical trends in penetration, integration and unit mass of devices has also clearly shown the importance of regularly updating the potential list of devices to be dismantled, among others to include new devices and to exclude those that are expected to fade-off due to integration or replacement.

4.2 Question 2: How can the stocks and flows of critical metals in car electronics be modelled in a socio-economic metabolism framework and how could a monitoring of these stocks and flows most effectively support public and industry decision making on recycling critical metals from automotive EE devices?

The results of this thesis show that by mapping trends at the car inflow, in combination with a dynamic MFA, it is possible to foresee changes at the EoL flow well before they occur. The early detection of trends can in this way inform dismantling policies regarding the selection of mandatory EE devices to dismantle as well as the required financing mechanisms to promote dismantling. Given the dynamics of the system and the speed of technological changes, it is nonetheless clear that a detailed one-time characterization and modelling of the system cannot provide policymakers with all the necessary knowledge to ensure a good lasting solution. An operative, living monitoring system built on methods and tools developed in this thesis could ensure that policies and strategies stay up to date and thereby enable more sustainable use and EoL recovery of CMs from car electronics.

Important flows to monitor in this context have been identified in this thesis: The inflow of embedded EE devices, the flows of second-hand spare parts (dismantled, installed and discarded) and the ASR. The spare-part replacement process is essential for the estimation of reuse and recycling rates for car EE devices as well as for estimating their lifetime. This process is one of the largest data gaps at the moment. Other important data gaps include longitudinal values for CM mass fractions in EE devices and in ASR.

The success of a possible monitoring system depends to a large extent on the accessibility to data to quantify EoL flows and the distribution of CM mass between embedded EE devices. Collaboration among all actors involved in the manufacturing, import and ELV treatment is important to ensure the successful transfer of consistent data at the right aggregation level to the relevant stakeholders.

MFA enables a comprehensive accounting of all physical flows and stocks of materials from which economic, thermodynamic and environmental assessments can derive. However, the complexity and time variability of car electronics poses a challenge for the comprehensive accounting of their material stocks and flows in an MFA framework. Previous estimations of CM in cars have used heterogeneous classifications of car subsystems that hinder usability of results in an MFA framework and mostly do not provide sufficient detail for informing dismantling-oriented policies. The nested hierarchical structure of car electronics defined in paper III, which includes, in descending hierarchical order: Car types, AECS, EE devices, EE components and critical metals facilitated MFA modelling by tracking goods (i.e., cars, EE devices and EE components) and substances (critical metals) consistently across car types. For example, this system enabled the mapping of *devices*, which are always part of larger control systems, through databases that only contain information about the presence of the control system. The classification of EE devices as *sensors*, *controllers* and *actuators* enabled a comprehensive mapping the distribution of CMs in the totality of embedded EE devices. The distinction between AECS and EE devices also allowed for a better understanding of trends such as integration and downsizing, and their individual effects on recycling potentials. Previous studies have used classification systems that look at the entire vehicle, grouping electronic and non-electronic components in predefined vehicle subsystems. As a result, the contribution of electronics to the total mass of CMs per car is not clearly identifiable. The classification system adopted in this thesis looks at car-embedded electronics as part of a complementary (independent) subsystem inside the car: the car's electrical subsystem. This allows mapping the total mass and distribution of CMs in the complete set of embedded electronics. The contribution of EE devices and EE components is clearly identifiable. In contrast to classification systems used in earlier studies, the one developed here has an appropriate granularity for informing car electronics dismantling policies. The classification system used here is also simple and flexible, being easily adaptable to account for embedded electronics across different car types and cohorts.

This thesis demonstrated that the estimation of CM stocks and flows is highly dependent on robust data sources from public and private databases. Although not originally intended for this purpose, the Autohandel database form Auto-i-DAT AG proved to be a very valuable resource of data for understanding the presence of electronics in cars. Still, it has limitations, for example related to harmonization (different manufacturers use different names for the same control systems) and in that it does not provide the chemical composition of the embedded EE devices. The IMDS database, in which "all materials present in finished automobile manufacturing are collected, maintained, analysed and archived"(83), has been used by several authors to estimate CM mass per car and in selected EE devices (45,46,48). However, IMDS data is subject to confidentiality by automobile manufacturers and their suppliers, which hampers usability. Adopting a harmonized structure of car electronics, such as defined in paper III, to report CM mass values at an aggregated level would improve the usability of future assessments based on confidential data. Access to data from both public and private databases is highly important, considering how expensive and challenging experiments are. For monitoring the inflow of EE devices in new cars it would be sufficient to provide average values for penetration, unit mass and CM mass content of EE devices. Such aggregation might help overcome difficulties related to confidential data from manufacturers.

Public statistics on car fleets are an essential resource for quantifying the stocks and flows of car electronics. The usefulness of public car statistics at the European (73) and Swiss level (60) for future assessments of stocks and flows of cars and embedded EE devices could be improved if cars were classified according to characteristics that correlate with the presence of electronics. In paper IV of this thesis, it was shown that the car's mass, engine displacement (or power) and cohort year were strongly associated with the penetration and the unit mass of the analysed AECS and EE devices. These characteristics should therefore ideally be reported on in the statistics.

Even though uncertainties are high, and it is challenging to take representative samples of the large and highly heterogeneous materials in shredder outputs and car EE components, experiments proved to be very important for understanding the fate of EE devices in ELV treatment processes, as well as for calibrating CM mass estimations. A monitoring system for car electronics should also include regular, for example yearly, measurements of the shredder outputs to identify possible changes that may not be detected otherwise, for example to spot new CM sources in cars. Efforts should be taken towards a reproducible sampling and measurement procedure, which can help reduce the uncertainty and improve the usability of experiments.

4.3 Conclusions and outlook

This research has demonstrated that the stocks and flows of CMs in car electronics are indeed significant, particularly when compared to WEEE, which provides a strong argument for including EoL car electronics in the amended Swiss regulation for electronic waste recycling.

A large number of CMs, including Nd, Dy, Au and Ag occur in many different car EE devices at a wide range of mass fractions. Although the mass fractions per car are low, the mass fractions per EE device and EE component can be high. Dismantling can substantially increase the mass fraction of CMs, and thereby facilitate the subsequent recovery. It was found that a relatively small number of devices are responsible for the majority of the mass stocks and flows of important CMs in car electronics. The fuse box, radio, navigation system, engine controller, alternator, electronic power steering motor, drive motor/generator and speakers were identified as promising candidates to include in a mandatory dismantling strategy. Further investigations regarding economic and environmental implications and possible financing mechanisms are needed for determining a final list of devices that have to be dismantled.

The costs per kilogram of recycling-oriented dismantling could be high, due to the small unit mass of EE devices. Considering the s-shaped curves that characterize penetration and unit mass over time, the more cost-effective recycling opportunities for car EE devices seem to lie at the beginning of penetration, when downsizing potentials for EE devices have not been fully realized. The total mass flows of EE devices increase and level-off parallel to penetration trends and despite strong downsizing trends. Monitoring penetration and unit mass trends for car electronics at the car inflow can inform the timely adjustment of dismantling targets and related financing mechanisms and thus help to guarantee the long-term effectiveness of recycling-oriented dismantling strategies.

MFA is a powerful tool to support decision making in this context, as it enables a comprehensive accounting of all physical flows and stocks of materials that are necessary in further energetic, environmental and economic assessments. MFA could serve as the backbone in a potential monitoring system for CMs in car electronics. A successful monitoring would require combined efforts from the actors in the passenger car system for collecting, structuring and reporting data at the necessary level of aggregation.

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Appendix: Papers

I. Widmer R, Du X, Haag O, **Restrepo E**, Wäger P. Scarce Metals in Conventional Passenger Vehicles and End-of-Life Vehicle Shredder Output. Environ Sci Technol. 2015;49(7):4591–9.

II. Du X, **Restrepo E**, Widmer R, Wäger P. Quantifying the distribution of critical metals in conventional passenger vehicles using input-driven and output-driven approaches: a comparative study. J Mater Cycles Waste Manag. 2015;17(2):218–28.

III. **Restrepo E**, Løvik AN, Wäger P, Widmer R, Lonka R, Müller DB. Stocks, Flows, and Distribution of Critical Metals in Embedded Electronics in Passenger Vehicles. Environ Sci Technol. 2017 Feb 7;51(3):1129–39.

IV. **Restrepo E**, Løvik AN, Widmer R, Wäger P, Müller DB. Historical Penetration Patterns of Automobile Electronic Control Systems and Implications for Critical Raw Materials Recycling. Resources. 2019 Mar 31;8(2):58.

V. **Restrepo E**, Løvik AN, Widmer R, Wäger P, Müller DB. Effects of car electronics penetration, integration and downsizing on their recycling potentials. Resour Conserv Recycl X. 2020;6:100032.

Paper I

Scarce Metals in Conventional Passenger Vehicles and End-of-Life Vehicle Shredder Output

Widmer R, Du X, Haag O, Restrepo E, Wäger P. Environ Sci Technol. 2015;49(7):4591–9.

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Scarce Metals in Conventional Passenger Vehicles and End-of-Life Vehicle Shredder Output

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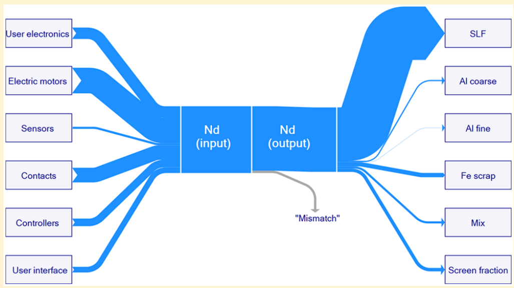
Supporting Information

ABSTRACT: Concurrent with the demand for cleaner, lighter, and more efficient vehicles, many scarce metals (SMs) are used in passenger vehicles because of their unique physical and chemical properties. To explore the recycling potential of these metals, it is important to understand their distribution in the vehicles as well as their fate at the vehicles' end-of-life. However, this information remains very scattered and sparse. In this paper, we present a study investigating the distribution of 31 SMs in selected electrical and electronic (EE) components of conventional passenger vehicles and in the end-of-life vehicle shredder fractions from a shredder plant in Switzerland. The results of the chemical analyses show that the mass fractions of Co, Sn, Sr, Ta, Y, and Zr were dominant with >20 000 g/t in the selected EE components and Ag, Ga, Mo, Sb, Sn, Sr, and Zr with >50 g/t in the analyzed shredder fractions. The largest masses of 17 SMs were found in the shredder light fraction, which is incinerated in municipal waste treatment plants mainly in Switzerland; thus, these SMs are currently not recovered. The SM mass fractions in both the EE components and the shredder fractions were projected to their total masses in 100 hypothetical midrange passenger vehicles. The resulting mass balance showed a mismatch of >50% for 23 metals, which indicates other important SM sources such as alloys.



■ INTRODUCTION

End-of life vehicles (ELV) have become a major waste stream globally and regionally. For 2010, 40.2 million and 7.8 million units of generated ELV were estimated globally and in the European Union (EU25),[1] respectively. Assuming an average mass of about 1400 kg per ELV,[2] the corresponding masses reached about 56×10^9 kg and 11×10^9 kg. In comparison, the mass of waste electrical and electronic equipment (WEEE) collected and treated in the EU27 in 2010 amounted to 3.1×10^9 kg.[3] In Switzerland, 80 000 and 100 000 ELV were shredded in 2010 and 2012, respectively (Figure 1). In 1996, Switzerland banned combustible wastes from landfills. Since then, the shredder light fraction (SLF), also known as Automobile Shredder Residue (ASR), from ELV shredding has been incinerated in Municipal Solid Waste Incinerators (MSWI).

ELV include vehicle categories M1 and N1 as defined in the EU ELV directive.[7] In this manuscript, we only consider category M1 (Directive 2001/116/EC), "vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat", and use "passenger vehicle", "passenger car", and "car" synonymously.

Increasing numbers and amounts of geochemically scarce metals (SM)[8,9] are used in the production of vehicles because of their unique physical and chemical properties. For example, neodymium is used in high-performance NdFeB permanent magnets in electrical machines,[10,11] and indium is essential for displays in user interface devices; both components are increasingly found in vehicles.[12] Many of the metals used in the vehicles are scarce and considered critical in terms of high supply risks and economic importance, as is the case for cobalt (Co), gallium (Ga), indium (In), niobium (Nb), platinum group metals (PGM), rare earth elements (REE), antimony (Sb), tantalum (Ta), and tungsten (W).[13−15] As the demand for these metals soars, concerns regarding their availability and sustainable use arise.[9,16−18] In this regard, it is paramount to know the fate of these metals at vehicles' end-of-life and to understand the link to the initial distribution in the vehicles.

While there are many studies investigating the more common metals used in the vehicles such as iron, aluminum, and copper mainly by looking at the ELV shredder output,[1,19] information remains scarce and scattered for the SM used in the vehicles.[20] Two studies[21,22] focused on specific vehicle brands and models and estimated metal distribution in hypothetical conventional passenger vehicles based on reported information from part suppliers. Two Japanese studies[23,24] (published in Japanese) reported the distribution of 24

Received: November 5, 2014
Revised: February 11, 2015
Accepted: February 26, 2015

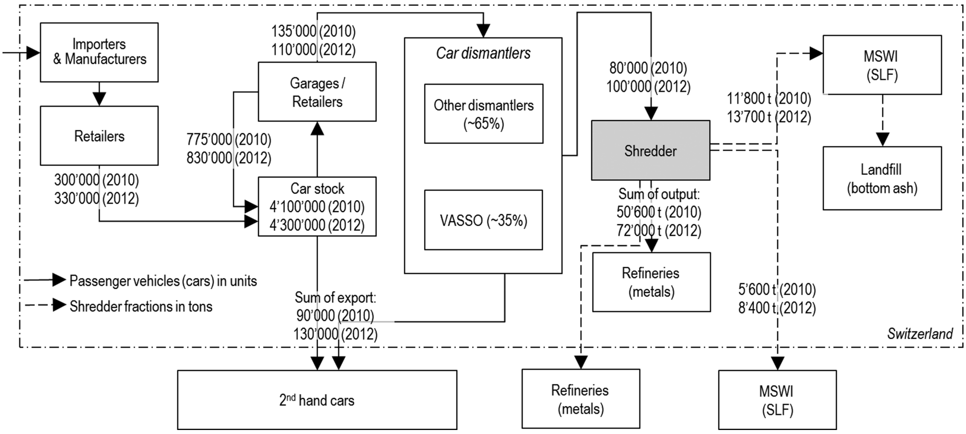


Figure 1. Flowchart for passenger vehicles (cars) imported, used, and recycled in Switzerland for the years 2010 and 2012 (quantity unit for vehicles is 1 and for shredder fractions is ton).[2,4−6]

elements in vehicle components as well as in selected shredder fractions of an ELV shredder in Japan. While the first study[24] was restricted to two particular models of vehicles manufactured in 1998 and 2002, the second[23] did not analyze all shredder fractions. The motivation for this study was to evaluate the potential to recover SM from ELV in the context of the revision of the Ordinance on the Return, Taking Back, and Disposal of Electrical and Electronic Equipment (ORDEE) led by the Swiss Federal Office for the Environment (FOEN). Besides WEEE, as it is defined in the European WEEE directive,[7,25] the revised ORDEE also includes the recovery of SM from electrical and electronic equipment (EE) embedded in ELV as well as buildings.[26−28] In particular, we wanted to address the following two questions: (1) Where and at what mass fractions (term defined in List SI 4 of the Supporting Information[29]) do we find SM in EE components and shredder fractions of similar cars (main research question)? and (2) Can the SM content of EE components plausibly explain their content in the shredder fractions and vice versa (exploratory research and minor question)?

■ METHODS

The selection process for particular SM and the hot spots of containing EE components to be investigated is based on preliminary studies[30−32] and on consultations with the Swiss FOEN to synchronize the procedures with related current projects. The following 31 SM have been chosen for investigation: silver (Ag), gold (Au), beryllium (Be), cerium (Ce), cobalt (Co), dysprosium (Dy), gallium (Ga), gadolinium (Gd), germanium (Ge), indium (In), lanthanum (La), lithium (Li), molybdenum (Mo), niobium (Nb), neodymium (Nd), palladium (Pd), praseodymium (Pr), platinum (Pt), rubidium (Rb), rhenium (Re), ruthenium (Ru), antimony (Sb), samarium (Sm), tin (Sn), strontium (Sr), tantalum (Ta), terbium (Tb), tellurium (Te), tungsten (W), yttrium (Y), and zirconium (Zr). The research consisted of two independent experiments to obtain the SM mass fractions in selected EE components from cars and in ELV shredder fractions. Though the EE components and shredder fractions were sampled and analyzed independently, the processed and analyzed material has been selected such that it closely matches the requirements of a mass flow analyses, that is, the material originated in both experiments from as similar as possible four-door middle class passenger vehicles manufactured between 2003 and 2008 by different manufacturers. Laying the focus on cars having an age range of 5−10 years at the time of shredding in September 2012, which is much less than the average ELV age of approximately 13 years, was intended to give us indications on the SM masses in ELV shredders to be expected in the near future. Subsequently, for both experiments, the obtained SM's mass fractions were projected to their total masses in the same hypothetical passenger vehicles. Finally, the two masses were contrasted in a mass balance to explore the relation between the amount of SM in the EE components and the shredder fractions. Figure 2 presents the overall structure of this research.

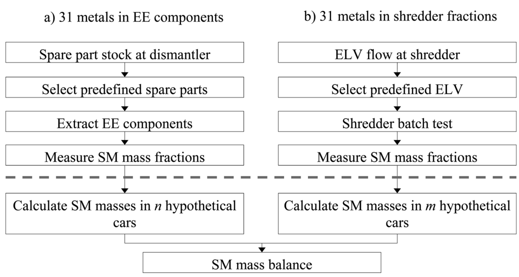


Figure 2. Overall structure of this research and the link between the two experiments. The number of $m = n = 100$ cars was chosen because this was the number of cars shredded in experiment b, and this number represents 0.1% of the ELV shredded in Switzerland in 2012.

Measuring the mass fractions in the EE components and the shredder fractions allowed us to address research question 1, while calculating the SM masses and establishing a mass balance addressed research question 2.

Experiment a: Scarce Metals in EE Components. *Sampling.* To study the 31 SM in EE components, the experiment started with the spare part catalogue of a Swiss commercial car dismantler and spare part dealer, which included 260 types of spare parts. The selected subset of

DOI: 10.1021/es505415d
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those types including at least one EE component comprised 110 types, which were grouped into nine EE device categories based on their functions: electric motors, consumer electronics, contacts, sensors, controllers, user interfaces, actors, lighting, and small parts. The dealer provided a total of 119 selected spare parts from the first six categories of the list (for the three remaining categories, see Figure SI 1). The selection was an iterative process among the involved experts to limit the number of EE devices to a representative mix from the defined cars and to other constraints such as budget, logistics, and time. The EE parts, documented with mass, make, model, and manufacturing year, were subsequently manually dismantled to extract those EE components in which according to the literature,[31,33] most of the SM are expected to occur. Depending on the shape and the material characteristics, different dismantling procedures were applied. For example, printed circuit boards (PCB) were removed using screw drivers and tweezers from EE devices such as radios, GPS, motor controllers, and instrument panels. All different populated PCB were considered one type of component to be analyzed in one sample.

Several populated PCB were further dismantled by removing resistors, capacitors, integrated circuits, etc. to gain detailed PCB composition data. However, for this experiment, only the mass fractions of the populated PCB were used.

The following 17 types of EE components were obtained, each containing multiple pieces of the same type: permanent magnets, electric brushes, commutators, liquid crystal display (LCD) glass, LCD foils (prism, polarizer and diffusor sheets), resistors of air mass meter, lambda sensors (sensor element), metal and plastic parts of antibrake locking system (ABS) sensor, populated and depopulated PCB, electrolytic and SMD capacitors, LED, resistors, integrated circuits (semiconductors), and metal parts of connectors (further details in Figures SI 1–SI 6 and Table SI 1).

Sample Preparation. Sample preparation included comminuting and homogenizing the EE components to particle sizes less than 0.5 mm. Depending on the brittleness and initial particle size of the individual samples, different size-reduction equipment was used (further details in Lists SI 1 and SI 3).

Chemical Analysis. The chemical analysis included semiquantitative and quantitative analysis. A semiquantitative analysis served as a first screening of a subset of 13 SM in 11 types of EE components including Ag, Co, Ga, Ge, La, Mo, Nb, Rb, Sb, Sn, Sr, W, and Zr. The analysis was carried out on an X-ray fluorescence (XRF) spectrometer using the Turbo-Quant method. A quantitative analysis was used to obtain the 31 SM mass fractions in the EE components. First, depending on the material of EE components and the SM to be analyzed, the EE components were digested by applying one of the following five different digestion methods: total microwave digestion, metal microwave digestion with hydrofluoric acid, plastics microwave digestion, aqua regia microwave digestion, and aqua regia open digestion. About 0.5 g of each homogenized sample was used for the microwave digestions, and about 1 to 3 g was used for the aqua regia open digestion. Several parallel digestions were done for each type of component (further details in List SI 2).

Twenty-nine SM (all except Co and Sn) were measured with an Agilent 7500ce Octopole Reaction System inductively coupled plasma mass spectrometer (ORS-ICP-MS) and a Thermoelement 2 high-resolution sector field inductively coupled plasma mass spectrometer (HRSF-ICP-MS). Co and Sn were measured with a Varian 735-ES inductively coupled plasma atomic emission spectroscope (ICP-OES). Linear calibrations were performed in accordance with the mass fraction ranges of the elements analyzed. The final mass fraction result for each element in each sample corresponds to the average of the measurements of the sample digested in parallel.

Because In has no undisturbed isotope, its mass fraction was calculated via the Sn mass fraction and the Sn-isotope ratio. For this, an additional measurement of the mass fraction of Sn was carried out using ORS-ICP-MS and HRSF-ICP-MS, and the value of In was corrected accordingly.

Mass Calculation. Mass fractions resulting from the chemical analysis were used to calculate the total mass M_x of each SM x in n hypothetical passenger vehicles. The assembly of such a vehicle consists of a number of EE devices, which are made by a number of EE parts that use EE components of an average mass, which contain an average mass fraction of the SM of interest. M_x is thus calculated according to the following eqs 1a and 1b:

$$M_x = n \sum_i w_{xi} M_i = M_x^{\text{in}} \tag{1a}$$

with M_i total mass of component i in 1 car,

$$M_i = \sum_k \#_k \times \sum_j \#_{jk} \times m_{ijk} \tag{1b}$$

with n, the number of hypothetical cars; w_{xi}, the average mass fraction of SM x in EE component i; M_x^{in}, the SM shredder input used in mass balance calculation; $\#_k$, the number of EE devices k in one car (e.g., EE devices are ABS- and fuel pumps, power windows, and controllers); $\#_{jk}$, the number of EE parts j in EE devices k (e.g., EE parts are electro motors and LCD); and m_{ijk}, the mass of EE component i in EE part j and component k (e.g., EE components are permanent magnets and LCD glass). This mass differs between various parts and devices (see Table SI 10 for details).

The assemblies of five hypothetical cars (high-end, low-end, midrange car, coupé high-end, and coupé low-end) with the respective numbers of EE devices, EE parts, and EE components are given in Tables SI 4 and SI 5. "High-end cars" are regarded as a highly electrified and automated vehicles with power windows, GPS, radio, ABS system, etc.; "low-end cars" are without power windows, GPS, ABS system, etc. The "midrange car" was used for the mass balance calculation.

Experiment b: Scarce Metals in Shredder Fractions. *Sampling.* The samples of ELV shredder fractions were taken in a Swiss shredder plant; for a simplified flow sheet, refer to Figure SI 7. For this purpose, a batch of 100 selected ELV was shredded on September 7, 2012. During 1 week, the material handler feeding the shredder set aside 100 ELV matching the same characteristics as in experiment a, that is, four-door middle class passenger vehicles manufactured between 2005 and 2008 by different manufacturers. These ELV were prepared for shredding according to Swiss regulations (at least all liquids, battery, catalyst, and tires removed). It was not checked if further dismantling had taken place, for example, removal of EE components. The total batch mass for the 100 ELV was 95.3 t. This shredding process generates seven shredder fractions of which six were sampled: SLF, screen fraction, coarse aluminum fraction, fine aluminum fraction, iron fraction, and mixed material fraction (mainly rubber, plastic, and wood, but also stainless steel). The remaining fraction consisting of electrical

DOI: 10.1021/es505415d
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machine chunks (mainly rotors and stators nicknamed "meat balls") was not sampled. The wet scrubber sludge, which is normally added to the SLF but not in this batch test, was also sampled to obtain its composition in addition to the one of the SLF without sludge. Another internal fraction, "Retour", consisting of material losses collected at various spots (e.g., falling off conveyor belts), which is normally fed back to the shredder input but not in this batch test was also sampled to allow for corrections. The mass share and the visual aspects of the shredder fractions are shown in Figures SI 8 and SI 9. Depending on the fractions, different sampling procedures were applied to collect samples of fractions as representative as possible (further details in List SI 3).

Sample Preparation. The samples of each fraction were reduced to size less than 0.5 mm. Depending on the materials, a cutting mill, centrifugal mill, or vibrating disc mill was used for the size reduction. A detailed description of the procedure for every sample can be found in List SI 5.

Since the shredding process produces large amounts of smallest particles (dust) that may attach to surfaces, a method was developed to remove these particles from the surfaces of the Fe and Al coarse fractions. Approximately 2.5 kg of each fraction was washed in an ultrasound bath with 1% nitric acid (HNO_3) for 1 h. The liquid solution was filtered off, and the washed Fe and Al pieces were dried at 40 °C, comminuted to be smaller than 0.5 mm by a cutting mill, and homogenized. These pieces and the filtrate were analyzed as separate fractions to determine the SM mass fractions and masses being transported either on the surface (here also called "crust") or in the matrix (here also called "core") of these fractions (further details in List SI 4).

Chemical Analysis. Semiquantitative analysis (for 13 SM in four shredder fractions) and quantitative analysis (for 31 SM in 10 shredder fractions) were done to measure the SM mass fractions in individual shredder fractions. The chemical analysis of the shredder fractions was performed with the same techniques and instruments as for the EE components in experiment a (List SI 2).

Mass Calculation. The SM mass fractions resulting from the chemical analysis were used to calculate their masses in the shredder fractions. The total mass M_x^{out} of SM x in all the shredder fractions of m shredded ELV is calculated according to the following eq 2:

$$M_x^{\text{out}} = \sum_i w_{xi} M_i \tag{2}$$

with w_{xi} as the mass fraction of SM x in shredder fraction i, and M_i as the mass of shredder fraction i of m shredded ELV.

Mass Balance. The SM total shredder input mass M_x^{in} in n = 100 hypothetical cars derived from experiment a and shredder output mass M_x^{out} in m = 100 ELV from experiment b were compared. To discuss the expected mismatch Δ, eq 3 was formulated based on the following three assumptions: (1) the SM total masses correspond to the total masses in all considered EE components in n cars, (2) their total mass also corresponds to the total mass in all considered shredder fractions from m shredded cars, and (3) the hypothetical cars in assumptions 1 and those in 2 are the same. By using eqs 1 and 2, eq 3 results

$$\Delta_x = M_x^{\text{out}} - M_x^{\text{in}} = \left(\sum_i w_{xi}^{\text{fraction}} M_i^{\text{fraction}}\right) - \left(n \sum_i w_{xi}^{\text{component}} M_i^{\text{component}}\right) \tag{3}$$

Any mismatch $\Delta_x \neq 0$ falsifies the above assumptions and calls for an explanation. However, it is not the scope of this research to explain all mismatches. We are rather interested to identify mismatches that could become the topic of future research. An estimate of potentially missing mass due to dismantling ELV prior to shredding is given in Table SI 3.

Data Uncertainty and Errors. The SM mismatches may be grouped according to errors occurring in the (1) shredder input, (2) shredder output, (3) hypothetical cars, or any combination thereof.

For both assumptions 1 and 2, the combined error of the mass fraction value is estimated according to Bachema's class c, 12–24%[34] (see Table SI 2 for details).

Although a small mismatch may support the above assumptions, it does not prove that the mass of that SM metal is balanced; random errors in the two experiments, the measurement of mass fractions, and their projections to total masses may have canceled out (see comments in Table SI 9 for additional details).

Shredder Input. The largest errors are to be expected from the fact that neither all EE components nor any non-EE component were analyzed and thus were not included in the projection of the total mass in the hypothetical cars. If the SM is common as an alloy of iron and aluminum used in the cars' body and engine, it would show in the analyzed shredder fraction, while it does not occur in the analyzed EE components. Hence, a large positive mismatch is to be expected for most of the SM masses, and for some, the mismatch should fit the SM masses found in the matrix of the Al coarse and Fe scrap fractions (see Table SI 9). The selection procedure of the EE components is supposed to contribute the major uncertainty on the input side.

Shredder Output. Some EE devices could have been removed from the ELV prior to shredding. This would result in SM masses being lower in all shredder fractions than those in all EE components.

The sampling procedure adds much uncertainty mainly due to the difficulties to homogenize the shredder fractions especially the Al and Fe coarse fraction.

Hypothetical Cars. The samples from EE components and shredder fractions were not from the same vehicles, although special care has been taken to match the type, the size, and the year of manufacturing. The projection of the SM mass in the EE components to hypothetical vehicles is based on a rather simple model and might result in SM contents much different from an actual vehicle.

Except for the chemical analysis, none of the measured or assumed values include uncertainties such as confidence intervals or probability distributions. This was beyond the scope of this research and will be part of future more detailed investigations.

■ RESULTS AND DISCUSSION

The measured mass fractions of 31 SM in the 17 EE components cover a wide range from 0.4–380 000 g/t. The first 10 SM ranked according to their mass fractions in the respective EE components are listed in Table 1; the complete list is given in Table SI 2.

DOI: 10.1021/es505415d
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Table 1. Top 10 SM Mass Fractions w_x in the 17 EE Components

SM	mass fraction w_x (g/t)	containing EE component
Zr	380 000	sensor element in lambda probe
Sr	84 100	magnets
Sn	74 100	resistors
Ta	32 500	SMD capacitors
Co	25 600	resistors from air mass meter
Y	25 400	sensor element in lambda probe
Mo	14 700	electric brushes
Nd	11 400	SMD capacitors
Pt	7 520	sensor element in lambda probe
La	7 180	magnets

Table 2. Top 10 SM Masses M_x Derived from EE Components in Five Hypothetical Car Models Ranked According to "Mid-Range Car"

	mass M_x (g) in one hypothetical car (values rounded to two significant digits; weighing precision ± 0.01 g)				
SM	high-end car	low-end car	midrange car	high-end coupé	low-end coupé
Sr	150.00	73.00	140.00	120.00	73.00
Sn	54.00	26.00	41.00	55.00	26.00
La	12.00	6.10	12.00	10.00	6.10
Co	6.20	3.10	6.00	5.20	3.10
Nd	3.10	1.60	2.40	3.00	1.60
Sb	2.50	1.20	1.90	2.50	1.20
Ag	1.60	0.75	1.30	1.60	0.75
Zr	2.10	1.00	1.30	1.70	1.00
Mo	1.00	0.50	1.00	0.81	0.50
Ta	0.98	0.50	0.70	1.00	0.50

Table 3. Top 10 SM Mass Fractions w_x in the Shredder Fractions

SM	mass fraction w_x (g/t)	containing shredder fraction
Sn	1380	screen fraction
Sr	816	SLF
Sb	285	SLF
Mo	135	sludge
Ga	82	coarse Al
Ag	70	screen fraction
Zr	60	SLF
Co	33	Fe scrap
Nb	32	Fe scrap
Ce	27	sludge

As expected, the mass fractions are highest in sensors, electronic components, and magnets; nevertheless, since some of these components have very low masses, those high mass fractions do not add significantly to the total mass in one car. For instance, the 380 000 mg/kg Zr in oxygen sensors add up to only 1.1 g in one car. Table SI 3 lists for all 31 SM, their maximum mass fraction, and maximum mass in the respective EE components as well as their total mass in one midrange car.

The SM masses were calculated for five different hypothetical cars: high-end and low-end car, midrange car, high-end and low-end coupé. "Car" refers to four-door cars, and "coupé" refers to two-door cars. Table 2 shows the top 10 SM masses in the five different vehicle models. The parameters required for the hypothetical car assembly used in eq 1 are given in Tables SI 4 and SI 5.

Table 4. Mismatch Δ_x of the 31 SM Masses M_x in 100 "Midrange" Cars between Shredder Input and Output Ranked According to the Relative Mismatch (Rel. Mismatch)[a]

SM	shredder input M_x^{in} (g)	shredder output M_x^{in} (g)	mismatch Δ_x	rel. mismatch δ_x
Te	0.01	39.00	38.99	99.97%
Nb	5.30	2100.00	2094.7	99.75%
Li	4.60	1700.00	1695.4	99.73%
Ga	4.10	1100.00	1095.9	99.63%
Sm	0.34	61.00	60.66	99.44%
Rb	0.74	120.00	119.26	99.38%
Ge	2.70	340.00	337.3	99.21%
W	2.70	270.00	267.3	99.00%
Ce	2.80	260.00	257.2	98.92%
Mo	100.00	6300.00	6200	98.41%
Ru	0.56	20.00	19.44	97.20%
Sb	190.00	5000.00	4810	96.20%
Pd	6.40	66.00	59.6	90.30%
Be	0.34	3.10	2.76	89.03%
Zr	130.00	1100.00	970	88.18%
Y	9.10	58.00	48.9	84.31%
Co	600.00	2700.00	2100	77.78%
Sn	4100.00	17000.00	12900	75.88%
Pr	7.30	30.00	22.7	75.67%
Gd	4.90	19.00	14.1	74.21%
Ag	130.00	470.00	340	72.34%
Dy	3.60	12.00	8.4	70.00%
Tb	0.77	1.50	0.73	48.67%
Sr	14000.00	14000.00	0	0.00%
Au	22.00	22.00	0	0.00%
Nd	240.00	210.00	−30	−14.29%
Ta	70.00	37.00	−33	−89.19%
La	1200.00	110.00	−1090	−990.91%
In	15.00	0.35	−14.65	−4185.71%
Pt	0.83	0.01	−0.819	−7445.45%
Re	0.00	not measured		

[a] $\delta_x = ((M_x^{out} - M_x^{in})/(M_x^{out}))$ is the relative mismatch. M_x^{in} and M_x^{out} values are rounded to two significant figures.

Using the model given in eq 1, the SM masses scale with the number of embedded EE components. Across the five hypothetical car models, the ranking among the top seven SM is the same. A plausible reason for this may be the oversimplified model used to assemble the car models from a few basic EE components.

In analogy to Table 1, Table 3 lists the top 10 SM ranked according to their mass fractions in the corresponding shredder fractions of 100 ELV; the complete list is given in Table SI 6.

Sn (w_{Sn} = 1380 g/t), Sr, Sb, and Mo are the most concentrated SM in the shredder fractions. In comparison, the highest Sn mass fraction in the EE components can be more than 50 times higher (w_{Sn} = 74 100 g/t in resistors) and in populated PCB (w_{Sn} = 21 500 g/t) still more than 15 times higher. This pattern can be observed also for the other investigated SM (comparing Tables SI 2 and SI 6). Thus, SM are thinned out during the ELV treatment, which is a major argument to recover SM before the shredding process by a focused dismantling to extract EE components.

Five SM were most concentrated in SLF ranging from w_{Sm} = 3.4 g/t to w_{Sr} = 816 g/t, and 10 metals were of highest mass

DOI: 10.1021/es505415d
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

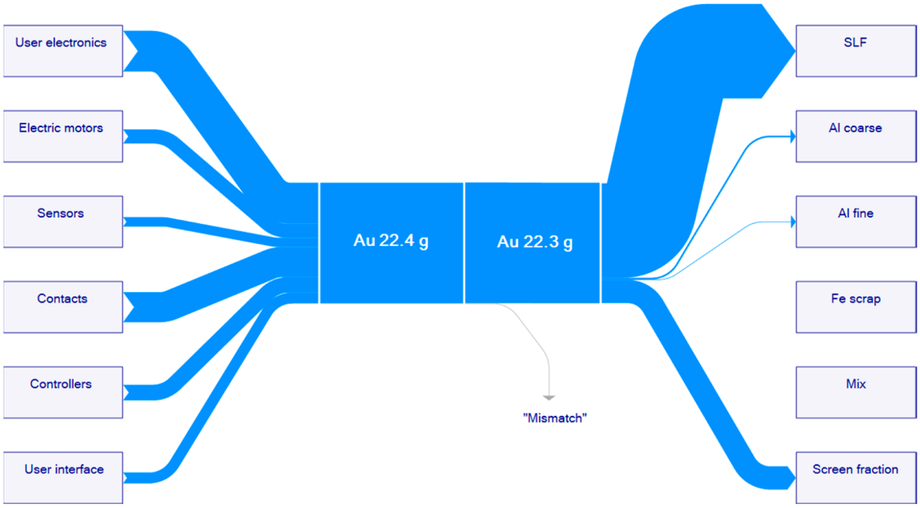

Figure 3. Distribution and total of Au mass in the EE components and shredder fractions of $n = m = 100$ hypothetical cars (precision: ± 0.1 g).

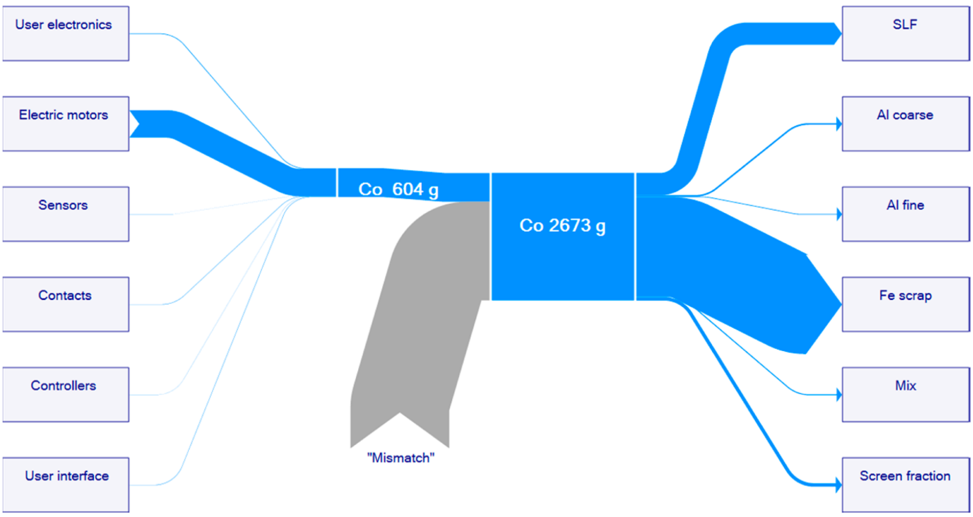

Figure 4. Distribution and total of Co in the EE components and shredder fractions (precision: ± 1 g).

fraction between $w_{Ru} = w_{Tb} = 0.4$ g/t and $w_{Ce} = 27$ g/t in the sludge fraction, which normally is mixed in the SLF.

Seventeen metals were found of largest mass in the SLF including Au, Ce, Dy, Gd, La, Nd, Pd, Pr, Rb, Sb, Sm, Sr, Tb, Te, W, Y, and Zr. The masses range from the lowest $M_{Tb} = 1$ g to highest $M_{Sr} = 11\,930$ g. This finding endorses that most of the SM are liberated in the shredder process and collected by other particles being transported by the massive air stream that ends up in the SLF after the air filter. This again is a general pattern and a major argument to recover the SM also after the shredding process by a post-treatment of the SLF, and if it is incinerated, a post-treatment of slag and flue ash.[35]

Eight metals occurred with the largest mass in the Fe scrap fraction: Co, Ga, Ge, Li, Mo, Nb, Ru, and Sn. The largest is $M_{Sn} = 6715$ g and lowest $M_{Ru} = 13.3$ g. All of them were predominantly in the matrix of the Fe coarse fraction. Neither the Fe scrap fraction nor the Al coarse fraction carried any substantial SM masses on their surfaces. This finding disproves the possibility that certain SM could leave the shredder via these fraction surfaces. A candidate could have been Nd as a constitute of magnetic particles sticking to ferromagnetic iron. However, the measured 208.3 g of total Nd leave the shredder in this order: SLF 172.5 g, Fe "core" 12.8 g, screen 10.9 g, mix 6.7 g, Al "core" 3.7 g, Fe "crust" 1.2 g, Al fine 0.5 g, and Al "crust" 0.1 g. Thus, only approximately 0.5% of Nd is transported by the iron surface.

To compare the mass of individual SM in the shredder input and output stream, the total SM mass in 100 hypothetical

DOI: 10.1021/es505415d
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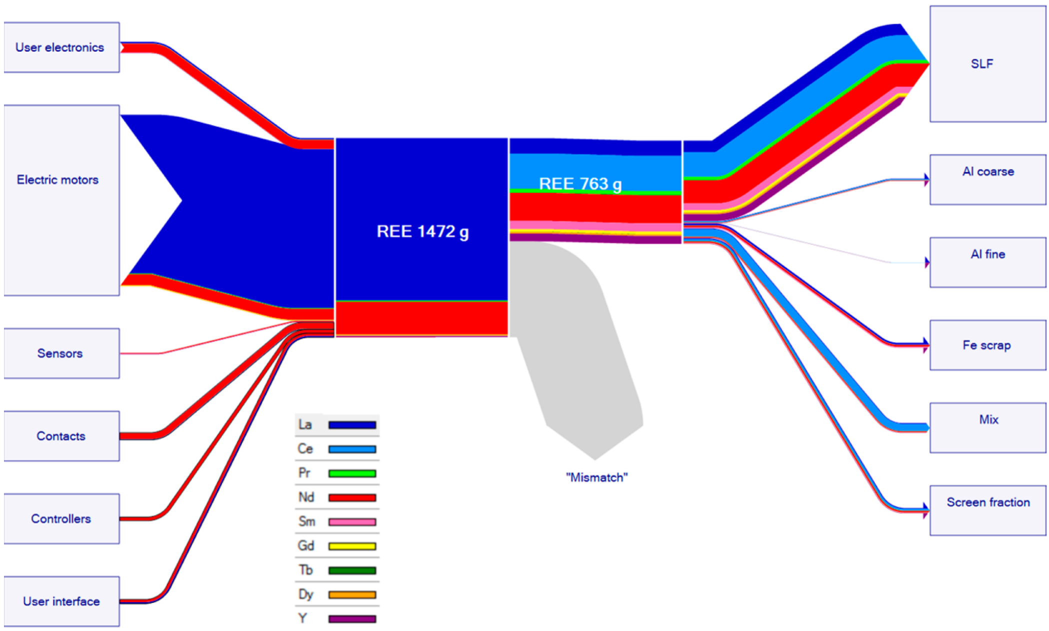

Figure 5. Distribution and total of some REE in the EE components and ELV shredder fractions (precision: ± 1 g).

midrange cars was calculated and compared to the total mass of the same metal in all shredder fractions, see Table 4. The results of this comparison are illustrated in Sankey diagrams for gold, cobalt, and the group of rare earth elements; Figures 3−5. The figures show on the left side the total SM mass distributed over the initially defined EE device categories and on the right side over the shredder fractions.

Three metals (Sr, Au, Nd) were observed with small rel. mismatches (between ca. ± 50%): δ_{Sr} = 0%, δ_{Au} = 0%, and δ_{Nd} = −14%. The mass balance for Au is shown in Figure 3: highest masses were with 5.6 g in "Contacts", 7.6 g in "Consumer Electronics", 17.5 g in "SLF", and 4.3 g in "Screen fraction".

Twenty-three SM were observed with a large positive rel. mismatch (> +50%): Te, Li, Nb, Ga, Sm, Rb, Ge, Ce, W, Mo, Ru, Sb, Pd, Zr, Be, Y, Sn, Co, Pr, Gd, Ag, and Dy (see Table 4).

These results confirm the error source on the input side as described in the Data Uncertainty and Errors section. Hence, depending on the SM, other sources in the car should explain the mismatch such as steel and aluminum alloys. This is indeed the case for Ge, Nb, Li, Ga, Co, and Mo, which were mostly solved in the matrix of the Al and Fe coarse fractions (> +50%) and at the same time were found to fit well the mass mismatch between output and input (see comparison list in Table SI 9). For example, the mass balance of Co is shown in Figure 4. 574 g of a total of 604 g of Co was found in "Electric motors". 2673 g of Co was found in all shredder fractions whereof 2070 g was in the matrix of "Fe scrap". The 2072 g of Co mismatch thus closely accords the Co mass in the "Fe scrap" matrix. Thus, it would be relevant to recover the SM functions in steel and aluminum by identifying effective ways to separate different alloys.

Four metals Ta, La, In, and Pt were observed with a large negative mismatch (< −50%); we did not further explore explanations for this except for La. Figure 5 shows all nine investigated REE with La and Ce showing large mismatches, that is, −954% and +99%, respectively. Most of the La input (1173 g of 1200 g) originates from the magnets in the "Electric motors", where La is alloyed in ferrite material. Only 10% (114 g) of that La mass was in the output, mainly in the SLF (85 g). One reason for the low output content could be the "meat ball" fraction (Cu/Fe from e-motors, see Figure SI 9), which had not been sampled because it was not considered to carry many other metals than Cu and Fe. A later visual inspection of the sample photographs showed, however, that some of the larger motor chunks, in particular the starter motors and generators, might have contained larger magnets, which could have added up to the approximately 1000 g missing.

Regarding SM in the shredder input, we could confirm that EE components in cars are important carriers of SM. Other sources of SM are significant, as the analysis of the "Fe scrap" and "Al coarse" fractions in the shredder output indicates.

Regarding the shredder output, a significant share of SM is found in the "SLF" and the "Screen fraction". Exceptions are SM that have been identified as alloying elements in iron and aluminum.

In view of an implementation of the revised ORDEE, the potential of manual dismantling with the option of a subsequent feeding of the dismantled EE components into established WEEE channels should be further investigated. WEEE channels already established under the ORDEE have proven to have higher recovery efficiency than ELV treatment in particular for precious metals. At the same time, the ongoing activities pointing at a better recovery of SM from the SLF through further processing before or after their incineration in an MSWI should be intensified.

DOI: 10.1021/es505415d
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Our methodology provided useful first indications on SM distribution in ELV and shredder fractions and provokes explanation gaps, which in turn allow us to formulate next research steps. The iterative processes required to filter the various material streams in view of gaining representative samples, for example, the selection of spare parts, strongly supported the integration of the involved stakeholders. The need to cooperate and find a consensus among them will certainly help in designing and implementing further projects that will pave the way to better reclaim SM also in ELV disposal.

■ ASSOCIATED CONTENT

Supporting Information

Graphics, photos, data and detailed descriptions, sample preparation, and chemical analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We would like to thank our project partners and sponsors for their continuous support: (1) the Swiss Federal Office of the Environment (FOEN), (2) the Foundation Auto Recycling Switzerland (SARS, in particular, the shredder plant operator Thommen AG), (3) the Office of Waste, Water, Energy, and Air of the canton of Zurich (WWEA), (4) the Vereinigung Schweizer Automobil-Importeure (autoschweiz), (5) the Automobil- und Motoren AG (AMAG), (6) Association of the Official Car Collection Point Proprietors of Switzerland and the Principality of Liechtenstein (VASSO, in particular, its member Truniger AG), and (7) the Sustainable Engineering Network Switzerland (SEN). A special thanks goes to our colleagues from analytical chemistry lab at Empa for cross-checking some results.

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DOI: 10.1021/es505415d
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Supporting Information for the manuscript:

Scarce Metals in Conventional Passenger Vehicles and End-of-Life Vehicle Shredder Output

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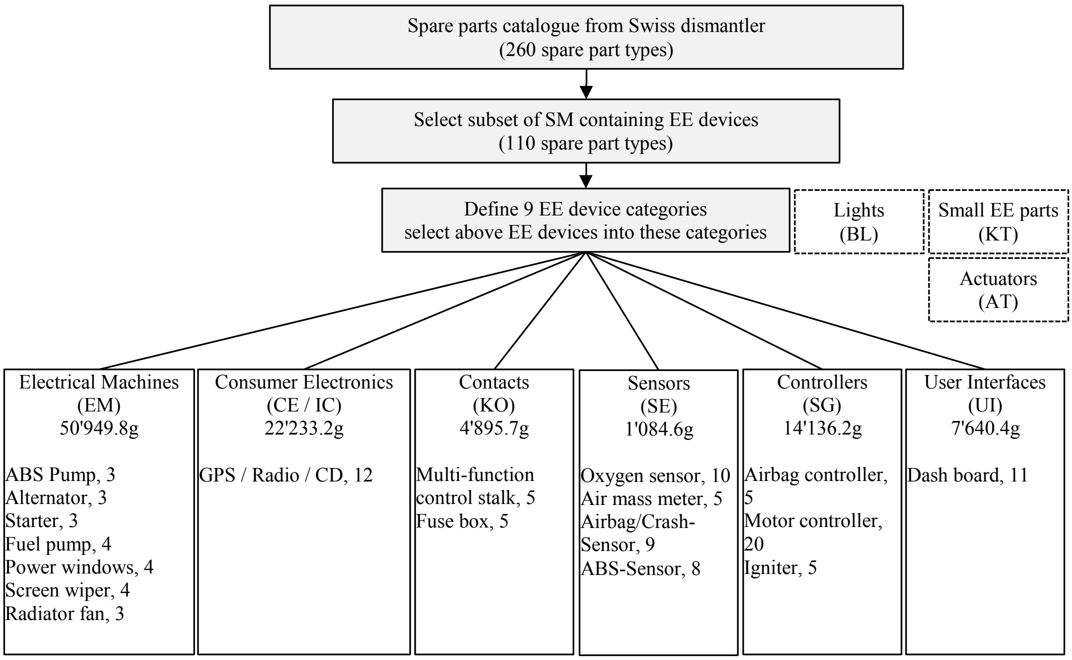


Figure SI 1: Selection procedure for EE devices from spare parts.

The considerations for the selection of device categories are documented in the report "Verwertung von Seltenen Technologiemetallen aus der Automobilelektronik in der Schweiz: Systemübersicht und Probenahmekonzept" (download).

excerpts:
The primary goal of this measurement campaign is to find evidence for the occurrence of the SM in the various components in order to gain an overview of SM in automotive electronics. It is not intended to acquire representative SM mass fractions for EE components from ELVs. Therefore, the following guidelines regarding the sampling result:

1. The number of analyzed components will be adjusted to the available parts in VASSO's spare parts store and is kept low. To allow meaningful statements about SM content in the electronic components, the number of analyzed components would have to be significantly higher (hundreds instead of dozens).
2. (For budget reasons) The number of samples to be analyzed is also kept small. For a more representative study the measurement of three, if not of 5 or more samples per sampled material would be necessary. In this measurement campaign, however, only 1 sample per material is measured.

The 3 categories which were neglected are:
Components from the device categories "Lighting" (BL), "Small parts" (KT) and "Actuators" (AT) were not selected. The reasons are as follows:

BL: The lamps used are commonly incandescent lamps, i.e. the SM content is low or known (contain W filaments with a total mass of a few hundred milligrams). Regarding the SM xenon technology might be of interest, however, according to VASSO still (almost) no bulbs of this type are found.
KT: Compared to EEE in vehicles their masses and the SM content are very low.
AT: These components are difficult to extract and thus not available for sampling.

119 EE devices from 6 out of 9 pre-defined EE device categories were picked from the spare part dealer's stock. The total mass was approximately 103 kg of which half accounted for Electrical Machines EM. 17 different types of EE components were extracted from the parts in the 119 EE

devices. The sampling plan of EE components, including the devices that provided the components for the final samples is presented in Table SI 1 below.

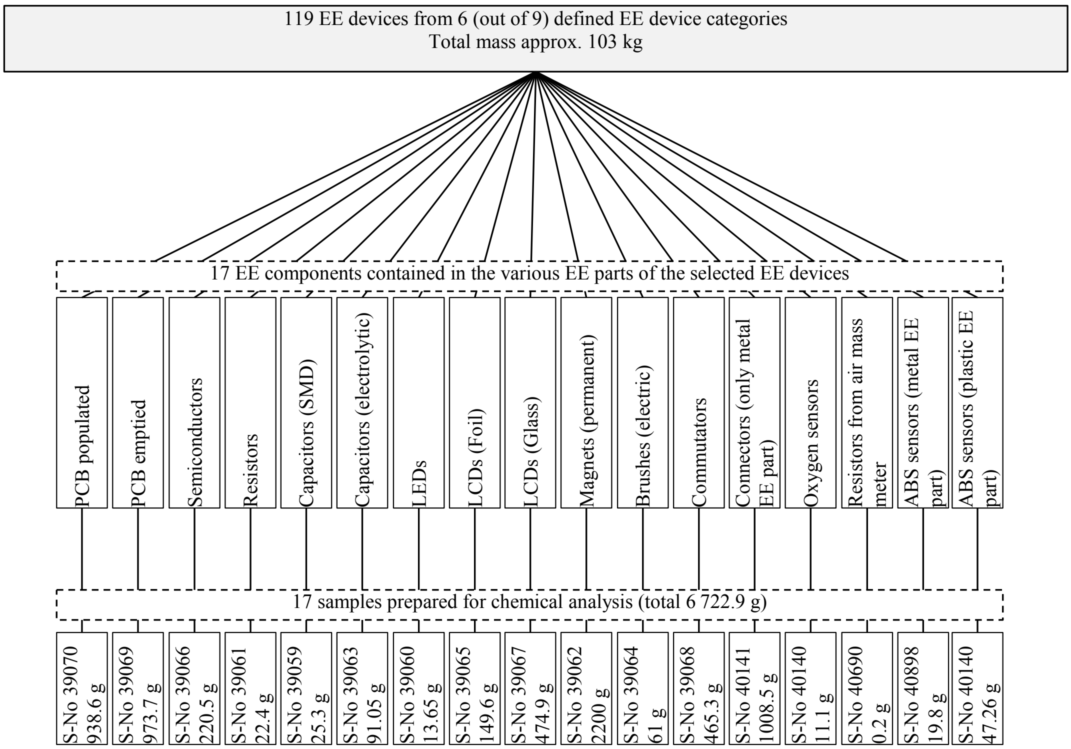


Figure SI 2: Selection procedure of EE components from 9 defined EE device categories

Table SI 1: Sampling plan of EE components

		17 sampled EE component types - Each consisting of multiple components - Each type was one sample for chemical analyses																
			Correspond to a populated PCB															
EE device category	**EE devices from which the EE components were extracted**	PCB populated	PCB emptied	Semiconductors	Resistors	Capacitors (SMD)	Capacitors (electrolytic)	LEDs	LCD Displays (Foil)	LCD Displays (Glass)	Magnets (permanent)	Brushes (electric)	Commutators	Connectors (only metal EE part)	Oxygen sensors	Resistors from air mass meter	ABS sensors (metal EE part)	ABS sensors (plastic EE part)
Electrical Machines (EM)	ABS pump										X	X	X	X				
	Alternator																	
	Starter motor										X	X	X					
	Fuel pump										X	X	X	X				
	Power windows										X	X	X	X				
	Wiper Motor										X	X	X	X				
	Radiator fan motor										X	X	X	X				
Consumer Electronics (CE)	GPS / Radio/ CD	X	X	X	X	X	X	X	X	X	X	X	X	X				
Contacts (KO)	Multi-function control stalk													X				
	Fuse box													X				
Sensors (SE)	Oxygen sensor													X	X			
	Air mass meter													X		X		
	Airbag / crash sensor													X				
	ABS sensor																X	X
Controllers (SG)	Airbag controller	X	X	X	X	X	X							X				
	Ignition controller																	
	Motor controller	X	X	X	X	X	X							X				
User Interface (UI)	Instruments	X	X	X	X	X	X	X			X	X	X	X				
Sample mass (in grams)		**938.6**	**973.7**	**220.5**	**22.4**	**25.3**	**91.1**	**13.7**	**149.6**	**474.9**	**2200.0**	**61.0**	**465.3**	**1008.5**	**11.1**	**0.2**	**19.8**	**47.3**

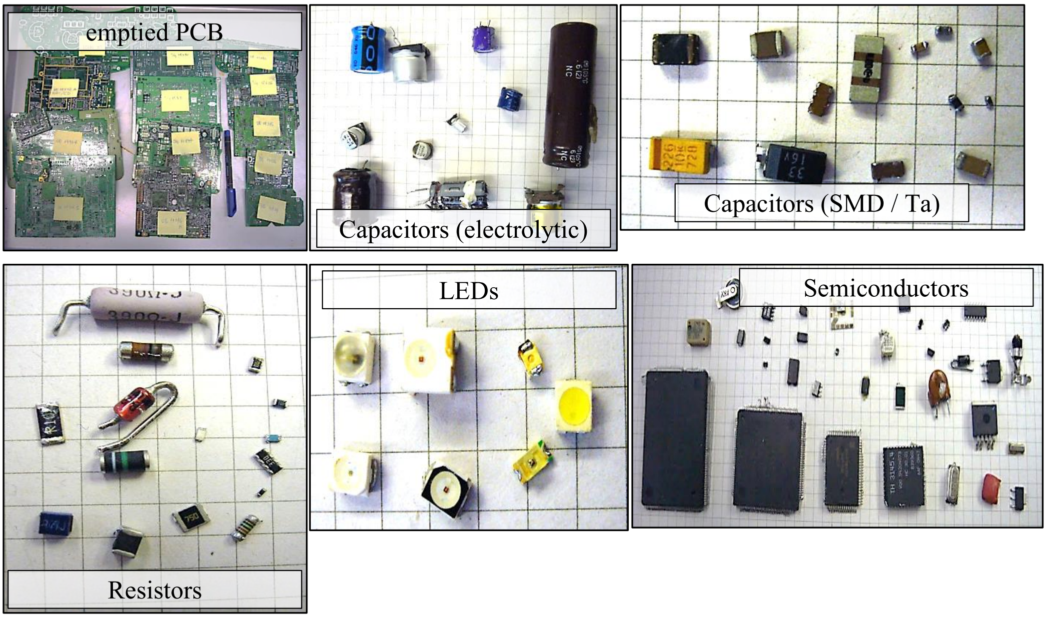


Figure SI 3: Photos of sampled EE components: emptied PCB and removed electronic components

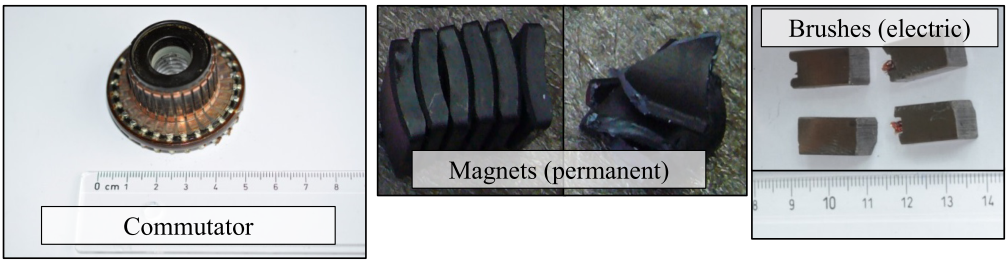


Figure SI 4: Photos of sampled EE components: components from electrical motors.

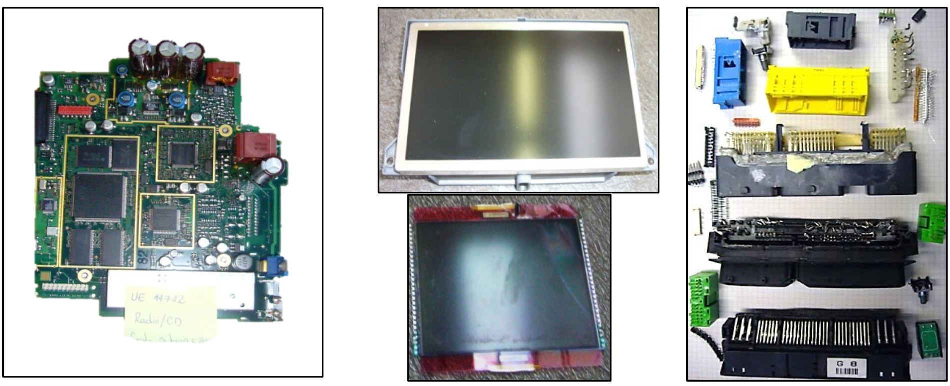


Figure SI 5: Photos of sampled EE components: populated PCB, LCD glass and foil and metal part of connectors.

Figure SI 6: Photos of sampled EE components: ABS sensor's plastic and metal part, sensor element in lambda probe (removed in picture) and resister from air mass flow meters.

List SI 1: Preparation of EE component samples for chemical analysis

- SMD capacitors, resistors, LED and sensor element in lambda probe (4 samples) were comminuted with a cryogenic mill under liquid nitrogen cooling. The comminution process was repeated until all the material passed through a 0.5 mm sieve.
- Populated and depopulated (emptied) PCB, integrated circuits (semiconductors) and commutators (4 samples) were treated with liquid nitrogen, sheared, and then crushed with a jaw crusher. Following, the material was submitted to a vibrating disc mill until it reached a particle size smaller than 0.5 mm.
- Electrolytic capacitors (1 sample) were crushed in a jaw crusher and then passed through a cutting mill until the particle size of the material was smaller than 0.5 mm. Then, the material was reduced to a particle size of less than 0.12 mm by a centrifugal mill.
- The metal part of the connectors (1 sample) was consecutively passed through a vibrating disc mill, a cutting mill and a centrifugal mill until its particle size was reduced to less than 0.12 mm.
- The LCD glass (1 sample) was first crushed in a jaw crusher and then separated into two fractions with particle sizes larger than 1 mm and smaller than 1mm. The fraction >1 mm was further reduced to less than 0.12 mm with a cutting and a centrifugal mill. The fraction >1 mm, which consisted of a mixture of glass and plastics, was reduced to less than 0.1 mm in a ball mill. In a last step, the fractions were recombined in one sample.
- Resistors from air mass meters were comminuted to a size less than 0.5 mm by means of a mortar.
- Magnets were first broken into pieces with a 60 ton press and then reduced to a particle size of less than 0.5 mm with a sequence of jaw crusher and ball mill.
- Electric brushes were reduced to a particle size of less than 0.5 mm with a jaw crusher and a ball mill.
- The EE particle size of LCD foils was reduced to 6 mm by means of a hole punch.
- The EE particle size of the plastic EE part of ABS sensors was reduced with a centrifugal mill in several loops until less than 0.12 mm.
- The size of the metal part of ABS sensors could not be reduced by means of the equipment available and hence was digested as such.

List SI 2: Chemical analysis for both experiments

- For a first screening a subset of 13 metals (Ag, Co, Ga, Ge, La, Mo, Nb, Rb, Sb, Sn, Sr, W and Zr) was semiquantitatively analyzed. The analyses were carried out using an X-ray fluorescence (XRF) spectrometer and the Turbo-Quant method (fundamental parameter calibration). The spectrometer was calibrated for samples of not geological origin. For each of the selected samples, an aliquot of the homogenized sample was introduced into an XRF cuvette and located into the automatic sampler where it was measured one time.

- Five different digestion methods were used in the quantitative analysis:
    1. Total microwave digestion: was used for samples consisting of non-elemental metal and other materials to determine mass fractions of all investigated elements except Ag. In a first stage the material was digested in a microwave vessel with a mixture of nitric acid (67-69%, p.a.), hydrochloric acid (37%, p.a.) and hydrofluoric acid (48%, p.a.) at 220°C and a maximum 400 psi. In a second stage, saturated boric acid was added to the remaining hydrofluoric acid and the material was further digested at 160°C.
    2. Metal microwave digestion with hydrofluoric acid (HF): was used for samples consisting of elemental metal to determine mass fractions of all investigated elements except Ag. In a first stage, the material was digested in a microwave vessel with a mixture of hydrochloric acid (37%, p.a.) and nitric acid (67-69%, p.a.) in a 1:3 ratio at 180°C and maximum pressure of 300 psi. In a second stage, hydrofluoric acid (48%, p.a.) was added and the material was digested at 220°C and 300 psi. In a third stage, saturated boric acid was added to the remaining hydrofluoric acid and the material was digested at 180°C and a maximum of 100 psi.
    3. "Plastics" microwave digestion: An extra of hydrogen peroxide was added to the total microwave digestion when organic matter was present in the sample in order to avoid overpressure due to formation of nitrogen oxides in the presence of nitric acid.
    4. Aqua-regia microwave digestion: was used for samples consisting of non-elemental metal and other materials to determine of Ag mass fractions. The material was digested in a microwave vessel with a mixture of hydrochloric acid (37%, p.a.) and nitric acid (67-69%, p.a.) in a 1:3 ratio. Temperature was sequentially increased to 170°C under unmonitored pressure.
    5. Aqua-regia open digestion: was used for samples consisting of non-elemental metals and other materials to determine Ag mass fractions, as well as for metallic samples that were not possible to homogenize to determine mass fractions of all elements except Ta, W and Zr. The material was digested in an open vessel with a mixture of hydrochloric acid (37%, p.a.) and nitric acid (67-69%, p.a.) in a 1:3 ratio at 150°C.
- For each sample, a single or several parallel digestions from the above were carried out depending on the material of the sample and the metals to be analyzed. A sub-sample of about 0.5 g of material from the homogenized sample was taken for the microwave digestions and of about 1 to 3 g for the aqua-regia open digestion.
- Out of the 31 metals, 29 metals (except Co and Sn) were measured with an Agilent 7500ce Octopole Reaction System Inductively Coupled Plasma Mass Spectrometer (ORS-ICP-MS) and a Thermoelement 2 High-Resolution Sector Field Inductively Coupled Plasma Mass Spectrometer (HRSF-ICP-MS). Co and Sn were measured with a Varian 735-ES Inductively Coupled Plasma Atomic Emission Spectroscope (ICP-OES). Linear calibrations were performed in accordance with the mass fraction ranges of the elements analyzed.
- The final mass fraction result for each element in each sample was the average of the measurements of the different digested sub-samples, respectively, total microwave and metal microwave digestions for all elements, except Ag and aqua regia digestions for Ag.
- Because In has no undisturbed isotope its mass fraction was calculated via the Sn mass fraction and the Sn-isotope ratio. For this, and additional measurement of the mass fraction of Sn was carried out using ORS-ICP-MS and HRSF-ICP-MS and the value of In was corrected accordingly.
- The combined uncertainty of the mass fraction value, taking into account the contributions of sample preparation, digestion and measurement, is estimated to be approximately between 12% and 24%. For elements in very small mass fractions, the uncertainty may increase 2% to 3% (Bachema, 2011).

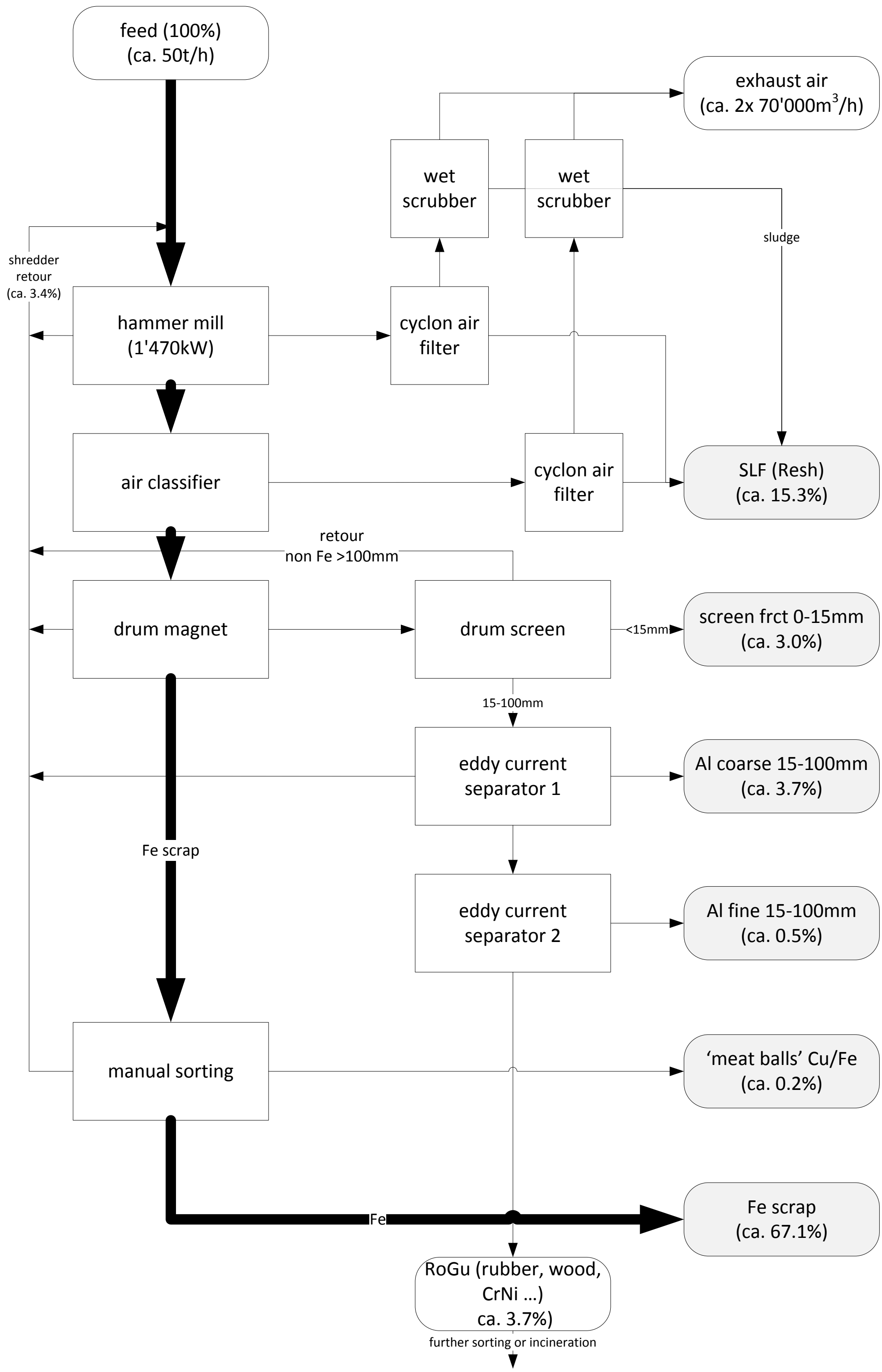

feed (100%)
(ca. 50t/h)
exhaust air
(ca. 2x 70'000m3/h)
wet scrubber
wet scrubber
sludge
shredder retour (ca. 3.4%)
hammer mill (1'470kW)
cyclon air filter
air classifier
cyclon air filter
SLF (Resh) (ca. 15.3%)
retour non Fe >100mm
drum magnet
drum screen
<15mm
screen frct 0-15mm (ca. 3.0%)
15-100mm
eddy current separator 1
Al coarse 15-100mm (ca. 3.7%)
Fe scrap
eddy current separator 2
Al fine 15-100mm (ca. 0.5%)
manual sorting
'meat balls' Cu/Fe (ca. 0.2%)
Fe
Fe scrap (ca. 67.1%)
RoGu (rubber, wood, CrNi ...) ca. 3.7%
further sorting or incineration

Figure SI 7: Flow sheet of the shredding process; share of shredder fraction masses are shown in percent of the total batch test output mass.

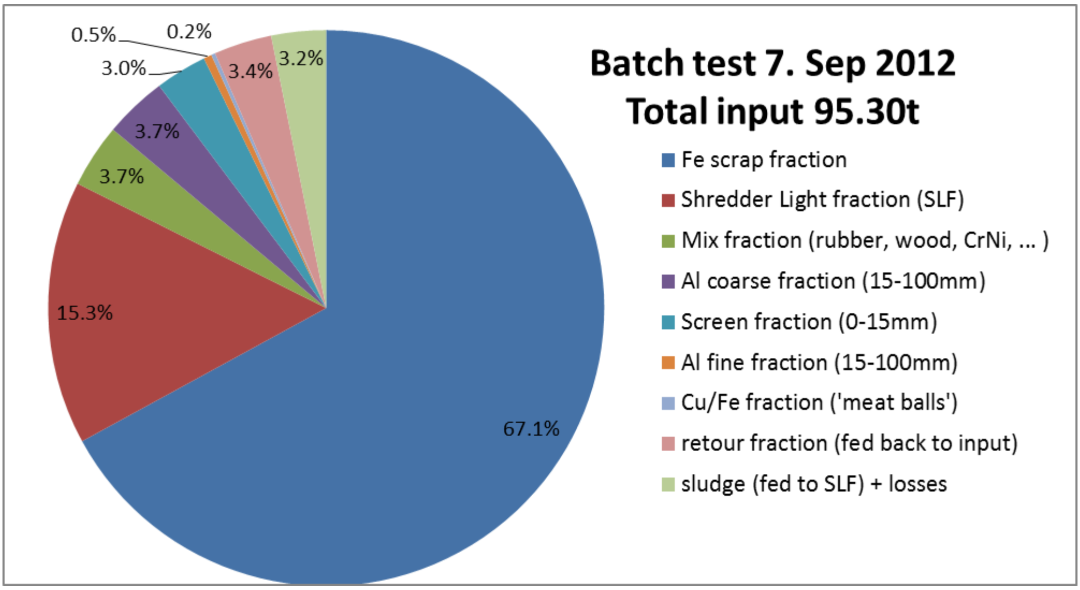


Figure SI 8: Mass distribution over the shredder fractions.

Figure SI 9: Snapshots of the shredder fractions considered in mass balance.

1) Fe scrap (or coarse) fraction, 2) Shredder Light fraction (SLF), 3) Mix (or RoGu) fraction (mainly, rubber, wood, CrNi, ...), 4) Al coarse fraction (15-100mm), 5) Screen fraction (0-15mm), 6) Al fine fraction (15-100mm), 7) Cu/Fe (or 'meat ball') fraction and 8) the retour fraction (fed back to input). Not shown is the sludge from the wet scrubber, which is fed to the SLF and of course also not shown are the losses.

List SI 3: Sampling of shredder fractions

The purpose of the sampling process was to collect as representative as possible samples of all the shredder fractions. Depending on the process and materials, different sampling procedures were applied.

Shredder light fraction (SLF): all material was dumped in a pile on the open ground, then mixed and divided into four smaller piles by a material handler. 2 x 60 Liter Euro stacking container material was collected by randomly shoving it from the output pile.

Screen fraction: 2 containers were collected by extracting single scoops in regular time intervals from existing material stream.

Coarse and a fine aluminum fraction: 1 container each of the material was randomly hand-picked from the collecting container at the end of the process.

Iron scrap fraction: 1 container of randomly grabbed material was hand-picked by four persons off the running conveyor belt.

Mixed material fraction: 1 container of material (mainly rubber, plastic and wood (ca. 60%) but also non Fe metals such as CrNi, Cu cables and PCB) was randomly shoved from the output pile at the end of shredding process.

Scrubber sludge fraction: 1 glass jar of (approx. 0.5 Liter) material was collected from the sump of the wet scrubber for each: the floating froth, the top and the bottom water layer.

"meat balls" fraction: (mainly rotors and stators) this material was not sampled.

List SI 4: Chemical analysis of the metal surface of the Al and Fe coarse fractions

1. The Al coarse and Fe scrap fractions (2.5±0.05 kg each sample) were washed in 1% HNO3.
2. the washed Al and Fe pieces were ground and analysed to establish the SM mass fraction in their volume (the inside of the metal pieces, also referred to as "core", "matrix" or "solvent")
3. The eluate was filtered and produced 3 fractions: 1) "grob": the scrubbed off layer on the filter, "fein": the filter itself containing particles >0.45µm and 3) the filtered eluate.
4. All 3 fractions were prepared and analysed to establish the SM mass fractions in each.
5. The cumulated mass fraction w_x^{all} (in mg/kg) of the SM x in all 3 fractions is calculated with the following equation:

$$w_x^{all} = \frac{m_x^{grob} + m_x^{fein} + m_x^{lösung}}{m_{total}}$$

with:

m_{total} the initial mass of the Al coarse and Fe scrap fractions to be washed (in g)

and using

$$m_x^{grob} = w_x^{grob} \times m_{grob}$$

with:

m_x^{grob} the mass of metal x in the scrubbed off layer on filter (in µg)

w_x^{grob} the mass fraction of metal x in the scrubbed off layer on filter (in mg/kg or ppm)

m_{grob} the mass of the scrubbed off layer on filter (in g)

$$m_x^{fein} = w_x^{fein} \times m_{fein}$$

with:

m_x^{fein} the mass of metal x in the filter (in µg)

w_x^{fein} the mass fraction of metal x in the filter (in mg/kg or ppm)

$m_{fein} = m_{filter\_after} - m_{filter\_before}$ the mass of the material deposited in the filter during filtering (in g)

$$m_x^{lösung} = c_x^{lösung} \times v_{lösung}$$

with:

$m_x^{lösung}$	the mass of metal x in the eluate (in µg)
$c_x^{lösung}$	the concentration of metal x in the eluate (in mg/L)
$v_{lösung}$	the volume of the scrubbed off the eluate (in mL)

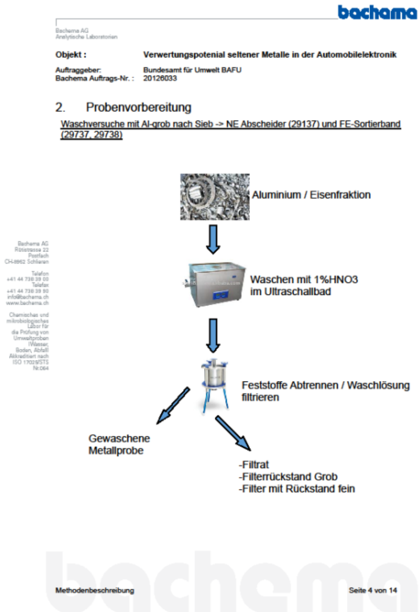
For the Al coarse fraction only one, for the Fe scrap fraction two valid measurements resulted; for the latter the average value was used. In case of measured values below detection levels the values for the calculations were set to zero. In case all measured values below detection levels the result of the calculations were set to "below threshold (b.t.)"

The terms "concentration" and "mass fraction" are defined in general and physical chemistry. A comprehensive overview is given in e.g. "Quantities, Units and Symbols in Physical Chemistry", page 77, second edition, published by the INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY, 1993". A brief summary is given in the following table:

Concentration type	Symbol	Definition	SI unit	other unit(s)
mass concentration	ρ_i or γ_i	m_i/V	kg/m³	g/100mL (= g/dL)
molar concentration	c_i	n_i/V	mol/m³	M (= mol/L)
number concentration	C_i	N_i/V	1/m³	1/cm³
volume concentration	ϕ_i	V_i/V	m³/m³	
Related quantities	**Symbol**	**Definition**	**SI unit**	**other unit(s)**
normality		c_i/f_{eq}	mol/m³	N (= mol/L)
molality	b_i	$n_i/m_{solvent}$	mol/kg	
mole fraction	x_i	n_i/n_{tot}	mol/mol	ppm, ppb, ppt
mole ratio	r_i	$n_i/(n_{tot} - n_i)$	mol/mol	ppm, ppb, ppt
mass fraction	w_i	m_i/m_{tot}	kg/kg	ppm, ppb, ppt
mass ratio	ζ_i	$m_i/(m_{tot} - m_i)$	kg/kg	ppm, ppb, ppt

Since different methods were used to chemically analyze and measure the content of SM in various matrices the authors were careful not to mingle the terms: whenever the SM is contained in a mass the term "mass fraction" is used, whenever the SM is contained in a volume the term "concentration" is used.

List SI 5: List of the applied procedures and their detailed description for the sample preparation



bachama

Bachema AG
Analytische Laboratorien

Objekt :	**Verwertungspotenial seltener Metalle in der Automobilelektronik**
Auftraggeber:	Bundesamt für Umwelt BAFU
Bachema Auftrags-Nr. :	20126033

2. Probenvorbereitung

Waschversuche mit Al-grob nach Sieb -> NE Abscheider (29137) und FE-Sortierband (29737, 29738)

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Chemisches und mikrobiologisches Labor für die Prüfung von Umweltproben (Wasser, Boden, Abfall) Akkreditiert nach ISO 17025/STS Nr.064

Methodenbeschreibung Seite 4 von 14

The list is embedded in this document (requires AcroExch to open it) or available as a pdf-document upon requested from the corresponding author.

Table SI 2: 31 SM mass fractions w_x (in mg/kg, g/t or also ppm) measured in the 17 EE components

Element	ABS sensors (metal EE part)	ABS sensors (plastic EE part)	Brushes (Electric)	Electrolytic Capacitors	SMD Capacitors	Commutators	Connectors (only metal EE part)	LCD Displays (Foil)	LCD Displays (Glass)	LEDs	Magnets	Sensor element in lambda probe	PCB populated	PCB without components	Resistors	Resistors from Air mass meter	Semiconductors
Ag	134.0	20.9 *	239.0	165.0	4 270.0	60.1*	902.0	<0.1	7.5	582.0	0.2	1.0	412.0	5.9*	3 980.0	6 630.0	508.0
Au	<0.1	1.7	0.1	1.4	108.0	0.6	57.2	<0.1	22.4	764.0	<0.1	2.1	121.0	33.0	61.1	<0.1	1 230.0
Be	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	4.7	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Ce	<0.5	7.9	2.3	4.5	19.0	6.2	2.6	<0.5	4.2	12.2	1.4	11.8	13.6	20.4	13.9	0.7	1.2
Co	11.3	1.7	2.3	4.8	99.0	3.9	33.0	31.7	4.0	5.3	3 500.0	3.0	122.0	6.9	71.7	25 600.0	274.0
Dy	<0.1	0.3	0.3	0.2	2 860.0	0.4	0.2	<0.1	0.4	5.2	12.1	1.7	10.6	1.2	31.3	<0.1	2.3
Ga	1.5	3.5	<1.0	22.6	1.8	3.9	2.1	<1.0	3.9	391.0	9.5	1.8	14.1	7.2	5.4	<1.0	1.9
Gd	<0.1	1.4	0.2	0.5	280.0	0.6	0.2	<0.1	5.8	13.0	24.8	1.1	4.3	3.0	10.3	0.3	2.1
Ge	4.2	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	16.0	<1.0	<1.0	<1.0	1.7	63.3	<1.0
In	n.a	n.a	<1.0	<0.1	3.0	n.a	3.0	<0.5	198.0	<0.1	n.a	<0.1	<0.1	n.a	<0.1	n.a	11.9
La	0.5	5.2	0.9	2.3	2 550.0	3.3	1.3	<0.1	2.9	2.8	7 180.0	4.0	22.2	11.6	164.0	2.9	13.7
Li	<10	<10	<10	<10	13.0	<10	<10	<10	<10	<10	<10	<10	31.0	22.0	453.0	<10	<10
Mo	45.5	0.8	14 700.0	26.4	21.4	8.4	30.0	<0.25	19.6	<0.25	18.5	10.2	6.6	3.4	14 100.0	3.6	148.0
Nb	3.0	2.3	0.8	6.4	4 350.0	2.2	3.2	<0.5	0.9	3.0	15.8	18.7	15.4	5.5	33.1	0.9	24.9
Nd	<0.1	55.9	7.4	6.7	11 400.0	4.5	1.9	<0.1	22.7	2.0	475.0	3.9	1 090.0	12.9	576.0	1.3	51.6
Pd	<0.5	7.1	0.6	<0.5	2 350.0	<0.5	0.6	<0.5	<0.5	61.6	14.7	49.9	25.4	6.6	316.0	156.0	18.3
Pr	<0.1	2.3	1.2	0.6	658.0	0.7	0.3	<0.1	0.6	0.5	28.2	1.0	16.6	2.7	38.6	<0.1	2.6
Pt	<1.0	<1.0	<1.0	<1.0	29.6	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7 520.0	<1.0	<1.0	1.4	<1.0	1.8
Rb	<0.2	4.7	0.8	3.3	0.3	2.0	1.2	<0.2	15.8	2.1	<0.2	7.7	2.4	2.6	0.3	<0.2	0.5
Re	<0.1	<0.1	0.2	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.4	0.2
Ru	2.0	<0.1	0.3	<0.1	1.2	0.2	4.0	<0.2	<0.1	<0.1	1.1	7.7	0.4	<0.1	6.1	2.3	0.5
Sb	1.1	14.5	224.0	250.0	1 070.0	665.0	543.0	137.0	1 430.0	59.3	0.4	<0.1	807.0	12.7	385.0	2 050.0	5 900.0
Sm	<0.1	0.6	5.0	0.3	133.0	0.4	0.3	<0.1	0.4	0.3	0.4	0.9	1.3	1.6	6.4	5.8	0.3
Sn	5 390.0	194.0	1 820.0	4 990.0	52 600.0	1 370.0	10 600.0	<1	453.0	53 600.0	22.1	288.0	21 500.0	20 200.0	74 100.0	20 400.0	14 700.0
Sr	22.1	415.0	7.5	34.2	2 380.0	156.0	53.5	<5.0	22 700.0	255.0	84 100.0	34.3	314.0	526.0	20.9	1 440.0	101.0
Ta	n.a	0.0	<0.5	1.1	32 500.0	0.0	<0.5	<0.5	5.4	<0.5	<0.5	2.2	469.0	0.0	6.2	n.a	1 710.0
Tb	<0.1	0.4	0.3	0.3	67.5	0.2	<0.1	<0.1	1.0	14.1	1.8	0.2	3.0	0.7	1.3	0.1	2.3
Te	<0.5	<0.5	1.6	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	3.4	<0.5	<0.5	1.2	<0.5	1.6
W	n.a	0.8	122.0	62.0	389.0	0.8	5.1	<1.0	15.8	0.8	2.9	0.6	6.3	1.0	6.3	n.a	233.0
Y	<0.1	1.6	1.7	0.5	1 030.0	1.2	0.6	<0.1	3.5	111.0	0.8	25 400.0	40.6	3.8	23.1	2.3	1.4
Zr	n.a	5.0	7.4	16.4	16 900.0	17.5	2.7	<1.0	194.0	19.4	1.2	380 000.0	563.0	58.3	227.0	n.a	118.0

< ###: value below detection level

###*: value might be too low due to digestion with HF instead of aqua regia.

n.a. value not available for In due to the lack of samples for re-measurement of Sn correction and for Ta, W and Zr due to the lack of samples for new digestion with HF.

The accredited Lab of Bachema AG describes its uncertainty of measurement in "Forum1416Bestimmungsunsicherheit.pdf" (referenced in the main manuscript). It follows the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM) and groups its applied analytical methods in 4 classes a) to d). For this research uncertainty class c) = 12%-24% applies. It reads: the relative combined standard uncertainty $u_{c,r}(y)$of output y of the measurand Y is:

$$u_{c,r}(y) = \frac{u_c(y)}{|y|} = 12\%$$

Given the expanded uncertainty $U = k \cdot u_c(y)$ and assuming a normal distribution density for the uncertainty and a confidence level $p = 95\%$ the coverage factor is $k_p = 2$ and the relative expanded uncertainty $U_{p,r}$

$$U_{p,r} = \frac{U}{|y|} = \frac{k_p \cdot u_c(y)}{|y|} = 24\%$$

Thus the measurand Y, the mass fraction w_x, is normally distributed with ${}^{\sigma}/{}_{w_x} = 12\%$ and the measurement is with a confidence level of 95% in the confidence interval $w_x - 24\%, \dots, w_x + 24\%$. These uncertainty value includes the entire procedure for chemical analysis applied at the Lab taking into account sample preparation, digestion and measurement etc.. For values approaching the detection limit, the uncertainty may increase by a factor of 2 to 3.

Table SI 3: Some key indicators for the 31 SM in the EE components in one mid-range car.

SM	Max. mass fraction $\frac{w_x}{\mathrm{g/t}}$	17 EE components with max. mass fraction	Max. mass $\frac{M_x}{g}$	error $\frac{u_{c,r}(M_x)}{g/com}$	11 EE components with max mass	Total mass $\frac{M_x}{g/car}$	error $\frac{u_{c,r}(M_x)}{g/car}$
Ag	6'630.0	Resistors from Air mass meter	0.16	0.019	Printed Wiring Boards (populated)	1.3	0.16
Au	1'230.0	Semiconductors	0.046	0.0055	Printed Wiring Boards (populated)	0.22	0.027
Be	4.7	Connectors (only metal EE part)	0.00079	0.000095	Connectors (metal EE part)	0.0034	0.00041
Ce	20.4	PCB without components	0.0052	0.00062	PCB (populated)	0.028	0.0034
Co	25'600.0	Resistors from Air mass meter	2	0.24	Magnets	6	0.73
Dy	2'860.0	Capacitors (SMD + Tantalum)	0.007	0.00084	Magnets	0.036	0.0044
Ga	391.0	LEDs	0.0055	0.00066	Magnets	0.041	0.0049
Gd	280.0	Capacitors (SMD + Tantalum)	0.014	0.0017	Magnets	0.049	0.0059
Ge	63.3	Resistors from Air mass meter	0.0092	0.0011	Magnets	0.027	0.0032
In	198.0	LCD Displays (Glass)	0.0085	0.001	Printed Wiring Boards (populated)	0.022	0.0027
La	7'180.0	Magnets	4.1	0.5	Magnets	12	1.4
Li	453.0	Resistors	0.012	0.0014	Printed Wiring Boards (populated)	0.046	0.0055
Mo	14'700.0	Brushes (Electric)	0.37	0.044	Brushes (electric)	1	0.12
Nb	4'350.0	Capacitors (SMD + Tantalum)	0.0091	0.0011	Magnets	0.053	0.0064
Nd	11'400.0	Capacitors (SMD + Tantalum)	0.41	0.05	Printed Wiring Boards (populated)	2.4	0.29
Pd	2'350.0	Capacitors (SMD + Tantalum)	0.0096	0.0012	Printed Wiring Boards (populated)	0.064	0.0077
Pr	658.0	Capacitors (SMD + Tantalum)	0.016	0.002	Magnets	0.073	0.0087
Pt	7'520.0	Sensor element in lambda probe	0.0083	0.001	Sensor element in lambda probe	0.0083	0.001
Rb	15.8	LCD Displays (Glass)	0.001	0.00012	ABS sensors (plastic EE part)	0.0074	0.00088
Re	0.4	Resistors from Air mass meter	0.000005	0.0000006	Brushes (electric)	0.000013	0.0000015
Ru	7.7	Sensor element in lambda probe	0.00068	0.000081	Connectors (metal EE part)	0.0056	0.00067
Sb	5'900.0	Semiconductors	0.31	0.037	Printed Wiring Boards (populated)	1.9	0.23
Sm	133.0	Capacitors (SMD + Tantalum)	0.00049	0.000059	Printed Wiring Boards (populated)	0.0034	0.00041
Sn	74'100.0	Resistors	8.2	0.98	Printed Wiring Boards (populated)	41	4.9
Sr	84'100.0	Magnets	48	5.8	Magnets	140	17
Ta	32'500.0	Capacitors (SMD + Tantalum)	0.18	0.021	Printed Wiring Boards (populated)	0.7	0.084
Tb	67.5	Capacitors (SMD + Tantalum)	0.0011	0.00014	Printed Wiring Boards (populated)	0.0077	0.00092
Te	3.4	Sensor element in lambda probe	0.00004	0.0000048	Brushes (electric)	0.0001	0.000013
W	389.0	Capacitors (SMD + Tantalum)	0.0031	0.00037	Brushes (electric)	0.027	0.0033
Y	25'400.0	Sensor element in lambda probe	0.028	0.0034	Sensor element in lambda probe	0.091	0.011
Zr	380'000.0	Sensor element in lambda probe	0.42	0.051	Sensor element in lambda probe	1.3	0.15

For the SM mass fractions all sampled 17 EE components are used; however, for the SM masses subset of 11 EE components used for the mass projection for the hypothetical cars is used. In this case the de-populated PWB and all the de-soldered electronic elements (resistors, capacitors, ICs and LEDs) are not included.
Depending on chemical element and sample, mass fraction threshold is from <0.1 mg/kg to <1.0 mg/kg and for Li it is <10.0 mg/kg).
EE component masses required for projections of total masses have a precision of 100 mg.
Same uncertainty of measurement as described in Table SI2.

Estimation of missing mass due to dismantling ELV prior to shredding

The average car's mass according to the average unladen mass (Leermasse) of passenger vehicles in Switzerland, has risen continuously from 1'300 kg (1996) to 1'500 kg (2008) (http://www.bfs.admin.ch/bfs/portal/en/index/themen/11.html); we use the average unladen mass of

1'400 kg, which is probably an upper limit since Swiss consumers tend to buy heavier cars then car owners in most of the EU. The unladen mass represents a ready to drive car with all liquids 100% filled up except fuel which is taken as 90% full, all accessories such as spare wheel, toolset, safety equipment etc. and includes a 75 kg driver.
All CH car dismantlers prepare cars for shredding i.e. they remove the required parts. Many also remove additional parts for 2nd-hand sale. Some may export 2nd-hand parts such as engine blocks but we did not investigate the 2nd-hand spare parts exports and not checked if further dismantling had taken place e.g. removal of EE components. The quick check below suggests that some spare parts beyond the legal requirement may indeed have been removed. The spare parts of interest are e.g. fenders (which would not contain SM hot spots) or doors which might contain power windows with motors which might contain SMs e.g. Nd or La.

The following estimate shows that some of the expected mass might be missing:

with:
1'400 kg average unladen car mass
950 kg actual car mass shredded
75 kg driver

and removed parts prior to shredding (ref: http://www.bafu.admin.ch/veva-inland/11827/11830/index.html?lang=de):
required (total ca. 200kg):

- All liquids (fuel, oil, water, coolant, ...), in some cases with the tank (e.g. CNG) >>> 60 kg
- Batteries >>> 20 kg
- Wheels / tires >>> 100 kg
- Catalyst (incl. part of exhaust system) >>> 20 kg

parts lost prior to shredding (total ca. 60kg) (these "losses" are normally added to the shredder in a weekly clean-up of the scrap yard, however, this wasn't the case during this batch test.):

- most windows are lost when the ELVs are stacked for shredding >>> 20 kg
- most salient parts are rear mirror, screen wipers, etc. >>> 20 kg
- toolset, safety equipment, etc. >>> 20 kg

recommended parts if feasible for reuse or recycling (ref: http://www.bafu.admin.ch/veva-inland/11827/11830/index.html?lang=de) (total ca. ???kg):

- All other parts >>> (unknown)

1'400 kg - 950kg - 75kg - 200 kg - 60 kg = 115 kg

these recommended parts might sum up to the 115 kg difference in the quick calculation above.

Table SI 4: Number of EE devices in 5 hypothetical car models

Devices	High-end car	Low-end car	Mid-range car (used in this study)	Coupé high-end	Coupé low-end
ABS pump	1	0	1	1	0
Power windows	4	0	4	2	0
GPS navigation system*	2	0	1	2	0
Radio / CD*	2	1	1	2	1
Instruments (User Interface)	1	1	1	1	1
Airbag / crash sensor	1	0	1	1	0

Airbag controller	1	0	1	2	0
Oxygen sensor	2	1	1	1	1
ABS sensor	4	0	4	4	0
The following EE devices are in all hypothetical car models by default:					
Devices	**Number of EE devices**				
Fuel pump	1				
Alternator	1				
Starter motor	1				
Wiper motor (wind screen)	1				
Radiator fan motor	1				
Multi-function control stalk	1				
Fuse box	1				
Air mass meter	1				
Motor controller	1				

* In the case of GPS unit and radio the number of devices is used to represent the size and control options of the devices, not the actual devices installed in the vehicle. This simplification is based on the number of printed circuit boards in the devices, which are the ones contributing to the mass of critical metals in the calculation. A simple radio with 1 cassette unit contains 1 printed circuit board and it is represented here as 1 radio - a radio with more options such as CD and Bluetooth has 2 or more printed circuit boards and it is represented as 2 radios.

Table SI 5: Assembly of EE device with EE parts and EE components in one hypothetical mid-range vehicle

Sample Nr	**EE components containing analyzed scarce metals**	**EE parts containing the EE components**	**average mass of EE component in EE part (in grams)**	**EE devices containing the EE parts**	**Number of EE parts per EE device**	**Our classification of EE devices**	**Subsystem (classification Alonso 2012)**
39070	Printed Wiring Boards (populated)	Circuit Boards	40.00	ABS pump	1	Electromotors (EM)	Steering & Brakes
40141	Connectors (metal EE part)	Contacts/Connectors	169.00	ABS pump	1	Electromotors (EM)	Steering & Brakes
39062	Magnets	Electromotors	234.00	ABS pump	1	Electromotors (EM)	Steering & Brakes
39064	Brushes (electric)	Electromotors	6.29	ABS pump	1	Electromotors (EM)	Steering & Brakes
39068	Commutators	Electromotors	24.70	ABS pump	1	Electromotors (EM)	Steering & Brakes
40141	Connectors (metal EE part)	Contacts/Connectors	35.70	ABS sensor	1	Sensors (SE)	Steering & Brakes
40901	ABS sensors (plastic EE part)	ABS sensor	53.64	ABS sensor	1	Sensors (SE)	Steering & Brakes
40898	ABS sensors (metal EE part)	ABS sensor	22.47	ABS sensor	1	Sensors (SE)	Steering & Brakes
39070	Printed Wiring Boards (populated)	Circuit Boards	41.20	Air mass meter	1	Sensors (SE)	Electrical
40141	Connectors (metal EE part)	Contacts/Connectors	17.50	Air mass meter	1	Sensors (SE)	Electrical
40690	Resistors from air mass meter	Air mass sensor	0.10	Air mass meter	1	Sensors (SE)	Electrical
39070	Printed Wiring Boards (populated)	Circuit Boards	10.30	Airbag / crash sensor	1	Sensors (SE)	Interior
40141	Connectors (metal EE part)	Contacts/Connectors	11.60	Airbag / crash sensor	1	Sensors (SE)	Interior
39070	Printed Wiring Boards (populated)	Circuit Boards	75.80	Airbag controller	1	Controllers (SG)	Electrical
39064	Brushes (electric)	Electromotors	6.29	Alternator	1	Electromotors (EM)	Electrical
39068	Commutators	Electromotors	24.70	Alternator	1	Electromotors (EM)	Electrical
39070	Printed Wiring Boards (populated)	Circuit Boards	1.80	Fuel pump	1	Electromotors (EM)	Fuel & Exhaust
40141	Connectors (metal EE part)	Contacts/Connectors	10.40	Fuel pump	1	Electromotors (EM)	Fuel & Exhaust
39062	Magnets	Electromotors	137.40	Fuel pump	1	Electromotors (EM)	Fuel & Exhaust
39064	Brushes (electric)	Electromotors	6.29	Fuel pump	1	Electromotors (EM)	Fuel & Exhaust
39068	Commutators	Electromotors	24.70	Fuel pump	1	Electromotors (EM)	Fuel & Exhaust
39070	Printed Wiring Boards (populated)	Circuit Boards	379.40	Fuse box	1	Contacts (KO)	Electrical
40141	Connectors (metal EE part)	Contacts/Connectors	9.50	Fuse box	1	Contacts (KO)	Electrical
39070	Printed Wiring Boards (populated)	Circuit Boards	302.77	GPS navigation system	1	Consumer Electronics (UE)	Info & Controls
40141	Connectors (metal EE part)	Contacts/Connectors	2.75	GPS navigation system	1	Consumer Electronics (UE)	Info & Controls
39062	Magnets	Electromotors	6.60	GPS navigation system	1	Consumer Electronics (UE)	Info & Controls

Sample Nr	EE components containing analyzed scarce metals	EE parts containing the EE components	average mass of EE component in EE part (in grams)	EE devices containing the EE parts	Number of EE parts per EE device	Our classification of EE devices	Subsystem (classification Alonso 2012)
39065	LCD Displays (Foil)	LCD Displays	13.60	GPS navigation system	1	Consumer Electronics (UE)	Info & Controls
39067	LDC Displays (Glass)	LCD Displays	43.17	GPS navigation system	1	Consumer Electronics (UE)	Info & Controls
39070	Printed Wiring Boards (populated)	Circuit Boards	160.30	Instruments (User Interface)	1	User Interface (UI)	Interior
40141	Connectors (metal EE part)	Contacts/Connectors	10.00	Instruments (User Interface)	1	User Interface (UI)	Interior
39062	Magnets	Electromotors	4.90	Instruments (User Interface)	3	User Interface (UI)	Interior
39068	Commutators	Electromotors	2.00	Instruments (User Interface)	3	User Interface (UI)	Interior
39070	Printed Wiring Boards (populated)	Circuit Boards	147.70	Motor controller	1	Controllers (SG)	Electrical
40141	Connectors (metal EE part)	Contacts/Connectors	35.60	Motor controller	1	Controllers (SG)	Electrical
39070	Printed Wiring Boards (populated)	Circuit Boards	25.80	Multi-function control stalk	1	Contacts (KO)	Interior
40141	Connectors (metal EE part)	Contacts/Connectors	106.80	Multi-function control stalk	1	Contacts (KO)	Interior
39062	Magnets	Electromotors	4.80	Multi-function control stalk	1	Contacts (KO)	Interior
40141	Connectors (metal EE part)	Contacts/Connectors	12.80	Oxygen sensor	1	Sensors (SE)	Fuel & Exhaust
40140	Sensor element in lambda probe	Lambda sensor	1.11	Oxygen sensor	1	Sensors (SE)	Fuel & Exhaust
40141	Connectors (metal EE part)	Contacts/Connectors	16.90	Power windows	1	Electromotors (EM)	Closures
39062	Magnets	Electromotors	144.10	Power windows	1	Electromotors (EM)	Closures
39064	Brushes (electric)	Electromotors	6.29	Power windows	1	Electromotors (EM)	Closures
39068	Commutators	Electromotors	24.70	Power windows	1	Electromotors (EM)	Closures
40141	Connectors (metal EE part)	Contacts/Connectors	63.80	Radiator fan motor	1	Electromotors (EM)	Electrical
39064	Brushes (electric)	Electromotors	6.29	Radiator fan motor	1	Electromotors (EM)	Electrical
39068	Commutators	Electromotors	24.70	Radiator fan motor	1	Electromotors (EM)	Electrical
39070	Printed Wiring Boards (populated)	Circuit Boards	302.77	Radio / CD	1	Consumer Electronics (UE)	Info & Controls
40141	Connectors (metal EE part)	Contacts/Connectors	2.75	Radio / CD	1	Consumer Electronics (UE)	Info & Controls

Sample Nr	EE components containing analyzed scarce metals	EE parts containing the EE components	average mass of EE component in EE part (in grams)	EE devices containing the EE parts	Number of EE parts per EE device	Our classification of EE devices	Subsystem (classification Alonso 2012)
39062	Magnets	Electromotors/CD reader	6.60	Radio / CD	1	Consumer Electronics (UE)	Info & Controls
39065	LCD Displays (Foil)	LCD Displays	13.60	Radio / CD	1	Consumer Electronics (UE)	Info & Controls
39067	LDC Displays (Glass)	LCD Displays	43.17	Radio / CD	1	Consumer Electronics (UE)	Info & Controls
39062	Magnets	Electromotors	529.00	Starter motor	1	Electromotors (EM)	Electrical
39064	Brushes (electric)	Electromotors	6.29	Starter motor	1	Electromotors (EM)	Electrical
39068	Commutators	Electromotors	24.70	Starter motor	1	Electromotors (EM)	Electrical
40141	Connectors (metal EE part)	Contacts/Connectors	56.30	Wiper Motor	1	Electromotors (EM)	Electrical
39062	Magnets	Electromotors	157.00	Wiper Motor	1	Electromotors (EM)	Electrical
39064	Brushes (electric)	Electromotors	6.29	Wiper Motor	1	Electromotors (EM)	Electrical
39068	Commutators	Electromotors	24.70	Wiper Motor	1	Electromotors (EM)	Electrical

EE component masses, required for projections to total masses have a precision of 10 mg.

Table SI 6: 31 SM mass fractions w_x in mg/kg, g/t or also ppm) measured in the analyzed shredder fractions of m=100 cars

Element	SLF	Screen fraction	Sludge	Al fine	Mix	Fe scrap "core"	Fe scrap "crust"	Fe scrap Total	Al coarse "core"	Al coarse "crust"	Al coarse Total
Ag	10.8	70.3	13.0	22.7	13.0	0.5	0.0	0.5	6.9	0.0	6.9
Au	1.2	1.5	0.4	0.2	b.t.	b.t.	0.0	0.0	0.1	0.0	0.1
Be	b.t.	1.0	b.t.	0.6	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.
Ce	12.5	4.6	26.6	2.0	15.5	b.t.	0.0	0.0	2.0	0.0	2.0
Co	31.7	24.7	28.0	29.7	5.6	32.4	0.1	32.5	8.9	0.1	9.0
Dy	0.7	0.3	1.3	b.t.	0.1	b.t.	0.0	0.0	b.t.	0.0	0.0
Ga	4.1	30.0	3.2	55.6	b.t.	10.1	0.0	10.1	81.9	0.0	81.9
Gd	1.1	0.4	2.2	0.1	0.3	b.t.	0.0	0.0	0.2	0.0	0.2
Ge	b.t.	b.t.	b.t.	b.t.	b.t.	5.3	0.0	5.3	b.t.	0.0	0.0
In	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	0.0	0.0	b.t.	0.0	0.0
La	5.8	2.4	8.5	0.9	1.5	0.2	0.0	0.2	1.0	0.0	1.0
Li	15.0	b.t.	15.0	b.t.	b.t.	22.0	0.1	22.1	20.5	0.0	20.5
Mo	110.0	25.0	135.0	18.7	23.9	70.6	0.1	70.7	8.5	0.1	8.6
Nb	5.8	b.t.	1.1	b.t.	b.t.	32.2	0.0	32.2	0.3	0.0	0.3
Nd	11.8	3.8	19.0	1.1	1.9	0.2	0.0	0.2	1.1	0.0	1.1
Pd	2.7	6.4	1.2	2.8	1.0	b.t.	0.0	0.0	0.6	0.0	0.6
Pr	1.7	0.8	3.0	0.3	0.3	b.t.	0.0	0.0	0.2	0.0	0.2
Pt	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	0.0	0.0	b.t.	0.0	0.0
Rb	7.4	2.7	4.7	b.t.	1.6	b.t.	0.0	0.0	b.t.	0.0	0.0
Re	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.
Ru	0.3	0.3	0.4	0.3	0.3	0.2	0.0	0.2	b.t.	0.0	0.0
Sb	285.0	108.0	85.2	13.0	83.1	2.7	0.0	2.7	12.3	0.1	12.4
Sm	3.4	0.8	2.7	0.1	0.4	0.1	0.0	0.1	0.1	0.0	0.1
Sn	350.0	1380.0	403.0	1150.0	83.4	105.0	0.1	105.1	176.5	0.8	177.3
Sr	816.0	174.0	314.0	16.5	173.0	18.6	0.9	19.5	21.8	0.9	22.7
Ta	0.7	2.6		b.t.	27.5	b.t.	0.0	0.0	b.t.	b.t.	b.t.
Tb	0.1	b.t.	0.4	b.t.	b.t.	b.t.	0.0	0.0	b.t.	b.t.	b.t.
Te	1.4	0.7	b.t.	b.t.	4.6	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.
W	9.6	7.6		3.5	2.3	1.6	0.0	1.6	3.6	0.0	3.6
Y	3.5	1.1	5.6	0.4	0.7	b.t.	0.0	0.0	0.3	0.0	0.3
Zr	60.3	60.8		46.1	7.6	b.t.	0.0	0.0	29.6	0.0	29.6

b.t. below threshold (depending on chemical element and sample threshold is from <0.1 mg/kg to <1.0 mg/kg and for Li it is <10.0 mg/kg)
0.0 below 0.1 mg/kg
empty no valid measurement
Same uncertainty of measurement as described in Table SI2.

Table SI 7: 31 SM masses M_x^{out} (in grams) in the shredder fractions with shredder fraction mass in tons for m=100 cars

Element	SLF	Screen fraction	Sludge	Al fine	Mix	Fe scrap "core"	Fe scrap "crust"	Fe scrap Total	Al coarse "core"	Al coarse "crust"	Al coarse Total
shredder fraction mass	14.62	2.86	0	0.45	3.53	63.9			3.48		
Ag	157.9	201.1	37.2	10.2	45.9	32.0	0.1	32.1	24.0	0.1	24.1
Au	17.5	4.3	1.1	0.1	b.t.	b.t.	0.0	0.0	0.2	0.0	0.2
Be	b.t.	2.9	b.t.	0.3	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.
Ce	182.8	13.2	76.1	0.9	54.7	b.t.	1.5	1.5	6.8	0.1	6.9
Co	463.5	70.6	80.1	13.4	19.8	2070.4	4.1	2074.5	31.0	0.3	31.2
Dy	10.2	0.9	3.7	b.t.	0.4	b.t.	0.1	0.1	b.t.	0.0	0.0
Ga	59.9	85.8	9.2	25.0	b.t.	645.4	0.5	645.9	285.0	0.1	285.1
Gd	16.1	1.1	6.3	0.0	1.1	b.t.	0.2	0.2	0.5	0.0	0.5
Ge	b.t.	b.t.	b.t.	b.t.	b.t.	338.7	0.4	339.1	b.t.	0.0	0.0
In	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	0.0	0.0	b.t.	0.0	0.0
La	84.8	6.9	24.3	0.4	5.3	12.8	0.4	13.1	3.3	0.0	3.4
Li	219.3	b.t.	42.9	b.t.	b.t.	1'405.8	3.7	1'409.5	71.3	0.0	71.4
Mo	1'608.2	71.5	386.1	8.4	84.4	4'511.3	5.3	4'516.7	29.5	0.5	30.0
Nb	84.8	b.t.	3.1	b.t.	b.t.	2057.6	1.7	2059.3	1.0	0.0	1.0
Nd	172.5	10.9	54.3	0.5	6.7	12.8	1.2	14.0	3.7	0.1	3.8
Pd	39.5	18.3	3.4	1.3	3.5	b.t.	0.0	0.0	1.9	0.0	1.9
Pr	24.9	2.3	8.6	0.1	1.1	b.t.	0.6	0.6	0.7	0.0	0.7
Pt	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	0.0	0.0	b.t.	0.0	0.0
Rb	108.2	7.7	13.4	b.t.	5.6	b.t.	0.2	0.2	b.t.	0.0	0.0
Re	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.
Ru	4.4	0.9	1.1	0.1	1.1	12.8	0.5	13.3	b.t.	0.0	0.0
Sb	4'166.7	308.9	243.7	5.9	293.3	172.5	1.2	173.7	42.8	0.2	43.0
Sm	49.7	2.3	7.7	0.0	1.4	6.4	0.7	7.1	0.2	0.1	0.3
Sn	5'117.0	3'946.8	1'152.6	517.5	294.4	6'709.5	5.4	6'714.9	614.2	2.7	616.9
Sr	11'929.9	497.6	898.0	7.4	610.7	1'188.5	56.9	1'245.4	75.7	3.2	78.9
Ta	10.2	7.4		b.t.	97.1	b.t.	0.0	0.0	b.t.	b.t.	b.t.
Tb	1.5	b.t.	1.1	b.t.	b.t.	b.t.	0.0	0.0	b.t.	b.t.	b.t.
Te	20.5	2.0	b.t.	b.t.	16.2	b.t.	b.t.	b.t.	b.t.	b.t.	b.t.
W	140.4	21.7		1.6	8.1	103.5	0.1	103.6	12.5	0.0	12.5
Y	51.2	3.1	16.0	0.2	2.5	b.t.	0.2	0.2	1.0	0.0	1.1
Zr	881.6	173.9		20.7	26.8	b.t.	0.9	0.9	102.8	0.1	103.0

b.t. below threshold (see Table SI 6)
0.0 below 0.1 g
empty no valid measurement

Table SI 8: 31 SM masses M_x^{EEdev} (in grams) in the 6 EE device categories in n=100 hypothetical mid-range cars (rounded to 2 significant figures; precision 0.01 g)

	ConsumerElectronics (CE)	Contacts (KO)	Controllers (SG)	Electromotors (EM)	Sensors (SE)	UserInterface (UI)	Total
Ag	26.00	27.00	12.00	38.00	21.00	7.50	131.50
Au	7.60	5.60	2.90	2.60	1.70	2.00	22.40
Be	0.00	0.06	0.02	0.17	0.09	0.00	0.34
Ce	0.86	0.58	0.31	0.55	0.29	0.23	2.82
Co	12.00	7.00	2.80	570.00	1.60	7.10	600.50
Dy	0.66	0.44	0.24	2.00	0.07	0.19	3.60
Ga	0.90	0.60	0.32	1.80	0.20	0.24	4.06
Gd	0.34	0.19	0.10	4.10	0.06	0.11	4.89
Ge	0.02	0.01	b.t.	2.60	0.04	0.02	2.69
In	1.70	0.04	0.01	0.27	0.20	0.01	2.22
La	11.00	4.40	0.50	1'200.00	0.25	11.00	1'227.15
Li	1.90	1.30	0.69	0.13	0.16	0.50	4.68
Mo	0.61	0.63	0.25	97.00	1.00	0.17	99.66
Nb	0.96	0.67	0.36	2.80	0.22	0.27	5.28
Nd	67.00	44.00	24.00	82.00	6.80	18.00	241.80
Pd	1.60	1.00	0.57	2.50	0.30	0.43	6.40
Pr	1.00	0.69	0.37	4.70	0.14	0.31	7.21
Pt	b.t.	b.t.	b.t.	b.t.	0.83	b.t.	0.83
Rb	0.28	0.11	0.06	0.11	0.14	0.04	0.74
Re	b.t.	b.t.	b.t.	0.00	0.00	b.t.	0.00
Ru	0.03	0.06	0.02	0.34	0.09	0.01	0.56
Sb	62.00	39.00	20.00	41.00	15.00	14.00	191.00
Sm	0.08	0.06	0.03	0.12	0.03	0.02	0.34
Sn	1'300.00	990.00	520.00	530.00	360.00	360.00	4'060.00
Sr	330.00	54.00	7.20	14'000.00	12.00	130.00	14'533.20
Ta	28.00	19.00	10.00	2.00	2.40	7.50	68.90
Tb	0.19	0.12	0.07	0.31	0.02	0.05	0.76
Te	b.t.	b.t.	b.t.	0.01	0.00	b.t.	0.01
W	0.52	0.32	0.16	1.50	0.15	0.11	2.76
Y	2.50	1.70	0.91	0.36	3.10	0.65	9.22
Zr	36.00	23.00	13.00	3.10	45.00	9.00	129.10

b.t. below threshold
0.00 below 0.01 g
Same uncertainty of measurement as described in Table SI2

Table SI 9: 31 SM masses M_x^{core} (in grams) in the matrix of the Al coarse and Fe scrap fractions (rounded to 2 sign. figures) ranked relative to the ' "core" in % of Total'.

SM	Fe scrap "core"	Al coarse "core"	sum "core"	Total output	"core" in % of Total	mismatch $\frac{\Delta_x}{g}$	rel. mismatch δ_x
Ge	340.00	b.t.	340.00	340.00	100.0%	336.4	99.2%
Nb	2'100.00	1.00	2'101.00	2'100.00	100.0%	2'139.8	99.8%
Li	1'400.00	71.00	1'471.00	1'700.00	86.5%	1'695.5	99.7%
Ga	650.00	290.00	940.00	1'100.00	85.5%	1'097.7	99.6%

Co	2'100.00	31.00	2'131.00	2'700.00	78.9%	2'068.5	77.4%
Mo	4'500.00	30.00	4'530.00	6'300.00	71.9%	6'219.6	98.4%
Ru	13.00	b.t.	13.00	20.00	65.0%	19.2	97.2%
Sn	6'700.00	610.00	7'310.00	17'000.00	43.0%	13'139.8	76.4%
W	100.00	13.00	113.00	290.00	39.0%	285.2	99.1%
La	13.00	3.30	16.30	110.00	14.8%	-1'086.3	-954.1%
Ag	32.00	24.00	56.00	470.00	11.9%	340.3	72.2%
Sm	6.40	0.17	6.57	61.00	10.8%	60.5	99.4%
Sr	1'200.00	76.00	1'276.00	14'000.00	9.1%	95.0	0.7%
Zr	b.t.	100.00	100.00	1'200.00	8.3%	1'078.2	89.3%
Nd	13.00	3.70	16.70	210.00	8.0%	-34.7	-16.7%
Sb	170.00	43.00	213.00	5'000.00	4.3%	4'801.0	96.2%
Pd	b.t.	1.90	1.90	65.00	2.9%	58.1	90.0%
Gd	b.t.	0.52	0.52	19.00	2.7%	14.2	74.4%
Ce	b.t.	6.80	6.80	260.00	2.6%	257.1	98.9%
Pr	b.t.	0.70	0.70	30.00	2.3%	22.4	75.5%
Y	b.t.	1.00	1.00	58.00	1.7%	49.1	84.3%
Au	b.t.	0.17	0.17	22.00	0.8%	-0.3	-1.2%
Be	b.t.	b.t.	b.t.	3.10	b.t.	2.8	89.2%
Dy	b.t.	b.t.	b.t.	12.00	b.t.	7.9	68.5%
In	b.t.	b.t.	b.t.	0.04	b.t.	-2.2	-5244.8%
Pt	b.t.	b.t.	b.t.	0.02	b.t.	-0.8	-3789.5%
Rb	b.t.	b.t.	b.t.	120.00	b.t.	121.1	99.4%
Ta	b.t.	b.t.	b.t.	110.00	b.t.	44.9	39.1%
Tb	b.t.	b.t.	b.t.	1.50	b.t.	0.7	47.5%
Te	b.t.	b.t.	b.t.	39.00	b.t.	38.7	100.0%
Re	b.t.	b.t.	b.t.	b.t.	b.t.	-0.0	b.t.

b.t. below threshold

To show correlations between SM content in the Fe scrap and Al coarse fractions matrix ("core") the respective values for the SM mismatch Δ_x and relative mismatch δ_x are listed in the last two columns.

We defined the SM mass balance mismatch Δ between shredder output mass M_x^{out} and shredder input mass M_x^{in} as:

$$\Delta_x = M_x^{out} - M_x^{in}$$

the relative mismatch δ is defined as:

$$\delta_x = \frac{M_x^{out} - M_x^{in}}{M_x^{out}}$$

the assignment of the error is defined as:

$\Delta = 0$; i.e. output and input are balanced (or errors have been cancelled out)

$\Delta > 0$; i.e. output larger than input, we missed something in the input thus it's an input error

$\Delta < 0$; i.e. input larger than output, we missed something in the output thus it's an output error

The "shredder input" according to these definitions is NOT the 95.3 t total mass of the 100 cars which physically went into the shredder but the total mass of all 31 SM found in the analyzed EE-components and projected to 100 hypothetical mid-range passenger vehicles.

Table SI 10: Average mass $\overline{m}$ of EE components considered for the calculation of mass of SM in one passenger vehicle. The device to which the components belong is also presented.

EE component	**EE device**	**Average EE component mass in grams**	**Number L of EE components used to determine the average mass**
Populated Printed Circuit Boards	ABS pump	40	1
	Fuel pump	1.8	4
	GPS navigation system	329.27	11
	Radio		
	Instruments (user interface)	160.30	11
	Multi-function control stalk	25.8	6
	Fuse box	379.40	4
	Air mass meter	41.2	1
	Airbag/crash sensor	10.28	7
	Airbag controller	75.78	5
	Motor controller	147.66	19
Connectors	ABS pump	169.03	3
	Fuel pump	10.40	4
	Power windows	16.92	4
	Wiper Motor	56.30	4
	Radiator fan motor	63.80	2
	GPS navigation system	5.5	8
	Radio / CD		
	Instruments (User Interface)	10.00	1
	Multi-function control stalk	106.78	5
	Fuse box	9.50	5
	Air mass meter	17.50	1
	Airbag / crash sensor	11.60	1
	Motor controller	35.60	2
	Oxygen sensor	12.78	10
	ABS sensor	35.70	1
Magnets	ABS pump	234.00	2
	Fuel pump	137.40	4
	Starter motor	528.97	3
	Power windows	144.10	4
	Wiper Motor	157.00	4
	GPS navigation system	13.17	4
	Radio / CD		
	Instruments (User Interface)	4.90	1
	Multi-function control stalk	4.80	1
Electric brushes	ABS pump	6.29	10
	Fuel pump		
	Alternator		

	Starter motor		
	Power windows		
	Wiper Motor		
	Radiator fan motor		
Commutators	ABS pump	24.70	20
	Fuel pump		
	Alternator		
	Starter motor		
	Power windows		
	Wiper Motor		
	Radiator fan motor		
	Instruments (User Interface)	2.00	1
LCD displays (foil)	GPS navigation system	13.6	11
	Radio / CD		
LCD displays (glass)	GPS navigation system	43.17	11
	Radio / CD		
Sensor element in lambda probe	Oxygen sensor	1.11	10
ABS sensor (plastic part)	ABS sensor	53.64	4
ABS sensor (metal part)	ABS sensor	22.47	4
Resistors from air mass meter	Air mass meter	0.10	2

The average mass of the components in the individual parts and devices was calculated as follows:

$$m_{ijk} = \overline{m} = \frac{1}{L}\sum_{l=1}^{L} m_l$$

With m_l being the mass of one particular component i contained in a certain part j of a specific device k; $\overline{m}$ is calculated from a set of L components i extracted from parts and devices of the same kind (means i, j and k = constant; L is given in the new Table SI 10). For example: the average mass $\overline{m}$ of the "Magnets" used in the "Electromotors" of a "Fuel pump" is 137.4 g, which was derived from weighing L=4 "Magnets" extracted from 4 different fuel pumps.

The average mass fraction w_{xi} of one particular component i (see Table SI 2) was obtained by mixing components (i=constant) found in selected j parts and k devices. The sample preparation procedure thus did the averaging, i.e. the average mass fraction was not calculated.

Paper II

Quantifying the distribution of critical metals in conventional passenger vehicles using input-driven and output-driven approaches: a comparative study

Du X, Restrepo E, Widmer R, Wäger P. J Mater Cycles Waste Manag. 2015;17(2):218–28.

Not included due to copyright restrictions

Paper III

Stocks, Flows, and Distribution of Critical Metals in Embedded Electronics in Passenger Vehicles

Restrepo E, Løvik AN, Wäger P, Widmer R, Lonka R, Müller DB. Environ Sci Technol. 2017 Feb 7;51(3):1129–39.

Environmental Science & Technology

Policy Analysis

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Stocks, Flows, and Distribution of Critical Metals in Embedded Electronics in Passenger Vehicles

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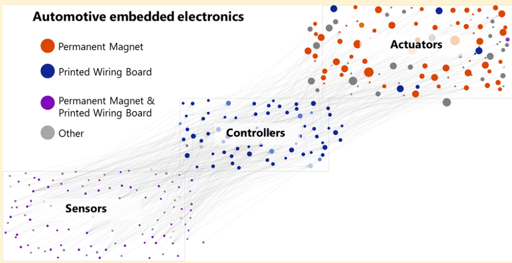
Supporting Information

ABSTRACT: One of the major applications of critical metals (CMs) is in electrical and electronic equipment (EEE), which is increasingly embedded in other products, notably passenger vehicles. However, recycling strategies for future CM quantities in end-of-life vehicles (ELVs) are poorly understood, mainly due to a limited understating of the complexity of automotive embedded EEE. We introduce a harmonization of the network structure of automotive electronics that enables a comprehensive quantification of CMs in all embedded EEE in a vehicle. This network is combined with a material flow analysis along the vehicle lifecycle in Switzerland to quantify the stocks and flows of Ag, Au, Pd, Ru, Dy, La, Nd, and Co in automotive embedded EEE. In vehicles in use, we calculated 5^{+3}_{-2} t precious metals in controllers embedded in all vehicle types and 220^{+90}_{-60} t rare earth elements (REE); found mainly in five electric motors: alternator, starter, radiator-fan and electronic power steering motor embedded in conventional passenger vehicles and drive motor/generator embedded in hybrid and electric vehicles. Dismantling these devices before ELV shredding, as well as postshredder treatment of automobile shredder residue may increase the recovery of CMs from ELVs. Environmental and economic implications of such recycling strategies must be considered.



1. INTRODUCTION

Recent concerns regarding the availability of raw materials for future technologies have motivated material criticality assessments.[1−4] According to Graedel et.al, 2015[4] rare earth elements (REE) are particularly critical considering the risk associated with the global supply being dominated by one country, while the criticality of precious metals (PMs) such as Ag, Au and Pd is regarded to economic importance, environmental implications and substitutability, respectively.

One of the major applications of critical metals (CMs) is in electrical and electronic equipment (EEE),[1,4] which is at the same time increasingly embedded in other products, notably automobiles.[5−9] Currently, embedded automotive electronics account on average for 30% of the total car cost (this percentage is expected to increase to 50% in 2030)[8] and already 15−25% of the global neodymium−iron-boron (NdFeB) permanent magnet production is used for automotive electronic applications.[7] It can therefore be expected that the amounts of CMs in end-of-life vehicles (ELVs) increase dramatically in the coming years.

Recycling emerges as a key strategy to ensure future access to CMs.[1] However, current treatment of ELVs favors the recycling of bulk metals like iron, aluminum and copper while most CMs end up in the automobile shredder residue (ASR) from which they are currently not recycled.[10]

The ongoing revision of the Swiss regulation on waste electrical and electronic equipment (WEEE) plans to set the legal framework for a mandatory dismantling and subsequent recycling of selected electrical and electronic (EE) devices embedded in ELVs, based on CM mass in the EE devices and when ecologically and economically feasible.[11] However, the mass distribution of CMs among the large variety of embedded automotive EE devices is still poorly understood and the devices to be included in the amended WEEE regulation are yet to be defined.

A comprehensive analysis of the CM mass distribution in embedded automotive electronics is challenging, mainly due to complexity of (i) the car fleet (many car types and cohorts containing different type and number of embedded electronics), (ii) an individual car (many embedded subsystems and EE devices), and (iii) electronics (many parts, components and materials).[12] Additionally, data availability from manufac-

Received: November 14, 2016
Revised: December 23, 2016
Accepted: January 18, 2017
Published: January 18, 2017

turers is hampered by trademark protection and confidentiality agreements.

Previous studies have mainly focused on calculating the mass of selected CMs in total vehicle stocks/flows or in specific car types. Xu et al.[13] and Andersson et al.[14] have calculated the mass of selected CMs in selected embedded automotive electronics in the flow of Japanese and Swedish ELVs, respectively. Xu et al. considered EE devices from two Toyota car models (conventional and hybrid) at different penetration rates depending on the ELV cohorts, whereas Andersson et al. considered EE devices from three hypothetical Volvo cars produced in 2012 for three different estimations of CM mass in the ELV flow. Of these two, only Xu et al. provides detail on the distribution of the CM mass among the EE devices considered. De Haan et al.[15] estimated the future inflow and stock of selected CMs in the Swiss vehicle fleet considering the share of different vehicle types. However, only one electronic device per CM and vehicle type was accounted for. Data from five studies analyzing the mass of selected CMs in specific vehicle types has been compiled by Du et al;[12] emphasizing the heterogeneity of results on CM mass per vehicle and the lack of detailed data at the EE device level. In general, previous studies provide limited information on the distribution of metal mass among vehicle electronics necessary to inform a dismantling strategy.

In this study, we aim to inform the dismantling strategy foreseen in the current revision of the Swiss WEEE regulation and address the following research questions:

1. What are the stocks and flows of selected CMs in embedded EE devices in passenger vehicles in Switzerland?
2. What is the mass distribution of the selected metals among embedded EE devices?
3. From a mass perspective, which EE devices justify a potential inclusion in the amended WEEE regulation?

The mass quantification is done by means of a layered material flow analysis comprising the vehicle life cycle, import, through use, to ELV treatment and incorporating a harmonized structure of vehicle electronics. The EE devices containing CMs are selected from all standard embedded electronics in the vehicle stocks and flows considered.

2. MATERIALS AND METHODS

A network structure of automotive electronics in passenger vehicles was combined with a layered material flow analysis (MFA)[16,17] to calculate the stocks and flows of selected CMs along the passenger vehicle life cycle in Switzerland (passenger vehicle system). The layered MFA approach, passenger vehicle system, data sources used for the mass quantification and related uncertainty considerations are presented below.

2.1. Layered Material Flow Analysis and Network of Automotive Electronics. CMs (substances) in passenger vehicles (goods) are mainly found in the embedded EE devices.[12] These EE devices (and in general, embedded electronics in products) interact with each other to accomplish specific functions within network structures called electronic control systems (ECS).[9,18−22] Depending on their function within an ECS, EE devices are classified as sensors, controllers and actuators.[9,18−21] The connection of these EE devices within ECS may be physical (through cables) or wireless.[9] Most previous studies analyzing CMs in passenger vehicles have overlooked the network structure of ECS, thus grouping EE with non-EE components such as the engine. As the grouping of car components varies among studies, their results are largely heterogeneous regarding CM mass per vehicle subsystem and the importance of individual EE devices for the total CM mass in vehicles is difficult to evaluate.[12]

In this contribution, we consider ECS as a higher hierarchical sublayer from which the other sublayers of goods and substances derive (Figure 1). ECS are then formed by EE

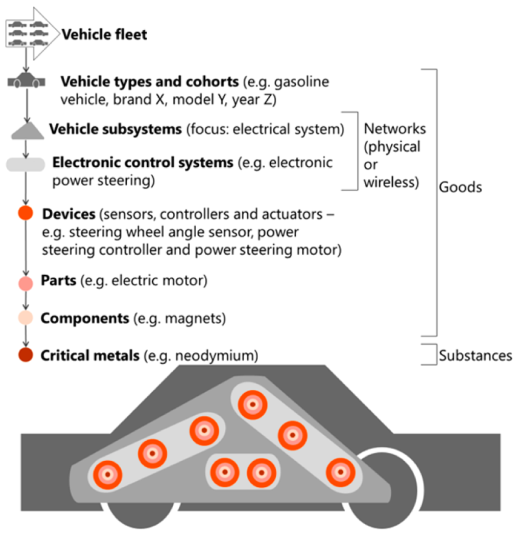


Figure 1. Material layers considered in this study. ECS are a sublayer of goods within passenger vehicles and represent the network structure in which embedded EE devices interact. EE devices, EE parts and EE components are subsequent layers of goods in which CMs are found.

devices containing EE parts in which EE components made of CMs are found. By incorporating the network structure of ECS within a MFA, the totality of EE devices (sensors, controllers and actuators) are accounted for. The grouping of EE devices remains consistent across different vehicle types. Therefore, our approach enables the identification of individual EE device's importance for the total CM mass in vehicles. A detailed description of this approach is provided in section 2 of the Supporting Information (SI).

2.2. System Description. Vehicles enter Switzerland through 33 official vehicle importers or by direct user import.[23,24] Subsequently, vehicles are registered at the Swiss Federal Roads Office (FEDRO) and enter the use phase.[23,25] There are three states in which a vehicle may exit the use phase: second hand vehicle, accident vehicle and ELV.[26] Second hand vehicles are either sold within the country or exported.[27] Depending on the damage, accident vehicles are repaired or treated as ELV.[26] ELVs are defined as "vehicles which are waste" according to the Swiss waste regulation.[28] The ELV treatment includes: depollution and dismantling (D&D), shredding and separation (S&S), and incineration of ASR in municipal solid waste incinerators (MSWI). After ELV treatment, CMs are distributed among the different material outputs of ELV treatment processes.[10,12] A detailed description of the system and its processes is provided in section 3 of the SI.

DOI: 10.1021/acs.est.6b05743
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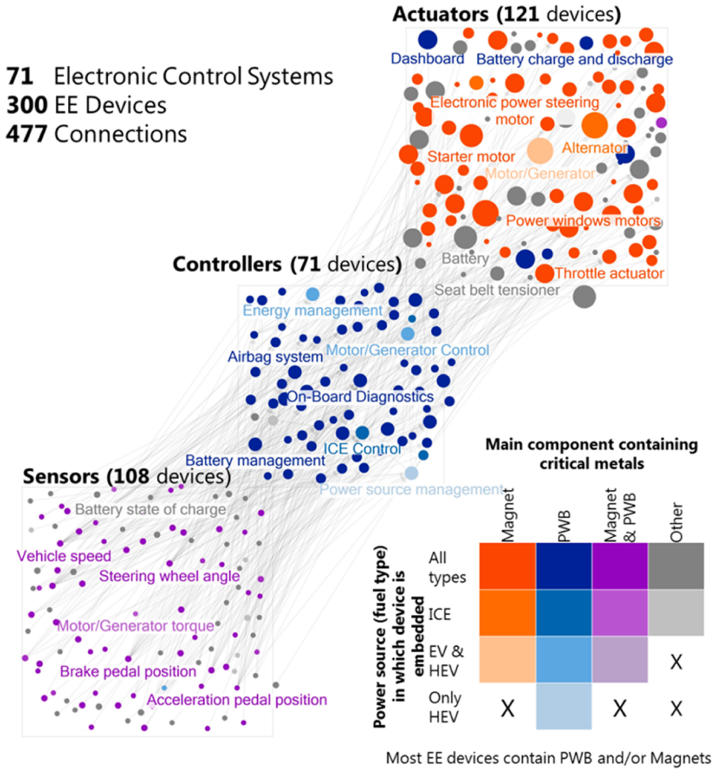

Figure 2. Network of automotive embedded EE devices per vehicle power source (fuel type). The nodes of the graph represent the EE devices. The size of the nodes is a qualitative representation of the EE device's mass. The color of the nodes represents the EE components containing CMs. The edges (lines) represent the connections of EE devices within ECS (physical or wireless). The name of selected devices is presented below and centered from the device. The names of all EE devices in the figure as well as their connections are provided in the SI, section 4. Acronyms and abbreviations are defined in the SI, section 1. In summary: 70% of the EE devices contain either permanent magnets or printed wiring boards (PWB). Magnets are mostly used in actuators, while PWBs are mostly used in controllers. Sensors contain both magnets and PWBs indistinctly. The remaining 30% of devices hold other EE components such as batteries, solenoids, LEDs and LCDs. In general, actuators have a larger mass than controllers and sensors.

2.3. Selection of Metals to Be Quantified and Corresponding EE Devices. The CMs analyzed were selected based on (i) their frequency of occurrence in EE devices in passenger vehicles and (ii) the mass of the EE devices containing the most frequent CMs. This was obtained by literature review of scientific studies analyzing the occurrence of ECS in different vehicle types,[19,20,29,30] technical books on automotive electronics,[22,31] technical catalogues of vehicle brands used in Switzerland,[32,33] scientific studies analyzing CMs in automotive electronics,[10,12,13,34,35] manufacturer reports on material composition of automotive EE devices and components,[36−42] and patents.[43−48] Additionally, we validated the composition of selected automotive electronic components by direct communication with expert manufacturers.[49−51] The results of the literature review leading to the selection of metals and devices considered are summarized in Figure 2; detailed results are provided in SI, section 4.

The following CMs were selected for further quantification: Ag, Au, Co, Dy, La, Nd, Pd, and Ru. The EE devices considered were controllers; in which printed wiring boards (PWBs) containing PMs (Ag, Au, Pd, and Ru) are predominantly used, and actuators; in which permanent magnets containing REE (Dy, La and Nd) and Co are predominantly used. Sensors were excluded due to their low mass relative to controllers and actuators.[10] This exclusion was based on rough estimations of the EE devices' mass and may have led to underestimation of CM mass in cases in which the mass fraction of the considered CMs is significantly higher in sensors than in controllers and actuators.

2.4. System Quantification. The total mass flow of vehicles imported and total stock of vehicles in use was calculated with information in the Swiss vehicle registration database (*MOFIS* database) from FEDRO.[52] The mass flow of vehicles exported was obtained from the import/export database (*Swiss-Impex* database) of the Swiss Federal Customs Administration.[53] The mass flow of deregistered vehicles and ELV was calculated by mass balance. Detailed data and calculations are given in the SI sections 5, 6, 7, and 8. The mass of ELV D&D output flows was calculated with transfer coefficients determined by Dix in an experiment at a Swiss

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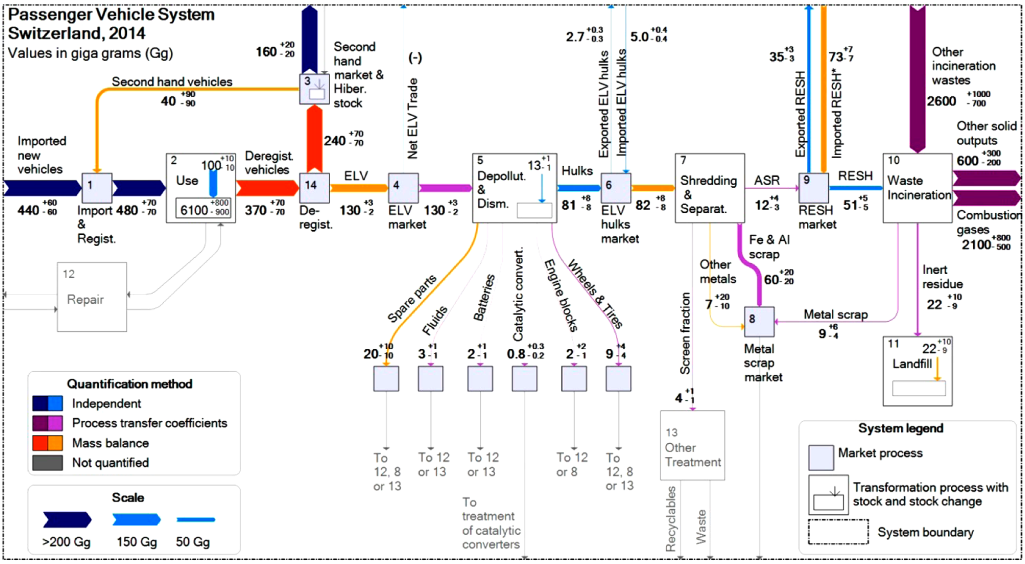

Figure 3. System of passenger vehicles in Switzerland, 2014. Material layer: passenger vehicles and ELV treatment output fractions. Values are given as median ±97.5th and 2.5th percentile of Monte Carlo simulation; equivalent to a 95% confidence interval. Uncertainty values are rounded to one significant digit, median values are rounded to the precision of the uncertainty, (−) indicates a value equal to zero. Process' inputs and outputs may not add up to the same number due to rounding. The arrow width is cut off at 200 Gg. Dark colors indicate values larger than 200 Gg, bright colors indicate values smaller than or equal to 200 Gg. Other metals from S&S include pieces of electrical machines. RESH: mix of ASR and nonautomobile shredder residue. Imported RESH* includes ASR from other countries as well as nonautomobile shredder residue from Switzerland and other countries. Acronyms and abbreviations are provided in SI, section 1. Figure data can be found the SI, Table S16.

ELV dismantling plant in 2014,[54] as well as by interviews at the same facility[55] and by mass balance. The mass flow of ELV hulks shredded was obtained from waste statistics of the Swiss Federal Office for the Environment (FOEN).[56] The mass of S&S outputs was calculated with transfer coefficients determined in a previous experiment by the authors at a Swiss shredder facility in 2014[10] and by mass balance. The mass of waste incineration outputs was calculated with transfer coefficients determined by Morf et al. at a Swiss MSWI in 2013.[34]

The mass of CMs in the import flow, in-use stock and ELV flow was calculated using eq 1.

$$M_E^i = \sum_{j,k} G_{ji} \cdot m_{kj} \cdot w_{Ekj} \tag{1}$$

Where M_E^i is the mass of metal E in vehicle stock/flow i, G_{ji} is the number of EE devices of type j in i, m_{kj} is the mass of component k containing metal E in device j and w_{Ekj} is the mass fraction of metal E in component k embedded in device j.

The CM masses were not quantified for deregistered and exported vehicles, because of lack of information regarding the vehicles' cohort, brand and model.

To obtain the number of EE devices G_{ji} we used the *Autohandel* database from the company Auto-i-Dat AG.[57] The *Autohandel* is a database for Swiss car dealers containing the number and type of the standard equipment embedded in vehicles registered in Switzerland since 2000. We first classified all the vehicles in the stocks and flows considered into vehicle types of the *Autohandel* (combinations of cohort, power source, brand and model); 128 brands and 6859 models registered in the *Autohandel* were considered. Vehicles of cohorts before 2000, or which we were not able to classify to *Autohandel* types, were classified as an average vehicle type of 2000. This classification may have led to overestimations of metal mass, in particular for devices that were penetrating around or right before the year 2000 (because the considered number of EE devices will be higher than the actual one). Underestimation may have occurred when the not-classified vehicles actually contain more EE devices. Therefore, the number of EE devices embedded in not-classified vehicles was considered highly uncertain in the final mass calculation.

The cohort, brand and model of vehicles imported and in stock were obtained from the *MOFIS* database. For ELV, these were obtained from the shredded ELV database of the Foundation Auto Recycling Switzerland (*SARS-ELV* database).[58] We then obtained the number of embedded EE devices per vehicle type from the *Autohandel* and scaled it up to the total number of vehicles in the respective stock and flow. Detailed calculations are presented in the SI, section 8. Following, we carried out a Pareto analysis[59] to reduce the list of EE devices to a "vital few" accounting for 80% of the total number of occurrences of EE devices in the vehicle stock or flow. The results of the Pareto analysis were compared against the list of EE devices obtained in section 2.3 to (i) make sure that none of the *heavy* EE devices were left out of our analysis, and (ii) complete the network of EE devices whenever the *Autohandel* only provided the name of one of the EE devices in a particular ECS. Details on the classification procedure and Pareto analysis are given in the SI sections 9 and 10.

The mass of components in devices was obtained from studies analyzing CM mass in automotive electronics (specific

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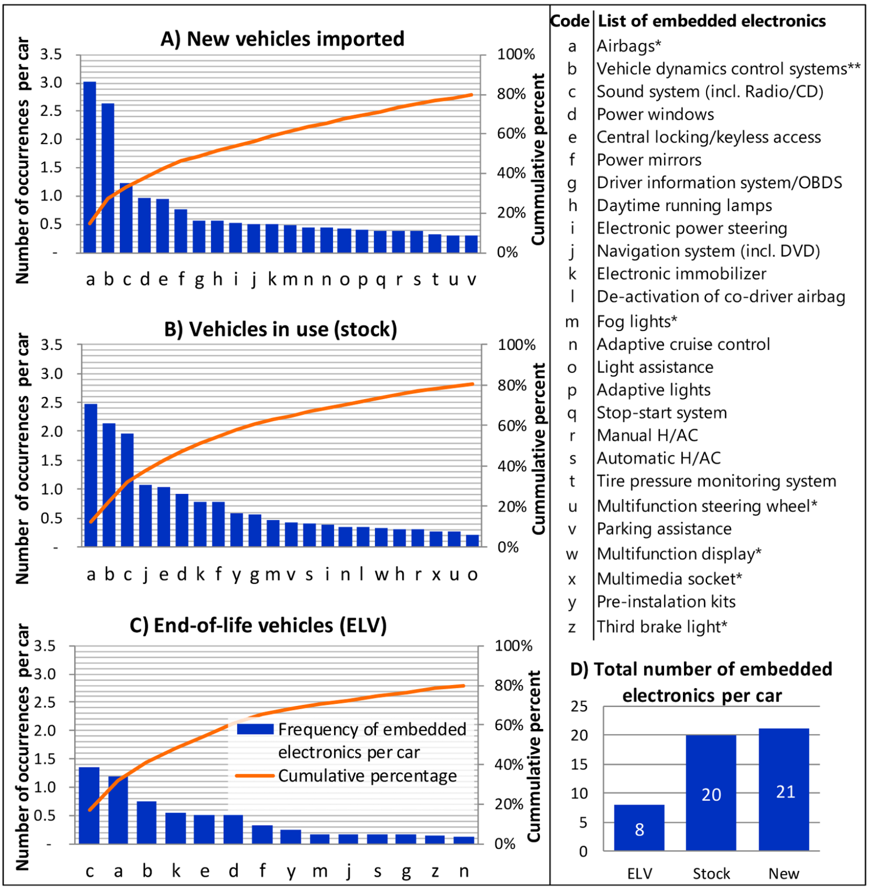

Figure 4. Frequency of embedded electronics in (A) flow of new vehicles imported, (B) stock of vehicles in use, and (C) flow of ELV in 2014. Figure 4D displays the total number of embedded electronics per car in the corresponding stock and flows. In panels A to C, the blue bars represent the number of specific electronics per car in the stock and flows considered; the value is displayed on the left axis. The cumulative percentage of this number of electronics with respect to the total number per car is represented by the orange line; the value is displayed on the right axis. *EE devices; the ECS network can be completed with information in Table S2 of the SI. **Vehicle dynamics control systems, including ABS, ESP, EBD, HHC, DSR, TCS, and CBC. Acronyms are provided in the SI, section 1. Detail data is provided in SI, section 10.

cohorts, power sources, brands, and models),[10,13,60] as well as from catalogues of vehicle electronics manufacturers,[61] and from direct measurements of a sample of spare parts at a Swiss ELV dismantler. The mass fraction of CMs in the components was obtained from studies analyzing CM mass in selected automotive EE components[10,13,62] and from patents of the materials used in the EE components.[63] All parameter data, including relative uncertainty and data sources are given in the SI, Table S4.

There is no official information regarding the type, number and mass of spare parts dismantled from ELV.[55] Additionally, there is an output fraction from S&S that has not yet been investigated: other metals parts larger than 100 mm, including pieces of electrical machines (e.g., magnets, coils and casings).[10] Therefore, we calculated the mass of CMs in a joint flow of spare parts and other metals separated after shredding by means of a combined mass balance of the D&D and S&S processes.

The allocation of the mass of CMs in incineration outputs to the input of ASR it also not known. Thus, it was not possible to calculate the mass of the selected metals found in ASR that is distributed among the waste incineration outputs.

2.5. Uncertainty Analysis. All the stocks and flows in this study were calculated by means of Monte Carlo simulation in order to account for data-related uncertainties. The detailed procedure is presented in the SI section 6.

3. RESULTS

Results are given as median ±97.5th and 2.5th percentile of Monte Carlo simulation; equivalent to a 95% confidence interval. Uncertainties are rounded to one significant digit and median values are rounded to the level of precision of the uncertainty; (−) indicates a value equal to zero.

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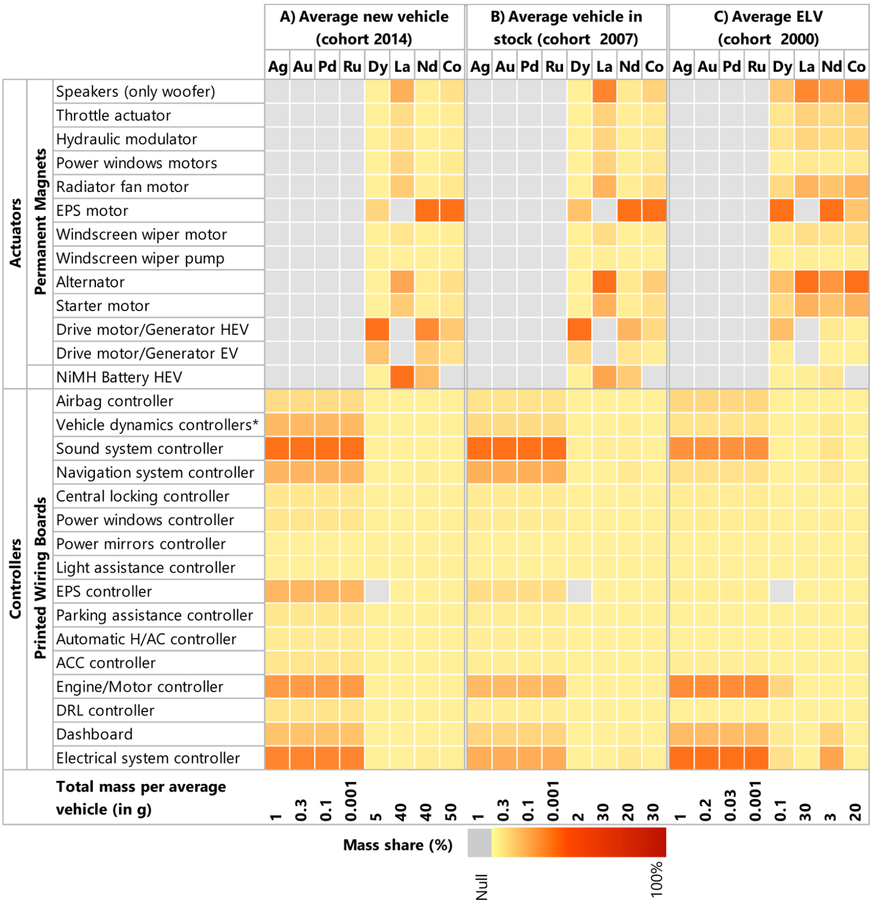

Figure 5. Distribution of CM mass in EE devices in an average (A) new vehicle, (B) vehicle in stock, and (C) ELV. The figure reads by element (columns): for each element, the color scale corresponds to the share of total element mass (in percentage) that is contained in a specific EE device per average vehicle. For example, in an average ELV, La is found mainly in the alternator, while in an average new vehicle it is found mainly in the NiMH battery of HEV. *Vehicle dynamics controllers include: ABS, ESP, EBD, HHC, DSR, TCS, and CBC. Acronyms are provided in the SI, section 1. Figure data is provided in the SI, Table S24.

The Swiss stock of passenger vehicles has steadily increased in the last decades; between 1990 and 2014 the vehicle stock increased by 50%.[64] In 2014, there were 4 000 000 vehicles in stock (approximately one vehicle per every two people),[52] 300 000 vehicles imported[24] and 100 000 ELVs shredded.[58] In terms of mass, in 2014, we calculated 6100^{+800}_{-900} Gg of passenger vehicle stock, 440^{+60}_{-60} Gg/a of imported new vehicles and 370^{+70}_{-70} Gg/a of deregistered vehicles (Figure 3). Out of the deregistered vehicles, about half (160^{+20}_{-20} Gg/a) were exported, 40^{+90}_{-90} Gg/a were registered again as second hand vehicles, and 130^{+3}_{-2} Gg/a were treated as ELV in Switzerland. The remaining vehicle mass indicates a hidden export, a hibernating stock (deregistered but not exported vehicles; see process 3 in Figure 3), or missing processes that were not accounted for in this study. The ELV flow is comparable to the total 130 Gg of WEEE treated in Switzerland in 2014.[65]

ELV D&D generated a total of 81^{+8}_{-8} Gg/a of ELV hulks; resulting from the removal of 2^{+2}_{-1} Gg/a engine blocks, 2^{+2}_{-1} Gg/a batteries, $0.8^{+0.3}_{-0.2}$ Gg/a catalytic converters, 9^{+4}_{-4} Gg/a wheels (including tires) and 3^{+1}_{-1} Gg/a fluids. We calculated an additional 20^{+10}_{-10} Gg/a of materials exiting from D&D, which may correspond to spare parts such as EE devices and car doors, as well as other materials such as plastics and glass.[55] At the S&S process, we computed output flows of 60^{+20}_{-20} Gg/a of iron and aluminum scrap and 12^{+4}_{-3} Gg/a ASR. By mass balance, we calculated an additional 7^{+20}_{-10} Gg/a of material exiting S&S. These correspond to pieces of electrical machines and other metal parts separated after shredding.[10] The large uncertainty of this value results from the mass balance calculation with uncertain parameters.

Metal scrap entered the recycling market, while ASR was incinerated at MSWI.[66] After incineration of mixed waste, we calculated an output of 9^{+6}_{-4} Gg/a of ferrous and nonferrous metals. The allocation coefficient of these metals' mass to ASR it is not currently known.

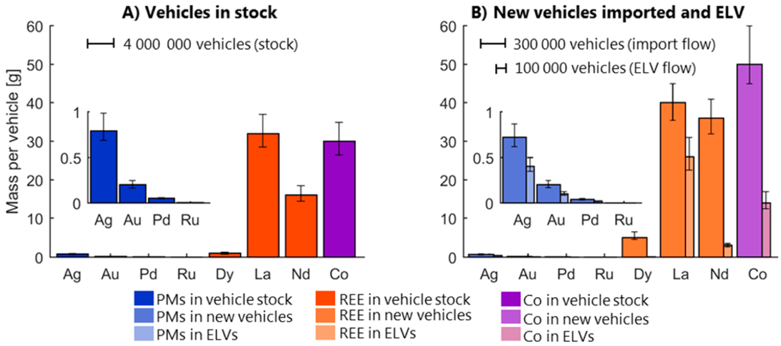

Figure 6. Stocks and flows of CMs in passenger vehicles in Switzerland, 2014. The width of bars is proportional to the number of vehicles. The total CM stock or flow can be calculated by multiplying the width times the height. The error bars display 97.5th and 2.5th percentile of Monte Carlo simulation; equivalent to 95% confidence interval. Values are rounded to one significant digit. Figure data is provided in Tables S21 to S23 of the SI.

Figure 4 shows the number of electronics embedded in vehicles imported, in stock and ELV as obtained from the *Autohandel* database; the list displays a mix of ECS and EE devices. The ECS networks can be completed with information in Table S2 of the SI in each case. We identified a direct correlation between the cohort year of the vehicles and the number of embedded ECS: the younger the vehicle, the higher the number of ECS (Figure 4D). In some cases, the number of EE devices per ECS per vehicle also increased with the cohort year; for example, the number of airbags per vehicle (code *a* in Figure 4) was 1.1 in ELV (Figure 4C), 2.5 in vehicles in stock (Figure 4B) and 3 in vehicles imported (Figure 4A). However, in other cases, the number of ECS decreased with the cohort year, such was the case for sound and navigation ECS (codes *c* and *j* in Figure 4) for which a decrease in number was identified in new vehicles imported compared to vehicles in stock. This decrease may be due to the integration of the radio and navigation system into one ECS. Another example of integration of EE devices and ECS was identified for ECS related to vehicle dynamics control (VDC, code *b* in Figure 4). Examples of ECS related to VDC are Antilock Braking System (ABS), Electronic Stability Program (ESP) and Traction Control System (TCS). These ECS have been progressively integrating and/or replacing each other to improve the overall VDC.[22,67] Even though the number of ECS related to VDC increases with cohort, most of them still control some of the same actuators, for example, throttle actuator and hydraulic modulator.[22] Thus, in some cases, due to ECS integration/replacement, the number of ECS increases with the cohort year, but the number of EE devices per ECS does not necessarily increase. Nevertheless, regardless of possible integrations of ECS and EE devices in vehicles, the total CM mass per vehicle increased from ELV to vehicles in stock, to new vehicles (Figure 5). This is due to, among others, the introduction of more CM intensive EE devices such as the drive motor/generator in electric and hybrid electric vehicles (HEV), which replaces both the starter motor and the alternator, but bears higher REE mass.

Figure 5 shows the distribution of CM mass in EE devices. In total, 16 ECS were commonly embedded in new vehicles imported, in stock and ELV. Altogether, these ECS share a total of 29 devices: 13 actuators; 12 of which contain permanent magnets, and 16 controllers containing PWBs. The largest hoards for REE mass in new vehicles were the electronic power steering (EPS) motor embedded in all types of vehicles, the drive motor/generator embedded in electric and HEV and the NiMH battery embedded in HEV (Figure 5A). In vehicles in stock, REE mass was similarly concentrated, except for La mass, which maximum mass was found in alternators embedded in conventional passenger vehicles instead of the NiMH battery (Figure 5B). The largest holders for REE mass in ELV were the alternator in conventional passenger vehicles as well as EPS motor and speakers in all types of vehicles (Figure 5C). Regarding PMs, the electrical system controller (fuse box), the sound system controller (radio), the navigation system controller and the engine/motor controller contained most of the PM mass in vehicles independent of cohort and type.

In the total automotive embedded EEE in the vehicle stock we calculated 5^{+3}_{-2} t PMs, 220^{+90}_{-60} t REE and 130^{+60}_{-50} t Co. The mass of Au in the stock of automotive EEE represents 24% of the Au mass in the stock of household and consumer electronics (household EEE) in 2014,[68] whereas the mass of Nd in the stock of automotive EEE is slightly higher than in the stock of household EEE in 2010: we calculated 70^{+30}_{-20} t Nd in the automotive EEE stock compared to ~60 t Nd in the stock of household EEE as calculated by Böni et al.[69]

Figure 6 shows the calculated mass of CMs (bar height) and number of vehicles (bar width) in the stock, import, and ELV flow in 2014; the area of the bars represent the total mass. The total CMs masses were more than 5 times higher in the vehicle import flow compared to the ELV flow, for example, we calculated 25^{+8}_{-6} t/a REE in new vehicles, compared to 3^{+2}_{-1} t/a REE in ELVs. About half of the mass increase results from the larger number of vehicles (3 times larger in the import than ELV flow), whereas the other half results from a higher CM mass per vehicle in the import flow (Figure 6B). It can therefore be expected that the amount of CMs in the ELV flow increases by a factor of 2 in the coming 15−20 years (average age of an ELV). Comparing the results per ELV, our results agree with lower-bound estimations in Xu et al.[13] and Andersson et al.;[14] which is coherent with the low share of HEV and high share of old conventional vehicles in the Swiss ELV flow. The low estimations may also be the result of not being able to classify vehicles that contain higher number of the EE devices considered and to the exclusion of sensors and structural parts from our calculations.

The distribution of CM mass in the ELV treatment system is presented in Figure 7. In agreement with Widmer et al., 2015,[10]

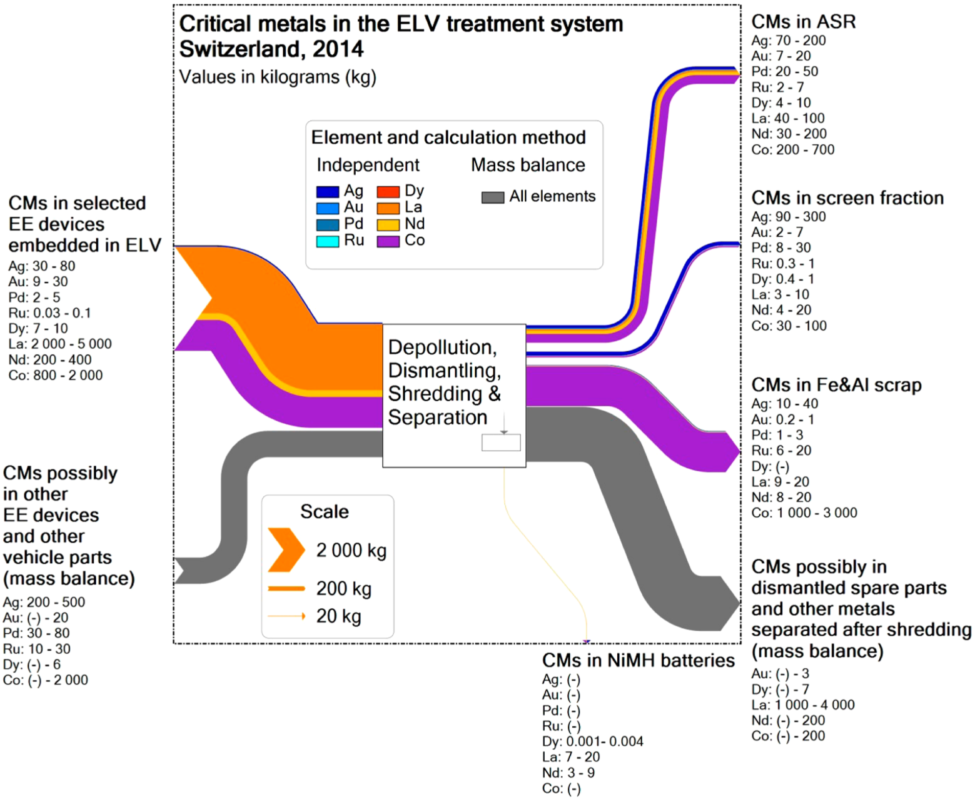

Figure 7. Stocks and flows of CMs in the Swiss ELV depollution, dismantling, shredding and separation processes in 2014. The arrow width represents the median value. The minimum and maximum values are given next to each quantified flow. Minimum and maximum are calculated according to the 2.5th and 97.5th percentile of Monte Carlo simulation; equivalent to 95% confidence interval. Values are rounded to one significant digit; (−) indicates a value equal to zero. Acronyms and abbreviations are provided in the SI, section 1. Figure data is provided in Table S18 of the SI.

after ELV treatment, the ASR and the screen fraction contained most number of CMs. However, potentially major flows of CMs in the ELV treatment, such as the flow of spare parts, remain highly uncertain. While the mass of goods (total mass) in the ELV treatment processes balanced reasonably well (Figure 3), the results showed a large imbalance for most of the CM masses (Figure 7). We calculated an excess mass of 40% Au, 60% Co, and more than 100% Ag, Pd, and Ru in the shredder output fractions compared to the calculated input mass. Likewise, we calculated an excess input mass of 10% Dy, 70% Nd, and more than 100% La compared to the mass in shredder outputs. Some reasons for the excess output include: (i) uncertainties in mass fraction of metals in the selected EE devices and shredder outputs, and (ii) exclusion of selected EE devices, EE components and other structural parts from our calculations, such as sensors (which may bear high mass fraction of CMs), cables (which may contain Ag and Au coatings) and the car's body-in-white (which contains Co as an alloying element).[10] The excess input of REE mass, or lack of REE output, may be explained by spare parts dismantled before shredding as well as to pieces of electrical machines being separated after shredding.[10,55]

Uncertainties in these results may be reduced by, among others, (i) considering EE devices with high mass fraction of CMs (*dense* EE devices) in addition to *heavy* EE devices; for example, the air mass sensor weighs only 100 g/car but its mass fraction of Ag is 20 times higher than in PWB,[10] and (ii) increasing the accuracy in mass fraction of metals in EE devices and ELV treatment outputs by experimental analysis as well as by data transfer from manufacturers.

4. DISCUSSION

With the main goal of informing the current revision of the Swiss WEEE regulation which plans to set the legal framework to require the dismantling and subsequent recycling of selected automotive electronics containing CMs, we calculated the stock, flows, and distribution of selected CMs in embedded electronics in passenger vehicles in Switzerland. The mass estimations provided by our study constitute one of the three criteria considered for the inclusion of automotive electronics in the amended WEEE regulation; the energetic, environmental, and economic implications of automotive electronics dismantling are still to be analyzed.

DOI: 10.1021/acs.est.6b05743
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Compared with the total stock of household and consumer electronics in Switzerland, automotive electronics constitute a significant stock of CMs. For Nd, the stock in automotive electronics is similar to that in household and consumer electronics, while the Au stock in automotive electronics is approximately one-fifth of the Au stock in household and consumer electronics.[68] Considering similarities in number of vehicles per capita,[70] similar results regarding the contribution of automotive electronics to the national stocks of Au and Nd in most west European countries may be expected.

The amounts of CMs in embedded electronics in ELVs, however, tend to be smaller than those in the total flow of WEEE: in Switzerland, the mass flow of Nd in ELVs is equal to 8% of the Nd mass flow in WEEE,[68] while for Au, the mass flow in ELVs is equal to 5% of the mass flow in WEEE.[68] An important explanation for the difference in relevance of automotive electronics for the in-use stocks and end-of-life flows of CMs is the fact that automobiles tend to have a longer lifetime than most household and consumer electronics. Nevertheless, as both the number of vehicles in use and the number of embedded electronics in vehicles have been rising steadily over the past years, the amounts of CMs in ELVs are likely to rise over the coming decades.

Additionally, despite integrations of ECS and EE devices, there is an increase in CM mass in automotive embedded electronics with time. This is due to, among others, the introduction of more CM intensive EE devices such as the drive motor/generator in electric and HEV, which replaces both the starter motor and the alternator, but bears higher REE mass.

In household and consumer electronics, trends in miniaturization have led to a reduce mass of CMs in WEEE, which represents a challenge in WEEE recycling.[7,71,72] Automotive electronics are less prone to a reduction in CM mass due to specifically high requirements regarding safety, workload, temperature resistance, and other factors. Existing WEEE recycling systems may therefore benefit from the inclusion of automotive electronics. Taking into account that automotive controllers are predominantly composed of PWBs, the inclusion of controllers in existing WEEE recycling systems that currently recover PMs from PWBs seems straightforward. Depending on the location of EE devices in vehicles, dismantling may represent additional recycling costs. Nevertheless, a positive cost-revenue evaluation of the dismantling of devices such as the navigation system and the engine/motor controller for a later recovery of PMs in WEEE recycling channels has been indicated by Sander et al. in a German study in 2014.[35]

In contrast to PMs, REE are usually not recycled from WEEE streams.[60] However, industrial recycling of REE from end-of-life magnets has been developed in Japan,[73] and NdFeB magnet to magnet recycling is operational at small scales in the U.S.[74] Challenges regarding the costs, logistics and environmental performance of these recycling options must still be considered.[7,13]

Even though dismantling automotive EE devices may help to increase the recovery of CMs from WEEE, this would lead to a reduction in the amounts of CMs in shredder output fractions such as the ASR, which is currently incinerated in MSWI, some of which recover PMs to certain extent.[75] Depending on the mass fraction of CMs in ASR, postshredder treatment to separate nonferrous metals from ASR[76] may facilitate the separation of CMs before incineration. The final recovery yield, costs and environmental implications of dismantling, post-shredder treatment and/or incineration of ASR need to be evaluated using a quantitative systems approach.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b05743.

Acronyms, abbreviations, parameter data and detailed calculations (PDF)

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ACKNOWLEDGMENTS

This study is part of the *Recycling Electronics from ELVs Project* (EVA) commissioned by the FOEN (acronyms are presented in section 1 of the SI). We thank the project partners for their financial and in kind contributions: SARS, AWEL, VAREX, auto-schweiz and VASSO; particularly its member Truninger AG. Special thanks to Auto-i-Dat AG for the access to the *Autohandel* database and FEDRO for the *MOFIS* database. Thanks to Felipe Vásquez for helpful discussions, to Esther Thiébaud for information on CM content in WEEE and to Steve Constantinides, John Ormerod and Robin Sommer for clarifications on metal content in automotive permanent magnets.

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DOI: 10.1021/acs.est.6b05743
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Supporting information to:

Stocks, Flows, and Distribution of Critical Metals in Embedded Electronics in Passenger Vehicles

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This document stands as supporting information for the article: "Stocks, Flows and Distribution of Critical Metals in Embedded Electronics in Passenger Vehicles".

This supplement contains:
76 Pages
24 Tables
3 Figures

Contents

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1. Acronyms and abbreviations

The acronyms and abbreviations are presented in alphabetic order.

Acronyms and abbreviations	**Description**
ABS	Antilock Braking System
ACC	Adaptive Cruise Control
ASR	Automobile Shredder Residue
auto-schweiz	Schweizer Automobil-Importeure (Swiss association of automobile importers)
CBC	Cornering Brake Control
CMs	Critical metals
DRL	Daytime Running Lamps
D&D	Depollution & dismantling
DSR	Driver Steering Recommendation
EBD	Electronic Brake-force Distribution
ECS	Electronic control systems
EE	Electrical and electronic
EEE	Electrical and electronic equipment
ELVs	End-of-life Vehicles
EPS	Electronic Power Steering
ESP	Electronic Stability Program
EU	European Union
EV	Electric vehicle (powered by an electric motor)

EVA	Elektronik-Verwertung-Altautos (Recycling Electronics form ELVs Project)
FEDRO	Swiss Federal Roads Office
FOEN	Swiss Federal Office for the Environment
H/AC	Heating and Air Conditioning
HEV	Hybrid electric vehicle (powered by both an electric motor and an internal combustion engine –gasoline or diesel–)
HHC	Hill-Hold Control
HMFA	Hierarchical material flow analysis
ICE	Internal combustion engine
LCD	Liquid crystal display
LED	Light-emitting diode
MOFIS	Automatisierte Fahrzeug und Fahrzeughalterregister (translated in this study as *vehicle registration database*)
MSWI	Municipal solid waste incinerator
NiMH	Nickel metal hydride
OBDS	On Board Diagnostics System
PGMs	Platinum group metals
PMs	Precious metals (in this study: Ag, Au, Pd and Ru)
PWB	Printed wiring board
REACH (EU REACH)	European Union Registration, Evaluation, Authorization and Restriction of Chemicals
REE	Rare earth elements (in this study: Dy, La and Nd)

RESH	Mixed shredder residue, including ASR and non-automobile shredder residue (In German: Reststoffe von Shredder)
RoHS (EU RoHS)	European Union legislation on the restriction of certain hazardous substances in electrical and electronic equipment
S&S	Shredding and separation
SARS	Foundation Auto Recycling Switzerland
SI	Supplementary information
TCS	Traction Control System
VAREX	Vereinigung Autorecycling und Export Schweiz (Swiss association of automobile recyclers and exporters)
VASSO	Vereinigung der offiziellen Autosammelstellenhalter der Schweiz un des Fürstentum Liechtensteins (Association of the Official Car Collection Point Proprietors of Switzerland and the Principality of Liechtenstein)
VDC	Vehicle Dynamics Control
WEEE	Waste Electrical and Electronic Equipment
AWEL	Amt für Abfall, Wasser, Energie und Luft (Office of Waste, Water, Energy, and Air of the canton of Zurich)

2. Layered material flow analysis and network of automotive electronics

In MFA, goods are related to substances by being physically composed of them; an MFA considering goods will regard substances within those goods as an additional material layer.[1]

A passenger vehicle is a complex system whose subsystems and components can be classified in many different ways depending on the goal of the research.[2] In this case, we are addressing the number of EE devices containing CMs in different vehicle types. All EE devices embedded in passenger vehicles are electricity consumers and form part of ECS comprised by the electrical system.[2–7] ECS are network structures in which the EE devices interact to accomplish specific functions in the vehicle. EE devices within ECS are classified as sensors, controllers and actuators and their interaction can be through cables or wireless. This interaction is explained in subsection 2.1 below.

By incorporating the network structure of ECS within a MFA, the totality of EE devices (sensors, controllers and actuators) are accounted for. Additionally, the grouping of EE devices remains consistent across different vehicle types, allowing the identification of individual EE device's importance for the total CM mass in passenger vehicles.

2.1. Automotive electronic control systems and corresponding EE devices

ECS manage specific responses of the vehicle according to the driver's desire as well as predefined fuel efficiency settings, emissions and safety standards. Depending on the automation level, ECS can be of two types: closed loop and open loop control systems.[2–6]

In both types of control systems, the central element is the control unit or *controller;* the number of controllers defines the number of control systems.[6] The controller is in charge of: i) receiving information about the desired state of the system to be controlled; also known as "*the plant*", ii) deciding what to do in order to provide that desired state ("thinking"), and iii) sending action commands to be applied onto the plant.[2,6] Action commands are then applied by *actuators*.[2,6]

In a closed loop control system, controllers receive feedback signals from the plant by means of *sensors*; depending on the plant's state, controllers may correct action commands.[2,6] In contrast, open loop control systems do not have a feedback from the *plant* and require a "wish" input from the user of the plant every time an action is to be performed.[2,6] The higher the level of automation, the higher the number of closed loop control systems within a car. A graphical representation of the two types of ECS can be found in Varmah, 2010, pages 2–3.[6]

3. Detailed system description

The Swiss system of passenger vehicles is represented in Figure S1. This representation was corroborated in a workshop with selected actors in the second hand market and end of life treatment stages.[8] The first process is the vehicle import, which is carried out by 33 authorized vehicle importers (currently importing 45 different brands) or by direct user import[9,10]. Afterwards, vehicles are registered in the Swiss motor-vehicle database (MOFIS database) hosted by the Federal Office of Roads (FEDRO).[9,11] There are three states in which a vehicle may exist the use phase: second hand vehicle, accident vehicle and ELV.[12] Second hand vehicles are sold again within the country or exported.[13] Depending on the damage, accident vehicles are repaired or treated as ELV.[12] ELV are defined as “vehicles which are waste” according to the Swiss waste regulation.[14] The ELV treatment processes are specified in by the Swiss Federal office for the Environment (FOEN) [14,15] and include:

Depollution: is the removal of hazardous materials and substances, as well as of materials that can be harmful to the shredding process. Such materials include, but are not limited to: batteries, fuels, air conditioning fluids, catalysts and tires. The removed materials may be reused or treated in designated waste treatment facilities.[14]

Dismantling: is the removal of spare parts that can be sold for replacement of damaged parts in vehicles, or recycled separately. Dismantlers can remove up to 349 different spare parts, depending onon: i) the spare parts inventory of the dismantler, and ii) the price of the spare parts.[16] If the stocks of certain spare parts are low and/or the prices are high, these parts are more likely to be dismantled. Dismantled parts undergo quality testing, if they do not meet the quality requirements for reuse, they are sent to material recyclers. Examples are aluminum wheels and catalytic convertors, which are valuable for their aluminum and platinum group metals content; respectively[16]. Spare parts are mainly dismantled from the younger ELVs, up to 15 years old.[16] After dismantling, the remaining vehicle hulks are sent to vehicle shredders. If the distance to the shredding facility is long, the hulks are first pressed.[16]

Shredding & separation: shredding is carried out with hammer mills.[17] Each shredded ELV in Switzerland is registered in a database hosted by the Foundation Auto Recycling Switzerland (SARS ELV database)[18]. After shredding, there are several stages of material separation aimed at setting apart ferrous and nonferrous metals from the rest of materials in ELVs. Metal scrap is later sent to metal recovery facilities, while the remaining fraction, known as automobile shredder residue (ASR),[17] is further incinerated in municipal solid waste incinerators (MSWI). Hammer mills also shred other types of waste, generating corresponding shredder residues. After shredding wastes separately (automobiles, large household electronics, etc.), shredder residues may be mixed.[19–22] The general designation of shredder residue in Switzerland is "RESH"; the same term is used for a mix of ASR with shredder residues resulting from other types of waste.

Waste incineration: RESH, including ASR, is incinerated at municipal solid waste incinerators (MSWI). At the waste incineration plant, ASR (or RESH) is mixed with other industrial waste and municipal solid waste (MSW). Incineration produces combustion gases and a solid fraction of minerals (e.g. glass) and metals.[23] The solid fraction is later treated to separate metals (ferrous, nonferrous and precious metals) from minerals and inert waste.[22–24]

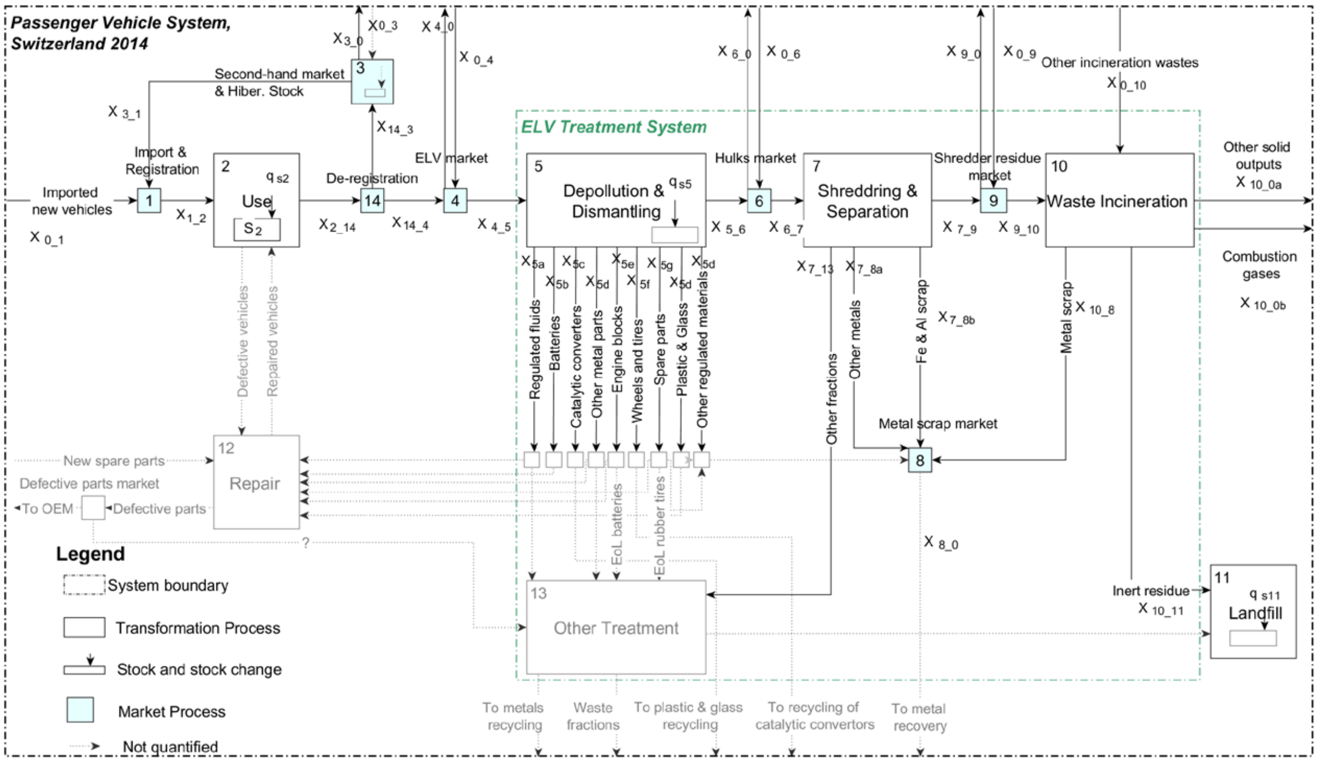

Figure S1. System of passenger vehicles in Switzerland, 2014. Processes and flows in grey have not been quantified. OEM: original equipment manufacturer, ELV: end-of-life vehicle.

4. Selection of critical metals, corresponding electronic control systems and EE devices considered in this study

The CMs analyzed were selected based on: i) their frequency of occurrence in EE devices in passenger vehicles and ii) the mass of the EE devices containing the most frequent CMs. This was obtained by means of literature review and communication with experts as presented below.

First, we summarized possible ECS and corresponding EE devices embedded in passenger vehicles from three power sources: i) internal combustion engine (ICE; including gasoline engine and diesel engine), ii) electric motor (electric vehicles), and iii) ICE and electric motor (hybrid electric vehicles; including gasoline/electric and diesel/electric). This information was collected from studies analyzing the number of ECS in vehicles,[3,5,25,26] technical books on automotive electronics[7,27] and technical catalogues of vehicle brands used in Switzerland.[28,29]

Second, we identified the occurrence of CMs in the EE devices above from scientific studies analyzing CMs in vehicle electronics,[17,30–35] manufacturer reports on material composition of automotive electronic devices and components[36–42] and patents.[43–48] Additionally, we clarified the composition of selected automotive electronic components by direct communication with expert manufacturers.[49–51]

A qualitative estimation of the mass of EE devices was obtained from Widmer et al., 2015[17] and from direct communication with an expert at a Swiss ELV dismantling facility.[52] This estimation represents the mass of individual EE devices relative to the other EE devices embedded in a vehicle. The qualitative mass is provided as a scale, including: xl, l, m, s, xs and xxs and where "xl" is the mass of the heaviest EE devices and "xxs" is the mass of the lightest EE devices in a vehicle. For the final mass calculation we considered devices with qualitative mass larger than "s" and excluded EE devices of masses "xs" and "xxs". A numerical estimation of the mass of the EE components within the EE devices larger than "s" was obtained from Widmer et al., 2015[17] and from direct measurements of a sample of spare parts at a Swiss ELV dismantling facility.[52]

The results of this literature review indicate that 70% of the EE devices in passenger vehicles contain either permanent magnets or printed wiring boards (PWB).[3,7,32,33,37,40,41] Magnets are mostly used in actuators, while PWBs are mostly used in controllers. Sensors contain both magnets and PWBs indistinctly. The remaining 30% of devices hold other EE components such as batteries, solenoids, LEDs and LCDs. In general, actuators have a larger mass than controllers and sensors.[17] The connections among EE devices may be physical or wireless.[4]

Regarding the material composition of EE components, the main magnetic materials used in automotive applications are ferrite and neodymium-iron-boron (NdFeB).[42,49–51,53,54] Both types of magnets may contain Co and REE; particularly La, Sm, Nd, and Dy.[43–48] However, the most commonly used ferrite magnets do not contain REE but are mainly composed of Sr and Fe.[49,50] Nevertheless, the share of ferrite magnets that use minor amounts of La and Co in automotive applications is increasing.[49] PWBs contain PMs, from which Ag, Au, Pd and Ru, predominate.[17,30,32,33] PWBs also contain minor amounts of REE.[17,30,31] Nickel metal hydride (NiMH) batteries used in hybrid vehicles contain REE, mainly Y, La, Ce, Pr, Nd and Gd.[31] LEDs contain Ga, In and Eu and LCDs contain In.[34,35] Physical connections among EE devices rely on cables containing Cu.

Based on the above, we selected the following CMs and PMs for further quantification: Ag, Au, Co, Dy, La, Nd, Pd and Ru. The EE devices considered were controllers and actuators containing permanent magnets and PWBs and of qualitative mass heavier than “s”. Sensors were excluded due to their small mass relative to other embedded devices. This exclusion may have led to underestimation of CM mass in cases in which the mass of CMs in the total number of sensors is large.

Table S1 provides the list of individual automotive embedded EE devices including the main EE component containing CMs. Table S2 provides the connections (physical or wireless) among these individual automotive embedded EE. The “source node” represents the EE device sending a signal; the “target node” represents the EE device receiving that signal. The ECS is determined by the controller in each case. These two tables are summarized in the network graph in Figure 2 of the main manuscript. The figure displays the connections among sensors, controllers and actuators in the corresponding ECS as well as the mass and composition of the EE devices.

The lists in Tables S1 and S2 are later used to: i) make sure that none of the *heavy* EE devices are left out of our calculation after carrying out the Pareto Analysis that provided the actual number of embedded electronics in Swiss cars, and ii) complete the results of the Pareto Analysis in cases in which the *Autohandel* database only provided the name of one EE device within an ECS or the name of the ECS and not the names of the actuators and controllers belonging to it. The detailed results of the Pareto Analysis and the final selection of EE devices to be investigated are presented in section SI 10.

Table S1. List of automotive embedded EE devices and EE components

Device type	**Device name**	**Main component containing CMs**	**Qualitative mass estimation***
actuator	Multifunction display	LCD	m
actuator	Head up displays	PWB	xs
actuator	Memory card	PWB	xxs
actuator	Air dam	Others	l
actuator	Flaps in front splitter and/or rear diffuser	Magnet	m
actuator	Foldable mirror motors	Magnet	xs
actuator	Rear air-brakes	Others	m
actuator	Rear spoiler	Magnet	m
actuator	Grill shutters	Magnet	m
actuator	Wheel shutters	Magnet	s
actuator	Speakers	Magnet	m
actuator	Shock absorbers	Solenoid	m
actuator	Shock absorbers on engine	Others	xxs
actuator	Solenoids for clutch actuation	Solenoid	xxs
actuator	Throttle actuator	Magnet	s
actuator	Hydraulic modulator	Magnet	m
actuator	Stepper motors (headlight control motors)	Magnet	s
actuator	Relays	Solenoid	s
actuator	Headlight door motor	Magnet	s
actuator	Headlight washer pump	Magnet	s
actuator	Airbag inflation device	Others	s
actuator	Passenger airbag ON/OFF indicator	LED	xxs
actuator	Warning lights	LED	xxs
actuator	Electrochromic material in the mirror	Others	xxs
actuator	Audible alarm	Magnet	xxs
actuator	Seat belt tensioner	Others	s
actuator	Radiator fan motor	Magnet	xl

Table S1. Cont.

Device type	Device name	Main component containing CMs	Qualitative mass estimation*
actuator	Dashboard	PWB	m
actuator	Light or display (usually in side mirrors)	LED	xxs
actuator	Wheel brakes	Others	m
actuator	Steering wheel vibrator	Magnet	xs
actuator	AC Compressor	Others	m
actuator	Electrical radiator blowers	Magnet	m
actuator	Door locks	Magnet	xs
actuator	DC brushless motors on hydraulic pump	Magnet	s
actuator	DC brushed motor on top lock mechanism	Magnet	s
actuator	Solenoids to control hydraulics	Solenoid	s
actuator	Lights	LED	xxs
actuator	Seat vibrator	Magnet	xs
actuator	Mobile phone	Others	xs
actuator	Electronic power steering motor	Magnet	m
actuator	Steering column adjuster	Magnet	m
actuator	Power seats motors (2, 3 or 4 electric motors)	Magnet	s
actuator	RF transmitter	Others	xxs
actuator	Hydraulic, pneumatic or electro. valve actuator	Magnet	xs
actuator	Piezoelectric valve actuator	Others	xs
actuator	Camshaft position pin actuator	Magnet	xs
actuator	Charge and discharge actuator	PWB	m
actuator	Power inverter	PWB	m
actuator	Alternator	Magnet	xl
actuator	Starter motor	Magnet	l
actuator	Battery	Others	l
actuator	Fuel injectors	Magnet	xs
actuator	Fuel pump	Magnet	s

Table S1. Cont.

Device type	Device name	Main component containing CMs	Qualitative mass estimation*
actuator	Spark plugs	Others	xs
actuator	Exhaust Gas Recirculation (EGR) valve	Magnet	xs
actuator	Fuel tank venting	Magnet	xs
actuator	Boost pressure actuator	Magnet/PWB	xs
actuator	Check engine light	LED	xxs
actuator	Intake manifold valve actuator	Magnet	xs
actuator	Air flap actuator	Magnet	xs
actuator	Linear purge valve	Magnet	xs
actuator	Distributor injection pump	Magnet	xs
actuator	Air control valve	Magnet	xs
actuator	CD drive motor	Magnet	xxs
actuator	Tape drive motor	Magnet	xxs
actuator	Radio	PWB	m
actuator	Antenna lift motor	Magnet	xs
actuator	Image projector	Others	xxs
actuator	Brake master cylinder	Others	m
actuator	ICE oil pump	Magnet	s
actuator	Transmission oil pump	Magnet	s
actuator	Idle-speed control actuator	Magnet	s
actuator	Speedometer	Magnet	xxs
actuator	Tachometer	Magnet	xxs
actuator	Odometer	Magnet	xxs
actuator	Fuel Gauge	Magnet	xxs
actuator	Check ICE light	LED	xxs
actuator	ICE coolant temperature gauge	Others	xxs
actuator	Gear shift position indicator	LED	xxs
actuator	Seat belt warning	LED	xxs

Table S1. Cont.

Device type	**Device name**	**Main component containing CMs**	**Qualitative mass estimation***
actuator	Oil pressure gauge	Magnet	xxs
actuator	Buzzers	Magnet	xxs
actuator	Digital clock	Magnet	xxs
actuator	Other lights	LED	xxs
actuator	Front, side and rear signaling lights	Others	xs
actuator	Visual indicator	Others	xxs
actuator	Motor/Generator	Magnet	xl
actuator	Infrared lights (active systems)	Others	xxs
actuator	Headlights	Others	m
actuator	Power windows motors	Magnet	s
actuator	Power seats (2, 3 or 4 electric motors)	Magnet	s
actuator	Headrest motor	Magnet	xxs
actuator	Trunk latch	Solenoid	s
actuator	Sunroof motors	Magnet	xxs
actuator	Interior and exterior lights	LED	xxs
actuator	RF link to telephone network	Others	xxs
actuator	Low-tire pressure display	LED	xxs
actuator	Head-up displays	Others	xs
actuator	Solenoid actuated valves	Solenoid	xs
actuator	Pressure regulated solenoids	Solenoid	xs
actuator	Shift solenoids	Solenoid	xs
actuator	Torque converter clutch solenoids	Solenoid	s
actuator	Automated manual transmission actuator	Magnet	s
actuator	Continuously variable transmission actuator	Magnet	s
actuator	2-4 wheel drive actuator	Magnet	m
actuator	Windscreen wiper motor	Magnet	m

Table S1. Cont.

Device type	Device name	Main component containing CMs	Qualitative mass estimation*
actuator	Rear wiper motor	Magnet	m
actuator	Defogger motor	Magnet	m
actuator	Windscreen wiper washer pump	Magnet	s
actuator	Joystick	Magnet	xs
actuator	Power mirror motors	Magnet	xxs
actuator	DC brushless motors	Magnet	m
actuator	Headlight dimmer	Others	xs
actuator	Headlight switch	Solenoid	xxs
controller	Accident Recorder	PWB	s
controller	Active Aerodynamics	PWB	s
controller	Active Cabin Noise Suppression	PWB	s
controller	Active Suspension	PWB	s
controller	Electronic Immobilizer	Others	xs
controller	Active Engine Vibration Control	PWB	xs
controller	Active Yaw Control	PWB	s
controller	Adaptive Cruise Control	PWB	s
controller	Adaptive Front Lighting	PWB	s
controller	Light Assistance Systems	PWB	xs
controller	Airbag Deployment Systems	PWB	s
controller	Antilock Braking System	PWB	s
controller	Auto-Dimming Mirrors	PWB	s
controller	Autonomous Emergency Braking Systems	PWB	s
controller	Battery Management System	PWB	m
controller	Blind Spot Detection	PWB	s
controller	Automatic H/AC	PWB	xs
controller	Cabin Environment Controls	PWB	s
controller	Communication Systems	PWB	s

Table S1. Cont.

Device type	Device name	Main component containing CMs	Qualitative mass estimation*
controller	Convertible Top Control	PWB	m
controller	Dedicated Short Range Communications	PWB	s
controller	Driver Drowsiness Detection	PWB	xs
controller	Electronic Power Steering	PWB	m
controller	Power Seats	PWB	xs
controller	Electronic Stability Program	PWB	xs
controller	Electronic Throttle Control	PWB	s
controller	Electronic Toll Collection	PWB	xs
controller	Electronic Valve Timing	PWB	m
controller	Energy management (EM)	PWB	m
controller	Electrical Energy Management (EEM)	PWB	s
controller	ICE Control Module	PWB	m
controller	Ignition System	Others	s
controller	Entertainment Systems	PWB	m
controller	Event Data Recorder	PWB	s
controller	Engine Torque Control	PWB	s
controller	Electronic Brake-force Distribution	PWB	s
controller	Hill Hold Control	PWB	s
controller	Stop-Start System	PWB	s
controller	Driver Information	PWB	s
controller	Intelligent Turn Signals	PWB	s
controller	Interior lighting	PWB	xs
controller	Lane Departure Warning	PWB	s
controller	Lane keeping assistance	PWB	m
controller	Motor/Generator Control Unit	PWB	m
controller	Navigation Systems	PWB	s
controller	Night Vision Systems	PWB	s

Table S1. Cont.

Device type	**Device name**	**Main component containing CMs**	**Qualitative mass estimation***
controller	On-Board Diagnostic Systems	PWB	m
controller	Parental Controls	PWB	xs
controller	Parking Assistance	PWB	s
controller	Power source management	PWB	m
controller	Pre-crash safety	PWB	s
controller	Rear-view Camera Systems	PWB	s
controller	Regenerative Braking	PWB	s
controller	Central Locking/ Keyless Access	PWB	xs
controller	Security Systems	PWB	s
controller	Tire Pressure Monitoring System	PWB	s
controller	Traction Control System	PWB	s
controller	Traffic Sign Recognition Systems	PWB	xs
controller	Transmission Control	PWB	m
controller	Windscreen wiper control	PWB	xs
controller	Power mirrors	PWB	xs
controller	Vehicle Dynamics Control	PWB	xs
controller	Electronic Differential Lock	PWB	xs
controller	Voice Control System for Phone	PWB	xs
controller	Electrically foldable mirrors	PWB	xs
controller	Driver Steering Recommendation	PWB	xs
controller	Fuel Injection System	PWB	xs
controller	Electric Sunroof	PWB	xs
controller	Engine Data Scan	PWB	m
sensor	Front camera	Others	xxs
sensor	Longitudinal acceleration sensor	Magnet/PWB	xs
sensor	GPS receiver	Others	xxs

Table S1. Cont.

Device type	Device name	Main component containing CMs	Qualitative mass estimation*
sensor	Vehicle speed sensor	Magnet/PWB	xs
sensor	ICE speed sensor	Magnet/PWB	xs
sensor	Steering wheel angle sensor	Magnet/PWB	xs
sensor	Acceleration pedal position sensor	Magnet/PWB	xxs
sensor	Throttle position sensor	Magnet/PWB	xs
sensor	Brake pedal position sensor	Magnet/PWB	xs
sensor	Yaw rate sensor	Magnet/PWB	xs
sensor	Microphones	Magnet/PWB	xxs
sensor	Wheel speed sensor	Magnet/PWB	xs
sensor	Vertical acceleration sensor	Magnet/PWB	xs
sensor	Key signal	Others	xxs
sensor	Lateral acceleration sensor	Magnet/PWB	xs
sensor	Vehicle level position sensor	Magnet/PWB	xs
sensor	Accelerometers on ICE	Magnet/PWB	xxs
sensor	Distance sensor (radar, lidar or image)	Others	xxs
sensor	Ambient light sensor	LED	xxs
sensor	Rain sensor	LED	xxs
sensor	Headlight position sensors	Magnet/PWB	xxs
sensor	RF receiver	Others	xxs
sensor	Key in ignition sensor	Magnet/PWB	xxs
sensor	Seat occupancy sensor	Others	xxs
sensor	Brake fluid pressure sensor	Magnet/PWB	xs
sensor	Seat belt tension restraint sensors	Magnet/PWB	xxs
sensor	Glare sensor	Others	xxs
sensor	Battery temperature sensors	Others	xxs
sensor	Battery voltage sensor	Others	xxs
sensor	Battery current sensors	Others	xxs

Table S1. Cont.

Device type	**Device name**	**Main component containing CMs**	**Qualitative mass estimation***
sensor	Battery state of charge	Others	xxs
sensor	Blind-spot image sensor (radar, ultrasonic)	Others	xxs
sensor	Temperature sensors	Others	xs
sensor	Pressure sensor	Magnet/PWB	xs
sensor	Humidity sensor	Others	xs
sensor	Gas Analyzers	Others	xxs
sensor	Mobile cellular	Others	xxs
sensor	Fluid pressure sensors	Magnet/PWB	xs
sensor	Position sensors	Magnet/PWB	xs
sensor	Power seats switch	Solenoid	xxs
sensor	Brake pressure sensor	Magnet/PWB	xxs
sensor	Crankshaft position sensor	Magnet/PWB	xs
sensor	Motor/Generator torque sensor	Magnet/PWB	xxs
sensor	Motor/Generator speed sensor	Magnet/PWB	xxs
sensor	Motor/Generator mode sensor	PWB	xxs
sensor	Fuel level sensor	Magnet/PWB	xxs
sensor	Vehicle operating status (moving/standing)	Magnet/PWB	xxs
sensor	ICE oil temperature sensor	Others	xxs
sensor	Lambda oxygen sensor	Others	xs
sensor	Induction air temperature sensor	Others	xs
sensor	Exhaust Gas Recirculation (EGR) sensor	Magnet/PWB	xxs
sensor	Camshaft position sensor	Magnet/PWB	xs
sensor	Intake manifold absolute pressure sensor	Magnet/PWB	xxs
sensor	Engine coolant temperature sensor	Others	xxs
sensor	Knock sensor	Magnet/PWB	xs
sensor	Oil level sensor	Magnet/PWB	xs
sensor	Engine coolant level sensor	Magnet/PWB	xxs

Table S1. Cont.

Device type	**Device name**	**Main component containing CMs**	**Qualitative mass estimation***
sensor	Air mass sensor	Magnet/PWB	s
sensor	Engine speed sensor	Magnet/PWB	xxs
sensor	Engine temperature sensor	Others	xxs
sensor	Switches	Solenoid	xxs
sensor	Angular rate sensor	Magnet/PWB	xxs
sensor	Seat position sensor	Magnet/PWB	xxs
sensor	Occupant weight sensor	Magnet/PWB	xs
sensor	Occupant position sensor	Magnet/PWB	xs
sensor	Clutch travel sensor	Magnet/PWB	xs
sensor	Clutch switch	Solenoid	xs
sensor	Gear position sensor	Magnet/PWB	xs
sensor	ICE temperature sensor	Others	xxs
sensor	External temperature sensor	Others	xs
sensor	Seat belt latch sensors	Magnet/PWB	xxs
sensor	Clutch pedal position sensor	Magnet/PWB	xs
sensor	Tire pressure sensors	Magnet/PWB	xs
sensor	Switches in dash and doors	Solenoid	xs
sensor	Potentiometers	Others	xxs
sensor	Motion sensors	Others	xxs
sensor	Proximity sensors	Others	xxs
sensor	Lane boundary sensor (optical infrared)	Others	xxs
sensor	Turn signal sensor	Others	xxs
sensor	Gyrocompass	Magnet/PWB	xs
sensor	Infrared sensor	Others	xxs
sensor	ICE coolant temperature sensor	Others	xxs
sensor	Intake air temperature sensor	Others	xs
sensor	Fuel tank pressure sensor	Magnet/PWB	xxs

Table S1. Cont.

Device type	Device name	Main component containing CMs	Qualitative mass estimation*
sensor	Fuel temperature sensor	Others	xxs
sensor	Oil temperature sensor	Others	xxs
sensor	Wiper washer fluid level sensor	Magnet/PWB	xxs
sensor	Brake fluid level sensor	Magnet/PWB	xxs
sensor	Brake master cylinder pressure sensor	Magnet/PWB	xxs
sensor	Rear camera	Others	xxs
sensor	Acoustic distance sensors	Others	xxs
sensor	Headrest position sensor	Magnet/PWB	xxs
sensor	Power windows position sensor	Magnet/PWB	xxs
sensor	Pressure sensors	Magnet/PWB	xs
sensor	Tilt sensors	Magnet/PWB	xxs
sensor	Vibration sensors	Magnet/PWB	xxs
sensor	GPS position sensor	Others	xs
sensor	Door ajar sensor (anti-theft sensor)	Magnet/PWB	xxs
sensor	Hood position sensor (anti-theft sensor)	Magnet/PWB	xxs
sensor	Transmission fluid temperature sensor	Others	xxs
sensor	Turbine speed sensor	Magnet/PWB	xxs
sensor	Input/output automatic transmission sensors	Magnet/PWB	xs
sensor	Brake light switch	Solenoid	xxs
sensor	Wiper switch	Solenoid	xxs
sensor	Power mirror switch	Solenoid	xxs
sensor	Driver desired speed	Others	xxs

*The qualitative mass is provided as a scale, including: xl, l, m, s, xs and xxs and where “xl” is the mass of the heaviest EE devices and “xxs” is the mass of the lightest EE devices in a vehicle.

Table S2. Network of automotive electronics

Source node	Target node
Front camera	Accident Recorder
Longitudinal acceleration sensor	Accident Recorder
GPS receiver	Accident Recorder
Vehicle speed sensor	Accident Recorder
ICE speed sensor	Accident Recorder
Steering wheel angle sensor	Accident Recorder
Acceleration pedal position sensor	Accident Recorder
Throttle position sensor	Accident Recorder
Brake pedal position sensor	Accident Recorder
Longitudinal acceleration sensor	Active Aerodynamics
Brake pedal position sensor	Active Aerodynamics
Steering wheel angle sensor	Active Aerodynamics
Vehicle speed sensor	Active Aerodynamics
Yaw rate sensor	Active Aerodynamics
Microphones	Active Cabin Noise Suppression
Longitudinal acceleration sensor	Active Cabin Noise Suppression
Wheel speed sensor	Active Suspension
Brake pedal position sensor	Active Suspension
Vertical acceleration sensor	Active Suspension
Key signal	Electronic Immobilizer
Lateral acceleration sensor	Active Suspension
Steering wheel angle sensor	Active Suspension
Vehicle level position sensor	Active Suspension
Accelerometers on ICE	Active Engine Vibration Control
Wheel speed sensor	Active Yaw Control
Lateral acceleration sensor	Active Yaw Control
Steering wheel angle sensor	Active Yaw Control
Yaw rate sensor	Active Yaw Control
Throttle position sensor	Active Yaw Control
Distance sensor (radar, lidar or image)	Adaptive Cruise Control
Vehicle speed sensor	Adaptive Cruise Control
Acceleration pedal position sensor	Adaptive Cruise Control
Brake pedal position sensor	Adaptive Cruise Control
Throttle position sensor	Adaptive Cruise Control
Steering wheel angle sensor	Adaptive Cruise Control
Yaw rate sensor	Adaptive Cruise Control
Lateral acceleration sensor	Adaptive Cruise Control
Wheel speed sensor	Adaptive Cruise Control
Vehicle speed sensor	Adaptive Front Lighting
Ambient light sensor	Adaptive Front Lighting
Rain sensor	Adaptive Front Lighting

Table S2. cont.

Source node	**Target node**
Steering wheel angle sensor	Adaptive Front Lighting
Distance sensor (radar, lidar or image)	Adaptive Front Lighting
Yaw rate sensor	Adaptive Front Lighting
Headlight position sensors	Adaptive Front Lighting
Front camera	Light Assistance Systems
RF receiver	Light Assistance Systems
Key in ignition sensor	Light Assistance Systems
Longitudinal acceleration sensor	Airbag Deployment Systems
Wheel speed sensor	Airbag Deployment Systems
Brake pedal position sensor	Airbag Deployment Systems
Seat occupancy sensor	Airbag Deployment Systems
Brake fluid pressure sensor	Airbag Deployment Systems
Seat belt tension restraint sensors	Airbag Deployment Systems
Wheel speed sensor	Antilock Braking System
Ambient light sensor	Auto-Dimming Mirrors
Glare sensor	Auto-Dimming Mirrors
Distance sensor (radar, lidar or image)	Autonomous Emergency Braking Systems
Vehicle speed sensor	Autonomous Emergency Braking Systems
Acceleration pedal position sensor	Autonomous Emergency Braking Systems
Brake pedal position sensor	Autonomous Emergency Braking Systems
Battery temperature sensors	Battery Management System
Battery voltage sensor	Battery Management System
Battery current sensors	Battery Management System
Battery state of charge	Battery Management System
Blind-spot image sensor (radar, ultrasonic or image)	Blind Spot Detection
Vehicle speed sensor	Blind Spot Detection
Temperature sensors	Automatic H/AC
Pressure sensor	Cabin Environment Controls
Humidity sensor	Cabin Environment Controls
Ambient light sensor	Cabin Environment Controls
Gas Analyzers	Cabin Environment Controls
GPS receiver	Communication Systems
Mobile cellular	Communication Systems
Fluid pressure sensors	Convertible Top Control
Temperature sensors	Convertible Top Control
Position sensors	Convertible Top Control
Front camera	Dedicated Short Range Communications
Steering wheel angle sensor	Driver Drowsiness Detection
Acceleration pedal position sensor	Driver Drowsiness Detection
Vehicle speed sensor	Driver Drowsiness Detection

Table S2. cont.

Source node	Target node
Steering wheel angle sensor	Electronic Power Steering
Wheel speed sensor	Electronic Power Steering
Power seats switch	Power Seats
Steering wheel angle sensor	Electronic Stability Program
Yaw rate sensor	Electronic Stability Program
Lateral acceleration sensor	Electronic Stability Program
Wheel speed sensor	Electronic Stability Program
Brake pressure sensor	Electronic Stability Program
Acceleration pedal position sensor	Electronic Throttle Control
Throttle position sensor	Electronic Throttle Control
RF receiver	Electronic Toll Collection
Crankshaft position sensor	Electronic Valve Timing
Throttle position sensor	Electronic Valve Timing
Fluid pressure sensors	Electronic Valve Timing
Acceleration pedal position sensor	Energy management
Vehicle speed sensor	Energy management
Brake pedal position sensor	Energy management
Battery state of charge	Energy management
Motor/Generator torque sensor	Energy management
Motor/Generator speed sensor	Energy management
ICE speed sensor	Energy management
Motor/Generator mode sensor	Energy management
Fuel level sensor	Energy management
Vehicle operating status (moving/standing)	Electrical Energy Management
Acceleration pedal position sensor	ICE Control Module
Throttle position sensor	ICE Control Module
ICE oil temperature sensor	ICE Control Module
Lambda oxygen sensor	ICE Control Module
Induction air temperature sensor	ICE Control Module
Exhaust Gas Recirculation (EGR) sensor	ICE Control Module
Camshaft position sensor	ICE Control Module
Crankshaft position sensor	ICE Control Module
Intake manifold absolute pressure sensor	ICE Control Module
Engine coolant temperature sensor	ICE Control Module
Knock sensor	ICE Control Module
Oil level sensor	ICE Control Module
Engine coolant level sensor	ICE Control Module
Air mass sensor	ICE Control Module
Key in ignition sensor	ICE Control Module
Engine speed sensor	ICE Control Module
Engine temperature sensor	ICE Control Module

Table S2. cont.

Source node	Target node
Battery voltage sensor	ICE Control Module
Key in ignition sensor	Ignition System
Multifunction display	Entertainment Systems
Switches	Entertainment Systems
Ambient light sensor	Entertainment Systems
Vehicle speed sensor	Event Data Recorder
ICE speed sensor	Event Data Recorder
Steering wheel angle sensor	Event Data Recorder
Angular rate sensor	Event Data Recorder
Acceleration pedal position sensor	Event Data Recorder
Throttle position sensor	Event Data Recorder
Brake pedal position sensor	Event Data Recorder
Seat position sensor	Event Data Recorder
Occupant weight sensor	Event Data Recorder
Wheel speed sensor	Engine Torque Control
Occupant position sensor	Event Data Recorder
Wheel speed sensor	Electronic Brake-force Distribution
Brake pedal position sensor	Electronic Brake-force Distribution
Ambient light sensor	Head up displays
Clutch travel sensor	Hill Hold Control
Clutch switch	Hill Hold Control
Gear position sensor	Hill Hold Control
Throttle position sensor	Hill Hold Control
Brake pedal position sensor	Hill Hold Control
Wheel speed sensor	Hill Hold Control
Longitudinal acceleration sensor	Hill Hold Control
ICE temperature sensor	Stop-Start System
External temperature sensor	Stop-Start System
Battery state of charge	Stop-Start System
Steering wheel angle sensor	Stop-Start System
Seat belt latch sensors	Stop-Start System
Brake pedal position sensor	Stop-Start System
Acceleration pedal position sensor	Stop-Start System
Clutch pedal position sensor	Stop-Start System
Crankshaft position sensor	Stop-Start System
Gear position sensor	Stop-Start System
Wheel speed sensor	Stop-Start System
Wheel speed sensor	Driver Information
ICE speed sensor	Driver Information
ICE temperature sensor	Driver Information
Tire pressure sensors	Driver Information

Table S2. cont.

Source node	Target node
Fuel level sensor	Driver Information
Vehicle speed sensor	Intelligent Turn Signals
Steering wheel angle sensor	Intelligent Turn Signals
Switches in dash and doors	Interior lighting
Potentiometers	Interior lighting
Ambient light sensor	Interior lighting
Motion sensors	Interior lighting
Proximity sensors	Interior lighting
Temperature sensors	Interior lighting
Vehicle speed sensor	Lane Departure Warning
Optical infrared image sensor (lane boundary sensor)	Lane Departure Warning
Turn signal sensor	Lane Departure Warning
Vehicle speed sensor	Lane keeping assistance
Optical infrared image sensor (lane boundary sensor)	Lane keeping assistance
Turn signal sensor	Lane keeping assistance
Brake pedal position sensor	Motor/Generator Control Unit
Acceleration pedal position sensor	Motor/Generator Control Unit
Vehicle speed sensor	Motor/Generator Control Unit
Motor/Generator speed sensor	Motor/Generator Control Unit
Motor/Generator torque sensor	Motor/Generator Control Unit
Motor/Generator mode sensor	Motor/Generator Control Unit
GPS receiver	Navigation Systems
Gyrocompass	Navigation Systems
Longitudinal acceleration sensor	Navigation Systems
Vehicle speed sensor	Navigation Systems
Infrared sensor	Night Vision Systems
Lambda oxygen sensor	On-Board Diagnostic Systems
ICE coolant temperature sensor	On-Board Diagnostic Systems
Intake air temperature sensor	On-Board Diagnostic Systems
Crankshaft position sensor	On-Board Diagnostic Systems
Intake manifold absolute pressure sensor	On-Board Diagnostic Systems
Fuel tank pressure sensor	On-Board Diagnostic Systems
Fuel temperature sensor	On-Board Diagnostic Systems
Oil temperature sensor	On-Board Diagnostic Systems
Wiper washer fluid level sensor	On-Board Diagnostic Systems
Vehicle speed sensor	On-Board Diagnostic Systems
Brake fluid level sensor	On-Board Diagnostic Systems
Wheel speed sensor	On-Board Diagnostic Systems
Longitudinal acceleration sensor	On-Board Diagnostic Systems

Table S2. cont.

Source node	**Target node**
Yaw rate sensor	On-Board Diagnostic Systems
Brake master cylinder pressure sensor	On-Board Diagnostic Systems
Steering wheel angle sensor	On-Board Diagnostic Systems
Throttle position sensor	On-Board Diagnostic Systems
Knock sensor	On-Board Diagnostic Systems
Camshaft position sensor	On-Board Diagnostic Systems
Fuel level sensor	On-Board Diagnostic Systems
Longitudinal acceleration sensor	Parental Controls
GPS receiver	Parental Controls
Vehicle speed sensor	Parental Controls
Vehicle speed sensor	Parking Assistance
Steering wheel angle sensor	Parking Assistance
Rear camera	Parking Assistance
Acoustic distance sensors	Parking Assistance
Acceleration pedal position sensor	Power source management
Vehicle speed sensor	Power source management
Brake pedal position sensor	Power source management
Battery state of charge	Power source management
Motor/Generator torque sensor	Power source management
Motor/Generator speed sensor	Power source management
ICE speed sensor	Power source management
Motor/Generator mode sensor	Power source management
Distance sensor (radar, lidar or image)	Pre-crash safety
Vehicle speed sensor	Pre-crash safety
Yaw rate sensor	Pre-crash safety
Longitudinal acceleration sensor	Pre-crash safety
Acceleration pedal position sensor	Pre-crash safety
Brake pedal position sensor	Pre-crash safety
Headrest position sensor	Pre-crash safety
Seat position sensor	Pre-crash safety
Gear position sensor	Rear-view Camera Systems
Rear camera	Rear-view Camera Systems
Brake pedal position sensor	Regenerative Braking
Vehicle speed sensor	Regenerative Braking
Battery state of charge	Regenerative Braking
RF receiver	Central Locking/ Keyless Access
Proximity sensors	Central Locking/ Keyless Access
Power windows position sensor	Central Locking/ Keyless Access
Key in ignition sensor	Central Locking/ Keyless Access
Key in ignition sensor	Automatic H/AC
Pressure sensors	Security Systems

Table S2. cont.

Source node	Target node
Switches	Security Systems
Microphones	Security Systems
Tilt sensors	Security Systems
Vibration sensors	Security Systems
Longitudinal acceleration sensor	Security Systems
Proximity sensors	Security Systems
GPS position sensor	Security Systems
Door ajar sensor (anti-theft sensor)	Security Systems
Hood position sensor (anti-theft sensor)	Security Systems
Tire pressure sensors	Tire Pressure Monitoring System
Temperature sensors	Tire Pressure Monitoring System
Wheel speed sensor	Tire Pressure Monitoring System
Wheel speed sensor	Traction Control System
Front camera	Traffic Sign Recognition Systems
Crankshaft position sensor	Transmission Control
Wheel speed sensor	Transmission Control
Throttle position sensor	Transmission Control
Gear position sensor	Transmission Control
Transmission fluid temperature sensor	Transmission Control
ICE coolant temperature sensor	Transmission Control
Turbine speed sensor	Transmission Control
Input/output automatic transmission sensors	Transmission Control
Brake light switch	Transmission Control
Wiper switch	Windscreen wiper control
Rain sensor	Windscreen wiper control
Power mirror switch	Power mirrors
Yaw rate sensor	Vehicle Dynamics Control
Wheel speed sensor	Vehicle Dynamics Control
Lateral acceleration sensor	Vehicle Dynamics Control
Wheel speed sensor	Electronic Differential Lock
Microphones	Voice Control System for Phone
Brake pressure sensor	Vehicle Dynamics Control
Accident Recorder	Memory card
Active Aerodynamics	Air dam
Active Aerodynamics	Flaps in front splitter and/or rear diffuser
Electrically foldable mirrors	Foldable mirror motors
Active Aerodynamics	Rear air-brakes
Active Aerodynamics	Rear spoiler
Active Aerodynamics	Grill shutters
Active Aerodynamics	Wheel shutters
Active Cabin Noise Suppression	Speakers

Table S2. cont.

Source node	**Target node**
Active Suspension	Shock absorbers
Active Engine Vibration Control	Shock absorbers on engine
Active Yaw Control	Solenoids for clutch actuation
Adaptive Cruise Control	Throttle actuator
Adaptive Cruise Control	Hydraulic modulator
Adaptive Front Lighting	Stepper motors (headlight control motors)
Adaptive Front Lighting	Relays
Adaptive Front Lighting	Headlight door motor
Adaptive Front Lighting	Headlight washer pump
Airbag Deployment Systems	Airbag inflation device
Airbag Deployment Systems	Passenger airbag ON/OFF indicator
Antilock Braking System	Hydraulic modulator
Antilock Braking System	Warning lights
Auto-Dimming Mirrors	Electrochromic material in the mirror
Autonomous Emergency Braking Systems	Hydraulic modulator
Autonomous Emergency Braking Systems	Warning lights
Autonomous Emergency Braking Systems	Audible alarm
Autonomous Emergency Braking Systems	Seat belt tensioner
Battery Management System	Radiator fan motor
Battery Management System	Relays
Battery Management System	Audible alarm
Battery Management System	Dashboard
Blind Spot Detection	Light or display (usually in side mirrors)
Blind Spot Detection	Audible alarm
Blind Spot Detection	Wheel brakes
Blind Spot Detection	Steering wheel vibrator
Automatic H/AC	AC Compressor
Cabin Environment Controls	Shock absorbers
Automatic H/AC	Electrical radiator blowers
Communication Systems	Door locks
Communication Systems	Speakers
Convertible Top Control	DC brushless motors on hydraulic pump
Convertible Top Control	DC brushed motor on top lock mechanism
Convertible Top Control	Solenoids to control hydraulics
Dedicated Short Range Communications	Multifunction display
Driver Drowsiness Detection	Speakers
Driver Drowsiness Detection	Lights
Driver Drowsiness Detection	Seat belt tensioner
Driver Drowsiness Detection	Steering wheel vibrator
Driver Drowsiness Detection	Seat vibrator
Voice Control System for Phone	Mobile phone

Table S2. cont.

Source node	Target node
Driver Drowsiness Detection	Electrical radiator blowers
Electronic Power Steering	Electronic power steering motor
Electronic Power Steering	Steering column adjuster
Engine Torque Control	ICE Control Module
Power Seats	Power seats motors (2, 3 or 4 electric motors)
Electronic Brake-force Distribution	Hydraulic modulator
Driver Steering Recommendation	Steering wheel vibrator
Electronic Stability Program	Throttle actuator
Electronic Stability Program	Hydraulic modulator
Electronic Stability Program	Fuel Injection System
Electronic Throttle Control	Throttle actuator
Electronic Toll Collection	RF transmitter
Electronic Valve Timing	Hydraulic, pneumatic or electromagnetic valve actuator
Electronic Valve Timing	Piezoelectric valve actuator
Electronic Valve Timing	Camshaft position pin actuator
Energy management	Charge and discharge actuator
Energy management	Power inverter
Electrical Energy Management	Alternator
Electrical Energy Management	Starter motor
Electrical Energy Management	Battery
Fuel Injection System	Fuel injectors
Fuel Injection System	Fuel pump
Ignition System	Spark plugs
ICE Control Module	Exhaust Gas Recirculation (EGR) valve
Fuel Injection System	Fuel tank venting
ICE Control Module	Radiator fan motor
ICE Control Module	AC Compressor
ICE Control Module	Boost pressure actuator
ICE Control Module	Throttle actuator
ICE Control Module	Check engine light
ICE Control Module	Intake manifold valve actuator
ICE Control Module	Air flap actuator
ICE Control Module	Linear purge valve
ICE Control Module	Distributor injection pump
ICE Control Module	Air control valve
Entertainment Systems	Multifunction display
Entertainment Systems	Speakers
Entertainment Systems	CD drive motor
Entertainment Systems	Tape drive motor
Entertainment Systems	Radio

Table S2. cont.

Source node	Target node
Entertainment Systems	Antenna lift motor
Event Data Recorder	Memory card
Head up displays	Image projector
Hill Hold Control	Brake master cylinder
Stop-Start System	Starter motor
Stop-Start System	Fuel pump
Stop-Start System	Fuel injectors
Stop-Start System	Throttle actuator
Stop-Start System	ICE oil pump
Stop-Start System	Transmission oil pump
Stop-Start System	Idle-speed control actuator
Driver Information	Speedometer
Driver Information	Tachometer
Driver Information	Odometer
Driver Information	Fuel Gauge
Driver Information	Check ICE light
Driver Information	ICE coolant temperature gauge
Driver Information	Gear shift position indicator
Driver Information	Seat belt warning
Driver Information	Oil pressure gauge
Driver Information	Speakers
Driver Information	Buzzers
Driver Information	Digital clock
Driver Information	Other lights
Intelligent Turn Signals	Front, side and rear signaling lights
Intelligent Turn Signals	Speakers
Interior lighting	Lights
Lane Departure Warning	Audible alarm
Lane Departure Warning	Visual indicator
Lane Departure Warning	Steering wheel vibrator
Lane keeping assistance	Audible alarm
Lane keeping assistance	Visual indicator
Lane keeping assistance	Steering wheel vibrator
Lane keeping assistance	Electronic power steering motor
Lane keeping assistance	Wheel brakes
Navigation Systems	Multifunction display
Navigation Systems	Speakers
Motor/Generator Control Unit	Motor/Generator
Motor/Generator Control Unit	Power inverter
Night Vision Systems	Image projector
Night Vision Systems	Infrared lights (active systems)

Table S2. cont.

Source node	**Target node**
Night Vision Systems	Headlights
Night Vision Systems	Audible alarm
On-Board Diagnostic Systems	Dashboard
Parental Controls	Throttle actuator
Parental Controls	Speakers
Parking Assistance	Throttle actuator
Parking Assistance	Electronic power steering motor
Parking Assistance	Wheel brakes
Pre-crash safety	Throttle actuator
Pre-crash safety	Wheel brakes
Pre-crash safety	Power windows motors
Pre-crash safety	Power seats (2, 3 or 4 electric motors)
Pre-crash safety	Headrest motor
Pre-crash safety	Seat belt tensioner
Power source management	Motor/Generator Control Unit
Power source management	ICE Control Module
Power source management	Wheel brakes
Power source management	Memory card
Power source management	Power inverter
Rear-view Camera Systems	Image projector
Rear-view Camera Systems	Speakers
Regenerative Braking	Wheel brakes
Regenerative Braking	Motor/Generator
Regenerative Braking	Battery
Central Locking/ Keyless Access	Door locks
Central Locking/ Keyless Access	Speakers
Central Locking/ Keyless Access	Trunk latch
Central Locking/ Keyless Access	Power windows motors
Central Locking/ Keyless Access	Sunroof motors
Central Locking/ Keyless Access	Interior and exterior lights
Security Systems	Audible alarm
Security Systems	Lights
Security Systems	RF link to telephone network
Tire Pressure Monitoring System	Low-tire pressure display
Traction Control System	Hydraulic modulator
Traction Control System	Throttle actuator
Traction Control System	Ignition System
Traction Control System	Fuel Injection System
Traction Control System	Warning lights
Traffic Sign Recognition Systems	Dashboard
Traffic Sign Recognition Systems	Head-up displays

Table S2. cont.

Source node	**Target node**
Transmission Control	Solenoid actuated valves
Transmission Control	Pressure regulated solenoids
Transmission Control	Shift solenoids
Transmission Control	Torque converter clutch solenoids
Transmission Control	Automated manual transmission actuator
Transmission Control	Continuously variable transmission actuator
Transmission Control	2-4 wheel drive actuator
Windscreen wiper control	Windscreen wiper motor
Windscreen wiper control	Rear wiper motor
Windscreen wiper control	Defogger motor
Windscreen wiper control	Windscreen wiper washer pump
Power mirrors	Joystick
Power mirrors	Power mirror motors
Electric Sunroof	DC brushless motors
Light Assistance Systems	Headlight dimmer
Light Assistance Systems	Headlight switch
Adaptive Cruise Control	ICE Control Module
Adaptive Cruise Control	Electronic Stability Program
Driver desired speed	Adaptive Cruise Control
Vehicle Dynamics Control	Antilock Braking System
Vehicle Dynamics Control	Traction Control System
Electronic Stability Program	Antilock Braking System
Electronic Stability Program	Traction Control System
ICE Control Module	Fuel Injection System
ICE Control Module	Ignition System
ICE Control Module	Engine Data Scan
Electronic Stability Program	Driver Steering Recommendation
Electronic Differential Lock	Electronic Stability Program
Central Locking/ Keyless Access	Electrically foldable mirrors
Electronic Immobilizer	ICE Control Module

5. List of variables and parameters

All the calculated variables are listed in Table S3. Table S4 lists the calculation parameters with their corresponding level of uncertainty and data source. The uncertainty levels are explained in the subsequent section 6.

Table S3. Calculated variables.

Mass flow of passenger vehicles, ELV and ELV treatment output fractions	
Symbol	**Description**
X_{0_1}	Mass of imported new vehicles
X_{1_2}	Mass of total vehicles registered
S_2	Mass of vehicles in stock
X_{3_1}	Mass of registered second hand vehicles
X_{2_14}	Mass of total de-registered vehicles
X_{14_3}	Mass of de-registered second hand vehicles
X_{3_0}	Mass of exported vehicles
q_{s2}	Change in vehicle stock mass
X_{14_4}	Mass of ELV generated
$X_{4\_0\_4}$	Mass of net ELV trade (import-export)
X_{4_5}	Mass of ELV treated in Switzerland
X_{5a}	Mass of regulated fluids
X_{5b}	Mass of batteries
X_{5c}	Mass of catalytic converters
X_{5d}	Mass of other depolluted parts and materials
X_{5e}	Mass of engine blocks
X_{5f}	Mass of wheels; including tires
X_{5g}	Mass of EE spare parts
q_{s5}	Mass of non-depolluted ELV
X_{5_6}	Mass of ELV hulks generated
X_{6_0}	Mass of ELV hulks exported
X_{0_6}	Mass of ELV hulks imported
X_{6_7}	Mass of ELV hulks shredded in Switzerland
X_{7_13}	Mass of other shredder output fractions
X_{7_8a}	Mass of Fe and Al scrap
X_{7_8b}	Mass of other metals resulting from shredding and separation
X_{7_9}	Mass of ASR
X_{9_0}	Mass of RESH exported
X_{0_9}	Mass of RESH imported
X_{9_10}	Mass of RESH incinerated in Switzerland
X_{10_8}	Mass of metal scrap resulting from MSW incineration
X_{0_10}	Mass of other incineration wastes
X_{10_0a}	Mass of other solid outputs from incineration
X_{10_0b}	Mass of combustion losses

Table S3. Cont.

Symbol	Description
Cont. Mass flow of passenger vehicles, ELV and ELV treatment output fractions	
Symbol	**Description**
X_{10_11}	Mass of inert residue
q_{s11}	Change of mass in landfill stock
Mass flow of critical and precious metals	
Symbol	**Description**
X_E_asr	Mass of metal E in ASR
X_E_FeAl	Mass of metal E in Fe and Al scrap
X_E_o	Mass of metal E in screen fraction
X_E_j	Mass of metal E in EE device j
Excess_E	Mismatch in mass of metal E between input and output of the ELV treatment system
T_Import_REE	Total mass of rare earth elements in the imported vehicles
T_Stock_REE	Total mass of rare earth elements in the vehicles in stock
T_ELV_REE	Total mass of rare earth elements in the ELV
T_Import_PM	Total mass of precious metals in the imported vehicles
T_Stock_PM	Total mass of precious metals in the vehicles in stock
T_ELV_PM	Total mass of precious metals in the ELV
T_Import_Co	Total mass of cobalt in the imported vehicles
T_Stock_Co	Total mass of cobalt in the vehicles in stock
T_ELV_Co	Total mass of cobalt in the ELV
E_ELV	Mass of metal E per ELV (mass per vehicle)
E_Import	Mass of metal E per vehicle imported (mass per vehicle)
E_Stock	Mass of metal E per vehicle in stock (mass per vehicle)
M_E^i	Total mass of metal E in vehicle flow or stock i
M_E^j	Mass of metal E in EE device j

Table S4. Calculation parameters, corresponding uncertainty level and data source. N: normal distribution, B: beta distribution, X: not a random variable, *: own estimation.

Symbol	Description	Value	Units	Data source	Distribution	Uncertainty level
n1	Number of registered vehicles in 2014	300 000	cars	55	N	I
Lm1	Average laden mass of registered vehicles in 2014	2 000	kg	55	N	II
Pl1	Average payload of registered vehicles in 2014	500	kg	55	N	II
d	Mass of driver	80	kg	56	N	I
e	Mass of second-hand vehicles exported	200 000	t	57	N	II
n2	Number of imported new vehicles in 2014	300 000	cars	55	N	I
Lm2	Average laden mass of imported new vehicles in 2014	2 000	kg	55	N	II
Pl2	Average payload of imported new vehicles in 2014	500	kg	55	N	II
n3	Number of vehicles in stock in 2014	4 000 000	cars	55	N	I
Lm3	Average vehicle's laden mass of stock in 2014	2 000	kg	55	N	II
Pl3	Average vehicle's payload of stock in 2014	400	kg	55	N	II
n4	Number of vehicles in stock in 2013	4 000 000	cars	55	N	I
v1	Mass of non-depolluted ELV	10 000	t	58	N	II
v3	Net mass trade of non-depolluted ELV (imported - exported)	-	t	58	N	I
h1	Mass of depolluted ELV in Switzerland (hulks generated)	80 000	t	58	N	II
h2	Mass of exported hulks	3 000	t	58	N	II
h3	Mass of imported hulks	5 000	t	58	N	II
b2	Mass of exported RESH	30 000	t	58	N	II
b3	Mass of RESH treated in Switzerland	50 000	t	58	N	II
r2	Mass fraction of RESH in MSW	0.02	kg/kg	19	B	III
y1	Mass fraction of solid material in MSW	0.2	kg/kg	23	B	IV
y2	Mass fraction of bottom ash >5mm in solid material	1	kg/kg	23	B	IV
y3	Mass fraction ferrous metals in solid material	0.02	kg/kg	23	B	IV
y4	Mass fraction of non-ferrous metals in solid material	0.003	kg/kg	23	B	IV
y5	Mass fraction of treated bottom ash in solid material	0.04	kg/kg	23	B	IV
y6	Mass fraction of micro bottom ash in solid material	0.1	kg/kg	23	B	IV
y7	Mass fraction of boiler ash in solid material	0.02	kg/kg	23	B	IV
y8	Mass fraction of ESP ash in solid material	0.1	kg/kg	23	B	IV
z1	Mass fraction of SLF in shredder input	0.2	kg/kg	17	B	IV
z2	Mass fraction Fe scrap in shredder input	0.7	kg/kg	17	B	IV
z3	Mass fraction of Al scrap in shredder input	0.04	kg/kg	17	B	IV
z6	Mass fraction of Mix in shredder input	0.04	kg/kg	17	B	IV
z8	Mass fraction of screen fraction in shredder input	0.03	kg/kg	17	B	IV
u2	Mass fraction of rubber in Mix	1	kg/kg	17	B	IV
f	Mass fraction of regulated fluids	0.02	kg/kg	59	B	IV
b	Mass fraction of battery	0.02	kg/kg	59	B	IV

Table S4. Cont. N: normal distribution, B: beta distribution, X: not a random variable, *: own estimation.

Symbol	Description	Value	Units	Data source	Distribution	Uncertainty level
c	Mass fraction of catalytic converter	0.01	kg/kg	[59]	B	IV
n5	Number of ELV shredded in 2014	100 000	ELV	[18]	B	I
auELV	Average unladen mass of ELV	1 000	kg	[18]	N	I
muELV	Total unladen mass of ELV shredded in Switzerland	100 000	t	[18]	N	I
mt	Average mass of 1 tire (including wheel)	20	kg	[16]	N	V
nt	Average number of tires per car	5	tires	[16]	N	I
me	Average mass of engine block (4 cylinders, 2 lt)	100	kg	[16]	N	V
kme	Fraction of ELV from which the motor is dismantled (cohort ≥2000)	0.2	-	[16]	N	V
Xl	Difference in average laden mass of stock in 2013 and 2014	5	kg	*	B	II
Xp	Difference in average payload of stock in 2013 and 2014	2	kg	*	N	II
Nd_asr	Mass fraction of Nd in ASR	0.00001	kg/kg	[17]	N	V
Dy_asr	Mass fraction of Dy in ASR	0.000001	kg/kg	[17]	B	V
Co_asr	Mass fraction of Co in ASR	0.00003	kg/kg	[17]	B	V
La_asr	Mass fraction of La in ASR	0.00001	kg/kg	[17]	B	V
Pd_asr	Mass fraction of Pd in ASR	0.000003	kg/kg	[17]	B	V
Ru_asr	Mass fraction of Ru in ASR	0.0000003	kg/kg	[17]	X	V
Ag_asr	Mass fraction of Ag in ASR	0.00001	kg/kg	[17]	B	V
Au_asr	Mass fraction of Au in ASR	0.000001	kg/kg	[17]	B	V
Nd_fe	Mass fraction of Nd in Fe scrap	0.0000002	kg/kg	[17]	B	V
Dy_fe	Mass fraction of Dy in Fe scrap	-	kg/kg	[17]	B	V
Co_fe	Mass fraction of Co in Fe scrap	0.00003	kg/kg	[17]	X	V
La_fe	Mass fraction of La in Fe scrap	0.0000002	kg/kg	[17]	B	V
Pd_fe	Mass fraction of Pd in Fe scrap	-	kg/kg	[17]	B	V
Ru_fe	Mass fraction of Ru in Fe scrap	0.0000002	kg/kg	[17]	X	V
Ag_fe	Mass fraction of Ag in Fe scrap	-	kg/kg	[17]	B	V
Au_fe	Mass fraction of Au in Fe scrap	-	kg/kg	[17]	X	V
Nd_al	Mass fraction of Nd in Al scrap	0.000001	kg/kg	[17]	X	V
Dy_al	Mass fraction of Dy in Al scrap	-	kg/kg	[17]	B	V
Co_al	Mass fraction of Co in Al scrap	0.00001	kg/kg	[17]	X	V
La_al	Mass fraction of La in Al scrap	0.000001	kg/kg	[17]	B	V
Pd_al	Mass fraction of Pd in Al scrap	0.000001	kg/kg	[17]	B	V
Ru_al	Mass fraction of Ru in Al scrap	-	kg/kg	[17]	X	V
Ag_al	Mass fraction of Ag in Al scrap	0.00001	kg/kg	[17]	X	V

Table S4. Cont. N: normal distribution, B: beta distribution, X: not a random variable, *: own estimation.

Symbol	Description	Value	Units	Data source	Distribution	Uncertainty level
Nd_mix	Mass fraction of Nd in Mix	0.000002	kg/kg	17	B	V
Dy_mix	Mass fraction of Dy in Mix	0.0000001	kg/kg	17	B	V
Co_mix	Mass fraction of Co in Mix	0.00001	kg/kg	17	B	V
La_mix	Mass fraction of La in Mix	0.000002	kg/kg	17	B	V
Pd_mix	Mass fraction of Pd in Mix	0.000001	kg/kg	17	B	V
Ru_mix	Mass fraction of Ru in Mix	0.0000003	kg/kg	17	B	V
Ag_mix	Mass fraction of Ag in Mix	0.00001	kg/kg	17	X	V
Au_mix	Mass fraction of Au in Mix	-	kg/kg	17	B	V
Nd_scr	Mass fraction of Nd in screen fraction	0.000004	kg/kg	17	B	V
Dy_scr	Mass fraction of Dy in screen fraction	0.0000003	kg/kg	17	X	V
Co_scr	Mass fraction of Co in screen fraction	0.00002	kg/kg	17	B	V
La_scr	Mass fraction of La in screen fraction	0.000002	kg/kg	17	B	V
Pd_scr	Mass fraction of Pd in screen fraction	0.00001	kg/kg	17	B	V
Ru_scr	Mass fraction of Ru in screen fraction	0.0000003	kg/kg	17	B	V
Ag_scr	Mass fraction of Ag in screen fraction	0.0001	kg/kg	17	X	V
Au_scr	Mass fraction of Au in screen fraction	0.000002	kg/kg	17	B	V
n2m	Number of imported vehicles classified into Autohandel types	200 000	cars	55,60	B	I
n3m	Number of vehicles in stock classified into Autohandel types	3 000 000	cars	55,60	B	I
n5m	Number of ELV classified into Autohandel types	30 000	ELV	55,60	N	I
wDym	Mass fraction of Dy in NdFeB magnets	0.1	kg/kg	48,61	N	V
wNdm	Mass fraction of Nd in NdFeB magnets	0.2	kg/kg	48,61	N	V
wLam	Mass fraction of La in mixed magnets	0.01	kg/kg	17	B	V
wDyp	Mass fraction of Dy in automotive PWBs	0.00001	kg/kg	17	B	V
wNdp	Mass fraction of Nd in automotive PWBs	0.001	kg/kg	17	B	V
wLap	Mass fraction of La in automotive PWBs	0.00002	kg/kg	17	B	V
wComf	Mass fraction of Co in mixed magnets	0.004	kg/kg	17	B	V
wComn	Mass fraction of Co in NdFeB magnets	0.2	kg/kg	48	B	V
wCop	Mass fraction of Co in automotive PWBs	0.0001	kg/kg	17	B	V
wPdp	Mass fraction of Pd in automotive PWBs	0.00003	kg/kg	17	B	V
wRup	Mass fraction of Ru in automotive PWBs	0.0000004	kg/kg	17	B	V
wAgp	Mass fraction of Ag in automotive PWBs	0.0004	kg/kg	17	B	V
wAup	Mass fraction of Au in automotive PWBs	0.0001	kg/kg	17	B	V
wDyf	Mass fraction of Dy in mixed magnets	0.00001	kg/kg	17	B	V
wNdf	Mass fraction of Nd in mixed magnets	0.001	kg/kg	17	B	V

Table S4. Cont. N: normal distribution, B: beta distribution, X: not a random variable, *: own estimation.

Symbol	Description	Value	Units	Data source	Distribution	Uncertainty level
wDyp14	Mass fraction of Dy in Airbag controller	0.000001	kg/kg	31	B	V
wDyp16	Mass fraction of Dy in Sound system controller	0.000001	kg/kg	31	B	V
wDyp18	Mass fraction of Dy in Central locking/Keyless access controller	0.0000005	kg/kg	31	B	V
wDyp20	Mass fraction of Dy in Power mirrors controller	0.00000003	kg/kg	31	B	V
wDyp26	Mass fraction of Dy in Engine/Motor controller	0.00002	kg/kg	31	B	V
wLab13	Mass fraction of La in NiMH Battery	0.02	kg/kg	31	B	V
wLap14	Mass fraction of La in Airbag controller	0.00002	kg/kg	31	B	V
wLap16	Mass fraction of La in Sound system controller	0.0002	kg/kg	31	B	V
wLap18	Mass fraction of La in Central locking/Keyless access controller	0.00002	kg/kg	31	B	V
wLap20	Mass fraction of La in Power mirrors controller	0.000001	kg/kg	31	B	V
wLap22	Mass fraction of La in Electronic power steering controller	0.000004	kg/kg	31	B	V
wLap26	Mass fraction of La in Engine/Motor controller	0.000001	kg/kg	31	B	V
wNdm6	Mass fraction of Nd in Electronic power steering motor	0.1	kg/kg	31	B	V
wNdb13	Mass fraction of Nd in NiMH Battery	0.01	kg/kg	31	B	V
wNdp14	Mass fraction of Nd in Airbag controller	0.00002	kg/kg	31	B	V
wNdp16	Mass fraction of Nd in Sound system controller	0.0002	kg/kg	31	B	V
wNdp18	Mass fraction of Nd in Central locking/Keyless access controller	0.00002	kg/kg	31	B	V
wNdp20	Mass fraction of Nd in Power mirrors controller	0.000001	kg/kg	31	B	V
wNdp22	Mass fraction of Nd in Electronic power steering controller	0.000004	kg/kg	31	B	V
wNdp26	Mass fraction of Nd in Engine/Motor controller	0.000001	kg/kg	31	B	V

6. Uncertainty analysis

We used a variety of data from different independent databases and experiments. The sources considered provided information only about selected components, in selected vehicles of specific power sources, brands, models and cohort years. To account for the related uncertainties, we carried out a Monte Carlo simulation to calculate all the stocks and flows in this study. We defined levels of uncertainty and assigned a corresponding relative uncertainty to all the parameters used in the calculations depending on: i) reliability of the data source, ii) quality of the data (e.g., free of typos), and iii) representativeness of the experiment's sample (e.g., number of vehicles, as well as cohort, brand and model analyzed in the experiment compared to the vehicles in the stocks and flows considered in this study). The relative uncertainty assigned corresponds to one standard deviation.

Table S6 lists the uncertainty levels considered. These levels group the different uncertainty values used throughout the calculations into: "very low" (level I), "low" (level II), "medium" (level III), "high" (level IV) and "very high" uncertainty (level V). Each uncertainty level translates to a relative uncertainty of the parameter value, in percentage. This percentage corresponds to one standard deviation from the parameter value. The choice of relative uncertainty is based on the actual value of the calculation parameter. For example, if the parameter is the number of cars in stock (cars in use, or "on the road") in Switzerland, the error in this number is considered to be very low considering that the cars have to pass a registration process in order to be allowed to be used in Switzerland. We consider that this registration process will *miss* very few cars and assume that there is low uncertainty in the final number of cars on the road. The car stock in 2014 was equal to 4 000 000 vehicles, assuming that more or less (+/-) 20 cars will be part of the Swiss stock without a registration number, this translates into a relative uncertainty of 0.005%. The same procedure was followed for all calculation parameters. All parameters with a relative uncertainty of 0.005% were grouped under uncertainty level I: very low uncertainty.

All parameters with relative uncertainties above zero were treated as random variables. A beta distribution was assigned to parameters limited between 0 and 1, e.g., transfer coefficients; a normal distribution was assigned to all other parameters. The Monte Carlo simulation was performed with MATLAB [62] with 1 0000 iterations.

In particular, to obtain the number of EE devices G_{ji} we used the *Autohandel* database from the company Auto-i-Dat AG.[60] The first reporting year in the *Autohandel* is the year 2000. Therefore, vehicles of cohorts before 2000, or which we were not able to classify to *Autohandel* types, were classified as an average vehicle type of 2000. Consequently, the number of EE devices embedded in these vehicles (G_{nji}) was considered highly uncertain (falling within the higher levels of uncertainty in the Monte Carlo simulation –levels IV and V in Table S6).

Similarly, the choice of relative uncertainty for the mass fraction of elements in EE components ($\mathrm{w}_{\mathrm{Ekj}}$) had high uncertainty (level V in Table S6), to reflect the differences in material composition across different manufacturers and years.

Table S5 summarizes the different uncertainty levels assigned depending on the data source and the parameter. Some examples are included to illustrate that different parameters can have different uncertainties even though the same data source is used. This occurs because the data source defines one parameter more accurately than the other. The relative error corresponding to each level of uncertainty is presented in Table S6.

Table S5. Uncertainty levels and sources of information; with examples.

Uncertainty level (from lowest to highest uncertainty)	**Data sources**	**Description of data source**	**Example of parameter data**
I	MOFIS database, 2015[55]	Vehicle registrations, including vehicle characteristics	Number of vehicles on the road
	SARS database, 2015[18]	ELV shredding statistics	Number of shredded ELV
	SARS database, 2015[18]	ELV shredding statistics	Average mass of shredded ELV
II	FCA, 2015[57]	Import/export statistics	Mass of exported vehicles
	MOFIS database, 2015[55]	Vehicle registrations, including vehicle characteristics	Average mass of vehicles on the road
	FOEN, 2014[58]	Waste statistics	Mass of non-depolluted ELV
	EU ELV regulation[63]	Mass of passenger vehicles	Average mass of driver
	Xu, et al., 2016[31]	Mass of EE components and critical metals in Japanese vehicles - experiment with one brand	Mass of NiMH battery in Toyota vehicles
III	SARS annual report, 2013[19]	ELV shredding statistics	Mass fraction of RESH in MSW
	Xu, et al., 2016[31]	Mass of EE components and critical metals in Japanese vehicles - experiment with one brand	Mass fraction of elements in NiMH battery in Toyota vehicles
	Autohandel database, 2015[60]	Standard equipment in Swiss vehicles	Number of controllers in classified vehicles imported and in use
IV	Morf, et al., 2012[23]	Mass flow experiment at a Swiss MSWI	Transfer coefficients of MSW process
	Widmer, et al., 2015[17]	Mass flow experiment at a Swiss ELV shredder	Transfer coefficients of shredding process
	Autohandel database, 2015[60]	Standard equipment in Swiss vehicles	Number of controllers in classified ELV
	Widmer, et al., 2015[17]	Mass of EE devices, components and scarce metals in Swiss ELV - experiment with a mix of brands and cohort years	Mass of EE components in Swiss vehicles
	Dix, 2014[59]	Mass flow experiment at a Swiss ELV dismantler	Transfer coefficients of depollution process
V	Autohandel database, 2015[60]	Standard equipment in Swiss vehicles	Number of EE devices in not-classified vehicles
	Kaufmann, 2016[52]	Mass of EE devices in Swiss ELV - interview/request for weighting selected spare parts from dismantled Swiss ELV	Mass of selected EE devices in Swiss vehicles
	Xu, et al., 2016[31]	Mass of EE components and critical metals in Japanese vehicles - experiment with one brand	Mass of selected EE components in Swiss vehicles
	Lee, 1988[64–68]	Patent NdFeB magnets - generalization of mass fraction of elements in magnets	Mass fraction of Co in NdFeB magnets
	Xu, et al., 2016[31]	Mass of EE components and critical metals in Japanese vehicles - experiment with one brand	Mass fraction of elements in selected vehicle controllers
	Widmer, et al., 2015[17]	Mass flow experiment at a Swiss ELV shredder - experiment with a mix of brands and cohort years	Mass fraction of elements in selected ELV shredder outputs

Table S6. Uncertainty levels and corresponding relative uncertainty of parameters.

Uncertainty level	**Relative uncertainty (in %)**
I	0.005
II	5
III	10
IV	15
V	25

7. Quantification of flows and stocks of passenger vehicles, ELV and ELV treatment output fractions

The total mass flow of imported new vehicles and registered vehicles was obtained from the average laden mass and payload of the vehicles. Laden mass and payload are registered in the MOFIS database.[55]

$$X_{0\_1} = n_2 * (l_2 - p_2 - d)$$ Equation S1

$$X_{1\_2} = n_1 * (l_1 - p_1 - d)$$ Equation S2

The mass of the second hand vehicles registered was obtained by subtracting the mass of new vehicles registered from the mass of the total vehicles registered

$$X_{3\_1} = n_1 * (l_1 - p_1 - d) - n_2 * (l_2 - p_2 - d)$$ Equation S3

The mass of de-registered vehicles was obtained by mass balance of the use phase (process 2).

$$X_{2\_14} = \frac{(h_1 - h_2 + h_3) * \{n_4 * [(l_3 - xl) - (p_3 - xp) - d)] + n_1 * (l_1 - p_1 - d) - n_3 * (l_3 - p_3 - d) - v_3\} - (h_1 + v_1) * (muELV - n_5 * d)}{(h_1 - h_2 + h_3)}$$

Equation S4

The mass of exported vehicles was obtained from waste statistics of the FOEN.[58]

$$X_{3\_0} = e$$ Equation S5

The change in mass of the vehicle stock was calculated as the difference between the mass of the stock in 2014 and the mass of the stock in 2013.

$$q_{s2} = n_3 * (l_3 - p_3 - d) - n_4 * [(l_3 - xl) - (p_3 - xp) - d)]$$ Equation S6

The mass of ELV generated was calculated by mass balance of the ELV market (process 4)

$$X_{2\_4} = \frac{v_3 * (h_1 + h_3 - h_2) + (h_1 + v_1) * (muELV - n_5 * d)}{h_1 - h_2 + h_3}$$ Equation S7

The net ELV trade was obtained from waste statistics of the FOEN.[58]

$$X_{4\_0\_4} = v_3$$ Equation S8

The mass of ELV treated in Switzerland was obtained from the mass of ELV hulks (imported, exported and treated in Switzerland) and the mass of non-depolluted ELV.

$$X_{4\_5} = \frac{(h_1 + v_1) * (muELV - n_5 * d)}{h_1 - h_2 + h_3}$$ Equation S9

The mass of regulated fluids, batteries and catalytic converters was obtained with transfer coefficients identified by Dix in an experiment at a Swiss ELV dismantling plant.[59]

$$X_{5a} = f * \left[\frac{(h_1 + v_1) * (muELV - n_5 * d)}{h_1 - h_2 + h_3}\right]$$ Equation S10

$$X_{5b} = b * \left[\frac{(h_1 + v_1) * (muELV - n_5 * d)}{h_1 - h_2 + h_3}\right]$$ Equation S11

$$X_{5c} = c * \left[\frac{(h_1 + v_1) * (muELV - n_5 * d)}{h_1 - h_2 + h_3}\right]$$ Equation S12

By interviewing an expert from the same Swiss dismantling facility where Dix carried out dismantling experiments,[52] we identified that engine blocks are dismantled only from ELV of cohorts after 2000. Wheels and tires are dismantled from all ELV as mandated by EU and Swiss ELV regulations.[63,69] The average mass of one engine block of 4 cylinders and 2 litter capacity was used as the average mass of engine blocks; the mass of a set of tires (including wheels) was used as the average mass of tires. These masses were provided by the same expert of the dismantling facility.[52] The total mass of engines and tires dismantled from ELVs was calculated by multiplying the percentage of ELVs from which engines and tires are dismantled by the average mass of engines and tires.

$$X_{5e} = k_{me} * m_e * \left[\frac{(h_1 + v_1) * (muELV - n_5 * d)}{(auELV - d) * (h_1 - h_2 + h_3)}\right]$$ Equation S13

$$X_{5f} = m_t * n_t * \left[\frac{(h_1 + v_1) * (muELV - n_5 * d)}{(auELV - d) * (h_1 - h_2 + h_3)}\right]$$ Equation S14

The mass of spare parts dismantled as well as the mass of other hazardous materials depolluted was calculated by mass balance of the dismantling and depollution processes (process 5).

$$X_{5d} = \frac{(h_1+v_1)*[(1-b-c-f)*(muELV-n_5*d)*(auELV-d)-(k_{me}*m_e+m_t*n_t)-(auELV-d)*(h_1-h_2+h_3)]}{(auELV-d)*(h_1-h_2+h_3)}$$

Equation S15

The mass of non-depolluted ELV, ELV hulks generated (depolluted ELV), ELV hulks imported and ELV hulks exported was obtained from waste statistics of the FOEN.[58]

$$q_{s5} = v_1$$ Equation S16

$$X_{5\_6} = h_1$$ Equation S17

$$X_{6\_0} = h_2 \quad \text{Equation S18}$$

$$X_{0\_6} = h_3 \quad \text{Equation S19}$$

The mass of shredded ELV was calculated by mass balance.

$$X_{6\_7} = h_1 - h_2 + h_3 \quad \text{Equation S20}$$

The mass of shredder outputs was calculated with transfer coefficients determined by Widmer et al. at a Swiss shredder facility.[17]

$$X_{7\_13} = (u_2 * z_6 + z_8) * (h_1 - h_2 + h_3) \quad \text{Equation S21}$$

$$X_{7\_8a} = (h_1 - h_2 + h_3) * (z_2 + z_3) \quad \text{Equation S22}$$

$$X_{7\_8b} = (h_1 - h_2 + h_3) * (1 - z_1 - z_2 - z_3 - u_2 * z_6 - z_8) \quad \text{Equation S23}$$

$$X_{7\_9} = z_1 * (h_1 - h_2 + h_3) \quad \text{Equation S24}$$

The mass of RESH exported and incinerated in Switzerland was obtained from waste statistics of the FOEN.[58]

$$X_{9\_0} = b_2 \quad \text{Equation S25}$$

$$X_{9\_10} = b_3 \quad \text{Equation S26}$$

The mass of RESH imported was calculated by mass balance of the RESH market (process9).

$$X_{0\_9} = b_2 + b_3 - z_1 * (h_2 - h_1 - h_3) \quad \text{Equation S27}$$

The mass of other incineration waste was calculated from the total mass of RESH incinerated and the percentage of RESH in MSW reported by SARS.[19]

$$X_{0\_10} = \frac{b_3\{1 - y_1 * [(1 + r_2) * (1 - y_2 - y_7 - y_8) - 2 * (y_3 + y_4 + y_5 + y_6)]\}}{r_2}$$

Equation 28

The mass of incineration outputs was calculated with transfer coefficients determined by Morf et al. at a Swiss MSWI,[23] Equations S29 to S31.

$$X_{10\_8} = \frac{b_3 * y_1 * (y_3 + y_4) * (1 + r_2)}{r_2}$$ Equation S29

$$X_{10\_0a} = \frac{b_3 * y_1 * (1 + r_2) * (y_2 + y_3 + y_4 + y_5 + 2y_6 + y_7 + y_8)}{r_2}$$ Equation S30

$$X_{10\_0b} = \frac{-b_3 * (1 + r_2) * (y_1 - 1)}{r_2}$$

$$X_{10\_11} = \frac{b_3 * y_1 * y_5 * (1 + r_2)}{r_2}$$ Equation S31

The change in landfill stock was calculated by mass balance of process 11.

$$q_{s11} = \frac{b_3 * y_1 * y_5 * (1 + r_2)}{r_2}$$ Equation S32

8. Quantification of flows and stocks of selected CMs in passenger vehicles, ELV and ELV treatment output fractions

The mass of the selected metals in shredder and separation output fractions was obtained by multiplying the mass fraction of metals in the outputs, determined in a previous experiment by Widmer et al.[17] by the calculated mass of the respective output.

$X\_Nd\_asr = X_{7\_9}*Nd\_asr$ Equation S33

$X\_Dy\_asr = X_{7\_9}*Dy\_asr$ Equation S34

$X\_Co\_asr = X_{7\_9}*Co\_asr$ Equation S35

$X\_La\_asr = X_{7\_9}*La\_asr$ Equation S36

$X\_Pd\_asr = X_{7\_9}*Pd\_asr$ Equation S37

$X\_Ru\_asr = X_{7\_9}*Ru\_asr$ Equation S38

$X\_Ag\_asr = X_{7\_9}*Ag\_asr$ Equation S39

$X\_Au\_asr = X_{7\_9}*Au\_asr$ Equation S40

$X\_Nd\_FeAl = (h_1-h_2+h_3)*(z_2*Nd\_fe + z_3*Nd\_al)$ Equation S41

$X\_Dy\_FeAl = (h_1-h_2+h_3)*(z_2*Dy\_fe + z_3*Dy\_al)$ Equation S42

$X\_Co\_FeAl = (h_1-h_2+h_3)*(z_2*Co\_fe + z_3*Co\_al)$ Equation S43

$X\_La\_FeAl = (h_1-h_2+h_3)*(z_2*La\_fe + z_3*La\_al)$ Equation S44

$X\_Pd\_FeAl = (h_1-h_2+h_3)*(z_2*Pd\_fe + z_3*Pd\_al)$ Equation S45

$X\_Ru\_FeAl = (h_1-h_2+h_3)*(z_2*Ru\_fe + z_3*Ru\_al)$ Equation S46

$X\_Ag\_FeAl = (h_1-h_2+h_3)*(z_2*Ag\_fe + z_3*Ag\_al)$ Equation S47

$X\_Au\_FeAl = (h_1-h_2+h_3)*(z_2*Au\_fe + z_3*Au\_al)$ Equation S48

$X\_Nd\_o = (h_1-h_2+h_3)*z_8*Nd\_scr$ Equation S49

$X\_Dy\_o = (h_1-h_2+h_3)*z_8*Dy\_scr$ Equation S50

$X\_Co\_o = (h_1-h_2+h_3)*z_8*Co\_scr$ Equation S51

$X\_La\_o = (h_1-h_2+h_3)*z_8*La\_scr$ Equation S52

$X\_Pd\_o = (h_1-h_2+h_3)*z_8*Pd\_scr$ Equation S53

$X\_Ru\_o = (h_1-h_2+h_3)*z_8*Ru\_scr$ Equation S54

$X\_Ag\_o = (h_1-h_2+h_3)*z_8*Ag\_scr$ Equation S55

$X\_Au\_o = (h_1-h_2+h_3)*z_8*Au\_scr$ Equation S56

The mass of the selected metals in a joint flow of spare parts and electrical machines separated after shredding was calculated by mass balance of the ELV treatment system. In this case, the subscript j indicates NiMH batteries.

$$Excess\_Dy = M_{Dy}^{ELV} - X\_Dy\_asr - X\_Dy\_FeAl - X\_Dy\_o - X\_Dy\_j \quad \text{Equation S57}$$

$$Excess\_La = M_{La}^{ELV} - X\_La\_asr - X\_La\_FeAl - X\_La\_o - X\_La\_j$$ Equation S58

$$Excess\_Nd = M_{Nd}^{ELV} - X\_Nd\_asr - X\_Nd\_FeAl - X\_Nd\_o - X\_Nd\_j$$ Equation S59

$$Excess\_Co = M_{Co}^{ELV} - X\_Co\_asr - X\_Co\_FeAl - X\_Co\_o - X\_Co\_j$$ Equation S60

$$Excess\_Pd = M_{Dy}^{ELV} - X\_Pd\_asr - X\_Pd\_FeAl - X\_Pd\_o$$ Equation S61

$$Excess\_Pt = M_{Pt}^{ELV} - X\_Pt\_asr - X\_Pt\_FeAl - X\_Pt\_o$$ Equation S62

$$Excess\_Ru = M_{Ru}^{ELV} - X\_Ru\_asr - X\_Ru\_FeAl - X\_Ru\_o$$ Equation S63

$$Excess\_Ag = M_{Ag}^{ELV} - X\_Ag\_asr - X\_Ag\_FeAl - X\_Ag\_o$$ Equation S64

$$Excess\_Au = M_{Au}^{ELV} - X\_Au\_asr - X\_Au\_FeAl - X\_Au\_o$$ Equation S65

The total mass of REE in vehicles imported was calculated by summing up the individual masses of the REE considered in the flow of vehicles imported. In the same manner, we calculated the total mass of REE in stock and ELV as well as the total masses of PGMs, Ag and Au in vehicles imported, in stock and ELV. The equations for the calculation of the import flow are shown below; the mass of the metal groups in the stock and ELV was calculated analogously.

$$T\_Import\_REE = M_{Dy}^{Import} + M_{La}^{Import} + M_{Nd}^{Import}$$ Equation S66

$$T\_Import\_PGM = M_{Pd}^{Import} + M_{Pt}^{Import} + M_{Ru}^{Import}$$ Equation S67

$$T\_Import\_Ag\_Au = M_{Ag}^{Import} + M_{Au}^{Import}$$ Equation S68

$$T\_Import\_Co = M_{Co}^{Import}$$ Equation S69

The mass of metals per ELV was calculated by dividing the total mass of the specific metal by the number of ELV considered. The case of Dy is shown below; the mass of the other metals was calculated analogously.

$$Dy\_ELV = \frac{M_{Dy}^{ELV}}{n_5}$$ Equation S70

The mass of metal *E* in vehicles imported, in-use and ELV was calculated by summing up the contributions of each EE device and component containing the metal in all vehicles.

$$M_E^i = \sum_{j,k} G_{ji} \cdot m_{kj} \cdot w_{Ekj}$$ Equation S71

The total number of devices j in vehicle stock or flow i was calculated by summing up the number of devices in classified and non-classified vehicles in that flow.

$$G_{ji} = G_{mji} + G_{nji}$$ Equation S72

The number of devices j in vehicles classified was obtained by multiplying the number of devices in vehicle type y by the number of vehicles in that vehicle type and then summing up over all vehicle types.

$$G_{mji} = \sum_{y} n_{mi}^{y} \cdot G_j^y$$ Equation S73

The number of devices in the non-classified vehicles was estimated from the number of devices in an average vehicle type of the corresponding vehicle cohort.

$$G_{nji} = \bar{G}_{mji}^{c} \cdot n_{ni}^{c}$$ Equation S74

The average number of devices in a vehicle cohort (including all brands and models in that cohort) was obtained by dividing the total number of devices in that cohort by the total number of vehicles.

$$\bar{G}_{mji}^{c} = \frac{G_{mji}^{c}}{n_{mi}^{c}}$$ Equation S75

9. Classification of vehicles imported, in stock, and ELV into vehicle types

We obtained the EE devices embedded in imported vehicles, vehicles in stock and ELVs from the *Autohandel* database.[60] For this, we first classified all the vehicles into 128 brands and 6 859 models registered in the *Autohandel*. The cohort, brand and model of vehicles imported and in use were obtained from the *MOFIS* database.[55] For ELV, these were obtained from the shredded ELV database of the Foundation Auto Recycling Switzerland (*SARS ELV* database).[18]
The cohort and brand distribution of the vehicles imported, in stock and ELV are presented in Table S7 to Table S11 below, including the number of vehicles that could be classified into vehicle types in the *Autohandel* database. A dash (-) indicates a value equal to zero. The results of the classification by cohort year are also illustrated in Figure S2 and Figure S3 for the vehicles in stock and the ELV, respectively.
In summary, we were able to classify 70% of the imported vehicles into 169 vehicle types (combinations of brands and models), 67% of the stock into 1 874 different vehicle types and 32% of the shredded ELV into 814 vehicle types of the *Autohandel* database.
The import (cohort 2014) was composed by 91 different brands of which we could classify 38. The stock was composed by 41 different cohort years, 386 different brands and 65 147 different models. Out of these, we were able to classify 25 cohorts, 81 brands and 31 059 models.
The vehicles in the ELV database were the most challenging to classify, because of three main reasons: i) the average cohort year of the ELVs was older than the year 2000, which is the earliest reporting year in *Autohandel*, ii) the brand and model were reported together in the *SARS ELV* database, while they were reported individually in the *Autohandel*, and iii) there were typos the *SARS-ELV* database. Out of the 10 426 different brand & models in the ELV database we were able to classify 2 856.

Table S7. Classification of MOFIS vehicles into Autohandel types by cohort year.

Cohort year	**Number of vehicles in stock (MOFIS)**	**Vehicles classified into Autohandel types**	**% Classified**
1975	1 532	-	-
1976	1 433	-	-
1977	1 537	-	-
1978	1 935	-	-
1979	2 189	-	-
1980	1 899	-	-
1981	2 136	-	-
1982	2 817	-	-
1983	2 471	-	-
1984	2 375	-	-
1985	2 796	-	-
1986	3 912	-	-
1987	5 016	-	-
1988	5 695	-	-
1989	7 959	-	-
1990	10 501	-	-
1991	12 949	36	0.3%
1992	14 390	20	0.1%
1993	16 331	15	0.1%
1994	22 331	174	1%
1995	31 048	342	1%
1996	42 154	4 510	11%
1997	55 337	13 410	24%
1998	81 960	32 531	40%
1999	112 470	74 808	67%
2000	138 533	96 546	70%
2001	161 278	112 406	70%
2002	173 629	122 597	71%
2003	181 165	132 797	73%
2004	201 850	146 968	73%
2005	215 697	158 631	74%
2006	236 711	175 057	74%
2007	259 801	194 339	75%
2008	272 794	205 276	75%
2009	258 822	191 389	74%
2010	294 045	215 498	73%
2011	324 944	240 893	74%
2012	332 644	243 103	73%
2013	312 333	223 421	72%
2014	**300 595**	**209 260**	**70%**
2015	307 710	173 318	56%
Total	**4 417 724**	**2 967 345**	**67%**

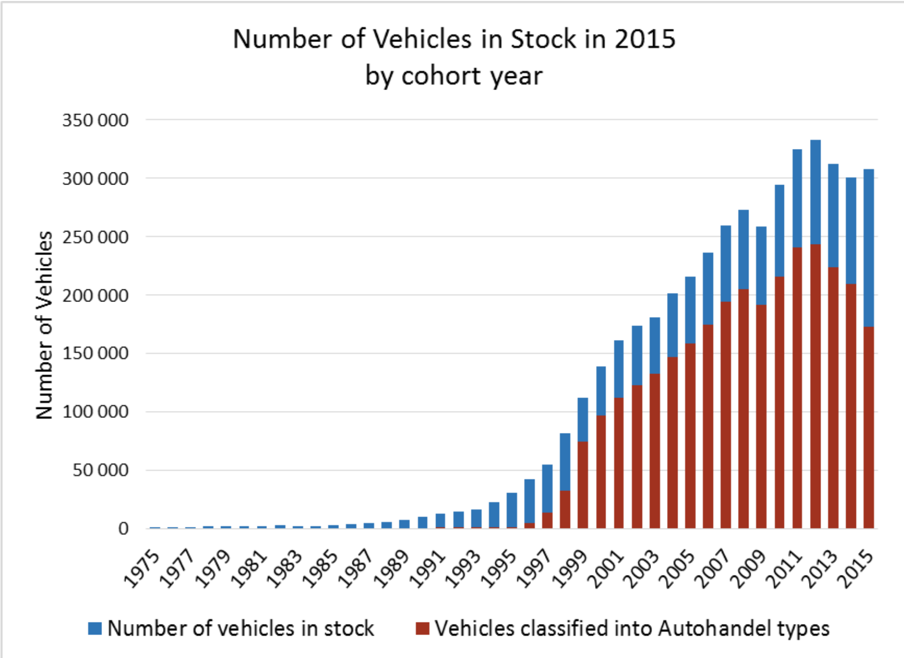

Figure S2. Classification of MOFIS vehicles into Autohandel types by cohort year.

Table S8. Classification of *MOFIS* vehicles into *Autohandel* types by brand. Only the 36 most common brands are listed.

Brand	**Number of vehicles in stock (MOFIS)**	**Vehicles classified into Autohandel types**	**% Classified**
VW	586 024	391 297	67%
AUDI	294 542	243 619	83%
OPEL	274 073	243 680	89%
BMW	265 675	1 447	1%
MERCEDES-BENZ	250 759	1	0%
TOYOTA	249 898	195 578	78%
RENAULT	210 243	142 442	68%
FORD	203 036	186 725	92%
PEUGEOT	199 017	185 042	93%
SKODA	163 001	158 751	97%
CITROEN	147 427	121 106	82%
FIAT	137 222	119 899	87%
SUBARU	129 386	67 309	52%
VOLVO	117 046	30 876	26%
MAZDA	107 758	77 704	72%
NISSAN	102 729	82 945	81%
SEAT	101 893	99 570	98%
HYUNDAI	101 632	91 369	90%
HONDA	100 843	81 985	81%
SUZUKI	85 462	63 461	74%
MITSUBISHI	71 203	57 815	81%
MINI	51 801	1 136	2%
ALFA ROMEO	49 583	43 604	88%
KIA	47 559	45 792	96%
PORSCHE	39 556	14 816	37%
DACIA	34 544	34 468	100%
CHEVROLET	33 121	29 720	90%
LAND ROVER	31 494	10 818	34%
SMART	29 092	20 019	69%
JEEP	26 270	22 135	84%
DAIHATSU	19 583	18 411	94%
SAAB	19 500	11 497	59%
JAGUAR	14 669	9 653	66%
CHRYSLER	14 456	9 606	66%
LANCIA	13 605	11 803	87%
LEXUS	13 174	11 892	90%
Total	**4 336 876**	**2 937 991**	**68%**

Table S9. Classification of *MOFIS* vehicles of first registration = 2014 into *Autohandel* types by brand. These vehicles represent the vehicles imported in 2014. Only the 36 most common brands are listed.

Brand	**Number of vehicles imported (MOFIS)**	**Vehicles classified into Autohandel types**	**% Classified**
VW	41 625	33 295	80%
AUDI	21 917	18 089	83%
BMW	21 480	-	-
SKODA	19 489	19 377	99%
MERCEDES-BENZ	18 907	-	-
OPEL	12 939	12 524	97%
FORD	12 632	11 946	95%
PEUGEOT	11 223	10 787	96%
RENAULT	11 180	6 910	62%
TOYOTA	11 117	10 360	93%
CITROEN	11 064	10 436	94%
HYUNDAI	11 023	10 818	98%
SEAT	9 343	9 338	100%
SUZUKI	8 443	7 738	92%
FIAT	8 210	7 811	95%
MAZDA	7 481	6 125	82%
NISSAN	6 680	4 591	69%
VOLVO	6 631	2 367	36%
SUBARU	6 121	1 867	31%
KIA	4 863	4 322	89%
DACIA	4 690	4 656	99%
MINI	4 293	-	-
HONDA	4 243	1 941	46%
LAND ROVER	3 486	569	16%
MITSUBISHI	3 442	2 672	78%
PORSCHE	3 294	810	25%
JEEP	3 060	2 831	93%
CHEVROLET	1 936	1 918	99%
ALFA ROMEO	1 665	1 469	88%
SMART	1 644	1 554	95%
LEXUS	842	595	71%
JAGUAR	692	24	3%
MASERATI	691	-	-
LANCIA	663	663	100%
SSANGYONG	548	136	25%
TESLA	479	476	99%
Total	**298 036**	**209 015**	**70%**

Table S10. Classification of *SARS-ELV* vehicles into *Autohandel* types by cohort year.

Cohort Year	**Number of ELVs (SARS-ELV)**	**ELV classified into Autohandel types**	**% Classified**
1960	5	-	-
1961	2	-	-
1962	8	-	-
1963	7	-	-
1964	10	-	-
1965	19	-	-
1966	24	-	-
1967	28	-	-
1968	60	-	-
1969	122	-	-
1970	157	-	-
1971	206	-	-
1972	210	-	-
1973	201	-	-
1974	162	-	-
1975	163	-	-
1976	179	-	-
1977	234	-	-
1978	292	-	-
1979	347	-	-
1980	340	-	-
1981	365	-	-
1982	483	-	-
1983	488	-	-
1984	548	-	-
1985	592	-	-
1986	842	-	-
1987	998	-	-
1988	1252	-	-
1989	1778	-	-
1990	2211	-	-
1991	2665	-	-
1992	3657	4	0.1%
1993	4455	2	0.04%
1994	6359	26	0.4%
1995	8198	79	1%
1996	9371	1145	12%
1997	9782	2072	21%
1998	10154	4666	46%
1999	9761	7295	75%
2000	7144	5407	76%
2001	4909	3705	75%

Table S10. Cont.

Cohort Year	Number of ELVs (SARS-ELV)	ELV classified into Autohandel types	% Classified
2002	3074	2292	75%
2003	1792	1305	73%
2004	1207	847	70%
2005	853	599	70%
2006	571	392	69%
2007	447	316	71%
2008	312	210	67%
2009	262	162	62%
2010	246	127	52%
2011	314	173	55%
2012	263	129	49%
2013	303	146	48%
2014	74	29	39%
Total	**98506**	**31128**	**32%**

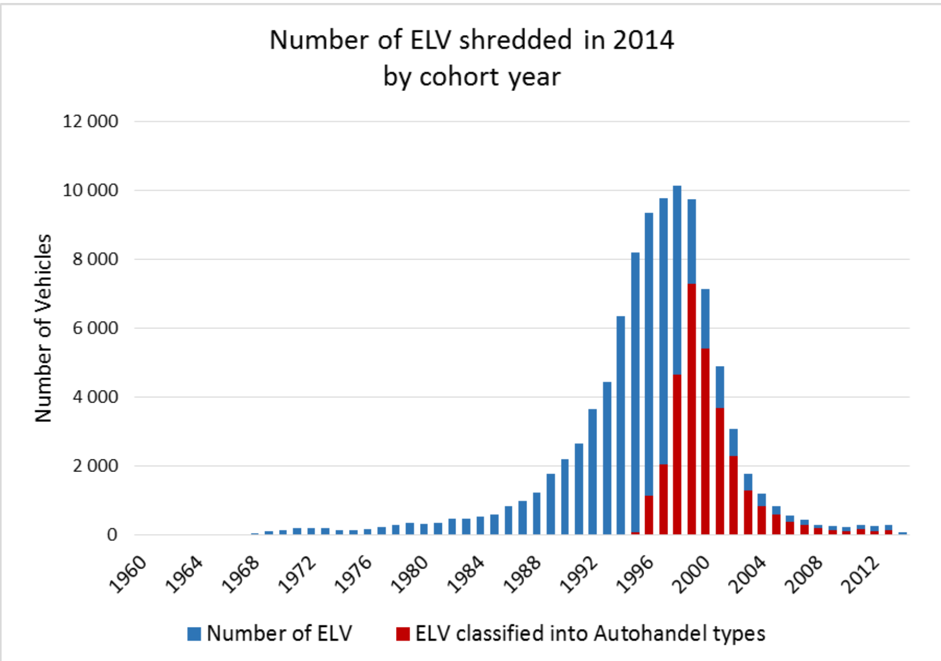

Figure S3. Classification of SARS ELV vehicles into Autohandel types by cohort year.

Table S11. Classification of *SARS-ELV* vehicles into *Autohandel* types by brand & model. Only the 36 most common brand & models are listed.

Brand and model	**Number of ELV (SARS-ELV)**	**ELV classified into Autohandel types**	**% Classified**
VW GOLF	2 596	-	-
VW POLO	2 141	405	19%
RENAULT Twingo	1 481	537	36%
FORD MONDEO 2.0	835	339	41%
VW PASSAT VARIANT	811	497	61%
SUBARU Legacy 2.0 4WD	785	149	19%
RENAULT ESPACE	780	728	93%
RENAULT CLIO 1.4	652	56	9%
OPEL Corsa B 14I	642	14	2%
SUBARU LEGACY 2.2 4WD	595	18	3%
PEUGEOT 106	557	109	20%
SEAT IBIZA	549	266	48%
Ford Ka 1.3	537	295	55%
FORD MONDEO 2.5 V6	528	253	48%
FORD FIESTA 1.2 16V	522	183	35%
VW PASSAT	507	132	26%
VW GOLF VARIANT	485	6	1%
RENAULT Megane Scenic	478	-	-
TOYOTA STARLET 1300 EFI	471	-	-
FIAT PUNTO 75	434	12	3%
NISSAN MICRA 1.3	384	112	29%
RENAULT CLIO	369	350	95%
PEUGEOT 205	352	-	-
AUDI A4	350	53	15%
SUBARU Justy 1.3 4WD	346	309	89%
AUDI A4 AVANT	340	75	22%
AUDI 80	339	-	-
SUBARU LEGACY 2.5 4WD	337	153	45%
PEUGEOT 106 1.1	331	324	98%
FIAT PUNTO 1.2 16V	325	324	100%
MAZDA 121	322	4	1%
Nissan Primera 2.0	310	109	35%
FIAT PUNTO 85 16V	306	122	40%
MITSUBISHI COLT 1.3	305	304	100%
TOYOTA COROLLA 1.6	302	46	15%
SUBARU IMPREZA 1.8 4WD	293	4	1%
Total	**21 697**	**6 288**	**29%**

10. Detailed results of Pareto analysis

The *Pareto principle* states that "in any population that contributes to a common effect, a relative few of the contributors—the vital few—account for the bulk of the effect".[70] Relying on this principle and to identify the "vital few" devices that are embedded in the vehicles considered, we carried out a *Pareto Analysis.*[70] For this, we first listed the total of EE devices, raked by number of occurrences in the vehicle stocks and flows considered. Then, we calculated the percentage of occurrence of each device with respect to the total and the cumulative percentage of occurrences. The EE devices accounting for 80% of the total occurrences of EE devices in the respective vehicle stock or flow were selected as the "vital few".

The results of the *Pareto Analysis* for the vehicle import flow, vehicle stock and ELV flow are summarized in Tables S12, S13 and S14, respectively.

For the final CM mass calculation, we considered EE devices that were both frequent and "heavy" (large mass compared to other EE devices). Therefore, the list of most frequently occurring EE devices obtained in the *Pareto Analysis* was compared against the list of EE devices obtained in Table S1 in which the mass of the EE devices relative to each other was presented. By doing so, we ensured that none of the *heavy* EE devices were left out of our analysis. Additionally, the list of EE devices in Table S2 provided the name of the sensors, controllers and actuators belonging to specific EE device or ECS provided by the *Autohandel* database.

The final list of EE devices analyzed in this study is presented in Table S15.

Table S12. EE devices in vehicles imported. Total number of vehicles classified to Autohandel types: 209 260. Total number of EE devices in these vehicles: 4 385 359. Only 90% of the total number of EE devices is listed.

Device/Control System	**Frequency**	**Cumm. Frequency**	**Cumm. Percent**
Airbags	634 016	634 016	14%
ABS/ESP/EBD/VDC/HHC/DSR/TCS/CBC	543 993	1 178 009	27%
Sound system (incl. Radio/Kassette/CD/...)	258 061	1 436 070	33%
Power windows system	203 166	1 639 236	37%
Central locking/keyless access system	199 666	1 838 902	42%
Power mirrors system	160 658	1 999 560	46%
Dashboard	117 313	2 116 873	48%
Daytime running lamps	116 920	2 233 793	51%
Electronic power steering	108 207	2 342 000	53%
Electronic immobilizer	106 166	2 448 166	56%
Navigation system (incl. DVD...)	106 391	2 554 557	58%
De-activation of co-driver airbag system	100 796	2 655 353	61%
Fog lights	94 713	2 750 066	63%
Adaptive Cruise Control	92 823	2 842 889	65%
Light assistance system	88 891	2 931 780	67%
Adaptive lights system	83 390	3 015 170	69%
Stop-start system	81 747	3 096 917	71%
Manual H/AC	81 323	3 178 240	72%
Automatic H/AC	79 906	3 258 146	74%
Tire Pressure monitoring system	67 845	3 325 991	76%
Multifunction steering wheel	65 331	3 391 322	77%
Parking assistance system	64 396	3 455 718	79%
Pre-installation kits for radio/mobile…	63 250	3 518 968	80%
Electro-hydraulic power steering	59 525	3 578 493	82%
Multimedia socket	47 934	3 626 427	83%
Anti-theft alarm system	43 499	3 669 926	84%
Keyless start system	41 508	3 711 434	85%
Multifunction display	36 291	3 747 725	85%
Seat heating system	28 122	3 775 847	86%
Electric sunroof	21 844	3 797 691	87%
Adaptive chassis control	21 027	3 818 718	87%
Block heater	20 981	3 839 699	88%
Electronic park brake	19 232	3 858 931	88%
Power outlets (ISO 4165)	19 190	3 878 121	88%
Rear camera	18 410	3 896 531	89%
Lane keeping assistance	15 283	3 911 814	89%
Automatic windscreen wipers	13 884	3 925 698	90%
Electrically foldable mirrors	12 600	3 938 298	90%
Driver drowsiness detection	11 549	3 949 847	90%

Table S13. EE devices in vehicles in stock. Total number of vehicles classified into Autohandel types: 2 967 345. Total number of EE devices in these vehicles: 60 352 913. Only 90% of the total number of EE devices is listed.

Device/Control System	**Frequency**	**Cumm. Frequency**	**Cumm. Percent**
Airbags	7 355 390	7 355 390	12%
ABS/ESP/EBD/VDC/HHC/DSR/TCS/CBC	6 370 317	13 725 707	23%
Sound system (incl. Radio/Kassette/CD/…)	5 798 278	19 523 985	32%
Navigation system (incl. DVD…)	3 198 662	22 722 647	38%
Central locking/keyless access system	3 062 039	25 784 686	43%
Power windows system	2 696 486	28 481 172	47%
Electronic immobilizer	2 315 419	30 796 591	51%
Power mirrors system	2 303 631	33 100 222	55%
Pre-installation kits for radio/mobile…	1 749 562	34 849 784	58%
Dashboard	1 694 327	36 544 111	61%
Fog lights	1 391 504	37 935 615	63%
Parking assistance system	1 246 843	39 182 458	65%
Automatic H/AC	1 174 231	40 356 689	67%
Electronic power steering	1 149 003	41 505 692	69%
Adaptive cruise control	1 030 078	42 535 770	70%
De-activation of co-driver airbag system	1 012 561	43 548 331	72%
Multifunction display	987 167	44 535 498	74%
Daytime running lamps	920 894	45 456 392	75%
Manual H/AC	911 234	46 367 626	77%
Multimedia socket	794 737	47 162 363	78%
Multifunction steering wheel	774 127	47 936 490	79%
Light assistance system	631 869	48 568 359	80%
Electrically foldable mirrors system	615 359	49 183 718	81%
Bluetooth hands free kit	587 713	49 771 431	82%
Power seats system	572 083	50 343 514	83%
Seat heating	554 728	50 898 242	84%
Tire pressure monitoring system	519 022	51 417 264	85%
Anti-theft alarm system	484 902	51 902 166	86%
Automatic widescreen wipers	372 468	52 274 634	87%
Headlamp washers	369 144	52 643 778	87%
Voice control system for telephone	367 850	53 011 628	88%
Electric sunroof	334 545	53 346 173	88%
Power outlets (ISO 4165)	328 307	53 674 480	89%
Outside temperature display	312 310	53 986 790	89%
Stop-start System	300 468	54 287 258	90%

Table S14. EE devices in ELV. Total number of vehicles classified into Autohandel types: 209 260. Total number of EE devices in these vehicles: 4 385 359. Only 90% of the total number of EE devices is listed.

Device/Control System	**Frequency**	**Cumm. Frequency**	**Cumm. Perc.**
Airbags	37 171	37 171	15%
Sound system (incl. Radio/Kassette/CD/...)	35 796	108 763	44%
ABS/ESP/EBD/VDC/HHC/DSR/TCS/CBC	23 232	119 431	48%
Electronic immobilizer	17 285	130 769	53%
Central locking/keyless access system	16 005	145 494	59%
Power windows system	15 596	160 681	65%
Power mirrors system	11 002	167 089	67%
Pre-installation kits for radio/mobile…	8 019	172 125	69%
Fog lights	5 260	174 626	70%
Navigation system (incl. DVD...)	5 120	179 606	72%
Dashboard	4 982	184 450	74%
Automatic H/AC	4 922	189 312	76%
Third brake light	4 698	193 786	78%
Multifunction display	4 615	198 318	80%
Manual H/AC	4 434	202 571	82%
Adaptive cruise control	4 016	206 169	83%
Warning buzzer for light	3 797	209 747	84%
Parking assistance system	3 779	213 508	86%
Daytime running light (DRL)	3 043	215 815	87%
Automatic windscreen wipers	2 572	217 916	88%
Outside temperature display	2 337	220 018	89%
Dynamic chassis control	2 103	221 887	89%
Seat heating	1 826	223 436	90%
Multifunction steering wheel	1 561	224 732	90%

Table S15. Selected EE devices for CM mass calculation.

Selected electric and electronic devices		
Actuators	Permanent mangnets	Speakers (only woofer)
		Throttle actuator
		Hydraulic modulator
		Power windows motors
		Radiator fan motor
		Electronic power steering motor
		Windscreen wiper motor
		Windscreen wiper fluid pump
		Alternator
		Starter motor
		Drive motor/Generator hybrid vehicle
		Drive motor/Generator electric vehicle
		NiMH Battery
Controllers	Printed Circuit Boards	Airbag controller
		ABS/ESP/EBD/VDC/HHC/DSR/TCS/CBC contro.
		Sound system controller (incl. Radio/CD)
		Navigation System controller (incl. DVD)
		Central locking/Keyless access controller
		Power windows controller
		Power mirrors controller
		Light assistance system controller
		Electronic power steering controller
		Parking assistance controller
		Automatic H/AC controller
		Adaptive cruise control (ACC) controller
		Engine/Motor controller
		Daytime running lamps controller
		Dashboard
		Electrical system controller

11. Detailed mass calculation results

Tables S16 to S24 present the results of the mass calculation for all variables considered. Result values are given as median ± 97.5th and 2.5th percentile of Monte Carlo simulation; equivalent to a 95% confidence interval. Uncertainties are rounded to one significant digit and median values are rounded to the level of precision of the uncertainty; (-) indicates a value equal to zero.

Table S16. Total mass flows and stocks of passenger vehicles, ELV and ELV treatment outputs. Flow values in Gg/a; stock values in Gg.

Mass flow of passenger vehicles, ELV and ELV treatment output fractions			
Symbol	**-**	**Median**	**+**
X_{0_1}	60	440	60
X_{1_2}	70	480	70
X_{3_1}	90	40	90
X_{2_3}	70	240	70
X_{3_0}	20	160	20
q_{S2}	10	100	10
X_{2_4}	2	130	3
$X_{4\_0\_4}$	-	-	-
X_{4_5}	2	130	3
X_{5a}	1	3	1
X_{5b}	1	2	1
X_{5c}	0.2	0.8	0.3
X_{5d}	10	20	10
X_{5e}	1	2	2
X_{5f}	4	9	4
q_{S5}	1	13	1
X_{5_6}	8	81	8
X_{6_0}	0.3	2.7	0.3
X_{0_6}	0.4	5.0	0.4
X_{6_7}	8	82	8
X_{7_13}	1	4	1
X_{7_8a}	20	60	20
X_{7_8b}	10	7	20
X_{8_0}	8	75	9
X_{7_9}	3	12	4
X_{9_0}	3	35	3
X_{0_9}	7	73	7
X_{9_10}	5	51	5
X_{10_8}	4	9	6
X_{0_10}	700	2 600	1 000
X_{10_0a}	200	600	300
X_{10_0b}	500	2 100	800
X_{10_11}	9	22	10
q_{S11}	9	22	10
S_2	800	6 100	800

Table S17. Mass of critical metals in ELV treatment outputs. All values in kg/a.

Mass of critical and precious metals in ELV treatment outputs			
Symbol	**-**	**Median**	**+**
XNd_asr	70	140	100
XDy_asr	4	8	6
XCo_asr	200	400	300
XLa_asr	30	70	50
XSm_asr	20	40	30
XPd_asr	10	30	20
XRu_asr	2	4	3
XAg_asr	60	130	90
XAu_asr	7	14	10
XNd_FeAl	6	14	8
XDy_FeAl	-	-	-
XCo_FeAl	800	1 800	1 000
XLa_FeAl	5	14	8
XPd_FeAl	1	2	1
XRu_FeAl	5	11	8
XAg_FeAl	10	20	20
XAu_FeAl	0.1	0.3	0.2
XNd_o	4	9	7
XDy_o	0.3	0.7	0.5
XCo_o	30	60	40
XLa_o	3	6	4
XPd_o	7	15	10
XRu_o	0.3	0.7	0.5
XAg_o	80	170	100
XAu_o	2	4	3

Table S18. Mass balance of the combined ELV dismantling, depollution, shredding and separation processes. All values in kg/a.

Mass balance of ELV management system																		
Metal	**Input (100 000 ELV)**			**Shredder outputs**												**Mismatch**		
				Other fractions			**Fe&Al scrap**			**ASR**			**NiMH Batteries**					
	-	**Median**	+	-	**Median**	+	-	**Median**	+	-	**Median**	+	-	**Median**	+	-	**Median**	+
Dy	3	10	4	0.3	1	1	-	-	-	4	8	6	0.001	0.002	0.002	7	1	6
La	1 000	3 000	2 000	3	6	4	5	14	8	30	70	50	5	12	8	1 000	2 000	2 000
Nd	100	300	100	5	9	9	6	14	8	70	140	100	2	5	3	100	100	100
Co	600	1 400	900	30	60	40	800	1 800	1 000	200	400	300	-	-	-	1 000	-800	1 000
Pd	1	3	2	7	15	10	1	2	1	10	30	20	-	-	-	30	-50	20
Ru	0.02	0.05	0.03	0.4	1	1	5	11	8	2	4	3	-	-	-	8	-20	6
Ag	20	50	30	80	170	100	10	20	20	60	130	90	-	-	-	200	-300	100
Au	7	16	10	2	4	3	0.1	0.3	0.2	7	14	10	-	-	-	10	-7	10

Table S19. Mass of critical metals in imported vehicles. All values in kg/a. In total 300 000 vehicles.

Metal	**-**	**MC median**	**+**
Dy	700	1 400	1 000
La	4 000	12 000	6 000
Nd	4 000	11 000	5 000
Co	6 000	15 000	8 000
Pd	7	16	11
Ru	0.1	0.3	0.2
Ag	100	300	200
Au	30	80	50

Table S20. Mass of critical metals in vehicles in stock. All values in kg. In total 4 000 000 vehicles.

Metal	**-**	**MC median**	**+**
Dy	3 000	7 000	4 000
La	50 000	140 000	80 000
Nd	20 000	70 000	30 000
Co	50 000	130 000	60 000
Pd	100	300	200
Ru	2	4	3
Ag	2 000	4 000	3 000
Au	500	1 200	800

Table S21. Mass of critical metals in an average ELV (average cohort 2000). All values in g/car.

Metal	**-**	**MC median**	**+**
Dy	0.02	0.10	0.03
La	7	26	10
Nd	1	3	1
Co	3	14	6
Pd	0.01	0.02	0.01
Ru	0.0001	0.0004	0.0002
Ag	0.1	0.4	0.2
Au	0.03	0.10	0.05

Table S22. Mass of critical metals in an average vehicle in stock (average cohort 2007). All values in g/car.

Metal	**-**	**MC median**	**+**
Dy	0.4	1.0	0.7
La	7	32	10
Nd	3	16	5
Co	7	30	10
Pd	0.01	0.05	0.02
Ru	0.0002	0.0008	0.0004
Ag	0.2	0.8	0.4
Au	0.1	0.2	0.1

Table S23. Mass of critical metals in an average new vehicle imported in 2014 (average cohort 2014). All values in g/car.

Metal	**-**	**MC median**	**+**
Dy	1	5	3
La	9	40	10
Nd	8	36	10
Co	10	50	20
Pd	0.01	0.04	0.02
Ru	0.0002	0.0007	0.0003
Ag	0.2	0.7	0.3
Au	0.1	0.2	0.1

Table S24. Distribution of CM mass in EE devices in an average passenger vehicle. All values in %

Selected electric and electronic devices			Distribution of critical metal mass in EE devices in an average passenger vehicle - in percentage (%)-							
			A) Average new vehicle (cohort 2014)							
			Ag	**Au**	**Pd**	**Ru**	**Dy**	**La**	**Nd**	**Co**
Actuators	**Permanent magnets**	Speakers (only woofer)	-	-	-	-	0.002	0.2	0.01	0.06
		Throttle actuator	-	-	-	-	0.001	0.05	0.003	0.02
		Hydraulic modulator	-	-	-	-	0.001	0.04	0.003	0.02
		Power windows motors	-	-	-	-	0.001	0.1	0.005	0.03
		Radiator fan motor	-	-	-	-	0.001	0.1	0.01	0.04
		Electronic power steering motor	-	-	-	-	0.1	-	0.4	0.5
		Windscreen wiper motor	-	-	-	-	0.0004	0.03	0.002	0.01
		Windscreen wiper fluid pump	-	-	-	-	0.0001	0.004	0.0003	0.001
		Alternator	-	-	-	-	0.002	0.2	0.01	0.1
		Starter motor	-	-	-	-	0.001	0.1	0.01	0.04
		Drive motor/Generator HEV	-	-	-	-	0.6	-	0.3	0.2
		Drive motor/Generator EV	-	-	-	-	0.2	-	0.1	0.05
		NiMH Battery HEV	-	-	-	-	0.0005	0.3	0.2	-
Controllers	**Printed Circuit Boards**	Airbag controller	0.03	0.03	0.03	0.03	0.00002	0.00004	0.00005	0.0002
		ABS/ESP/EBD/VDC/HHC/DSR/TCS/CBC contro.	0.1	0.1	0.1	0.1	0.0004	0.0001	0.01	0.000
		Sound system controller (incl. Radio/CD)	0.2	0.2	0.2	0.2	0.0001	0.003	0.003	0.001
		Navigation System controller (incl. DVD)	0.1	0.1	0.1	0.1	0.0004	0.0001	0.01	0.001
		Central locking/Keyless access controller	0.02	0.02	0.02	0.02	0.000003	0.00002	0.00002	0.0001
		Power windows controller	0.02	0.02	0.02	0.02	0.0001	0.00002	0.001	0.0001
		Power mirrors controller	0.0004	0.0004	0.0004	0.0004	0.000000005	0.00000002	0.00000002	0.000002
		Light assistance system controller	0.0002	0.0002	0.0002	0.0002	0.000001	0.0000002	0.00001	0.0000
		Electronic power steering controller	0.1	0.1	0.1	0.1	-	0.00002	0.00002	0.001
		Parking assistance controller	0.02	0.02	0.02	0.02	0.0001	0.00002	0.001	0.0001
		Automatic H/AC controller	0.01	0.01	0.01	0.01	0.0000	0.00001	0.001	0.0000
		Adaptive cruise control (ACC) controller	0.02	0.02	0.02	0.02	0.0001	0.00002	0.001	0.0001
		Engine/Motor controller	0.1	0.1	0.1	0.1	0.0015	0.00001	0.00001	0.001
		Daytime running lamps controller	0.02	0.02	0.02	0.02	0.0001	0.00002	0.001	0.0001
		Dashboard	0.1	0.1	0.1	0.1	0.0003	0.0001	0.005	0.000
		Electrical system controller	0.2	0.2	0.2	0.2	0.0008	0.0002	0.01	0.001
		Total mass per average vehicle (in g)	**1**	**0.3**	**0.06**	**0.001**	**5**	**40**	**40**	**50**

Table S24. Cont. All values in %

Selected electric and electronic devices			Distribution of critical metal mass in an average passenger vehicle - in percentage (%)-							
			B) Average vehicle in stock (cohort 2007)							
			Ag	**Au**	**Pd**	**Ru**	**Dy**	**La**	**Nd**	**Co**
Actuators	**Permanent magnets**	Speakers (only woofer)	-	-	-	-	0.01	0.2	0.03	0.1
		Throttle actuator	-	-	-	-	0.002	0.1	0.01	0.03
		Hydraulic modulator	-	-	-	-	0.002	0.05	0.01	0.03
		Power windows motors	-	-	-	-	0.002	0.05	0.01	0.03
		Radiator fan motor	-	-	-	-	0.004	0.1	0.01	0.1
		Electronic power steering motor	-	-	-	-	0.23	-	0.4	0.4
		Windscreen wiper motor	-	-	-	-	0.001	0.03	0.005	0.02
		Windscreen wiper fluid pump	-	-	-	-	0.0002	0.005	0.001	0.003
		Alternator	-	-	-	-	0.01	0.2	0.03	0.1
		Starter motor	-	-	-	-	0.004	0.1	0.02	0.1
		Drive motor/Generator HEV	-	-	-	-	0.6	-	0.2	0.1
		Drive motor/Generator EV	-	-	-	-	0.1	-	0.04	0.01
		NiMH Battery HEV	-	-	-	-	0.00	0.1	0.1	-
Controllers	**Printed Circuit Boards**	Airbag controller	0.03	0.03	0.03	0.03	0.0000	0.0001	0.0001	0.000
		ABS/ESP/EBD/VDC/HHC/DSR/TCS/CBC contro.	0.05	0.05	0.05	0.05	0.001	0.0001	0.01	0.00
		Sound system controller (incl. Radio/CD)	0.3	0.3	0.3	0.3	0.0005	0.01	0.01	0.00
		Navigation System controller (incl. DVD)	0.2	0.2	0.2	0.2	0.002	0.0002	0.02	0.001
		Central locking/Keyless access controller	0.01	0.01	0.01	0.01	0.00001	0.00002	0.00005	0.0001
		Power windows controller	0.01	0.01	0.01	0.01	0.0002	0.00002	0.002	0.0001
		Power mirrors controller	0.0003	0.0003	0.0003	0.0003	0.00000001	0.00000002	0.00000004	0.00000
		Light assistance system controller	0.0001	0.0001	0.0001	0.0001	0.000001	0.0000001	0.00001	0.000001
		Electronic power steering controller	0.05	0.05	0.05	0.05	-	0.00001	0.00003	0.000
		Parking assistance controller	0.01	0.01	0.01	0.01	0.0002	0.00002	0.002	0.0001
		Automatic H/AC controller	0.01	0.01	0.01	0.01	0.0001	0.00001	0.001	0.0001
		Adaptive cruise control (ACC) controller	0.01	0.01	0.01	0.01	0.0001	0.00001	0.001	0.0001
		Engine/Motor controller	0.1	0.1	0.1	0.1	0.005	0.00001	0.00002	0.001
		Daytime running lamps controller	0.01	0.01	0.01	0.01	0.0001	0.00001	0.001	0.0001
		Dashboard	0.1	0.1	0.1	0.1	0.001	0.0001	0.01	0.001
		Electrical system controller	0.2	0.2	0.2	0.2	0.003	0.0003	0.03	0.002
		Total mass per average vehicle (in g)	**1**	**0.3**	**0.06**	**0.001**	**2**	**30**	**20**	**30**

Table S24. Cont. All values in %

Selected electric and electronic devices			Distribution of critical metal mass in an passenger vehicle - in percentage (%)- C) Average ELV (cohort 2000)							
			Ag	Au	Pd	Ru	Dy	La	Nd	Co
Actuators	Permanent magnets	Speakers (only woofer)	-	-	-	-	0.1	0.2	0.1	0.2
		Throttle actuator	-	-	-	-	0.03	0.1	0.04	0.1
		Hydraulic modulator	-	-	-	-	0.03	0.1	0.03	0.1
		Power windows motors	-	-	-	-	0.01	0.02	0.01	0.02
		Radiator fan motor	-	-	-	-	0.1	0.1	0.1	0.1
		Electronic power steering motor	-	-	-	-	0.3	-	0.2	0.1
		Windscreen wiper motor	-	-	-	-	0.02	0.04	0.02	0.04
		Windscreen wiper fluid pump	-	-	-	-	0.002	0.01	0.003	0.01
		Alternator	-	-	-	-	0.1	0.3	0.1	0.3
		Starter motor	-	-	-	-	0.1	0.1	0.1	0.1
		Drive motor/Generator HEV	-	-	-	-	0.1	-	0.01	0.002
		Drive motor/Generator EV	-	-	-	-	0.01	-	0.001	0.0002
		NiMH Battery HEV	-	-	-	-	0.0002	0.005	0.02	-
Controllers	Printed Circuit Boards	Airbag controller	0.1	0.1	0.1	0.1	0.001	0.0001	0.001	0.001
		ABS/ESP/EBD/VDC/HHC/DSR/TCS/CBC contro.	0.03	0.03	0.03	0.03	0.004	0.00003	0.01	0.0003
		Sound system controller (incl. Radio/CD)	0.2	0.2	0.2	0.2	0.003	0.003	0.02	0.002
		Navigation System controller (incl. DVD)	0.03	0.03	0.03	0.03	0.004	0.00004	0.01	0.0004
		Central locking/Keyless access controller	0.01	0.01	0.01	0.01	0.0001	0.00001	0.0001	0.0001
		Power windows controller	0.01	0.01	0.01	0.01	0.001	0.00001	0.005	0.0001
		Power mirrors controller	0.0002	0.0002	0.0002	0.0002	0.0000001	0.00000001	0.0000001	0.000002
		Light assistance system controller	0.00001	0.00001	0.00001	0.00001	0.000001	0.00000001	0.000002	0.0000001
		Electronic power steering controller	0.01	0.01	0.01	0.01	-	0.000002	0.00001	0.0001
		Parking assistance controller	0.004	0.004	0.004	0.004	0.001	0.000004	0.002	0.00004
		Automatic H/AC controller	0.003	0.003	0.003	0.003	0.0005	0.000004	0.002	0.00004
		Adaptive cruise control (ACC) controller	0.01	0.01	0.01	0.01	0.001	0.00001	0.002	0.0001
		Engine/Motor controller	0.2	0.2	0.2	0.2	0.1	0.00001	0.000	0.00
		Daytime running lamps controller	0.003	0.003	0.003	0.003	0.0004	0.000004	0.001	0.0000
		Dashboard	0.1	0.1	0.1	0.1	0.02	0.0001	0.05	0.001
		Electrical system controller	0.3	0.3	0.3	0.3	0.04	0.0003	0.1	0.00
		Total mass per average vehicle (in g)	**1**	**0.2**	**0.03**	**0.001**	**0.1**	**30**	**3**	**20**

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Paper IV

Historical Penetration Patterns of Automobile Electronic Control Systems and Implications for Critical Raw Materials Recycling

Restrepo E, Løvik AN, Widmer R, Wäger P, Müller DB. Resources. 2019 Mar 31;8(2):58.

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Historical Penetration Patterns of Automobile Electronic Control Systems and Implications for Critical Raw Materials Recycling

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Received: 14 March 2019; Accepted: 28 March 2019; Published: 31 March 2019

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Abstract: Car electronics form a large but poorly utilized source for secondary critical raw materials (CRMs). To capitalize on this potential, it is necessary to understand the mechanism in which car electronics enter and exit the vehicle fleet over time. We analyze the historical penetration of selected car electronic control systems (ECS) in 65,475 car models sold in the past 14 years by means of statistical learning. We find that the historical penetration of ECS tends to follow S-shaped curves, however with substantial variations in penetration speed and saturation level. Although electronic functions are increasing rapidly, comfort-related ECS tend to remain below 40% penetration even after 14 years on the market. In contrast, safety regulations lead to rapid ECS penetration approaching 100%, while environmental emission regulations seem to indirectly push related ECS to a medium penetration level (e.g., growing to 60% after six years). The trend towards integration of individual ECS poses long-term challenges for car electronics dismantling and recycling. Monitoring the ECS embedded in new cars, such as carried out in this study, can inform timely updates for such strategies. The results also provide a framework for developing scenarios to identify related future CRM stocks and flows.

Keywords: car electronics; technological diffusion; critical raw materials; urban mine; machine learning; statistical learning

1. Introduction

Recent studies [1–16] have found that cars have a large potential for recovering critical raw materials (CRMs). Critical metals (CMs) are of particular interest, due to their increased use in car electronics [7–9,11,13,17]. Regarding rare earth element (REE) content in car electronics, Restrepo et al. [8] estimated that the neodymium stock in Swiss car electronics (around 70 t) in 2014 was similar to that in information and communication technologies (ICT) and consumer electronics. Fishman et al. [14] indicated that the neodymium stock in alternative energy vehicles (AEVs) in the United States was about 50% of the 2017 in-ground reserves, and Xu et al. [7] estimated that in 2030 about half of the neodymium demand for the production of new cars in Japan could be covered with neodymium recovered from end-of-life vehicle (ELV) electronics. Estimates of gold content per car vary from 0.2 g/t [10] to 6 g/t [4] of vehicle scrap, which is comparable to the average ore grade of gold deposits worldwide (1 g/t) [18]. Dismantling car electronics could increase the ore grade (mass fraction) of CMs to several orders of magnitude.

The ongoing revision of the Swiss regulation on waste electrical and electronic equipment (WEEE) plans to "set the framework for a mandatory dismantling and subsequent reuse/recycling of selected electrical and electronic (EE) devices embedded in end-of-life vehicles (ELVs), based on CRM mass in the EE devices and when ecologically and economically feasible" [8,19]. The EE devices to be included in the amended regulation are yet to be defined.

Until now, car electronic control systems (ECS) have been embedded in cars mostly independently to accomplish specific functions in the car [20]. However, new ECS are cross-functional, integrating many of the former functions accomplished by individual ECS [20]. The physical form in which new ECS are embedded in cars varies largely across car types and cohorts (production year). For example, the controllers in new ECS can be embedded as dedicated electronic control units (ECUs), integrated circuits in existing ECUs, or as mere software add-ons [20]. The same applies to the corresponding sensors and actuators, for which the size and material composition varies widely. These new developments in automobile ECS pose a challenge for the accounting of the number of embedded ECS as well as of the mass and composition of their related electrical and electronic (EE) devices (i.e., sensors, controllers and actuators).

The use of ECS and corresponding EE devices in vehicles, as well as their composition, is poorly understood, which hampers the development of recycling strategies for CRMs in cars. The changing composition of cars driven by the diffusion of new technologies makes it especially difficult to design policies that will remain effective in the medium or long term. In this context, it is important to understand the mechanisms by which car electronics penetrate across different car types—including the speed of technological diffusion and its response to external factors, such as rising safety and environmental standards—so that relevant scenarios for future car composition may be analyzed. In addition, it is also crucial to identify which technical car characteristics correlate with the presence of ECS, to facilitate a more accurate classification of cars in future estimations of related CRM content for the totality of the car fleet [21,22]. With this in mind, and with the main goal of informing the current revision of the Swiss WEEE regulation, we address the following research questions:

1. What are typical penetration patterns of car ECS over time?
2. What are the car characteristics correlating with the presence of car ECS in different car types?
3. What are the implications of the past trends in ECS penetration for the future recycling of car electronics?

To answer these questions, we apply statistical learning [23] to a dataset of 65,475 car models sold in Switzerland over the past 14 years.

This study informs the current revision of the Swiss WEEE regulation and contributes to improving the prospective accounting of CRM stocks and flows in car electronics by breaking down the historical penetration patterns of selected car ECS. Our study illustrates the impact of safety and environmental regulations as well as of ECS integration on the speed of technological change in the car electronics sector. The methods and results provide a framework for developing scenarios for related future material stocks and flows, and demonstrate how car statistics can be compiled to better reflect differences in equipment level and CRM content.

2. Materials and Methods

2.1. Selection of Automobile Electronic Control Systems to Consider in This Study

We begin by recalling the main function of a car, which is to transport people or goods. This function is bound by five main requirements or (elastic) constraints related to: (i) passenger and pedestrian safety, (ii) passenger comfort, (iii) information/communication with passenger, other cars and infrastructure, (iv) fuel and energy efficiency, and (v) environmental emission control. ECS are embedded in cars to accomplish one or a combination of these functions (constraints). Each ECS comprises sensors, controllers, and actuators [8]. To ensure accounting consistency, we focused on the number of ECS disregarding the physical form in which its constituent elements were implemented.

Established ECS (with penetration rates over 10% in 2015) were easily classifiable under the main constraints above, while the classification of new ECS (with penetration rates below 10% in 2015) was challenging because of their cross-functional nature. Consequently, we made a distinction between established and new ECS and set them aside into two groups to analyze their trends separately: group A consisted of established ECS and group B consisted of emerging ECS.

The ECS in both groups are however related. Specifically, ECS in group B build upon ECS in group A by integrating them into cross-functional systems. To understand this relationship, it is useful to think in terms of the hierarchical networked structure of automobile ECS as defined by Restrepo et al. [8]. Under this structure, the emerging ECS in group B enter the ECS network as higher hierarchical entities to which existing ECS in group A subordinate. In terms of the car's automation level as defined by SAE International (Society of Automotive Engineers) [24], established ECS in group A belong to the lowest automation level (Level 0—*no automation*), while new ECS in group B belong to higher automation levels (Levels 1 to 5—*active driver assistance*, *partial automation*, *conditional automation*, *high automation*, and *full automation*, respectively).

To represent ECS in group A, we selected five of the most frequently embedded ECS identified by Restrepo et al. [8]. To represent ECS in group B we selected three emerging ECS in the realm of autonomous driving that built upon the ECS in group A. The selection of the ECS in group A ensured enough data records to analyze: (1) the most important car characteristics correlating with the presence of the selected ECS, and (2) typical penetration patterns of ECS over time, including ECS integration. Trends in ECS integration were further exemplified with two ECS in group A. ECS in group B served to illustrate the general trend towards self-driving cars. The selected ECS are presented in Table 1.

Table 1. Electronic control systems (ECS) selected for analysis.

Selected ECS	Description/Function
Group A	*Established ECS frequently embedded in cars*
CC	Comfort
ESP	Safety
ABS	Safety
Navi	Information/Communication
Stop-start	Fuel efficiency/Environmental emission control
Group B	*Emerging ECS building upon ECS in group A*
Traffic jam assist	Cross-functional
Parking pilot	Cross-functional
Highway autopilot	Cross-functional

CC: cruise control, ESP: electronic stability program, ABS: antilock-braking system, Navi: navigation system, Stop-start: stop-start system.

2.2. Data Set

Through the *Autohandel* database [25] we obtained information about the standard embedded equipment in 65,475 car models registered in Switzerland between 2001 and 2015, amounting to a total of 113,727 dataset records.

Each car was specified by the production year, market price, market class and 11 technical characteristics: mass, engine displacement, fuel type, engine/motor power, number of cylinders, body type, number of seats, number of doors, transmission type, drive type and number of gears (14 car characteristics in total). The distribution of the dataset is summarized in Figure 1 for six selected car characteristics; the distribution of the remaining eight characteristics is presented in the Supplementary Information (SI) Figure S1. Most of the cars were of gasoline and diesel fuel types (Figure 1C), had an average mass of 1500 kg (Figure 1D) and an engine displacement of around 2000 cm^3 (Figure 1B). These average characteristics correspond to an "average vehicle", such as a VW Golf or Ford Focus [26].

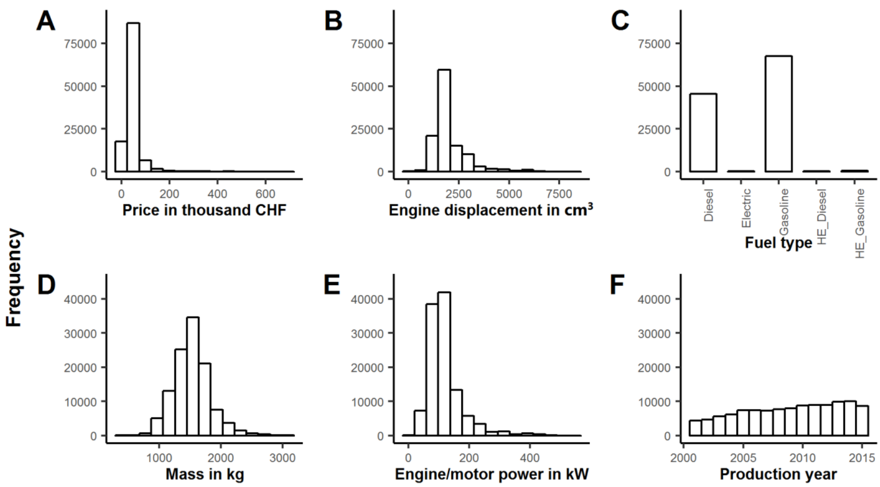

Figure 1. Distribution of cars in the dataset by: (**A**) price, (**B**) engine displacement, (**C**) fuel type, (**D**) mass, (**E**) engine/motor power, and (**F**) production year. Note the y-axis scale difference between the two rows of plots. The distribution of cars by the remaining eight characteristics is presented in Figure S1 of the SI.

2.3. *Analysis of Historical Trends and Indicators for the Use of Automobile Electronic Control Systems*

The analysis of the trends was done by means of *statistical learning*, understood as a "[vast] set of statistical tools for understanding data" [23]. All of the statistical analyses were carried out in R [27]. The specific packages used for the analyses are listed in Table S1 of the SI. Figure 2 summarizes the steps of the statistical analysis.

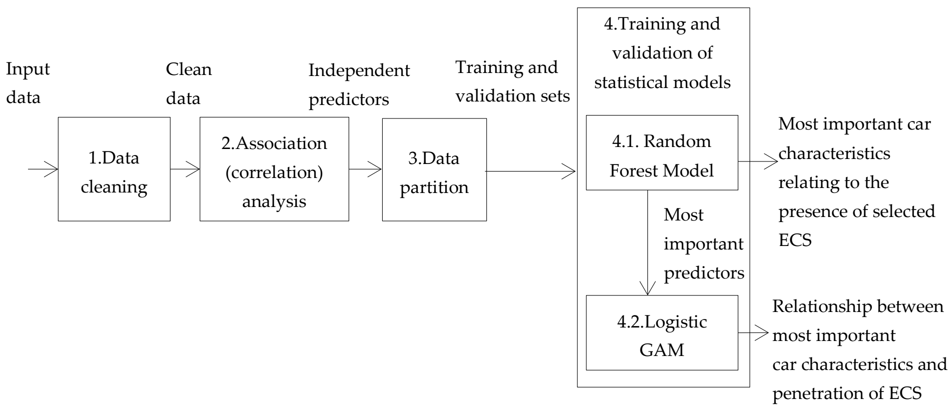

Figure 2. Steps in the statistical analysis and corresponding results (to the right of the figure).

The average penetration of the selected ECS was obtained by dividing the number of corresponding ECS embedded in cars by the total number of cars analyzed. The past trend in the penetration of each ECS was obtained by performing this calculation by year. Trends in ECS integration were illustrated for two ECS within group A: the anti-lock braking system (ABS) and the electronic stability program (ESP).

The most important car characteristics relating to the presence of the ECS in group A in cars were identified by calculating the Gini variable importance measure (Gini VIM) after fitting a random forest model to the dataset. The relationship between the above characteristics and the penetration of ECS in group A was identified by fitting a logistic regression generalized additive model (Logistic GAM) to the dataset.

We defined the 14 car characteristics as the input variables (also referred to as predictors). The input variables included both numerical (e.g., engine displacement) and categorical (e.g., fuel type) data types. Table S2 of the SI details the data types of the input variables. The output variable, or response, was the number of embedded ECS, which for each ECS analyzed was either one (1) or zero (0), therefore dichotomous.

Data cleaning consisted of removing records with incomplete data and typos. Association analysis was carried out to discard redundant variables before further statistical analysis. Specifically, we calculated the *Goodman and Kruskal's tau measure of association*, τ(x,y) [28] which indicates the association (or correlation) between two input variables x and y on a scale from zero to one. For cases with τ(x,y) > 0.5, it was considered that the variables x and y were associated (correlated) or dependent. However, no combination of input variables displayed τ(x,y) higher than 0.4. Hence, all input variables were included in the subsequent statistical analysis. The Goodman and Kruskal's tau measure of association (τ(x,y)) is presented in the correlogram of Figure S2 in the SI.

Subsequently, we randomly split the data into a training set and a validation set, each containing 50% of the original data. A statistical model was fit (trained) using the training set; validation consisted of using the trained model for predicting the (already known) response in the validation set [23]. We thereby estimated the *model accuracy*, specified as the fraction of cars for which the presence (zero or one) of the given ECS was correctly predicted.

2.3.1. Random Forest Model for Identifying the Indicators for the Use of ECS in Cars

In statistical models, variable importance measures (VIMs) allow identifying the input variables to which changes the output variable responds more strongly [29]. These input variables are called the *most important* input variables and are the ones that contribute the most to overall model accuracy [23,29]. Here, we used VIMs to identify the car characteristics that best explain the presence of the selected ECS and can thus be assumed as *indicators* for their use in cars.

According to a comprehensive review on VIMs by Wei et al. [29], VIMs based on random forest models are particularly suitable for categorical outputs, such as the ones in this study. Thus, we fit a random forest model to the dataset and used a VIM based on it.

Random forest is a machine learning algorithm belonging to the *decision tree* methods for regression and classification [23,29]. As such, random forest involves segmenting the predictor space into a number of simple regions for which a prediction is made [23]. The name "decision tree" derives for the fact that the set of splitting rules can be summarized in a tree. In the specific case of random forest, multiple trees are produced and combined to yield a single consensus prediction [23].

Specifically, we calculated the *Gini VIM* based on a random forest which gives a quantitative measure for the most influential input variables in the model [29]. The most influential or most important variable is understood as the input variable X_i that leads to the largest decrease in node impurity when chosen as the splitting variable at any father node [23,29]. "Summing all the impurity decreases resulting from X_i across each tree in the forest provides an overall measure of the contribution of X_i to the accuracy of model prediction" [29]. Further detail on random forest and the Gini VIM can be found in references [23,29].

2.3.2. Logistic Generalized Additive Model (GAM) for Examining the Relationship Between the Indicator Characteristics and the Penetration of ECS

We made use of the inference advantages of generalized additive models (GAMs) for revealing the relationship between the past penetration of a given ECS and the indicator characteristics identified above. Specifically, we fit a logistic regression GAM (Logistic GAM) to the dataset. Logistic regression was chosen due to its suitability for dichotomous (categorical with only two categories) responses [23];

the generalized-additive version of the logistic regression was chosen in order to account for likely non-linear relationships between the input and the output variables [23].

GAMs "provide a general framework for extending a standard linear model by allowing non-linear functions of each of the variables, while maintaining additivity" [23]. In the specific case of classification problems using the logistic regression model, each linear component of the *logit* (log of the odds) is replaced with a (smooth) non-linear function $f_j\ (X_i)$ in order to allow for non-linear relationships between each predictor X_i and the response [23]. Further reading on Logistic GAM can be done in reference [23].

3. Results and Discussion

3.1. Historical Trends in Penetration of Automobile Electronic Control Systems (ECS)

Note that these results are calculated on the basis of the standard equipment embedded in the car models analyzed. Selected ECS may have been added to the car models following customized configurations at the time of purchase. Therefore, the values for the penetration rate presented here are conservative and may tend to underestimate the real penetration rate of ECS.

3.1.1. Established ECS

The average penetration of the ECS in group A for the time period 2001 to 2015 is presented in Figure 3. The average penetration values can be found in Table S3 of the SI; average penetration values for additional ECS not analyzed in detail in this study are provided in Table S4.

Figure 3A shows the average penetration of the cruise control system (CC), which is included in vehicles with the purpose of keeping the car's speed at a predefined level [30]. It can be observed that even though the CC was present in cars during the 14 years of analysis, its penetration remained close to 40% for the entire period. Considering that the CC was first introduced towards the beginning of the 1990s [30,31], and that the proportion of high-end car classes in the dataset was about 50% (see the sum of "luxury", "upper class" and "upper middle class" cars in panel A of Figure S1 in the Supplementary Information), this implies that even after 25 years on the market the CC has still not penetrated beyond the high-end car classes.

Figure 3B presents the penetration of the electronic stability program (ESP)–a safety device. The ESP is a vehicle dynamics system encompassing other systems, such as the ABS and the traction control system (TCS) [20]. It was first introduced at the beginning of the 1990s with the overall role of preventing the vehicle's tendency to "plow" or "become unstable and brake away to the side" [20]. Due to its safety benefits, the ESP became mandatory for most new car models since 2011 (regulation EC No 661/2009) [32]. Existing vehicle types were given additional time to comply with this requirement: by 2014 the regulation was extended to new cars registered. As a result of the safety benefits of the ESP and the placement of the safety regulation, the average penetration increased to 80% in 2015.

The trend in the adoption of the navigation system (Navi) is presented in Figure 3C. The penetration of the Navi increased from 35% to 50% in the first six years of analysis (2001–2007). A fairly stable penetration of around 50% can be observed after 2007 with a slight decrease at the end of the study period. Considering that the Navi was first introduced around 1980 [33], it can be inferred that it took about 30 years for this technology to penetrate through half of the car types (and beyond the high-end classes).

Figure 3D displays a rapid adoption of the stop-start system after 2010. Specifically, the penetration of the stop-start system increased from 5% in 2010 to 60% in 2015. This rapid adoption may be attributed to the implementation of the Euro 5 emission standard (regulation EC No 764/2008) for new car type approvals in 2009 [34]. The stop-start system can help reduce up to 10% fuel consumption by turning off the internal combustion engine (ICE) during idling situations (as in the case of stops at traffic lights or jams) and turning it on again upon driver's demand [35]. This function is particularly useful in diesel cars (both ICE and hybrid electric types) for achieving the emission standards set by the

Euro 5 regulation [35]. We can infer that even though the stop-start system is not directly mandated by the Euro 5 regulation, its utility to achieve the required standards particularly for diesel cars has established it as a common ECS in a short period of time.

The average penetration of ECS obtained above is consistent with average penetration values reported by the DAT group (Deutsche Automobil Treuhand GmbH (Ostfildern, Germany)) in German cars during the time period 2001–2015 [36].

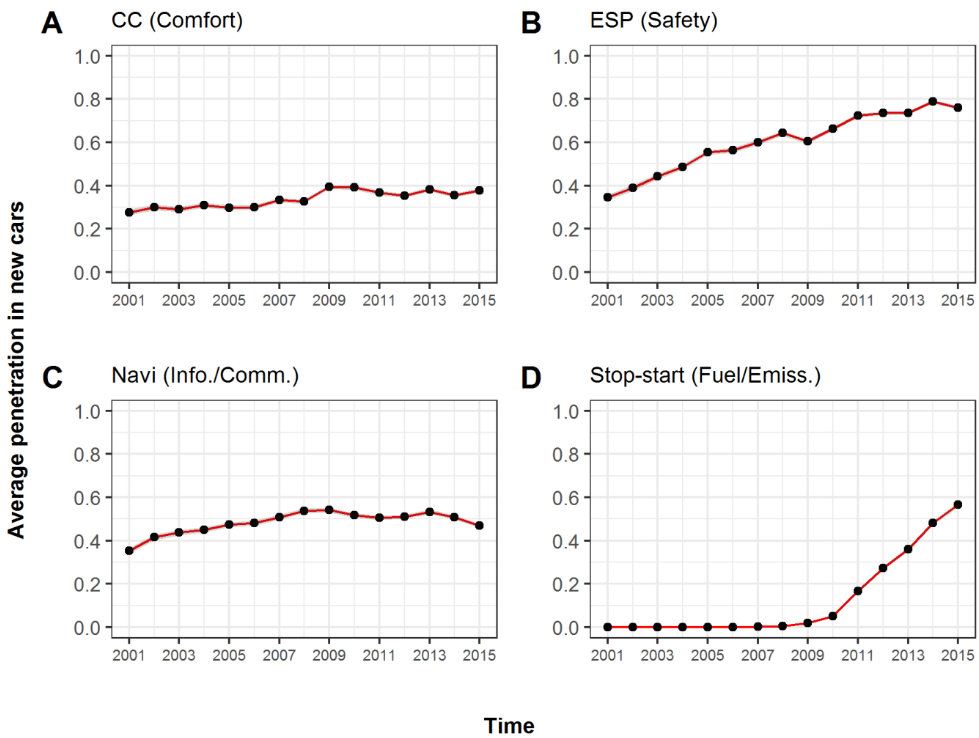

Figure 3. Average historical penetration of established ECS in new cars: (**A**) cruise control (CC)–representing comfort ECS, (**B**) electronic stability program (ESP)–representing safety ECS, (**C**) navigation system (Navi)—representing information/communication ECS, and (**D**) stop-start system—representing fuel efficiency/emission control ECS. The curves are accompanied by a gray ribbon corresponding to the 95% confidence interval (CI) of the mean. In this case, the gray ribbon is almost invisible, due to the CI being very narrow. Figure data are presented in the SI Table S3.

3.1.2. Emerging ECS

The historical trends for ECS in group B are presented in Figure 4. Figure 4A shows the penetration of the parking pilot. In this case, we use the name "parking pilot" to describe the system that allows the vehicle to take over steering functions while parking the car [37]. More precisely, the parking system considered here belongs to automation level 4 as described by SAE International (Society of Automotive Engineers) [24]. Other names include "park assist" or "intelligent parking". "Park pilot" may also be used by some car manufacturers to describe a lower-level automation parking system in which warning signals are sent to aid the driver with parking maneuvers while remaining in full control of the car. The latter shall not be confused with the parking pilot system considered here.

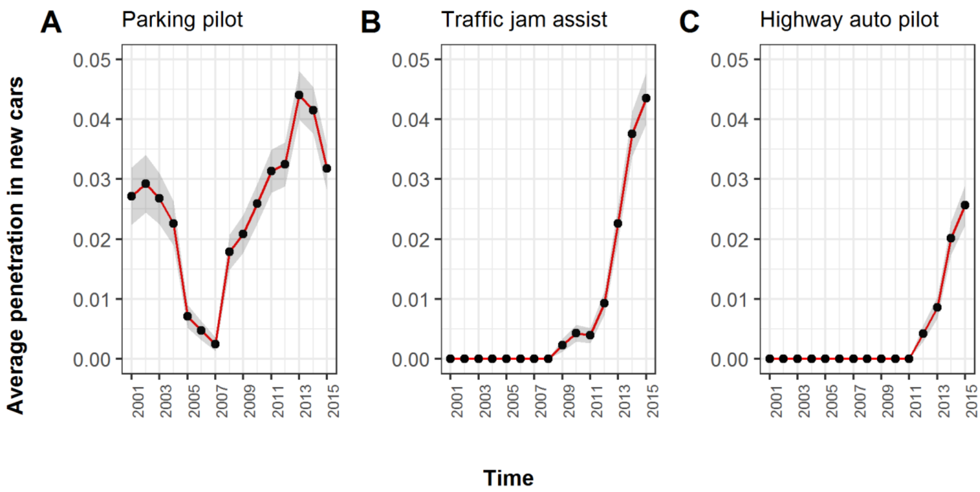

Figure 4. Average historical penetration of emerging automobile ECS in new cars: (**A**) parking pilot, (**B**) traffic jam assist, and (**C**) highway autopilot. All ECS are cross-functional, integrating other ECS. The gray ribbon represents the 95% confidence interval (CI) of the mean. Figure data are presented in the SI Table S3.

Even though the parking pilot (automation level 4) has been present in newly registered cars during the whole study period its penetration has remained below 4% (except for two years: 2013 and 2014 in which it was between 4% and 5%). Additionally, a declining penetration to levels of less than 1% was observed during the period 2005–2007. The temporary decreases in penetration levels might be attributed to technical challenges in the implementation of the parking pilot, as is typical for early-stage technologies [38].

Essentially, the penetration of all ECS in group B remained well below 5% during the study period. The traffic jam assist (Figure 4B) started penetrating in 2009 while the highway autopilot (Figure 4C) started penetrating in 2012. Both penetrations still remained below 5% and 3% in 2015, respectively. This is in agreement with the early state of innovation for these technologies as well as with current safety regulations restraining the broad use of autonomous cars [39,40].

3.1.3. ECS Integration

Figure 5 illustrates the dependencies between the established ECS in group A and the emerging ECS in group B. The y-axis represents the levels of car automation defined by SAE International [24], and the x-axis represents the approximate year in which the ECS was first introduced.

As it can be appreciated the ECS in group B build upon ECS in group A as higher hierarchical entities increasing the car's automation level. In the highest automation levels 4 and 5, ECS also start integrating other high level ECS and no longer only those in the lower levels of automation. The car's automation level increases with the addition of new ECS and with time.

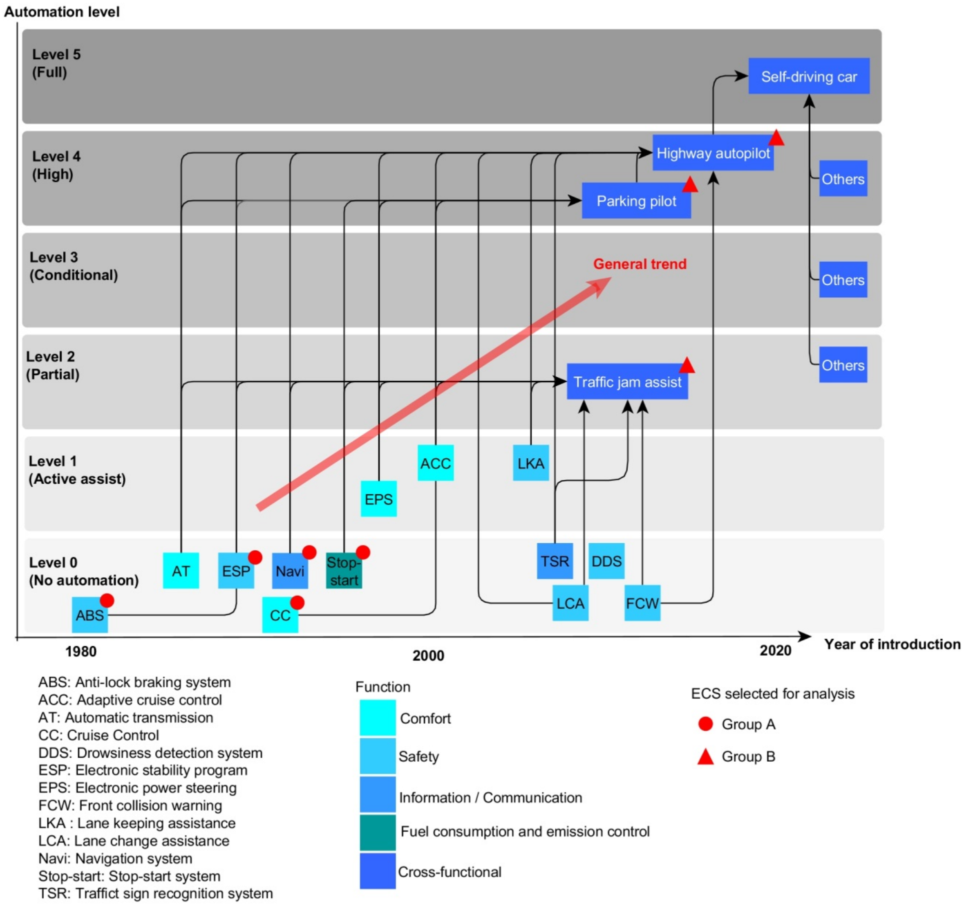

Figure 5. General trend in ECS integration in new cars. The y-axis represents the levels of car automation as defined by SAE International [24] and the x-axis represents the approximate year in which the ECS was first introduced. Data sources [8,25,40,41].

An example of past ECS integration is the ESP, which combines several functions that were previously performed by independent ECS, among them the ABS. Figure 6 shows how the ABS as a separate ECS has steadily been replaced by the higher-level ESP (which contains the ABS function). The dotted red line presents the combined penetration of the systems (ESP or ABS), the starred dark-blue line represents the penetration of the ESP (including ABS) and the diamond light-blue line represents the penetration of the single version of the ABS (ABS alone). The vertical red-dashed lines represent, from left to right, the year in which the ABS became mandatory for all newly registered cars, the year in which the ESP became mandatory for new type approvals, and the year in which the ESP became mandatory for all newly registered cars. New type approvals refer to new car models being registered; new registrations mean all new cars (including previously existing models).

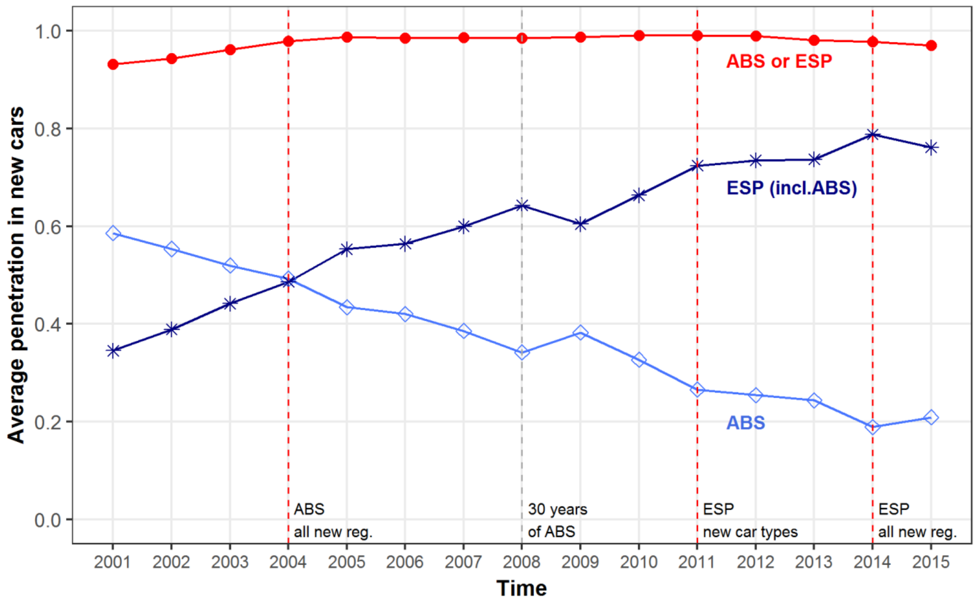

Figure 6. Historical integration trends for the ESP and its subordinate ABS in new cars. The dotted red line above presents the combined penetration of the systems (ESP or ABS), the starred dark-blue line represents the penetration of the ESP (including ABS) and the diamond light-blue line represents the penetration of the single version of the ABS (ABS alone). The vertical dashed red lines indicate the year in which the ABS and the ESP became mandatory for new car types and all newly registered cars (all new reg.). The vertical dashed gray line marks the 30th anniversary of the ABS. Figure data can be found in the SI Table S3.

The ABS made its first commercial appearance in 1978 with the purpose of preventing the wheels from locking during emergency braking [42]. Due to the success preventing fatalities in emergency braking situations, the ABS was made mandatory for all new registrations in 2004 [42]. Related systems, such as traction control, emergency braking and hill-hold control system, have followed the development of the ABS aiding with other aspects of vehicle dynamics [20]. As most of these systems involve manipulation of the brake calipers, integration becomes natural. This integration occurs mostly within the overarching ESP (also known by other commercial names, such as electronic stability control (ESC) or vehicle dynamics control (VDC)) [20].

The light-blue line in Figure 4 shows that the penetration of the single version of the ABS declined from almost 60% in 2001 to less than 20% in 2015. Beginning in 2004, the penetration of the single version ABS was overtaken by that of the ESP. By 2015 the ESP had reached around 80% penetration. These results indicate a "lifetime" for the single version of the ABS of around 40 years, with integration into the ESP starting somewhere in the middle of this time period.

The combined penetration of the ABS and the ESP has been close to 100% since 2005 (red-dotted line), indicating that the compliance with the ABS regulation has been met by embedding either the single version of the ABS or the integrated version of it within the ESP. Additionally, this combined penetration exhibits a slight decrease in 2014, which might be an indication of further integration of these systems into new ECS.

3.2. Indicators for the Historical Use of Automobile ECS

To better understand indicators for the existence of ECS, we trained a random forest model that predicts the presence of specific ECS based on the set of car characteristics. Figure 7 presents the importance of the input variables when estimating the penetration of each of the ECS in group A. The importance is given in terms of the Gini VIM and it is expressed relative to the maximum; a value close to one indicates an important input variable.

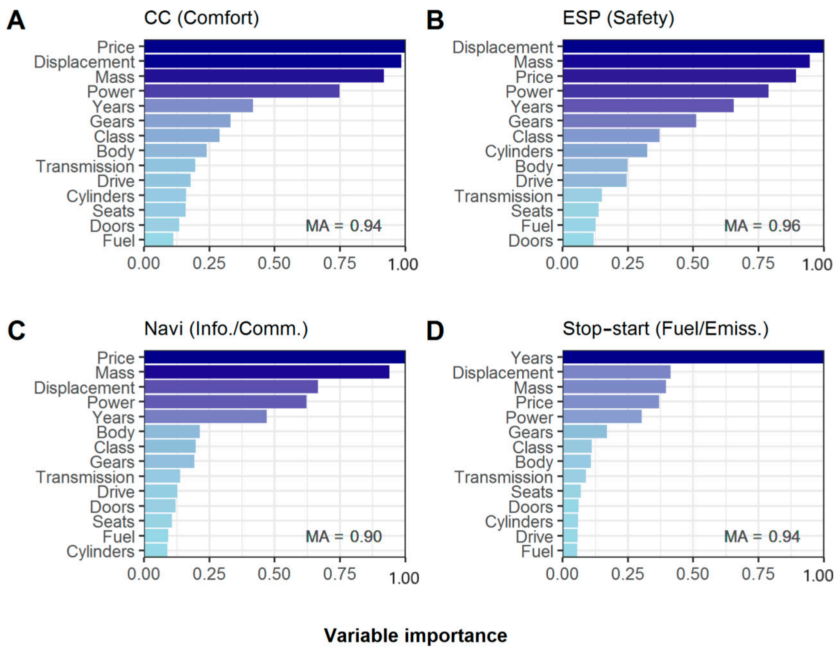

Figure 7. Importance of car characteristics for estimating the presence of established automobile ECS: (**A**) cruise control (CC), (**B**) electronic stability program (ESP), (**C**) navigation system (Navi) and (**D**) stop-start system. Variable importance is given relative to the maximum. A value close to one indicates an important variable. The most important variables are displayed in darker shades of blue. MA = Model Accuracy.

In general, the most important input variables were: price, mass, engine displacement, power, and production year of the cars. Evidently, the price was the most important variable for estimating the average penetration of the two non-regulated ECS (CC and Navi). This is expected since adding more functions (particularly related to comfort) to the car naturally leads to a higher price. The car's mass had a Gini VIM larger than 0.8 in three out of the four cases analyzed, becoming the second most important input variable after the price. This implies that the car's mass serves as a good indicator for the presence of the ECS analyzed. The next important variable was the engine displacement, followed by the engine/motor power and the production year of the cars.

The car's production year was the most important variable in the model estimating the average penetration of the stop-start system. This reflects the fact that environmental regulations specify an implementation year in which all newly registered cars must comply with a given emission standard.

The car's class, body type, number of gears, transmission type, drive type, number of doors, number of seats and number of cylinders had Gini VIM less than 0.5 in all models, becoming of little importance for the estimation of the penetration of the ECS considered.

In summary, and disregarding the car's price, there would be three indicators for the presence of the ECS analyzed (in order of importance): mass, engine displacement, and production year of the cars. In cars without an ICE, the drive motor power may replace the engine displacement indicator (the association between engine/motor power and engine displacement is positive, with a value of 0.34 out of 1; see Figure S2 of the SI).

The fuel type seemed to have particularly low importance for the average penetration of the ECS considered. This implies that considering the car's fuel type in the estimation of the selected ECS would not significantly improve the accuracy of such estimation, compared to including the car's mass or the car's production year. The fuel type can, however, be important for other ECS, especially those related to fuel management or engine/drive motor control [43]. Considering that there will be a larger variety of fuel types in the future (electric, hybrid-electric, and hydrogen) we presume that the estimation of ECS related to fuel management system and engine/drive motor would be of relevance for further models. Consequently, we include the relationship between the fuel type and the penetration of the selected ECS in the subsequent analysis.

The relationship between each of the most important car characteristics (including fuel type) and the presence of the cruise control system (CC) is presented in Figure 8. The same is presented for the stop-start system in Figure 9. The results for the ESP and the navigation system can be found in Figures S3 and S4 of the SI, respectively. The blue lines in panels A to E are smoothing splines fit the quantitative variables *Price*, *Displacement*, *Mass*, *Power*, and *Years*; the degrees of freedom are noted on the y-axis. The scale of the y-axis represents the Logistic GAM transformation of the output variable, and it is not given in the units of the response. The plots thus express how the output variable responds to a change in the input variable and not the value of the output variable corresponding to the input. For an estimated value of the output variable corresponding to each input variable see Figures 10 and 11. Panel F shows a step function fit the qualitative variable *Fuel*. In all cases, the dashed red lines represent the 95% confidence interval of the fitted function. A more extended description of Logistic GAM and the graphical representations presented here can be found in reference [23].

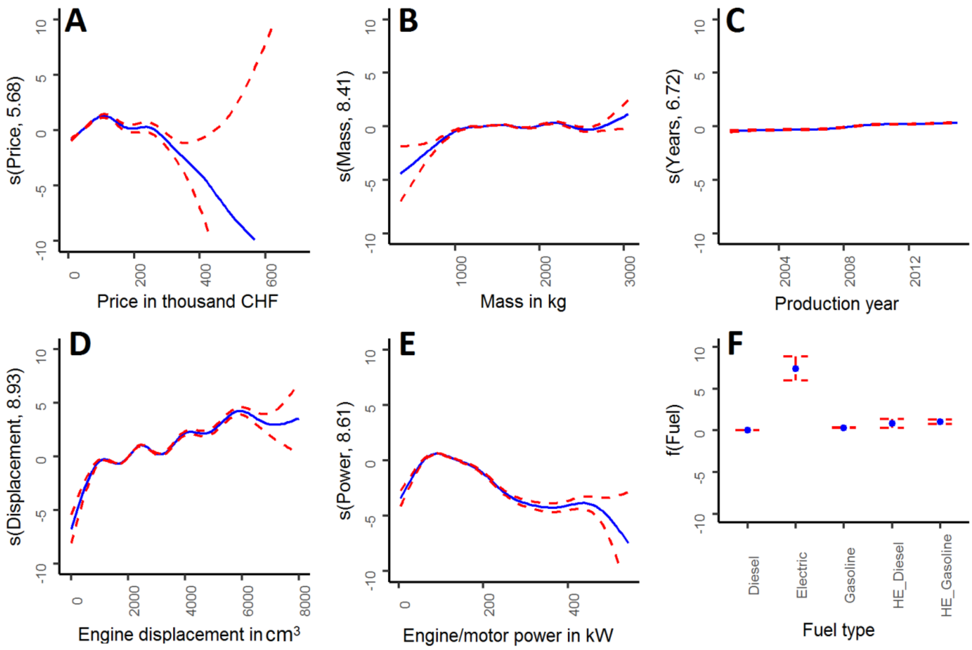

Figure 8. Relationship between car characteristics and the presence of the cruise control system (CC) in new cars. The blue lines represent the smoothing splines fit to each predictor after a Logistic GAM: (**A**) price, (**B**) mass, (**C**) production year, (**D**) engine displacement, (**E**) engine/motor power, (**F**) fuel type. The red dotted lines correspond to the confidence interval of the estimated function. The scale of the y-axis corresponds to the model transformation of the response variable and it is not given in the units of the response; the value in parenthesis indicates the degrees of freedom of each function (smoothing spline). The model's validation accuracy was equal to 0.70.

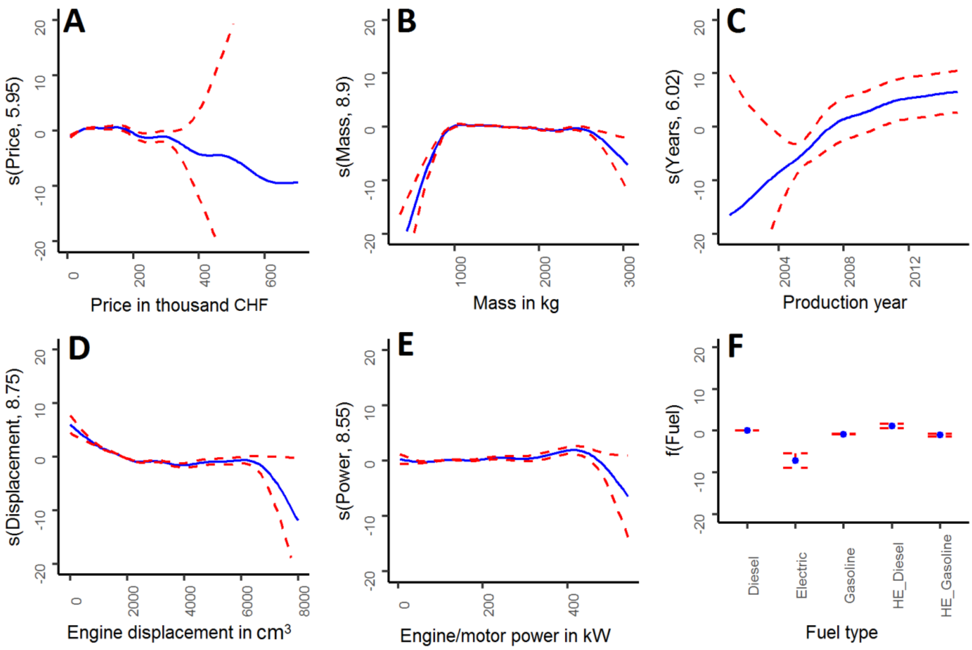

Figure 9. Relationship between car characteristics and the presence of the stop-start system in new cars. The blue lines represent the smoothing splines fit to each predictor after a Logistic GAM: (**A**) price, (**B**) mass, (**C**) production year, (**D**) engine displacement, (**E**) engine/motor power, (**F**) fuel type. The red dotted lines correspond to the confidence interval of the estimated function. The scale of the y-axis corresponds to the model transformation of the response variable and it is not given in the units of the response; the value in parenthesis indicates the degrees of freedom of each function (smoothing spline). The model's validation accuracy was equal to 0.87.

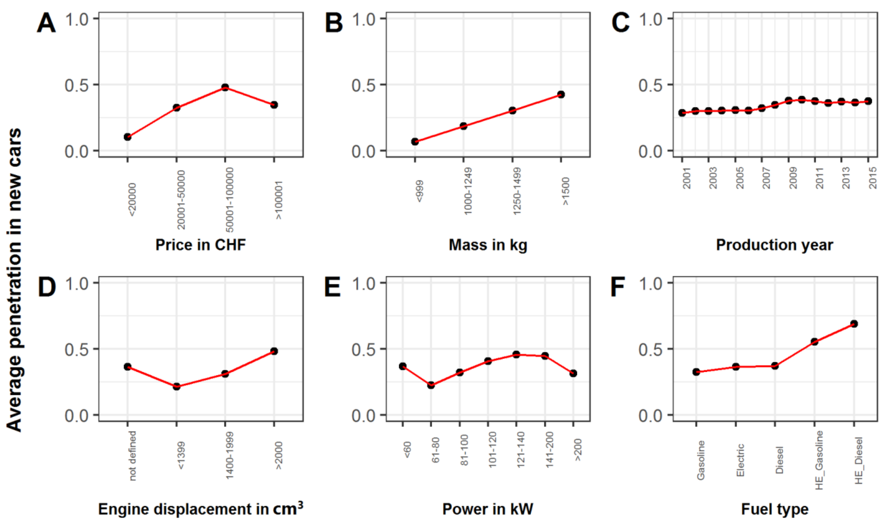

Figure 10. Average predicted penetration of the cruise control (CC) in the validation set by the car's: (**A**) price, (**B**) mass, (**C**) production year, (**D**) engine displacement, (**E**) power, (**F**) fuel type.

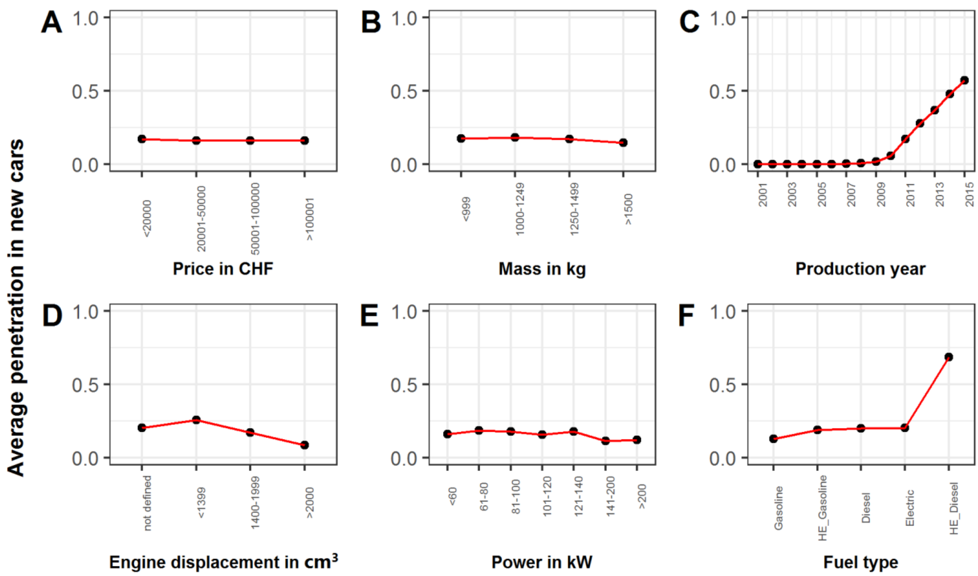

Figure 11. Average predicted penetration of the stop-start system in the validation set by the car's: (**A**) price, (**B**) mass, (**C**) production year, (**D**) engine displacement, (**E**) power, (**F**) fuel type.

Figure 8A indicates that, holding all other variables fixed, the penetration of the CC rapidly increases with the price for cars of prices less than 100,000 CHF, which is most cars in the dataset (and in general). This is in agreement with the fact that the CC is a comfort system, therefore more likely to exist as a standard feature in cars of higher price ranges. The flattening and subsequent decrease of the curve above 100,000 CHF is likely due to a small number of specialized cars found in this range and for which the CC is less common (e.g., sports cars). The CC also seems less common for small cars of masses < 1000 kg (Figure 8B). Except for local wiggles, Figure 8D indicates that the penetration of the CC increases rapidly with the engine displacement: the larger the engine of the car the more likely it is to contain a CC. Regarding the engine/motor power of the cars, Figure 8E indicates that the penetration of the CC is highest for cars of engine/motor power around 100 kW. Likewise, the CC seems more likely to exist in electric cars than in hybrid and conventional cars (Figure 8F). The production year of the cars (Figure 8C) explains very little of the penetration among different car models, compared to other characteristics, such as displacement, mass, and fuel type.

In contrast, Figure 9C indicates that the existence of the stop-start system clearly increases with time. As expected, the stop-start system is more likely to exist in diesel cars, especially in hybrid-electric diesel ones (Figure 9F), reflecting the fact that the stop-start system is particularly suitable to achieve efficiency in fuel consumption in these types of cars [35]. In addition, the stop-start system seems less common for small cars and large cars and (mass < 1000 kg and mass > 2500 kg), Figure 9B. The high uncertainties in panel A of Figures 8 and 9 are due to the small number of cars at very high price ranges in the dataset. Likewise, the larger uncertainties for electric car types (panel F in both Figures 8 and 9) result from the smaller number of electric cars in the data set.

Figures 10 and 11 show the prediction of the penetration of the CC and the Stop-start in the validation set using the models described in Figures 8 and 9, respectively. The y-axis is given in the units of the response and corresponds to the average penetration of the ECS by each of the predictor variables considered. In simple terms, the predicted value is the likelihood of a car containing the ECS times the corresponding number of cars. Panel C in both figures shows how the prediction in the validation set closely resembles the *real* average penetration of the ECS in time presented in Figure 3 above.

The plots in Figures 8 and 9 complement the historical patterns in Figure 3 by illustrating how the penetration of the selected ECS relates to the characteristics of the car. As seen for the CC in Figure 3, even if a comfort-related ECS has existed in cars for over 14 years, its penetration may remain below 40%. Figure 8 complements this finding by indicating that despite seemingly stable penetration rates, future shifts in consumer preference, e.g., towards larger cars with higher engine displacement, may lead to substantial changes in the overall penetration rate of this ECS; a shift towards electric cars in the future may also increase such penetration. An increase of hybrid cars—particularly using diesel fuel might uplift the average penetration of fuel efficiency ECS (such as the stop-start system). Preferences for larger cars (high mass) may trigger the penetration of both comfort and fuel efficiency ECS. However, this assumes that changes in car characteristics *cause* effects in the penetration of ECS, which may not be the case. In fact, the opposite may be true. For example, an increase in ECS penetration may be the *cause* of an increase in car mass. Future estimations of ECS penetration should not be based on assumptions about the development of car characteristics only.

As seen for the ESP and the stop-start system in Figure 3, once an ECS delivers safety and/or environmental benefits at reasonable costs, a fast penetration in newly registered cars, most likely reaching 80% or higher, can be expected following the implementation of a corresponding regulation. Both the time to reach saturation and the saturation level seem to depend on whether the regulation affects the implementation of an ECS directly or indirectly. Safety regulations directly mandate the installation of a given ECS in two stages: (i) new type approvals and (ii) new registrations. New type approvals refer to new car models; new registrations mean all new cars (including previously existing models). As in safety regulation (EC) 661/2009 there is usually a fixed date in which a certain ECS must be implemented in new type approvals (i.e., the ESP in 2011) while existing vehicle types "should be allowed an additional time period to comply with the requirements" [34,41]. As seen for the ESP, the result of such regulation is a rapid adoption almost reaching full penetration (80%) within three years of implementation in new type approvals.

In contrast, environmental regulations, which tend to stipulate emission limits without mandating certain technologies, seem to trigger both (i) changes in the car characteristics (e.g., fuel type and engine displacement) and (ii) increased installation of specific ESC in certain car types exclusively. As seen for the stop-start system, the result of adopting the Euro 5 regulation [34] was a rapid penetration, however, reaching only 60% penetration after five years of implementation. This derives from the fact that the stop-start system is mainly suited for diesel cars [35] and that there are other means to achieve what the regulation requires. For example, in the case of fuel efficiency, this can also be achieved, among others, by combined efforts of more efficient internal combustion engines, a switch to electric and hybrid-electric drives and an improved tire-pressure monitoring system [33,34].

The key factor influencing rapid penetration and high saturation levels seems to be regulation, either related to safety or fuel consumption/environmental emissions. In addition, increases in car's mass and engine displacement seem to be related to an increase in ECS penetration, particularly for ECS related to comfort.

Similar penetration curves were observed for comfort and information/communication ECS: a slow penetration over the 14 years of analysis. Likewise, the penetration curves of safety and fuel efficiency/emission control ECS were similar: a rapid penetration following the implementation of a respective regulation. In general:

1. Comfort-related ECS, as well as ECS related to information, communication, and entertainment, tend to remain below 50% for more than 10 years as long as under reasonable implementation costs no significant safety or environmental benefits are provided.
2. Safety-related ECS can be expected to grow rapidly to approach 100% penetration within two to five years of implementation of the regulation.
3. Fuel efficiency- and environmental emission-related ECS tend to grow rapidly after the implementation of the regulation. The saturation level seems to depend on the benefits of the ECS for achieving the specific standards for different car types.

3.3. Autonomous Cars and Other Trends in the Automobile Sector

Transferring the results of this study to the realm of autonomous cars, it seems more likely that higher levels of automation would be first achieved for larger cars (larger masses, larger engine displacements), while small cars would remain in the lower automation levels where the average penetration of ECS is low. However, these *cause and effect* relationships were not analyzed in this study. An assessment of the future developments of ECS and the path to autonomous cars requires tools outside this study, such as scenario analysis [44].

Considering that ECS necessary for self-driving tasks rely on the existence of other lower-level ECS, it seems likely that the penetration of fully autonomous cars would happen rather slowly, unless truly disruptive changes affecting the car characteristics, safety and environmental standards take place. On the other hand, as high automation levels rely on a host of higher- and lower-level ECS, external trends that favor autonomous cars could lead to massive increases in the amount of ECS. Examples of such developments would be a preference towards shared mobility, which could trigger the growth of self-driving features in cars or liberalization of the regulatory framework [39,40,45]. The level of ECS penetration in new cars depends on the interaction of such trends in consumer behavior, technological maturity, physical constraints, and regulatory framework. Future research should, therefore, explore how the penetration of ECS may develop under different scenarios of such external drivers.

3.4. Implications for Critical Raw Material (CRM) Content in Cars

Increased penetration of ECS does not necessarily mean an increased number of related EE devices (sensors, controllers, and actuators) and a corresponding increased CRM content in cars. Some authors argue that the number of physical, electronic control units (ECUs/controllers) is likely to decrease with increasing integration of ECS [20,46]. Moreover, increased penetration of an ECS may be accompanied by a mass reduction for the related EE devices, as exemplified by the hydraulic actuator in the ESP/ABS and related systems [20,47]. For a single car, integration trends may reduce the number of EE devices and miniaturization may reduce the mass of the related CRMs. The total stocks and flows of CRMs in cars may nevertheless increase, due to the increased penetration of ECS in all car types. Future estimations of CRM stocks and flows in car electronics should account for the effects of all of these trends.

3.5. Implications for Policy on Car Electronics Dismantling

Considering the trends in ECS penetration and integration identified in this study, a potential list of mandatory EE devices to be dismantled from cars would need to be updated on a regular basis. In addition, in order to capture differences in embedded ECS in different car types, such a list may benefit from a definition at the level of car functions instead of at the level of specific EE devices. For example, it would be more inclusive to decree the dismantling of "controllers (ECUs) related to vehicle dynamics" instead of mandating the dismantling of "ABS controllers".

The growing penetration of ECS in new cars will eventually be mirrored in end-of-life vehicles (ELVs), and may bring advantages to the recycling of car electronics through economies of scale. Disadvantages might arise depending on the level of miniaturization of the related EE devices.

Considering the average lifetime of cars in Switzerland (15–20 years), the analysis of ECS penetration in new cars presented in this study provides robust estimations for the ECS penetration in ELVs in the short to medium term. However, the long term seems more uncertain, particularly considering the rapid increase in ECS integration and the effects that new safety and environmental emission regulations have on the penetration of ECS. Continued analysis of ECS penetration in new cars, such as carried out in this study, can support a timely update of ELV-related regulations.

4. Conclusions

The results illustrate several important trends and indicators for the penetration of electronic control systems (ECS) in cars. Some ECS, typically those affected by regulations on safety, fuel efficiency and/or emissions, have increased rapidly to high levels. Examples include the stop-start system and the electronic stability program (ESP). Other ECS, typically those that are unaffected by regulation, have been stable at intermediate penetration levels for many years. Examples include the navigation system and the cruise control system (CC). Higher-level cross-functional ECS related to autonomous driving have increased fast, but are still at low levels (<5% of new cars in 2015). In parallel to these increasing ECS penetration levels, there are clear indications of integration of different ECS, as shown for the ABS and ESP. In general, there are two major trends that are coinciding: (i) automation of cars, (ii) integration of ECS. The combined effects of these trends on critical raw material (CRM) use in car electronics and their recycling potentials need to be considered. The results presented here provide a foundation for a subsequent estimation of CRM content in cars and the definition of related car recycling policy.

We found that the four most important car characteristics indicating the presence of ECS are price, mass, engine displacement (or power), and production year. Fuel type did not appear among the most important predictors for the selected ECS, but may nevertheless be very important for other ECS related to fuel and energy management. Statistics and models of the passenger car fleet should therefore ideally employ car classification systems based on the aforementioned characteristics to be useful for prospecting secondary raw materials in car electronics.

The statistical analysis presented allows inferences about ECS penetration in the short to medium term. For example, preferences towards larger cars (high mass, high engine displacement) may be associated with increased use of embedded ECS. However, long-term penetration of ECS is influenced by the interaction of external drivers, such as regulatory framework, technological maturity, and consumer behavior. In particular, regulations that favor automated driving may drive a large increase in lower- and higher-level ECS. Future estimations should account for the influence of these external drivers on the penetration of automobile ECS and related material content.

Supplementary Materials: The following are available online at http://www.mdpi.com/2079-9276/8/2/58/s1, Figure S1: Distribution of the dataset by additional car characteristics, Figure S2: Association (correlation) among input variables, Figure S3: Relationship between selected car characteristics and the penetration of the electronic stability program (ESP) in new cars, Figure S4: Relationship between selected car characteristics and the penetration of the navigation system (Navi) in new cars, Figure S5: Average predicted penetration of the electronic stability program (ESP) in the validation set, Figure S6. Average predicted penetration of the navigation system (Navi) in the validation set, Table S1: R software packages used in the statistical analysis, Table S2: Description of car characteristics considered in this study, Table S3: Average penetration of the investigated ECS by production year of the cars, Table S4: Average penetration of additional ECS by production year of the cars.

Author Contributions: Conceptualization, E.R., A.N.L., R.W., P.W. and D.B.M.; formal analysis, E.R.; funding acquisition, E.R., R.W., P.W. and D.B.M.; investigation, E.R.; methodology, E.R., A.N.L. and D.B.M.; project administration, R.W. and P.W.; supervision, R.W., P.W. and D.B.M.; validation, E.R., A.N.L., R.W. and D.B.M.; visualization, E.R.; writing—original draft, E.R.; writing—review & editing, E.R., A.N.L., R.W., P.W. and D.B.M.

Funding: This research was funded by the Swiss Federal Office for the Environment (FOEN) as part of the project "Recycling Electronics from ELVs–EVA". The project partners include: Auto-Schweiz (Swiss association of automobile importers), AWEL (Office of Waste, Water, Energy, and Air of the Canton of Zurich), SARS (Foundation Auto Recycling Switzerland), VASSO (Association of the Official Car Collection Point Proprietors of Switzerland and the Principality of Liechtenstein), and VAREX (Swiss Association of Automobile Recyclers and Exporters).

Acknowledgments: Special thanks to Auto-i-Dat AG for access to the Autohandel database. Thanks to the following project partners for their feedback on the original manuscript: Isabelle Baudin from FOEN, Daniel Christen from SARS and Andreas Kaufmann from VASSO.

Conflicts of Interest: The authors declare no conflict of interest. The study was designed in collaboration with the project partners. The funders had no role in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

ABS	Anti-lock braking system
CC	Cruise control
CI	Confidence interval
CRM	Critical raw material
EC	European Commission
ECU	Electronic control unit
ELV	End-of-life vehicle
ESP	Electronic stability program
GAM	Generalized additive model
HE	Hybrid electric
ICE	Internal combustion engine
Navi	Navigation system
SAE	Society of automotive engineers
SI	Supplementary information
Stop-start	Stop-start system
TCS	Traction control system
VIM	Variable importance measure

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Supporting Information to:

Historical Penetration Patterns of Automobile Electronic Control Systems and Implications for Critical Raw Materials Recycling

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This supplement contains:
12 Pages
6 Figures
4 Tables

Contents

Figures

Tables

1. Software

All the statistical analysis was carried out in R [1]. The R packages used are listed in Table S1 below.

Table S1. R software packages used in the statistical analysis.

Task	R package and reference
Plots: Histograms, historical penetrations, and variable importance results	cowplot[2] easyGgplot2[3] ggplot2 [4] gridExtra[5] grid[6] reshape2[7]
Computing the average penetration of ECS	dplyr[8] summarySE (function)[9] officer[10] flextable[11] magrittr[12]
Random forest model	ranger[13]
Logistic GAM	mgcv[14] mgcViz[15]

2. Model variables

Table S2 below lists the 14 car characteristics considered in the study (input variables), including their unit, categories (or value ranges), model variable name and data type.

The output variables (ECS considered) are listed in Table 1 of the methods section in the main manuscript. All output variables were of dichotomous data type (categorical with only two categories – one and zero)

Table S2. Description of car characteristics considered in this study.

Characteristic	**Unit**	**Range/categories**	**Variable name**	**Data type**
Price	CHF	[7 948–702 240]	Price	integer
Production year	a	[2001–2015]	Years	integer
Engine displacement	cm3	[0-8 285]	Displacement	integer
Mass	kg	[350 - 3 050]	Mass	integer
Fuel type	n.a.	Electric Hybrid electric-diesel Hybrid electric-gasoline Diesel Gasoline	Fuel	categorical
Engine/Motor Power	kW	[4 - 552]	Power	integer
Body type	n.a.	Convertible Coupe Sedan Sports car Station wagon SUV Van	Body	categorical
Drivetrain type	n.a.	All wheel Front wheel Rear wheel	Drive	categorical
Transmission type	n.a.	Automatic Manual Semi-automatic Stepless	Transmission	categorical
Number of seats	n.a.	[1-9]	Seats	integer
Class	n.a.	Mini Small Low-medium Upper-medium Upper Luxury	Class	categorical
Number of doors	n.a.	[2-5]	Doors	integer
Number of engine cylinders	n.a.	0,2,3,4,5,6,8,10,12	Cylinders	integer
Number of gears	n.a.	[1-8]	Gears	integer

n.a. : does not apply.

3. Additional dataset distribution plots

Figure S1 below presents the distribution of the cars by the remaining eight characteristics considered.

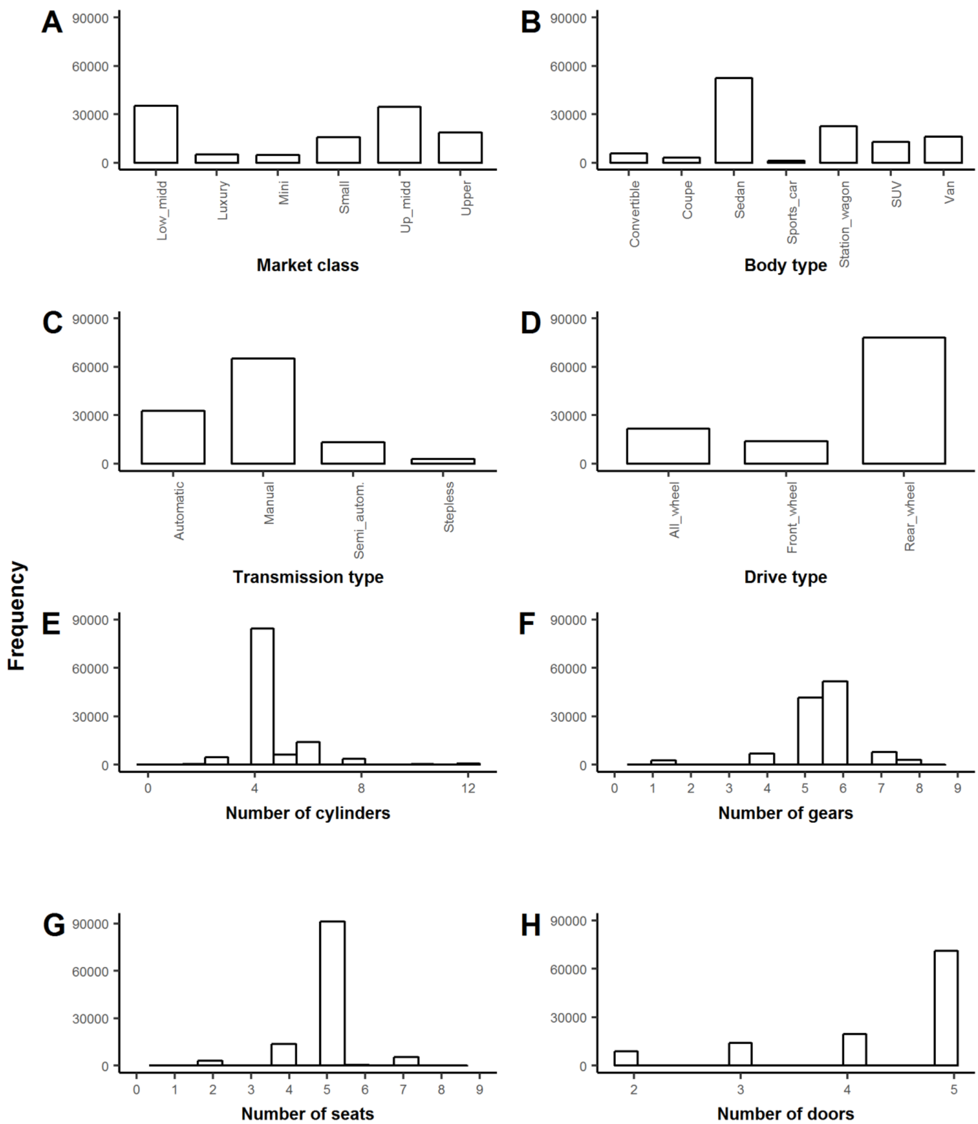

Figure S1. Distribution of the dataset by additional car characteristics: A) market class, B) body type, C) transmission type, D) drive type, E) number of cylinders, F) number of gears, G) number of seats and H) number of doors.

4. Association analysis

We analyzed the association among the input variables in order to discard redundant input variables from the statistical analysis. Specifically, we computed the *Goodman and Kruskal's tau measure of association (τ(x,y))* which indicates, with a value ranging from zero (0) to one (1) whether two input variables x and y are independent or perfectly predictable from each other. This measure was preferred due to its suitability for associations between numerical and categorical variables [16].

The correlogram in Figure S2 below presents the association between all pairs of input variables. The scale on the right side indicates the level of association: 0 (white) means the variables are independent; 1(bright red) means the variables are redundant. For example, the number of engine cylinders ("Cylinders") exhibited a slight ability to explain the size of the car's engine (τ(x,y) = 0.39). Likewise, the car class ("Class") slightly explained variations in the car's mass (τ(x,y) = 0.39). As all associations were weak (τ(x,y) <0.5) the variables were considered to be independent.

Figure S2. Association (correlation) among input variables. The association is measured by the Goodman and Kruskal's tau measure of association (τ(x,y)) which ranges between 0 (no association) and 1(perfect association).

5. Average historical penetration of automobile electronic control systems

Data for the average penetration of established and emerging ECS displayed in Figure 3, Figure 4 and Figure 6 in the main manuscript is presented in Tables S3 below. Table S4 presents additional ECS not analyzed in detail in this study.

Table S3. Average penetration of the investigated ECS by production year of the cars.

Year	CC	ESP	ABS	ABS or ESP	Navi	stop_start	auto_pilot	jam_assist	park_pilot
2001	0.28	0.35	0.59	0.93	0.34	-	-	-	0.03
2002	0.30	0.39	0.55	0.94	0.40	-	-	-	0.03
2003	0.29	0.44	0.52	0.96	0.42	-	-	-	0.03
2004	0.31	0.49	0.49	0.98	0.45	-	-	-	0.02
2005	0.30	0.55	0.43	0.99	0.47	-	-	-	0.01
2006	0.30	0.56	0.42	0.99	0.47	-	-	-	0.00
2007	0.33	0.60	0.39	0.99	0.49	0.001	-	-	0.00
2008	0.33	0.64	0.34	0.99	0.52	0.004	-	-	0.02
2009	0.40	0.60	0.38	0.99	0.53	0.02	-	0.002	0.02
2010	0.39	0.66	0.33	0.99	0.50	0.05	-	0.004	0.02
2011	0.37	0.72	0.27	0.99	0.47	0.14	-	0.003	0.03
2012	0.35	0.74	0.26	0.99	0.48	0.25	0.004	0.01	0.03
2013	0.38	0.74	0.24	0.98	0.50	0.33	0.01	0.02	0.04
2014	0.36	0.79	0.19	0.98	0.46	0.40	0.02	0.03	0.03
2015	0.38	0.76	0.21	0.97	0.45	0.49	0.02	0.04	0.03

CC: Cruise control, ESP: Electronic stability program, ABS: anti-lock braking system, navi: Navigation system, stop_start: Stop-start system.

Table S4. Average penetration of additional ECS by production year of the cars.

Year	EPS	TPMS	FCW	EBS	DAD	EDR	LCA	LDW	LKA	DSR	PA	PDC	ADAS	ACC
2001	0.04	0.03	-	0.22	-	-	-	0.12	-	-	-	0.12	-	-
2002	0.05	0.07	-	0.32	-	-	-	0.15	-	-	-	0.15	-	0.003
2003	0.07	0.09	-	0.43	-	-	-	0.13	-	-	-	0.13	-	0.004
2004	0.09	0.11	-	0.54	-	-	0.001	0.14	0.002	-	-	0.14	-	0.01
2005	0.13	0.15	-	0.62	-	-	0.002	0.16	0.01	0.001	-	0.16	-	0.02
2006	0.16	0.15	-	0.62	-	-	0.002	0.17	0.01	0.01	-	0.17	-	0.02
2007	0.16	0.18	-	0.64	-	-	0.003	0.22	0.02	0.01	-	0.21	-	0.04
2008	0.18	0.20	-	0.63	-	-	0.003	0.23	0.03	0.01	-	0.23	-	0.04
2009	0.15	0.20	-	0.66	0.002	0.002	0.01	0.22	0.02	0.02	-	0.22	-	0.03
2010	0.15	0.19	-	0.66	0.004	0.004	0.01	0.21	0.03	0.01	-	0.21	-	0.03
2011	0.15	0.25	-	0.69	0.003	0.004	0.02	0.20	0.05	0.01	-	0.20	0.002	0.03
2012	0.15	0.31	0.004	0.69	0.01	0.01	0.02	0.23	0.07	0.02	0.01	0.22	0.002	0.03
2013	0.15	0.43	0.01	0.73	0.02	0.02	0.03	0.26	0.07	0.03	0.01	0.24	0.002	0.03
2014	0.16	0.59	0.02	0.67	0.03	0.04	0.05	0.26	0.08	0.04	0.01	0.24	0.002	0.04
2015	0.14	0.72	0.03	0.67	0.04	0.04	0.06	0.27	0.09	0.04	0.01	0.26	0.003	0.03

EPS: Electronic power steering, TPMS: Tire pressure monitoring system, FCW: Front collision warning, EBS: Emergency braking system, DAD: Drowsiness and attention detection, EDR: Event data recorder, LCA: Lane change assist, LDW: Lane departure warning, LKA: Lane keeping assist, DSR: Driver steering recommendation, PDC: Park-distance control, PA: Basic park assist, ADAS: Advance driver assistance system, ACC: Adaptive Cruise Control

6. Additional results of Logistic GAM

Figure S3 and Figure S4 show the Logistic GAM for the ESP and the Navi, respectively. The corresponding predictions in the validation set are shown in Figure S5 and Figure S6, respectively.

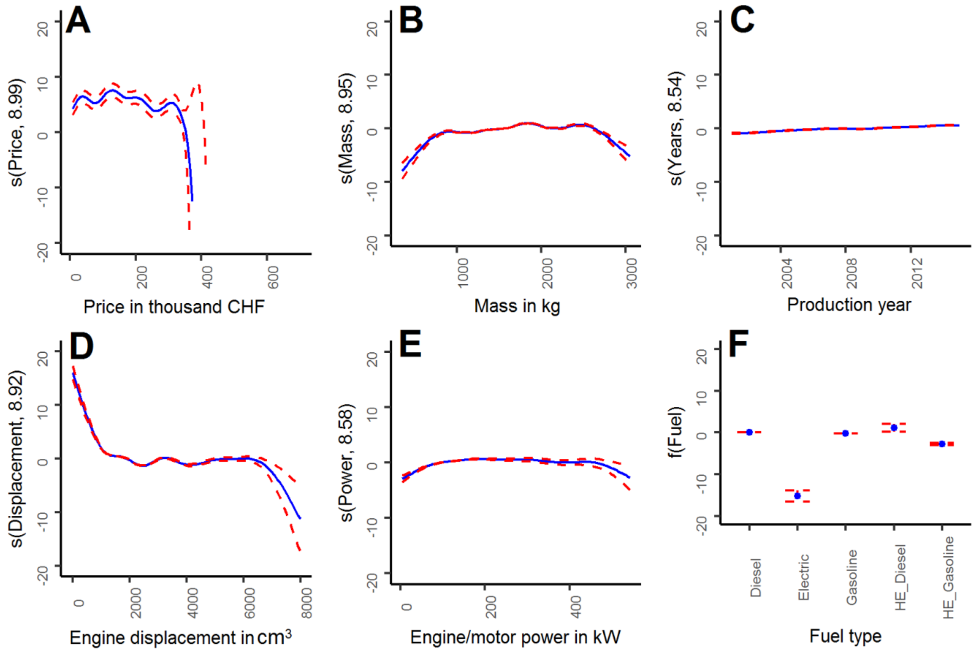

Figure S3. Relationship between car characteristics and the presence of the electronic stability program (ESP) in new cars. The blue lines represent the smoothing splines fit to each predictor after a Logistic GAM: (A) price, (B) mass, (C) production year, (D) engine displacement, (E) engine/motor power, (F) fuel type. The red dotted lines correspond to the confidence interval of the estimated function. The scale of the y-axis corresponds to the model transformation of the response variable and it is not given in the units of the response; the value in parenthesis indicates the degrees of freedom of each function.

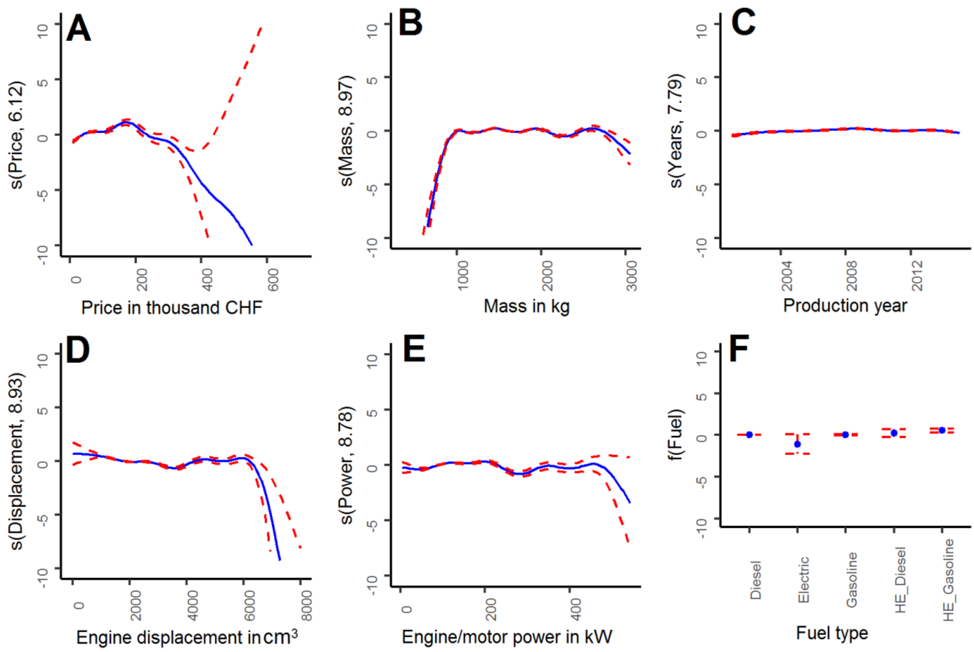

Figure S4. Relationship between selected car characteristics and the penetration of the navigation system (Navi) in new cars. The blue lines represent the smoothing splines fit to each predictor after a Logistic GAM: (A) price, (B) mass, (C) production year, (D) engine displacement, (E) engine/motor power, (F) fuel type. The red dotted lines correspond to the confidence interval of the estimated function. The scale of the y-axis corresponds to the model transformation of the response variable and it is not given in the units of the response; the value in parenthesis indicates the degrees of freedom of each function.

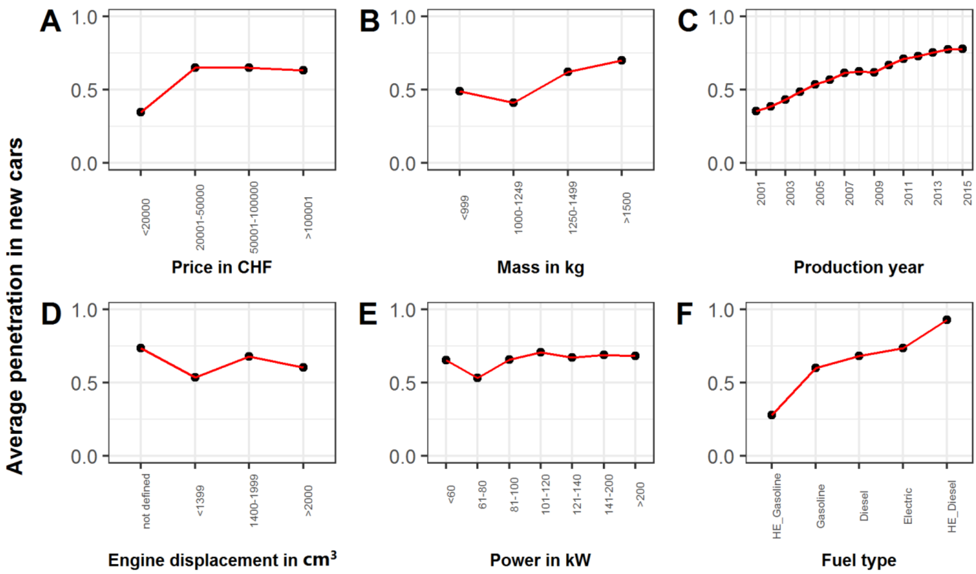

Figure S5. Average predicted penetration of the electronic stability program (ESP) in the validation set by the car's: (**A**) price, (**B**) mass, (**C**) production year, (**D**) engine displacement, (**E**) power, (**F**) fuel type.

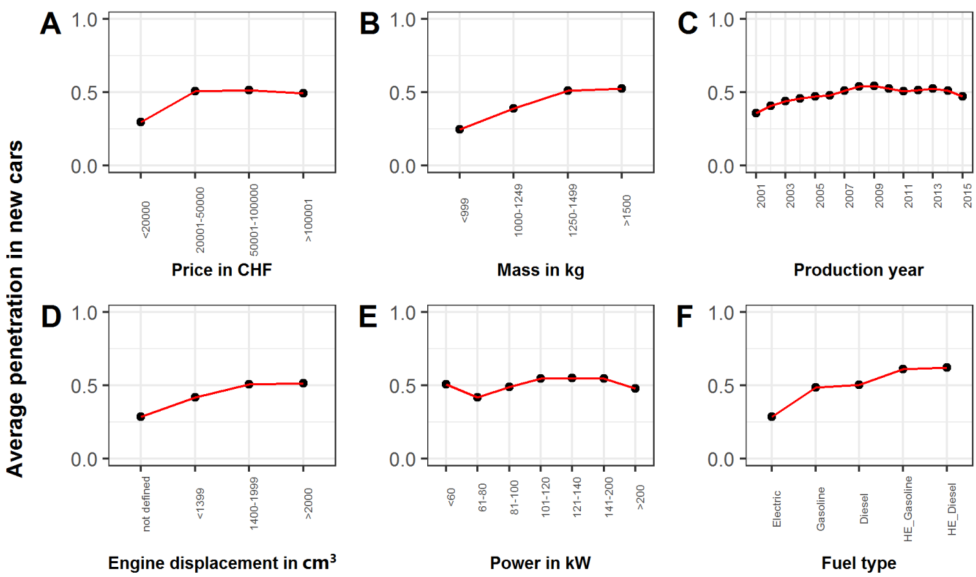

Figure S6. Average predicted penetration of the navigation system (Navi) in the validation set by the car's: (**A**) price, (**B**) mass, (**C**) production year, (**D**) engine displacement, (**E**) power, (**F**) fuel type.

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Paper V

Effects of car electronics penetration, integration and downsizing on their recycling potentials

Restrepo E, Løvik AN, Widmer R, Wäger P, Müller DB. Resour Conserv Recycl X. 2020;6:100032.

Resources, Conservation & Recycling: X 6 (2020) 100032

Contents lists available at ScienceDirect

Resources, Conservation & Recycling: X

journal homepage: www.journals.elsevier.com/resources-conservation-and-recycling-x

Effects of car electronics penetration, integration and downsizing on their recycling potentials

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ARTICLE INFO

Keywords:
Critical metals
End-of-life vehicles
Circular economy
Electronics miniaturization
Electronic waste
Embedded electronics

ABSTRACT

Car electronics form an extensive yet untapped source for secondary critical raw materials. To seize their recycling potentials it is imperative to understand how the number and volumes of car electric and electronic (EE) devices are affected by trends in: i) car typology, ii) penetration and integration of automobile electronic control systems (AECS), and iii) unit mass of EE devices. We used a layered dynamic material flow analysis (MFA) incorporating comprehensive data series to analyze the aforementioned trends and their influence on end-of-life mass flows of two automobile EE devices in Switzerland over the period 1975 to 2015. We found that there has been an increased penetration of the EE devices coinciding with a replacement of unifunctional devices by multifunctional ones (integration) and a decrease in their unit mass (downsizing). Both penetration and unit mass changed most rapidly in the 1990s and have flattened after the year 2000. Penetration outweighed integration and downsizing, so that before stabilizing, it caused a rapid increase in the mass flows of the EE devices. Due to the long lifetime of cars, changes in penetration, integration and downsizing are still evident at the end-of-life flows, but can be expected to slow down considerably between 2015 and 2025. The results demonstrate that monitoring of the trends at the car inflow, in combination with a dynamic MFA, can be used to anticipate changes in end-of-life flows 10–20 years before they occur and to timely inform recycling policies.

1. Introduction

Due to their economic importance, indispensability in future clean-energy technologies, and environmental implications of their production, among others, metals such as neodymium and gold have been labelled *critical* in various contexts (Graedel et al., 2015; European Commission, 2016). Recycling *critical metals* (CMs) from products where they are widely used arises as a strategy to alleviate criticality (European Commission, 2014; Graedel et al., 2015).

Ranging between 0.2 g/t and 6 g/t (Du et al., 2015), the gold mass fraction in cars, mainly found in the embedded electronics controllers, is similar to the average ore grade in gold mines worldwide; which is around 1 g/t (Bull and Bear Media Group, INC 2019). The mass fraction of Nd in cars, mainly found in the embedded electric motors, can be around 300 g/t (Du et al., 2015). In dismantled controllers and electric motors from cars, the mass fraction of CMs can be several orders of magnitude higher.

Car electronics are expected to account for half of the car's cost in 2030 (PwC, 2013) and the number of cars being sold worldwide is expected to increase from around 80 million in 2018 to around 120 million in 2020 (ACEA, 2018). Considering the mass fraction of CMs in car electronics and their expected increased penetration in the growing number of cars being sold, car electronics represent an important potential source of CMs.

Despite this potential, there is currently no regulation for treating end-of-life (EoL) car electronics in Europe (European Parliament and The Council, 2000). Worldwide, end-of-life vehicle (ELV) treatment remains centered on shredding without much pre-shredder dismantling of electronics (Sakai et al., 2013; Rosa and Terzi, 2018; Cucchiella et al., 2016). Switzerland is pioneering in this field by revising the current regulation for electronic waste recycling (VREG by its German acronym) (FOEN, 1998). One of the goals in this revision is to introduce a mandatory dismantling of selected car electronics for subsequent recycling when economically and environmentally sensible (FOEN, 2013). Parallel to this, the ELV Directive (European Parliament and The Council, 2000) of the European Union is also under review (European Commission, 2019a), including an evaluation of the feasibility of setting material-specific recycling targets that may encourage dismantling

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https://doi.org/10.1016/j.rcrx.2020.100032
Received 1 December 2019; Received in revised form 31 January 2020; Accepted 3 February 2020
Available online 04 February 2020
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of EE devices as a result. Among others, the complexity and time-variability of car electronics pose a challenge when defining the specific electric and electronic (EE) devices to include in the revised Swiss regulation as well as the financial mechanisms to support dismantling.

To remain effective in the long term, dismantling strategies must consider the effects of changes in penetration of automobile electronic control systems (AECS) and unit mass of EE devices on the number and volumes of EE devices reaching end of life. For example, does the reduction in unit mass (downsizing) of EE devices and the integration of AECS outweigh the penetration trends, thus making the recovery of CMs from EoL car electronics less attractive in the future?

Because of lack of available time series data, previous studies (Fishman et al., 2018; Xu et al., 2018; Restrepo et al., 2017; Xu et al., 2016) have focused on estimating the total mass of CMs in car stocks and flows, without further analysis of the individual trends that affect these flows and stocks. Most studies have mainly considered changes in penetration of car types and corresponding AECS; for example increased penetration of electric cars and corresponding electric traction systems, while assuming a constant EE device as well as related embedded components and materials mass over time; for example constant mass of the traction motor. Changes in the unit mass of selected car EE devices over time have been considered by Xu et al. (2016) in an estimation of the future flows of rare-earth elements in Japan. However, none of the studies so far have analyzed the historical (*real*) integration and downsizing of car electronics. The role of AECS integration is particularly relevant because of the fade-out of *unifunctional* AECS that become part of new, *multifunctional* ones (Restrepo et al., 2019). Downsizing trends in the realm of consumer electronics have been associated with a reduction in the total mass of precious metals available for recycling (Bangs et al., 2016). By not considering car electronics integration and downsizing, the available studies are likely to overestimate the recycling potentials. The lack of explicit analysis of trends also prevents further inferences to inform dismantling strategies; it remains unclear how integration and downsizing affect the potential for recycling car electronics.

The main goal of this contribution is to inform end-of-life management of car electronics by analyzing the historical developments of penetration rates, integration and EE device downsizing for two well-established AECS and corresponding EE devices for which we collected comprehensive data. We consider the trends in isolation and also analyze their combined effects on the numbers and volumes of car EE devices reaching end of life. We address the following questions:

1 What are the historical trends in AECS penetration, AECS integration, number and unit mass of car EE devices per AECS and per car?
2 What are the effects of the above trends on the total mass inflow and end-of-life mass flow of car EE devices?

To answer these questions we use a layered dynamic material flow analysis (MFA) model supported by comprehensively collected historical data series for car typology, AECS penetration and unit mass for the two selected EE devices in Swiss cars between 1975 and 2015. We then discuss the implications of the above trends for the recycling of EE devices in current car recycling processes as well as under the possible recycling strategy considering a mandatory selective dismantling.

2. Methods

2.1. System definition

The Swiss passenger car system has been defined in (Restrepo et al., 2017). The part of the system considered here is presented in Fig. 1. We focus on the historical developments of the car stock (number of cars in use) as well as the related inflow (number of new cars registered), and flow of ELVs treated in Switzerland. The calculation period is defined from 1975 to 2015. A detailed description of the system considered is provided in the supplementary information (SI), section 1.

All cars in the model contain AECS which are composed of EE devices (Restrepo et al., 2017). Fig. 1 presents this nested structure in the use phase of cars. Specifically, we considered five layers in the model: i) number of cars, ii) mass of cars, iii) number of AECS (0 or 1 per car), iv) number of EE devices per AECS, and v) mass of EE devices. We estimated a corresponding inflow, stock and outflow for each of these layers.

We selected two AECS with high penetration rates and good data availability for a detailed analysis: The antilock-braking system (ABS) and the electronic stability control system (ESC). In these AECS, the controller and actuator are physically assembled as one piece. We therefore considered this assembly as one single EE device and refer to it as the “actuator assembly” or the “assembly” interchangeably. Sensors are not considered in this analysis.

2.2. Mathematical model formulation

We adopted a stock-driven approach in which the number of cars per capita and the population define the stock of cars (Fig. 1), as described by B. Müller (2006); Modaresi and Müller (2012); Pauliuk et al. (2012); Løvik et al. (2014), and Vásquez et al. (2016). The model is described in detail in the SI, section 1.

Having the number of cars, we estimated the total mass m of a specific EE device D in the inflow, stock and outflow of cars by cohort and calculation year. We assumed that the lifetime of EE devices was equal to the lifetime of the cars, implying that these EE devices were not exchanged during the car's lifespan. The mathematical model for estimating this total mass also considers the penetration of AECS and unit mass of corresponding EE devices by cohort and calculation year as described in Eq. 1.

$$m_{c,t}^{D} = \sum_{j} n_{c,j,t} \times r_{c}^{E} \times u_{c,j}^{D,E} \tag{1}$$

Here, c is the car cohort, t is the calculation year and j is the car type. Variable n represents the number of cars, r is the average penetration (between 0 and 1) of the specific AECS (E) that contains device D, and u is the average unit mass of EE device D in E. The car types j were defined as different categories of car mass (as a range) because the car mass is correlated with the mass of the ABS and ESC actuator assemblies: a heavier car requires a heavier actuator assembly in order to deliver the required braking force (Loritz, 2019). Only the mass of the devices (not their penetration rate) was assumed to depend on the car type. The total mass of device D at time t can be obtained by summation of $m_{c,t}^{D}$ over all cohorts.

The total mass of cars in the stock or the flows, M_t, was also calculated, using Eq. 2. Here, U_c is the average mass of cars of cohort c.

$$M_t = \sum_{c} n_{c,t} \times U_c \tag{2}$$

2.3. Parameter estimation

2.3.1. Number of cars by cohort and car mass category

Historical data on new car registration and car stock were obtained from the Swiss Federal Statistical Office (SFO, 2015) and from the Swiss Federal Roads Office (FEDRO, 2016). Historical data on shredded ELVs were obtained from the Foundation Auto Recycling Switzerland (SARS, 2015, 2013). The last were used to calibrate the lifetime distribution parameters of the dynamic MFA model as detailed in the SI, section 1.

2.3.2. Penetration rate and integration of electronic control systems by cohort

The electronic stability control (ESC) is a *multifunctional* AECS in charge of vehicle dynamics that has been progressively integrating other related *unifunctional* systems such as the anti-lock braking system

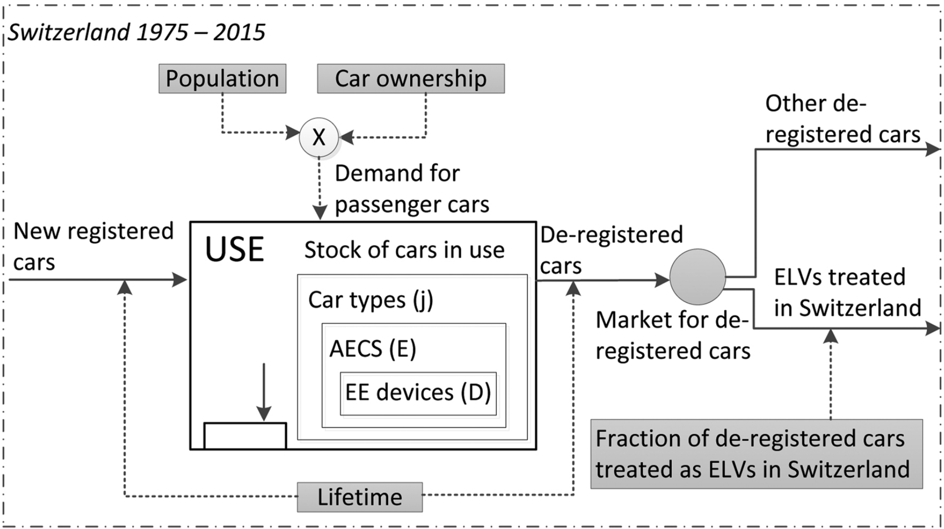

Fig. 1. Passenger car model and drivers considered in the analysis. The *use* phase shows the nested structure of car electronics, i.e.: cars contain automobile electronic control systems (AECS) E, which in turn contain electric and electronic (EE) devices D. The parameters of the stock-driven dynamic MFA model to determine the historical number of cars in stocks and flows are presented in the grey boxes. ELVs: End-of-life vehicles.

(ABS) (Robert Bosch GmbH, 2014; European Parliament and The Council, 2009). A car would contain the unifunctional ABS or the multifunctional ESC (which always contains the ABS function), but not both. Some historical data (2001–2015) on the average penetration of the ESC and the ABS in new Swiss cars by cohort were obtained from a previous study which showed that the penetration followed an s-shaped curve (Restrepo et al., 2019). We fitted logistic functions to the available values in order to obtain time series for the whole calculation period. To capture the introduction trends of the ABS we collected additional data points before 2001 from Edgar (2014) and performed two logistic regressions in this case: One for the increasing part of the penetration curve and one for the decreasing part of it. Details about the logistic regressions and corresponding calibration of the curves are provided in the SI, section 2.

2.3.3. Number and mass of electric and electronic devices by cohort and car mass category

Both AECS considered contain one actuator assembly, which generally consists of three parts: a pump motor (DC electric motor), a hydraulic unit (aluminum block with channels and valves), and an electronic control unit (e.g., printed wiring board) (ACtronics LTD, 2019; Robert Bosch GmbH, 2014, 2019b, 2019a). Fig. 2 presents an ABS actuator assembly including its components; the ESC actuator assembly has a similar configuration. The mass of the “EE device” in this study corresponds to the complete assembly as shown in Fig. 2, panel A. Together, the electric motor and the aluminum block comprise approx. 80 % of the mass of the assembly; the control unit constitutes the remaining 20 % of the assembly’s mass (Widmer et al., 2015). Approximately 15%–30% of the mass of the electric motor lies in the permanent magnets, which can account for approx. 20 % of the total mass of the assembly (Widmer et al., 2015).

To determine the average unit mass of the ABS and ESC actuator assemblies (as in Fig. 2, panel A) by cohort we first collected manufacturers’ data on the unit mass of state-of-the-art actuators, meaning the mass of the latest actuator technologies introduced to the market in a specific cohort year. Because of the high market share of ABS and ESC actuators manufactured by Bosch, e.g., larger than 50 % for the ABS actuator (European Commission, 2019b), we assumed that the mass values for the state-of-the-art assemblies manufactured by this company were representative for the assemblies in the model and relied mainly on data from this manufacturer (Ebber, 2014; BOSCH, 2019; Robert Bosch GmbH, 2014, 2019b, 2019a). Additional data points from anonymous manufacturers were gathered from Edgar (2014). The manufactures’ values served as reference for estimating the unit mass of the assemblies by car mass category and cohort, which was done in collaboration with an industry expert (Loritz, 2019). The estimated unit mass was later validated and corrected with measurements of the unit mass of actuators assemblies dismantled from Swiss ELVs. Using the data from the dismantling experiment, we found that the ratio of ABS mass to car mass was in the range of 0.07 % to 0.19 % (see SI Table S6). For a specific car type and cohort, and whenever the estimated unit mass lied outside this range, the estimate was adjusted up or down to stay within this range. Last, we computed the weighted average unit mass of the actuator assemblies by cohort as the sum of the product of the validated unit mass of the assembly and the share of cars in a specific mass category by cohort. The detailed mass estimation approach, including experimental results is presented in the SI section 3.

3. Results and discussion

3.1. Individual trends: Number of cars, car mass, AECS penetration, AECS integration, number of EE devices and mass of EE devices

The number of cars in use (stock) in Switzerland has increased fast, from 1.8 million in 1975 to around 4.5 million cars in 2015. In 2015, the number of cars per capita (car ownership) was approx. 0.5. The number of new car registrations sharply increased from 120 000 in 1975 to approx. 290 000 cars per year in 1981. This number has remained between 250 000 and 350 000 cars per year during the period 1982-2015. The number of ELVs treated in the country has also increased drastically from approx. 20 000 ELVs per year in 1975 to approx. 100 000 ELVs per year in 2015. However, the ELVs treated in the country represented only about 40 % of the total de-registered cars, while the large majority of the remaining 60 % of de-registered cars is exported to other countries. Detailed results on the inflow, stock and EoL flow of cars (number) for the period 1975–2015 are provided in

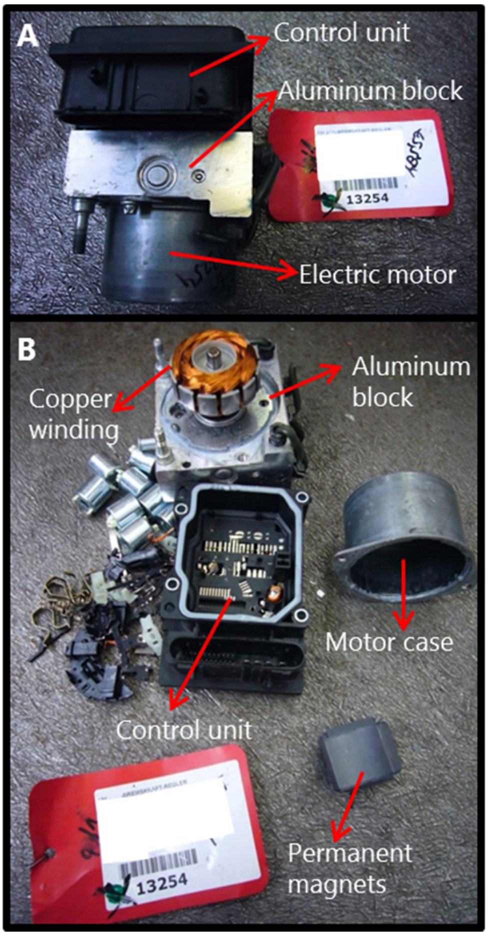

Fig. 2. ABS actuator assembly, the ESC assembly has a similar configuration. A) Overview, B) Disassembled actuator. Car's cohort year: 2006. Mass of complete assembly as in panel A: 1.6 kg. Photos and measurements by the author.

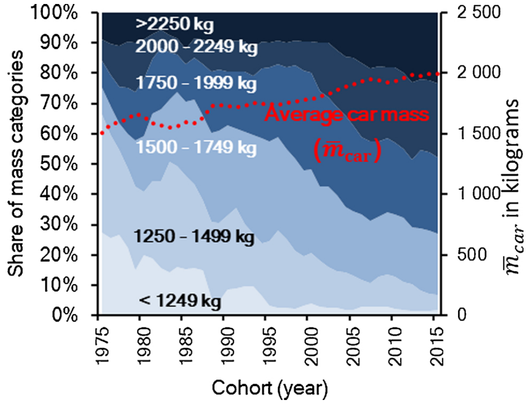

Fig. 3. Share of cars by mass category and cohort. The share of cars (%) in each category is provided in the left-hand y-axis. The average car mass ($\bar{m}_{car}$) by cohort is represented by the red dotted line; the mass values are provided in the right-hand y-axis. Figure data are provided in Table S2 of the SI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

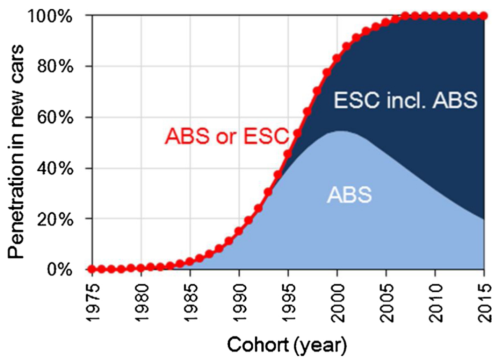

Fig. 4. Average penetration of the ABS and ESC systems by cohort. Since each control system contains only one actuator assembly, the penetrations values also correspond to those of their respective actuator assemblies. The time series are provided in SI, Table S4.

Table S3 of the SI.

Fig. 3 shows that the average mass of cars has increased over time (dotted red line in Fig. 3). The portion of heavy cars (of mass larger than 1500 kg) increased from approx. 30 % in 1975 to over 90 % in 2015.

As observed in Fig. 4, the ABS was introduced in 1978 and its penetration increased fast until 2001. After 2001 this penetration started to decline due to the penetration of the ESC, which integrates the ABS function. The integration of the ABS function into the ESC has thus resulted in a displacement of the unifunctional ABS by the multifunctional ESC. Even though the ESC encompasses more functions than the ABS it does not require additional actuator assemblies (actuators and controllers) to perform the various braking-related functions (Robert Bosch GmbH, 2014). In this sense, the ABS actuator assembly has been integrated in and replaced by the ESC actuator assembly. As both control systems contain one actuator assembly each, the time series in Fig. 4 also correspond to the penetration of the respective actuator assemblies in new cars. In 2015, all new cars (100 %) contained either the unifunctional ABS or the multifunctional ESC system (red-dotted line in Fig. 4); with the large majority (80 % of cars) containing the ESC (dark-blue wedge in Fig. 4).

The unit mass of the state-of-the-art ABS actuator assembly has declined from 6.2 kg to 1.1 kg (by a factor of 6) between 1989 and 2013 (light-blue circles in Fig. 5). The unit mass of the most modern ESC actuator assembly declined from 4.3 kg to 1.6 kg (by a factor of 2) between 2010 and 1995 (dark-blue squares in Fig. 5). This implies that both actuator assemblies have been progressively able to deliver the same functions with decreasing mass. Possible contributors to this mass decrease are: i) the use of lighter metal alloys in the hydraulic unit (e.g. aluminum), ii) the use of lighter materials in the casings of the motor and control unit (lighter metal alloys and lighter plastics), iii) a decrease in the mass of the control units, for example due to the use of denser integrated circuits (Wong and Iwai, 2005), and iv) the use of rare earth elements (REE) such as lanthanum, neodymium and dysprosium in the motor magnets, which can significantly improve the power-to-weight ratio of the magnets (Robert Bosch GmbH, 2019a; Constantinides, 2016). Nevertheless, increasing the number of functions per actuator assembly has implied an increase in its unit mass: the unit mass of the multifunctional ESC has always been larger than the mass of the unifunctional ABS at all points in time.

However, despite the declining mass of state-of-the-art devices, the average mass of the devices installed in cars has stabilized at around 2.5 kg for the ABS and 3.1 kg for the ESC (Fig. 5). Even though lighter

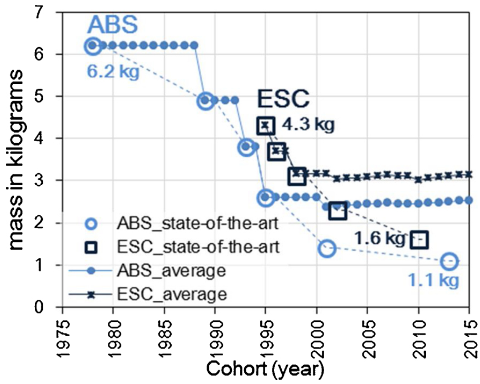

Fig. 5. Unit mass of the ABS and ESC actuator assembly by cohort. The light-blue circles and the dark-blue squares represent the unit mass of the state-of-the-art actuator ABS and ESC assemblies, respectively, as obtained from manufactures' data. Dashed lines are provided in both cases to guide the eye as to how the trend for the unit mass of the state-of-the-art actuators develops. The light-blue dotted line represents the estimated average unit mass of the ABS actuator assembly by cohort; the dark-blue starred line represents the estimated average unit mass of the ESC actuator assembly. Figure data are presented in Table S5, Table S9 and Table S10 of the SI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

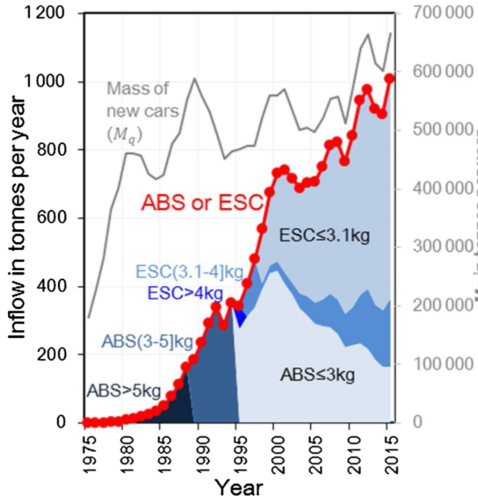

Fig. 6. Mass inflow of ABS and ESC actuator assemblies, Switzerland 1975–2015. The red-dotted line represents the combined inflow of actuator assemblies and the blue wedges represent the inflow of different generations of actuator assemblies; values are provided on the left-hand axis. The total mass inflow of cars is represented by the grey line; values are provided in the right-hand y-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

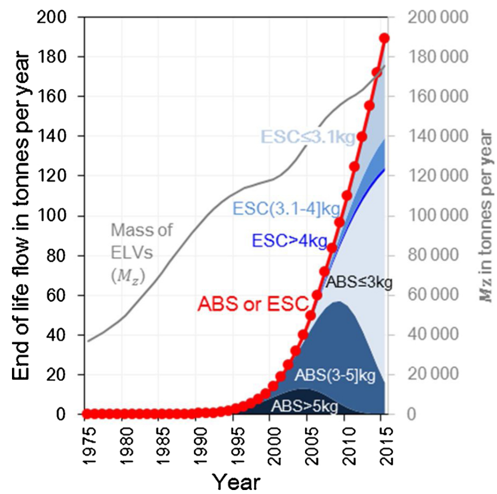

Fig. 7. End-of-life (EoL) mass flow of ABS and ESC actuator assemblies, Switzerland 1975–2015. The red-dotted line represents the combined EoL flow of actuator assemblies and the blue wedges represent the EoL flow of different generations of actuator assemblies; values are provided on the left-hand axis. The total EoL mass flow of cars is represented by the grey line; values are provided in the right-hand y-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

actuator assemblies existed in the market in 2015, it seems like an average car was still equipped with relatively heavier types of actuators that already existed on the market 15 years before that. The discrepancies between the unit mass of the state-of-the-art actuator assemblies and their estimated average unit mass by cohort can be explained by four effects: i) the increased penetration of heavier cars after 1995 (refer to Fig. 3) which required accordingly heavier ABS and ESC actuator assemblies from the available options –a heavier car requires a heavier actuator (Loritz, 2019), ii) a "common parts" approach from the original equipment manufacturer (OEM) in which the same type of "heavy" actuator assembly is installed across a range of car sizes (masses) (Loritz, 2019), iii) decision of the OEM to install older, thus cheaper versions of the ABS and ESC actuator assemblies –lighter actuators are usually more costly due to the use of more specialized materials (Loritz, 2019), and iv) sample of ELVs that may have led to overestimation of the assembly's average mass: only selected cohorts and mass categories were considered in the experiment; see SI section 3.

3.2. Combined trends: Effects of penetration, integration and downsizing on the total mass flows of EE devices

Until 1995, the inflow of actuator assemblies was dominated by the heavier, early generations of ABS actuator assemblies of mass larger than 3 kg (darkest blue wedges in Fig. 6). The total mass of ESC actuator assemblies entering use surpassed the mass of ABS ones in 2003. Parallel to the replacement of ABS by ESC, there was a continual downsizing of both types of actuator assemblies: The inflow of light actuator assemblies (of mass less than 3.1 kg) grew fast since 1995, accounting for 80 % of the inflow in 2015. Nevertheless, the total mass inflow of actuators increased due to: i) the increase in average actuator mass per car due to the replacement of ABS by ESC (refer also to Fig. 5), ii) the increased penetration of the ESC in all car types (refer also to Fig. 4), iii) a growing number of vehicles entering use per year.

Fig. 7 shows that the combined EoL mass flow of ABS and ESC actuator assemblies increased fast after 1995 (red-dotted line). In 2015, the trend still pointed sharply upwards. Considering the saturation in penetration reached by 2008 (Fig. 4), we can expect the flows to grow further but at a slower pace between 2015 and 2025, with remaining growth being driven mainly by the switch to ESC, the switch to heavier car types and an increasing number of ELVs. As seen in Fig. 5 there are further downsizing potentials for the average actuator assemblies installed in new cars. If these are realized, the mass flow of the actuator assemblies may even decline. Similarly, the mass flows of ABS and ESC assemblies could fade-out if their functions are integrated in new EE devices. However, due to the lifetime of cars (approx. 17 years, see SI), such changes would only affect ELVs after a delay, and we therefore expect EoL mass flows to continue growing at least until 2030.

For the entire calculation period, the EoL flow was dominated by the ABS actuator assemblies, still comprising more than 60 % of the EoL mass flow in 2015. This reflects the dominance of the ABS actuator assemblies in the car inflow up until the year 2000. We expect the EoL flow to change from a majority of ABS to a clear majority of ESC in the near future. The EoL mass flows of ABS assemblies larger than 3 kg had decreased substantially by 2015, and are today probably marginal, as confirmed by the dismantling experiment (see SI Table S6). The average mass of EoL actuator assemblies is expected to increase slightly in the coming years due to the switch to ESC and heavier cars.

3.3. Implications for recycling

3.3.1. Current treatment of end-of-life car electronics

The current dismantling rate of ABS actuator assemblies is around 10 % (Restrepo et al., 2017) with an average dismantling time of about 13 min per assembly as estimated in our experiment (Table S6 of the SI). At present, this dismantling is done manually. The dismantled actuator assemblies are offered in the second-hand spare parts market; the exact percentage of second-hand assemblies sold and reused is however unknown. The remaining 90 % of the EoL ABS actuator assemblies are shredded with the ELVs (Restrepo et al., 2017). After car shredding, materials such as aluminum from the hydraulic unit and copper from the electric motor winding might be recovered, while the materials within the motor magnets and printed wiring boards are currently not recovered (Widmer et al., 2015). Considering that EoL flows of heavier (> 3 kg) ABS actuator assemblies peaked before 2010, the highest recycling opportunity for the materials within these assemblies has already passed. There is no information about dismantling and shredding for the ESC actuator assembly. However, considering that their EoL flows are still growing, we expect their highest recycling opportunities to occur in the future.

3.3.2. Possible mandatory dismantling of selected end-of-life car electronics

The economic feasibility of EE device dismantling for material recovery depends strongly on the costs per kilogram of material dismantled. The possible dismantling for material recovery strategy being considered in Switzerland may be supported by a “polluter-pays principle”, as is currently done for the disposal of car shredder light fraction, also known as automobile shredder residue (FOEN, 2019b) and/or a voluntary “advance recycling contribution”, as is currently the case for electronic waste (FOEN, 2019a). Let the cost per kilogram of dismantled material (e.g. in \$/kg), C, be defined by Eq. 3:

$$C = \frac{c}{m} \quad (3)$$

where c is the dismantling cost per unit and m is the unit mass of the EE device. According to our dismantling experiment, the time to dismantle the actuator assemblies is not correlated with their unit mass (see Table S6 and corresponding Figure S8, panel B in the SI). It is thus reasonable to assume that c is independent of m, so that a reduction of m will lead to a corresponding increase of C. We estimated that the average unit mass of new ABS actuator assemblies decreased from 6.2 kg in 1978 to 2.5 kg in 2015 (Fig. 5). This would correspond to a 60 % increase in the dismantling costs per kilogram in this time period, assuming constant labor costs. Similarly, the average unit mass of the ESC actuator assembly was estimated to decrease from 4.3 kg in 1995 to 3.1 kg in 2015 (Fig. 5). This would correspond to almost 30 % increase in the dismantling cost per kilogram. However, as presented in Fig. 5, downsizing leveled off already around the year 2000. Consequently, we can expect the dismantling costs per kilogram for the ABS and ESC actuator assemblies to also stabilize between 2015 and 2025, or even decrease slightly due to the transition from ABS to ESC and towards heavier car types.

These examples illustrate the importance of considering downsizing and integration trends in the design of policies to promote recycling, especially when these policies include a financing mechanism and target devices with a large downsizing potential. In addition to downsizing, changing material compositions, e.g. due to changing market prices for the materials and material substitution can have a substantial effect on the economic feasibility of dismantling for material recovery. Additionally, it should be considered that if the dismantled EE devices are in condition to be reused, this dismantling strategy could cause an increase in the supply of second-hand EE devices, which could be associated with a reduced production of new spare parts and corresponding resource consumption. This increased supply of spare parts may, at the same time, negatively affect the second-hand market. Tradeoffs between the environmental benefits resulting from reduced resource consumption and the potential repercussions on the second-hand spare-part market need to be resolved with additional measures, for example by incentivizing a higher reuse rate for specific EE devices.

Considering similarities in their car fleet (Eurostat, 2017), the same patterns for the EoL flows of ABS and ESC actuator assemblies, with similar implications for recycling, can be expected in most west European countries. We can also expect similar patterns for other EE devices in cars that have penetrated in the past 30 years, especially when they include actuator assemblies with electric motors. However, due to the lack of comprehensive data series, including the mass and cohort of the cars, it is not possible to make further inferences about the developments of the end-of-life flows for other types of EE devices.

4. Conclusions and outlook

The size of the mass flows of ABS and ESC actuator assemblies is the result of three overlapping trends: an increased penetration of ABS and ESC systems, a replacement of the ABS by the ESC (integration) and a decrease in the unit mass of their actuator assemblies over time (downsizing). Penetration and unit mass followed s-shaped curves, both changed most rapidly in the 1990s and they have flattened since the 2000s. Penetration outweighed both integration and downsizing, so that before stabilizing, it caused the total mass inflow of actuator assemblies to increase rapidly over time. Due to the long lifetime of cars, the effects of penetration, integration and downsizing are still evident at the end-of-life flows, but can be expected to slow down considerably between 2015 and 2025. The estimation of the mass flows of critical metals reaching end of life requires data series about material composition in the different generations of actuator assemblies considered here and remains to be assessed.

We demonstrated that a possible mandatory dismantling for material recovery in this case may be challenged by increasing costs per kilogram of material dismantled, resulting from the progressive decrease in the unit mass of the ABS and ESC actuator assemblies. However, as downsizing settles, so will the dismantling costs, which shows future opportunities for dismantling for material recovery. Automated or machine-assisted dismantling could help to reduce the dismantling time per unit and thus the total dismantling costs. If the EoL EE devices dismantled are in condition to be reused, this dismantling strategy can be associated with a reduced production of new spare parts and corresponding resource consumption, which ultimately results in environmental benefits. At the same time, the surplus of second-hand spare parts can negatively affect the second-hand market. These potential tradeoffs need to be tackled with additional measures, for example by incentivizing a higher reuse rate for specific EE devices.

Comparable developments for the EoL flows and dismantling costs of the ABS and ESC actuator assemblies can be expected in most west European countries, considering the similarities in their vehicle fleet. Due to the current lack of comprehensive data about penetration and unit mass, it is not possible to make further inferences about mass flow developments for other types of EE devices.

By monitoring the trends analyzed here at the car inflow, in combination with a dynamic MFA, we can foresee changes in the end-of-life flows of car electronics 10–20 years before they arise. This time period should be sufficient to plan and adapt recycling strategies, for example regarding which EE devices have to be mandatorily dismantled and how much financing would be needed for this at different points in time. The success of such monitoring depends on the accessibility to data about penetration and unit mass of new car EE devices. It is thus crucial that these data are made available to the stakeholders taking charge of such monitoring.

CRediT authorship contribution statement

Eliette Restrepo: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Amund N. Løvik:** Conceptualization, Methodology, Formal analysis, Writing - review & editing. **Rolf Widmer:** Supervision, Project administration, Funding acquisition. **Patrick Wäger:** Supervision, Funding acquisition. **Daniel B. Müller:** Supervision, Conceptualization, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the Swiss Federal Office for the Environment (FOEN) as part of the project “Recycling Electronics from ELVs –EVA”. The project partners include: Auto-Schweiz (Swiss association of automobile importers), AWEL (Office of Waste, Water, Energy, and Air of the Canton of Zurich), SARS (Foundation Auto Recycling Switzerland), VASSO (Association of the Official Car Collection Point Proprietors of Switzerland and the Principality of Liechtenstein), and VAREX (Swiss Association of Automobile Recyclers and Exporters).

Special thanks to Mario Loritz for guidance in the estimation of the ABS and ESC actuators mass. We express our gratitude to Andreas Kaufmann and the members of VASSO for their contributions to the dismantling experiment. For providing feedback on the unit mass estimation approach we thank Romain Billy, Helen A. Hamilton, Marta Roca Puigròs, Simona Sharma and Chipo Sitotombe.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.rcrx.2020.100032.

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Supporting Information to:
Effects of car electronics penetration, integration and downsizing on their recycling potentials

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1. Stock-driven dynamic MFA of Swiss cars

1.1. Model variables and parameters

Table 1 below summarizes the model variables (number of vehicles) and parameters considered in the dynamic material flow analysis (MFA) model of Swiss cars.

Table S1. Dynamic MFA model variables and parameters.

q_t	Inflow in year t
s_t	Stock at the end of year t
$s_{t,c}$	Stock at the end of year t of cohort c
ds_t	Stock change in year t
x_t	Outflow in year t
$x_{t,c}$	Outflow in year t from cohort c
$z_{t,c}$	End-of-life vehicles (ELVs) treated in Switzerland in year t of cohort c
$w_{t,c}$	Other de-registered vehicles: exported vehicles, hibernating stocks and second-hand vehicles registered again in year t of cohort c
u_a	Probability of vehicles leaving use after a years in stock
v_a	Probability of vehicles in initial stock leaving use after a years after model start
h	Share of outflow treated as ELVs in Switzerland
λ	Scale parameter of the Weibull distribution
k	Shape parameter of the Weibull distribution
τ	Mean lifetime parameter of the exponential decay function
p_t	Population in year t
r_t	Car ownership in year t

1.2. Basic assumptions and model framework

There are several methods to estimate the stock and flows of cars over time (Libertiny 1993, Sterman 2003, Müller 2006). We adopted a stock-driven approach in which the number of cars per capita and the population define the stock of cars, as described by B. Müller (2006), Modaresi and Müller (2012), Pauliuk et al. (2012), Løvik et al. (2014), and Vásquez et al. (2016). The main purpose of the dynamic MFA model is to estimate the number and cohort of end-of-life vehicles generated in Switzerland over time. Additionally, the model estimates the required number of new registrations (inflow) and the composition of the stock in terms of cohorts. A graphical definition of the model is provided in Figure S1.

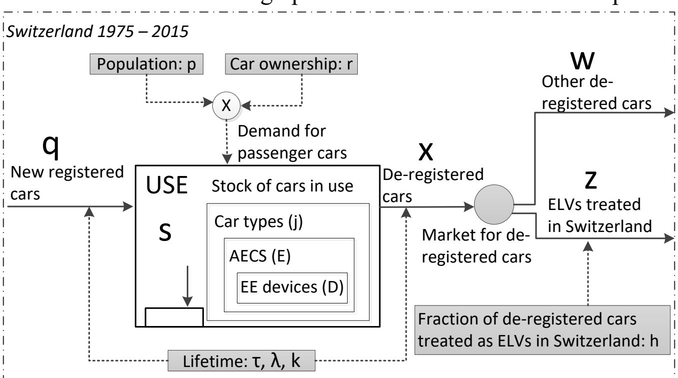

Figure S1. Dynamic MFA model definition.

The basic assumption is that the residence time of vehicles in use is governed by a lifetime probability distribution, u, which is assumed to be the same for vehicles of all types and cohorts. The probability distribution relates the outflow of vehicles from the use phase of a given cohort, c, in a given year, t, to the inflows in past years. Formally, it can be represented by the following equation:

$$x_{t,c} = q_c u_{t-c} \tag{1}$$

Where $x_{t,c}$ is the number of vehicles of cohort c leaving use in year t, q_c is the number of new vehicles registered in cohort year c, and u_{t-c} is the probability of a vehicle of cohort c leaving use in year t ($t - c$ = age of the vehicle). The probability distribution u is assumed to follow a Weibull distribution, specified by the scale parameter λ and the shape parameter k. See section 1.5 below (model calibration) for an explanation of how the continuous Weibull probability density function (PDF) is transformed to a discrete probability distribution.

The total outflow in year t can be calculated as:

$$x_t = \sum_{c=c0}^{t} q_c u_{t-c} \tag{2}$$

Where $c0$ is the year of the first cohort to be considered in the model.

For mass balance to hold, the change in stock within one year must be equal to the difference between the inflow and the outflow:

$$ds_t = s_t - s_{t-1} = q_t - x_t \tag{3}$$

where s_t is the number of vehicles in stock at the end of year t. This relationship also holds for individual cohorts:

$$ds_{t,c} = s_{t,c} - s_{t-1,c} = q_{t,c} - x_{t,c} \tag{4}$$

where $s_{t,c}$ is the number of vehicles in stock of cohort c at the end of year t. Note that the inflow, $q_{t,c}$, will be non-zero only when $t=c$, since we assume that all newly registered vehicles were produced in the same year as they enter use.

A large share of de-registered Swiss vehicles are exported (Restrepo *et al* 2017). We calculate the number of ELVs treated in Switzerland as a fraction, h, of the total outflow of de-registered vehicles. This fraction is assumed to be a constant. Additionally, we use the flow of ELVs for model calibration as explained in section 1.5 below.

$$z_{t,c} = h\, x_{t,c} \tag{5}$$

It is assumed that h is independent of the cohort and type of vehicle.

1.3. Model solution

To allow the model to stabilize, we start it some years earlier, i.e., the model is run from t=1950 to t=2015. However, all presented results are given only from 1975 to 2015. The number of vehicles in use is treated as the driver of the system. Historical stock data are given from statistics until 2015 (SFO 2015, FEDRO 2016). In the following, we explain how the remaining variables are computed given data only on the total number of vehicles in the stock and the lifetime distribution function.

Initial stock, c=1950

An initial stock of vehicles existed in 1950. The vehicles in the initial stock are all assigned to cohort 1950, as more detailed information is not available. The initial stock of this cohort is then simply given as:

$$s_{1950,1950} = s_{1950} \tag{6}$$

To account for the fact that the initial stock in reality was composed of different cohorts, it is assumed to leave use following a different probability distribution than the later cohorts, with v_a being the probability of leaving use a years after model begin:

$$x_{t,1950} = v_{t-1950}\, s_{1950} \tag{7}$$

Specifically, we assume the initial stock to leave use following an exponential decay function (details described in the calibration chapter). The stock of cohort 1950 can be calculated for all other years:

$$s_{t,1950} = s_{1950,1950} - \sum_{t=1951}^{2050} x_{t,1950} \tag{8}$$

All other cohorts, c=1951,1952, …, 2015

For all other cohorts, the following algorithm is used to calculate the required inflow, q_t, the outflows, $x_{t,c}$ and the stock, $s_{t,c}$:

repeat for t: 1951, 1952, …, 2050 {

Calculate the stock change in year t:

$$ds_t = s_t - s_{t-1} \tag{9}$$

Calculate outflows in year t from already existing cohorts (c < t):

$$x_{t,c<t} = \sum_{c=1950}^{t-1} x_{t,c} \tag{10}$$

Calculate the required inflow in year t to meet the stock change, considering also the outflow of this new cohort in the same year:

$$q_t = \frac{ds_t + x_{t,c<t}}{1 - u_0}$$
(11)

Calculate the outflows from the new cohort, *c=t*, in all future years *t*':

repeat for all *t'* ≥*c*: {

$$x_{t',c} = q_c \, u_{t'-c}$$
(12)

}

Calculate the stock of the new cohort in all future years:

repeat for all t'≥c: {

$$s_{t',c} = q_c - \sum_{t'=c}^{2050} x_{t',c}$$
(13)

}

}

1.4. Parameter estimation and data sources

Stock

For the years 1950 to 2015 the vehicle stock by calculation year and year of first registration (cohort) was obtained from the Swiss Federal Statistical Office (FSO)(SFO 2015) and from the Swiss Federal Roads Office (FEDRO)(FEDRO 2016). The stock data until the year 1970 was available at a 10-year interval (1950, 1960 and 1970); between 1975 and 1980 the data were available at a 5-year interval (1975, 1980). After 1980 the data were available on a yearly basis.

The vehicle stock for the years with no data available was estimated by means of logistic regression between the years of available data using Equation 14 below.

$$f(t) = \frac{C_0 + C_1}{1 + e^{-\frac{t-t_i}{\tau}}} + C_0$$
(14)

Where C_0 is the start value, C_1 is the end value, t_i is the inflection time and τ is the time span for transition.

The number of Swiss cars in stock for the period 1950-2015 is presented in Figure S2. The term "observation" is used for specifying data collected from independent sources (not calculated). The red-crossed line presents the estimated values by logistic regression.

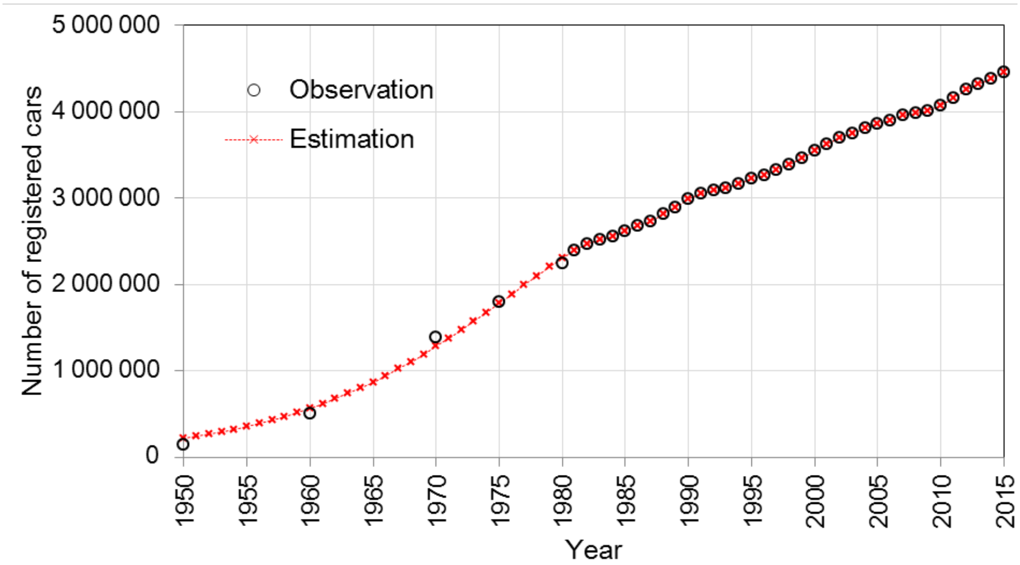

Figure S2. Historical number of registered cars on the road in Switzerland (car stock).

Imports and new registrations

For the results on the inflow, presented in the main paper, we used historical data on new registrations rather than the inflow predicted by the model. Imports were estimated from trade data obtained for the years 1962 to 2015.[21] New registrations from 1980 to 2015 were obtained from FSO and FEDRO (SFO 2013b, 2013a, FEDRO 2016) Figure S3 shows the data collected.

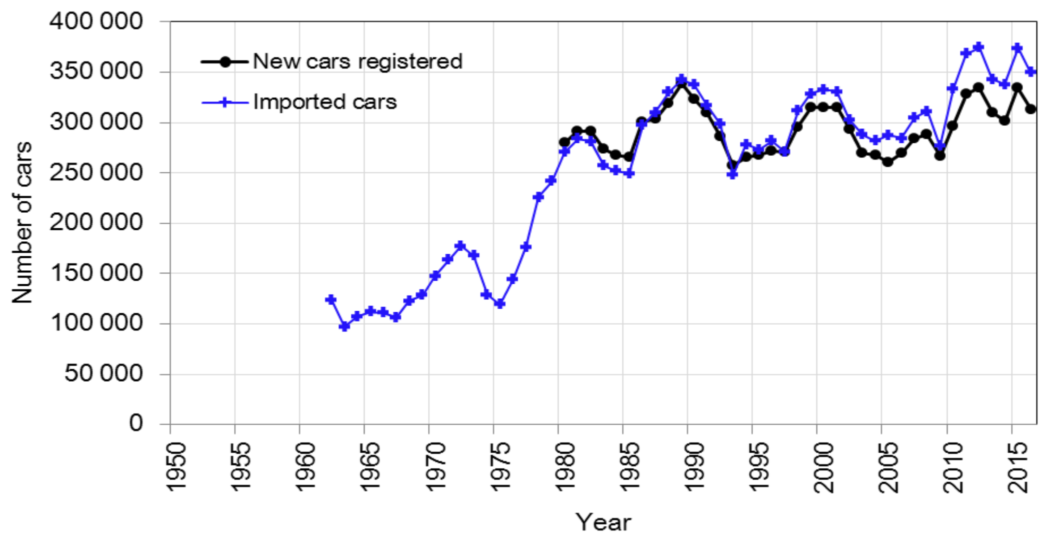

Figure S3. Historical car imports and new registrations in Switzerland. Sources: FSO, FEDRO and UN-COMTRADE.

Shredded ELVs

We obtained data on the number of shredded ELVs in 2013 and 2014 from SARS (SARS 2015, 2013), Figure S4. These data on shredded ELVs were used for the calibration of the model as explained in section 1.5 below.

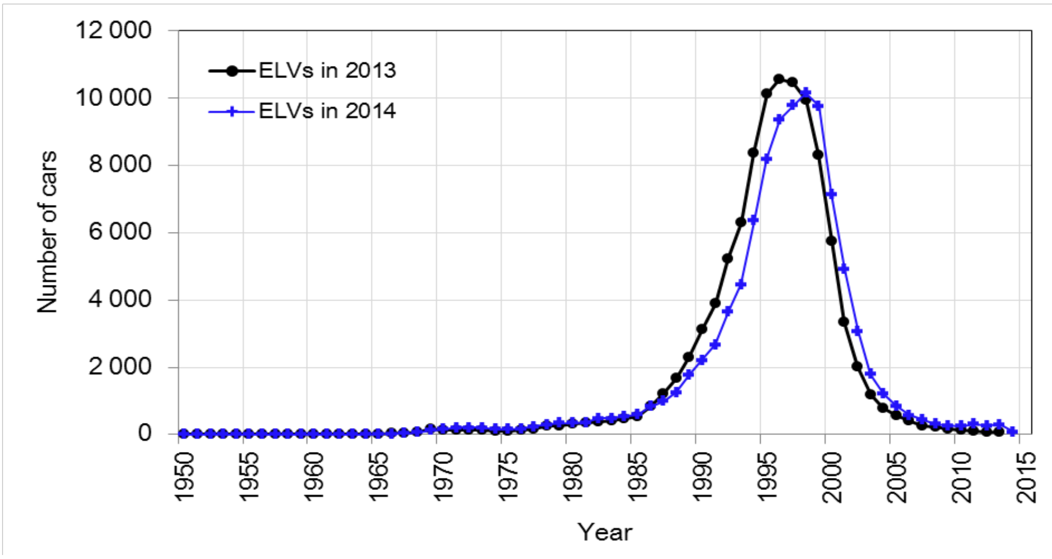

Figure S4. Number of ELVs shredded by cohort in 2013 and 2014. Source: SARS.

Share of cars by mass category and cohort

The share of cars by mass category and cohort was assumed to be equal to that of cars in stock in 2015. To define the mass categories, we first identified the mass distribution of the stock in 2015. This mass distribution (histogram) of the cars in stock in 2015 is presented in Figure 5, panel B. The share of cars in each mass category and cohort is presented in Table S2.

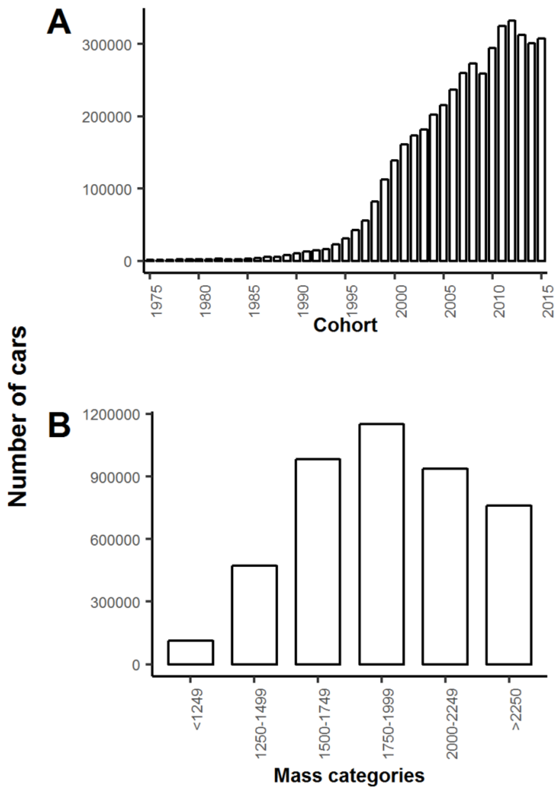

Figure S5. Distribution of the stock of cars in 2015 by A) cohort and B) mass category.

Table S2. Share of cars by mass category and cohort. The share of cars is given between 0 and 1, indicating that either 0% or 100% of the cars in a given cohort are found in a corresponding mass category. The gray shade indicates, from darker to lighter: the highest to smallest share of cars. The total stock of cars in 2015 (number of registered cars on the road) was equal to 4 417 721 cars.

Cohort year	**Share of cars by mass category**						**Number of cars by cohort**	**Average car mass by cohort /kg**
	<1249	**1250-1499**	**1500-1749**	**1750-1999**	**2000-2249**	**>2250**		
1975	0.27	0.39	0.09	0.09	0.07	0.09	1 532	1 504
1976	0.26	0.34	0.10	0.10	0.10	0.10	1 433	1 578
1977	0.27	0.28	0.09	0.12	0.14	0.11	1 537	1 598
1978	0.23	0.26	0.11	0.15	0.15	0.10	1 935	1 622
1979	0.15	0.28	0.15	0.16	0.16	0.10	2 189	1 664
1980	0.20	0.21	0.19	0.19	0.13	0.09	1 899	1 642
1981	0.19	0.26	0.22	0.18	0.08	0.07	2 136	1 582
1982	0.16	0.29	0.24	0.20	0.06	0.06	2 817	1 570
1983	0.14	0.36	0.21	0.16	0.06	0.07	2 471	1 555
1984	0.16	0.33	0.25	0.12	0.05	0.08	2 375	1 556
1985	0.15	0.31	0.24	0.13	0.05	0.12	2 796	1 598
1986	0.16	0.27	0.28	0.14	0.06	0.09	3 912	1 587
1987	0.15	0.23	0.28	0.17	0.08	0.09	5 016	1 635
1988	0.06	0.25	0.29	0.20	0.09	0.10	5 695	1 727
1989	0.05	0.26	0.31	0.20	0.09	0.10	7 959	1 735
1990	0.08	0.24	0.30	0.18	0.09	0.10	10 501	1 726
1991	0.09	0.26	0.26	0.19	0.10	0.09	12 949	1 717
1992	0.10	0.20	0.31	0.20	0.10	0.10	14 390	1 725
1993	0.10	0.17	0.33	0.19	0.09	0.12	16 331	1 756
1994	0.07	0.17	0.35	0.23	0.09	0.10	22 331	1 745
1995	0.03	0.21	0.33	0.24	0.08	0.10	31 048	1 749
1996	0.03	0.25	0.31	0.24	0.08	0.09	42 154	1 738
1997	0.02	0.23	0.30	0.27	0.08	0.10	55 337	1 752
1998	0.02	0.19	0.30	0.31	0.08	0.09	81 960	1 764
1999	0.03	0.16	0.28	0.33	0.09	0.10	112 470	1 779
2000	0.04	0.17	0.28	0.32	0.10	0.10	138 533	1 777
2001	0.03	0.15	0.24	0.32	0.16	0.10	161 278	1 811
2002	0.03	0.13	0.27	0.29	0.18	0.10	173 629	1 826
2003	0.02	0.12	0.25	0.29	0.19	0.13	181 165	1 861
2004	0.02	0.12	0.22	0.30	0.20	0.15	201 850	1 889
2005	0.02	0.11	0.21	0.28	0.22	0.15	215 697	1 909
2006	0.03	0.09	0.21	0.26	0.24	0.17	236 711	1 932
2007	0.03	0.08	0.21	0.26	0.24	0.19	259 801	1 954
2008	0.03	0.10	0.20	0.25	0.25	0.18	272 794	1 939
2009	0.03	0.10	0.21	0.25	0.23	0.18	258 822	1 923
2010	0.02	0.10	0.21	0.24	0.25	0.18	294 045	1 934
2011	0.02	0.09	0.21	0.23	0.25	0.20	324 944	1 954
2012	0.02	0.09	0.19	0.22	0.26	0.23	332 644	1 988
2013	0.02	0.07	0.21	0.26	0.23	0.22	312 333	1 979
2014	0.01	0.06	0.21	0.26	0.24	0.22	300 594	1 994
2015	0.02	0.05	0.20	0.25	0.24	0.24	307 708	1 994

1.5. Model calibration

The above-explained model solution requires that the stock (S_t) and the probability distributions (u_a and v_a) are known. While the stock is given from statistics and scenarios, the probability distributions must be estimated indirectly from other observed data (either the inflow or the outflow). Specifically, we need to estimate the parameters of the Weibull distribution, λ and *k*, and the share of ELVs treated in Switzerland, *h*. The PDF of the Weibull distribution is defined as:

$$f(t) = \begin{cases} \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{k-1} e^{-\left(t/\lambda\right)^{k}} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{15}$$

To be compatible with the model framework, we need to translate this continuous PDF to a discrete distribution with probabilities assigned to each age *a* = 0, 1, 2, …, 100. The discrete distribution can be obtained by integrating *f(t)* in consecutive time spans of 1 year. For *a*=0, we integrate from *t*=0 to *t*=0.5:

$$u_0 = \int_0^{0.5} f(t)\ dt \tag{16}$$

For all other values of *a* we use the following equation:

$$u_a = \int_{a-0.5}^{a+0.5} f(t)\,dt \tag{17}$$

The integration start and end at half-years is to account for the fact that the inflow occurs throughout the year rather than as a single large inflow at the beginning of the year. The above equation is equivalent to assuming that the inflow occurs as a single large inflow at the middle of the year. An exponential decay function was used for the initial stock. The exponential decay function defines the development of a stock variable, *s*, over time as:

$$s = s_0 e^{-\frac{t}{\tau}} \tag{18}$$

Where s_0 is the initial value of *s* at *t*=0. The constant τ is the mean lifetime of the units composing the stock. The initial stock was assumed to follow an exponential decay function with mean lifetime equal to half of the mean lifetime of the Weibull distribution used for all other cohorts. The exponential decay function was translated into a discrete probability distribution *v* using the following equations:

$$v_0 = 1 - e^{-\frac{0.5}{\tau}} \tag{19}$$

$$v_a = e^{-\frac{a-0.5}{\tau}} - e^{-\frac{a+0.5}{\tau}} \tag{20}$$

The calibration was done by running the model with different values for *h*, λ and *k* and finding the combination that gave the best fit to the observed age distribution of the shredded ELVs $Z_{t,c}$. The calibration was made against $Z_{t,c}$ because it is the variable that we are most interested in predicting. Data on the cohort distribution of shredded ELVs was available for two years: 2013 and 2014 (refer to Figure S4). We used the data for 2013 to calibrate the model and the data from 2014 to do an independent test.

To determine the degree of fit, we calculated the coefficient of determination, R^2, from the residuals:

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2} \tag{21}$$

where y_i is observation i, $\hat{y}_i$ is the corresponding model prediction and $\bar{y}$ is the mean of all observations. The observations y_i are here the number of vehicles shredded from each cohort in year 2013 or 2014. Figure S6 shows the result of the calibration. The best fit was found for h=0.422, λ=18.3 and k=5.5. The Weibull parameters correspond to a mean lifetime of 16.9 years. Figure S6B shows the coefficient of determination as a function of λ and k for the optimal value of h. The predicted and observed number of shredded vehicles per cohort in 2013 and 2014 are shown in Figure S6C and Figure S6D respectively. The coefficient of determination was 0.972 for the calibration set and 0.956 for the test set. In terms of total number of vehicles shredded (sum of all cohorts), the model predicted 7% too few in 2013 (calibration set) and 2% too few in 2014 (test set).

As can be seen in Figure S6A, the predicted inflow is lower than the observed inflow for past years, especially between 1980 and 2000. Possible explanations are: 1) Some of the imported vehicles are not new. Their lifetime in the Swiss stock is therefore shorter than what is indicated by their age at shredding; 2) The lifetime of vehicles was shorter in past years. 3) Exported second-hand vehicles may on average be younger than the ELVs treated in Switzerland. Calibration of the lifetime distribution using data on ELVs treated in Switzerland might therefore lead to an overestimation of the residence time of vehicles in the Swiss stock, which in turn will cause the model to underestimate the required inflow in past years.

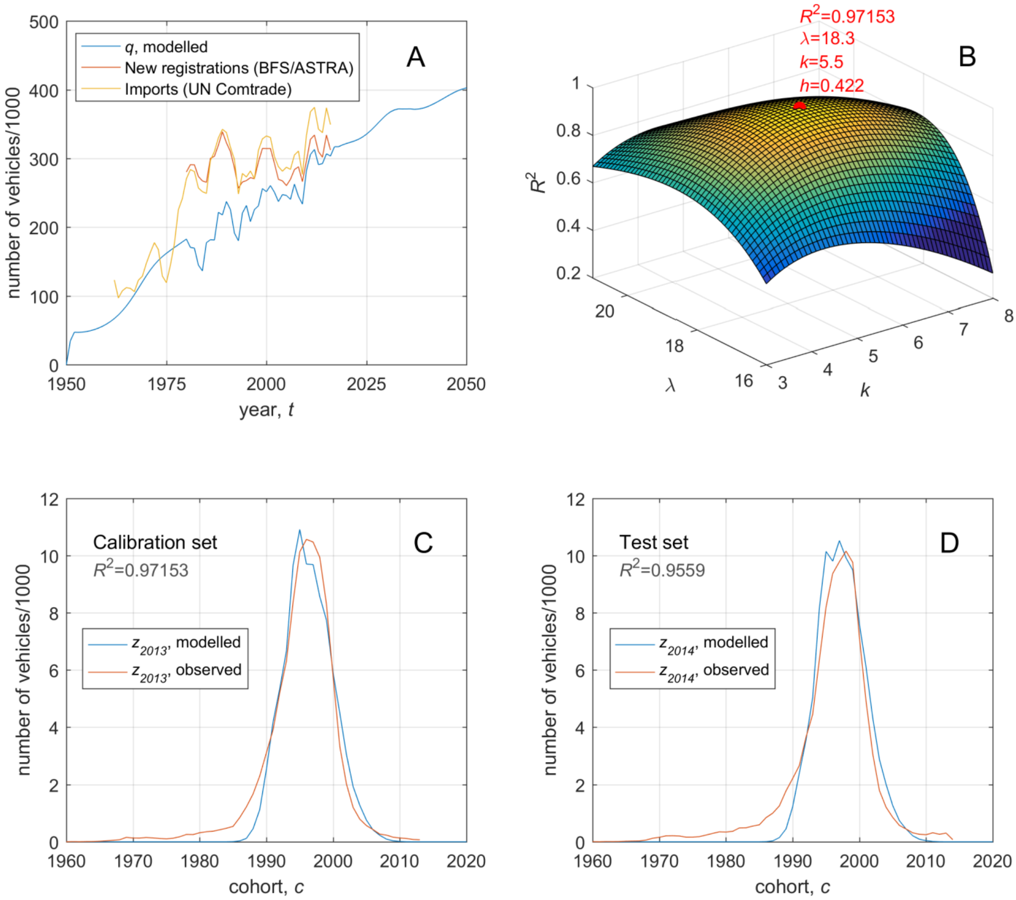

Figure S6. Dynamic MFA model calibration. A) Modelled inflow, q, compared to observed new registrations and imports. B) Coefficient of determination, R2, calculated for different values of the Weibull distribution parameters λ and k, with h fixed at 0.422. Best fit shown in red. C) Modelled numbered of ELVs treated in Switzerland in 2013 (blue) compared to the observed number of ELVs treated in 2013 (orange), by cohort. D) Modelled numbered of ELVs treated in Switzerland in 2014 (blue) compared to the observed number of ELVs treated in 2014 (orange), by cohort.

1.6. Model results: inflow, stock and end-of-life (EoL) flow of cars (number of cars) 1975-2015

Table S3. Inflow, stock and EoL flow of cars (number of cars) by calculation year.

Calculation year	Inflow	Stock	EoL flow
1975	119 590	1 781 139	24 520
1976	144 767	1 886 431	25 836
1977	176 273	1 992 366	27 310
1978	225 609	2 098 349	29 006
1979	241 877	2 203 786	30 956
1980	280 452	2 308 095	33 169
1981	291 066	2 394 455	35 639
1982	290 890	2 473 318	38 347
1983	273 886	2 520 610	41 262
1984	267 488	2 552 132	44 337
1985	265 467	2 617 164	47 515
1986	300 170	2 678 911	50 726
1987	303 302	2 732 720	53 896
1988	319 406	2 819 548	56 949
1989	338 969	2 895 842	59 814
1990	322 974	2 985 397	62 432
1991	310 193	3 057 798	64 756
1992	286 289	3 091 228	66 755
1993	256 917	3 109 523	68 414
1994	265 892	3 165 042	69 733
1995	267 975	3 229 176	70 728
1996	272 214	3 268 093	71 438
1997	270 625	3 323 455	71 930
1998	295 165	3 383 307	72 312
1999	314 691	3 467 311	72 729
2000	314 482	3 545 247	73 354
2001	314 580	3 629 713	74 356
2002	293 034	3 700 951	75 850
2003	269 711	3 753 890	77 849
2004	267 476	3 811 351	80 240
2005	260 682	3 861 442	82 798
2006	269 748	3 900 014	85 250
2007	283 972	3 955 787	87 365
2008	287 971	3 989 811	89 032
2009	266 478	4 009 602	90 288
2010	296 597	4 075 825	91 298
2011	327 955	4 163 003	92 288
2012	334 045	4 254 725	93 459
2013	310 154	4 320 885	94 915
2014	301 942	4 384 490	96 630
2015	334 204	4 458 069	98 475

2. Penetration of ABS and ESC systems

We fitted logistic functions (see Equation 14 above) to the penetration values of the ABS and ESC between 2001 and 2015 estimated by (Restrepo et al 2019) in order to obtain penetration curves for the whole calculation period (1950 - 2015). To capture the introduction trends of the ABS we collected additional data points before 2001 from (Edgar 2014) and performed two logistic regressions in this case: One for the increasing part of the penetration curve and one for the decreasing part of it. The resulting penetration curves for the ABS and ESC for the period 1975 – 2015 are shown in Figure S7. The data to create the figure are presented in Table S4.

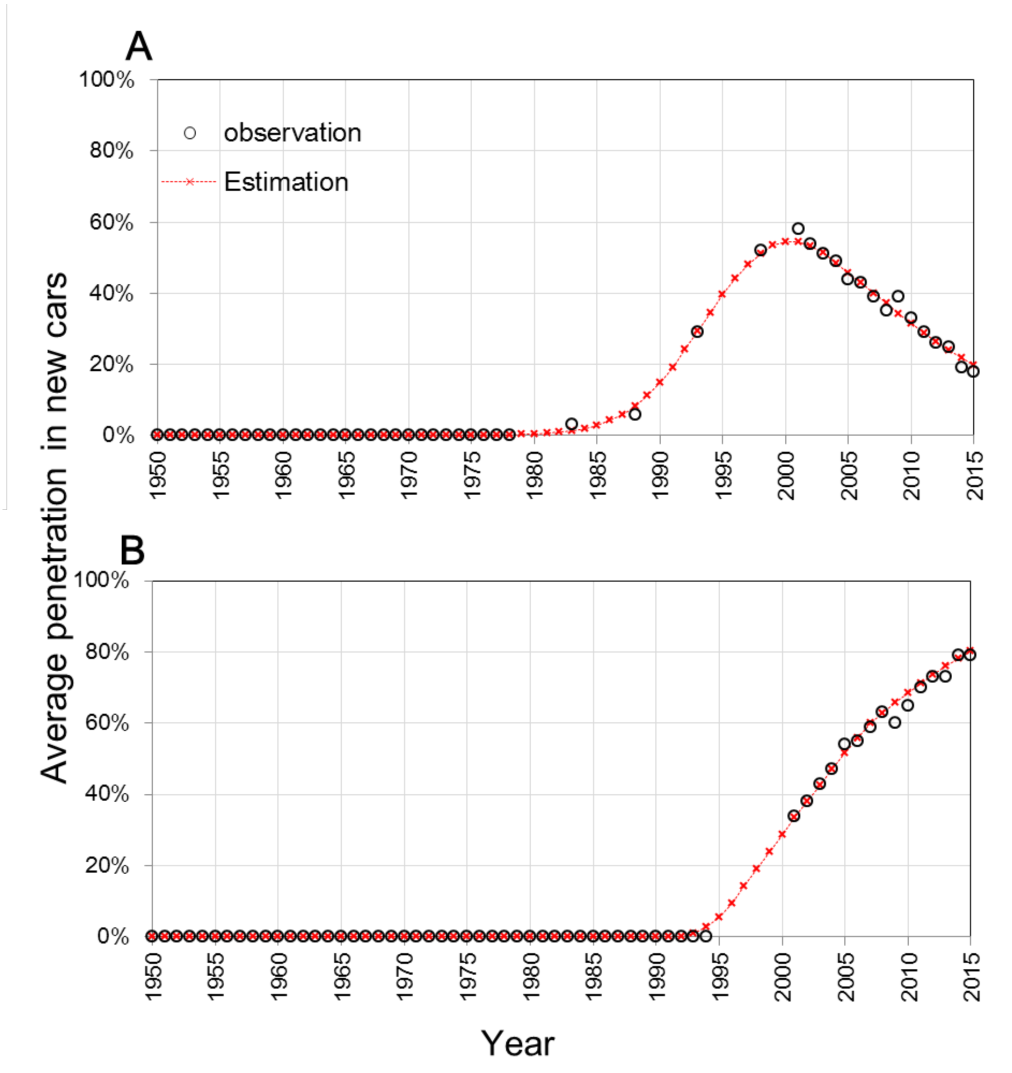

Figure S7. Historical penetration of the ABS (panel A) and ESC (panel B) systems.

Table S4. Penetration of the ABS and ESC systems. Values range from 0 to 1 (0 to 100% penetration in new cars).

Cohort year	ABS penetration		ESC penetration	
	Observation	Estimation	Observation	Estimation
1950-1977	-	-	-	-
1978	0.002	0.002	-	-
1979	NA	0.003	-	-
1980	NA	0.005	-	-
1981	NA	0.01	-	-
1982	NA	0.01	-	-
1983	0.03	0.01	-	-
1984	NA	0.02	-	-
1985	NA	0.03	-	-
1986	NA	0.04	-	-
1987	NA	0.06	-	-
1988	0.06	0.08	-	-
1989	NA	0.11	-	-
1990	NA	0.15	-	-
1991	NA	0.19	-	-
1992	NA	0.24	-	-
1993	0.29	0.29	-	0.01
1994	NA	0.35	-	0.03
1995	NA	0.40	NA	0.06
1996	NA	0.44	NA	0.09
1997	NA	0.48	NA	0.14
1998	0.52	0.51	NA	0.19
1999	NA	0.54	NA	0.24
2000	NA	0.55	NA	0.29
2001	0.58	0.54	0.34	0.33
2002	0.54	0.53	0.38	0.38
2003	0.51	0.51	0.43	0.43
2004	0.49	0.48	0.47	0.47
2005	0.44	0.46	0.54	0.52
2006	0.43	0.43	0.55	0.56
2007	0.39	0.40	0.59	0.60
2008	0.35	0.37	0.63	0.63
2009	0.39	0.34	0.60	0.66
2010	0.33	0.31	0.65	0.69
2011	0.29	0.29	0.70	0.71
2012	0.26	0.26	0.73	0.74
2013	0.25	0.24	0.73	0.76
2014	0.19	0.22	0.79	0.78
2015	0.18	0.20	0.79	0.80

3. Unit mass of ABS and ESC actuator assemblies

For the estimation of the unit mass of the assemblies we first collected manufacturers' data on the unit mass of state-of-the-art actuators, meaning the mass of the latest actuator technologies introduced to the market in a specific cohort. These values served as reference for estimating the unit mass of the assemblies by car mass category, which was done in collaboration with an industry expert (Loritz 2019). The estimated actuator assembly mass was later validated and corrected with measurements of the mass of the actuator assembly in Swiss ELVs.

3.1. Manufacturers' data

Due to the high market share of ABS and ESC actuators manufactured by Bosch, e.g., larger than 50% for the ABS actuator (European Commission 2019), we assumed that the unit mass values for the assemblies manufactured by this company were representative for the state-of-the-art assemblies in the model. Most of the manufacturers' data in this step thus comes from publically available information from Bosch (Ebber 2014, BOSCH 2019, Robert Bosch GmbH 2014, 2019b, 2019a). Additional data points from anonymous manufacturers were gathered from Edgar (2014). The collected data are presented in Table S5.

Table S5. Manufacturer's data on the mass of ABS and ESC actuator assemblies. Values in kilograms.

Year	ABS actuator assembly mass/kg	Source for ABS data	ESC actuator assembly mass/kg	Source for ESC data
1978	6.2	(Edgar 2014)		
1989	4.9	(Robert Bosch GmbH 2014)		
1993	3.8	(Robert Bosch GmbH 2014)		
1995	2.6	(Robert Bosch GmbH 2014)	4.3	(Ebber 2014)
1996			3.7	(Ebber 2014)
1998			3.1	(Ebber 2014)
2001	1.4	(Robert Bosch GmbH 2014)		
2002			2.3	(Ebber 2014)
2010			1.6	(Robert Bosch GmbH 2019b)
2013	1.1	(Robert Bosch GmbH 2019a)		

3.2. Experimental data

The unit mass of the ABS actuator assemblies dismantled from 18 ELVs was measured at a Swiss ELV dismantling facility. The assemblies were dismantled manually under normal operating conditions. The name of the manufacturer of the assemblies was not recorded. The experimental ratios of actuator assembly mass over car mass (ABS_{mass}/car_{mass}) were assumed to be representative for all cars in the model and were used in the subsequent calibration of the unit mass of the actuator assemblies by car mass category and cohort as explained in section 3.3 below.

The results of the dismantling experiment are presented in Table S6. Scatter plots of the correlation between the experimental variables are presented in Figure S8. Even though the mass of the actuator assembly is meant to be correlated with the car mass, we did not find strong evidence of this correlation. This can be explained by a "common parts approach" of the original equipment manufacturer (OEM) in which the same type of actuator assembly is installed over a range of car types (mass categories) (Loritz 2019). Additionally, even though a lighter actuator assembly can be installed in some car types, an OEM can decide against the installation of this lighter actuator because of costs reasons: a lighter actuator is usually more expensive due to the use of more specialized materials (Loritz 2019). We also did not find correlation between the mass of the ABS actuator assembly and the dismantling time or the car cohort.

Table S6. Results of dismantling experiment for unit mass of ABS actuator assembly. The cars were dismantled in 2017.

Cohort year	Car mass/kg	ABS actuator assembly mass/kg	Dismantling time/min	ABS_{mass}/car_{mass}
2006	1880	2.2	5	0.12%
2009	1930	2.2	3	0.11%
2008	2305	2.4	25	0.10%
2007	1722	1.7	15	0.10%
2010	1470	2.5	3	0.17%
2011	2030	2.4	15	0.12%
2010	2910	2.7	2	0.09%
2012	1730	2.3	20	0.13%
2010	2040	1.9	11	0.09%
2011	2210	2.5	10	0.11%
2011	1601	2.25	7	0.14%
2013	1370	1.9	11	0.14%
2013	1530	2	4	0.13%
2014	1813	2.6	60	0.14%
2012	3000	1.95	8	0.07%
2012	1546	3	15	0.19%
2015	1660	2.4	7	0.14%
2016	1660	2.15	15	0.13%
Average	1911.5	2.3	13.1	
Mode	1660	2.4	15	
Max	3000	3	60	
Min	1370	1.7	2	

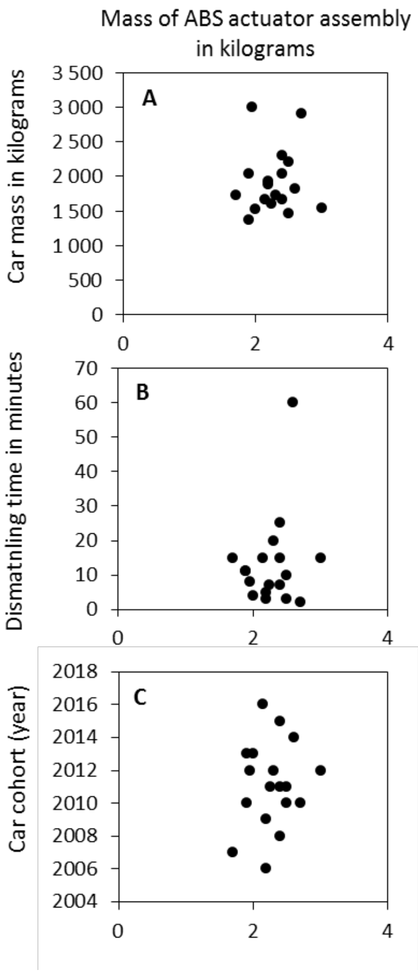

Figure S8. Scatter plots of ABS actuator assembly mass and: A) car mass, B) dismantling time, C) car cohort. No correlation can be identified.

3.3. Unit mass estimation and calibration approach

With the manufacturers' data from Table S5 and in collaboration with an industry expert (Loritz 2019) we assigned a possible mass of the ABS and ESC actuator assembly by car mass category and cohort. The term "possible mass" is used to reflect the following constraints: i) at a given point in time, a car cannot contain an ABS actuator that has not yet been offered in the market, but it can, *in theory*, contain any of the ABS actuators offered until that point in time, ii) even though possible in theory, a car *cannot* contain an actuator from any mass; the mass of the actuator corresponds to the mass of the car (Loritz 2019). The correlation between mass of actuator and car mass was however not provided by the manufacturer. We therefore assumed that the ratios of actuator assembly mass over car mass (ABS_{mass}/car_{mass}) were representative for all cars in the model and proceeded to calibrate the assigned possible unit mass as follows: For a specific mass category, whenever the ratio of possible unit mass of actuator assembly over car mass deviated from the experimental values calculated in Table S6, we reassigned another possible mass from the available options until the ratio of possible unit mass over car mass followed within the experimental values. “Available options” were those actuator assemblies that were produced until that point in time.

Once the unit mass of the ABS actuator assembly was calibrated, we proceeded to calibrate the unit mass of the ESC actuator assembly. For this estimation, we again first assigned a possible mass from the available options for ESC actuator mass by cohort and mass category. We then calibrated this by considering the following constraint: For a given cohort and mass category, the ESC actuator assembly is always heavier than the ABS actuator assembly (Loritz 2019). Additionally, we assumed that the ratio of ESC actuator assembly mass over car mass was the same as for the ABS actuator assembly ($ABS_{mass}/car_{mass} = ESC_{mass}/car_{mass}$). The possible unit mass of ESC actuator assembly was then adjusted in two ways: i) whenever it was lower than the mass of the ABS assembly for a given cohort and car mass category, we reassigned a higher ESC assembly mass form the available options, and ii) whenever the ratio of ESC_{mass}/car_{mass} deviated from the experimental values, we reassigned another possible unit mass from the available options until the ratio fell within the experimental values. The calibrated unit mass of the ABS and ESC actuator assemblies is provided in Table S7 and Table S8, respectively.

In a final step, the weighted average unit mass of the actuator assemblies by cohort was calculated as the sum of the product of the calibrated unit mass (in Table S7 and Table S8) and the share of cars by mass category (in Table S2) over the respective car cohort. The weighted average unit masses of the ABS and ESC actuators by car cohort and mass category are presented in Table S9 and Table S10, respectively.

Table S7. Calibrated possible mass of ABS actuator by car cohort and mass category. The gray shade indicates, from darker to lighter, the heaviest and lightest mass of ABS actuator assemblies.

Cohort year	Calibrated possible mass of ABS actuator assembly by mass category /kg					
	<1249	1250-1499	1500-1749	1750-1999	2000-2249	>2250
1975						
1976						
1977						
1978	6.20	6.20	6.20	6.20	6.20	6.20
1979	6.20	6.20	6.20	6.20	6.20	6.20
1980	6.20	6.20	6.20	6.20	6.20	6.20
1981	6.20	6.20	6.20	6.20	6.20	6.20
1982	6.20	6.20	6.20	6.20	6.20	6.20
1983	6.20	6.20	6.20	6.20	6.20	6.20
1984	6.20	6.20	6.20	6.20	6.20	6.20
1985	6.20	6.20	6.20	6.20	6.20	6.20
1986	6.20	6.20	6.20	6.20	6.20	6.20
1987	6.20	6.20	6.20	6.20	6.20	6.20
1988	6.20	6.20	6.20	6.20	6.20	6.20
1989	4.90	4.90	4.90	4.90	4.90	4.90
1990	4.90	4.90	4.90	4.90	4.90	4.90
1991	4.90	4.90	4.90	4.90	4.90	4.90
1992	4.90	4.90	4.90	4.90	4.90	4.90
1993	3.80	3.80	3.80	3.80	3.80	3.80
1994	3.80	3.80	3.80	3.80	3.80	3.80
1995	2.60	2.60	2.60	2.60	2.60	2.60
1996	2.60	2.60	2.60	2.60	2.60	2.60
1997	2.60	2.60	2.60	2.60	2.60	2.60
1998	2.60	2.60	2.60	2.60	2.60	2.60
1999	2.60	2.60	2.60	2.60	2.60	2.60
2000	2.60	2.60	2.60	2.60	2.60	2.60
2001	1.40	1.40	2.60	2.60	2.60	2.60
2002	1.40	1.40	2.60	2.60	2.60	2.60
2003	1.40	1.40	2.60	2.60	2.60	2.60
2004	1.40	1.40	2.60	2.60	2.60	2.60
2005	1.40	1.40	2.60	2.60	2.60	2.60
2006	1.40	1.40	2.60	2.60	2.60	2.60
2007	1.40	1.40	2.60	2.60	2.60	2.60
2008	1.40	1.40	2.60	2.60	2.60	2.60
2009	1.40	1.40	2.60	2.60	2.60	2.60
2010	1.40	1.40	2.60	2.60	2.60	2.60
2011	1.40	1.40	2.60	2.60	2.60	2.60
2012	1.40	1.40	2.60	2.60	2.60	2.60
2013	1.10	1.40	2.60	2.60	2.60	2.60
2014	1.10	1.40	2.60	2.60	2.60	2.60
2015	1.10	1.40	2.60	2.60	2.60	2.60

Table S8. Calibrated possible mass of ESC actuator assembly by car cohort and mass category. The gray shade indicates, from darker to lighter, the heaviest and lightest mass of ESC actuator assemblies.

Cohort year	Calibrated possible mass of ESC actuator assembly by mass category /kg					
	<1249	1250-1499	1500-1749	1750-1999	2000-2249	>2250
1975						
1976						
1977						
1978						
1979						
1980						
1981						
1982						
1983						
1984						
1985						
1986						
1987						
1988						
1989						
1990						
1991						
1992						
1993						
1994						
1995	4.30	4.30	4.30	4.30	4.30	4.30
1996	3.70	3.70	3.70	3.70	3.70	3.70
1997	3.70	3.70	3.70	3.70	3.70	3.70
1998	3.10	3.10	3.10	3.10	3.10	3.70
1999	3.10	3.10	3.10	3.10	3.10	3.70
2000	3.10	3.10	3.10	3.10	3.10	3.70
2001	3.10	3.10	3.10	3.10	3.10	3.70
2002	2.30	2.30	3.10	3.10	3.10	3.70
2003	2.30	2.30	3.10	3.10	3.10	3.70
2004	2.30	2.30	3.10	3.10	3.10	3.70
2005	2.30	2.30	3.10	3.10	3.10	3.70
2006	2.30	2.30	3.10	3.10	3.10	3.70
2007	2.30	2.30	3.10	3.10	3.10	3.70
2008	2.30	2.30	3.10	3.10	3.10	3.70
2009	2.30	2.30	3.10	3.10	3.10	3.70
2010	1.60	1.60	3.10	3.10	3.10	3.70
2011	1.60	1.60	3.10	3.10	3.10	3.70
2012	1.60	1.60	3.10	3.10	3.10	3.70
2013	1.60	1.60	3.10	3.10	3.10	3.70
2014	1.60	1.60	3.10	3.10	3.10	3.70
2015	1.60	1.60	3.10	3.10	3.10	3.70

Table S9. Weighted average mass of the ABS actuator assembly by car cohort and mass category. The gray shade indicates, from dark to light, the heaviest and lightest mass of ABS actuator assemblies.

Cohort year	Average mass of ABS actuator assembly by mass category /kg						Weighted average /kg
	<1249	1250-1499	1500-1749	1750-1999	2000-2249	>2250	
1975	-	-	-	-	-	-	-
1976	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-
1978	1.40	1.62	0.71	0.93	0.96	0.59	6.20
1979	0.93	1.71	0.95	0.98	1.02	0.61	6.20
1980	1.22	1.30	1.15	1.17	0.82	0.55	6.20
1981	1.17	1.59	1.37	1.12	0.51	0.45	6.20
1982	0.98	1.78	1.46	1.25	0.37	0.35	6.20
1983	0.87	2.26	1.28	0.98	0.35	0.46	6.20
1984	0.99	2.06	1.53	0.76	0.34	0.52	6.20
1985	0.95	1.91	1.51	0.78	0.29	0.75	6.20
1986	0.98	1.70	1.74	0.86	0.40	0.53	6.20
1987	0.92	1.43	1.74	1.04	0.51	0.56	6.20
1988	0.35	1.57	1.83	1.25	0.57	0.64	6.20
1989	0.22	1.27	1.51	0.99	0.44	0.48	4.90
1990	0.41	1.20	1.47	0.86	0.46	0.50	4.90
1991	0.45	1.29	1.29	0.92	0.50	0.46	4.90
1992	0.48	1.00	1.50	0.96	0.49	0.47	4.90
1993	0.36	0.66	1.24	0.73	0.36	0.44	3.80
1994	0.25	0.65	1.32	0.89	0.33	0.36	3.80
1995	0.09	0.55	0.86	0.63	0.22	0.25	2.60
1996	0.07	0.66	0.80	0.63	0.21	0.24	2.60
1997	0.06	0.59	0.78	0.69	0.21	0.26	2.60
1998	0.06	0.50	0.79	0.80	0.22	0.24	2.60
1999	0.08	0.43	0.74	0.86	0.25	0.25	2.60
2000	0.10	0.43	0.72	0.82	0.27	0.25	2.60
2001	0.04	0.22	0.63	0.83	0.41	0.26	2.38
2002	0.04	0.19	0.69	0.76	0.47	0.26	2.41
2003	0.03	0.17	0.66	0.76	0.48	0.33	2.43
2004	0.03	0.17	0.56	0.78	0.51	0.38	2.43
2005	0.02	0.16	0.55	0.74	0.58	0.39	2.44
2006	0.04	0.13	0.56	0.67	0.63	0.43	2.46
2007	0.04	0.11	0.54	0.68	0.62	0.48	2.47
2008	0.04	0.14	0.52	0.64	0.64	0.47	2.45
2009	0.04	0.15	0.53	0.64	0.61	0.47	2.44
2010	0.03	0.14	0.53	0.62	0.65	0.47	2.45
2011	0.03	0.13	0.55	0.59	0.65	0.52	2.47
2012	0.02	0.12	0.49	0.58	0.66	0.60	2.48
2013	0.02	0.09	0.54	0.67	0.61	0.57	2.50
2014	0.02	0.08	0.54	0.68	0.61	0.58	2.51
2015	0.02	0.07	0.53	0.65	0.63	0.61	2.51

Table S10. Weighted average mass of the ESC actuator assembly by car cohort and mass category. The colors indicate, from darker to lighter, the heaviest and lightest mass of ESC actuator assemblies.

Cohort year	Average mass of ESC actuator assembly by mass category /kg						Weighted average /kg
	<1249	1250-1499	1500-1749	1750-1999	2000-2249	>2250	
1975	-	-	-	-	-	-	-
1976	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-
1984	-	-	-	-	-	-	-
1985	-	-	-	-	-	-	-
1986	-	-	-	-	-	-	-
1987	-	-	-	-	-	-	-
1988	-	-	-	-	-	-	-
1989	-	-	-	-	-	-	-
1990	-	-	-	-	-	-	-
1991	-	-	-	-	-	-	-
1992	-	-	-	-	-	-	-
1993	-	-	-	-	-	-	-
1994	-	-	-	-	-	-	-
1995	0.15	0.90	1.42	1.05	0.36	0.42	4.30
1996	0.09	0.94	1.14	0.89	0.29	0.34	3.70
1997	0.09	0.84	1.11	0.99	0.30	0.37	3.70
1998	0.07	0.59	0.94	0.95	0.26	0.34	3.16
1999	0.10	0.51	0.88	1.02	0.29	0.35	3.16
2000	0.12	0.52	0.86	0.98	0.32	0.36	3.16
2001	0.09	0.48	0.75	0.99	0.49	0.37	3.16
2002	0.06	0.31	0.82	0.91	0.56	0.37	3.03
2003	0.06	0.28	0.78	0.90	0.57	0.46	3.06
2004	0.04	0.29	0.67	0.93	0.61	0.54	3.07
2005	0.04	0.26	0.66	0.88	0.69	0.55	3.08
2006	0.07	0.21	0.66	0.80	0.76	0.61	3.10
2007	0.07	0.18	0.64	0.81	0.74	0.69	3.13
2008	0.07	0.23	0.62	0.77	0.76	0.66	3.11
2009	0.07	0.24	0.64	0.76	0.73	0.66	3.10
2010	0.04	0.17	0.64	0.74	0.77	0.67	3.02
2011	0.03	0.14	0.66	0.71	0.77	0.74	3.06
2012	0.02	0.14	0.58	0.69	0.79	0.86	3.08
2013	0.02	0.11	0.64	0.80	0.72	0.81	3.11
2014	0.02	0.09	0.65	0.81	0.73	0.83	3.13
2015	0.03	0.08	0.63	0.78	0.75	0.87	3.14

4. Additional results

Figure S9 shows that the combined stock of ABS and ESC actuator assemblies in 2015 was around 12 000 t (red-dotted line). The peak mass stock of ABS actuator assemblies occurred in 2008 and it was equal to around 4 600 t. In 2015, virtually all of the heavy ABS actuator assemblies (> 3 kg) had left the stock of cars. After 1995, the stock of ABS and ESC actuator assemblies has been dominated by light actuators (≤ 3.1 kg).

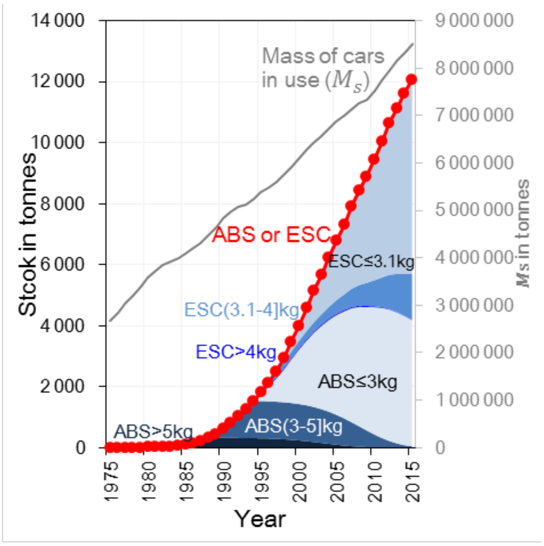

Figure S9. Stock of ABS and ESC actuator assemblies, Switzerland 1975-2015. The blue wedges represent the stock of different generations of actuator assemblies; values are provided on the left-hand axis. The red-dotted line represents the combined stock of actuator assemblies. The total mass of cars in use is represented by the gray line; values are provided in the right-hand y-axis.

Figure S10 shows that the combined EoL mass flow of actuator assemblies has been considerably smaller than the inflow for the whole calculation period. For example, the EoL mass flow of actuator assemblies in 2015 was about 20% of the mass inflow in the same year. This reflects, primarily, the time delay between inflow and EoL flow. Another important factor contributing to the reduced EoL flow is the large export of cars, which is currently more than half of the total outflow of de-registered cars.

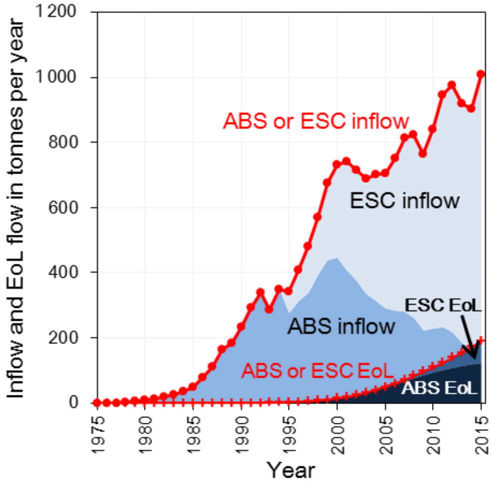

Figure S10. Mass inflow and EoL mass flow of ABS and ESC actuator assemblies, Switzerlnad 1975-2015. Part of the area representing the inflow is hidden behind the EoL flow.

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Eliette Restrepo

Improving the Recovery of Critical Metals from End of Life Vehicles

Doctoral Thesis

Eliette Restrepo

ISBN 978-82-326-4532-9 (printed version)
ISBN 978-82-326-4533-6 (electronic version)
ISSN 1503-8181

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