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

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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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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

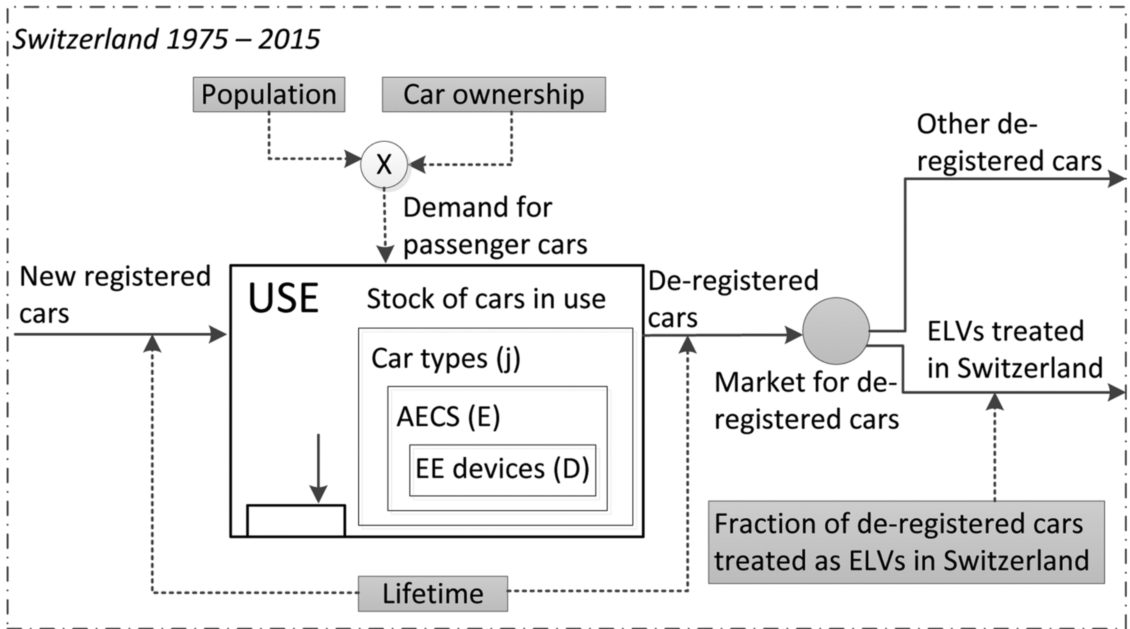


**Fig. 1.** Passenger car model and drivers considered in the analysis. The *use* phase shows the nested structure of car electronics, i.e.: cars contain automobile electronic control systems (AECS) E, which in turn contain electric and electronic (EE) devices D. The parameters of the stock-driven dynamic 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

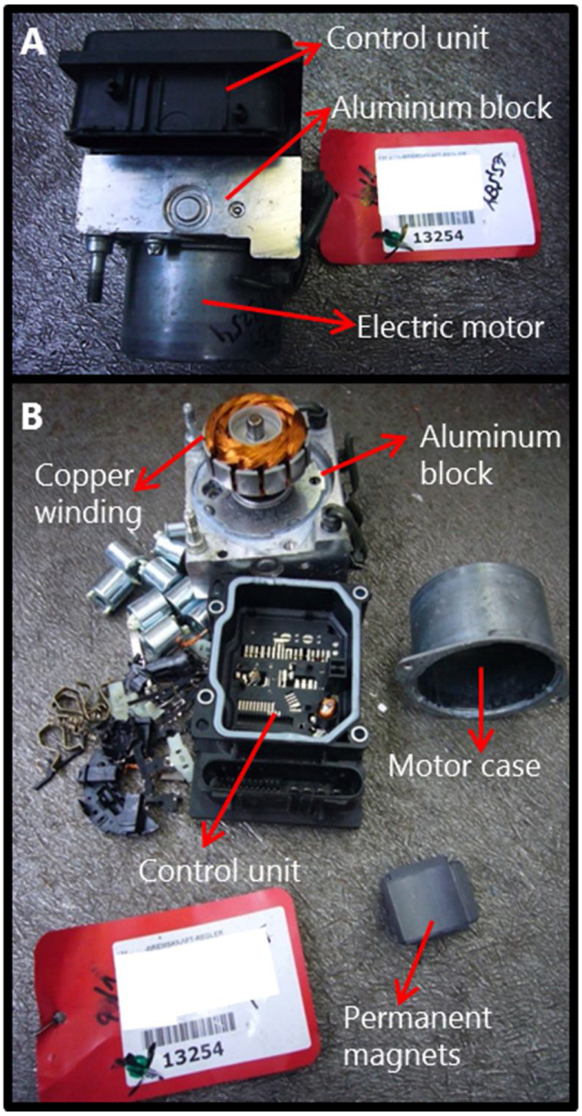


**Fig. 2.** ABS actuator assembly, the ESC assembly has a similar configuration. A) Overview, B) Disassembled actuator. Car's cohort year: 2006. Mass of complete assembly as in panel A: 1.6 kg. Photos and measurements by the author.

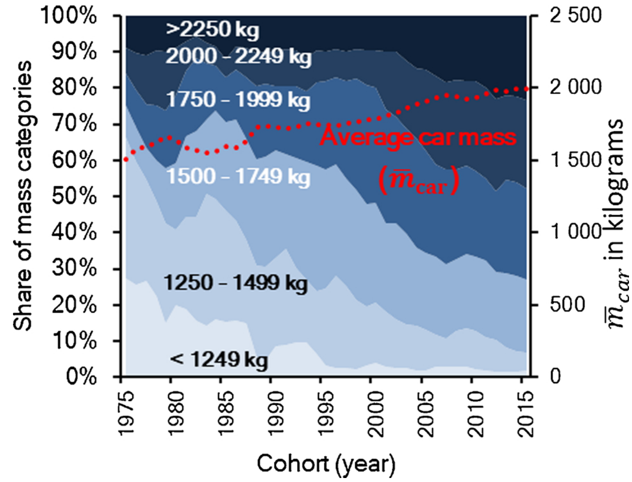


**Fig. 3.** Share of cars by mass category and cohort. The share of cars (%) in each category is provided in the left-hand y-axis. The average car mass ($\bar{m}_{car}$) by cohort is represented by the red dotted line; the mass values are provided in the right-hand y-axis. Figure data are provided in 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.)

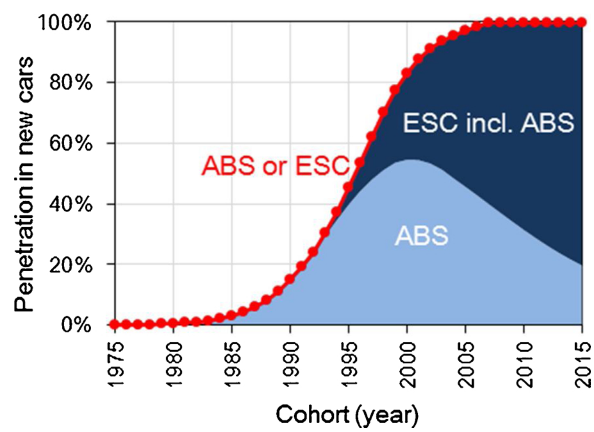


**Fig. 4.** Average penetration of the ABS and ESC systems by cohort. Since each control system contains only one actuator assembly, the penetrations values also correspond to those of their respective actuator assemblies. The time series are provided in SI, Table S4.

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

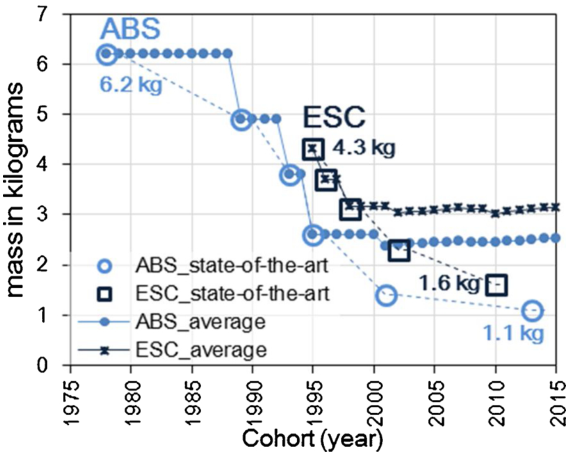


**Fig. 5.** Unit mass of the ABS and ESC actuator assembly by cohort. The light-blue circles and the dark-blue squares represent the unit mass of the state-of-the-art actuator ABS and ESC assemblies, respectively, as obtained from manufactures' data. Dashed lines are provided in both cases to guide the 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.)

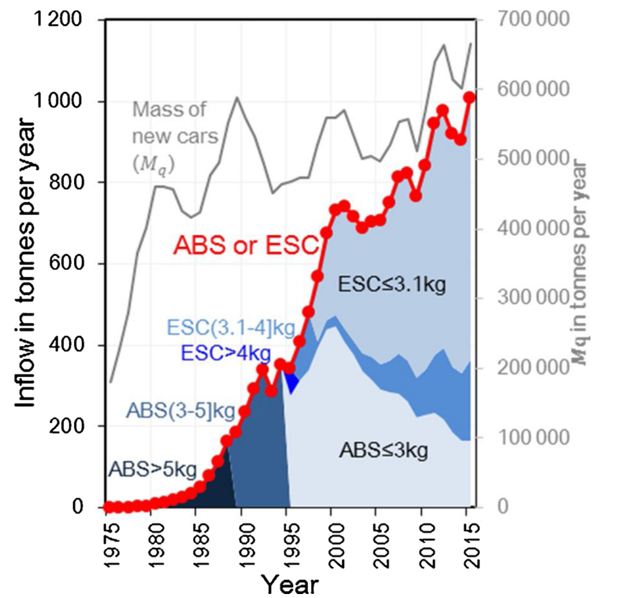


**Fig. 6.** Mass inflow of ABS and ESC actuator assemblies, Switzerland 1975–2015. The red-dotted line represents the combined inflow of actuator assemblies and the blue wedges represent the inflow of different generations of actuator assemblies; values are provided on the left-hand axis. The total mass 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.)

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

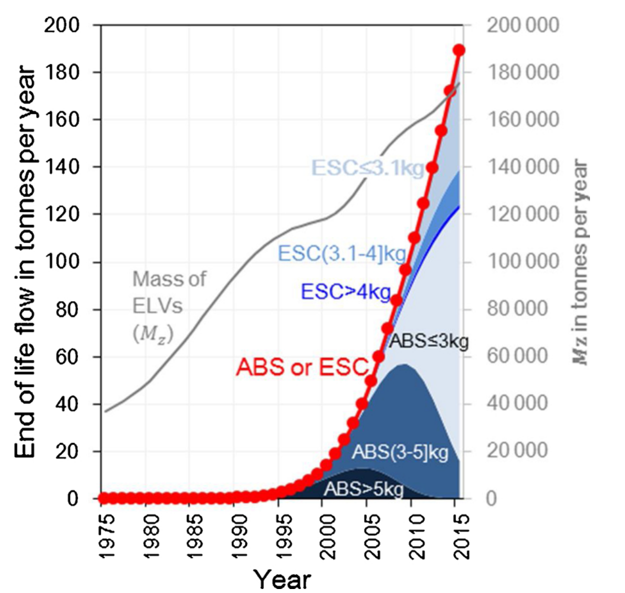


**Fig. 7.** End-of-life (EoL) mass flow of ABS and ESC actuator assemblies, Switzerland 1975–2015. The red-dotted line represents the combined EoL flow of actuator assemblies and the blue wedges represent the EoL flow of different generations of actuator assemblies; values are provided on the left-hand 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.)

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:

$$C = \frac{c}{m} \tag{3}$$

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.

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## 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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