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Plastics in passenger cars

A comparison over types and time

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In cooperation with : Volvo Cars

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Summary

This study was conducted as part of the project Explore – Exploring the opportunities for advancing vehicle recycling industrialization in the research program Closing the loop, funded by Mistra - The Swedish Foundation for Strategic Environmental Research. One of the goals of Explore is to analyze the Swedish future vehicle fleet's material content and its implication for adapting the recycling system. One of the research questions concerns how material flows entering and exiting the vehicle fleet may evolve over the next decades considering various technology trends. This report covers the content of polymer materials in light passenger cars. The results will be used in explorative scenarios of the Swedish future vehicle fleet but is also of general interest and thus reported separately. In the study, a set of data on polymer materials in passenger cars relevant for the Swedish market was compiled and analyzed. The analysis aimed to clarify the quantity of polymer materials in absolute and relative terms (kilograms and percent, respectively) as well as the distribution over polymer types. In addition, the analysis also aimed at clarifying if polymer materials in cars vary with weight class, power train and production year.

Data was compiled from a2mac1, Volvo Cars, and a literature study. A2mac1 is a company with a commercial data base for cars. It supports the automotive industry with detailed data on material compositions and several other parts and component analyses. It holds full vehicle teardown data for over 700 car models at the time of writing this report. It is widely used in the automotive industry to provide data on competitor's car technologies and for general benchmarking purposes. The a2mac1 teardown data is generated through dismantling of the entire vehicle and documentation of each of the parts. For the material data, the amount of plastic and elastomer material in each material categories were summed up, but for some material categories the weight share of plastic and elastomer material had to be predicted. Primarily, data on cars that are representative for the current Swedish fleet was extracted from a2mac1. In total 44 models, ranging from production years between 2003 and 2018, were analyzed. Out of these, four models were reported over several production years. The summed plastic and elastomer weights were then compared with each other and to data found in literature. The data from the a2mac1 cars was compared in terms of production year, powertrain, and weight class.

The a2mac1 data was compared to data from Volvo cars Bill of Materials (BOM) that originates from supplier information for each car part. The International Material Data System (IMDS) categories are used for these parts and substances, which is different from the categories for a2mac1. The Volvo data in this study represents six Volvo passenger car models produced in 2018. Volvo and a2mac1 had different material categories, which is why it was necessary to define polymeric material for each and estimate the weight shares of plastic and elastomer material for each material category based on the information given.

The literature study showed many variables affecting the use of plastics and elastomers in cars. Some examples are the material properties, the price of plastics and substituting materials, the oil price, production costs and legislation.

In the a2mac1 files, some material categories were reported at the component level or with substantial shares of unknown materials, for example electric components. In order not to exclude the polymers in such categories from the study, the amounts of plastic and elastomer material in those categories were estimated. The challenges of distinguishing general material categories into more specific materials (ex. amount of plastics in the category 'several components'), or general polymer categories into more specific plastic categories (ex. 'other plastics' into Polypropylene) or

distinguishing the plastics' structure (ex. thermoplastic vs. thermoset Polyurethane) became a limiting factor for both the accuracy of the final data and the types of conclusions that could be drawn. It may also be relevant for other data reported in literature but cannot be confirmed since few studies specify how data was obtained and what choices regarding material categories were made.

The a2mac1 results showed that the polymer shares in selected cars were similar for all data sources analysed, regardless of production year, powertrain, or weight class. We did not observe any significant difference between weight classes, powertrains nor over time for the selected vehicles. When we compared car models in series, we did not note any increasing or decreasing trends in the five cars models we looked at. Compared to the Volvo BOMs, the a2mac1 cars were within the same range (about 20 percent) of plastic material, but with a much larger spread. The Volvo cars had plastic and polymer weight shares that were very similar to each other.

Our a2mac1 results suggest that the trends of increasing polymeric material weight shares reported from the middle of the 1950s up to year 2000 is no longer occurring, and that there is a constant trend (neither increasing nor decreasing) from 2000-2018, regardless of the powertrain. Our percentages were in a similar range as the literature. The values that we calculated from the a2mac1 cars was a share of 16-21 percent for plastics content and a share of 16-23 percent for the elastomers. These percentages did not include tires, batteries or liquids as they represent the after-pre-treatment weight of the cars. From the data results from a2mac1 and from interaction with industry professionals, we conclude that the typical Swedish car produced up until around 2025 the share of plastics and elastomers is likely to remain relatively constant.

We saw some trends towards the use of more thermoplastic vulcanizate, thermoplastic elastomer (TPV; TPE) and acrylonitrile-butadiene-styrene (ABS) plastics in battery electric vehicles (BEVs) than in other powertrains. Ethylene-propylene-diene monomer (EPDM) appeared to be more common in gasoline and diesel cars. Polypropylene (PP) was very common in all cars, as was polyurethane (PUR). Other common plastics and elastomers were polyamide (PA), polyethylene (PE), polybutylene terephthalate; polyethylene terephthalate (PBT; PET). Neither from literature nor from information given by industry professionals, there are no indications of a forthcoming significant switch to fibre-reinforced plastic composites for the average light-duty car.

Sammanfattning

Denna studie gjordes som en del av projektet Explore - Exploring the opportunities for advancing the vehicle recycling industrialization i forskningsprogrammet Closing the loop, finansierat av Mistra. Ett av målen med Explore är att analysera den svenska framtida fordonsflottans materielinnehåll och dess konsekvenser för att anpassa återvinningssystemet. En av frågorna handlar om hur material som strömmar in och ut ur fordonsflottan kan utvecklas under de närmaste årtiondena med tanke på olika tekniktrender. Denna rapport täcker innehållet av polymermaterial i lätta personbilar. Resultaten kommer att användas i explorativa scenarier av den svenska framtida fordonsflottan men är också av allmänt intresse och rapporteras därmed separat. I studien sammanställdes och analyserades en uppsättning data om polymera material i personbilar relevanta för den svenska marknaden. Analysen syftade till att klargöra kvantiteten polymermaterial i absoluta och relativa termer (kg respektive procent) samt fördelningen över polymertyper. Dessutom syftar analysen också till att klargöra huruvida polymera material i bilar varierar med viktklass, drivlina och produktionsår.

Data sammanställdes från a2mac1, Volvo Cars och en litteraturstudie. A2mac1 är ett företag med en kommersiell databas för bilar. Den stöder bilindustrin med detaljerade uppgifter om materialkompositioner och flera andra delar och komponentanalyser. Den innehåller fullständiga materialnedbrytningar för över 700 bilmodeller när rapporten skrevs. Verktyget används allmänt inom bilindustrin för att tillhandahålla data om konkurrenternas biltekniker och för allmän benchmarking. A2mac1 data genereras genom demontering av hela fordonet och dokumentationen av var och en av delarna. För materialdata sammanfattades mängden plast- och elastomer-material i varje materialkategori, men för vissa materialkategorier var andelen plast och elastomer uppskattade. För det första extraherades data om bilar som är representativa för den nuvarande svenska flottan från a2mac1. Totalt analyserades 44 modeller, alla från produktionsår mellan 2003 och 2018. Av dessa rapporterades fyra modeller över flera produktionsår. De summerade plast- och elastomervikterna jämfördes sedan med varandra och med litteraturdata. Uppgifterna från a2mac1-bilarna jämfördes med avseende på produktionsår, drivlinor och viktklass.

A2mac1 data jämfördes med Volvo Bill of Materials (BOM) från leverantörsinformation inlämnad för varje bildel. IMDS (International Material Data System) kategorier används för dessa delar och ämnen, vilket skiljer sig från kategorierna för a2mac1. Volvos data i den här studien representerar sex Volvo-personbilar som producerades 2018. Volvo och a2mac1 hade olika materialkategorier, varför det var nödvändigt att definiera polymera material för varje och uppskatta procenten av plast och elastomer för varje materialkategori baserat på den information som fanns tillgänglig.

Litteraturstudien visade att många variabler påverkar användningen av plast och elastomer i bilar. Några exempel är materialegenskaperna, priset på substituerande material, oljepriset, produktionskostnader och lagstiftning.

I a2mac1-filerna rapporterades några materialkategorier på komponentnivå med stora andelar av okända material, till exempel elektriska komponenter. För att inte utesluta polymererna i sådana kategorier från studien uppskattades mängderna av plast och elastomer i dessa kategorier. Utmaningarna att särskilja allmänna materialkategorier i mer specifika material (ex. Mängd plast i kategorin "flera komponenter") eller allmänna polymerkategorier i mer specifika plastkategorier (t.ex. "annan plast" i polypropen) eller särskilja plasten " struktur ” (ex. termoplastisk mot härdad polyuretan) blev en begränsande faktor för både noggrannheten hos slutdata och de typer av

slutsatser som kunde dras. Det kan också vara relevant för andra data som rapporteras i litteraturen men kan inte bekräftas eftersom få studier specificerar hur data erhölls och vilka val av materialkategorier som gjordes.

Resultaten visade att polymerfraktionerna (i procent av den totala massan av plast och / eller elastomer) av summan av plast och elastomer var lika för alla analyserade datakällorna oavsett produktionsår, drivlina eller viktklass. Vi observerade inte någon markant skillnad mellan viktklasser, drivlina eller över tiden för fordonet a2mac1. När vi jämförde bilmodeller i serie såg vi inte några noterbara uppåt- eller nedåtgående trender för de fem bilmodellerna vi observerade. Jämfört med Volvo BOM:arna var de två bilarna inom samma område (ca 20 procent) av plastmaterialinnehåll, men med en mycket större spridning. Volvos bilar hade plast- och polymerhalter som var väldigt lika varandra.

Våra a2mac1-resultat tyder på att den rapporterade ökningen av polymermaterial som från cirka 1950 fram till år 2000 inte längre sker, och att en konstant (varken stigande eller sjunkande) trend ägde rum 2000–2018 för bilflottan, oavsett drivlinan. Våra procentsatser var inom ett liknande intervall som för litteraturen. Värdena för plastinnehåll som vi beräknat från a2mac1-bilarna var 16–21 procent och för elastomer var dom 16–23 procent. Dessa procentsatser omfattade inte däck, batterier eller vätskor eftersom de inte är inkluderade i bilens efterbehandlingsvikt. Utifrån resultaten från a2mac1 och från email och konversationer med branschpersonal så drar vi slutsatsen att den typiska svenska bilen som är producerad fram till omkring 2025 inte kommer att få någon signifikant ökning eller minskning av dess procenthalt av plaster och elastomer.

Vi såg några trender mot användningen av mer termoplastisk vulkanisatplast; termoplastisk elastomer (TPV;TPE) och akrylnitril- butadien- styre-monomer (ABS) i elbilar (BEV) än i andra drivlinor. Etenpropengummi (EPDM) tycktes vara vanligare i bensin- och dieseldrivna bilar. Polypropylen (PP) var mycket vanligt i alla bilar, liksom polyuretan (PUR). Andra vanliga plast- och elastomerkategorier var polyamid (PA), polyeten (PE), polybutentereftalat; polyetentereftalat (PBT; PET). Från litteraturen finns inga tecken på ett stort skifte till fiberförstärkta plastkompositer för lätta bilar.

Term or Abbreviation	Definition
After-pre-treatment weight	Weight of the vehicles without the parts that are removed before dismantling and shredding; i.e. the car weight without the batteries, tires, and liquids. The catalyst is usually removed, but it is relatively light-weight and is included in the weights of cars in our results.
BOM	Bill of Materials – A list of, amongst other information, the weights of each part of a vehicle model.
Curb Weight	Stated total car weight in the a2mac1 files, or the sum of the weights (including batteries, tires, and liquids) for the Volvo BOMs. We use the definition of curb weight without the weight of the weight of the driver for both a2mac1 and the Volvo BOMs.
Elastomer (According to ISO standard 472:2013)	Macromolecular material which returns rapidly to its initial dimensions and shape after substantial deformation by a weak stress and release of the stress Note 1 to entry: The definition applies under room temperature test conditions. (ISO/IEC, 2013)
Monomer (According to ISO standard 472:2013)	Chemical compound, usually of low molecular mass, that can be converted into a polymer by combining it with itself or with other chemical compounds. (ISO/IEC, 2013)
Natural Polymer	Polymers found in nature such as DNA, RNA, spider silk, hair, cellulose, rubber tree latex and cellulose, and nylon. (Council, 2019)
Polymer	Compound containing many interlinked monomers.
Plastic (According to ISO standard 472:2013)	Material which contains as an essential ingredient a high polymer and which, at some stage in its processing into finished products, can be shaped by flow Note 1 to entry: Elastomeric materials, which are also shaped by flow, are not considered to be plastics. Note 2 to entry: In some countries, particularly the United Kingdom, the term "plastics" is used as the singular form as well as the plural form. (ISO/IEC, 2013)
Thermoset	Three-dimensional networks that do not melt once formed. (Council, 2019)
Thermoplastic	One-dimensional networks that can be melted. (Council, 2019)

1 Introduction

This report is part of the project Explore within Mistra's program Closing the loop. It regards the contents of different polymer materials in parts in current and future vehicles in Sweden.

The use of plastics in passenger cars has become more common due to the materials' properties and substitutability with several metals used in cars. The automotive industry makes up a large part of the plastics used. It used up 8.9 percent of plastics in 2015 for EU-28 countries. (Schönmayr, 2017) In the past decades, the trends have shown a general increase of plastics in most passenger cars. A passenger car is a very complex machine with several components and sub-systems. There are various rules and regulations on its safety and environmental output that affect its design and materials choices. For instance, EU regulations and goals for reducing greenhouse gases also affect the design choice by incentivising car manufacturers to use light-weighting materials so that their cars have higher fuel efficiencies. Other additional rules make the choice of light-weighting materials more complex, especially when considering recycling. The costs of raw materials and technology investment costs also affect the car manufacturers' choice of materials and manufacturing methods. Also, design aspects, such as such as pedestrian and traffic safety, handling of high temperatures and fitting of components also affect these choices.

Different powertrains have fundamental differences in their design. In recent decades, new powertrains have emerged and become more prevalent. Internal combustion engines vehicles (ICEV) use fuels of varying sorts: gasoline, diesel, gas, and ethanol. Hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV) combine the combustion engine with a propulsion battery, potentially saving energy in specific driving conditions, such as city driving. Battery electric vehicles (BEV) use a larger battery and have the potential for even greater energy savings. It is therefore of interest to see if there is any difference in the plastics content of these newer powertrains in relation to ICEVs, as their portion in the vehicle fleet is growing.

2 Goal/Scope

The goal of the study was to estimate the weights and weight percentages of plastic and elastomer material in the typical Swedish car produced from around the year 2000 and up to 2025. In addition to comparing the car models by their production year, the car models were categorized and compared by their five powertrains and four weight classes. Additionally, the types of polymer materials in the car models were also compared by the powertrain and production year of the cars.

Car material weight data from a2mac1 was used to achieve the goal, but additional data from Volvo Cars and literature information were used to compare the results.

3 Method

First, a literature review was done to get an overview of the plastic and elastomer data that has been compiled by others and is publicly available.

Second, car material information from a2mac1, a car dismantling service, was gathered. a2mac1 is a commercial data base that supports the automotive industry with detailed data on material compositions and parts- and component-analyses. It holds full vehicle teardown data for over 700 car models at the time of the time of writing this report. It is widely used in the automotive industry to provide data on competitor's car technologies and for general benchmarking purposes. The a2mac1 teardown data is generated through dismantling of the entire vehicle and documentation of each of the parts. For the material data, each part's material composition is predicted (since supplier information is unavailable publicly) and the weight of the part is added into one of the material categories. The choice of cars is described in more detail in the subsections.

Third, the bill of materials (BOM) for six Volvo cars in production was used in conjunction with the International Material Data System (IMDS) categories to summarize their weights in several categories. This data is based on information from the supplier-side of Volvo provided by Andreas Andersson from Volvo Cars. The suppliers' breakdowns of materials in all parts are put together to represent the total weights for each IMDS material category. The weights represented in this way should be more accurate than the data from the a2mac1 data since they come directly from the suppliers who have better control the materials in their parts. The Volvo BOM data is for vehicles produced around the same time the report is written, 2018.

The summation of plastic and elastomer weights for the cars was done for the three sources. The material categories weren't always clearly defined as a plastic or elastomer category, so approximations were made with the help of information from literature and experience. The percent plastic and polymer were calculated for the curb weight and after-pre-treatment weight of the vehicles. A comparison of the material data of the three sources was done. The variables that were compared were weight class, power train and production year.

3.1 Literature Review

A literature review was done in conjunction with our data collection from a2mac1 and Volvo to understand and compare our results with technological trends, legislation, production and recycling. Along with this, additional information was gathered about the trends of cars in production to focus the data collection parts on the right car models. Discussions were also carried out with Andreas Andersson and Tom Engblom at Volvo Cars. The information from these sources was compared with the collected data to draw the final conclusions.

3.2 Method for a2mac1

To complement the literature review, data from a car dismantling service A2mac1 was used for several models over a span of almost two decades (2001-2018). This data estimated the total polymer portion of each car. The weights of the vehicles were compared to each other in the different weight categories:

- less than 1000kg,
- 1000-1249kg,
- 1250-1499kg,
- over 1000kg;

and different powertrains:

- ICEV Gasoline,
- ICEV Diesel,
- HEV,
- PHEV,
- BEV.

The choice of passenger cars for the a2mac1 car dismantling data was based on a combination of:

1. Data availability in a2mac1
2. BEV/PHEV: most sold vehicles according to BIL Sweden and Eurostat
3. If there were several production years for one model, they were prioritized
4. Spreading of vehicles over the four different weight ranges

Below are tables showing the cars chosen for the a2mac1 analysis.

Table 1: Vehicles for which a2mac1 data was obtained and plastic/polymer fractions were calculated for. Please observe in the notes below that some models were discarded due to incomplete or insufficient data.

Car Model	Manufacturer	Fuel Type	Production Year	Weight [kg]
2011 Audi 1.4 TFS1-Tronic Ambition	Audi	Gasoline	2011	1 158
2013 Audi A3 1.4 TFSi Attraction	Audi	Gasoline	2013	1 178
BMW 5 Series 3.0 i Sport 2003	BMW	Gasoline	2003	1 621
BMW 5 Series 520i 2017	BMW	Gasoline	2017	1 567
BMW 5 Series 523i 2010	BMW	Gasoline	2010	1 645
Ford Focus 1.6 EcoBoost Titanium 2011	Ford	Gasoline	2011	1 366
Kia Picanto 1.0 Active 2012	Kia	Gasoline	2011	929
Kia Picanto 1.1 EX Pack 2007	Kia	Gasoline	2006	949
Kia Niro 1.6 Gdi HEV Active 2016	Kia	HEV	2016	1 425

Mitsubishi OutLander PHEV Business Nav Safety 2014	Mitsubishi	PHEV	2014	1 884
Nissan Leaf 2011	Nissan	BEV	2011	1 520
Nissan Leaf SV 2017	Nissan	BEV	2016	1 525
Nissan Leaf Tekna 2018	Nissan	BEV	2018	1 577
Nissan Qashqai 2.0 Visia 2008	Nissan	Gasoline	2008	1 413
Nissan Qashqai+2 2.0 CVT All-Mode Connect Edition 2012	Nissan	Gasoline	2012	1 623
Renault Captur 0.9 TCe Expression 2013	Nissan	Gasoline	2013	1 206
Renault Clio 0.9 TCe Dynamique 2013	Renault	Gasoline	2013	1 138
Renault Clio III 1.6l 16V 2005	Renault	Gasoline	2005	1 223
Skoda Fabia 1.2 TSi Ambition 2014	Skoda	Gasoline	2014	1 074
Tesla Model-S 2013	Tesla	BEV	2013	1 955
Toyota Aygo 1.0 VVT-i C-play 2014	Toyota	Gasoline	2014	878
Toyota Auris 1.8 HSD Dynamic nav. comfort 2013	Toyota	HEV	2013	1 396
Toyota Prius 1.5 Base 2004	Toyota	HEV	2004	1 350
Toyota Prius 1.8 Hybrid Touring 2016	Toyota	HEV	2015	1 418
Toyota Prius 1.8 VVT-i Hybrid Lounge 2016	Toyota	HEV	2016	1 421
Toyota Prius 1.8 PHV 2017	Toyota	PHEV	2017	1 551
Toyota Prius 1.8 Plug-in Hybrid 2012	Toyota	PHEV	2012	1 441
Volkswagen Golf V 1.9 TDi Comfort 2006	Volkswagen	Diesel	2006	1 361
Volkswagen Golf V 2.0 TDi 140 Carat 2004	Volkswagen	Diesel	2003	1 390
Volkswagen Golf VI 2.0 TDi Comfortline 2009	Volkswagen	Diesel	2008	1 345
Volkswagen Golf VII 2.0 TDi DSG Highline 2013	Volkswagen	Diesel	2013	1 441
Volkswagen Passat 1.9 TDi 2005	Volkswagen	Diesel	2005	1 558
Volkswagen Passat Variant 2.0 TDi SCR Highline 2015	Volkswagen	Diesel	2015	1 789
Volkswagen Golf VI 1.4 TSi Highline 2009	Volkswagen	Gasoline	2008	1 406
Volkswagen Golf VII 1.4 TSi Comfortline 2013	Volkswagen	Gasoline	2013	1 249
Volkswagen Golf VII GTI 2.0 2015	Volkswagen	Gasoline	2014	1 440
Volkswagen Passat 1.4 Tsi ACT Comfortline 2015	Volkswagen	Gasoline	2014	1 370
Volkswagen Polo 1.90 Tsi Highline 2018	Volkswagen	Gasoline	2017	1 175
Volkswagen Golf VII GTE 2015	Volkswagen	PHEV	2015	1 569
Volvo S60 2.4 D5 Summum 2011	Volvo	Diesel	2010	1 642
Volvo S90 2.0 D4 Momentum 2017	Volvo	Diesel	2017	1 734
Volvo V40 D4 Summum 2013	Volvo	Diesel	2012	1 574
Volvo XC60 2.4D Basis 2009	Volvo	Diesel	2009	1 838
Volvo XC90 D5 Inscription 2015	Volvo	Diesel	2015	2 141

Several material categories exist in the a2mac1 files and for some of the cars it was not possible to discern the polymer material from other materials in some of the categories. The weights in these categories are essentially an uncertainty added to the real weight of polymer materials. To minimize this error, the weights in these categories were multiplied by a percentage we approximated for plastics or elastomer material. In other words, we estimated the amount of plastic and/or elastomer material in the categories that didn't explicitly state the specific plastic or elastomer weight. Section 3.2.1 shows how this was done in more detail.

3.2.1 Categories a2mac1

The categories that are found in the a2mac1 files are in the tables below. 100 percent of the weights in the plastics and elastomers categories were added to the polymer weight, while only the plastics category was added to the plastics weights. The elastomer categories are below.

Table 2: Elastomer categories in the a2mac1 data. The weights from these categories were only added to the polymer weights, not the plastics weights.

Category, Elastomers	Description
ACM; CSM	Acrylonitrile-Chlorinated Polyethylene-Styrene Terpolymer; chopped strand mat (or) chlorosulphonated polyethylene (rubber)
BR	butadiene rubber
CR	Polychloroprene Rubber
Elastomers + plastic	-
EPDM	ethylene-propylene-diene monomer
NBR	nitrile butadiene rubber
NR	natural rubber
Other Elastomers	-
SBR	Styrene butadiene rubber

There was no distinction between thermoplastics and thermoset plastics in the a2mac1 files. Some categories can be both. Although there was a category for carbon fiber, only one of the vehicles had more than 0kg. It isn't stated if the carbon fiber is a composite with a polymer or woven.

The plastics and rubbers most often include some types of filler materials, but we did not attempt to approximate the amount of fillers or separate their weight from the weight of the whole plastic parts.

Table 3: Plastics category in the a2mac1 data. An additional column for type of polymer has been added. *Likely Thermoplastic* means that both copolymers are separately thermoplastic. *Can be both* means that the plastic can be either thermoplastic or thermoset plastic. Note that PUR and TPV; TPE can be elastomers, but this table represents a2mac1's categorization of the materials.

Category, Plastics	Description	Thermoplastic or Thermoset Plastic
ABS	acrylonitrile-butadiene-styrene	Thermoplastic
ABS-PC	acrylonitrile-butadiene-styrene/polycarbonate alloy	Thermoplastic
ASA; SMA	Acrylic-styrene-acrylonitrile/styrene maleic anhydride	Likely Thermoplastic
Fluorinated polymers	-	Can be both
Other plastics	-	Can be both
PA	Polyamide, nylon	Thermoplastic
PA6-MD35	Nylon 6, copolymer	Likely Thermoplastic
PBT; PET	Polybutylene terephthalate; polyethylene terephthalate	Thermoplastic
PC	Polycarbonate	Thermoplastic
PE	Polyethylene	Thermoplastic
PF	Phenolic, phenol formaldehyde	Thermoset
PMMA	Polymethyl methacrylate	Thermoplastic
POM	Polyoxymethylene	Thermoplastic
PP	Polypropylene	Thermoplastic
PPO; PPE; PPS	Polyphenylene Oxide; Polyphenylene Ether; Polyphenylene Sulfide	Likely Thermoplastic
PS	Polystyrene	Thermoplastic
PUR	Polyurethane	Can be both
PVC	Polyvinyl chloride	Thermoplastic
TPV; TPE	Thermoplastic Vulcanizate; Thermoplastic Elastomer	Likely Thermoplastic
UP	Unsaturated Polyester	Thermoset

The 'Coating' categories are for non-paint and non-lacquer coatings that can usually be found inside the vehicle.

Table 4: The 'Coating' categories in the a2mac1 data along with our estimated percentages of plastics. The estimated percent plastic is also our estimated percent polymer material. The Notes-column explains our estimations.

Category, 'Coating'	Estimated Percent Plastic (also Polymer Material) [%]	Notes
Alcantara	100	A microfiber material made up of 68 percent polyester and 32 percent polyurethane resin (Fung, 2000).
Carpet	100	Usually a synthetic polymer.
Fabrics	0	Could be any material, including pure leather or natural materials.
Leather	0	-

The next categories are for 'Insulation', which is made of fibrous materials and foams, most of which are polymer in this project.

Table 5: The 'Insulation' categories in the a2mac1 data along with our estimated percentages of plastics and polymer content in each material category. The Notes-column explains our estimations.

Category, 'Insulation'	Estimated Percent Plastic [%]	Estimated Percent Polymer Material [%]	Notes
Cardboard	0	0	-
Carpets+Sound Dampening / Sound Dampening	100	100	Carpets and sound dampening are likely made of felt, glass fibers, polyurethane foam and/or PET fibers (Ki-Seok & al., 2011). We assume no glass fibers for simplicity.
Elastomer + foam	0	100	Both are polymeric, only foam might be plastic, but more likely elastomer.
Fiber	0	0	Likely glass wool.
Glued sound insulation	100	100	Carpets and sound dampening are likely made of felt, glass fibers, polyurethane foam and/or PET fibers (Ki-Seok & al., 2011). We assume no glass fibers for simplicity.
Natural Fibers	100	100	Could be cellulose or other plastic fibers
Recycled fibers	100	100	Assumed to be plastic.
Synthetic fibers	100	100	Assumed to be plastic.

In the next category is unfortunately more difficult to discern the polymer materials from metals, because they are added together by a2mac1. See subsection 3.2.1.2 for more information

Table 6 : 'Metal + Others' categories in the a2mac1 data along with our estimated percentages of plastics and polymer content in each material category. The Notes-column explains our estimations, as well as the notes in the following subsections.

Category, 'Metal + Others'	Estimated Percent Plastic [%]	Estimated Percent Polymer Material [%]	Notes
Metal + Elastomers	0	30	Assumed to be mostly tires. Tires aren't included in the plastics and polymer summations. The weights from this category aren't included in the plastics summations and part of the weight is deleted from the weight. The percent elastomeric material is assumed to be the same as for plastics in the 'Metal+Plastic' category (Sullivan, Kelly, & Elgowainy, 2015).
Metal + Plastic	30	30	An assumption is made that the plastics are 30 percent based on their interpretation of this category in a similar study. (Sullivan, Kelly, & Elgowainy, 2015)

Table 7 shows the rest of the categories that are mostly electronic and motor parts. Additional notes on the category choices can be found in Appendix I.

Table 7 : 'Other' category in the a2mac1 data along with our estimated percentages of plastics content in each material category. The Notes-column explains our estimations, as well as the notes in the following subsections.

Category, 'Other'	Estimated Percent Plastic [%]	Notes
Electric motor	15	The plastics percent in engine for a 2010 Toyota Venze 2.7, 182hp litre engine (Sullivan, Kelly, & Elgowainy, 2015) was 15 percent. The plastic content may be different for battery-driven vehicles, but we have not investigated this specifically.
Electronic components	(10+50)/2=30	Taking the median of the plastics value in a Li-ion Battery (Ellingsen, o.a., 2013)and the assumption made for this category by a group doing a similar study (Sullivan, Kelly, & Elgowainy, 2015).
NA	0	Could be anything, therefore vehicles with disproportionately high weights in this category are not used in the comparison. The value is set to 0 because only vehicles with low weights in this category are used for comparison.
Several components	50	Amount of plastics based on another group's interpretation of this category in a similar study. (Sullivan, Kelly, & Elgowainy, 2015)
Wire harness	18	The median weight percentage for aluminium and copper wires is used. (Jorquera & Lindblad, 2016)

3.3 Method for Volvo BOM data

The section below shows what categories from the Volvo BOM and IMDS data were chosen to represent plastic and polymeric material, for comparison with the a2mac1 data as closely as possible. Additionally, the plastic and polymer material percentages and weights from here were used to compare to similar values in literature.

3.3.1 Categories Volvo BOM data

There are differences in the choice of categories to divide the materials' weights in the Volvo BOM data and a2mac1 data. The BOM materials are classified according to IMDS and it is the suppliers themselves that decide in which category their part will be. Below are the category choices for the BOM/IMDS Volvo data. Additional notes on the category choices can be found in Appendix I.

Table 8: Some of the categories in the BOM/IMDS files. All the categories that have at least some polymeric material are in this table.

Description (Classific.)	**Estimated** Percent [%]	Notes
Thermoplastics	100	
filled Thermoplastics	100	
unfilled Thermoplastics	100	
Thermoplastic elastomers	100	
Elastomers / elastomeric compounds	100	
Duromers	100	
Polyurethane	100	
Unsaturated polyester	100	
Other duromers	100	
Plastics (in polymeric compounds)	100	
Textiles (in polymeric compounds)	100	
Lacquers	100	
Adhesives, sealants	100	
Underseal	100	
Modified organic natural materials (e.g. leather, wood, cardboard, cotton fleece)	100	Mostly cellulose and some leather (Andersson, 2019)
Ceramics / glass	0	
Other compounds (e.g. friction linings)	0	
Electronics (e.g. pc boards, displays)	(38+31)/2 = 35	The average of two categories from a German waste management consultant website (Elektro-Ade, 2017) is used: Display devices (flat-screen displays) and small appliances and devices. The percent plastic in each category is 38 and 31 percent, respectively, from which the average is used.
Electrics	18% of 11% = 2%	We assume that this category is made of the starter battery, propulsion battery (if there is one), and wiring wire harness. The average weight percent for aluminium and copper wires is 18 percent (Jorquera & Lindblad, 2016). The plastic percent of wiring in this category is approximated to be 11 percent (Ellingsen, o.a., 2013) (Kiyotsugu, 2013).

4 Literature Review

The literature review was done to compare the results obtained from the a2mac1 and Volvo data. The sources were a combination of articles and reports from various sources.

4.1 Plastics and Weight Trends in passenger cars

The amount of plastics increased drastically since the middle of the 1900s up to 2000, since cars in early days used to be made of metals almost exclusively. Pradeep et al. write that cars used to include about 9kg (20lb) of plastics in the 1960s, whereas in 2010 their total was 162kg (357lb). (Pradeep, Iyer, Kazan, & Pilla, 2017). A. T. Kearney puts in their analysis that the plastics content in the 1970s was at least 66kg (6 percent of 1100kg) and in 2010 it is up to 224kg (16 percent of 1400kg) on average (Rouilloux & Znojek, 2012).

Car weight has also been changing slightly in the past decades. A. T. Kearney writes that the average vehicle weight has been increasing from at least 1,100kg in 1970 to at least 1,400kg in 2010, and that the estimated average weight for 2020 will be 1,100kg, see Figure 1.They do not explicitly state which market it is for, but we assume that it is for the worldwide market. Ford writes that there are a lot more SUVs being sold in the German market now, so they expect the weight of the average vehicle to increase in the coming years (Neborg & Schmidt, 2018).

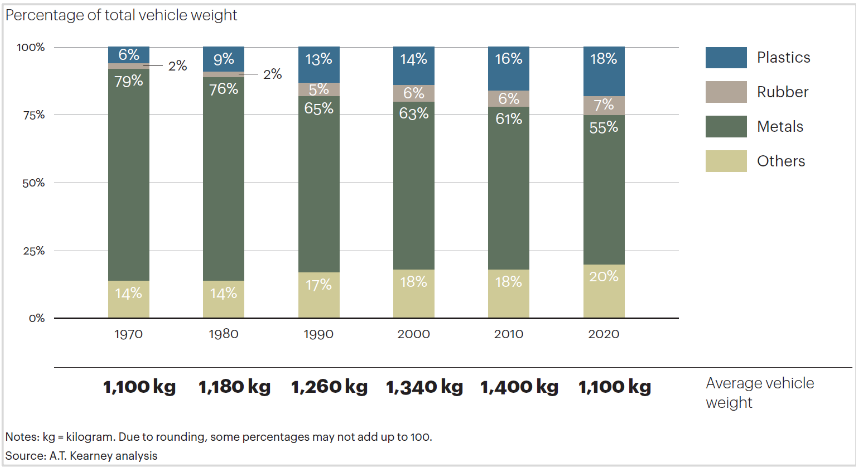


Figure 1: The A.T. Kearney graph of the percentage material of total vehicle weight, from their report: Plastics. The Future for Automakers and Chemical Companies (Rouilloux & Znojek, 2012). A similar graph from the a2mac1 data is shown for comparison in Figure 51.

One of the reasons for changing to more plastics over time is that it has some favorable properties over metals. For example, metals can rust, which plastics do not. Also, plastics can give a premium feel to a car at low cost, and in more recent decades the radar safety components can be built behind a plastic bumper since the waves can travel through. (Englblom, 2019)

4.2 Plastics trends in the past 20 years and future speculations

4.2.1 Literature data on plastics and elastomer material

The data found in the literature is presented graphically in section 5.2.1 (including both material weights and percentages), but it is also presented in text in this section:

According to Applied Plastics Engineering Handbook, weight-percent plastics in cars has increased very slightly from around 21 to 22 percent from 2004 to 2011, respectively, for European cars (Pradeep, Iyer, Kazan, & Pilla, 2017).

The American Chemistry Council writes that the total weight of plastics and polymers in North American light vehicles was high in 2010, at 343 pounds per vehicle (approx. 156kg), and afterwards it dipped to minimum in 2013 and has been growing slightly thereafter. In 2017 the average weights of the most prevalent polymers and composites in light vehicles were: PP (not including TPO): 86lb per vehicle, PU: 62 lb per vehicle, Nylon: 36 lb per vehicle. (American Chemistry Council, 2018). There is between 88-92lb in a category called 'Other' in the data for these years.

Another source writes that the average plastics and composites content for North American domestic light vehicles in 2000 and 2009 was 130 kg and 174kg per vehicle, respectively, the rubber content was 75kg and 96kg, and the coatings content was 11kg and 15kg, and total vehicle weights were 1770kg and 1776kg. (Keoleian & Sullivan, 2012)

Yet another source puts the plastics and plastic composites of U.S.A. light vehicles for 2000 and 2010 at 286lb (230kg) and 378lb (171kg) per vehicle, respectively, and rubber at 166lb (75kg) and 200lb (91kg), and coatings at 25lb (11kg) and 34lb (15kg), and total vehicle weights at 3,902lb (1770kg) and 4,040lb (1833kg). (Davis, Diegel, & Boundy, 2012)

AT Kearney writes that the amount of plastics in 1970, 2000 and 2010 has increased from 6, 14 and 16 percent respectively, and that the rubber has increased 2, 6, and 6 percent, making their sum 8, 20, and 22 percent. Unfortunately, just like in our a2mac1 data, there is a category, 'other', that adds an error interval between 14-20 percent in AT Kearney's report. It is, however, interesting to note that the 'other' category also increased steadily throughout the same years. Additionally, the average vehicle weights in 1970, 2000, and 2010 were 1,100, 1,180, and 1,400, respectively. Unfortunately, they did not comment on how they found their data, where it came from, or how they identified the 'average' vehicle. (Rouilloux & Znojek, 2012)

4.2.2 Materials and component trends

Plastics compete with metals in several car parts. Some of the benefits to plastics are that they are relatively cheap, and they can still give a premium feel that customers want. Another benefit is that they are lighter, which is good for better fuel efficiency since about 80 percent of the vehicle energy consumption depends on the vehicle weight (Engblom, 2019). Figure 2, from a report by McKinsey, shows that a fender made of plastic is about 20 percent lighter than one made of steel, but 20 percent heavier than one made of aluminium. Magnesium, another light weighting material, is about two-thirds the weight of aluminium (Meridian, 2019). The prices are also listed in the McKinsey diagram, which shows that the steel and plastic fenders are both the cheapest alternatives of choices of materials, but plastics fenders are lighter. Plastic-, instead of metal-, fuel tanks have several benefits, such as better structural integrity, corrosion resistance and seamless construction (Krebs). The instrument panel in older Volvo vehicles used to be made of a metal frame, but nowadays it is made of plastics that are screwed together (Englblom, 2019).

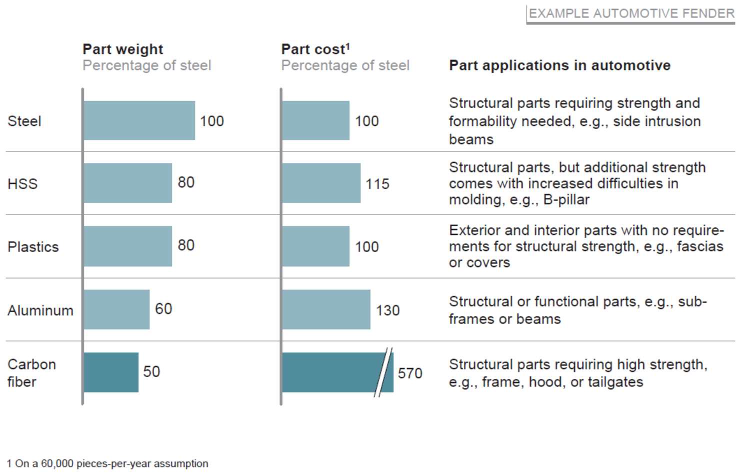


Figure 2: The relative part weights and part costs for car fenders, depending on the material choice. Steel, high strength steel, plastics, aluminum, and carbon fiber are listed. (Heuss, Müller, Sintern, Starke, & Tschiesner, 2012)

In North America, the average fuel efficiency of vehicles has been steadily increasing from 19.8 miles per gallon (MPG) in 2000, to 22.6 MPG in 2010, to 25.2 MPG in 2017. The American Chemistry Council states that it is due to a combination of chemistry and lightweight materials, as well as engine technologies. (American Chemistry Council, 2018).

Oil prices are also responsible for the price of gasoline that users will be paying. North America is known to have larger average vehicle weights than Europe, but in 2008 the increase in oil prices, and likely the economic crisis, led the sale of smaller and more fuel-efficient cars in North America. The average vehicle weight decreased in 2008-2009, and it went back up again after the oil prices decreased and the economic crisis subsided. (American Chemistry Council, 2018) The prices of plastics are dependent on the prices of its raw material, and therefore plastics prices are sensitive to fluctuations in the oil market.

One plastics technology is light plastic foams in the vehicle cavities to increase safety. The foam fills up spaces in the body between sections, making the structure of the vehicle stronger. Rollover and vehicle-to-vehicle side-impact accidents can be less serious with this addition, because the integrity of the roof and door structures would crumple less (Paulino & Teixeira-Dias, 2011). It is unclear how the addition of foams changes the total plastics content of the vehicle or if they would make the recyclability of the vehicle more difficult in the process.

Wires and printed circuit boards have become more prevalent in cars due to engine, air conditioning, infotainment, and safety components becoming more advanced (Cucchiella, D'Adamo, Rosa, & Tezi, 2015). Additionally, the electrification due to electric propulsion means that there is more wiring in a BEV, HEV, and PHEV, than an ICE. The plastics in wiring, as mentioned in the Method, are generally made of PVC and PEX (Jorquera & Lindblad, 2016). PVC is thermoplastic, and thus easy to recycle, but PEX is thermoset and therefore more difficult to recycle into polyethylene due to the extra molecular bonding.

In a mail from Anna Henstedt from Bil Sweden says that VW's development team stated that the plastics have increased slightly from 18 to 20 percent., and that Opel's development team stated that the plastics percentage has been constant lately (Henstedt, 2019).

In a mail from Ford they write that the metal content of cars in the German market has only decreased from 75.9 to 75.5 percent from cars sold in 1995 to 2000, respectively. Additionally, Ford writes that the vehicle weight is going up and more SUV-like vehicles are being sold. The increase in vehicle size doesn't necessarily mean more plastics, because, as Ford says, heavier vehicles require more powerful, and therefore larger, engines and brakes which are made of aluminium and high-strength steel. (Neborg & Schmidt, 2018)

Bil Sweden stated that weight percentage of plastics in cars is stable, but the car size is increasing, meaning that more total plastics is used in absolute terms. (Henstedt, 2019) In personal communication with Tom Engblom (2019) and Andreas Andersson (2019) from Volvo, they agreed that there is no significant change in plastics content for cars that are in the pipeline for production in the coming years.

For cars with li-ion batteries such as BEVs and some HEVs and PHEVs, there is an extra incentive to use lightweight materials because the li-ion battery is so expensive.

There are several parts in cars that are usually made of specific polymer types. Figure 3 shows a North American plastics breakdown where the most common type of plastic used in cars is polypropylene (PP), and second is polyurethane (PUR). In Volvo passenger cars, exterior parts are made of primarily of PP with differences in filler materials. Some of these parts are bumper casings, air deflectors under the car, fender flares, containers/fuel tanks, and wheel arches. (Engblom, 2019) One trend in design for car manufacturers has been to limit the mixing of recyclable and non-recyclable plastics in parts, to increase material recyclability for cars. European car manufacturers often use the same suppliers, or they often use the same specifications that have been developed over the years with regards to requirements of surface finish and temperature resistance. (Engblom, 2019)

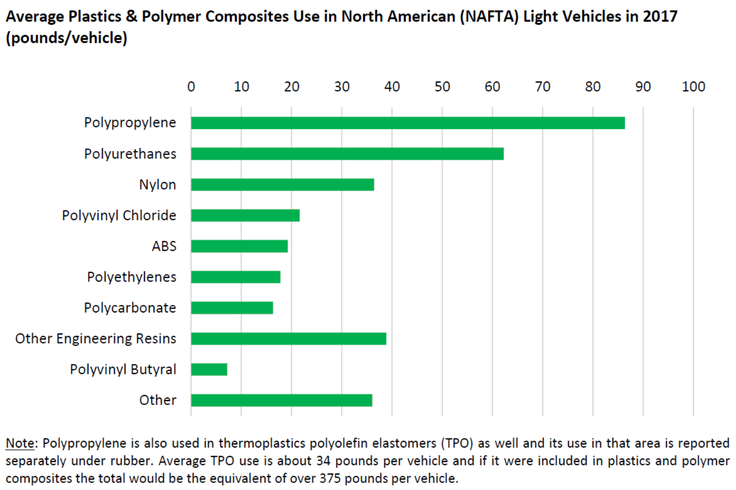


Figure 3: The weight of PP is about 87 pounds (39.5kg) and PE is about 62 pounds (28kg) in this source from the American Chemistry Council. (2018)

Finally, just like switching to plastics for low-weighting influences the fuel consumption, switching powertrains altogether can also influence the car's fuel consumption. Figure 4 from an article comparing cars with different powertrain with their fuel consumption shows how switching to a HEV or a BEV from a gasoline vehicle lowers fuel costs. According to the figures, an increase in curb weight will have a greater effect on the fuel consumption of a gasoline vehicle vs. a BEV.

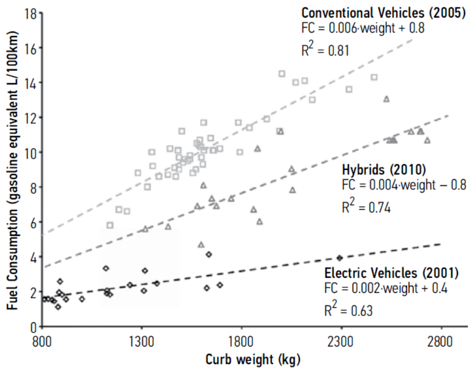


Fig. 1. Fuel use versus vehicle weight for conventional, hybrid and electric drivetrains illustrating that the more efficient a powertrain is, the less its energy use depends on weight (ADAC 2008; National Highway Traffic Safety Administration 2006; Meier-Engel 1999)

Figure 4: How differences in powertrains and curb weight affect the fuel consumption. The trend lines show that for cars of the same curb weight, BEVs are more fuel efficient than HEVs and gasoline vehicles, and that HEVs are more fuel efficient that gasoline vehicles. (Wilhelm, Hofer, Schenler, & Guzzella, 2012)

Thus, the trends in materials and components is not as simple as it was since the middle of the 1900s. Fuel prices, trends in automotive technology, and materials that compete against plastics have an impact on the amount of plastics in an average vehicle.

4.2.3 Fibre-reinforced polymer composites

Fibre-reinforced plastic composites have several benefits over metals. Their part weight can be about half of the weight of a steel part, or about 38 percent of an HSS part. They also have better corrosion resistance, excellent strength-to-weight and stiffness-to-weight ratios, good electrochemical insulation and fatigue endurance (Rouilloux & Znojek, 2012). Nanomaterial reinforced polymer composites can also conduct heat much more effectively than regular polymers, giving them the unique ability to replace metal gears (Fan & Njugana, 2016). Larger engine parts have also been successfully created with carbon fibre polymer composites (Corey, Madin, & Williams, 2015). Two types of common composite fibres are glass fibre and carbon fibre.

Car manufacturers look at different options when attempting to reach a goal, such as high fuel efficiency. They will often choose the solution that minimizes the costs required to reach the goal. Some of the competing solutions with changing to high-tech materials such as composites are decreasing rolling-resistance and aerodynamic drag and minimizing drivetrain losses (Wilhelm, Hofer, Schenler, & Guzzella, Optimal Impementation of Lightweighting and Powertrain Effeciency Technology in Passengers' Vehicles, 2012). There are also other hurdles that stand in the way of fibre-reinforced polymer composites replacing metals altogether. Composites are harder to design and manufacture because the direction of the grains influence the direction in which the composite is stronger and weaker and have a significant effect on long-term wear of the part. The safety aspect of composites is difficult to assess, since there is the potential for greater variations between parts. This means that separate non-destructive testing, such as acoustic emission detection or thermal, ultrasonic or x-ray imaging is required for each part. There are also difficulties in assembly because of greater shape variations than other plastics which require extra steps in the manufacturing process. (Fan & Njugana, 2016) (Heuss, Müller, Sintern, Starke, & Tschiesner, 2012) All these extra steps in design and production add up to extra costs for manufacturers and suppliers of vehicle parts.

The trends for carbon fibre composites are mixed. In an article that mentions a 2016 report by IHS Chemical called "Weight Reduction in Automotive Design & Manufacture", the use of carbon fibres in the automotive industry is predicted to increase from 3,400 tonnes to 9,800 tonnes from 2013 to 2030 (plasticstoday, 2015), most likely in the USA region. A report by McKinsey from 2012 predicts that the price class of vehicle will ultimately determine the type of light weighting materials that it will have in the future, see Figure 5 and Figure 6. Conventional vehicles, which are the most prevalent in Sweden, will not have carbon fibre content in 2030, but upper-medium and luxury cars will have up to 36 percent light weighting material, partly due to decreases in future costs. (Heuss, Müller, Sintern, Starke, & Tschiesner, 2012)

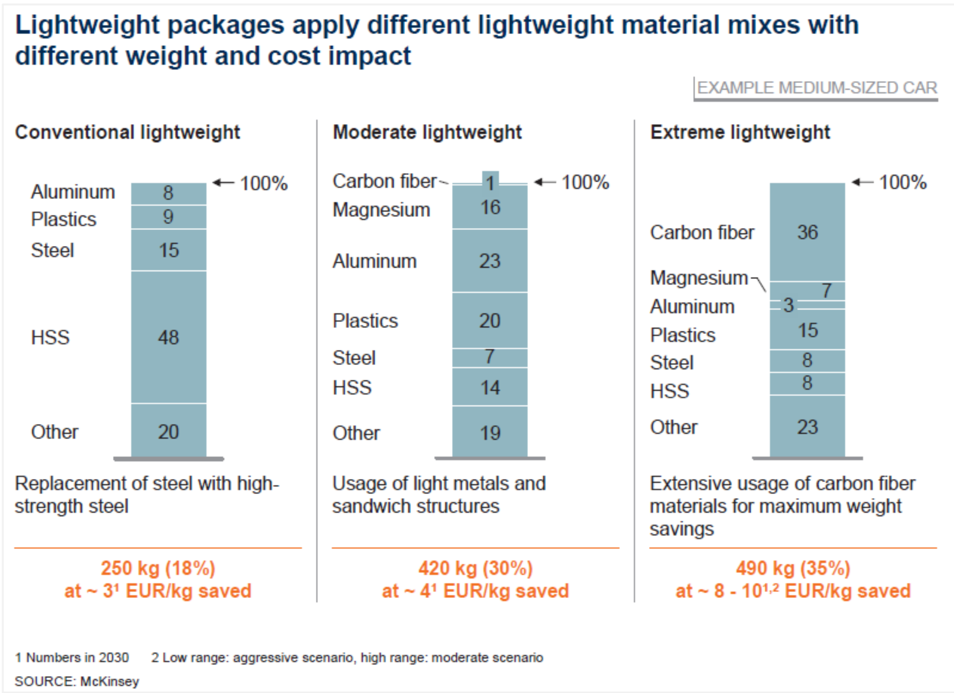


Figure 5: An example for the material breakdown of a medium-sized car. The use of carbon-fibre is non-existent in conventional lightweight cars, about 1 percent in moderate lightweight cars, and 36 percent in extreme lightweight cars. Source of figure: McKinsey (Heuss, Müller, Sintern, Starke, & Tschiesner, 2012).

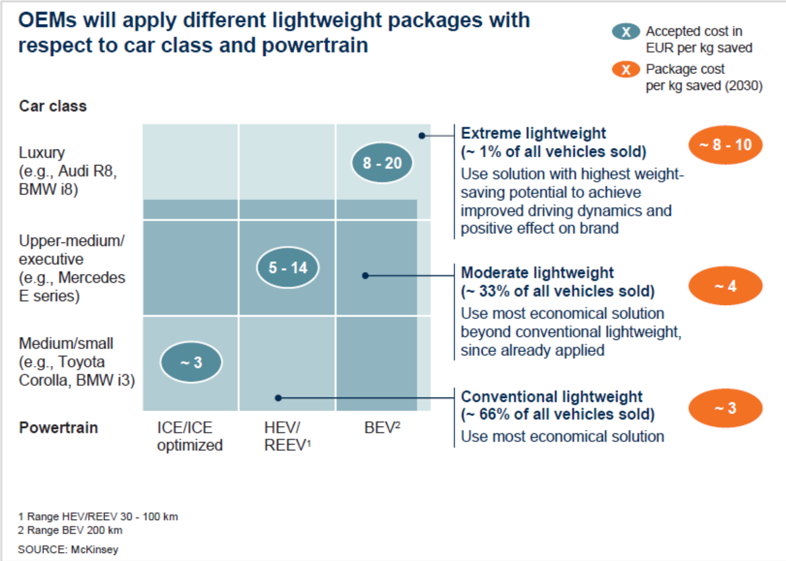


Figure 6: Distribution of lightweight classes amongst powertrains and car class. According to these graphs, McKinsey predicts that cheaper (i.e. more mass-produced in the current market) BEVs will have more light weighting carbon fibre components than their ICEV and HEV counterparts. Source of figure: McKinsey (Heuss, Müller, Sintern, Starke, & Tschiesner, 2012).

An article about the UK steel company Tata Steel who predicts that "… aluminium and carbon fibre-reinforced plastic will have a relatively low impact [compared to steel] in [ex. EVs and PHEVs] for two reasons: firstly, they will remain prohibitively expensive; secondly they are less sustainable when looking at the full life cycle." (Bakewell, 2018)

In an email conversation with Ford, they comment that there are no trends towards replacing metal with carbon fibre in mass-produced vehicles. BMW has stated that they will not continue to use carbon fibre for future vehicle bodies, and Ford, Opel, and Volkswagen don't have any applications using it either. (Neborg & Schmidt, 2018) There are no signs of composites (or thermoset plastics) increasing in any substantial amount for Volvo either (Andersson, 2019).

4.2.4 Electrification and autonomous cars for future mobility and effect on plastics

The HEVs, PHEVs, and BEVs on roads mean that more cars use batteries, and hence more electric equipment than before. The industry shift toward autonomous driving leads to even more electrification of vehicles due to the needed electrical components for the technology to function. The addition of electronic components means that there is an opportunity for plastics to be used in components with desired specific properties that certain types of plastics can fulfill. Electrification generally requires materials that:

- have specific electrical properties,
- fulfill safety standards,

- fulfill specific temperature requirements,
- are chemically resistant to electrolytes, coolants, etc.,
- can conduct heat,
- can shield against outside sources of electromagnetic radiation,
- are flame retardant,
- are halogen free,
- have distinctive colors. (Polymers, 2019)

Some plastic types that are likely to be used because of increased electrification are PAs, PPAs, PBTs. The materials will need a combination of fillers to have the desired properties for the specific component. (Polymers, 2019)

One source speculates that the development of self-driving vehicles and ride-sharing platforms will create new opportunities for plastics and composites due to increased safety requirements and new vehicles architectures (American Chemistry Council, 2018). Another source speculates that future autonomous car technology may enable greater weight reductions due to the improved vehicle-to-vehicle communications that would decrease the need for as much occupant protection. The parts that would, according to the study, be eliminated are 87 common and heavy car components, such as side intrusion beams and bumper beams. Additionally, eliminating steering equipment, such as steering wheels, gear shifters and pedals could decrease the need for materials even more. But the author writes "It will require that all vehicles are autonomous and would have been for several generations of vehicles to evolve out all potential failure points." (Njuguana, 2016) Tom E. from Volvo Cars believes that there could be a market for special city cars with designs and specification that are adjusted for ease of use. He speculates that the materials in these cars could be made of a higher amount of plastic than the cars produced by Volvo today, and their design would be much simpler because they don' t need the requirements of driving in settings outside the city. However, he also says that Volvo doesn't have any dramatical material changes to their cars in ongoing projects, so cars up to about 2025 will look like how they look today. (Engblom, 2019)

4.3 Production

One big reason for why there is an inherent resistance to change to new materials for parts is that there are big costs for retooling. A source from 2004 states that the cost of manufacturing tools and machines for new vehicles is about 40 percent investment for a new vehicle (Edwards, 2004). This cost falls mostly on the supplier side of the automobile industry, so the costs will not necessarily fall on the car companies. However, the resistance to change is still dependent on the suppliers' ability to produce novel parts with the tools that they have already invested in.

The manufacturing aspect of composites is responsible for much of its feasibility in replacing parts that are metal. One of the benefits of composites is that they are easier to assemble because fewer parts are required, and thus makes for easier manufacturing. Additionally, tooling costs are about 40 percent of steel-stamping. (Rouilloux & Znojek, 2012)

4.4 Legislation

As of 2015, the End of Life Vehicle (ELV) EU directive 2000/53/EG has set the target that at least 85 percent of the vehicle materials are to be reused & recycled, and 95 percent must be reused & recovered (Commission, 2000). This EU directive puts pressure on suppliers and car manufacturers to design parts and vehicles that can be more easily recycled. One problem for car manufacturers has been when additives in plastics are banned because they are still required to recycle a big portion of the cars' materials. In the past years there have been bans on flame-retardant Persistent Organic Pollutants (POPs) that have been commonly used in plastics, because of their toxicological effects. These flame-retardant chemicals (nowadays substituted with antimony oxide) can be found in in polyurethane foams, ABS and HIPS plastics, and electrical parts and casings for cars (Leslie, Leonards, Brandsma, de Boer, & Jonkers, 2016) (Mehlhart, Möck, & Goldmann, 2018). The Stockholm convention on POPs bans several of these above a very low threshold level. A Dutch article showed that 14 percent of POP-BDE showed up in the recycled plastics for the transport sector (Leslie, Leonards, Brandsma, de Boer, & Jonkers, 2016). For example, a ban on Decabromodiphenyl ether (decaBDE) has been issued recently by the Stockholm convention, forcing the plastics manufacturers to readjust by using substitutes. Also, the European Association of Automotive Suppliers (ACEA), stated in their report that the workload for authorized treatment facilities to dismantle wiring components that include decaBDE would increase (Mehlhart, Möck, & Goldmann, 2018). The big factor on the use of plastics for cars is that difficult for car companies to rid their recycled plastics parts of these compounds because the threshold is so low compared to what is used in them (ACEA-CLEPA Position Paper EU Plastics Strategy, 2018). However, decaBDE has very recently been set to a 500ppm limit, which is on the higher end of what was possible.

Apart from the POPs being a potential issue in the recycling of plastics, there are other factors that may move car manufacturers away from using plastics. In Sweden, there is a carbon-dioxide tax on the burning of fossil fuels, which would apply even to plastics that are burned after usage in cars. Although this tax may have the positive effect on the environment of decreasing the use of non-renewables, it also pushes OEMs away from using plastics due to the extra costs at End-of-Life (EoL).

The EU Regulation No 443/2009 has also been moving CO_2 emission targets with several amendments, meaning that car manufacturers must take measures to reduce the carbon footprint of their cars to comply. The previous sections took up some of the ways that this could be done, such as switching powertrains, switching materials, and design considerations to decrease air drag.

5 Results

The results of the a2mac1, Volvo BOM, and the literature search are presented. The results are presented for easy comparison between the different sources when possible. From the results of all the sources we discuss how we believe the amount of plastics and polymers in passenger cars will develop in their design and recycling until the year 2035.

5.1 A2mac1 Results

The a2mac1 files provided more specific information about the different car models than did the Volvo BOM and literature study. We therefore leaned heavily on the results obtained from a2mac1 for the purposes of identifying patterns in the use of plastics and polymers in cars. We mostly used the Volvo BOMs and literature for comparison. For the numerical data of the graphs in this section, see Table 13 to Table 16 in Appendix II.

5.1.1 a2mac1 Plastic and Polymer Weights after-pre-treatment weights for all cars

The results for total vehicle weight, polymer material weights, and polymer material percentages for the chosen a2mac1 cars are shown in the following graphs. Since the vehicle choice was, primarily, based on the average vehicle found on Swedish roads, the average weights of the vehicles based on powertrains were also calculated and are discussed in later sections of the report. Important to note is that the cars were not divided into weight categories in Figure 7 to Figure 11. For similar graphs with the sum of plastics and elastomer amounts instead of only plastics, see Figure 60 Figure 61 in Appendix II.

Figure 7 shows that the curb weights of the average gasoline vehicle is much less than for diesels, PHEVs and BEVs. HEVs are also lighter than most PHEVs and BEVs. The plastics and polymer materials in diesels in the past two decades is around 50-100kg more than for the other powertrains, but they are also heavier than gasoline vehicles, HEVs and PHEVs.

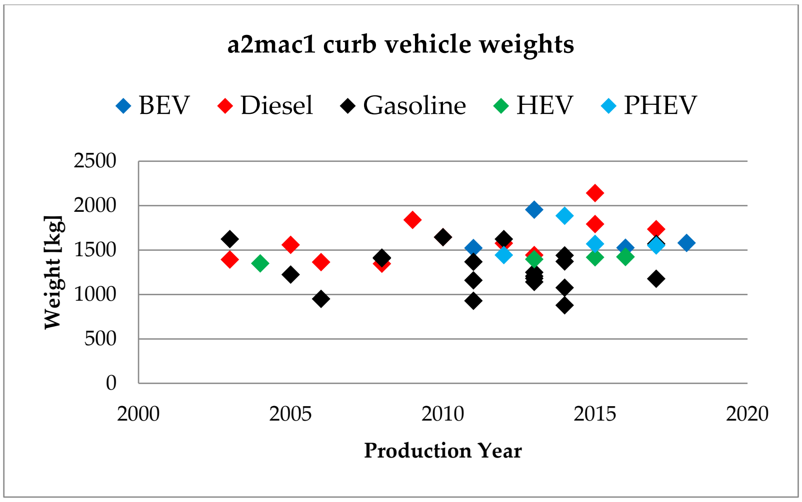


Figure 7: The curb total vehicle weights for the all chosen a2mac1. The average weights of cars for each powertrain were: gasoline (1194.9kg), diesel (1506.8kg), HEV (1312.6kg), PHEV (1516.6kg), and BEV (1618.0kg).

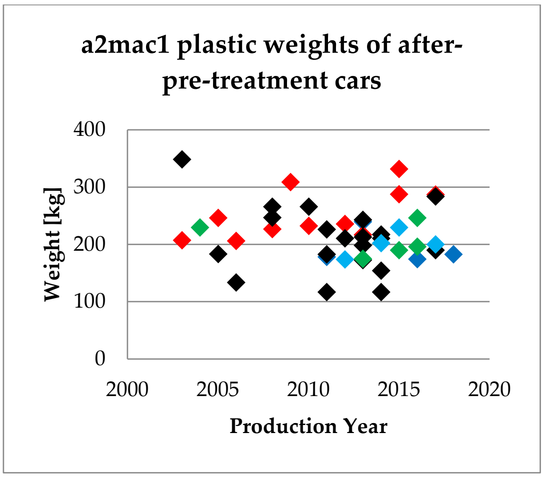


Figure 8: The calculated weights of plastics for the chosen after-pre-treatment cars.

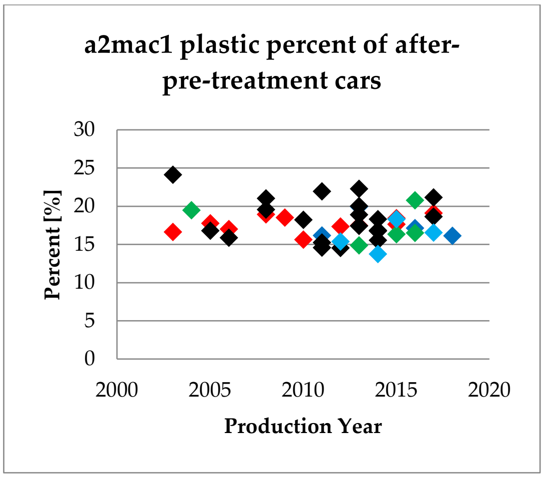


Figure 9: The calculated percent plastic material of after-pre-treatment weights of all a2mac1 cars.

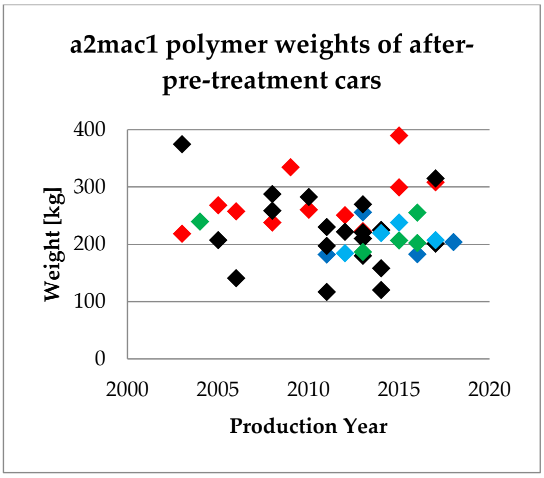


Figure 10: The calculated weights of polymer material for the chosen after-pre-treatment cars.

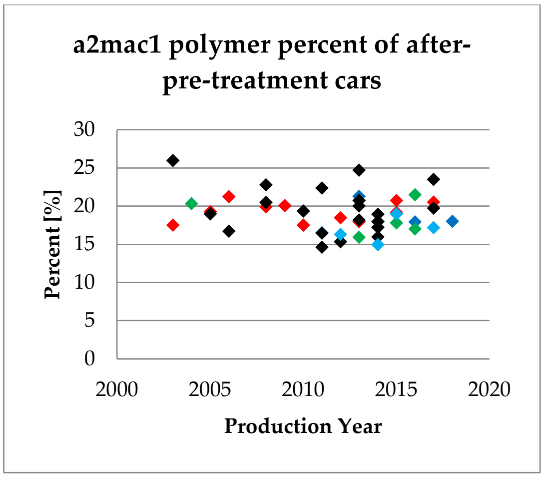


Figure 11: The calculated percent polymer of after-pre-treatment weights of all a2mac1 cars.

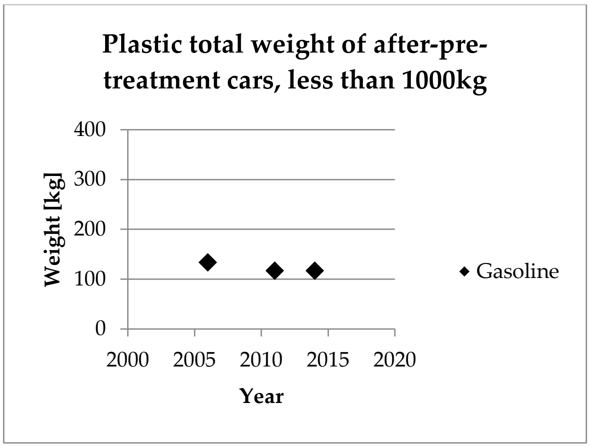
5.1.2 a2mac1 plastic and polymers in after-pre-treatment car weights for different weight classes

The weights of plastics and polymer materials in the vehicles were broken down into four weight classes to identify patterns. The weights for plastics and polymer material in these categories were compared to the weight of the vehicle after-pre-treatment weight. The weight classes were based on the reported curb weight in the a2mac1 files.

For graphs comparing the plastic and polymer material percentages of the curb weight instead of the after-pre-treatment weight, please refer to Figure 52 to Figure 59 in the Appendix II.

5.1.2.1 Plastics

The weights and percentages of plastics in the gasoline vehicles are uniform (about 120kg or 15 percent). In the larger weight classes, the percent of plastics increases up to almost 25 percent in some instances. The range for all cars is about 13-25 percent. In cars that weigh 1500kg or more, the plastics weights for the average gasoline and diesel vehicles are greater than for PHEVs and BEVs, but the weight percentage of plastics is still about the same for all powertrains.



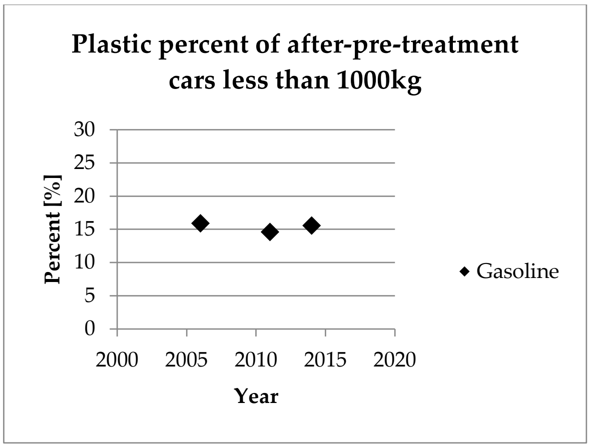
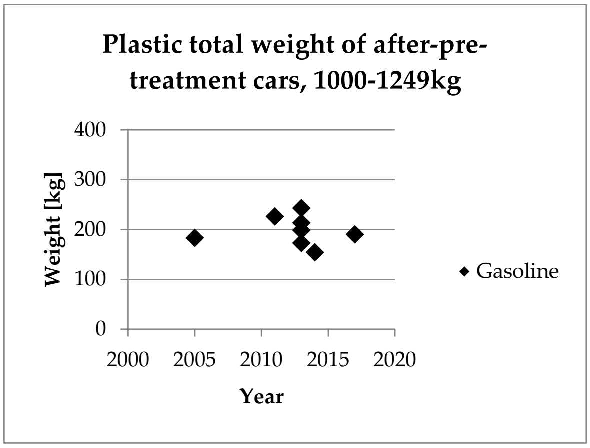


Figure 12: A2mac1 weights of plastics in after-pre-treatment cars <1000kg.

Figure 13: A2mac1 percent of plastics weight in after-pre-treatment cars <1000kg.



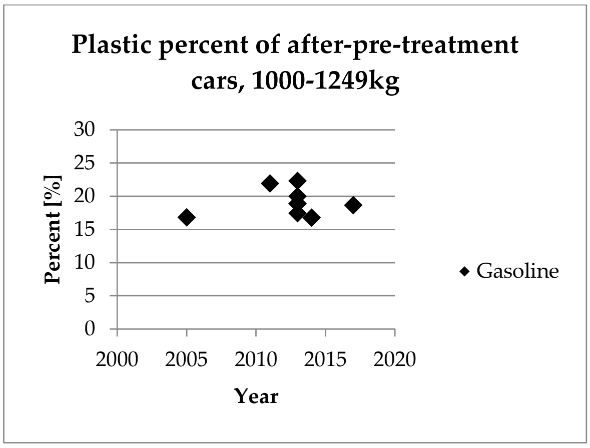
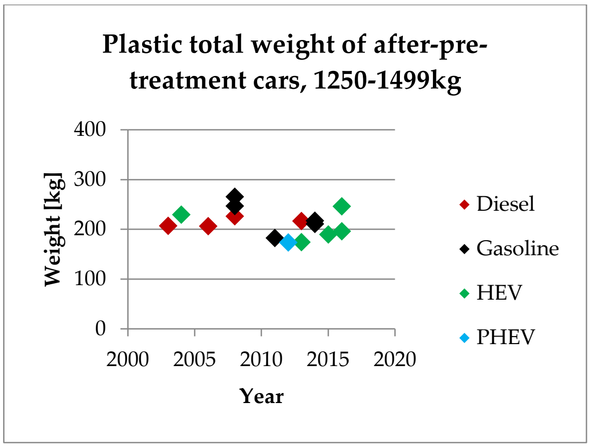


Figure 14: A2mac1 weights of plastics in after-pre-treatment cars 1000-1249kg.

Figure 15: A2mac1 percent of plastics weight in after-pre-treatment cars 1000-1249kg.



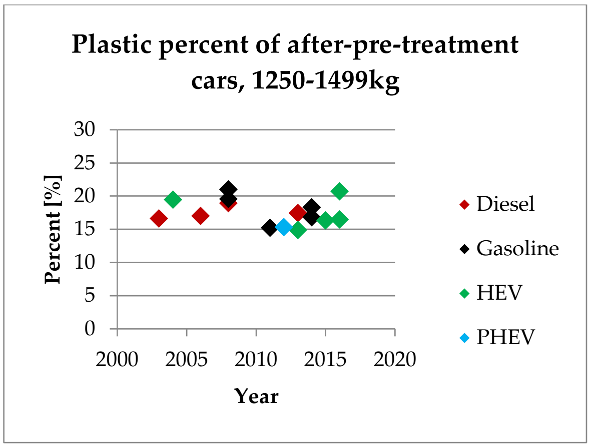


Figure 16: A2mac1 weights of plastics in after-pre-treatment cars 1250-1499kg.

Figure 17: A2mac1 percent of plastics weight in after-pre-treatment cars 1250-1499kg.

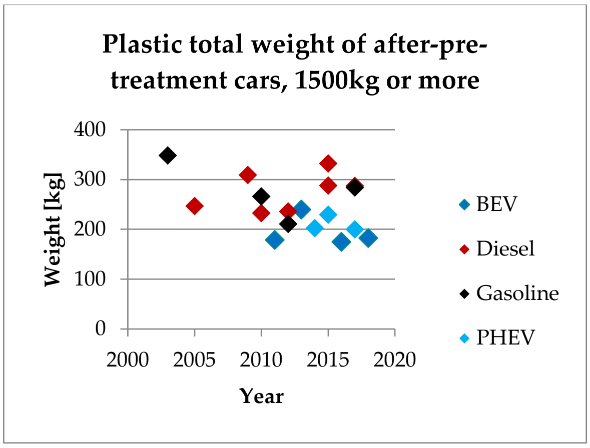


Figure 18: A2mac1 weights of plastics in after-pre-treatment cars >1500kg.

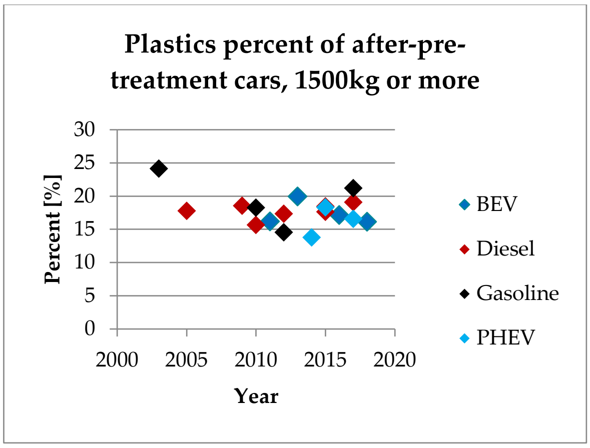


Figure 19: A2mac1 percent of plastics weight in after-pre-treatment cars >1500kg.

5.1.2.2 Polymers

The polymer material content was also observed for the a2mac1 cars at different weight classes. The general trends were the same as for the plastics. We did not see any different patterns than for the plastics. The percentages ranged from about 15 to 27 percent.

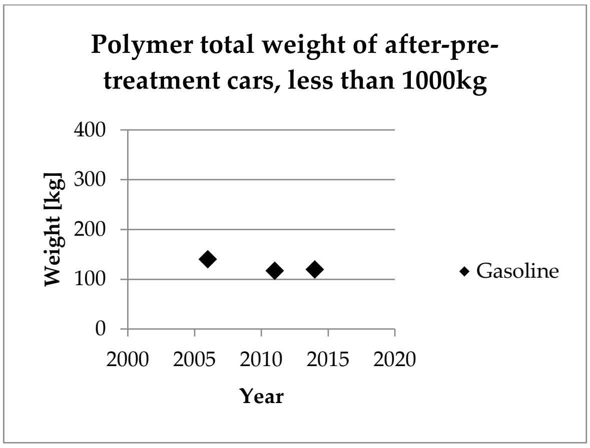


Figure 20: A2mac1 weights of plastics in after-pre-treatment cars <1000kg.

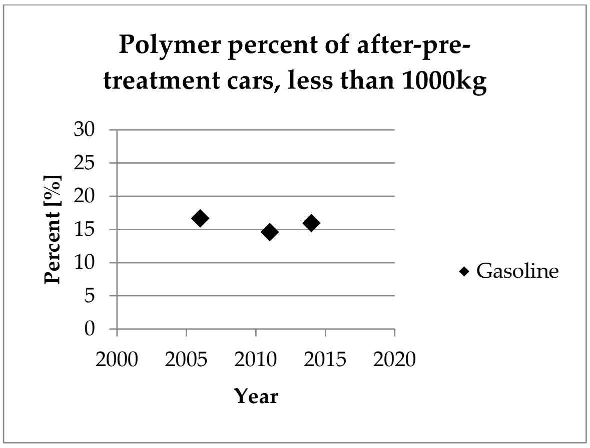
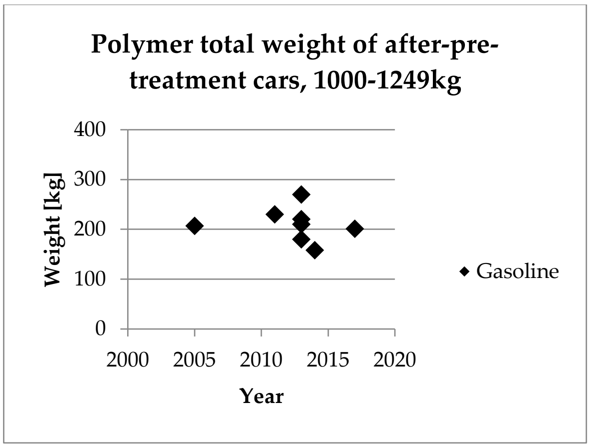


Figure 21: A2mac1 percent of plastics weight in after-pre-treatment cars <1000kg.



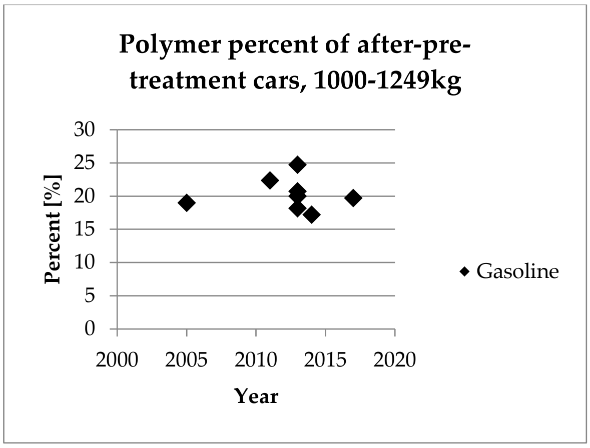
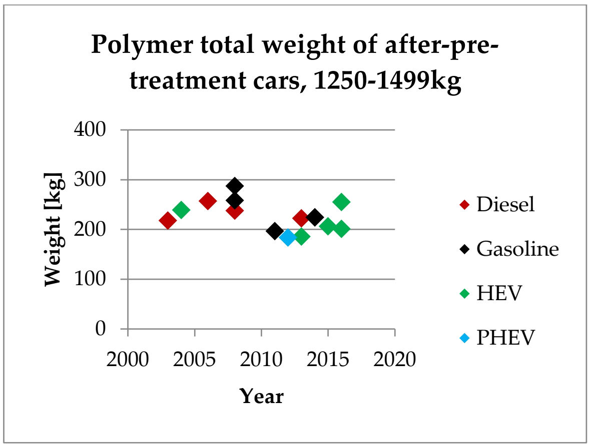


Figure 22: A2mac1 weights of plastics in after-pre-treatment cars 1000-1249kg.

Figure 23: A2mac1 percent of plastics weight in after-pre-treatment cars 1000-1249kg.



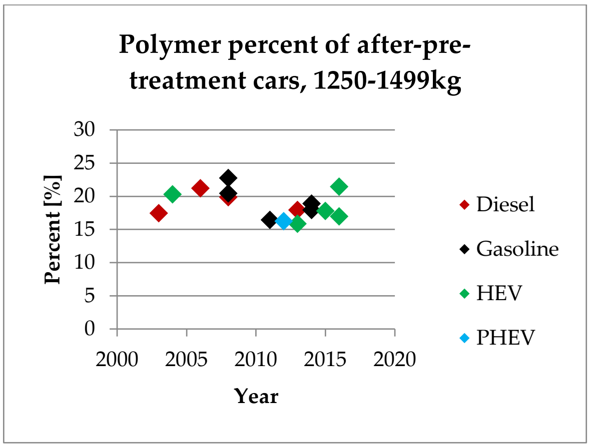
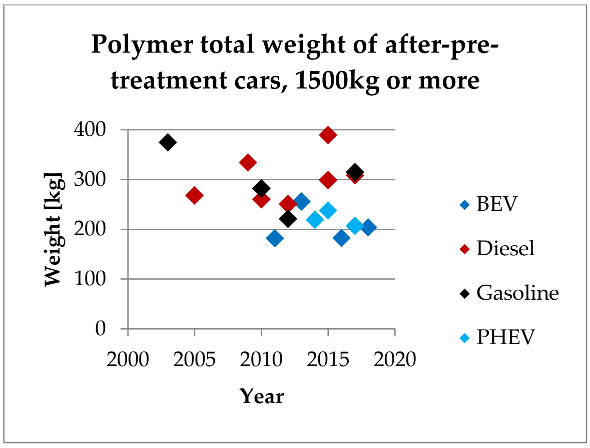


Figure 24: A2mac1 weights of plastics in after-pre-treatment cars 1250-1499kg.

Figure 25: A2mac1 percent of plastics weight in after-pre-treatment cars 1250-1499kg.



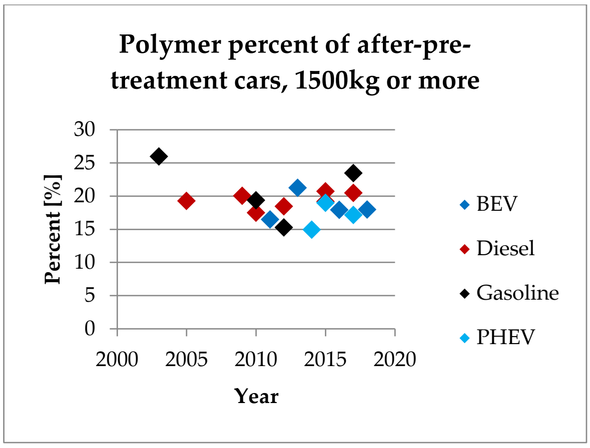


Figure 26: A2mac1 weights of plastics in after-pre-treatment cars >1500kg.

Figure 27: A2mac1 percent of plastics weight in after-pre-treatment cars >1500kg.

Note that a big increase for a single data point between plastics and polymers means that a relatively large part of the polymer material is made of elastomers. For instance, in the 1250-1499kg weight category, the gasoline car produced in 2006 is one example of a car that has more elastomer material than most other cars.

5.1.3 Series Comparisons

Comparisons between cars in the same series were done for the a2mac1 files spanning the past two decades. The reason was to find if there were any increases or decreases in plastics or polymeric material use that could be attributed to design changes that have happened in the past. A homogeneous increase or decrease for all series would be clear sign that something had changed in their design. Four series were chosen and each car model in each series was chosen so that it would resemble the other models in the series as closely as possible. The powertrains for the cars were gasoline, diesel, hybrid, and battery driven.

Table 9: A table with the car models in the four series chosen for comparison.

Car Series	Powertrain	Car Model	Production Year	Stated Curb weight in a2mac1 [kg]	After-pre-treatment total weight [kg]
Nissan Leaf	BEV	Nissan Leaf	2011	1 520	931
		Nissan Leaf SV	2016	1 525	868
		Nissan Leaf Tekna	2018	1 577	903
BMW 5 Series	Gasoline	BMW 5 Series 3.0 i Sport	2003	1 622	1 169
		BMW 5 Series 520i	2010	1 645	1 243
		BMW 5 Series 523i	2017	1 567	1 030
Volkswagen Golf	Diesel	Volkswagen Golf V 1.9 TDi Comfort	2003	1 390	1 029
		Volkswagen Golf V 2.0 TDi 140 Carat	2006	1 361	1 010
		Volkswagen Golf VI 2.0 TDi Comfortline	2008	1 345	1 020
		Volkswagen Golf VII 2.0 TDi DSG Highline	2013	1 441	1 040
Toyota Prius	HEV	Toyota Prius 1.5 Base	2004	1 350	1 015
		Toyota Prius 1.8 Hybrid Touring	2015	1 418	956
		Toyota Prius 1.8 VVT-i Hybrid Lounge	2016	1 421	990

Although there are some slight increases and decreases for the separate cars throughout the years, there was no obvious upward or downward trend of their curb weights.

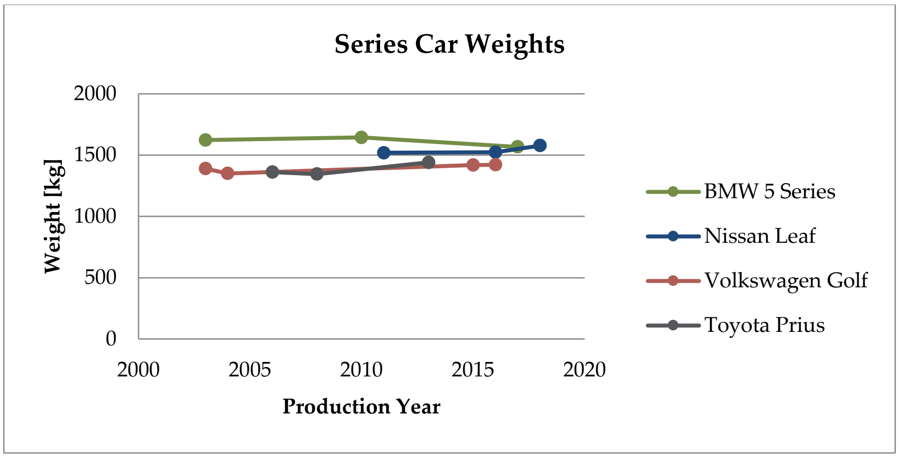


Figure 28: Curb weights for the four different car series from a2mac1.

Apart from the weight of plastics and polymer material on the BMW 5 series which showed some downward and upward changes between its models, the cars showed no major changes in plastics weights. The BMW 5 series seems to have less plastics and polymer material in its later models than it did in 2003. The BMW 5 series also has more plastic material, by about 50 to 200kg, than all the other series, and even the models with less plastic material still had more than any of the other cars in the other series.

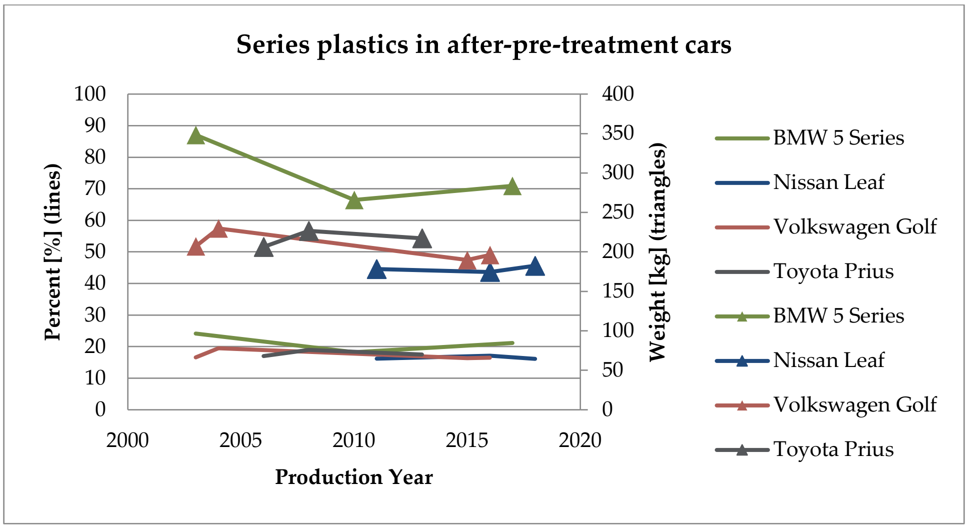


Figure 29: The polymer weight percent (lines) and weight of four car series from a2mac1.

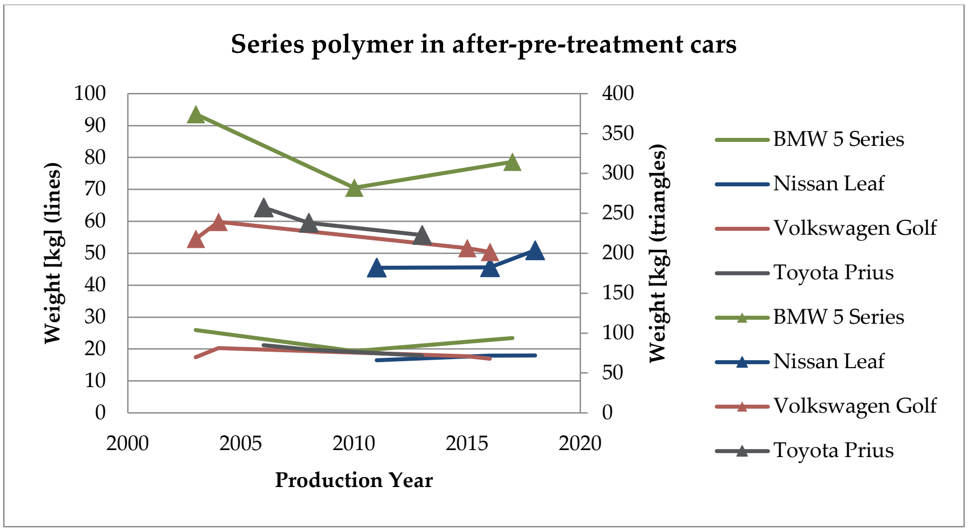


Figure 30: The plastics weight percent (lines) and weight of four car series from a2mac1.

5.1.4 Plastic categories, powertrains and years

The following subsection puts together the a2mac1 data for the plastic and elastomer categories for different powertrains and for different production years.

A2mac1 has several categories in two groups called 'Elastomers' and 'Plastics'. The following graphs will only look at the material data from these categories. Section 3.2.1 showed how the plastics and elastomer material also exists in categories that are not in the 'Elastomer' or 'Plastics' groups, so it should be no surprise to the reader that there are additional polymeric materials in the cars that is not considered and compared in this section. We believe that the plastics and polymers in this section are of kind that can be separated from other materials relatively easily since they were identified and usually measured to the nearest hundredth of a kilogram in the files. Additionally, since the accuracy seems to be so high in the files, the values in these categories can also be the minimum amount of these plastics in each car. Table 10 shows what the weights for the top six categories are for each powertrain. Table 11 shows the same information, but for the cars produced in four different yearly intervals from 2000 to 2020. The pie charts in this section contain the percentages of the top six plastic and elastomer categories of the total weight in the plastic and elastomer categories. Each category has a unique color to make comparison easier.

Table 10: The top six categories in the plastic and elastomer category groups for the averages of different powertrains, and the total weight of both categories.

Fuel Type	Categories [kg]							Total [kg]
BEV	**ABS**	**ABS-PC**	**PUR**	**Other plastics**	**TPV;TPE**	**PP**	**Other categories**	
	7	8	9	10	11	54	30	122
Diesel	**Other plastics**	**EPDM**	**PE**	**PA**	**PUR**	**PP**	**Other categories**	
	10	11	12	17	20	70	55	185
Gasoline	**EPDM**	**Other plastics**	**PE**	**PA**	**PUR**	**PP**	**Other categories**	
	7	9	11	14	16	65	31	145
HEV	**PBT;PET**	**PA**	**Other plastics**	**PUR**	**PE**	**PP**	**Other categories**	
	6	8	10	10	12	67	33	142
PHEV	**Other plastics**	**PBT;PET**	**PA**	**PUR**	**PE**	**PP**	**Other categories**	
	6	8	10	10	11	72	29	141

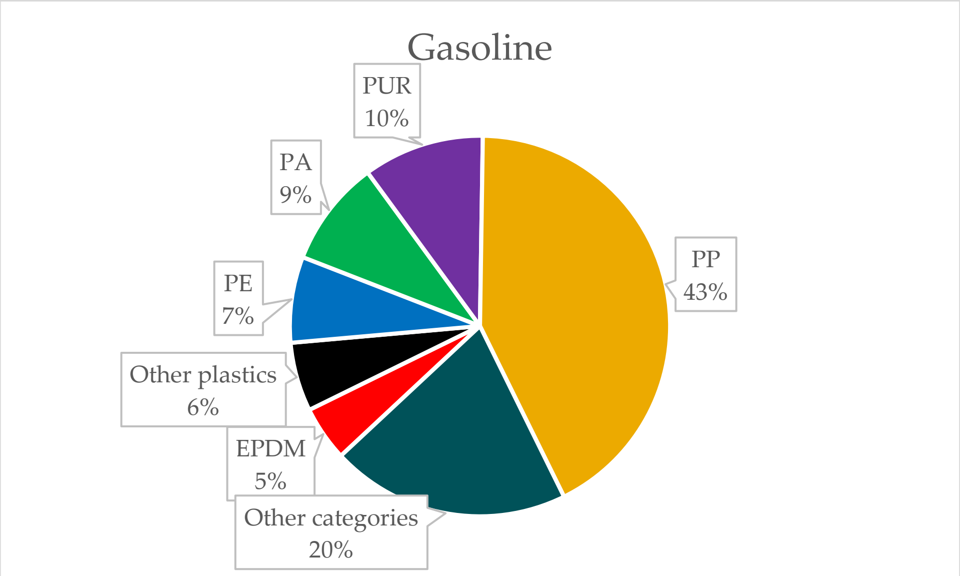


Figure 31: a2mac1 top six plastic and elastomer categories of the averages of all gasoline vehicles. 'Other categories' contains the weights of the remaining categories.

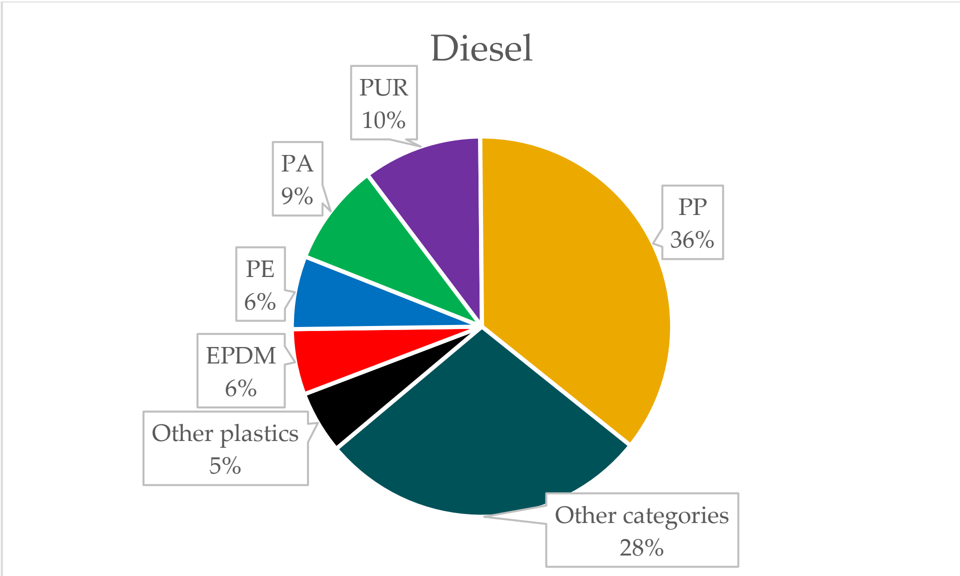


Figure 32: a2mac1 top six plastic and elastomer categories of the averages of all diesel vehicles. 'Other categories' contains the weights of the remaining categories.

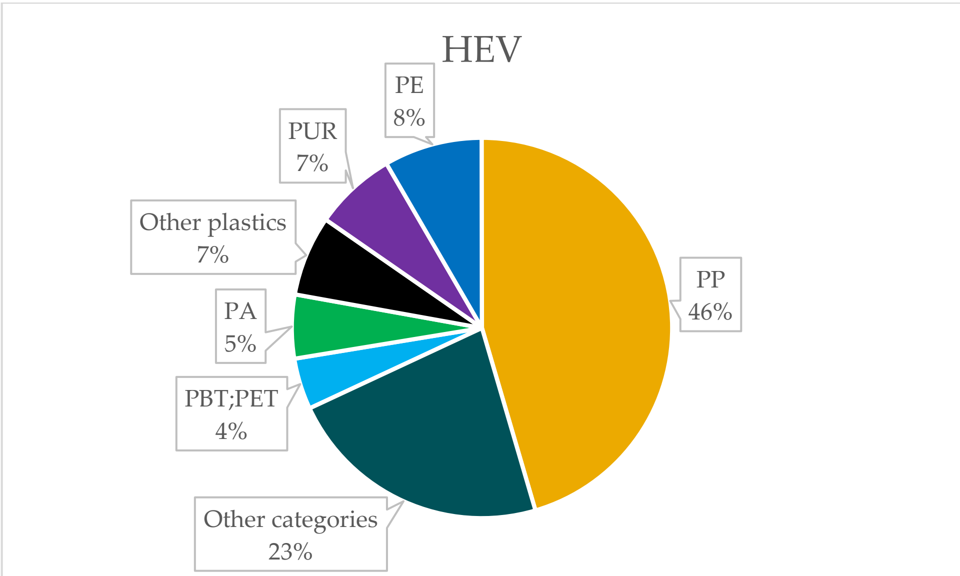


Figure 33: a2mac1 top six plastic and elastomer categories of the averages of all HEVs. 'Other categories' contains the weights of the remaining categories.

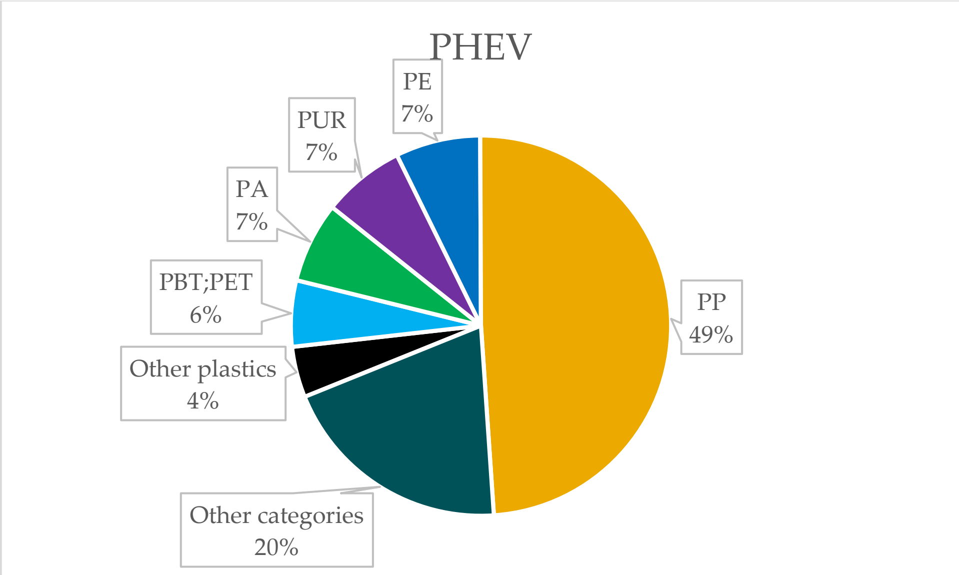


Figure 34: a2mac1 top six plastic and elastomer categories of the averages of all PHEVs. 'Other categories' contains the weights of the remaining categories.

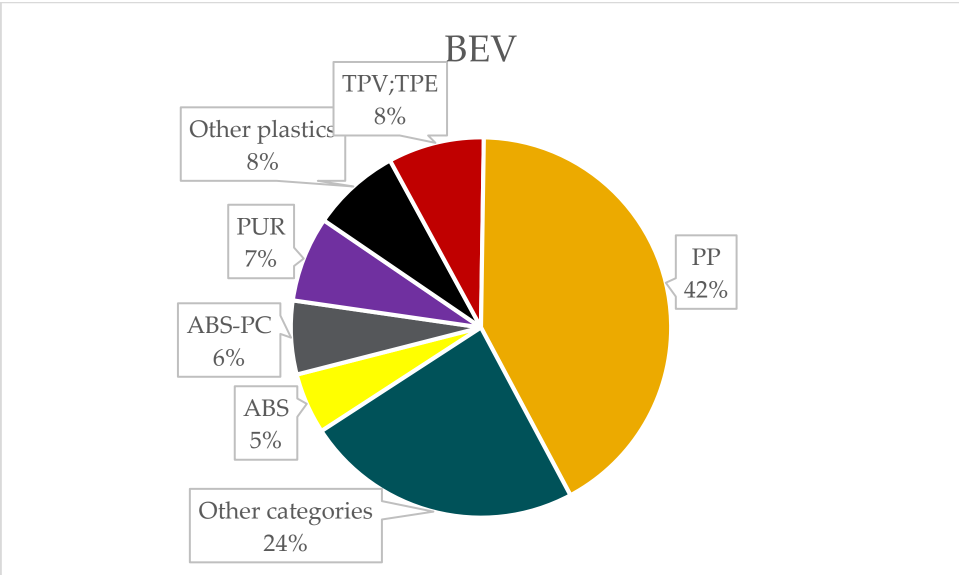


Figure 35: a2mac1 top six plastic and elastomer categories of the averages of all BEVs. 'Other categories' contains the weights of the remaining categories.

Note that the 'Other plastics' category exists for cars of all powertrains from 5-8 percent. Other categories than the top 6 are from 20-28 percent. The next table and pie charts compare cars of different production years rather than powertrains.

Table 11: The top six categories in the plastic and elastomer category groups for the averages of different yearly intervals, and the total weight of both categories.

Production Year	Categories [kg]							Total [kg]
2001-2005	**PE**	**PA**	**EPDM**	**PUR**	**Other plastics**	**PP**	**Other categories**	
	11	14	16	16	20	66	42	174
2006-2010	**Other plastics**	**PE**	**EPDM**	**PUR**	**PA**	**PP**	**Other categories**	
	10	11	11	15	15	57	45	155
2011-2015	**ABS**	**Other plastics**	**PE**	**PA**	**PUR**	**PP**	**Other categories**	
	6	8	10	11	15	67	33	145
2016-2020	**PBT; PET**	**ABS**	**PE**	**PA**	**PUR**	**PP**	**Other categories**	
	7	8	11	13	15	72	39	158

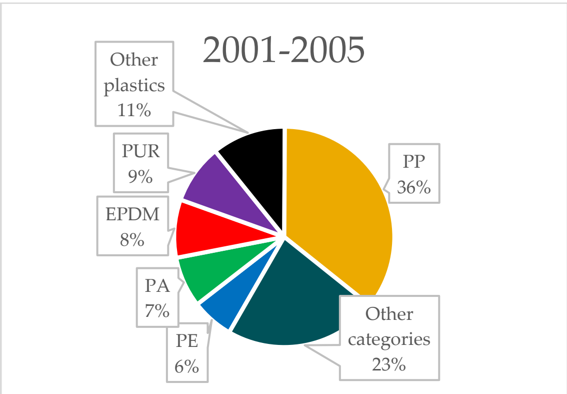


Figure 36: Pie chart of the top 6 plastic and polymer categories in the years 2001-2005.

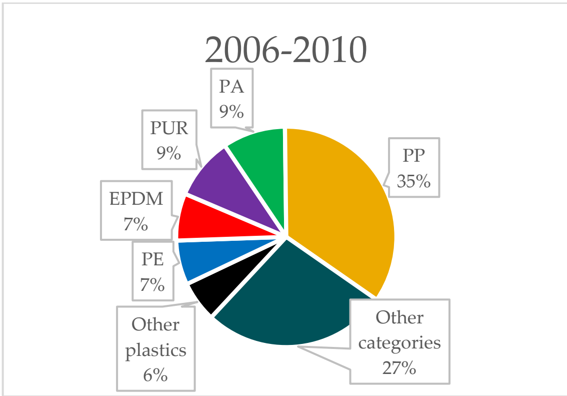


Figure 37: Pie chart of the top 6 plastic and polymer categories in the years 2001-2005.

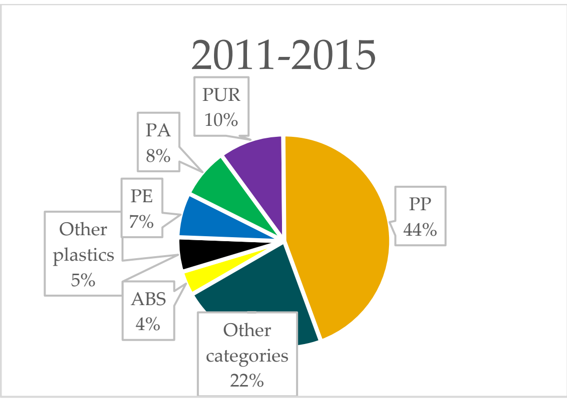


Figure 38: Pie chart of the top 6 plastic and polymer categories in the years 2001-2005.

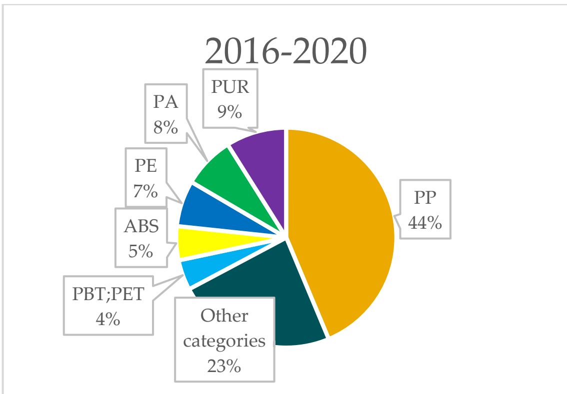


Figure 39: Pie chart of the top 6 plastic and polymer categories in the years 2001-2005.

The 'Other plastics' categories for the four year-intervals is, respectively, 11, 6, 5 percent, and not present in the top 6 for the 2016-2020 interval.

Looking at all the pie charts we see that PP plastic is most common at 35-49 percent. PUR is also in all pie charts at 7-10 percent. PA is present at 5-9 percent but is not top 6 for the BEVs. PE is present at 6-8 percent but is also not top 6 for the BEVs. EPDM is present at 5-6 percent only in gasoline and diesel cars, and 7-8 percent from 2000-2010. PBT; PET is only is at 4-6 percent in HEV and PHEV powertrain cars only, and in 2016-2020. Two categories, TPU; TPE and ABS, are only found in the top six categories for BEVs at 8 and 5 percent, respectively.

The total weight of the material in the plastic and polymer groups varies slightly between both the powertrains. BEVs have the lowest amount at 122kg and diesels the highest at 185kg. The rest of the cars are around the middle mark in-between.

5.1.5 Some deviations and uncertainties found in the a2mac1 data

The difference between the curb weights on the a2mac1 files and the sum of the weight categories is not always zero for the cars, see Table 12. The error margin from these deviances in weights need to be added to the total error margin and considered in the analysis of the results. The maximum difference in deviance was about 69kg or 4 weight-percent.

Not all a2mac1 data could be used for material weight comparisons for different reasons. For five of the cars, there was over 280kg in the category 'Other>NA', whereas all the other cars had under 1.5kg in this category. The extra errors would make the comparison less meaningful if the cars were included in the summations of plastics and polymers. For one car there was simply no material weight data. For the last car, the total weight of in the a2mac1 file is about 1ton lower than the weight on the car manufacturer's website, and therefore the model was not included in the comparison.

5.2 Comparisons of plastic and polymer content from different sources

In the following section we present the results from a2mac1, the Volvo BOMs and literature side-by-side for comparison. The data from a2mac1 could be converted into equivalents (with some approximations) to either the Volvo BOMs or the literature data.

5.2.1 Plastics and Polymer Curb weight comparisons (a2mac1 vs. literature)

The sums of the plastics content and plastics + elastomer content from the sources discussed in 4.2 were compiled into graphs below for comparison with the data from a2mac1 and Volvo. Unfortunately, only Applied Plastics Engineering Handbook explicitly states that they cover European data, and AT Kearney doesn't specify for which region their data is for. The rest of the data points are for the North American or U.S. markets.

For the literature data, there was more data available for plastics than for polymer material (plastics + elastomer). In the a2mac1 results, the shapes of the plastics graphs and the polymer materials graphs are very similar. Therefore, the additional data point in Figure 40 can be used with the rest of the data points to see the general trend of polymeric materials from 2000-2020. The trend for the plastics in Figure 40 is a slight increase of about 1-6 percent over the past two decades. The European source (Applied Plastics Engineering Handbook) puts the plastics at 21 percent in 2004 and 22 percent in 2011, so its total polymeric fraction (including elastomers) must be greater than those percentages. Plastics percentages for the NA/U.S. sources (8-10 percent) are notably lower than the European source (21-22 percent) and AT Kearney (14-18 percent). The differences between the NA/U.S. sources are much less dramatic, giving us the confidence to presume that the AT Kearney is not a NA/U.S. source. (Note that AT Kearney's analysis includes 18 to 20 percent material weight in an "other" category, part of which could be plastics.)

The three N.A./U.S. sources had similar percentage values, so the deviation of the AT Kearney and the Applied Plastics Engineering Handbook values for the worldwide (we believe), and European values is likely due to a real difference in the plastic materials of cars between the regions. Additionally, the difference between the European data and the rest of the data shows that the polymeric material data for passenger cars between markets should not be compared directly.

5.2.1.1 Plastics

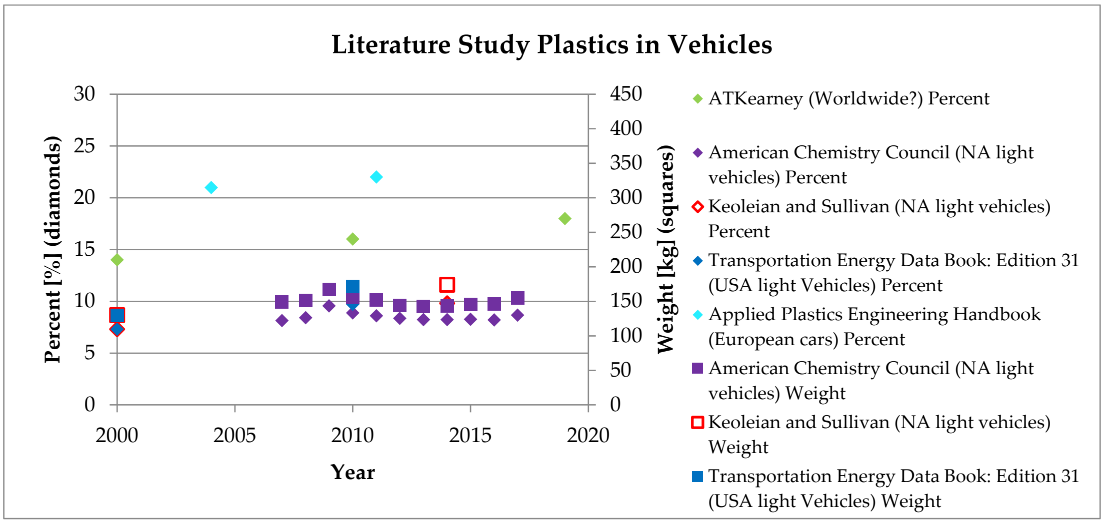


Figure 40: Plastics content of light cars from five sources. The weights have been converted from pounds to kilograms, where it was necessary for comparison. The diamond-shaped data points show the percent plastic material (left axis) and square-shaped data points show the total plastics weight (right axis). We assume that the plastic weight percentages for these studies are in terms of the vehicle curb weights.

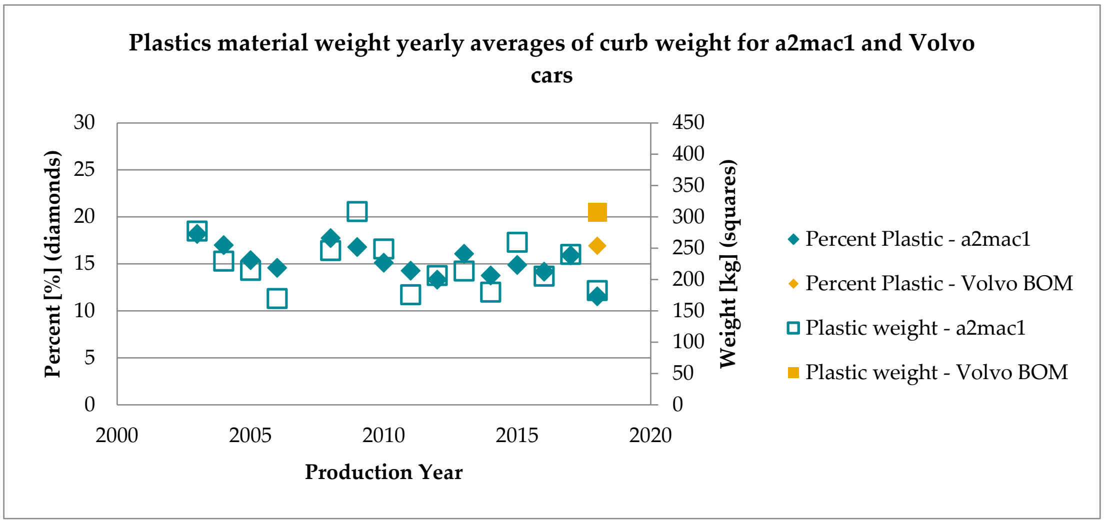


Figure 41: The average percentages and weights of plastics in the a2mac1 for the years that the a2mac1 cars were chosen for. The Volvo BOM data for cars 2018 cars were also averaged and placed into the graph.

In Figure 41, the a2mac1 percentages (represented by diamond data points) are within 11 to 19 percent plastic, with no upwards or downwards trends. These values are generally greater than most of the N.A./U.S. values, within the same interval as the AT Kearney data points, but less than the European data point. Figure 41 also shows the average of the Volvo BOM data points, which is for cars produced in 2018. The percent plastic is about 16-17 percent, which is like the a2mac1 data, but still less than the European data for the American Chemistry Council in Figure 40.

5.2.1.2 Polymer

The NA/U.S. polymeric fractions spanned from a minimum of 12 percent in 2000 to a maximum of 16 percent in 2009. The similarities of the shapes of the American Chemistry Council graphs in Figure 40 and Figure 42 indicate that the elastomer content fluctuates with the similar proportions as plastics.

Figure 42 shows the polymeric fractions and weights of several sources. The AT Kearney polymer fraction increased linearly from 20 to 25 percent from 2000-2019. (Note that this fraction is the minimum amount of polymer material as the “other” category of material is between 18 and 20 percent from 2000 to 2020.) The European polymeric fractions from Applied Plastics Engineering book would likely be greater than the AT Kearney fractions if they had been measured. They would likely be in the range of 25-30 percent from comparing the two graphs. However, in Figure 43, none of the data points for a2mac1 or the Volvo BOM are over 20 percent, so our data from these sources are about 1-6 percent less than for AT Kearney, and they would be up to about 10 percent less than the European data from the Applied Plastics Engineering book, if it had been recorded.

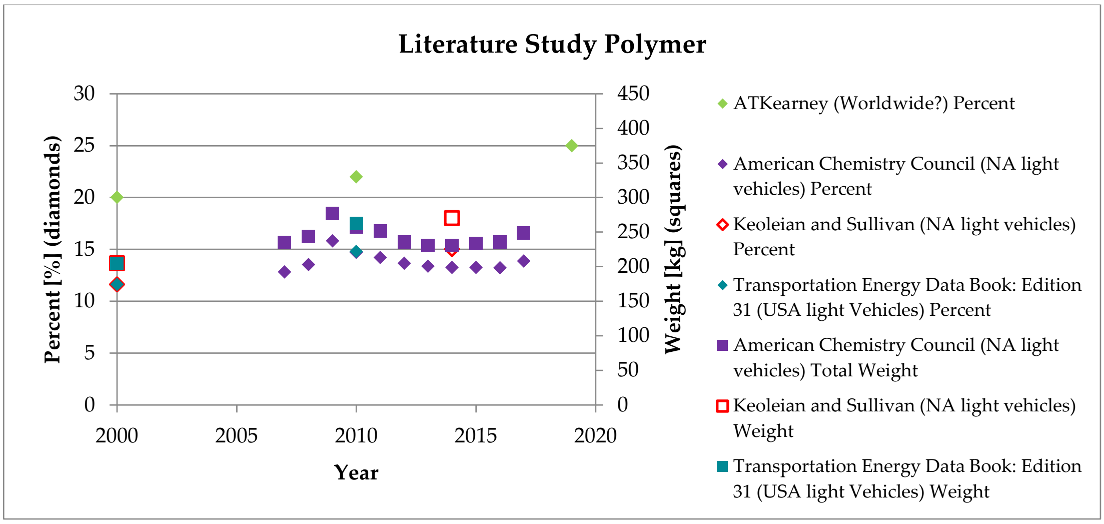


Figure 42: Plastics and elastomer (polymer) content of light cars from five sources. The weights have been converted from pounds to kilograms, where it was necessary for comparison. The diamond-shaped data points show the percent plastic material (left axis) and square-shaped data points show the total plastics weight (right axis). We assume that the polymer weight percentages for these studies are for in terms of the curb weights of the vehicles.

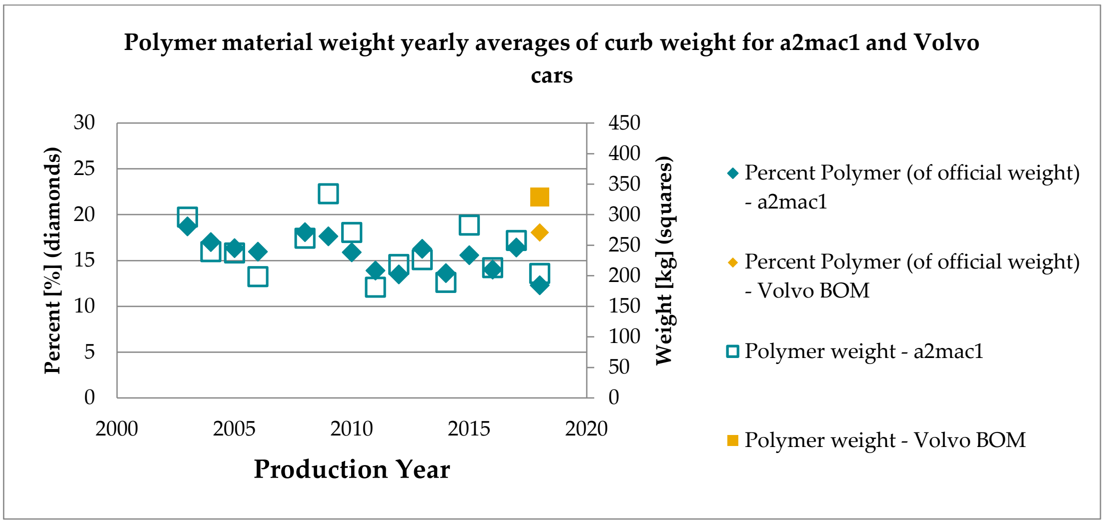


Figure 43: The average percentages and weights of polymeric materials in the a2mac1 for the years that the a2mac1 cars were chosen for. The Volvo BOM data for cars 2018 cars were also averaged and placed into the graph.

5.2.2 Plastics and polymer weights in after-pre-treatment comparisons (a2mac1 vs. Volvo BOM)

This section compares the a2mac1 and Volvo BOMs plastics and polymer material in car after-pre-treatment weights with each other. The weights and percentages of material are compared to the stated curb weights in the a2mac1 files, and the sum of the weights from all categories in the Volvo BOMs.

For a2mac1 graphs of the percentage plastic and polymer of the cars in respect to the curb weight instead of the after-pre-treatment weight, look at Figure 62 and Figure 63.

5.2.2.1 Plastics

The Volvo cars in Figure 47 have a narrow distribution of percentages of plastic, around 20 percent, for all cars. This means that there are unlikely any big design changes in the cars that have to do with changes in the materials. The a2mac1 cars in Figure 48 are more in numbers and have a wider distribution of percentages of plastic, from about 14 to 25 percent for all powertrains. The gasoline, HEV, PHEV, and BEV powertrains appear to have a wider distribution than the diesel powertrains which have values relatively close to 18 percent. The Volvo cars have a slightly higher average plastics percentage than any of the powertrains in the a2mac1 files. The difference could be due to more material or it could fall inside the errors of our estimation of plastics content due to the difficulties of categorization.

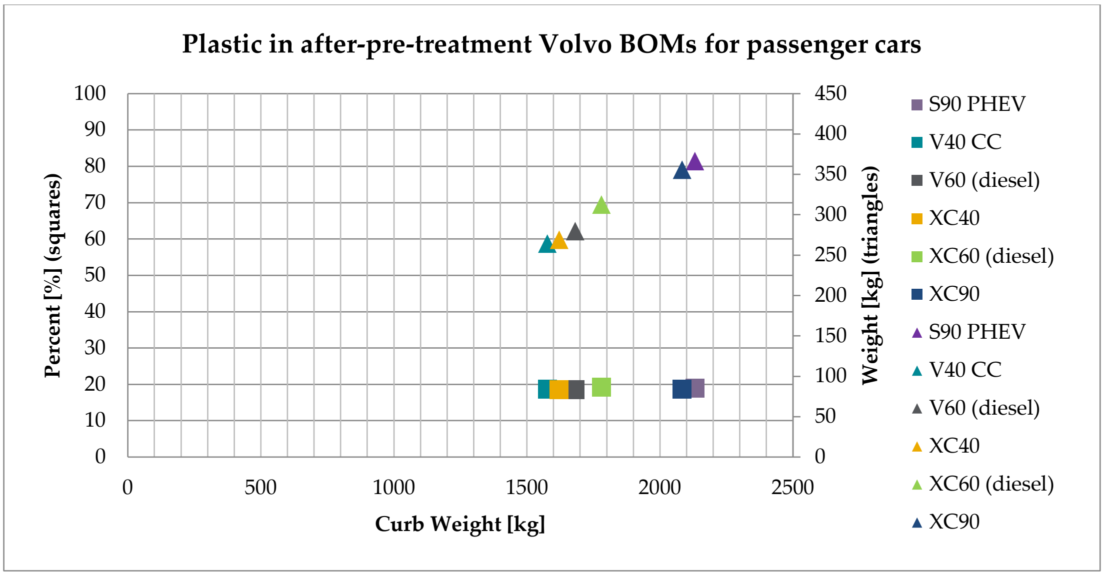


Figure 44: Plastic material percent (of after-pre-treatment weight) and plastic material weight from the Volvo BOMs for passenger cars produced in 2018. The squares correspond to the percent plastic material (left axis) and the triangles for the weight of plastic material (right axis), for the different models. The percent is for plastic in after-pre-treatment.

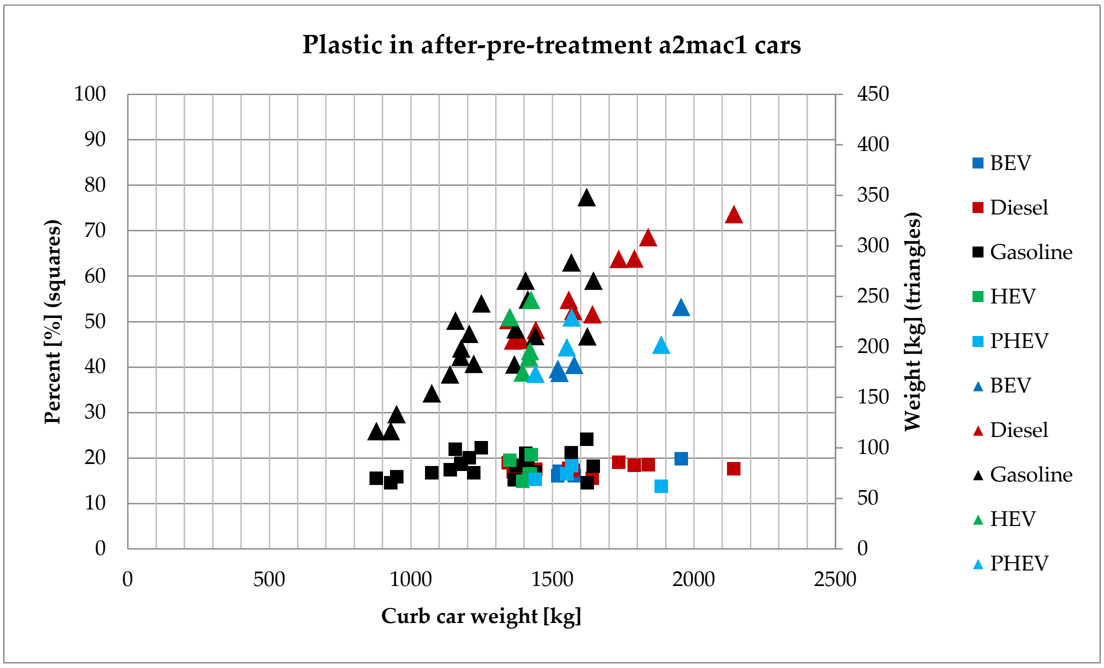


Figure 45: Plastic material percent (of after-pre-treatment weight) and plastic material weight from the a2mac1 passenger cars produced from 2003-2020. The squares correspond to the percent plastic material (left axis) and the triangles for the weight of polymer material (right axis), for the different models. The percent is for polymer in after-pre-treatment.

From these graphs we can clearly see the trends that show how heavier vehicles have more plastic material in them. The differences in percentage plastics in each powertrain could be due to several design factors rather than differences of materials choices specific to the powertrain technologies.

5.2.2.2 Polymer

The polymer materials percentages for a2mac1 have a wider distribution than the plastic materials for Volvo cars in Figure 46. The XC60, and XC90, and S90 PHEV have larger percentages than the other cars, meaning that the elastomeric material in these cars is slightly greater. The greater variation in percentages of the polymer material than the plastic material in the Volvo cars means that generally the Volvo cars have the same amounts of plastics, but certain models have elastomer material than others.

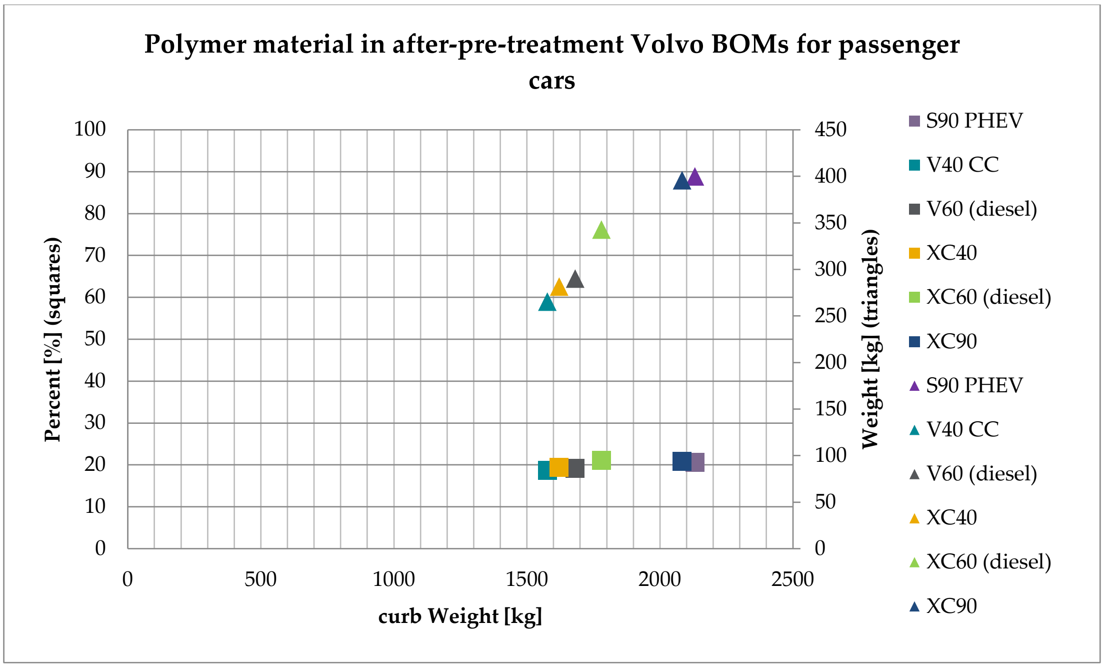


Figure 46: Polymer material percent (of after-pre-treatment weight) and polymer material weight from the Volvo BOMs for passenger cars produced in 2018. The squares correspond to the percent polymer material (left axis) and the triangles for the weight of polymer material (right axis), for the different models. The percent is for polymer in after-pre-treatment.

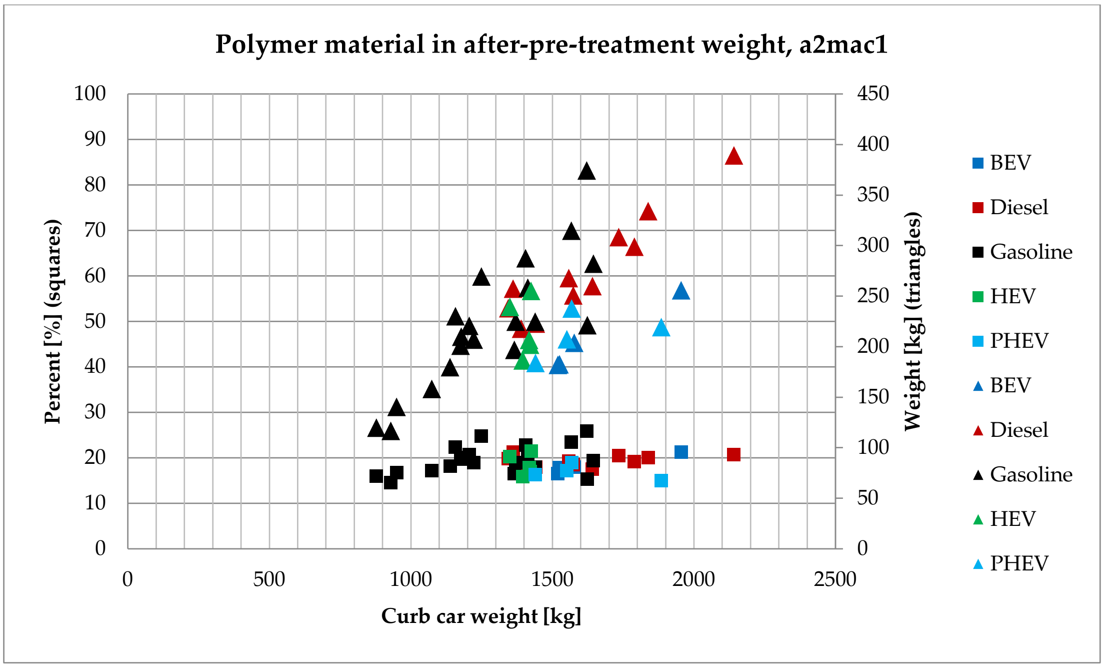


Figure 47: Polymer material percent (of after-pre-treatment weight) and polymer material weight from the a2mac1 passenger cars produced from 2003-2020. The squares correspond to the percent polymer material (left axis) and the triangles for the weight of polymer material (right axis), for the different models. The percent is for polymer in after-pre-treatment.

The polymer materials percentages in the a2mca1 cars range from about 15 to 26 percent. BEVs and PHEVs have slightly lower percentages than the rest, but since they also have fewer data points.

The HEVs are all around the same curb weight, yet the spread in the percentage polymeric material is still wide, pointing to, perhaps, large differences in design within this powertrain.

6 Discussion

6.1 Comparisons

We compared the data from the Volvo BOM with the a2mac1 data to see if the choices in categories were done similarly. The a2mac1 cars had a bigger spread of percentage plastic material in the cars than the Volvo cars, but the average for the Volvo cars was still in the middle range of this spread, around 20 percent, see Figure 44 and Figure 45. The overall trend in the plastic and polymer material for the a2mac1 cars over time is very steady and flat over the twenty-year period in Figure 9 and Figure 11. The trends for the graphs are quite similar for all drivetrains. However, there are some differences in the vehicle weights, which leads to certain powertrains (namely gasoline and diesel ICEVs), in section 5.1.1, having more plastic material in them, solely because the cars are heavier.

In 5.1.2 we compared different weight classes for plastic and polymer total and percentage weights. We found that the plastics and polymer percentages were steady for each respective drivetrain. The plastics and polymer weights of ICE cars in the over 1500kg weight class were slightly higher than the rest of the cars with different powertrains. It was harder to do a weight comparison of other cars. There were only gasoline ICEVs and the diesel ICEVs in the lower two weight divisions, so it would have been beneficial for comparison if we had found some cars with other powertrains within these weight divisions because the other powertrains only appeared in at most two weight divisions. We didn't find cars under 1250kg for HEVs, PHEVs, and BEVs that were top sellers in the Swedish market. Perhaps the size differences between the cars were not enough for their design to have an observable impact in the materials differences. Comparing the averages for our vehicles with even larger cars or vans might give more insight into the components and types of materials that must change with the weight of the vehicle.

In section 5.1.3 we compared four car series that all had 3-4 cars manufactured in the past two decades: one gasoline ICEV (BMW 5), one diesel ICEV ((Volkswagen Golf), one HEV (Toyota Prius), and one BEV (Nissan Leaf). All series except for the BMW 5 series showed a constant amount of plastic material throughout the years. The BMW5 series first model had a higher weight and percentage plastic than the other two, but the difference is too small to be considered significant. It is important to note that the models may have had different options or upgrades that could have been the reason for some of the plastics weight variation. All the BMW cars in the series still had more plastic material than the other cars in the other series.

In section 5.1.4 the top plastic and elastomer categories for a2mac1 in terms of weight were compared for different powertrains and years. The most common plastics and elastomers were PP, PUR, PA, PE, EPDM, PBT; PET, TPU; TPE, and ABS. PP was overwhelmingly present in cars of all categories and powertrains, which is in accordance with our literature study, and PUR was also very common. More EPDM was present in gasoline and diesel cars and cars chosen between 2000-2010, but this might be because there weren't many other cars with other powertrains that were available within that period. We saw some trends towards the use of more TPV; TPE, ABS-PC, and

ABS plastics in BEVs than in other powertrains and there was more use of PBT; PET in HEVs and PHEVs. PA and PE were common in all cars but did not have its own "top 6" category for BEVs.

In section 5.2.1 we compared the literature data with the a2mac1 vehicles to see if they followed a similar trend or deviated from it. From looking at the graphs we see that the trends are quite similar: there has been little change of the total amount of plastic and polymer material in cars in the past two decades. The data from the literature review, a2mac1, and Volvo had some similarities and some differences. The percentages for the a2mac1 and Volvo BOM car plastics and polymers were in between the averages for N.A./U.S. values, like A. T. Kearney's presumed worldwide values, and less than the European values from the Applied Plastics Engineering Handbook. The trends of the N.A./U.S. values varied between 2000-2020, much like the a2mac1 values. However, there was a small increase for both A.T. Kearney and the European values that we couldn't see in the a2mac1 values, possibly due to the uncertainties and sources of error, see section 6.2.

6.2 Uncertainties, sources of error

There are, as mentioned several in the Method, many sources of error in the a2mac1 data that attribute to a less-than-perfect representation of the total plastic content of vehicles in the past decades. From looking at the data for the a2mac1 files it became apparent that the car dismantling categorization was not always consistent. Firstly, some vehicles simply had most of their weights in the 'Other>NA' category, rendering them unusable for comparison to the other vehicles. Secondly, the entire or part of the weight of tires might be in several categories: 'Metal+Elastomers', 'Natural Rubber', or even in 'Other>Several Components'. However, since none of these category weights were consistently above average tire weights or the minimum weight for the tires' separated material weights it became obvious that the dismantling method wasn't the same for all vehicles. This lack of consistency unfortunately translated to errors in the comparison of plastics and polymers for the chosen cars. Thirdly, when all the weights for the a2mac1 categories were added up, they deviated up to 4 percent from the stated weight in the file.

The Method section showed several sources for inaccuracy of the real plastics and elastomer contents of vehicles from available data. From the a2mac1 dismantling side it seems difficult to separate and identify many types of plastics, hence some of the broader categories such as 'Metals+Plastics' and 'Other>Several Components'. The a2mac1 files had component breakdowns for the cars that weren't available for all the cars. It is possible that having access to more information about what components are in each category could have helped in better estimates with a smaller error. The Volvo BOMs are a combination of many suppliers' material information put into IMDS categories. This task is very difficult to do with full accuracy, because for some parts could be interpreted to be in more than one single category. For both the a2mac1 data and the Volvo data, approximations had to be done for electrical parts that unfortunately shrouded information about how the propulsion battery components (and the additional wiring) in HEVs, PHEVs, and BEVs are different from an ICE. Electric component generally include more and smaller parts than most other vehicle parts so this may be a reason for the lack of detail in this category.

The incomplete information for some of the a2mac1 cars certainly brings to question the validity of the information for the cars that were used in the report. However, upon comparison with the percentages of plastics/polymers with the literature (for European cars) and with the Volvo BOMs we see that the numbers are in the same range. Additionally, the a2mac1 car weights had high detail, with weights usually accurate up to a hundredth of a kilogram. We believe that weights in the specific plastic and elastomer categories were accurate, and that any inconsistency in data was due to materials being placed in general categories rather than being misplaced into a specific category.

There are many uncertainties from the data in the literature. For most of sources, it was never explicitly stated how the information was gathered. It would be interesting to get more information on the methodology of gathering the data that was used. It would also be of good use to get a clear definition of what is meant by plastic or elastomer in some articles, as some sources were better than others at describing this aspect. Additionally, it is useful to know what the vehicle weight is defined as, since differences in this interpretation can mean differences in the weight by over 100kg. Finally, the meaning of 'average vehicle' should be illuminated as it can mean many things when there is a plethora of car models with different production years to make the meaning more unclear without a more thorough description.

A problem of categorization appeared when we tried to interpret 'plastics' or 'polymer material' in the literature. Most sources discuss the plastics content in vehicles, but it is not as common for a source to list exactly what polymer compounds are included in their definition of 'plastic'. Furthermore, the addition of fillers to most plastics means that there is another variation in the type of plastics quality (although we did not look at this specifically in the study). Also, whether liquids are included in the total weight of the vehicle is a factor that can throw off a total polymer percent estimate. We therefore cannot say that the literature sources interpreted plastics and polymers in the same way that we did. It is also likely that the data from other sources was gathered in a way that was different from us.

6.3 Discussion on future trends

From the literature review, we found that it is unlikely that any new and better technology (currently known) on its own will cause big shifts in regarding polymers in cars in the coming years. The availability and price of resources, as well as legislation, play a big role in the decisions taken by the automotive industry. The ban of certain POP substances, manufacturing and design difficulties of composites and rising oil prices push up the prices of manufacturing plastics. There is also an intrinsic resistance to change in production due to the cost of retooling already existing production equipment. Fibre composite materials have some advantageous properties in light-weighting, but the hurdles to its inclusion in light-duty cars make it difficult to become more widely used. The literature study found that certain trends towards using polymer parts, such as replacing metal fuel tanks with plastics and the use of polymer foams. Also, more circuit boards and wiring are present with the increasing electrification of vehicles.

Several experts from the automobile industry agree that the use of more composites in cars is unlikely to happen anytime soon, but there are still those who write that the production of carbon fiber will increase in coming decades, likely for high-end cars. Future technologies, such as self-driving cars, may affect the design of vehicles in the future, but this will have a minor impact on materials in end-of-life vehicles within the time-scope aimed for in of this work.

6.4 Recommendations for improved accuracy in future work

For future work in this area, we recommend to consider the issues we identified regarding the collection of data and estimation of accurate polymer materials content in cars. If one is to use a2mac1 to determine the materials content, it is very useful to download several product trees for different cars to get a better understanding for which categories the battery and wheels are placed in, and to note any inconsistencies.

There has been a shift to new powertrains in the last decades, and the information in a2mac1, of course, has fewer cars of "newer" powertrains the traditional ones. The more cars that become available for each category, the more data points will become available, and the better a comparison will be. In a few years, more data will likely become available on new HEV, PHEV, and BEV models which will enable improved comparisons between cars of different powertrains.

When selecting vehicles from a2mac1, we found that HEVs, PHEVs, and BEVs were heavier than most ICE gasoline cars because there were only ICE gasoline the two lighter categories. To do a better comparison in future work, it would be beneficial to first do a mapping of the weights of the vehicles of different powertrains so that it is easier to observe which ones are directly comparable by weight of plastic and polymer material. The rest can still be compared with the percentage of plastics and polymer material, similar to the comparisons we focused on in this report.

There can be many variations in data specificity, in different parties' interpretations of the definitions of plastic/elastomer/polymer materials, in what defines an 'average' vehicle, and in what region the data is collected for. It is important to state the choice of data explicitly so that proper comparisons can be made. If comparing to other sources it should be known that there are likely differences in the choice of, for example, an average vehicle on the road in a certain year and region.

7 Conclusions

We chose the a2mac1 cars for representing the Swedish fleet using its data for light-duty cars. Other sources have likely chosen cars based on other criteria, but we did not find any detailed descriptions of which cars were chosen in those sources, nor why they were chosen. The literature study showed that the plastic weight share in cars has increased compared from early measurements between the 1950s up to year 2000. Between the 2000-2018, some literature sources showed a slight increase in plastic and polymeric weight shares while others showed no increase. The NA/U.S. sources showed a constant trend (neither increasing nor decreasing) whereas the European and worldwide sources showed a slight increase of a few percent. However, many of these sources lacked transparency as to their selection of cars, indicating the need for a more analyses with better descriptions of the data used for the calculations.

We deemed the a2mac1 data we collected as more reliable than literature sources because we had control over the selection of cars. Our a2mac1 results suggest that the trends of increasing polymeric materials reported from the middle of the 1950s up to year 2000 is no longer occurring, and a constant trend (neither increasing nor decreasing) is taking place from 2000-2018, regardless of the powertrain. Additionally, we didn't find any clear difference in weight shares of plastic and polymer materials between cars of the different powertrains. We also didn't find any clear difference in the weight shares of plastics and polymers between cars of different weight classes. When we compared car models in series over time we also did not note any upwards or downwards trends in the five cars models we observed. Based on the data results from a2mac1 and our interactions with industry professionals, we conclude that the typical Swedish car produced up until around 2025 in not likely to have any significant increase or decrease in its plastic and elastomer shares compared to today's.

We found that the a2mac1 data could be inconsistent at times. There were sometimes data gaps when most of the materials weights were placed in collective categories instead of being spread throughout more specific categories. We also suspect that their method of placing components and parts in categories was not done in a standardized way, based on comparing the weights of the same categories for similar cars. Because of these uncertainties, we acknowledge that the possibility exists that we may have missed some more subtle trends that may have occurred in the past two decades for light-duty vehicles.

There was a larger spread of plastic and polymer weights on the a2mac1 cars than the Volvo BOM cars, which is likely due, in part, to the different approaches of collecting the weights and categorizations.

Our a2mac1 weight shares of plastic and polymer materials for the cars selected to represent the Swedish market were slightly higher than the N.A./U.S. cars from multiple sources, another source's worldwide cars, and slightly lower than a European source's cars. We found that heavier vehicles had similar weight shares of polymer material as lighter vehicles. This also means that heavier vehicles have more polymer material in total weight than the lighter vehicles. Thus, the total weight and number of vehicles sold is likely to be more decisive for the amount of plastics that can be recycled from vehicles in the coming decades in Sweden than foreseeable changes in car designs.

We saw some trends towards the use of more TPV; TPE, ABS-PC, and ABS plastics in BEVs than in other powertrains. There was also more PBT and PET in HEVs and PHEVs than in other powertrains. EPDM appeared to be more common in gasoline and diesel cars. PP was very common in all cars, as was PUR. PA and PE were common in all cars but were not among the top six polymer categories ranked by shares in BEVs.

The use of polymer fibre composites is touted by some sources as being a material for the future, but further research into literature, interaction with industry professionals, and interviews with Volvo has showed us that there is no major shift to substitute existing materials to polymer fibre composites in the near future for the average light-duty car. One source (Heuss, Müller, Sintern, Starke, & Tschiesner, 2012) writes that BEVs and PHEVs will have slightly more composites than traditional ICEs, and that high-end cars will be the cars with the most composite materials, because of the high price. Thus, the weight shares of composite plastics found in average light-duty cars will continue to be very small in the next few years.

We believe that the a2mac1 files give a minimum amount of specific material categories in their cars, so we don't expect to have overestimated the plastic and polymeric material amounts in our estimations, at least not by a sizeable amount. Since our calculated trend is constant, we can say with a high degree of certainty that the averages of plastics and polymeric materials in light-duty vehicles have not decreased substantially in the Swedish market since 2000.

The literature study in this work brought to light some considerations for predicting the future use of plastics. The car manufacturers' choice of using plastics and polymers is not restricted to just a few choices but is instead based on (but not limited to) the interdependent variables of material properties, pricing (of materials and oil), manufacturing costs and capability, and legislation.

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Appendix I

Notes on Categories for a2mac1

Paints, Lacquers, Adhesives and Sealants

The A2mac1 data doesn't have a category for paints and lacquers because they are already painted on the surfaces of the materials. For this reason, the weight of the polymer materials will be slightly more than if they weren't coated. As a reference, one North American source puts the total weight of coatings for the average 2016 NA light vehicle at 26 pounds (approx. 11.8kg), dry weight (American Chemistry Council, 2018). This weight is for the paint covering the entire car and the painted plastic portion will only be a certain percentage that varies between car models. For the a2mac1 file, we included this weight in the summation of plastic and polymer weights.

Tires

We saw in an a2mac1 product tree for one car that the weight of the wheels was in the 'NA' category. Not all cars had weights high enough to contain the wheels in the 'NA' category, so we assumed that their weights could be in different categories.

The tires are removed for reuse or recycling in separate facilities, so their weights must be removed from the a2mac1car weights. According to Michelin, "A standard car tire contains 18 percent natural rubber, i.e. about 1.35kg per tire" (Michelin, 2016). The average weight of natural rubber of the cars in the A2mac1 files is only 0.42ktg, so a large part of the tires' natural rubber must be in another category. The assumption is made that the tires are mainly in the 'Metal+Elastomer' category, which has an average weight of 32.13kg and ranges from 6.72kg to 144.24kg. Some of the weight of the tires is likely also spread throughout the 'Natural Rubber', and 'Other>Several Components' categories.

The weight of the hubcaps also needs to be removed. In one a2mac1 product tree we had available, the total weight of the four hubcaps were 2.584kg. Since we don't have more information about the material of the hubcaps for each of the cars, we cannot make a distinction in the categorization. We will assume for simplicity that the weights of the hubcaps are in either the 'Metal+Elastomer' or 'Other>Several Components' categories.

Since the weights do not appear to be consistent, we had to make some assumptions for the summation of the after-pre-treatment weight and the elastomeric material in the a2mac1 files. The weight of the four wheels, the spare wheel, and the hubcaps are 85.162kg in the product tree file available for the 2003 Ford Focus C-Max 1.8l (the material information was unavailable for the parts). This weight was subtracted from the curb weights of all vehicles in the order: 'Metal+Others', 'Natural Rubber', 'Other>Several Components', the rest of the elastomer categories, 'Metal+Plastics', 'Other Plastics'. Note that the different vehicles may have different sizes or types of tires, but we did not account for this.

Batteries

The starter battery (for all vehicles) and the propulsion battery (for HEVs, PHEVs, and BEVS) are not considered part of the after-pre-treatment weight, because they are removed before the cars are dismantled. The weights of the batteries are most likely found in two separate categories: starter batteries in ‘Several Components’ and traction batteries in ‘Electronic Components’. In one of the product trees for a Ford Focus C-Max 1.8l in the product tree of an a2mac1 file the starter battery was split into three categories, with most of the weight in the ‘Several Components category’. For the propulsion battery, we deduced from the weights of the powertrains in the ‘Electronic Components’ category that the bulk of the weight was found there, see Figure 48.

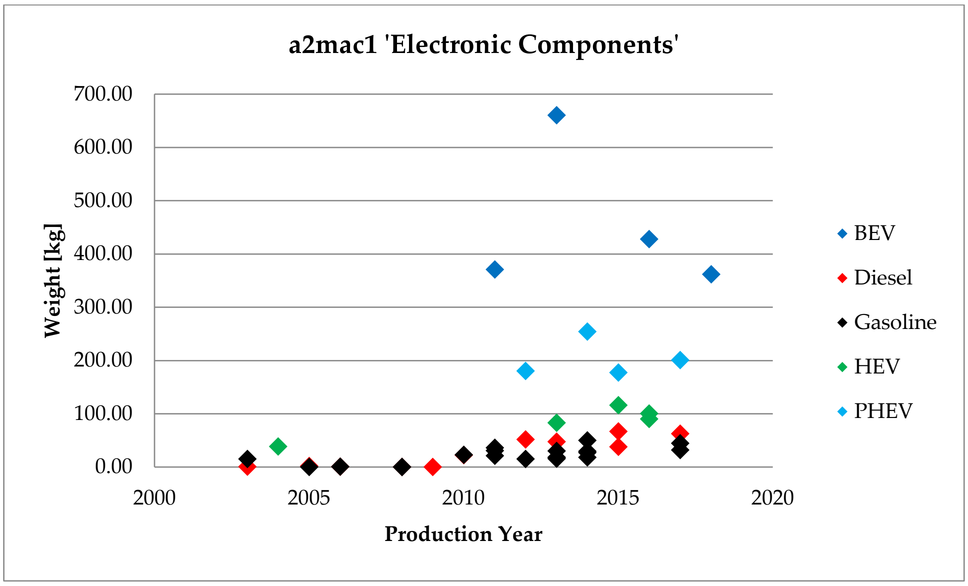


Figure 48: The weights of the ‘Electronic Components’ category. The powertrains with larger weights are the BEV, PHEV, and HEV categories. We therefore assumed that the propulsion battery weights are in this category for a2mac1.

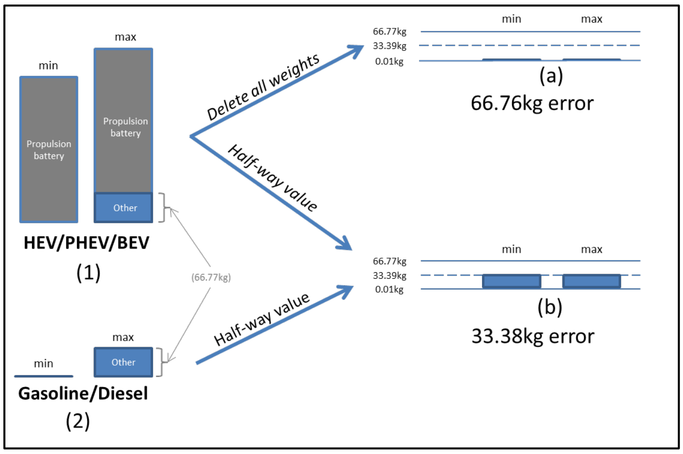


Figure 49: Result of deleting vs. averaging a2mac1 ‘Electronic Components’ category weights for cars with propulsion batteries and averaging for cars without propulsion batteries. Approximating all weights to the median value of 33.38kg gives a smaller error than deleting the weights for all cars. The weight range of 0.01kg to 66.77kg was determined from the cars without propulsion batteries and the same range is assumed to be valid for the cars with propulsion batteries.

The starter battery weight is 16.932kg for a Ford Focus C-Max 1.8l in the product tree of an a2mac1 file. We rounded up this weight to 17kg and used it as a reference for all starter batteries. Thus, for the after-pre-treatment weight, we added the 'Several Components' category and subtracted 17kg from it, and for the plastic/polymer weights we only multiplied the factor by the remaining weight from this category after subtracting the 17kg starter battery weight.

The weight of a propulsion battery can vary much more between vehicles, as seen in Figure 48 for the 'Electronic Components' category. For gasoline and diesel powertrains, the weights in this category range from 0.01kg to 66.77kg, so the category must include more than just propulsion batteries. Unfortunately, it is difficult to separate the weight of the propulsion batteries from other electronic components any further without additional information than what we had available. We chose to minimize the error from this category as much as possible by averaging the weights for the diesel and gasoline powertrains and applying this same approximation to the cars with propulsion batteries (HEVs, PHEVs, and BEVs). The reason for doing this is that the cars with propulsion batteries will have "hidden" weights of other electrical components in the totals, so merely deleting the entire category would mean that the errors would be much greater, see Figure 49. By forcing the weights to be the half-way value of 33.39 across all powertrains we increased the error of the gasoline and diesel powertrains but made it smaller in the others. The powertrains are thereby more comparable than before, with an error of 33.38kg instead of 66.76kg, assuming a normal distribution of weights in this category.

Wires

Using wire data from (Jorquera & Lindblad, 2016), the weight fraction of PVC and PEX in copper cables is 12 weight-percent and in aluminum cables is 24 weight-percent. Since the a2mac1 data doesn't specify which types of cables are used, the median, 18 weight-percent, will be used for the purposes of estimating the polymer content in the a2mac1 data. The wires are in the category 'Other>Wire Harness'. For electric propulsion a battery, electric motor and power cables are required, so we expected higher numbers of wire data for HEVs, PHEVs, and BEVs. However, Figure 50 shows that the difference between the gasoline car average and HEVs, PHEVs, and BEVs is minimal, and that the diesel car average was about the same as the other HEVs, PHEVs, and BEVs. We therefore believe that a portion of the wiring may be in some other category, but we cannot deduce due to lack of information.

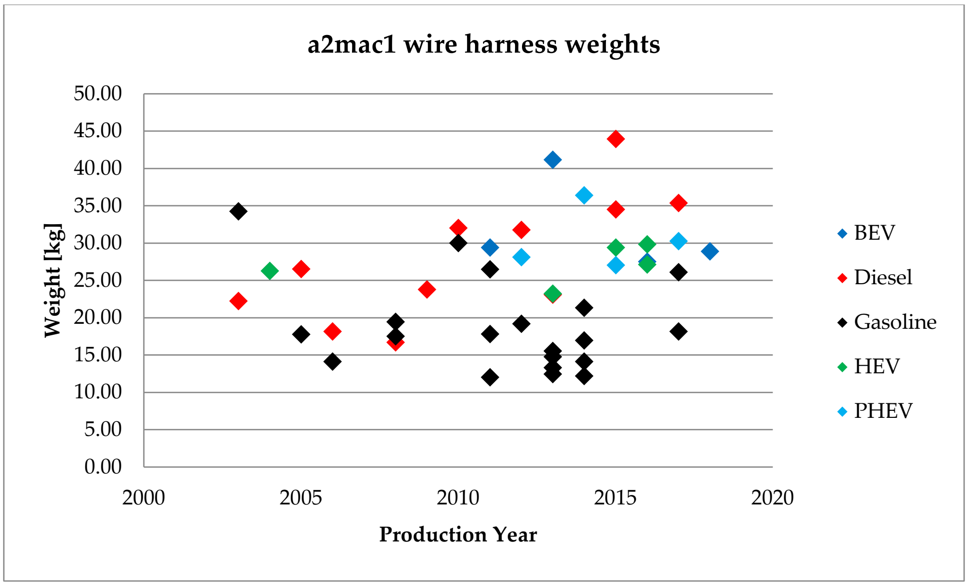


Figure 50: The a2mac1 'Wire Harness' category weights for all vehicles. The weights for gasoline vehicles are almost the same as the weights for HEVs, PHEVs, and BEVs, and the diesel vehicles are almost the same as the propulsion battery vehicles.

'Other>NA'

There are no trends for polymeric content in this category, so it is therefore not possible to set a good estimate for the percent plastic or polymer. A high weight in this category corresponds to a high error margin in the weight estimates. Fortunately, most a2mac1 files had weights from 1.35kg and less. However, five cars weighed above 288kg. The error margin for these vehicles were too high for a comparison with the rest of the vehicles, and therefore their data wasn't used in the estimation of plastic and polymer weights. By doing this, more subtle differences between the plastic and polymer weights could be observed for the rest of the vehicles.

Fluids

Some fluids are included in the total weight of the cars in the A2mac1 files. In an a2mac1 product tree, the liquids included are: Fuel, engine oil, gearbox oil, coolant, brake fluid, power steering fluid, and window washing liquid. The weights in the fluid category are not included in the after-pre-treatment weights.

Notes on Categories for Volvo BOM data

Tires and liquids

Tires aren't included in the weight of after-pre-treatment because they are removed, along with the battery, before the cars are dismantled. Since the tires are made of several parts, the weight is spread throughout the IMDS categories. 85.162kg was the weight of the wheels from the a2mac1 product tree for the 2003 Ford Focus C-Max 18.l, so the Volvo BOM after-pre-treatment weights will be subtracted by the same amount for a better comparison. 80 percent is elastomeric material (including fillers), so for the polymeric material sum, the weight subtracted for the weight of the tires will be 68.13kg (80 percent of 85.162kg) (Gursel, Akca, & Sen, 2018).

Liquids are also not included in the weight of the after-pre-treatment because the car is drained before it is dismantled. Their weights are subtracted for the after-pre-treatment weight but added up for the curb weight.

Electronics, electrics, and batteries:

The Volvo data has a category named "Electronics (e.g. pc boards, displays)". To make an estimate for the polymeric compounds in this category, an average of two categories from a German waste management consultant website (Elektro-Ade, 2017) is used: *Display devices (flat-screen displays)* and *small appliances and devices*. The percent plastic in each category is 38 and 31 percent, respectively, making the average 34.5 percent.

The 'Electrics' category in the Volvo data is assumed to be made of the starter battery, the propulsion battery (if there is one), and electric wiring. For the after-pre-treatment weight, which doesn't include the starter or propulsion batteries, we needed to subtract the weight of the batteries from this category. To do this we approximated the weight of the battery in this category as the fraction of the weight of a generic propulsion battery of the sum of the generic propulsion battery and generic wiring harness. The battery weight for a BEV propulsion battery is about 250kg (Ellingsen, o.a., 2013) and the weight of the wiring harness for a HEV/BEV is about 30kg (Kiyotsugu, 2013), but will of course vary for the different powertrains. Thus, the percent of battery weight in the 'Electrics' category is estimated to be about 30kg/ (250kg + 30kg) = 11 percent. For the weight of plastics, the same 18 percent plastic weight may be used as it is on the wiring harness category in the A2mac1 data but multiplied by the 11 percent wiring in the 'Electrics' category, resulting in about 2 percent plastics.

Coatings

Although the paints and lacquers may not be considered actual recyclable material, their weights are still included in painted plastic and elastomer parts in a2mac1. The surface area that is covered by paints and lacquers will vary between cars, so to simplify the calculation we assume that half the paint and lacquer weights will be added from the Volvo BOM cars for both the plastic and polymer material weight summations. This way the a2mac1 and Volvo BOM cars are comparable.

Appendix II

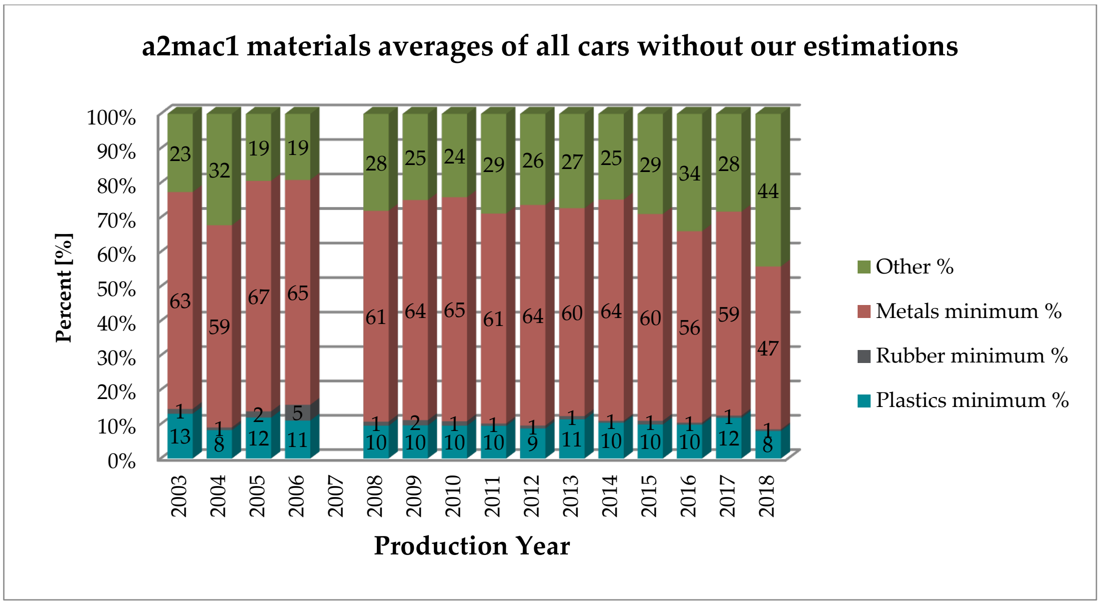
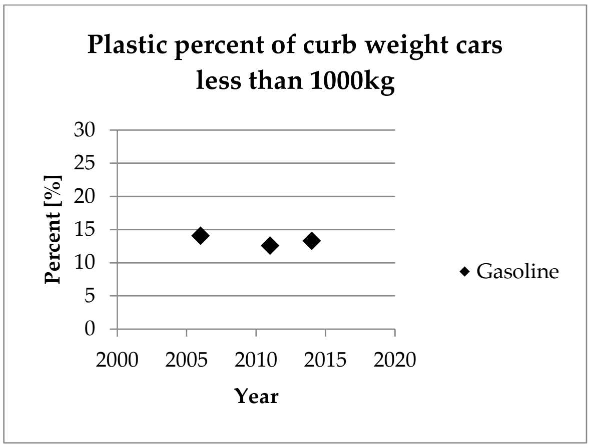


Figure 51: The graph shows the sum of all the pure metal, rubber (elastomer), and plastic categories. 'Other' in this instance means all the categories that aren't purely metal, rubber, or plastic, including categories such as 'Metal+Others' etc. All cars in each year are averaged, regardless of powertrain or model.

Table 12: Differences in curb weight given stated on the a2mac1 file and the sum of all the weight categories. The standard error is estimated to be the difference between the maximum and minimum differences is (54-(-15)) = 69kg, or (3-(-1)) =4 percent.

Car Model	Curb Weight [kg]	Sum of material categories [kg]	Difference [kg]	Difference [%]
Volvo XC90 D5 Inscription 2015	2 141	2 087	54	3
2011 Audi 1.4 TFS1-Tronic Ambition	1 158	1 158	0	0
2013 Audi A3 1.4 TFSi Attraction	1 178	1 178	0	0
BMW 5 Series 3.0 i Sport 2003	1 622	1 586	36	2
BMW 5 Series 520i 2017	1 567	1 524	43	3
BMW 5 Series 523i 2010	1 645	1 605	39	2
Ford Focus 1.6 EcoBoost Titanium 2011	1 366	1 337	29	2
Kia Niro 1.6 Gdi HEV Active 2016	1 425	1 386	39	3
Kia Picanto 1.0 Active 2012	929	907	21	2
Kia Picanto 1.1 EX Pack 2007	949	929	20	2
Mitsubishi OutLander PHEV Business Nav Safety 2014	1 884	1 835	49	3
Nissan Leaf 2011	1 520	1 535	-15	-1
Nissan Leaf SV 2017	1 525	1 502	22	1
Nissan Leaf Tekna 2018	1 577	1 552	25	2
Nissan Qashqai 2.0 Visia 2008	1 413	1 383	30	2
Nissan Qashqai+2 2.0 CVT All-Mode Connect Edition 2012	1 623	1 586	37	2
Renault Captur 0.9 TCe Expression 2013	1 206	1 186	20	2
Renault Clio 0.9 TCe Dynamique 2013	1 138	1 114	25	2
Renault Clio III 1.6l 16V 2005	1 223	1 197	25	2
Skoda Fabia 1.2 TSi Ambition 2014	1 074	1 051	23	2
Tesla Model-S 2013	1 955	1 926	28	1
Toyota Auris 1.8 HSD Dynamic nav. comfort 2013	1 396	1 361	35	3
Toyota Aygo 1.0 VVT-i C-play 2014	878	857	21	2
Toyota Prius 1.5 Base 2004	1 350	1 322	27	2
Toyota Prius 1.8 Hybrid Touring 2016	1 418	1 379	39	3
Toyota Prius 1.8 PHV 2017	1 551	1 509	42	3
Toyota Prius 1.8 Plug-in Hybrid 2012	1 441	1 408	32	2
Toyota Prius 1.8 VVT-i Hybrid Lounge 2016	1 421	1 380	41	3
Volkswagen Golf V 1.9 TDi Comfort 2006	1 361	1 329	32	2
Volkswagen Golf V 2.0 TDi 140 Carat 2004	1 390	1 358	32	2
Volkswagen Golf VI 1.4 TSi Highline 2009	1 406	1 378	28	2
Volkswagen Golf VI 2.0 TDi Comfortline 2009	1 345	1 314	31	2
Volkswagen Golf VII 1.4 TSi Comfortline 2013	1 249	1 228	21	2
Volkswagen Golf VII 2.0 TDi DSG Highline 2013	1 441	1 410	31	2
Volkswagen Golf VII GTE 2015	1 569	1 535	33	2
Volkswagen Golf VII GTI 2.0 2015	1 440	1 408	31	2
Volkswagen Passat 1.4 Tsi ACT Comfortline 2015	1 370	1 339	32	2
Volkswagen Passat 1.9 TDi 2005	1 558	1 521	38	2
Volkswagen Passat Variant 2.0 TDi SCR Highline 2015	1 789	1 745	44	2
Volkswagen Polo 1.90 Tsi Highline 2018	1 175	1 151	24	2
Volvo S60 2.4 D5 Summum 2011	1 642	1 642	0	0
Volvo S90 2.0 D4 Momentum 2017	1 734	1 688	47	3
Volvo V40 D4 Summum 2013	1 574	1 536	37	2
Volvo XC60 2.4D Basis 2009	1 838	1 810	28	2



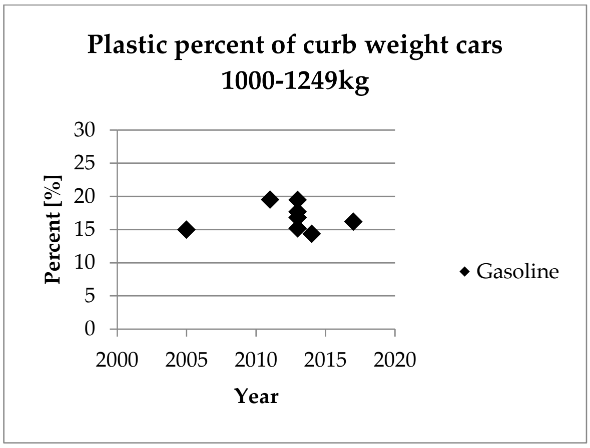
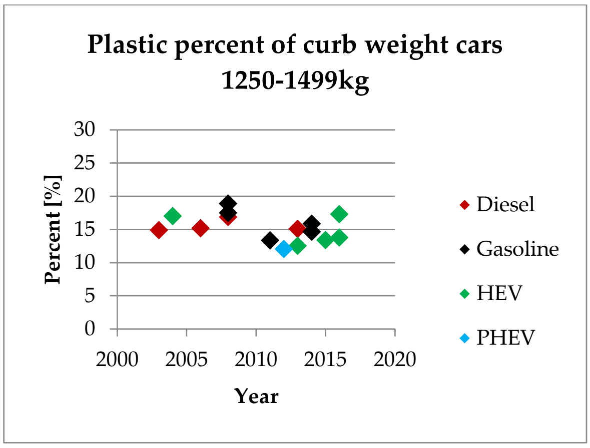


Figure 52 A2mac1 percent of plastics weight in cars (curb weight) <1000kg.

Figure 53 A2mac1 percent of plastics weight in cars (curb weight) 1000-1249kg.



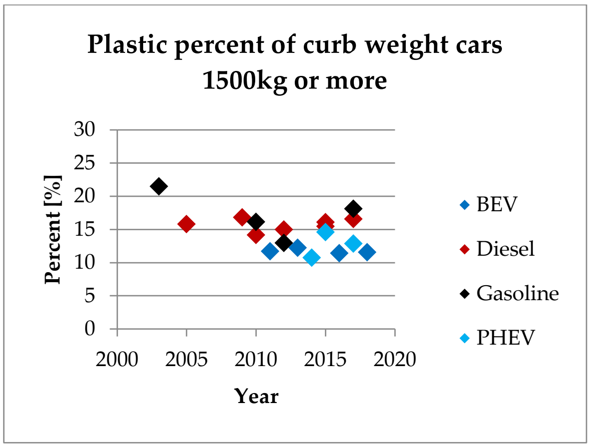


Figure 54 A2mac1 percent of plastics weight in cars (curb weight) 1250-1499kg.

Figure 55 A2mac1 percent of plastics weight in cars (curb weight) >1500kg.

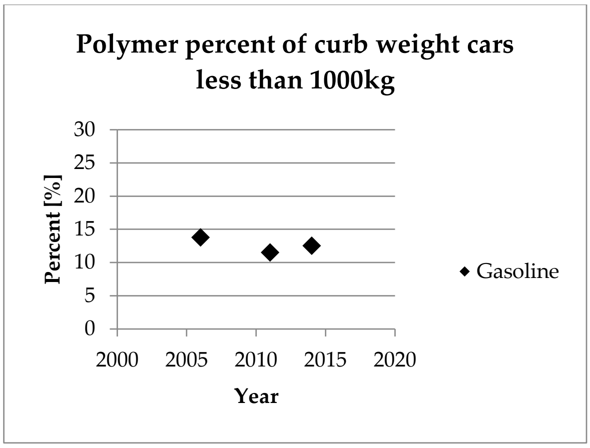


Figure 56 A2mac1 percent of polymer material weight in cars (curb weight) <1000kg.

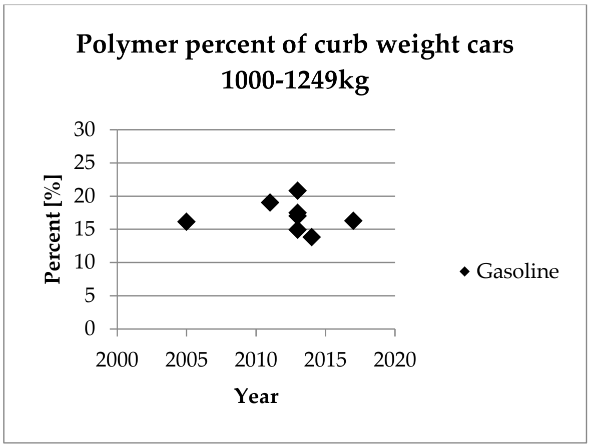


Figure 57 A2mac1 percent of polymer material weight in cars (curb weight) 1000-1249kg.

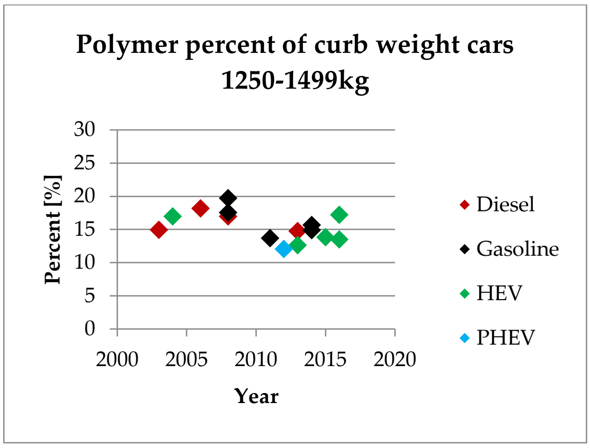


Figure 58 A2mac1 percent of polymer material weight in cars (curb weight) 1250-1499kg.

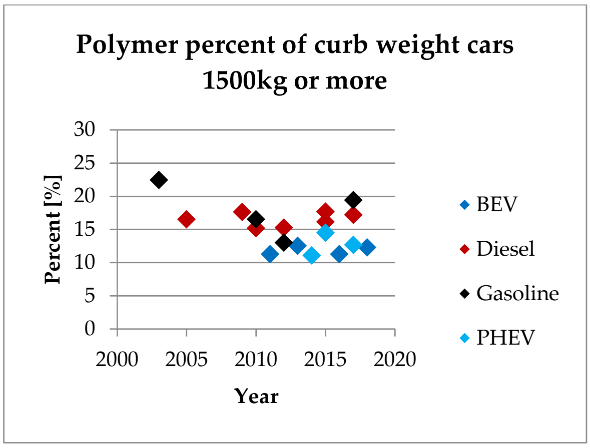


Figure 59 A2mac1 percent of polymer material weight in cars (curb weight) >1500kg.

Table 13: A2mac1 files, weight division: less than 1000kg. Note that this data is calculated from the a2mac1 files and includes the estimates written about in the Method.

Car Model	Fuel Type	Production Year	Plastics total weight [kg]	Polymer total weight [kg]	Plastics Percent of curb weight [%]	Plastics percent of curb weight [%]	Plastics Percent of after-pre-treatment [%]	Polymer Percent of after-pre-treatment [%]
Kia Picanto 1.0 Active 2012	Gasoline	2011	117	117	13	12	15	15
Kia Picanto 1.1 EX Pack 2007	Gasoline	2006	133	140	14	14	16	17
Toyota Aygo 1.0 VVT-i C-play 2014	Gasoline	2014	117	120	13	13	16	16

Table 14: A2mac1 files, weight division: between 1000-1249kg. Note that this data is calculated from the a2mac1 files and includes the estimates written about in the Method.

Car Model	Powertrain	Production Year	Plastics total weight [kg]	Polymer total weight [kg]	Plastics Percent of curb weight [%]	Plastics percent of after-pre-treatment [%]	Plastics Percent of curb weight [%]	Polymer Percent of curb weight [%]
2011 Audi 1.4 TFS1-Tronic Ambition	Gasoline	2011	**230**	**226**	**20**	**19**	**22**	**22**
2013 Audi A3 1.4 TFSi Attraction	Gasoline	2013	210	198	17	17	20	19
Renault Captur 0.9 TCe Expression 2013	Gasoline	2013	220	213	18	17	21	20
Renault Clio 0.9 TCe Dynamique 2013	Gasoline	2013	180	173	15	15	18	17
Renault Clio III 1.6l 16V 2005	Gasoline	2005	207	183	15	16	19	17
Skoda Fabia 1.2 TSi Ambition 2014	Gasoline	2014	158	154	14	14	17	17
Volkswagen Golf VII 1.4 TSi Comfortline 2013	Gasoline	2013	269	243	19	21	25	22
Volkswagen Polo 1.90 Tsi Highline 2018	Gasoline	2017	201	190	16	16	20	19

Table 15: A2mac1 files, weight division: between 1250-1499kg. Note that this data is calculated from the a2mac1 files and includes the estimates written about in the Method.

Car Model	Fuel Type	Production Year	Plastics total weight [kg]	Polymer total weight [kg]	**Plastics Percent of curb weight [%]**	Plastics percent of after-pre-treatment [%]	Plastics Percent of curb weight [%]	Polymer Percent of curb weight [%]
Volkswagen Golf V 1.9 TDi Comfort 2006	Diesel	2006	**257**	**206**	**18**	**15**	**21**	**17**
Volkswagen Golf V 2.0 TDi 140 Carat 2004	Diesel	2003	218	207	15	15	17	17
Volkswagen Golf VI 2.0 TDi Comfortline 2009	Diesel	2008	238	227	17	17	20	19
Volkswagen Golf VII 2.0 TDi DSG Highline 2013	Diesel	2013	223	217	15	15	18	17
Ford Focus 1.6 EcoBoost Titanium 2011	Gasoline	2011	197	183	14	13	16	15
Nissan Qashqai 2.0 Visia 2008	Gasoline	2008	258	247	18	17	20	20
Volkswagen Golf VI 1.4 TSi Highline 2009	Gasoline	2008	287	266	20	19	23	21
Volkswagen Golf VII GTI 2.0 2015	Gasoline	2014	225	211	15	15	18	17
Volkswagen Passat 1.4 Tsi ACT Comfortline 2015	Gasoline	2014	225	217	16	16	19	18
Kia Niro 1.6 Gdi HEV Active 2016	HEV	2016	255	247	17	17	21	21
Toyota Auris 1.8 HSD Dynamic nav. comfort 2013	HEV	2013	186	175	13	13	16	15
Toyota Prius 1.5 Base 2004	HEV	2004	239	230	17	17	20	19
Toyota Prius 1.8 Hybrid Touring 2016	HEV	2015	207	190	14	13	18	16
Toyota Prius 1.8 VVT-i Hybrid Lounge 2016	HEV	2016	202	196	14	14	17	17
Toyota Prius 1.8 Plug-in Hybrid 2012	PHEV	2012	184	174	12	12	16	15

Table 16: A2mac1 files, weight Division: 1500 kg or more. Note that this data is calculated from the a2mac1 files and includes the estimates written about in the Method.

Car Model	Fuel Type	Production Year	Plastics total weight [kg]	Polymer total weight [kg]	Plastics Percent of curb weight [%]	Plastics percent of after-pre-treatment [%]	Plastics Percent of curb weight [%]	Polymer Percent of curb weight [%]
Nissan Leaf 2011	BEV	2011	**182**	**178**	**11**	**12**	**17**	**16**
Nissan Leaf SV 2017	BEV	2016	182	175	11	11	18	17
Nissan Leaf Tekna 2018	BEV	2018	204	183	12	12	18	16
Tesla Model-S 2013	BEV	2013	256	240	13	12	21	20
Volvo XC90 D5 Inscription 2015	Diesel	2015	389	332	18	15	21	18
Volkswagen Passat 1.9 TDi 2005	Diesel	2005	268	247	17	16	19	18
Volkswagen Passat Variant 2.0 TDi SCR Highline 2015	Diesel	2015	299	288	16	16	19	18
Volvo S60 2.4 D5 Summum 2011	Diesel	2010	**260**	**232**	**15**	**14**	**17**	**16**
Volvo S90 2.0 D4 Momentum 2017	Diesel	2017	308	287	17	17	20	19
Volvo V40 D4 Summum 2013	Diesel	2012	251	236	15	15	18	17
Volvo XC60 2.4D Basis 2009	Diesel	2009	334	309	18	17	20	19
BMW 5 Series 3.0 i Sport 2003	Gasoline	2003	374	348	22	21	26	24
BMW 5 Series 520i 2017	Gasoline	2017	315	284	19	18	23	21
BMW 5 Series 523i 2010	Gasoline	2010	282	266	17	16	19	18
Nissan Qashqai+2 2.0 CVT All-Mode Connect Edition 2012	Gasoline	2012	221	211	13	13	15	15
Mitsubishi OutLander PHEV Business Nav Safety 2014	PHEV	2014	219	202	11	11	15	14
Toyota Prius 1.8 PHV 2017	PHEV	2017	207	200	13	13	17	17
Volkswagen Golf VII GTE 2015	PHEV	2015	238	229	15	15	19	18

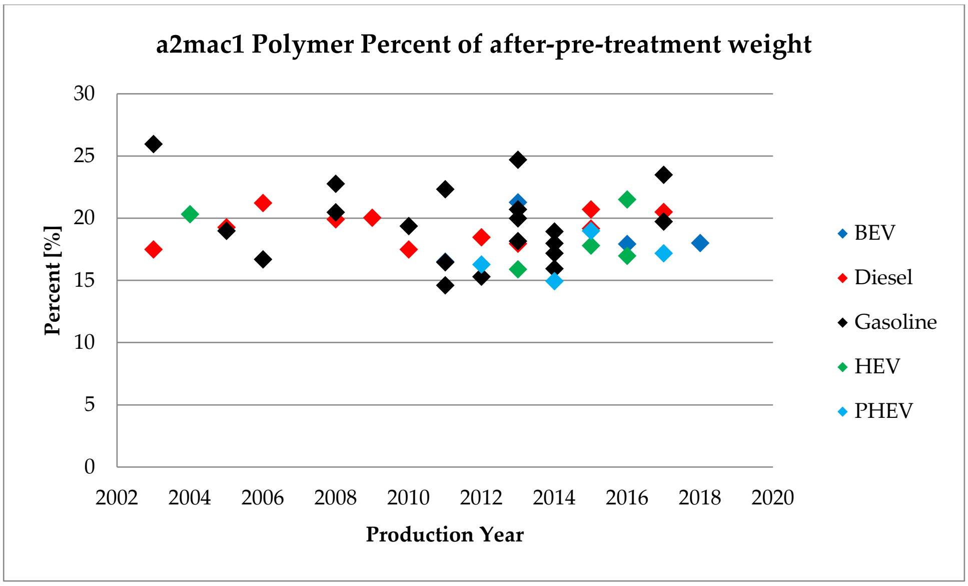


Figure 60: The percent polymer material for the chosen a2mac1 cars. The weights include our estimated values for plastics, elastomers, and coatings on plastic and elastomer parts.

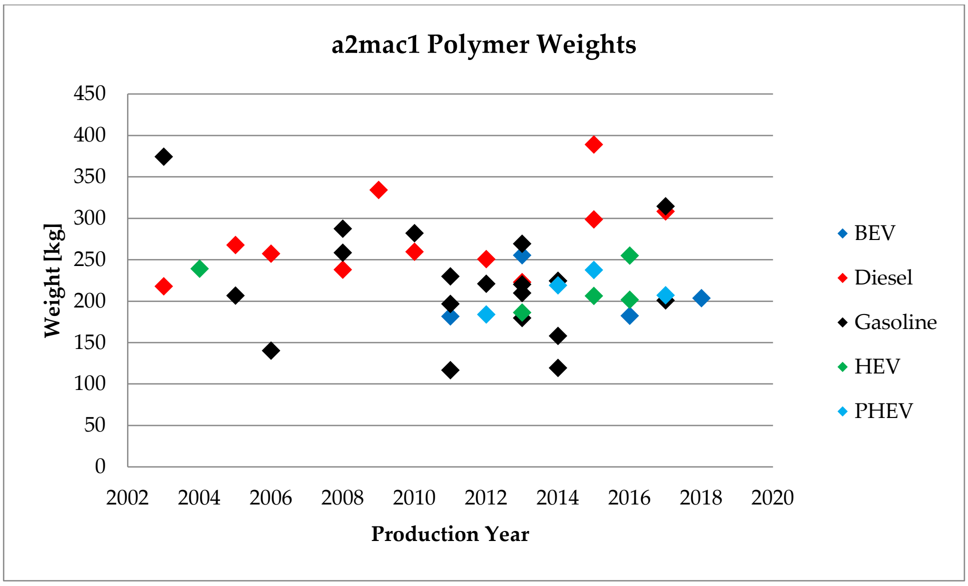


Figure 61 The weights of polymer material for the chosen a2mac1 vehicles. The weights include our estimated values for plastics, elastomers, and coatings on plastic and elastomeric parts.

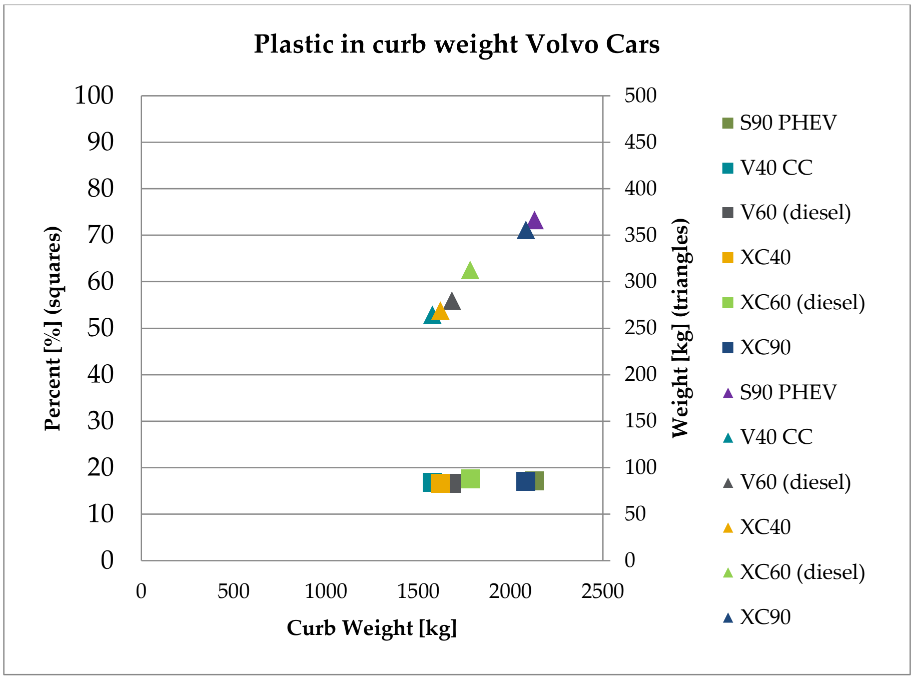


Figure 62 Plastic material percent (of curb weight) and plastic material weight from the Volvo BOMs for passenger cars produced in 2018. The percent is for plastic in after-pre-treatment.

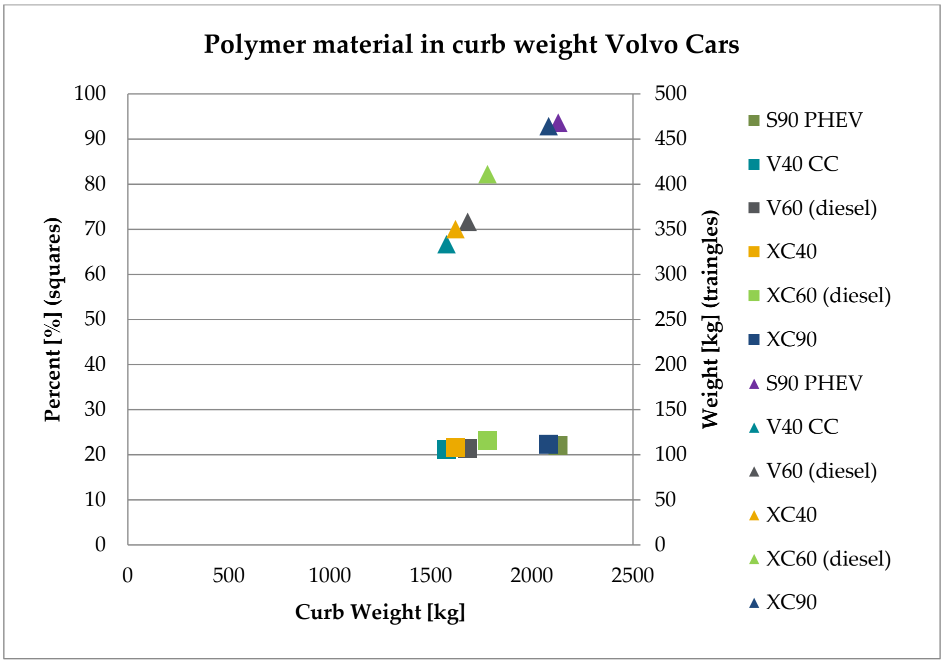


Figure 63 Polymer material percent (of curb weight) and polymer material weight from the Volvo BOMs for passenger cars produced in 2018. The percent is for polymer in after-pre-treatment.

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