

Waste recovery of end-of-life vehicles

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Abstract. The waste from end-of-life vehicles can be economically reused or forwarded for disposal. The UE 2000/53/EC directive imposes a recovery rate from end-of-life vehicles on the level of 95% of their weight and a recycling rate on the level of 85%. Changes in the material structure of vehicles observed in recent years indicate a gradual replacement of ferrous metals traditionally used in the automotive industry with plastics and composites, which mainly results from the need to reduce the vehicle weight, fuel consumption and CO₂ emission. Hence, the share of recyclable materials diminishes and the share of materials difficult (thus expensive) to recycle increases. The paper presents problems related to the recovery of materials from end-of-life vehicles. It presents the methods of waste management and identifies relations between the changes in the material structure and the recyclability of end-of-life vehicles. The paper also presents a comparison of the recovery rates possible to obtain using the best available technologies and the actual recovery rates from the recycling networks.

1. Introduction

The UE 2000/53/EC directive has introduced requirements related to the obtainment of minimum recovery and recycling rates of end-of-life vehicles (ELV). The recovery rate that must be obtained in a recycling network currently amounts to 95% of the ELV weight and the recycling rate is 85%. The differences between these rates account for the waste burnt for energy recovery.

The main factors impactful on the level of the obtained rates are:

- vehicle material structure,
- vehicle year of manufacture,
- recycling infrastructure accessible in a given area,
- applied material recycling technologies.

In the further part of the paper, the author sheds some light on the influence of the vehicle material composition on the possibilities of waste recycling from end-of-life vehicles. In section 2, changes (starting from 1960s of the last century to date) in the material structure of vehicles have been presented. Section 3 describes the methods of waste management and the benefits of recovering of selected types of waste. The influence of the change of the material structure on the recyclability has been discussed in section 4. The author particularly focused on the problem of the application of plastics, composites and titanium and nickel alloys. Section 5 includes information on the possibly obtainable recovery rates using the best available technologies and the actual recovery rates for the ELV recycling networks located in developed countries. In the final part of the paper, the influence of the change in the material



structure on the recycling rates has been summarized and the conditions for the upkeep of the ELV recyclability and recovery rates have been indicated.

2. Changes in the material structure of passenger vehicles in time

When analysing the material structure of passenger vehicles throughout the years, one can observe changes in this structure and trends related to the use of individual materials. The changes in the applied materials result from:

- the need to reduce vehicle weight with a view to reducing the fuel consumption and CO₂ emission,
- improvement of vehicle safety and traveling comfort,
- replacement of expensive materials with cheaper ones to live up to the market pressure,
- the need to allow for environmental impacts of vehicles throughout their entire life cycle.

The key role in the selection of materials used in vehicles today play the costs and the need to meet the legal requirements and reduce the vehicle weight, thus the emission of CO₂ while maintaining the technical parameters of the parts and subcomponents. The environmental impacts throughout the vehicle life cycle are the least important, unless they directly result from the legislation, as is in the case of the CO₂ emission.

The reduction of the vehicle weight forces replacing steel with aluminium, plastics and polymer based components. Since 2008, the average vehicle weight has been reduced by 20% [1]. According to the analysts, in Europe by 2020, the average vehicle weight will be close to that of the 1970s of the last century and will be of 1100 kg. The share of steel in the 1960s of the last century was as much as 76% while in 2015 it was only 55% (table 1). The share of plastics increased from 2% in the 1970s to 16% in 2010 and, according to the forecasts for the year 2020, it will grow to 18% of the vehicle weight [1].

Nowadays, more than a hundred types of plastic are used in the average vehicle. For instance, polypropylene (PP) is used in dashboards, wheel covers, and some engine parts; polyurethane (PUR) is employed in seats; polyethylene (PE) in carpets and polyamide (PA) in parts that need to be heat- and chemical-resistant. Mass-volume plastics – acrylonitrile butadiene styrene (ABS), PP, PUR, and nylon – account for 70 percent of the plastics used in a car, while composites and higher-end plastics account for the rest [1].

Table 1. Change in the average material structure in passenger cars [2,3].

Year of production	1965	1985	1995	2005	2015
Component	%	%	%	%	%
Steel	76,0	68,0	63,5	56,0	54,8
Aluminium	2,0	4,5	7,0	10,0	14,3
Other non-ferrous metals	4,0	3,0	3,0	3,0	3,3
Polymers	2,0	10,0	12,5	15,0	17,0
Others	16,0	14,5	14,0	16,0	10,6
Total	100,0	100,0	100,0	100,0	100,0

Material structure varies depending on the type of vehicle (category), the manufacturer and even the geographical area. For example, light duty pickup trucks manufactured in the US contain much more aluminium than their European counterparts (138 kg against 59 kg) while in premium passenger cars, European manufacturers use more aluminium than the Americans [4]. Contemporary body-in-white of a typical economy passenger vehicle is made from different types of steel, aluminium, irons and plastics, while in premium class vehicles, carbon fibers and composite are used more often.

3. Ways of waste disposal from ELV

Waste from the ELV can be recovered or disposed at landfills, i.e. neutralized without economic application (figure 1). In terms of environment protection, the care for natural resources as well as for economic reasons, it is appropriate to treat waste so that it leads to its recovery.

End-of-life vehicle waste			
Recovery			Landfilling
Recycling		Energy recovery	
Product recycling ie. reuse of parts and components	Material recycling		

Figure 1. End-of-life vehicles treatment possibilities.

Recovery consists in using parts and subassemblies (directly or following a regeneration) as spares or recovering materials or the energy contained in the waste. It is divided into recycling and energy recovery.

Recycling denotes a processing of waste in a production process in order to obtain substances or materials of their primary application or other application except energy recovery and recycling of materials to be used as fuels or for backfilling. Two basic types of recycling can be distinguished: product recycling and material recycling. The division is made based on the level of processing of the recovered materials.

Product recycling consists in recovering from an ELV of parts and subassemblies that are in good condition. Parts recovered in this way become spares. According to the Polish law, this is a recovery process that consists in checking, cleaning or repair, within which the products that were once waste are prepared for reuse [5]. Some of the parts or subassemblies can be reused immediately after removal from the ELV without the need to restore their technical parameters. In other situations, it is necessary to regenerate parts to restore their functionality to a level close or identical to that of a new product by a combination of actions such as disassembling, application of regenerative layers, renewal of subcomponents, repair and fitting.

Table 2. Energy savings from material recovery of selected components and materials [6].

Components	Energy savings [%]
Aluminium	95
Copper	85
Steel and cast iron	74
Lead	65
Zinc	60
Thermoplastic polymers	60
Oils	33

Material recycling consists in converting into raw materials of parts and subassemblies that cannot be further used in product recycling. It is the preferred form of waste treatment in the EU but, at the same time, it is, technically, organizationally and economically the most difficult form of recycling. The benefits from the reuse of materials are not only environmental (consequence of waste disposal at landfills) but it is also the protection of the non-renewable resources and preservation of energy. For a variety of materials, the production of recycled raw materials is less energy consuming than obtaining of the same at their primary source. The energy saving resulting from the recovery, compared with the energy to be used to obtain metals from their primary source is in the range from 60% to 95% (table 2). For example, manufacturing of 1 kg of base oil from regenerated used oils requires approx. 1/3 less energy than manufacturing the base oil from crude oil [6]. The most energy efficient is the recycling of aluminum that ensures saving of over 95% of energy needed for the production of this metal from its primary source from bauxites, thus reducing the emission of greenhouse gases by 95%. For glass, the costs of energy drop by approx. 2%–3% when using 10% of glass cullet during production. Besides,

each ton of glass manufactured from the recycled cullet gives a saving of 1 ton of primary resources, including 590 kg of sand, 185 kg of soda ash, 172 kg of limestone and 72 kg of feldspar [7]. The recycling of 1 ton of steel allows a saving of 1 134 kg of iron ores, 635 kg of coal and 55 kg of calcium [8]. The production of 1 ton of steel from primary resources requires energy input of approx. 20 GJ, while recycling of steel saves up to 75% of this energy [8].

The material recycling of noble metals also gives significant savings. In primary production, in order to obtain 1 kg of platinum group metals, it is necessary to excavate approx. 150 tons of ore from the depth of approx. 1000 m [6]. This ore, aside from the platinum group metals, contains large amounts of copper, nickel as well as other metals (chromium, iron, cobalt, bismuth, selenium, arsenic, tellurium - all in the form of sulphur compounds). During the process of excavation, 400 tons of waste and slag are generated that are useless and must be landfilled. Besides, this process requires much energy. Compared to the above, recycled materials do not require further, costly processing. Recycling eliminates the need for energy as the production and the pollution during the recycling process is many times smaller, compared to the process of excavation.

The materials contained in the ELV are subject to recovery or neutralization (landfilling) or, partly, both of these processes.

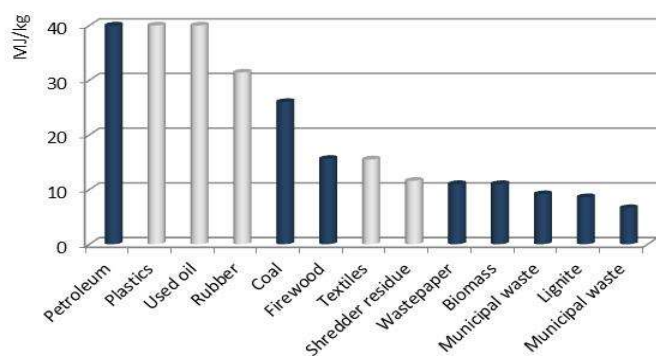


Figure 2. Calorific value of selected waste from vehicles compared to other energy sources [9,10,11]

Table 3. Calorific value of selected materials used in vehicles [11,12]

Materials	Calorific value [MJ/kg]
Plastics	40
Polyester resin and epoxy resin	33–34
Phenolic molding compound	32
Phenolic molding compound (with 30% of glass fiber)	25
Melamine resin	28
Urea-formaldehyde resin	18
Leather	19
Wood	16–20
Rubber	30
Fuels	40
Textiles	15

The ELV should be processed in such a way as to recover the greatest possible amount of materials, parts and subassemblies for further reuse. The greatest the share of recycling, the lesser the environmental impact of the end-of-life vehicles, provided that the environment friendly technologies are applied. The outstanding ELV materials should be subject to energy recovery. This is particularly the case for materials whose material recycling is unprofitable or the market does not offer technologies

or processing facilities for this type of recycling. This type of recovery is used for mixed materials (e.g. light fraction after shredding) or for plastics and elastomers of high calorific value (figure 2).

Out of the materials applied in vehicles, the best for energy recovery are plastics, rubber elements, used oils and fabrics (table 3).

4. Changes in the material structure vs. recyclability

The share of ferrous metals in the construction of vehicles gets reduced with time. Due to the fact that metals are the most recyclable materials, the newer the vehicle, the more difficult it is to obtain a high recycling rate. Besides, the more varied the material structure of a vehicle, the more expensive and complex the dismantling and the recycling process. It is noteworthy, however, that steel manufacturers have also improved their product for the needs of the automotive industry. The innovations are related to the sole product – dual grades, tailored blanks – and the process of production (e.g. laser welding), thus leading to better parameters of the manufactured steel (it is stronger and more rigid). Therefore, the weight of the vehicle components can be reduced maintaining their original properties. According to ArcelorMittal, a multinational steel manufacturing corporation, only five grades of steel were available to the automotive industry in 1960, while today, the industry has more than 175 grades of steel at its disposal [4]. The current grades of steel, such as advanced high-strength steel (AHSS) and ultra high-strength steel (UHSS) are much stronger, lighter, and processing-friendly for various vehicle manufacturing applications. Iron and steel form the critical elements of the structure for the vast majority of vehicles (mostly in economy segment of cars) and are low-cost materials. The prime reason for using steel in the body structure is its inherent capability to absorb impact energy in a crash situation [13].

Despite the above, the share of plastics in the overall weight of vehicles is still increasing. The main advantage of plastics is that they are lighter and can be freely formed. The increased application of plastics is caused by legislation that forces the manufacturers to reduce the fuel consumption and the emission of CO₂ as well as to increase comfort of passengers.

The downside of the application of plastics is that they are difficult to recycle, mainly due to their multiple varieties. Additionally, some of the plastics lose their properties during recycling. Another problem is the lack of technological infrastructure, i.e. material recycling facilities specializing in recovery of given types of plastics. Therefore, the increased use of plastics shifts the environmental impacts generated by a vehicle from the operation stage to the ELV stage. In theory, the technologies of recycling of different types of plastics have been developed, yet, in practice, the economical aspects and market accessibility to technologies limit their application. Another problem is the lack of market for the recycled materials. For the above reasons, plastic waste is not recycled at specialized facilities but processed as light fraction after shredding (combustion combined with energy recovery or landfilling). In the US, only metals are recovered and the outstanding materials (including plastics) are forwarded for landfill (15-20% of the weight of the ELV waste). In Europe, plastics must be processed due to recovery and recycling rates related legislation, but it increases the costs of the entire process.

A downside of some of the plastics is the loss of their properties after processing. As a result, the recycled plastics cannot be used for the same purposes as the ones made from primary materials. They can be reused for another purpose, where the initial technical parameters are not required (strength). An example is the use of materials from polypropylene bumpers for the production of heater core housings, HVAC covers or vent tubes. After yet another processing, the materials from these parts can again be reused for the production of floor mats.

Plastics and composites in automotive applications are heterogeneous, have strong connections to other plastics, and are thus difficult to liberate for recycling [14]. For example, within the seating section of a vehicle, there can be five different types of plastics and composites, some being thermoplastics and others thermosets. This complicates the recovery process since in order for it to be effective, all of these materials would have to be recovered and separated at the end of life processing.

Thermoset materials present a further challenge since they cannot be melted down and recycled due to their permanent cross-link structure. They will not remelt or regain processability. The only option for mechanical recycling is to pulverize these materials for reuse as fillers [14].

One of the possible ways to reduce the environmental footprint is to produce plastics from plants instead of petroleum. Bioplastics are produced from renewables, with two main agricultural sources – starch-based, derived mostly from sugar cane, and corn, potatoes, beets, and oil polymers [1]. For automotive applications, bio-plastics are currently limited to interior trims and non-structural components [14]. Bioplastics will remain non-cost competitive with traditional plastics and will at best supply 20% of total plastics needs.

Another difficult-to-recycle material is composites. A composite is composed of high-performance fiber (such as carbon or glass) in a matrix material (epoxy polymer) that, when combined, provides enhanced properties compared with the individual. These materials allow a reduction of the vehicle mass while maintaining the strength parameters, because these components are of high strength and rigidity. With composite materials, the car manufacturers get high strength-to-weight and stiffness-to-weight ratios, as well as excellent energy absorbing capability per mass [13]. Parts made from composites do not corrode as is in the case of steel or aluminium. It is not fully explored, though, how they undergo the process of aging, as they have been used in aviation and in the automotive industry for a relatively short time. Composites are used in many interior and exterior applications in cars, and polymer composites – especially carbon-fiber-reinforced composites – presents major light weighting opportunities for structural vehicle components (body-in-white and chassis components). At a weight 50% lighter than conventional steel and 30% lighter than aluminium, more automakers use these materials as the body structure or other car components [13]. They allow to significantly reduce overall vehicle weight while maintaining or improving safety and performance.

Fiber-reinforced plastic composites provide many benefits compared to steel as well as regular plastics (table 4).

Table 4. Advantages of fiber-reinforced plastic composites [1,13]

Criteria	Advantages
Weight	Even 50% lighter than conventional steel and 30% lighter than aluminium
Manufacturing	Faster to assemble, as fewer parts are required, which cuts manufacturing costs and complexity
Tooling	Less than half the cost (40%) of steel stamping
Damage resistance	Ding and dent superior to that of aluminium and steel panels
Corrosion resistance	Better corrosion resistance than most materials
Internal damping	Less noise, less vibration, less harshness
Design	More versatile – molding offers geometric details, shape complexity, and a depth-of-draw range unavailable with metal stamping

Despite a variety of advantages of composites, their application, particularly in the main structural components, is still limited. The barriers in their application cover a wide range of issues related to forming and joining combined with the high cost and limited supply of these materials. Composites were initially developed to be applied in aviation where the costs are not the most important factor when selecting a construction material. The cost of carbon fiber composites is at least 20 times higher than that of steel, which substantially limits its use in the automotive industry [15].

Another development trend followed by the manufacturers is the application of other metals such as titanium or nickel based alloys. They are highly durable, have low density and very good resistance to corrosion and oxidation. A downside, similarly to composites, is their price. Titanium alloys are used in high temperature zones and in high strength components, such as exhaust systems, suspension springs, valve springs or connecting rods [13].

Steel, despite its dropping share in the vehicle overall vehicle weight, will still remain the main construction material in the nearest future, owing to the costs of its production and wide application in the automotive industry. Vehicle end-users are not willing to pay more for the reduction of the vehicle weight. These costs are absorbed by the manufacturers, particularly in the production of small and medium class vehicle segments. Besides, a modification of the vehicle material structure requires

investments in the adaptation of the production lines, which is another capital expenditure for the carmakers. Therefore, it is expected that steel and aluminium will remain the key materials used in the production of bodies-in-white and the share of aluminium will grow [4]. This primarily results from the fact that the technological advancement in steel processing has reached such a level that further weight reduction may be difficult to obtain. Aluminium is the easiest replacement in terms of organization of the vehicle production compared to plastics, magnesium or carbon fiber. The advantages of aluminium are its low density, high energy absorption, strength and lower mass compared to steel components.

Table 5. Material composition of selected bodies-in-white [4]

BIW Material composition	Weight reduction	Increased cost	Models	Market segment
AHSS-intensive steel	22%/72,8kg	147\$	Hundai Genesis	Economy
AHSS steel, aluminum, composites	24,5%/80,3kg	176\$	BMW 7 series, Lexus LC500	Luxury
Aluminum-intensive	35%/114,8kg	720\$	Jaguar XF Rane Rover, Audi A8	Luxury Premium
Carbon fibre	50%/164kg	2512\$	BMW i3 Lamborghini Aventador	Super premium Sports cars

Note: Weight reduction and cost figures are as per 2012 research study

5. ELV waste recovery rates

An ELV must undergo a recovery. Whether the recycling will be economically justified, depends on the type of material. As a matter of principle, almost all materials used in the production of vehicles can be reused. The cost of recovery for some of the materials is sometimes so high that it is unprofitable to recover certain components and subassemblies. In that case, it is more economical to apply energy recovery. It should be noted, however, that, from the point of view of the protection of natural resources, recycling is a better option and is recommended by the 2000/53/EC Directive.

For the calculation of the recovery rate, maximum theoretical rates are assumed of the individual materials, based on the best available technologies. In practice, the recovery rates obtained when disposing ELVs are lower (table 6). Due to the costs of labour, not all parts are dismantled and after shredding of a vehicle obtaining such a high recovery rate is impossible as is in the case of segregated materials. The actual recovery rates listed in table 6 pertain to the markets of developed countries. In the developing markets, these rates are even lower.

Passenger vehicles are made from steel and aluminium, i.e. metals that are easily recyclable. Steel is the most recoverable material, primarily owing to the simplicity of magnetic separation. The costs of steel production from waste are much lower compared to the production from the iron ore. Even for steel, however, loss of some elements occurs, because their presence in the alloys is not accounted for or the alloys are simply contaminated [16]. Aluminium, similarly to steel, does not lose its properties during the recycling process, yet the varieties of aluminium alloys used in the production of vehicles do not facilitate the recycling process. Recycling rates for metals are very high, both potential and actual. Metals are recovered mainly through the shredding process and then magnetic segregation (ferrous metals), flotation, or eddy currents (non-ferrous metals). Upon separation of the fraction, the metallic scrap is melted and reused in production.

Table 6. Type of materials, their recovery rates and methods of recovery [based on 17,18,19]

Type of material	Recycling rate using best available technologies	Recovery rate using best available technologies	Recovery rate from network	Recovery method
Ferrous metals – Steel	100%	100%	90–98%	Shredding & remelting
Ferrous metals – Cast iron	100%	100%	80–90%	Shredding & remelting
Non ferrous metals – Pb	100%	100%	80–98%	Dismantling, mechanical separation & remelting Shredding & remelting
Non ferrous metals – Al	100%	100%	80–95%	Dismantling, mechanical separation & remelting Shredding & remelting
Non ferrous metals – Cu, Zn	100%	100%	60–80%	Dismantling, mechanical separation & remelting Shredding & remelting
Thermoplastics (unfilled)	100%	100%	50–70%	Dismantling, separation & dedicated recycling processes Shredder light fraction recycling Incineration
Thermoplastics (glass filled)	67%	100%	50–70%	Dismantling, separation & dedicated recycling processes Shredder light fraction recycling Incineration
Thermosets (unfilled)	100%	100%	50–70%	Dismantling, separation & dedicated recycling processes Shredder light fraction recycling Incineration
Thermosets (glass filled)	67%	100%	50–70%	Dismantling, separation & dedicated recycling processes Shredder light fraction recycling Incineration
Elastomers	80%	100%	50–70%	Dedicated recycling processes Shredder light fraction recycling Incineration
Glass	100%	100%	50–100%	Remelting
Safety glass	94%	94%	50–94%	Separation & remelting
Oils	100%	100%	50–100%	Refining Incineration
Other fluids (lubricants, all chemical fluids)	83%	83%	50–80%	Dedicated recycling processes
Modified organic natural materials (leather, wood, cotton fleece,...)	95%	100%	50–70%	Dedicated recycling processes Shredder light fraction recycling
Carbon or natural reinforced polymers	67–80%	80–100%	50–70%	Dedicated recycling processes
Electronic and electric	80%	98%	60–85%	Sorting and dedicated recycling processes
Ceramics	43%	43%	20%–40%	Dedicated recycling processes
Silicone fiberglass	80%	80%	50%–70%	Dedicated recycling processes

The greatest problem are new technological solutions, particularly the application of composites, carbon fibers or glass fiber reinforced polymers. Currently, there are no technologies that would enable an easy and economical recovery of these materials while their application is becoming increasingly popular. Plastics are also difficult-to-recycle materials, characterized by a wide variety of applications, relatively low costs of production and easy forming. Unfortunately, in terms of recycling the problem is that most of the plastics cannot be mixed with one another as each type of plastic has different chemical composition (hence different melting or decomposition temperature) and mechanical properties. This makes that significant part of the plastic waste (as much as half of it) from vehicles is landfilled.

Deep dismantling and segregation of materials enable their recycling, yet, for economic reasons, only large subassemblies are dismantled and the vehicle body with the outstanding components is shredded. Despite the fact that 50% of the light fraction upon shredding can be used as fuel and there exist new technologies allowing the use of up to 95% of the mass of the light fraction within the recycling process, practically 2/3 of the materials are landfilled [20]. As a result, the recovery rate currently required in the EU on the level of 95% of the vehicle weight, is practically very difficult and, in some cases, even impossible to obtain. For such a material as glass, whose potential recovery rate is 100%, has the actual rate below 50% in some countries because it is not dismantled from the vehicle and due to frequent loss during the ELV recovery process. The lowest actual recovery rates have modified organic natural materials and fiber reinforced plastics (a maximum of 70%) despite the fact that, in theory, they can be reused in 100%. The reason for this situation is the lack of proper marking of components made from these materials and no recycling technologies for these types of materials accessible on local markets.

6. Conclusions

The automotive industry is undergoing an evolution caused by changes in the expectations of the end-users and the legislation forcing the carmakers to reduce vehicle exhaust emissions. Bringing these two factors together, i.e. reducing the vehicle weight while maintaining or even improving the vehicle parameters (aesthetic, comfort, durability or resistance to corrosion) forces the engineers to seek new innovative materials. They have to allow for other aspects such as the cost of the implementation of the new solutions.

The market is being stormed by other stakeholders such as Tesla or Airbus (Airbus has developed a flying vehicle under the name of Pop Up) who modify the perception and functionalities of today's vehicles. They force the manufactures of conventional vehicles to be innovative as regards their vehicles and their production process. The effect of the said innovation is, *inter alia*, the application of new types of materials.

All these changes in the material structure indicate a more costly and difficult recovery of the ELV materials. Reduced use of steel and ferrous metals as well as their substitution with plastics and composites causes a decrease in the recovery rate. Comparing the material composition of vehicles from 1995 and vehicles from 2005 (table 1) and assuming average recovery rates obtained in the recycling network (table 6), the recovery rate of end-of-life vehicles dropped by 2 percentage points.

This constitutes a challenge for the recycling industry that has to adapt to the new conditions in order to maintain recycling and recovery rates imposed by the 2000/53/EC Directive. The conditions for maintaining high recovery and recycling rates for the ELV are as follows:

- deeper dismantling at the treatment facilities,
- improvement of technologies of light fraction segregation after shredding, i.e. mixed fraction of waste obtained after shredding of the body at an industrial shredder and separating of the metal fractions,
- investment in technical infrastructure: plastic processing facilities (mixed plastics in particular, as is the case for many vehicle subassemblies) as well as facilities processing composites and carbon fibers.

Otherwise, it will not be possible to maintain the currently obtained high recovery rates reaching in some countries even more than 95% of the end-of-life vehicle weight.

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