Analysis of the Cost of Recycling Compliance for the Automobile Industry

by

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Abstract

Cars are one of the most recycled commercial products. Currently, approximately 75% of the total vehicle weight is recycled. The EU directives on End-of-life vehicles try to push the recycling process further: it fixed the percentage of recyclability (85%) and recoverability (95%) automotive companies have to reach for their new vehicles in 2015. Complying with these directives will imply a cost, which will be borne by one or several of the stakeholders of the automotive life cycle. This cost will not only depend on the type of the vehicle but also on where the vehicle will be recycled and which recycling processes will be used.

The scope of this thesis is to study the recycling cost sensitivity to regional practices and to vehicle's type.

A technical cost model has been developed to calculate the cost of applying the regulation. Based on the list of parts of a particular vehicle, this tool allows to determine which parts have to be removed to reach the recycling target and the cost associated with this removal. The model was run for a sample group of vehicles and for different regional inputs. The goal is to pinpoint the major recycling cost drivers and discuss how the total cost can be reduced. Finally, this work analyses the magnitude of exposure of a vehicle manufacturer in Europe.

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1 Work Motivation

1.1 Automotive Material Consumption Concerns:

1.1.1 Environmental Burdens

The motivation for this work comes first from the observation of the material consumption of the automotive industry. The automobile is a major material consumer. Its material consumption represents actually around one third of the total U.S consumption; it is one of the most intensive material consumers among all other industries. As shown in Table 1.1 [Keolian et al. 97], it consumes more than 24 millions tons per year of a great variety of materials.

Material	Automotive Consumption	Total U.S. Consumption	Automotive Percentage
Aluminum (tons)	1,292,598	15,011,000	18.9%
Copper and Cu Alloy (tons)	299,970	2,996,519	10.0%
Gray Iron (tons)	2,295,000	6,473,000	35.5%
Ductile Iron (tons)	942,000	3,116,000	30.2%
Malleable Iron (tons)	167,000	280,000	59.6%
Total Iron(tons)	3,404,000	9,869,000	34.5%
Lead (tons)	864,628	1,244,000	69.5%
Plastic(tons)	998,537	30,758,288	3.2%
Platinum (tons)	26,363	63,698	41.4%
Natural Rubber (tons)	680,406	910,212	74.7%
Synthetic Rubber (tons)	1,129,342	1,946,920	58.0%
Alloy Steel (tons)	489,000	4,101,000	11.9%
Stainless Steel (tons)	250,000	1,514,000	16.5%
Total Steel (tons)	11,092,000	82,241,000	13.5%
Zinc (tons)	268,000	1,165,000	23.0%
Total	**24,198,843**	**161,689,636**	

Table 1-1: Material Use by the Automotive Industry, 1992

While looking at these numbers, the first environmental burden that comes in mind is material scarcity. Indeed, resources available on earth are not unlimited. If the primitive materials consumption continues and if nothing is done to stop it or regenerate the resources, future generations could lack some of them. Before considering this issue, it is important to figure out the primary materials content of a car. A previous study [Keolian et al. 97] observed that the recycled content of an average car in 1994 was more than 33%, this precise percentage corresponding only to the metal recycled content. While this percentage is important, the amount of primary materials consumed is still big enough to engage some thinking about its environmental consequences.

The problem of material scarcity has found two types of answers through history. The first one was developed by economists. They argued that the more the demand of one material grows, the more its price and subsequently the need for a substitute material will increase, raising the incentive to create substitute materials. In that optimistic perspective, technological progress should be the answer to material scarcity in so far as it will provide new materials and avoid material depletion. The second perspective on this issue was developed by political scientists. For them, the diminution of material supply ultimately leads to a decline in the economy since once the resources are depleted, nothing can be done to regenerate them. From that pessimistic point of view, technological progress is accelerating material scarcity. Looking retrospectively, it is difficult to support entirely one or the other of these perspectives. Indeed, it is really difficult to predict when a specific material will be lacking if it is eventually going to disappear. For example, several years ago, some predicted the scarcity of aluminum while, today, it does not seem to be an issue anymore. There are too many uncertainties linked to technological progress to be sure that substitutes will always be found. And, even if substitutes are found, the actual observed decrease in natural materials reserves should be sufficient to justify actions to limit material depletion.

On another hand, there are indirect environmental burdens created by materials consumption: the different emissions and waste associated with the primary materials processing, whether they concern emissions in the air, in the water or in the land. For example, aluminum production is associated with gas and particulate emissions and generates huge quantity of wastewater.

Another environmental consequence raised by this consumption is that the quantity of materials consumed increases in tandem with the waste produced. On this particular point, the good news is that the automobile is the holder of another record; it is the world most recycled consumer product. In terms of recycling, the automotive industry is actually doing quite well. Nowadays, in the United States, 95% of all vehicles go through the recycling process at their end of life. This collection rate is very high. By comparison, it is only of 52%, 55% and 42% for appliances, aluminum cans or paper products

[MOEA 03]. Moreover, the efficiency of the recycling industry leads to a 75 % weight of vehicle recycled. Finally, the remaining 25%, known as Auto Shredder Residue (ASR), go to landfill. ASR is mainly composed of foams and fluff (40-52%), plastics (20-27%), rubbers (18-22%) and metals (4-15%) and there is currently no cost-effective recycling technology for plastics and foam. Furthermore, these materials are often contaminated by other materials present in the ASR stream. In the end, it is currently more cost effective for the auto recyclers to landfill this waste than to recycle it.

Thus, even if the automobile is doing well in terms of recycling, 25% of 10 to 14 millions of vehicles reaching their end-of-life each year [USCAR 1998] represent 5 millions annual tons of ASR for the US. Not only does this have a great environmental impact for society, it also corresponds to a significant economic burden. Indeed, auto recyclers have to pay for the disposal of the ASR (around $50/ton in the US nowadays) which is currently not recycled. Furthermore, landfilling is not a sustainable solution for vehicle waste. First, it is expensive and second it has indirect costs on the habitat. Nobody wants to leave next to a landfill. This question of landfill location is particularly relevant in countries were population density is high and consequently is landfill cost, like in Europe.

1.1.2 Future consumption trends

The actual trend of the automotive industry is not in favor of a decrease in material consumption. On one hand, the number of vehicles' registrations in the US is increasingly, as shown in Figure 1-1 [FHWA 02]. The number of vehicles increases by around 2% per year since 1960, which brings the number of vehicles currently in circulation in the US to more than 250 millions.

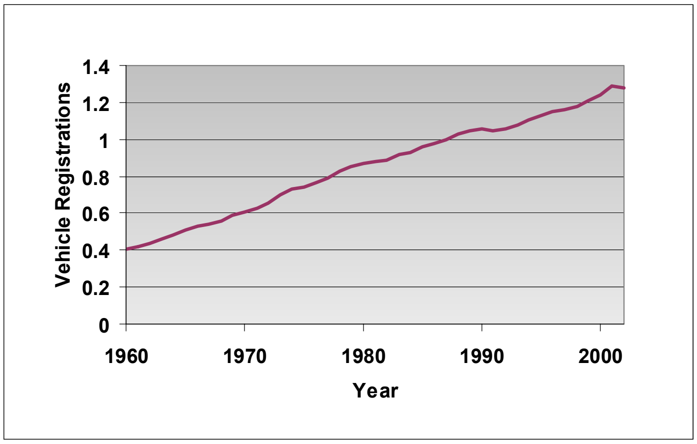

Figure 1-1: Evolution of US vehicles' registrations indexed on 1987 registrations (1987=1)

On the other hand, the evolution of the fleet size distribution is also going to contribute to an increase in material consumption, as shown in Figure 1-2[Davis and Diegel 03]. Indeed, the last decades saw a general trend toward an increase of the proportion of large vehicles in the fleet. Thus, not only the number of vehicles is getting bigger, but the average vehicle is likely going to consume more and more materials.

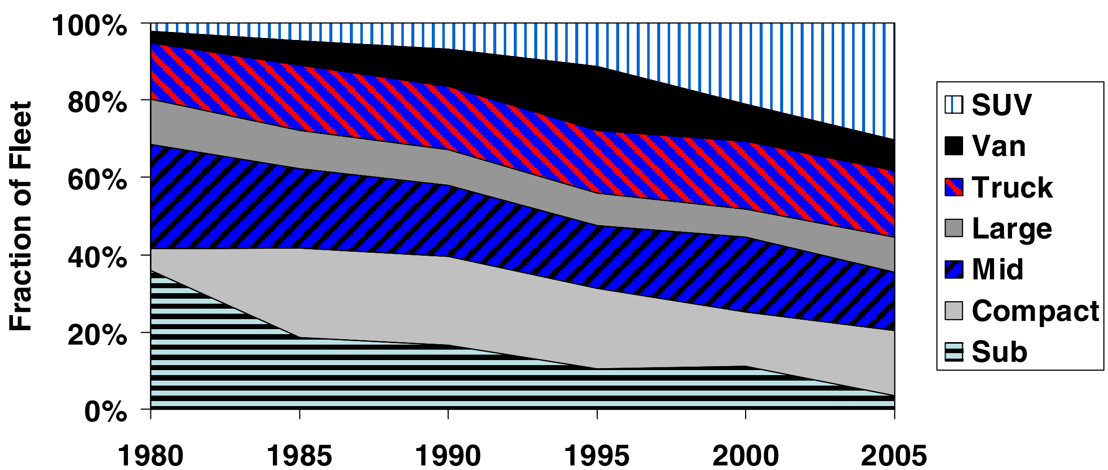

Figure 1-2: US fleet size distribution [Davis and Diegel 03]

Moreover, these trends are not specific to the US. If we take a look at a global level, the world population will increase by 33% by 2030 [DESA 02] and the economic growth of developing countries will be associated with new vehicles demand, and thus, new material consumption. Finally, the projected material consumption due to the automotive industry is tremendous, as shown in Figure 1-3. This projection expects the annual consumption of materials due by the automotive industry to increase by 140% by 2050!

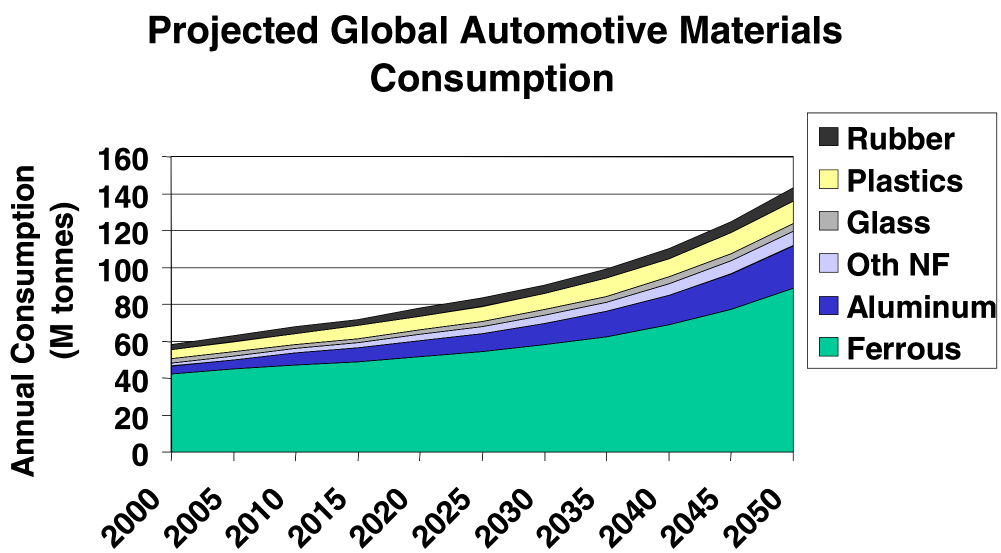

Figure 1-3: Projection of global material consumption due to the automotive industry [WBCSD 04]

1.1.3 Environmental Policies

When governments judge that the price of a material does not reflect the cost borne by society whether this cost concerns emissions, waste or disposal of this material, they can limit these environmental externalities by implementing policies. Several policy regulations have been taken in the US to limit the first environmental burdens we pointed out, i.e. material depletion and emissions generated by the production of primary materials, like the Clean Air Act or the Resource Conservation and Recovery Act.

Concerning recycling issue, there is no current policy incentives in the US to increase the actual recycling rate of the automobile industry. As we pointed out earlier, the huge amount of waste generated by end-of-life vehicle is a great burden for society and recycling is one of the solutions to reduce it. Even if the recycling rate of the automobile industry is high, around 25% of end-of-life vehicles' weight- the ASR- is currently going to landfill.

A policy solution to reduce this amount of ASR would be to engage the responsibility of the automakers in the recycling system, i.e. place the responsibility on automotive firms

to take back vehicles. Engaging producers' responsibility in the management of the end-of-life of the product creates not only an incentive to reduce the amount of waste generated by their products but also encourage them to change the design of their products to be more recyclable.
Governments can use several regulatory tools to involve producers' responsibility in the end-of-life of their products; "polluter pays" is the motto of these types of regulation.
In Europe, this idea has found its way since several years now. The first country to engage extended producers' responsibility in the recycling process was Sweden in 1984. The aluminum industry has been imposed to reach a mandatory recycling target of 75 % for aluminum cans, while the current recycling target was around 63%. The aluminum industry ultimately decided to put in place a deposit-refund system to reach this target. The recycling target was reached in 1987 and the recycling rate continued to increase afterward to reach 92% by 1995. Another successful regulation[1] was taken by Germany in 1991. A Packaging regulation was issued making producers responsible for managing packaging waste. As a result, packaging recycling increased from 52% to 84% in 1996.

To go back to our topic, in 2000 an EU directive[2] engaging producer responsibility in managing end-of-life vehicles was adopted. These new EU directive fixes the percentage by weight of vehicle that has to be recycled.

The directive distinguishes three types of materials which can be counted in the recycling target:

- ✓ **Reused:** A part is reused if the component is used for the same purpose.
- ✓ **Recycled:** A component is recycled if it is processed in a production process for the original purpose or for other purposes. This excludes the processing for use as any means of generating energy.
- ✓ **Recovered:** A part is recovered if it is reused, recycled or used as an energy source.

[1] Packaging Ordinance of 1991, amended 21st of August 1998
[2] EC Directive 2000/53/EC on end-of-life vehicles

It also fixes the percentage of weight that has to be reached in each of these categories:

	Reused/Recycled	Reused/Recovered
By 2006	80%	85%
By 2015	85%	95%

Table 1-2: EU recycling targets

1.1.4 European Directive Compliance Concerns

The recycling targets of the European directive are above the actual average recycling rates, compliance with the regulation will thus imply a cost which will be borne by automakers. We already pointed out that automakers will have to find a way or another to reduce the amount of ASR in order to reach the recycling target.

The bad news is that the amount of typical ASR materials, i.e. plastics and foams is globally increasing in vehicles. Indeed, if we take a look at the evolution of the plastic percentage in a typical family vehicle in Figure 1-4 [Keolian et al. 97], chosen as an example of an average car; between 1980 and 1994, the use of plastics is increasing while the average weight is slightly decreasing. These two effects combined ultimately result in a more important proportion of plastics in vehicles.

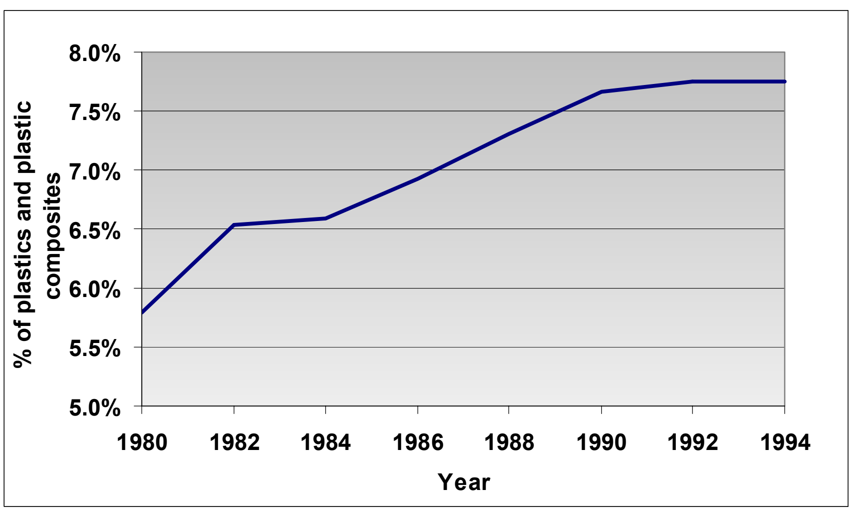

Figure 1-4: Evolution of the percentage of plastics in a typical family vehicle

Increasing the global recycling rate will imply finding a way to deal with these plastics. Thus, these are the materials which should catch the attention of automotive producers.

The focus of this work is to study the cost implications of reaching the recycling rate for the current recycling industry. As a result, we do not study new technologies to recycle ASR but concentrate our analysis on the cost of compliance of the present recycling industry to these new regulations.

1.2 Problem Statement[REK1]

Nowadays, a typical end-of-life-vehicle (ELV) goes first to the dismantler and then to the shredder. The actual recycling rate of the industry is around 75% by mass. Applying the European Directives on end-of-life vehicles requires, among other things, increasing this rate. Implementing this policy becomes an issue because reaching the 80% and 85% recovery targets will increase the cost of operating the system. Indeed, as pointed out earlier, decreasing the quantity of automotive materials that go to landfill will only be achieved by either using new separations techniques or removing more plastics parts manually at the dismantler stage.

- Increasing recycling rate will increase cost

This work concentrates on the compliance of the current recycling industry to the regulation; thus, the eventuality of using new technologies is not considered. The other solution implies that dismantlers would have to remove more parts than they currently do. Since they are currently not removing these parts because they are not profitable, enforcing the regulation will generate a cost for them.

- Cost increase will vary by stakeholder

This cost will be borne by one or several of the stakeholders of the automotive life cycle. Understanding how these costs vary for each stakeholder is critical to understand the relative benefit of the policy and to ensure that the policy does not compromise the economic viability of the system. Ascertaining the key cost drivers and how they affect the cost of compliance would help to quantify the different policy effects.

- Previous studies on this issue:

Several studies have been conducted on automobile recycling, studying, among other things, how different vehicle types affect the dynamics of the actual recycling industry, or calculating the cost of compliance to the European Directive -[Kirchain 99], [Hong 00]. The main contribution of the work done for this thesis is that a tool was created in order to use data collected in field. Removal times provided by automakers were used in this work to calculate the different costs as well as precise list of parts for several vehicles. This thesis addresses new issues, like the impact of a change in vehicle fleet composition and the effect of changes in recycling industry locations.

- Methods needed to quantify these costs and identify leverage points:

One way to characterize this cost is to study the net cost of compliance, i.e. the profit reduction due to the application of the regulation. This cost represents the difference between the actual revenue of the recycling industry compared to its future revenue while enforcing the regulation, in other terms; it quantifies the loss for the recycling industry due to the regulation. This work focuses on the cost of reaching the recycling target, i.e. the impact of reaching the recovery target is not studied.

The cost of compliance can be considered from two points of view. On the one hand, the compliance cost of the first actor of the recycling chain, e.g. the dismantler is estimated. On another hand, as we pointed out earlier, reaching the recycling target will certainly imply to diminish the ASR. Thus, shredders will send less material to landfill and consequently pay less for the disposal of the ASR. That way, increasing the recycling target could actually increase the profit of the shredder. In order to study this effect, the cost consequences for the whole recycling system {dismantler + shredder} were estimated.

- Magnitude of exposure of automobile manufacturers:

Another concern is the determination of the price that automakers will presumably have to pay up front for each vehicle launched. Indeed, while the compliance cost depends on the vehicle type and the location, it is very likely that the up front price will be set per vehicle ignoring the specific vehicle characteristics. For example, in the Netherlands, where a collective system has already been set up, automakers have to pay a fixed amount of 45 euros for all types of vehicles[3]. It is thus interesting to study the magnitude of exposure of a manufacturer to the regulation and characterize the incentives created by the regulation. If the sum paid up front is the same for each vehicle, it might be more interesting for automakers to launch a certain type of vehicle. Ultimately, the regulation could have the side effects of changing the actual fleet composition. To study this eventuality, we computed the compliance cost for the actual European annual fleet of an automaker and studied how variations in this fleet composition could affect the total cost.

[3] Environmental Management Act, Bulletin of Acts and Decrees 2002, number 239

2 Modeling the recycling industry

2.1 Description of the recycling industry

2.1.1 The recycling chain

By many measures, the recycling of end-of-life vehicles is currently an efficient process with 75% of vehicles recycled or reclaimed and a collection rate of around 95% [Bellman and Kahre 99]. The elements of the recycling chain which deal directly with ELVs can be divided into three major steps: pretreatment, dismantling, and shredding. Emerging from each of these steps is a set of parts or materials which then pass to more specialized facilities for reprocessing.

At its end-of-life, a vehicle typically goes first to the storeyard of a dismantler, which can either be open and exposed to the elements or covered. The dismantler first removes all hazardous parts and fluids. This step is called pretreatment. The fluids typically removed include engine oil, coolant, refrigerant, steering oil, washer fluid, antifreeze, transmission oil, brake fluid, fuel, coolant and any remaining fuel. These fluids can either be removed by gravity or using pumps. At this stage, the dismantler typically also removes the tires, batteries, airbags and all parts presenting a potential hazard. While the ELV directive in Europe states that these parts have to be removed by law, the situation is relatively different in the US. ELV management is actually controlled by state legislation, which can vary widely. For example, 48 states have a legislation concerning scrap tires, 40 of them have a scarp tire disposal fee programs while 33 forbid whole tires to go to landfill [Staudinger and Keoleian 01].

In addition to those parts removed according to regulatory fiat, dismantlers remove all the parts they think will be profitable. Typically, profit generating parts are either those that can be reused and will be sold on the secondhand parts market or those that have a significant material value. Depending on their intended end-use, these profit-generating parts either will be sent to a shredder or be sold to other recycling industries.

At the end of its journey through the dismantler, the hulk is typically crushed. It is then easy to handle and to transport to the next step: the shredder. The shredder takes the compacted car through hammermills. These hammermills shred the vehicle, i.e. they reduce it from hulk to “fist-sized pieces”. The ferrous material is then separated using standard magnets. The separation of the non-ferrous metals form the rest of the stream is made at the shredder using air separation. The balance of the material, the "heavy blend", is sent to the non ferrous separator where "eddy current magnets" isolate the non-ferrous materials. The remainder of the vehicle, the Auto Shredder Residue then goes then to the landfill. Figure 2-1 illustrates the main steps of the recycling process.

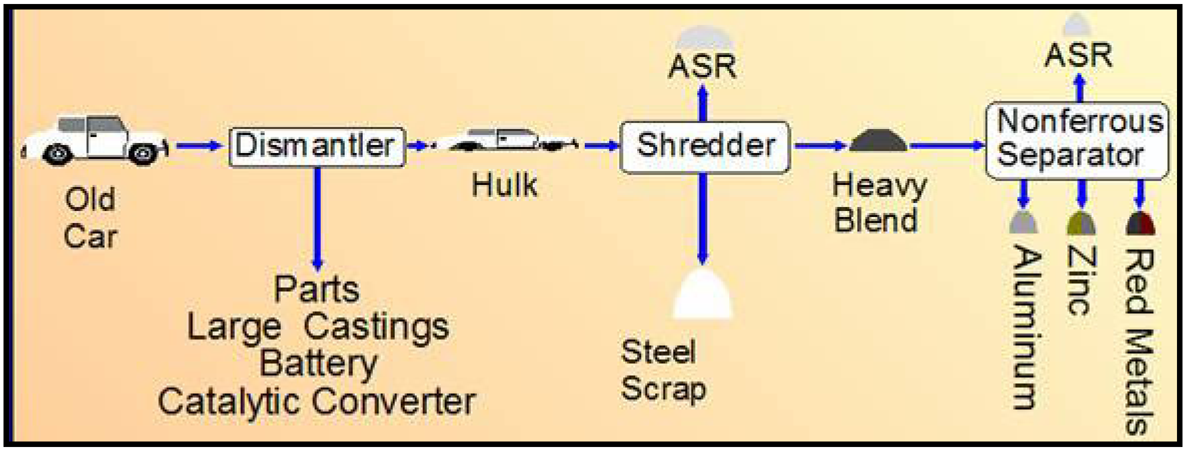

Figure 2-1: The Typical Recycling Process For End-Of-Life Vehicles, [Field et al. 94]

2.1.2 The recycling industry in the US

Automobile recycling is a extensive business within the United States. Nowadays, around 11 million vehicles are recycled each year [Recycling Today 05], which represents $5 billions in sales. The automotive recycling industry employs more than 40 000 people in more than 7000 businesses throughout the country. A typical recycling company has less than 10 people [ARA 05]. The individual facilities are connected to facilities all over the world by satellite, telephone or computer. Thus, it is very easy for recyclers to locate a part.

The primary source of revenue for dismantlers derives from demand for used parts [GLIRM 98]. Then, comes the revenue from the different metals – ferrous scrap being the next most important source of revenue. The process of ferrous metals recovery is very efficient, approaching 100%, while the recovery of non ferrous metals still needs some improvement. The remaining ASR is estimated at 600 pounds per vehicle (approximately 19% of vehicle mass) which correspond to around 3 millions tons of ASR per year ~1.5% of the solid waste generated in the US each year.

2.1.3 The recycling industry in Europe

In Europe, the number of vehicles recycled each year reaches 9 millions, which corresponds to 2.2 millions of tons of waste. The recycling industry infrastructure does not vary much from one country to another. Like in the US, the profit is principally made on sale of used parts and metals [Plastics in ELV 05]. In the Netherlands, the removal of some parts (bumpers, rear lights, ABS grills, PA and ABS wheel covers, safety belts and PU foam) is made possible by a 45 euros tax paid by the first customer registering the car[4] [EMA 02].

Even though some countries have stringent ELV legislation on the books (e.g., Germany), there are still numerous non-approved dismantlers among the operating facilities. For example, it is estimated that, in France, 2000 dismantlers operate among which only 900 have a fully valid operating permit. Another interesting thing to stress is that some manufacturers have contracted dismantler facilities in some countries in order to be sure that their ELVs are treated in an environmentally friendly manner.

[4] Environmental Management Act, Bulletin of Acts and Decrees 2002, number 239

3 Model Infrastructure

3.1 Technical Cost Modeling

For this study, a Technical Cost Model (TCM) was created of the dismantler and shredder operations. The Technical Cost Modeling technique was developed within the Materials Systems Laboratory at the Massachusetts Institute of Technology and is used in this work to calculate the costs of the different stakeholders within the recycling chain. TCM allows the user to identify the key cost drivers of a process thanks to sensitivity analysis.

A typical technical cost model makes use of information concerning factor costs (e.g., wage), financial conditions (e.g., discount rate), process and product specification. These several inputs are used to compute a set of fixed and variable costs, which are the outputs of the model. These outputs are calculated using both financial methods and technical relationships dependent on the process.

The variable costs that are computed typically include material, labor, and energy costs, while the fixed costs typically concern the machinery, tooling, building, and the overhead and maintenance costs.

When creating a TCM, one can add some inputs to improve the flexibility of the model such as a choice to consider if the facility is dedicated. If it is not the case, then the costs are calculated proportionally to the number of products processed. For example, within the scope of this work, the facilities were assumed to be non-dedicated. Thus, all the fixed costs were proportional to the capacity used and the labor costs only concerns the labor needed for the number of vehicles treated.

The main advantage of TCM is that it provides a powerful tool to run sensitivity analysis on the different model inputs and allows the user to pinpoint the key cost drivers of a process. In this study, it was used to identify the key cost elements influencing the net costs incurred by various stakeholders in and across the automobile recycling system.

3.2 Overall Model Description

The model infrastructure was built following the flow of the recycling process (cf. Figure 3-1). The goal of the model is to determine the net cost of compliance to the regulation. Thus, the principal input of the model is the recycling rate targeted. Once the recycling rate is chosen, one has to enter in the model a set of vehicle-specific data (i.e., parts characteristics, removal times). Indeed, one of the goals of this model is to see how differences in vehicle types affect this cost. Another set of necessary inputs is a list of second hand material prices, which are used to determine the revenue flows between the different actors of the recycling chain. Finally, one needs to enter all the operational inputs corresponding to the facilities description. Some of these inputs are country specific, such as the wage or the landfill price, while others are the same for all countries, such as the lifetime of the machinery or the interest rate. All these inputs and their origins will be described in detail later in this chapter. Figure 3-1 presents a list of the key model inputs.

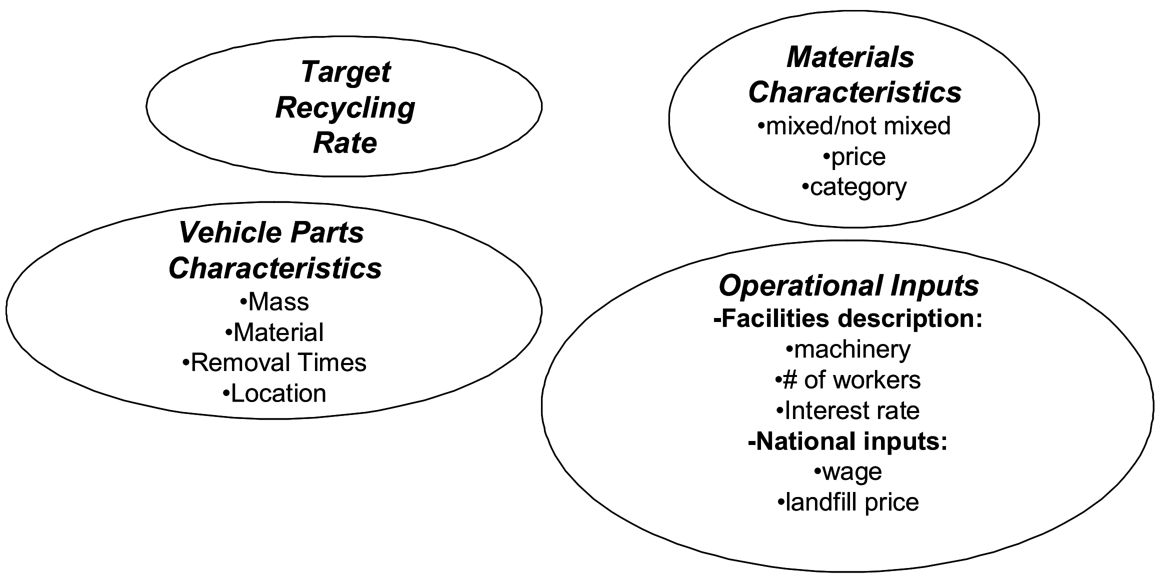

Figure 3-1: Key Model Inputs for MSL/MIT Vehicle Recycling Model

The analytical aspects of the model are most intensive around the set of decisions made at the dismantling facility. This focus emerges partly out of a recognition that near-term compliance with the ELV directive will largely occur through modification of dismantler behavior and because of the complexity of modeling the decisions which occur there. As pointed out in the problem statement, increasing the recycling rate will imply removing more plastics part at the dismantling stage. Given this requirement, the modeling issue is to determine how the dismantler is going to choose which parts to remove. For the purposes of this study, it was assumed that the dismantler would make the rational choice of removing the set of parts that reach the target at the lowest cost. To model this decision, a removal order was determined. The detail of the calculation of this order will be discussed later in this chapter. Figure 3-2.below illustrates the general flow of inputs/outputs within the model of the dismantling stage.

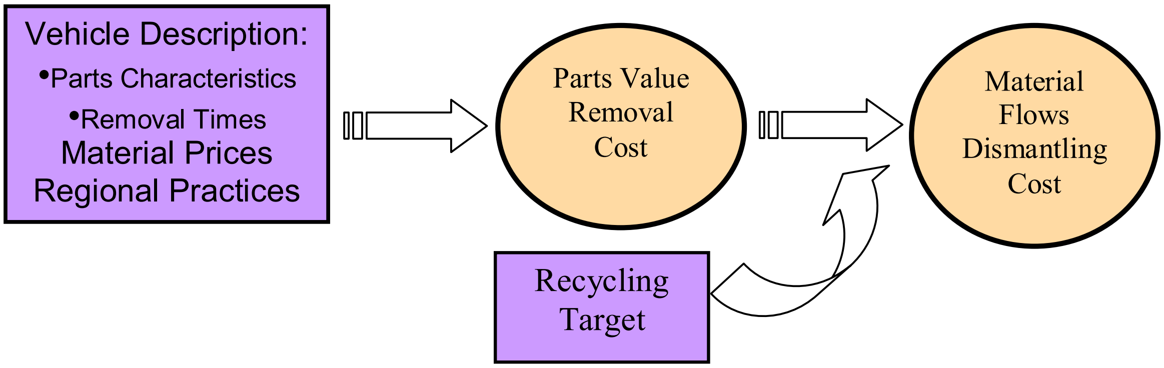

Figure 3-2: Infrastructure for the Dismantling Facility Model

The shredder facility is taken into account within the model by calculating its operational costs. Similar to the dismantler, these costs are divided between fixed costs and variable costs. Some of the operational inputs are the same as for the dismantler facility such as the wage, interest rate, and lifetime of the machinery. Another set of inputs is specific to the shredder facility: characteristics of the machinery, efficiency of the process, i.e. the composition of the flow of materials before and after the shredder separation, number of employee. Finally, the shredder cost is calculated by aggregating fixed and variable costs. Ultimately, by forecasting costs and revenues for both the dismantler and the shredder over a range of conditions, the model allows users to compute the net cost of compliance for one or both of the actors of the recycling chain in response to changes in products, operating conditions, or policy.

3.3 Facility Description

3.3.1 Dismantler and Shredder

Dismantler and shredder facility costs were based on information collected from facilities in Europe (see **Appendix IV** for detail on facilities major inputs). For all model results presented in this thesis, capital equipment (and their associated costs) for both facilities were assumed to be non-dedicated. This assumption corresponds well with current practice, wherein dismantling facilities handle many different types of vehicles and where shredders handle both various vehicles as well as other products (e.g., whitegoods). As will be demonstrated in Chapter 5, this assumption, although reasonable, has little effect on most results. This emerges because fixed costs do not represent the majority of recycling costs. Following the assumption about fixed costs, it was assumed that dismantlers would adjust their workforce depending on the volume of cars they have to process. On the other hand, shredders are not only processing ELV waste, they are also processing other post-consumer wastes.

An efficiency of 95% for the dismantler was assumed, i.e. 95% of weight of the parts removed was counted as recycled. For example, if the dismantler removes a 10 kg weight, it was assumed that 95%*10=9.5 kg were counted in the percentage weight recycled. Parts are removed by hand. While one can argue that a portion of the part is broken or left on the vehicle during the removal, the process is usually very precise. That is why an efficiency of 95% was assumed for this process.

Shredders are very efficient facilities. Shredders are functioning in closed loop, material entering at one end of the facility is going out at the other hand. Thus, the efficiency was set up to 100%. However, there is some inefficiency in the separation process, i.e. basic separation techniques lead to a certain level of contamination of the other material flows [Staudinger and Keoleian 01]. Table 3-1 shows the values chosen to take into account this contamination.

Output Stream Content / Input Stream	Ferrous Metal	Non Ferrous Metal	ASR
Ferrous Metal	95%	4%	1%
Non Ferrous Metal	5%	90%	5%
ASR	5%	5%	90%

Table 3-1: Shredder input-output materials flow composition assumptions

For example, 95% of the ferrous metals were assumed to end up in the output ferrous stream of the shredder while 4% will be found in the non-ferrous metal output stream and 1% will be landfilled.

3.3.2 Regional Differences

All the facility costs were calculated based on European data. Thus, all the following costs are country specific:

- Wage
- Electricity cost
- Building and renting costs
- Landfill Cost
- Machine Cost

A depreciation time of respectively seven and twelve years was assumed for the light and the heavy equipments; see **Appendix IV** for further details.

3.4 Dismantling stage modeling

3.4.1 Removal Order Calculation

3.4.1.1 Removal order considerations

As was stressed previously, in a market-based system the dismantler is expected to remove only those parts that have some net value. Regulation adds those parts necessary for compliance. Thus, the modeling challenge is to forecast the set of parts the dismantler is going to chose to remove for arbitrary sets of vehicle characteristics, operating characteristics, and regulatory requirements. Based on this removal order, it is then possible to compute operating costs, materials revenues, and aggregate cost.

At first sight, this task may seem straightforward: the dismantler should only remove parts whose values are higher than removal costs. The difficulty comes from the fact that these numbers are linked to the order in which the parts are removed. In fact, each part's removal cost depends, in part, on the characteristics of those parts already removed. For example, a part located at the surface of the vehicle is in direct access for the dismantler and does not require the removal of any other part. However, reaching a part in the core infrastructure of the vehicle will require the removal of many parts. Thus, the removal cost of a part should depend on the set of parts already removed. In that perspective, a part should be associated with a set of predecessors; a group of parts that have to be removed to reach the part concerned. A part can indeed only be reached if the parts in the layer above it and in direct contact with it are already removed.

Thus, for each part, there is a trade-off between the value of that part and the effort required to remove it. The difference between these two values characterized a removal potential for each part. The more this removal potential is, the more it is likely that the part is going to be removed. A part with a high value even if located deep in the vehicle infrastructure can be profitable to removed and thus, come first in the removal order. To illustrate this likelihood of parts to push themselves upfront to be removed, the term "buoyancy" has been used. Determining the best removal order for a dismantler using this idea has been studied previously [Kirchain 99].

In this thesis, the interdependence between each part removal was ignored, i.e. each part's removal was not linked to the removal of its predecessors. This decision was made for two main reasons. First, creating a precedence table, containing all the links between the different parts, was infeasible with the resolution of the dataset in hand; there were more than 1500 types of parts for each vehicle, and several parts for each different type. One could have overcome this difficulty by gathering the parts in subgroups like was done in previous works. However, there is a second reason why no precedence table was used. Indeed, the idea was to create a model that could allow the user to use data collected on the field to calculate compliance cost. Since precedence tables are not generated by auto companies, they were not available for this study.

Although no precedence table was used, some assumptions on the removal times (see Part 4.4) were used to give priority for removal to parts of the upper layers of the vehicle.

Even if the interdependence between parts removal was not taken into account, the parts had to be sorted to determine which set of parts were going to be removed by the dismantler to reach a specific target. In the model, the removal order is calculated once, i.e. the parts are sorted in descending removal potential – this potential will be discussed in detail in the next paragraph. The percentage weight recycled was then calculated for each sorted part. Thereby, all possible scenarios, each comprised of removing a subset of ordered parts, could be analyzed and associated with a specific recycling rate. The model also allows the user to determine the different characteristics of the set of parts chosen to reach the recycling target, i.e. their value, removal costs, composition, weight. For example, if one wants to reach a recycling target of 80%, the model will not only provide the list of parts to be removed to reach this target but also the different costs and revenues associated with this removal and the composition of the parts. The subtlety of the removal order obtained is that the parts are sorted by value but this order is not necessarily the order in which they will actually be removed by the dismantler.

3.4.1.2 Removal order computation

This section explains the heuristics used to sort the parts in efficient removal order. It details how different sets of parts are identified and sorted in order to determine the removal order. The different sets of parts identified are shown in Figure 3-4 . This set comprises the profitable parts and then different subsets of non-profitable parts: the small ones and the ones that are going to help to reach the recycling target. The identification of these different types of parts is examined through this section. The general strategy of the model is to identify those parts that fall into each category subsequently. Thereby reducing the size of the set of parts for which complex analytics are required.

The first parts identified within the model are the profitable parts. These parts are the first to appear in the list of parts to be removed to reach the recycling target because dismantlers will remove them with or without the existence of a recycling target. They actually help to get closer to the recycling target and are a source of revenue. Thus, dismantlers will remove them with or without having to reach a specific recycling target because they are a source of revenue anyway.

A part is identified as profitable if its value is higher than its removal cost. To find these parts, the net removal value of each type of part i was calculated as:

$$NRV_i = RV_i - RC_i$$

where NRV_i (\$) is the net removal value of type i parts, RV_i (\$) and RC_i (\$) are respectively the removal value and the removal cost for this type of part.

The removal value is calculated as follow:

$$RV_i = MV_i - OC_i$$

where MV_i is the material value of type i parts and OC_i is the opportunity cost of part *i*. The opportunity cost corresponds to the revenue the dismantler would make by selling the parts to the shredder. Thus, a part is profitable if it generates a higher profit when sold individually than with the rest of the hulk.

Finally, the removal value and the removal cost are calculated as follow:

$$RV_i = \#Parts_i \times W_i * MV_m - OC_i$$

$$RC_i = RT_i * w$$

where $\#Parts_i$ is the number of parts of type i, W_i (kg) is the weight of type i parts, MV_m ($/kg) is the mass material value of the parts, RT_i (hr) is the time necessary to remove one type i part, and w ($/hr) is the hourly wage. (The detailed calculation of the removal time will be explained in section 4.4.). Based on this calculation, the profitable parts are the ones for which the Net Removal Value is positive.

Once the profitable parts are identified, the remaining parts were divided into two groups depending on their size. Indeed, the parts were sorted by weight and the smallest parts of the vehicle, corresponding to 1.5% of the total vehicle weight, were excluded. For the Luxury Car for example, it corresponded to all the parts weighting less than 16.5g. This threshold was chosen arbitrarily in order to facilitate the treatment of the data without significantly influencing the results. Figure 3-3 below shows the threshold chosen for the different vehicles.

Vehicle Type	Weight Threshold (g)	# of parts excluded	Total # of parts
Compact	16.5	4539	6602
Luxury Car	16.5	5162	7594
Truck	25	5142	7251
Small SUV	23	4992	7181
Big SUV	21	7693	10831

Figure 3-3: Small Parts Weight Threshold (corresponding to 1.5% of mass of the vehicle)

Thus, all the larger non-profitable parts were isolated. At that point, one needed to find the set of non-profitable parts which would enable the dismantler to reach the recycling target at least cost. To characterize the ability of a part to increase the recycling rate at the lowest cost, a removal resistance was computed for each part: V. The goal was to quantify the dollar amount to invest to remove one kilogram of this part, given by the following formula:

V = Net Removal Cost ($)/Part Weight (kg)-Opportunity Cost ($/kg),

As shown in the formula above, V is not only linked to the removal cost but also to the opportunity cost of the part. Thus, it corresponds to the actual cost of removing this part for dismantlers because it takes into account the fact that they lose the benefit of selling the part to the shredder. Parts are sorted by ascending removal resistance, V. This method brought thus upfront the ones which will allow the dismantler to reach the recycling target at the lowest cost. Indeed, the larger the removal potential the more it costs to remove one kilogram of a particular type of part. Thus, removing first the parts with the lowest V allows the dismantler to reach the target at the lowest cost. If two types of parts have the same removal resistance, the heavier ones were chosen to be removed first.

Finally, the removal order calculation can be summarized as in the schematic of Figure 3-4:

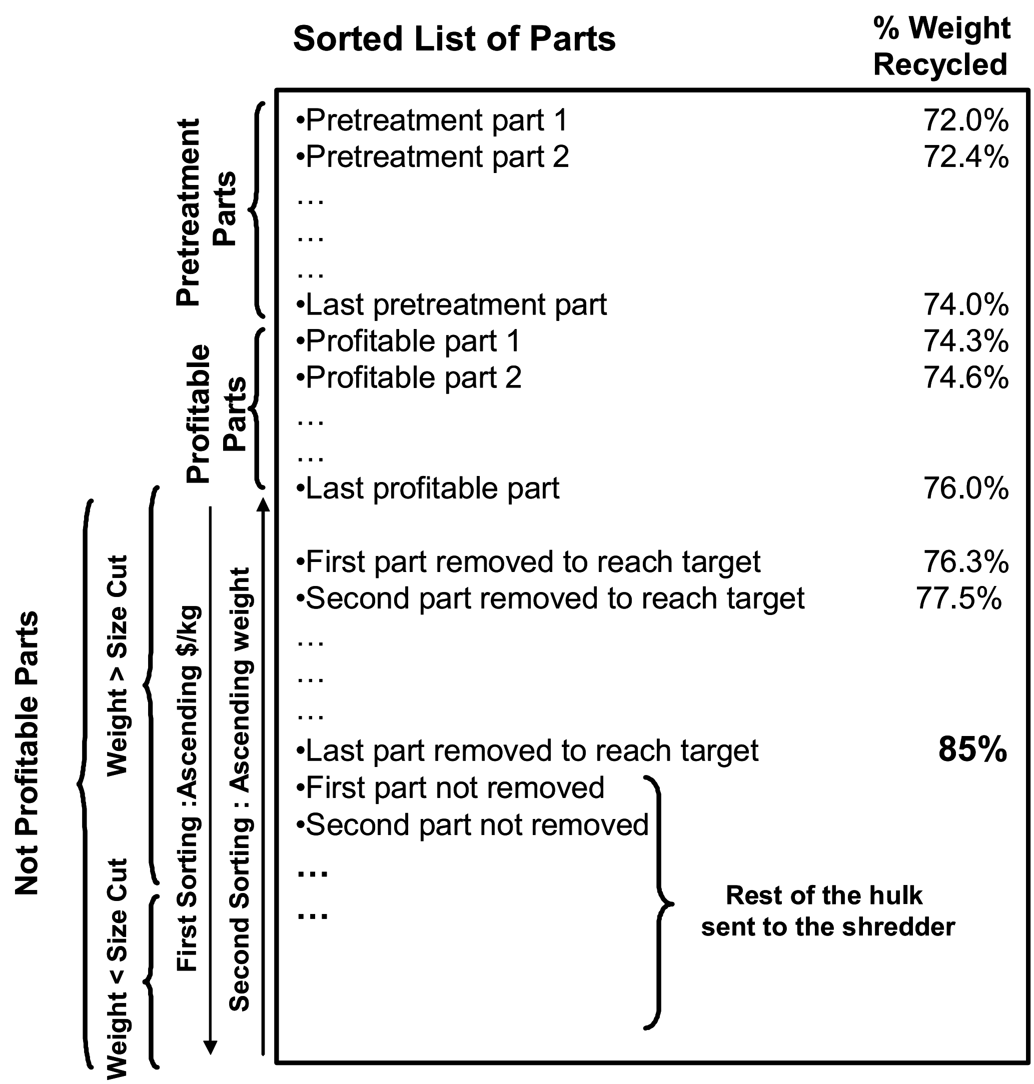

Figure 3-4: Removal Order Calculation Schematic (Algorithm sorting criteria are shown on the left)

One concern raised by this removal order calculation is that, even if a part has a higher V than another one, if this other part is large enough, it could be more judicious to remove it first to reach the target faster. It is useful to take an example to clarify this argument: Assuming Part A and Part B are two different parts of a vehicle, it costs \$5/kg to remove part A and \$10/kg to remove part B, and the weight of parts A and parts B are respectively 1 kg and 2 kg. Finally, after having sorted the parts as described above, it happened that Part A is sorted just before part B. If one supposed that, after having removed all the parts sorted before these two parts, the dismantler needs 1.5 kg to reach the final recycling target. Part A being just before Part B in the removal order, to reach the target, the removal order calculation described above will imply that both parts should be removed. It is actually true that removing part A first is less costly. However, the sole removal of part B would have been sufficient to reach the target.

This consideration is interesting and justified but is not relevant in this work. Indeed, the study focuses on variation of percentages of recycling rate. Going from one recycling rate to another requires removing between 12 and 25 kg of parts. The weight resolution of our dataset being very fine, this corresponds to a large number of parts. Thus, removing one more part or one part before the other does not make much difference.

3.4.2 Dismantling Cost

For the purposes of the model, dismantling cost is divided into three categories: Material Revenues, Labor Cost and Other Costs.

To determine the Material Revenue, the model must project the magnitude and composition of material flows entering and emerging from the dismantler. These material flows derive from three sources: the dismantler purchases the end-of-life vehicle, sells some profitable parts and the rest of the hulk to the shredder.

The profitable parts can be divided into two categories: the ones that are going to be resold and reused for the same purpose and the ones that are going to be sold for their material value. In our study, we focused only on the material value of the parts. The idea is to illustrate the case of an end-of-life vehicle for which there is no market for secondhand parts, i.e. an older, obsolete model. This represents an upper bound for the cost, since most of dismantlers profit usually comes from the secondhand parts they sell. The Material Revenue is thus calculated by subtracting the cost of the purchase of the

hulk from the revenue generated by the parts sold and the sale of the vehicle remainder to the shredder. The choice of the prices for these different materials will be discussed later.
The Labor Cost was calculated by multiplying the total dismantling time for the vehicle by the hourly labor rate. However, the total dismantling time does not correspond to the total required production time. Indeed, there are some inefficiencies that make the total required production time higher than the actual production time needed To take into account these inefficiencies and to compute the required production time, the time was divided in four categories: unpaid downtime, idle time, paid breaks and unplanned downtime. Unpaid downtime is the time corresponding to the expected downtime of the machine for maintenance and thus, is unpaid. On the contrary, the unplanned downtime is not expected and decreases the amount of time available for production. Finally, the Idle Time helps to take into account workforce inefficiency; it corresponds to a time where the workers do not work because of insufficient demand (or in the case of a dismantler, insufficient supply of ELVs). With these definitions:

- Available Production Time (hours/shift) =
  Hours per shift-Unplanned Downtime-Planned Downtime-Idle Time-Paid Break
- Paid Time (hours/shift) =Number of hours per shift-Planned downtime

Using this division of time, the model is able to account for labor inefficiencies. Table 3-2 shows the baseline downtime assumptions used in all subsequent analyses.

Time Category	**Planned Downtime**	**Unplanned Downtime**	**Idle Time**	**Paid Break**
Dismantler	0.4	0.1	0.8	0
Shredder	1	1	0.3	0.2

Table 3-2: Time category for two facilities (hours/ 8 hours shift)

Finally, the Other Costs correspond to transportation cost, pressing cost and facility cost. The transportation cost corresponds to the cost of bringing the vehicle on site.
At the end of the dismantling, the end-of-life vehicle was assumed to be pressed on the dismantler's site before being sent to the shredder, which results in a pressing cost at the dismantling stage. Finally, the facility cost corresponds to all the fixed cost associated

with the dismantling, i.e. the machinery cost, the tooling cost, the overhead and the building costs.

3.5 Shredder Cost

The shredder costs can be divided between material costs and facility costs.

The materials flows at the shredder facility are similar to the dismantler's. The hulk is purchased from the dismantler. At the end of the shredding process, the materials were tracked according to three categories: ferrous metals, non-ferrous metals and Auto Shredder Residue (ASR). The shredder was modeled assuming that the metals are sold to the metal recycling industry and that the ASR is disposed of at a landfill at a cost. The shredder revenue is thus the difference between the revenue from metals sold and the cost of the hulk added to the cost of sending the ASR to landfill.

To compute the facility cost for the shredder, since the shredder was assumed to be a non dedicated facility; all the costs were calculated per vehicle. They entail labor, energy, machinery, overhead and building costs.

4 Case Specific Inputs: Vehicle & Materials Characteristics

4.1 Vehicles Dataset

To gain refine into model operation and to gain insight into pending system costs, five vehicle case studies were executed. The data on these five vehicles was provided by an US based car manufacturer with operations and sales in Europe. Each dataset contained detailed part and dismantling information. The datasets were collected by a professional dismantler whose goal was to break down the vehicles as thoroughly as possible. For each type of part, its unit weight, composition, and the number of occurrences within the vehicle were recorded. Concerning the composition of the parts, the data included a material category, material type and name corresponding to the predominant material present in the part. If the part was composed of a mixture of materials, up to XXX additional minor materials were listed. The percentage of each material was not provided. However, when the dataset was created, the goal of the dismantler was to break down the parts as much as possible. As such, reports from the dismantlers were that components were mostly homogenous. To accommodate this uncertainty in the model an input parameter was provided which adjusted uniformly the assumed fraction of minor constituents. For all analyses presented in this thesis this value was set to 5% (i.e., mixed-material components contained on average 95% of the dominant material). This value provided good agreement for the known overall composition of the vehicles being studied. Finally, some of the parts were associated with a dismantling time and all the parts were located in the car by a code corresponding to their assembly.

4.2 Fluids and pretreatment parts

The dataset did not include the fluids and some other pretreatment parts. To calculate the fluids removal cost, the mean dismantling times for a set of fluids from a previous study [Paul 04] were used. In this study, most of the fluids were gravity drained except from the gasoline -siphoned out of the tank- and the refrigerant-removed by a negative pressure system. The amount of fluids to be removed in each of the case vehicles was recorded in their corresponding dismantling guide. For those fluids with no known removal rate, a typical rate of .16 liters per minute (i.e., that of brake fluid) was used. The maximum removal time of the fluids was computed; assuming that all the fluids were removed at the same time. This time was used within the model as the total time for removal. Finally, ten minutes were added to the total to take into account the time necessary to set up the vehicle.

Table 4-1 shows an example of the list of fluids removed and their removal rate at the first step of the pretreatment of a Large Car. For this car, only the removal time of the steering oil was extrapolated.

Fluid	Content	Volume or Weight	Removal Times (s)	Removal Rate (kg/min or L/min)
Engine Oil	Oil	6.6L	154	2.57
Transmission oil	Oil	10.6L	164	3.88
Refrigerant 134A	Refrigerant 134	.8kg	363	0.13
Coolant	Coolant	13.1L	597	1.32
Steering oil	Oil	1.0L	384	0.16
Brake Fluid	Oil	0.5L	192	0.16

Table 4-1: List of fluids (Large Car)

After the fluids, certain hazardous parts have to be removed by regulation during the pretreatment. Thus, to calculate the pretreatment cost, the concerned parts were isolated using the dismantling guide provided online by the automaker. Figure 4-1 shows an example of a dismantling manual that can be found on the web.

Activity Ref Area #	Part Name	Material	Qty	Total Volume or Weight
0.1	Engine oil	Oil		5.7 L
0.2	Front axle oil	Oil		.08 L
0.3	Engine oil filter	Multiple	1	0.55 kg
0.4	Steering oil	Oil		1.10 L
0.5	Coolant	Coolant		14.0 L
0.6	Refrigerant 134A	Refrigerant 134		0.80 kg
0.7	Passenger air bag	Multiple	1	3.84 kg
0.8	Driver side air bag	Multiple	1	1.03 kg
0.9	Spare tire	EPDM	1	15.35 kg
0.10	Fuel tank	PE	1	16.14 kg
0.11	Tires	EPDM	4	61.48 kg
0.12	Rear axle oil	Oil		1.9 L
0.13	Transfer case oil	Oil		1.40 L
0.14	Transmission oil	Oil		10.60 L
0.15	Brake fluid	Oil		0.70 L
0.16	Battery	Multiple, including lead	1	21.6 kg
0.17	Wheel weights	Lead	4	0.20 kg

Information & Comments:

Total Volume or Weight = single part material multiplied by the quantity.

[REK2]

Figure 4-1: Typical Dismantling Manual providing reference list of pretreatment parts

Table 4-2 shows the list of pretreatment parts for the Large Car, their material composition, weight and removal times. All pretreatment parts were assumed to have no positive part value (see Appendix II). The removal times were calculated proportionally to part weights on the basis of those found in the Honda study [Paul 04] and by USCAR [USCAR 98, unpublished data]. For the parts whose weight varies widely from one vehicle to another, a reasonable removal rate was assumed and used for all the vehicles. For other parts, like the tires or the airbags, the same removal time was assumed for all vehicle types.

Part Name	Material	Quantity	Total Weight (kg)	Removal Time (min)	Removal Rate Used (if necessary) (kg/min)
Battery	Multiple, including lead	1	16.4	0.5	32.8
Passenger Air Bag	Multiple	1	3.8	4	-
Driver side Air Bag	Multiple	1	1.3	2	-
Fuel Tank	HDPE	1	11.0	1.5	7.3
Spare tire	EPDM	1	4.6	1	-

Tires	EPDM	4	40.0	4	-

Table 4-2: List of regulated pretreatment parts (Large Car)

4.3 Materials Lists

For the set of vehicles considered, their parts were recorded with a set of around 270 different materials (see **Appendix I**). Materials prices used the model were based on information within the American Metal Market [AMM 04], the US RecyclingNet website, [RN 4] and Plastic News [PN 05]. These sources also provided the cost of the hulk paid by the dismantler to purchase the end-of-life vehicle. (cf. Appendix II for the complete list of input prices).

To assess the impact of mixed materials on process economics, a discount factor was applied to the price of the predominant virgin material within the mixture. For example, a discount factor of 0.6 was assumed for the mixed polymers, leading to a relationship for a part predominantly made of TPO of the form:

Price (Mixed TPO) =0.6*Price (TPO).

For simplification, the prices do not reflect the difference between two mixed materials with the same main material. For example, TPO mixed PE will have the same price as TPO mixed with Steel. This simplification might lead to overvalue of the mixed polymers. However, sensitivity was conducted on polymer prices (see Results chapter later) and lead to the conclusion that variation in these prices has only limited effect on overall cost of complying with the regulation.

4.4 Removal Times

Some removal times were recorded within the vehicle datasets. Unfortunately, this only occurred for a small number of parts (around 1%). To compute removal order and dismantler operating costs, it was necessary to estimate the omitted removal times.

To do so, a statistical analysis was carried out on those parts that were associated with a removal time. For each type of part, the dataset provided a reference number indicating the location of the part in the vehicle (see Appendix III for and example of the list of locations for a compact car). Based on analysis of all available data on removal and part characteristics, the two most meaningful drivers of part removal time were part mass and location within the vehicle.

Following these observations, a simple regression model was developed around two assumptions:

1) for each type of part, the removal time is made up of the sum of a component proportional to the number of parts of that type and of another component proportional to their weight.
2) the coefficients of this correlation depends on the part's location; i.e. for each type of part i and for each location l, there are two coefficients A_l and B_l such as:

$$t_i = A_l * w_i + B_l * n_i ,$$

where t_i (min) is the removal time, w_i (kg) and n_i are respectively the weight and the number of parts of type i. The coefficient Bi corresponds to that time required to identify, locate, and sort a given part and its required removal tools. Ai captures those removal effects associated with number or extent of connection interfaces as well as handling effort proportional to part weight. A lack of data decomposing these two effects forced a simplified structure assuming that for each type of part these two effects were of similar magnitude. As such, for each type of part i and for each location l:

$$\frac{t_i}{2} = A_l * w_i = B_l * n_i$$

Overall, there were 160 different locations referenced in the vehicles database. Some locations did not contain any parts with recorded removal times. These remaining locations were divided into two groups, whether they were corresponded to upper layers of the car or not, as determined by engineering experts. Parts not located in an upper layer were assumed to be not easily dismantled or accessed and corresponded mainly to large metal parts which would go to the shredder. Lower level parts were assigned a high removal time for each of these categories. Upper level parts with no recorded removal times were assigned times based on analogous locations with recorded information. (See Appendix III for an example of removal times input).

5 Results

5.1 Scenarios

5.1.1 Vehicle Selection

The goal of this work was to study the cost impact of complying with the current regulation in Europe. Thus, a specific set of vehicle in the dataset was chosen, corresponding to models of the actual European vehicle fleet. A panel of five vehicles was selected (see Table 5-1 below.).

	Metal	Non-Metal	Total Weight (kg)
Vehicle 1 : Compact car	68.1%	31.9%	1259
Vehicle 2 : Large Car	68.7%	31.3%	1512
Vehicle 3 : Truck	74.6%	25.4%	2051
Vehicle 4 : Small SUV	72.3%	27.7%	2060
Vehicle 5 : Big SUV	74.4%	25.6%	2373

Table 5-1: Weight composition of the panel of vehicles

5.1.2 Countries Selection

Comparing data collected on costs for facilities in various countries, little difference was observed in machines prices, energy cost, and material prices. The main differences across countries were in landfill cost and labor cost. Comparing the different data, it appeared that each country could be related to a certain level for each data, For example, concerning the labor cost, one could divide the countries in three categories whether the labor cost was low, medium or high. Thus, three profiles –low, medium and high- were defined for each of these data. Table 5-2 shows the range of cost for each profile.

Profile	Landfill Price Range (€/sqm)	Worker wage range (€/hr)
Low	25-30	6 10
Medium	45-67	12 15
High	90-96	19-23

Table 5-2: Cost Profile Definition

With three levels each for landfill and labor costs, there should be nine profile types in total. However, some profiles could not be related to any specific country. For example, there is no country with high wages and low landfill price. As such, only five cost profiles were distinguished which represented actual conditions. Each country could be related to one of these profiles. One country in each of this profile was arbitrarily chosen for this study. Table 5-3 shows the panel of countries chosen, their cost profile, and the corresponding costs.

Country	Landfill Price (€/sqm)	Landfill Profile	Worker wage (€/hr)	Wage Profile
France	53	Medium	15	High
Germany	65	Medium	19	High
Greece	54	Medium	8	Low
Norway	96	High	20	High
Poland	25	Low	10	Low

Table 5-3: Countries Panel Characteristics

5.2 Net cost of compliance calculation

As pointed out earlier, this work focuses on the analysis of the variation of the net cost of compliance (NCOC). To compute this number, the difference between the revenue of the dismantler after he had removed all the profitable parts and his revenue at a given recycling target was calculated.

$$NCOC = R_{bef} - R_{after}$$

Where $NCOC$ (\$) is the net cost of compliance

and R_{bef} and R_{after} (\$) are respectively the revenues before and after the regulation

Figure 5-1 shows the calculation of the net cost of compliance for the dismantler in France for the Large Car. Without the regulation, the dismantler makes around \$12, as represented by the dashed line near the top of the figure. It corresponds to around 76% of the weight of the car recycled. The negative slope of the dismantler revenue curve shows that increasing the recycling rate decreases the dismantler revenue. For example, reaching the 85% recycling rate will cost around \$45. Thus, the net cost of compliance is (\$12+\$45=) \$57 for this recycling target.

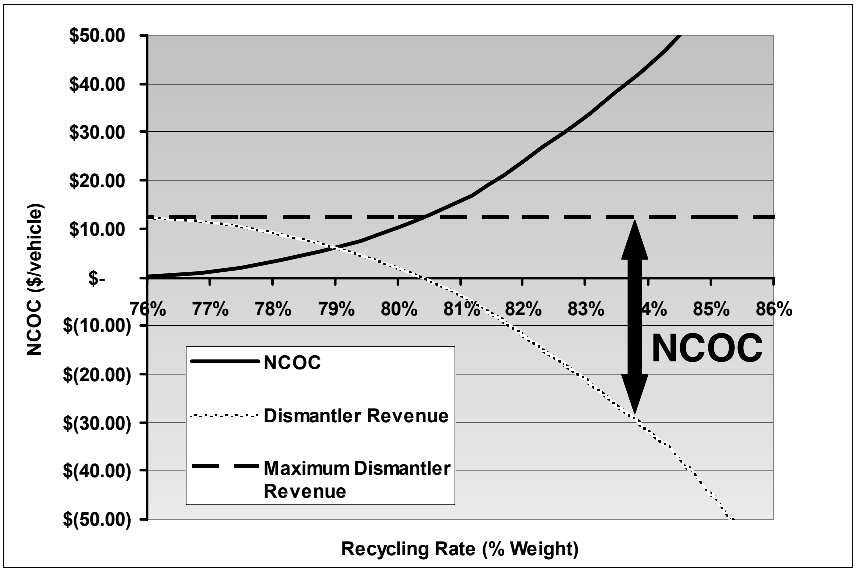

Figure 5-1: Net Cost of Compliance {Dismantler} (Large Car, France)

In this work, the net compliance cost was computed for both the dismantler alone as well as for the whole recycling system, i.e. {Dismantler + Shredder}. The consequences of complying with the regulation can actually be negative for one actor of the recycling chain and positive for the other. Reaching the recycling target implies, removing non-metal parts at the dismantler a practice which adds removal time and little (if not negative) material revenue. This same practice removes plastic parts from the hulk makes it more profitable for the shredder. Less plastic in the hulk results indeed in a smaller quantity of the hulk going to landfill as ASR, thus the shredder will have to pay less for landfill. Finally, increasing the target can be more profitable for the shredder and thus we have to consider the system {dismantler + shredder} to study the impact of the regulation for the whole system.

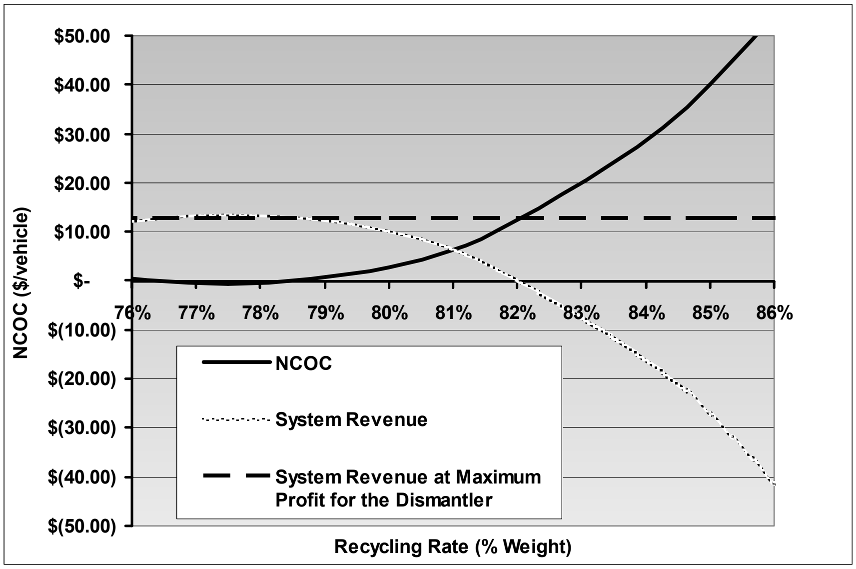

Figure 5-2: Net Cost of Compliance {Dismantler + Shredder} (Large Car, France)

Figure 5-2 shows the NCOC for the dismantler and the shredder combined. As pointed out before, increasing the recycling rate at the beginning makes the hulk more profitable for the shredder. In that case, increasing the recycling rate until around 77.5% actually improves the system revenue. After that, the system revenue decreases. Figure 5-3 illustrates how the NCOC differs depending on whether only the dismantler or the whole system is considered. As explained above, the NCOC for the dismantler alone is always higher than for the whole system.

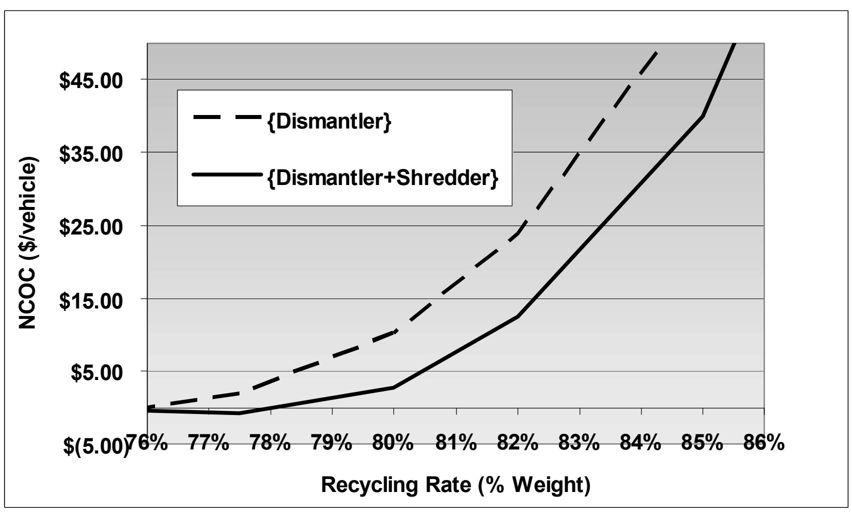

Figure 5-3: Comparison of the NCOC (Large Car, France)

5.3 Net cost of compliance sensitivity analysis

5.3.1 National sensitivity analysis

Having defined the NCOC, its sensitivity to regional location was studied. Figure 5-4 and Figure 5-5 show respectively the net cost of compliance for the dismantler and for the whole system for different recycling targets for the Large Car.

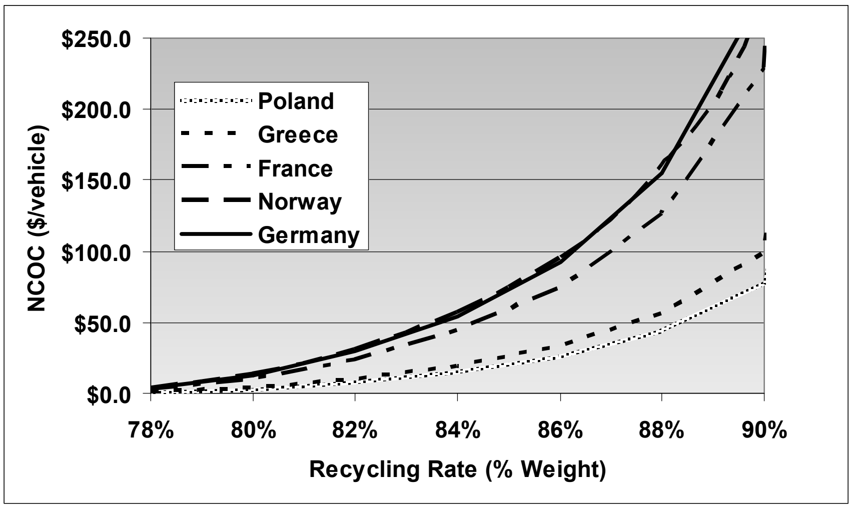

Figure 5-4: Dismantler NCOC for the Large Car in Various Countries

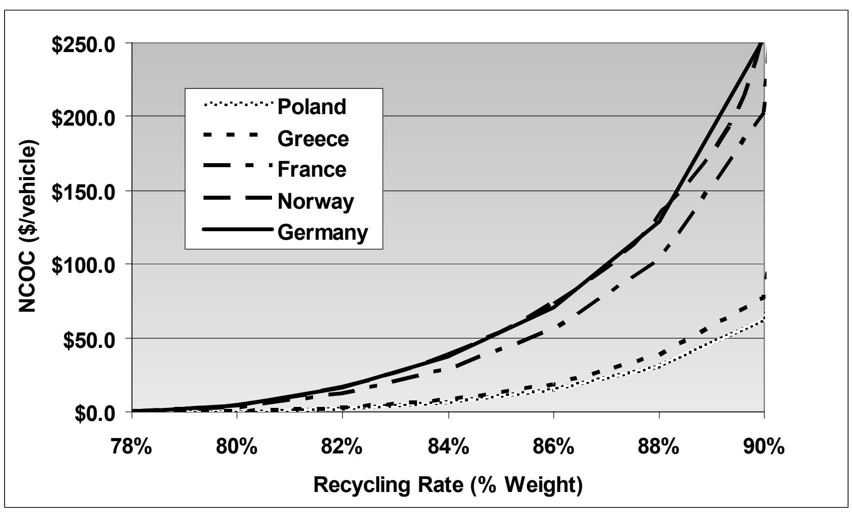

Figure 5-5: System {Dismantler + Shredder} NCOC for the Large Car in Various Countries

The first thing to notice is that, as pointed out earlier, the cost of compliance is less important for the system than for the dismantler alone. There are even certain rates for which the cost is null for the whole system while it is positive for the dismantler. Second, the cost varies widely depending on the country. We will study later the major cost drivers that lead to this variation. An interesting point to notice for the moment is that, at certain recycling targets, there is no cost for complying with the regulation in the low labor and low landfill price countries.

5.3.2 Labor Cost

5.3.2.1 Driving role of labor

To study the role of various cost drivers within the total cost, the cost breakdown at the profitable point for the dismantler was studied, cf. Figure 5-6. The values on the chart correspond to the different non-null dismantler costs in Germany for the Compact Car.

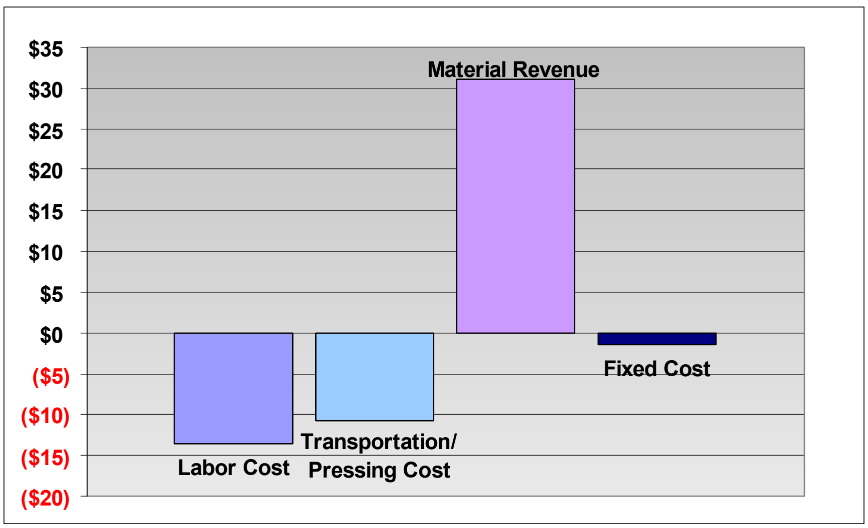

Figure 5-6: Cost breakdown at dismantler profit maximizing point (Compact, Germany)

Labor Cost is the main component of the costs while material cost is the sole source of revenue. While transportation/pressing cost and fixed costs are non-negligible part of the total cost, they are fixed and thus, do not affect the NCOC. The only components of the NCOC are finally the material revenue and the labor cost. Figure 5-7 shows the variation of these two costs for different recycling rates.

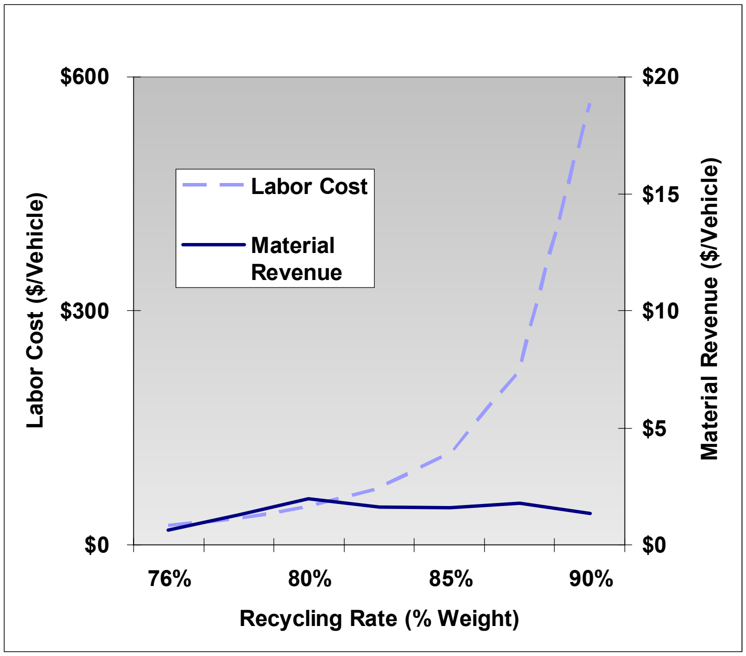

Figure 5-7: Labor Cost and Material Revenue, NCOC, Dismantler, Germany, Compact Car

The importance of the Labor Cost is striking; it is the one that varies the most when the recycling rates increase. Increasing the actual recycling target requires the removal of more parts at the dismantler stage. While these parts have some material value, they are not removed currently because their removal cost is too high. Labor Cost is influenced by removal times and wage. While removal times are fixed inputs, it is possible to find different level of wage across Europe. The next session studies the effect of wage variation on the NCOC.

One could be surprised by the fact (as shown in Figure 5-7) that the material revenue of the dismantler can decrease while the recycling rate increases. Intuitively, one would expect an increase in Material Revenue if the dismantler removes more parts. Whether or not this occurs actually depends on the material value of the additional parts removed to increase the recycling rate. If the unit material price of these parts is higher than the unit hulk price, then removing these parts will increase the Material Revenue. However, if the unit material price is less than the unit hulk price, then removing these parts will decrease the Material revenue.

5.3.2.2 Wage sensitivity analysis

The model was run to study the NCOC sensitivity to wage variation. A wage adjustment factor, similar to the adjustment factor for material prices as seen in Chapter 3.3, was used to explore the impact of wage on NCOC. The wage adjustment factor is a number by which the different wages are multiplied. It is important to note that different countries are considered and thus, at a given wage factor, the wages associated are different from one country to another. Figure 5-8 shows the different dismantler NCOC in different countries for the Compact Car with a target recycled rate set at 85%. Trends were similar for other recycling targets and other vehicles.

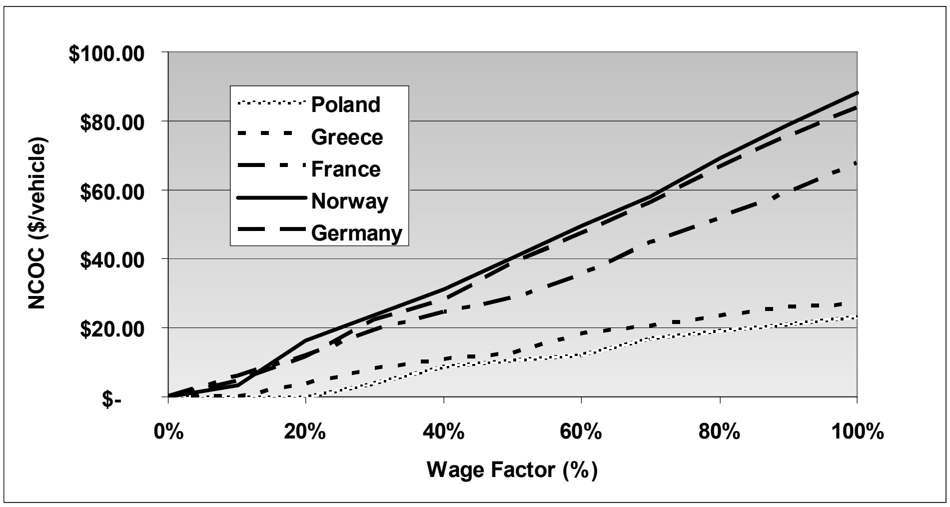

Figure 5-8: Dismantler NCOC for different levelsof wage (Compact Car, % Weight Recycled: 85%)

The first thing to notice is that, when there is no labor cost, there is no NCOC. The second thing is that it seems that the NCOC is almost linearly correlated to the wage. Another manner to show that is to represent the NCOC in function of the wage for each country as shown in Figure 5-9.

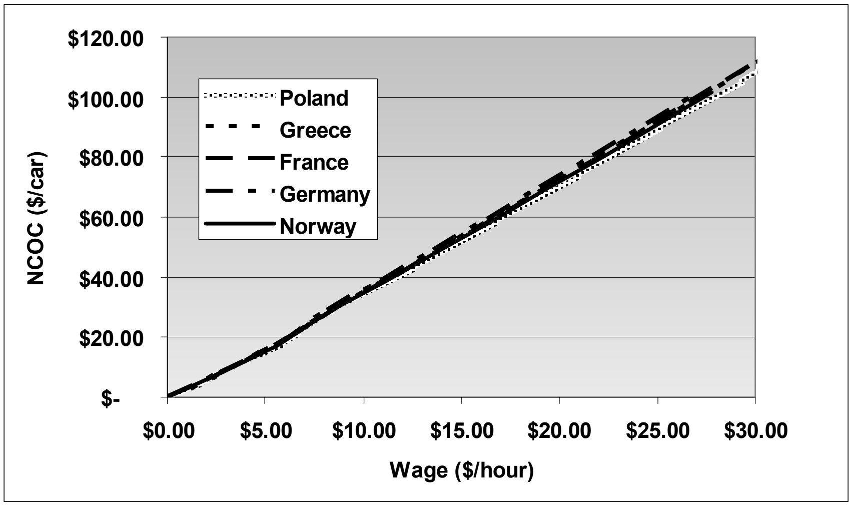

Figure 5-9: Dismantler NCOC (Compact Car, Recycling Rate: 85%)

This graph is important for the rest of the analysis. It shows in fact that the NCOC is linearly correlated to the wage. Thus, the only difference between one country and another is the wage. In the rest of the study, results are shown only for Poland and Germany representing the lower and upper bound of the NCOC, respectively.

5.3.3 Vehicle type sensitivity analysis

5.3.3.1 Vehicle type comparison

The variation of the NCOC depending on vehicle type is shown in Figure 5-10 comparing costs in Poland and Germany. Notably, the NCOC varies widely between one car and another. For example, reaching the 85% target in Poland is three times more costly for the Compact Car than it is for the Truck. One interesting characteristic of these curves is that the NCOC increases considerably for recycling rates above 85% for all vehicles.

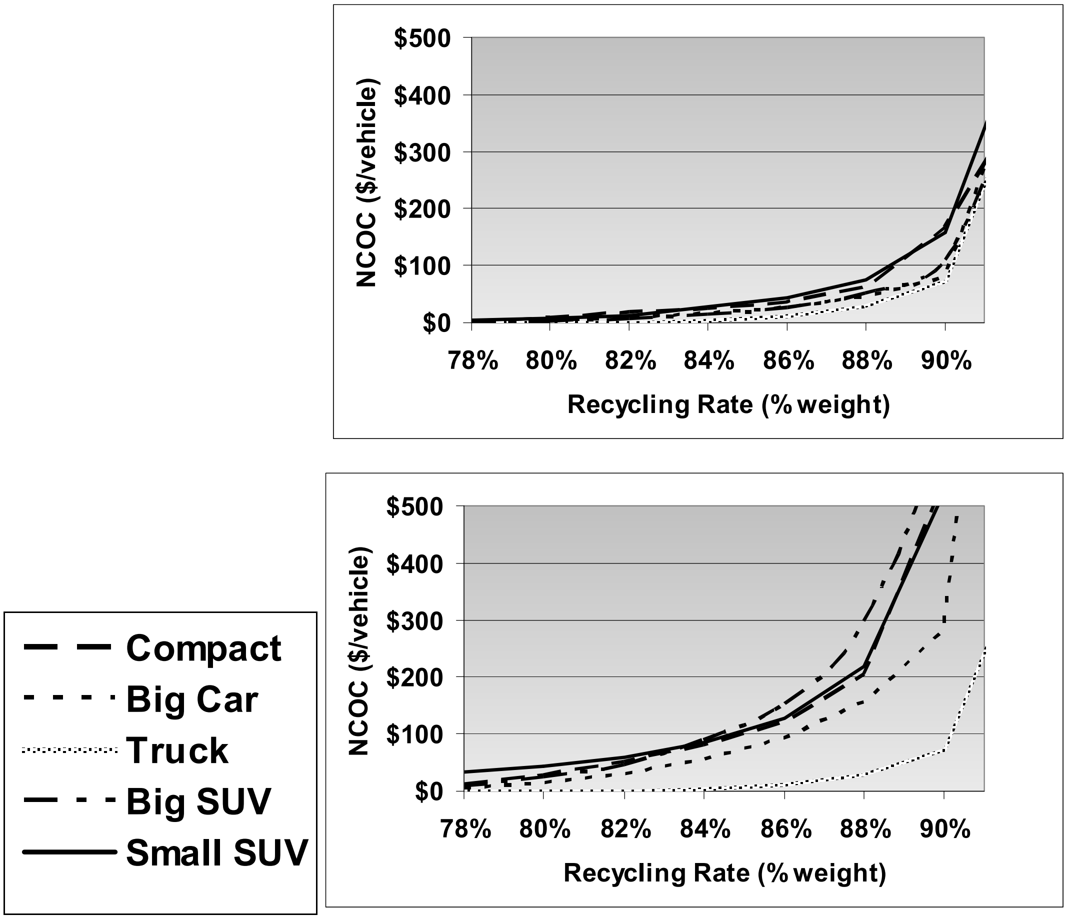

Figure 5-10: Dismantler NCOC in Poland, and Germany for different Vehicle Types

Figure 5-11 shows the NCOC for specific recycling targets: 80%, 85% and 90%. Reaching the first recycling target will cost less than $40 for all vehicles in all countries. Getting to 85% will at most double the cost. The NCOC will stay below $100 for this target. However, increasing the recycling target of another 5% will make the cost soar and pass the $500 for certain vehicles.

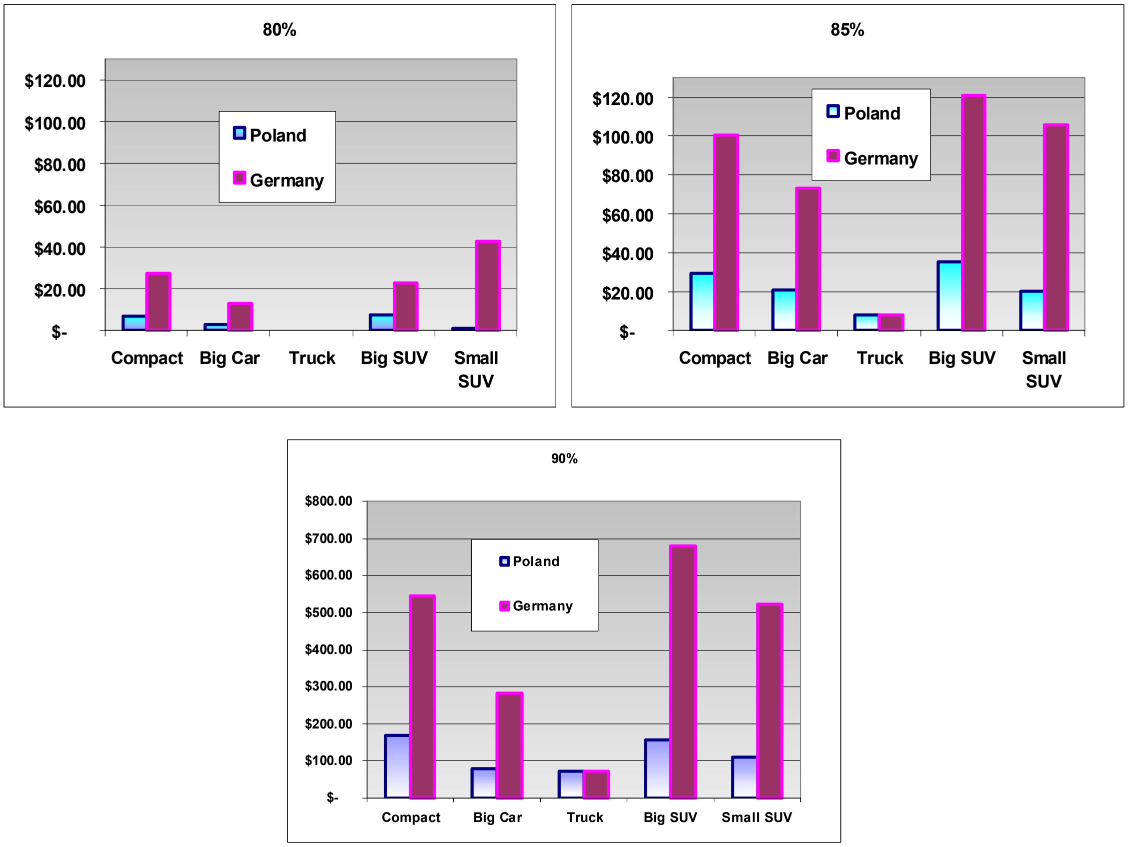

Figure 5-11: NCOC for various vehicles in Poland & Germany for 80%, 85% and 90% recycling rate

5.3.3.2 Normalized NCOC

While it is interesting to study the relative differences between one vehicle and another, it is equally critical to identify the underlying driver for the difference. Indeed, as the recycling rate is calculated in percentage mass, it is interesting to study the impact of vehicle mass on the cost of reaching a specific target. To gain this insight, this section explores the NCOC normalize by vehicle weight (i.e., the cost by divided by the weight of each vehicle).

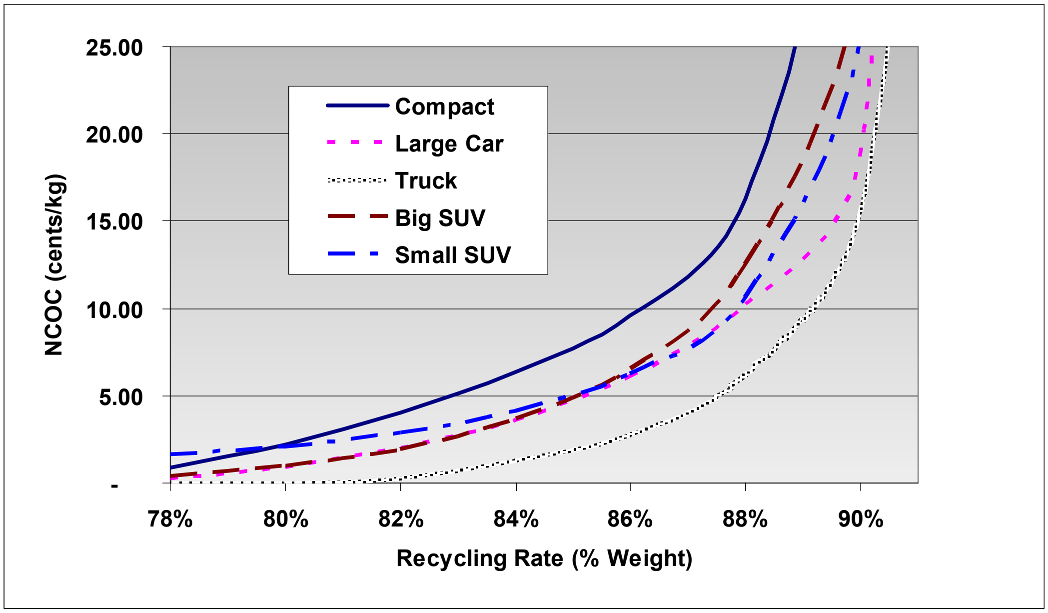

Figure 5-12: Mass Normalized NCOC for the Dismantler (Poland)

Figure 5-12 shows an example of the mass normalized NCOC in Poland for the panel of vehicles considered. Although the NCOC still differs from one vehicle to another, the curves are universally closer. To show this similarity, Figure 5-13 and Figure 5-14 show the NCOCs indexed to that a one vehicle, the Compact Car. These figures reveal the relative variation in the NCOC and the mass-normalized NCOC across the vehicle types. It shows immediately that the mass-normalized costs fall within a much closer range than the total costs.

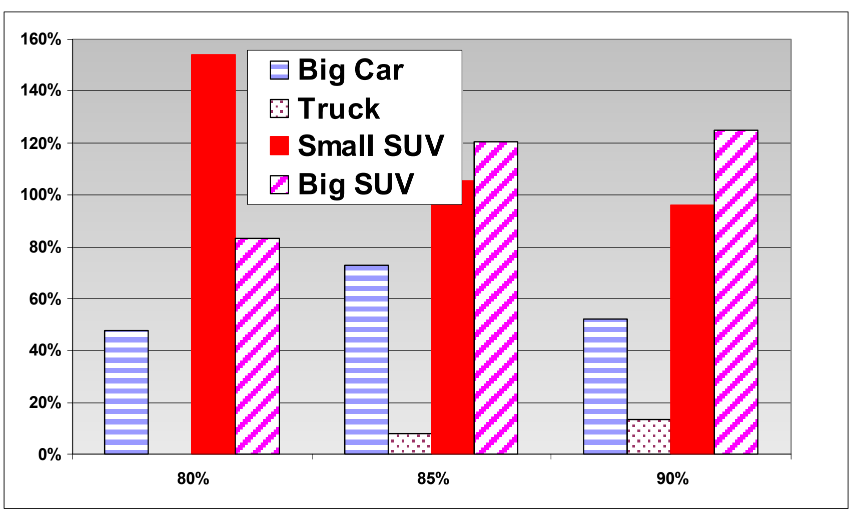

Figure 5-13: NCOC indexed on the Compact Car NCOC

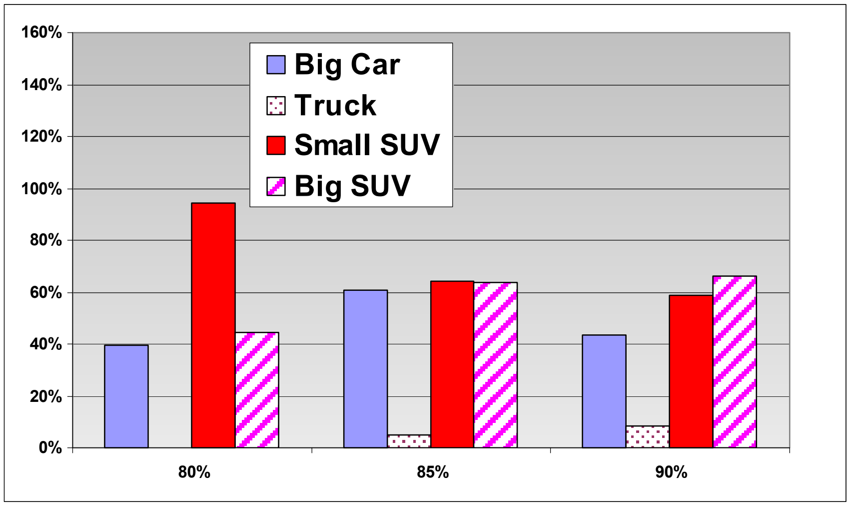

Figure 5-14: Normalized NCOC indexed on the Compact Car NCOC

5.3.3.3 Elasticity

Another useful perspective on the interrelationship of cost, mass, and vehicle design is the relative effort of extracting additional weight from a particular vehicle. Does it require the same effort to remove an extra percent of weight from all vehicles? A quantity that provides insight into answering this question is the elasticity relating weight and removal cost? Specifically, the quantity that is studied is:

$$E_{i,j} = \frac{\frac{\Delta cents/kg_{i.j}}{cents/kg_i}}{\frac{\Delta\%_{i,j}}{\%_i}}$$

where $\%_i$, $\%_j$ are two different recycling rates,

$\Delta\%_{i,j} = \%_j - \%_i$,

$cents/kg_i$ is the amount of cents/kg necessary to reach the recycling rate $\%_i$,

and $\Delta cents/kg_{i.j} = cents/kg_j - cents/kg_i$

In this study, a 2% range increase was used to compute the elasticities for the different vehicles. Figure 5-15 shows the corresponding elasticities:

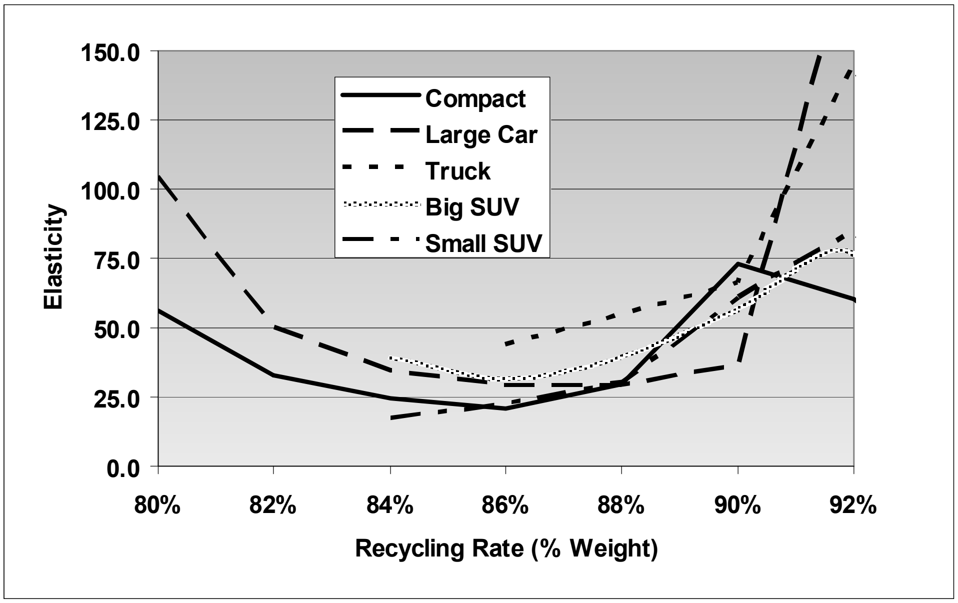

Figure 5-15: Weight Elasticity to Normalized NCOC (Poland)

Several useful insights can be derived from this calculation. First, it requires effort for the two cars compared to the other vehicles to reach the 84% recycling rate. Between 84% and 90%, the elasticities of all vehicles stay in the same range. Thus, in this range of rates, the effort needed to increase the recycling target is comparable for all vehicles. Finally, all elasticities increase considerably beyond 90%. Thus, targeting a recycling rate higher than 90% would be very costly for this set of technologies. This graph also shows that, with the legislation currently in place, reaching the 85% target will be much easier for big vehicles (truck, SUVs) than for small vehicles (both compact and large cars).

5.3.4 Net Cost of Compliance Sensitivity to Material Prices

As explained in Part 3.3, whereas material prices used in the model were based on actual reported values, these values can vary considerably over time. Furthermore, the value of some low-worth secondary materials (e.g., polymers) may be substantially impacted by the increased availability of these materials after broad implementation of the ELV directive. To explore the impact of any such variation cost sensitivity to material price variation was carried out using a multiplier factor within the model. Two factors were created one for metals and another for the others materials. Varying these factors allows the user to study the NCOC sensitivity to material price variation. In this part, we study the impact of metals and polymer prices variation on the compliance cost.

5.3.4.1 Metals

The default value used in the model for the metal factor is 90%. Figure 5-16 below shows how a variation of this factor affects the cost. Instead of showing the value of the metal factor on the x-axis, the steel price was chosen to be referenced in order to correlate the factor to an actual price. The corresponding metal factor can be deduced by dividing the steel price shown by the baseline steel price of 0.13,:

Steel Price=Metal

Factor*0.13

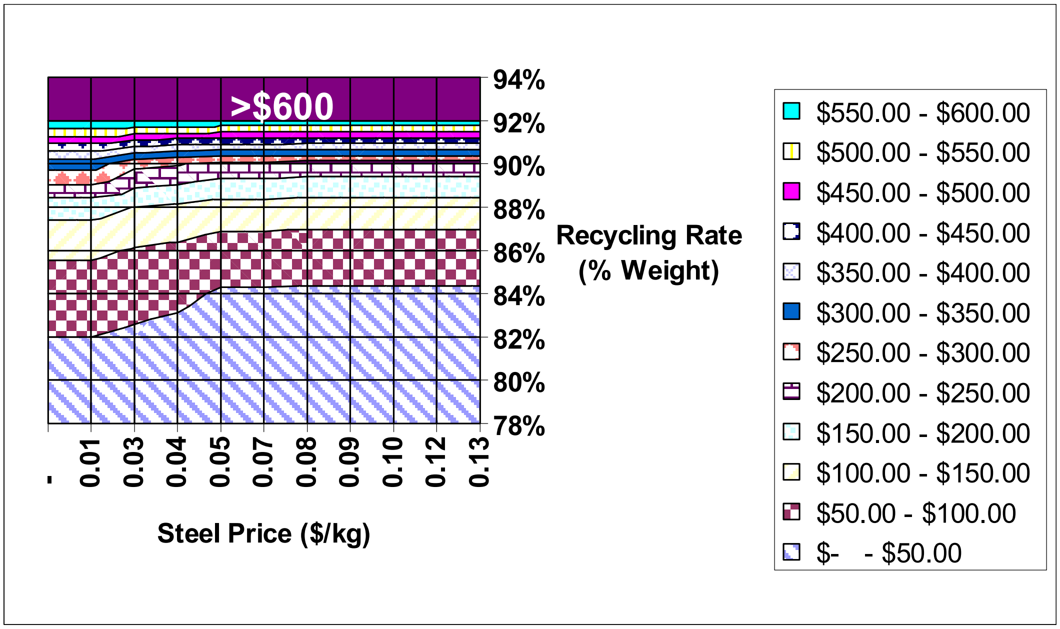

Figure 5-16: Dismantler NCOC sensitivity to Metal Price (Large Car, France)

This results show first that there is a threshold for the metal factor above which the variation of metal price does not have an influence. In that case, it corresponds to a steel price of $0.05/kg, which correspond to a 40% metal factor. This threshold can be explained if we look at the variation of the weight percentage recycled depending on the metal factor when the dismantler revenue is maximum.

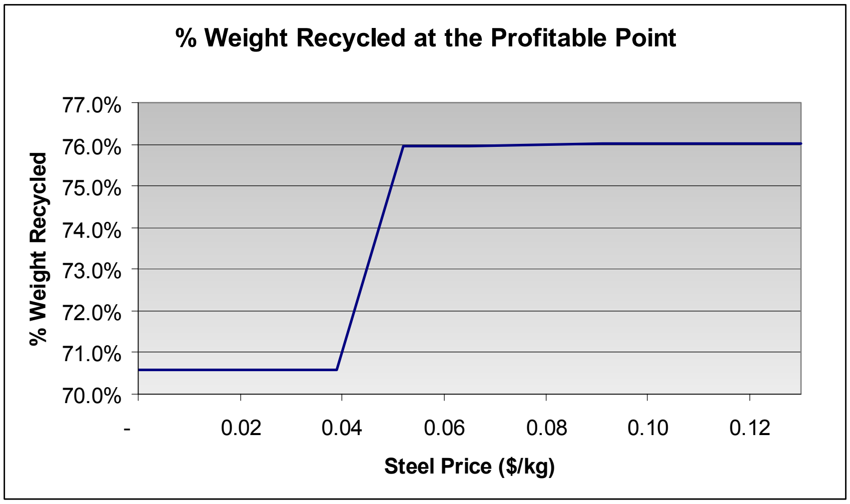

Figure 5-17: Percentage Weight Recycled at Dismantler Profit Maximum (Large Car, France)

When the metal factor is below 40%, no metal parts are profitable enough to be removed. The metal factor has to reach 40% to begin removing a set of small metal parts. After that, increasing the metal price does not significantly change the set of metal parts that are profitable for the dismantler. This occurs because metal parts are predominantly found within inner layers of the vehicle and are associated with large dismantling times. That is why a jump is observed in Figure 5-16; before the threshold, the difference between the desired recycling rate and the one the dismantler would chose rationally is very high while after the threshold, the targeted recycling rates are closer enough to the one without regulation, thus, the NCOC still increases but in a more moderate manner.

The second interesting point of this graph is that, the higher the recycling rate is, the less influence on the NCOC the metal prices have. This comes from the fact that to reach the high recycling rates, the dismantler will have to remove plastic parts. This removal is costly first because these plastic parts are more and more difficult to remove and second because they do not have a significant material value to cover these high removal costs. Thus, for the higher recycling rates, the NCOC is controlled by the high removal cost of these non metal parts and not by the revenue of the sale of the metal parts, that is why varying the metal prices at these rates does not affect much the NCOC.

5.3.4.2 Polymers and Thermoplastics

The default value used in the model to adjust the polymer and thermoplastics is 60%.

It corresponds for example to a unit price of $0.39/kg for the PC. Figure 5-18 below shows an analysis similar to that of Figure 5-17 above except that the PC price has been used as reference to study the effect of the variation of the non-metal price adjustment factor.

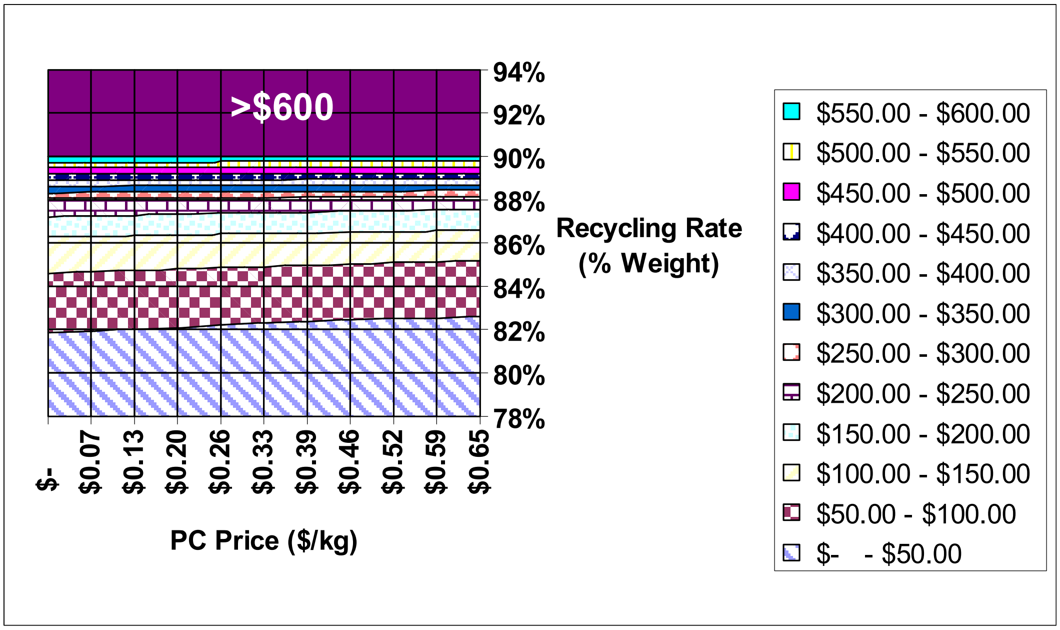

Figure 5-18: Dismantler NCOC sensitivity to Polymers and Thermoplastics Price (Large Car, France)

The conclusions drawn from this graph are twofold. On one hand, at a given recycling rate, the NCOC is decreasing almost linearly with the adjustment factor. Indeed, at the targeted recycling rates considered, the dismantler is removing a considerable amount of plastic parts. Thus, increasing their material value will diminish his costs proportionately and consequently the NCOC.

On another hand, net effect of this the variation due to changing plastics price is not large compared to total NCOC. This variation ranges between $2 at 78% to $20 at 94%. This absolute variation is small compared to the variation of the whole NCOC. If it is compared to the NCOC for a null adjustment factor for each of the recycling rate, it corresponds to 40% of the NCOC at 78% and goes below 2% after 90%., see Figure 5-19 below.

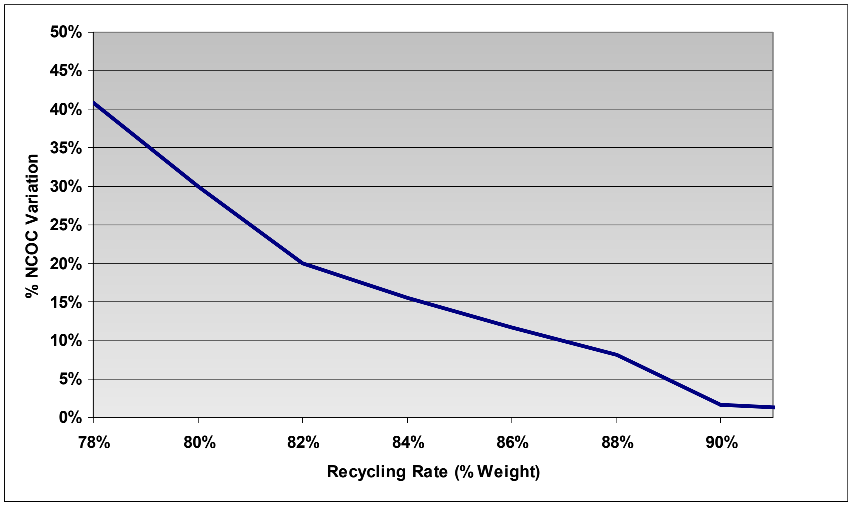

Figure 5-19: Influence of Polymers and Thermoplastics Prices variation at different recycling rates

The current regulation is targeting the 80% and 85% recycling rates. At these rates, the NCOC found in the model can vary between 10% and 30% depending on the price of the polymers. This is a worst case scenario since it is really unlikely that the prices of the materials decrease to zero or increase a lot. Thus, the results should not be really affected by changes in plastic prices.

5.3.4.3 Magnitude of Exposure of a Vehicle Manufacturer: NCOC of an Average European Vehicle

Manufacturers would presumably have to pay an upfront fee for recycling vehicles they put on the market. This fee is to be compared to the actual amount which will be paid to reach the recycling target. To compute this amount, one needs to evaluate the NCOC of an average European Car. This cost corresponds to the sum of the costs of the different types of cars weighted by the proportion of each type of car in Europe. Figure 5-20 shows the 2004 European Fleet sales by market segment [Automotive News 04]

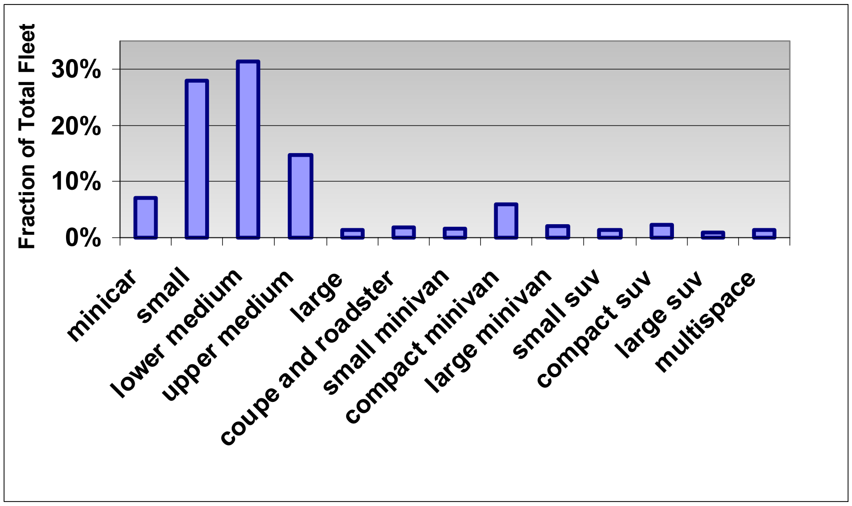

Figure 5-20 European Fleet Sales Composition

The number of segments described above is much bigger than five, the number of vehicles of this study. To analyze the NCOC of an average new European vehicle, each market segment was associated with one of the vehicles of the dataset. Table 5-4 shows the correspondence between the actual market segments and their corresponding vehicle type in the dataset.

Market Segment	Model Category
minicar	Compact
small	Compact
lower medium	Compact
upper medium	50% Compact/50% Large
large	Large
coupe and roadster	Compact
small minivan	Small SUV
compact minivan	Small Suv
large minivan	Large SUV
small suv	Small SUV
compact suv	50% Small/50% Large SUV
large suv	Large SUV
multispace	Small SUV

Table 5-4: Correspondence Table between European Market Segments and Model Categories

In order to get a better estimation of the cost, some models were associated with a mix of the model categories. For example, the NCOC of the upper medium car was associated with half the sum of the NCOC of the Compact and the Large Car.

Both NCOC for the dismantler and the shredder were computed in Poland and Germany to have a lower and an upper bound for the NCOC.

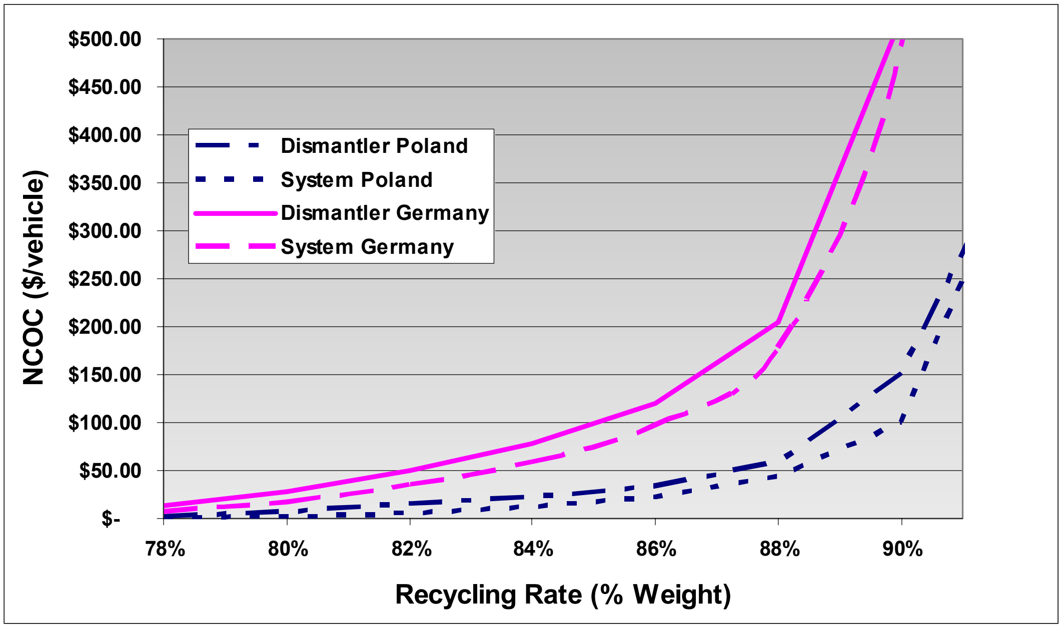

Figure 5-21: NCOC for an Average European Car

While, for the same labor cost, both dismantler and system NCOC are in the same range, the costs vary widely between one country and another. For the 80% recycling target, the NCOC adds up to a few dollars in Poland while it already reaches 30 dollars in Germany. At 85%, the NCOC in Poland is around $30 dollars while the NCOC for the dismantler reaches already $100 in Germany. With this amount of money, one could reach the 89% target.

6 Conclusions

After analyzing carefully the variation of the Net Cost of Compliance[5] for different case studies, it appears that vehicle type and location have a significant effect on this variation. While labor can be labeled as the key cost driver of the NCOC regional variation, vehicle mass is the key driver of the variation of the NCOC by vehicle type.

Applying the European Directives on ELV will undoubtedly imply a cost. By law this cost is to be borne by automobile manufacturers. As such, a critical question for manufacturers is the manner in which this cost will vary based on the sales and operating characteristics of the automaker; how will it vary with the portfolio of vehicles sold; how will it vary with the distribution of sales across Europe. Thanks to the Technical Cost Modeling Technique, this work has provided a preliminary assessment to answer these questions, showing for a range of cases the expected cost to the OEM, the NCOC, as a function of both vehicle type and recycling location. Additionally, this work has provided insights into the major cost drivers of the NCOC and its sensitivity to several key factors.

The first conclusion of this work is that both vehicle type and recycling location have a significant effect on the NCOC. For example, reaching the 85% in Germany can lead to a range in NCOC of more than a \$100 depending on vehicle type. Similarly, the cost of reaching this target varies widely depending on the location- for example, the costs varies by \$55 for the Large Car depending if it is recycled in Poland or in Norway.

Labor cost plays a singularly critical role in establishing of the cost of applying the regulation. Since labor cost is linked to the location of the recycling industries, NCOC will primarily depend on where the vehicles will be recycled. This sensitivity to the location raises an issue for the recycling directive. If automakers have to pay a fee upfront for recycling their vehicle, how is this fee going to be calculated? Is it going to depend on the location of the sale of the car or on the production location? If the fee depends on where the vehicle sale took place, then there will be an incentive for recycling industries to be relocated in countries with low wage where the cost of compliance will be the lowest. If the fee depends on the production location, then manufacturers will have an incentive to build production plants in low wage countries. These basic answers to two

[5] Net Cost of Compliance (NCOC) was defined as the added cost to recyclers (dismantlers or dismantlers and shredders) incurred as a result of achieving higher rates of recycling.

different strategies of applying the regulations give examples of issues concerning the profitability of the actual recycling industries that the European Directive will raise, how will they be subsidized to reach the recycling rates targeted, what will be the incentives to avoid the relocation of the recycling infrastructure?

Second, the cost of compliance will vary widely between one vehicle and another. While some big vehicles, like trucks, could reach the recycling target at very low cost due to their high metal composition, it will be more costly to recycle SUVs than cars. However, the normalized costs for all vehicles, except the trucks are in a much closer range. Furthermore, there seem to be a threshold above which the recycling rates are going to be much more difficult to reach. Indeed, reaching more than 90% of the cars recycled will increase dramatically the NCOC. This variation of the NCOC by vehicle type raises several issues. On the one hand, cost could vary widely between one car manufacturer and another, depending on their portfolio of vehicles. On another hand, this may exacerbate or mitigate the effect of the location as vehicle sales characteristics will also vary by region.

Moreover, the NCOC is sensitive to material prices. While metals prices have a important effect on the NCOC, variations on actual plastic prices affect less the NCOC. This is actually an encouraging result since currently the second-hand market for this type of materials is quite small with only a few used plastics having a positive resale value. As such, the values generated in this work should approximate actual costs even with little near-term development for the secondary plastics market. However, if some plastic prices were to be more attractive –for example, if new technologies were put in place-, these prices could be influential since the plastic content of vehicles is constantly growing.

Overall, the costs of applying the pending regulation will vary widely depending on several points. This work analyzed the key cost drivers of the NCOC, e.g. the vehicle type and the location of the recycling industry. This analysis was conducted observing the actual recycling industry. It would be interesting to study how this recycling system will evolve with the implementation of the regulation given the existing different operating conditions across Europe.

7 Future work

This work concentrates on a few American-produced (albeit European-sold) vehicles. While these vehicles are useful to diagnose the different drivers of the cost of compliance, it is possible that they are not illustrative of typical vehicles that will be recycled in Europe. Future work should include more vehicles, preferably including European-designed vehicles, in order to represent more accurately the fleet studied. Considering the data needed to carry out this analysis, it will be useful to obtain more precise removal times for these vehicles. Indeed, removal time is linked to labor cost and, since labor is the main cost driver of the NCOC, it would be critical to get more accurate data to quantify the cost of compliance.

In this thesis, the NCOC was studied of the current recycling industry. With currently implemented technology, the only means of achieving higher recycling rates is to manually remove plastics from the waste. Once the vehicle has been shredded most identifying characteristics are obscured and plastics are highly commingled. As such, this manual removal is only feasible at the dismantler. Fortunately, some emerging technologies could allow recyclers to recover more non-metals from ELV without such manual intervention. Studying in depth these new separation technologies and their benefits would be beneficial to understand their impact on regulatory cost. Moreover, one should study the relative benefits of plastic recycling versus energy recovery solutions in reaching the recycling targets.

The actual recycling facilities -whether in Europe or in the US- are so numerous that it is already difficult to enforce the regulations in place in these different countries. One of the issues of the European Directive is how it is going to be enforced. How is Europe going to verify the efficiencies of the different recycling facilities? If problems are found, which consequences will there be for the facilities? It would be useful to first study how the European Directive is enforced across Europe and second the consequences of the enforcement policy on the recycling industries. It actually seems likely that the regulation enforcement will vary from one country to another, thus, one could study how this variation affects the different recycling industries in place.

Finally, the effect of the policy on the automakers would be an interesting issue to study. On the one hand, automakers are making more and more environmentally friendly vehicles. It is true that the directive encourages Design for the Environment (DFE) practices, but one could study if this new trend is only the result of the influence of the regulation or not. One could, for example, compare the behavior of automakers in countries where there is no regulations. On the other hand, automakers could take part in the recycling process, which is already the case in some European Countries. In France for example, automakers appoint dismantlers to take care of their ELV. The effect of the directive in the way car manufacturers are creating and disposing of the vehicles would be hard to quantify, but very helpful in order to make effective future regulations.

8 Appendices

Appendix I: Materials Table

Material SHORT ID	Material Category	Material Type	Material Name	Mixed (0=Yes,1=No)
1	Electronics	Electronics	copper	0
2	Electronics	Electronics	electronics	0
3	Electronics	Electronics	electronics	1
4	Electronics	Electronics	magnet	1
5	Electronics	Electronics	mixed pa	0
6	Electronics	Electronics	pa	0
7	Electronics	Electronics	pbt	1
8	*Fuels and Auxiliary Means*	*Brake fluid*	*fluid*	*1*
9	*Fuels and Auxiliary Means*	*Copper*	*coolant*	*1*
10	*Fuels and Auxiliary Means*	*Fuels*	*grease*	*1*
11	*Fuels and Auxiliary Means*	*Lubricants*	*fluid*	*1*
12	*Fuels and Auxiliary Means*	*Lubricants*	*grease*	*1*
13	*Fuels and Auxiliary Means*	*Lubricants*	*oil*	*1*
14	*Fuels and Auxiliary Means*	*Other fuels and auxiliary means*	*charge*	*1*
15	*Fuels and Auxiliary Means*	*Other fuels and auxiliary means*	*fluid*	*1*
16	*Fuels and Auxiliary Means*	*Preservative*	*fluid*	*1*
17	Light Alloys, Cast and Wrought Alloys	Aluminum and Aluminum alloys	aluminum	0
18	Light Alloys, Cast and Wrought Alloys	Aluminum and Aluminum alloys	aluminum	1
19	Light Alloys, Cast and Wrought Alloys	Magnesium and magnesium alloys	magnesium	0
20	Light Alloys, Cast and Wrought Alloys	Magnesium and magnesium alloys	magnesium	1
21	*Nonferrous Heavy Metals, Cast and Wro*	*Brass*	*brass*	*0*
22	*Nonferrous Heavy Metals, Cast and Wro*	*Brass*	*brass*	*1*
23	*Nonferrous Heavy Metals, Cast and Wro*	*Brass*	*copper*	*0*
24	*Nonferrous Heavy Metals, Cast and Wro*	*Bronze*	*bronze*	*0*
25	*Nonferrous Heavy Metals, Cast and Wro*	*Bronze*	*bronze*	*1*
26	*Nonferrous Heavy Metals, Cast and Wro*	*Copper*	*bronze*	*1*
27	*Nonferrous Heavy Metals, Cast and Wro*	*Copper*	*copper*	*0*
28	*Nonferrous Heavy Metals, Cast and Wro*	*Copper*	*copper*	*1*
29	*Nonferrous Heavy Metals, Cast and Wro*	*Copper*	*lead*	*0*
30	*Nonferrous Heavy Metals, Cast and Wro*	*Lead*	*lead*	*0*
31	*Nonferrous Heavy Metals, Cast and Wro*	*Lead*	*lead*	*1*
32	Other Material and Material Compounds	Ceramics/glass	bulb	0
33	Other Material and Material Compounds	Ceramics/glass	bulb	1
34	Other Material and Material Compounds	Ceramics/glass	ceramic	0
35	Other Material and Material Compounds	Ceramics/glass	ceramic	1
36	Other Material and Material Compounds	Ceramics/glass	fiberglass	0
37	Other Material and Material Compounds	Ceramics/glass	fiberglass	1
38	Other Material and Material Compounds	Ceramics/glass	glass	0
39	Other Material and Material Compounds	Ceramics/glass	glass	1
40	Other Material and Material Compounds	Ceramics/glass	graphite	0
41	Other Material and Material Compounds	Modified organic natural materials	carpet	1
42	Other Material and Material Compounds	Modified organic natural materials	charcoal	0
43	Other Material and Material Compounds	Modified organic natural materials	charcoal	1
44	Other Material and Material Compounds	Modified organic natural materials	fabric	0
45	Other Material and Material Compounds	Modified organic natural materials	fabric	1
46	Other Material and Material Compounds	Modified organic natural materials	fiber	0
47	Other Material and Material Compounds	Modified organic natural materials	fiber	1
48	Other Material and Material Compounds	Modified organic natural materials	fiberglass	1
49	Other Material and Material Compounds	Modified organic natural materials	glass	0
50	Other Material and Material Compounds	Modified organic natural materials	graphite	0
51	Other Material and Material Compounds	Modified organic natural materials	graphite	1
52	Other Material and Material Compounds	Modified organic natural materials	leather	0
53	Other Material and Material Compounds	Modified organic natural materials	leather	1
54	Other Material and Material Compounds	Modified organic natural materials	nylon	0
55	Other Material and Material Compounds	Modified organic natural materials	nylon	1
56	Other Material and Material Compounds	Modified organic natural materials	other	1
57	Other Material and Material Compounds	Modified organic natural materials	paper	0
58	Other Material and Material Compounds	Modified organic natural materials	paper	1
59	Other Material and Material Compounds	Modified organic natural materials	polyester	1
60	Other Material and Material Compounds	Other compounds(e.g. friction linir	carbon fiber	1
61	Other Material and Material Compounds	Other compounds(e.g. friction linir	charcoal	1
62	Other Material and Material Compounds	Other compounds(e.g. friction linir	fiberglass	1
63	Other Material and Material Compounds	Other compounds(e.g. friction linir	friction lining	0
64	Other Material and Material Compounds	Other compounds(e.g. friction linir	friction lining	1
65	Other Material and Material Compounds	Other compounds(e.g. friction linir	graphite	0
66	Other Material and Material Compounds	Other compounds(e.g. friction linir	graphite	1
67	Other Material and Material Compounds	Other compounds(e.g. friction linir	other	0
68	Other Material and Material Compounds	Other compounds(e.g. friction linir	other	1

Appendix I (continued):

Material SHORT ID	Material Category	Material Type	Material Name	Mixed (0=Yes,1=No)
59	Other Material and Material Compounds	Modified organic natural materials	polyester	1
60	Other Material and Material Compounds	Other compounds(e.g. friction linin	carbon fiber	1
61	Other Material and Material Compounds	Other compounds(e.g. friction linin	charcoal	1
62	Other Material and Material Compounds	Other compounds(e.g. friction linin	fiberglass	1
63	Other Material and Material Compounds	Other compounds(e.g. friction linin	friction lining	0
64	Other Material and Material Compounds	Other compounds(e.g. friction linin	friction lining	1
65	Other Material and Material Compounds	Other compounds(e.g. friction linin	graphite	0
66	Other Material and Material Compounds	Other compounds(e.g. friction linin	graphite	1
67	Other Material and Material Compounds	Other compounds(e.g. friction linin	other	0
68	Other Material and Material Compounds	Other compounds(e.g. friction linin	other	1
69	Other Material and Material Compounds	Other compounds(e.g. friction linin	paper	0
70	Other Material and Material Compounds	Other compounds(e.g. friction linin	propellant	1
71	*Polymer Materials*	*Duromer*	*epdm*	*1*
72	*Polymer Materials*	*Duromer*	*filter*	*0*
73	*Polymer Materials*	*Duromer*	*foam*	*0*
74	*Polymer Materials*	*Duromer*	*foam*	*1*
75	*Polymer Materials*	*Duromer*	*ps*	*0*
76	*Polymer Materials*	*Duromer*	*pu*	*0*
77	*Polymer Materials*	*Duromer*	*pur*	*0*
78	*Polymer Materials*	*Duromer*	*pur*	*1*
79	*Polymer Materials*	*Duromer*	*pvc*	*0*
80	*Polymer Materials*	*Elastomers*	*epdm*	*0*
81	*Polymer Materials*	*Elastomers*	*epdm*	*1*
82	*Polymer Materials*	*Elastomers*	*foam*	*1*
83	*Polymer Materials*	*Elastomers*	*mixed abs*	*0*
84	*Polymer Materials*	*Elastomers*	*mixed pa*	*1*
85	*Polymer Materials*	*Elastomers*	*mixed pbt*	*1*
86	*Polymer Materials*	*Elastomers*	*mixed pp*	*1*
87	*Polymer Materials*	*Elastomers*	*neoprene*	*1*
88	*Polymer Materials*	*Elastomers*	*nylon*	*1*
89	*Polymer Materials*	*Elastomers*	*pa*	*0*
90	*Polymer Materials*	*Elastomers*	*pa*	*1*
91	*Polymer Materials*	*Elastomers*	*pc*	*0*
92	*Polymer Materials*	*Elastomers*	*pe*	*0*
93	*Polymer Materials*	*Elastomers*	*pet*	*1*
94	*Polymer Materials*	*Elastomers*	*pp*	*0*
95	*Polymer Materials*	*Elastomers*	*pp*	*1*
96	*Polymer Materials*	*Elastomers*	*pvc*	*0*
97	*Polymer Materials*	*Elastomers*	*pvc*	*1*
98	*Polymer Materials*	*Polymeric compound*	*adhesive*	*0*
99	*Polymer Materials*	*Polymeric compound*	*carpet*	*0*
100	*Polymer Materials*	*Polymeric compound*	*epdm*	*0*
101	*Polymer Materials*	*Polymeric compound*	*fabric*	*0*
102	*Polymer Materials*	*Polymeric compound*	*fiberglass*	*0*
103	*Polymer Materials*	*Polymeric compound*	*foam*	*0*
104	*Polymer Materials*	*Polymeric compound*	*nylon*	*0*
105	*Polymer Materials*	*Polymeric compound*	*other*	*1*
106	*Polymer Materials*	*Polymeric compound*	*pa*	*0*
107	*Polymer Materials*	*Polymeric compound*	*polyester*	*0*
108	*Polymer Materials*	*Polymeric compound*	*polyester*	*1*
109	*Polymer Materials*	*Polymeric compound*	*pvc*	*0*
110	*Polymer Materials*	*Thermoplastics*	*abs*	*0*
111	*Polymer Materials*	*Thermoplastics*	*abs*	*1*
112	*Polymer Materials*	*Thermoplastics*	*acetyl*	*0*
113	*Polymer Materials*	*Thermoplastics*	*acrylic*	*0*
114	*Polymer Materials*	*Thermoplastics*	*asa*	*1*
115	*Polymer Materials*	*Thermoplastics*	*brass*	*0*
116	*Polymer Materials*	*Thermoplastics*	*epdm*	*0*
117	*Polymer Materials*	*Thermoplastics*	*epdm*	*1*
118	*Polymer Materials*	*Thermoplastics*	*fabric*	*0*
119	*Polymer Materials*	*Thermoplastics*	*fiber*	*0*
120	*Polymer Materials*	*Thermoplastics*	*foam*	*0*
121	*Polymer Materials*	*Thermoplastics*	*hcpp*	*0*
122	*Polymer Materials*	*Thermoplastics*	*hcpp*	*1*
123	*Polymer Materials*	*Thermoplastics*	*hd*	*1*
124	*Polymer Materials*	*Thermoplastics*	*hdpe*	*0*
125	*Polymer Materials*	*Thermoplastics*	*hdpe*	*1*
126	*Polymer Materials*	*Thermoplastics*	*ldpe*	*1*
127	*Polymer Materials*	*Thermoplastics*	*mixed abs*	*0*
128	*Polymer Materials*	*Thermoplastics*	*mixed abs*	*1*
129	*Polymer Materials*	*Thermoplastics*	*mixed asa*	*0*
130	*Polymer Materials*	*Thermoplastics*	*mixed asa*	*1*
131	*Polymer Materials*	*Thermoplastics*	*mixed pa*	*0*
132	*Polymer Materials*	*Thermoplastics*	*mixed pa*	*1*
133	*Polymer Materials*	*Thermoplastics*	*mixed pbt*	*0*
134	*Polymer Materials*	*Thermoplastics*	*mixed pbt*	*1*
135	*Polymer Materials*	*Thermoplastics*	*mixed pbtp*	*0*
136	*Polymer Materials*	*Thermoplastics*	*mixed pby*	*1*
137	*Polymer Materials*	*Thermoplastics*	*mixed pc*	*0*
138	*Polymer Materials*	*Thermoplastics*	*mixed pc*	*1*
139	*Polymer Materials*	*Thermoplastics*	*mixed pet*	*0*
140	*Polymer Materials*	*Thermoplastics*	*mixed pom*	*0*

Appendix I (continued):

Material SHORT ID	Material Category	Material Type	Material Name	Mixed (0=Yes,1=No)
141	Polymer Materials	Thermoplastics	mixed pp	0
142	Polymer Materials	Thermoplastics	mixed pp	1
143	Polymer Materials	Thermoplastics	mixed ppe	0
144	Polymer Materials	Thermoplastics	mixed ppe	1
145	Polymer Materials	Thermoplastics	mixed pvc	0
146	Polymer Materials	Thermoplastics	mixed pvc	1
147	Polymer Materials	Thermoplastics	mixed sma	0
148	Polymer Materials	Thermoplastics	mixed st	0
149	Polymer Materials	Thermoplastics	mixed teo	0
150	Polymer Materials	Thermoplastics	mixed tes	0
151	Polymer Materials	Thermoplastics	mixed tpo	0
152	Polymer Materials	Thermoplastics	mixed up	0
153	Polymer Materials	Thermoplastics	mxied abs	0
154	Polymer Materials	Thermoplastics	npc	1
155	Polymer Materials	Thermoplastics	nylon	0
156	Polymer Materials	Thermoplastics	nylon	1
157	Polymer Materials	Thermoplastics	other	0
158	Polymer Materials	Thermoplastics	other	1
159	Polymer Materials	Thermoplastics	pa	0
160	Polymer Materials	Thermoplastics	pa	1
161	Polymer Materials	Thermoplastics	paper	0
162	Polymer Materials	Thermoplastics	pbt	0
163	Polymer Materials	Thermoplastics	pbt	1
164	Polymer Materials	Thermoplastics	pbtp	0
165	Polymer Materials	Thermoplastics	pbtp	1
166	Polymer Materials	Thermoplastics	pc	0
167	Polymer Materials	Thermoplastics	pc	1
168	Polymer Materials	Thermoplastics	pct	0
169	Polymer Materials	Thermoplastics	pcv	0
170	Polymer Materials	Thermoplastics	pcx	0
171	Polymer Materials	Thermoplastics	pdm	1
172	Polymer Materials	Thermoplastics	pe	0
173	Polymer Materials	Thermoplastics	pe	1
174	Polymer Materials	Thermoplastics	ped	0
175	Polymer Materials	Thermoplastics	ped	1
176	Polymer Materials	Thermoplastics	pehd	0
177	Polymer Materials	Thermoplastics	peld	1
178	Polymer Materials	Thermoplastics	peo	0
179	Polymer Materials	Thermoplastics	pet	0
180	Polymer Materials	Thermoplastics	pet	1
181	Polymer Materials	Thermoplastics	petp	0
182	Polymer Materials	Thermoplastics	pf	0
183	Polymer Materials	Thermoplastics	phenolic	1
184	Polymer Materials	Thermoplastics	plastic	0
185	Polymer Materials	Thermoplastics	pmma	0
186	Polymer Materials	Thermoplastics	pmma	1
187	Polymer Materials	Thermoplastics	polyester	0
188	Polymer Materials	Thermoplastics	pom	0
189	Polymer Materials	Thermoplastics	pom	1
190	Polymer Materials	Thermoplastics	pp	0
191	Polymer Materials	Thermoplastics	pp	1
192	Polymer Materials	Thermoplastics	ppa	0
193	Polymer Materials	Thermoplastics	ppe	1
194	Polymer Materials	Thermoplastics	ppo	0
195	Polymer Materials	Thermoplastics	pps	0
196	Polymer Materials	Thermoplastics	propylene	0
197	Polymer Materials	Thermoplastics	ps	1
198	Polymer Materials	Thermoplastics	pu	0
199	Polymer Materials	Thermoplastics	pur	0
200	Polymer Materials	Thermoplastics	pvc	0
201	Polymer Materials	Thermoplastics	pvc	1
202	Polymer Materials	Thermoplastics	pxc	0
203	Polymer Materials	Thermoplastics	rim	0
204	Process Polymers	Lacquers	epdm	0
205	Process Polymers	Lacquers	mixed abs	0
206	Process Polymers	Lacquers	pp	0
207	Special Metals	Platinum/Rhodium	pa	0
208	Steels and Iron materials	Cast Iron	cast iron	0
209	Steels and Iron materials	Cast Iron	iron	0
210	Steels and Iron materials	Cast Iron	iron oxide	0
211	Steels and Iron materials	Cast Iron	magnet	0

Appendix I (continued):

Material SHORT ID	Material Category	Material Type	Material Name	Mixed (0=Yes,1=No)
212	*Steels and Iron materials*	*Steels/Cast steel/Sintered steel*	*aluminum*	*0*
213	*Steels and Iron materials*	*Steels/Cast steel/Sintered steel*	*copper*	*0*
214	*Steels and Iron materials*	*Steels/Cast steel/Sintered steel*	*graphite*	*0*
215	*Steels and Iron materials*	*Steels/Cast steel/Sintered steel*	*magnet*	*0*
216	*Steels and Iron materials*	*Steels/Cast steel/Sintered steel*	*other*	*0*
217	*Steels and Iron materials*	*Steels/Cast steel/Sintered steel*	*pet*	*0*
218	Light Alloys, Cast and Wrought Alloys	Aluminum and Aluminum alloys	steel	0
219	Light Alloys, Cast and Wrought Alloys	Aluminum and Aluminum alloys	steel	1
220	*Nonferrous Heavy Metals, Cast and Wro*	*Zinc*	*zinc*	*1*
221	Other Material and Material Compounds	Modified organic natural materials	shoddy pad	0
222	Other Material and Material Compounds	Modified organic natural materials	shoddy pad	1
223	Other Material and Material Compounds	Modified organic natural materials	tape	1
224	Other Material and Material Compounds	Modified organic natural materials	wood	0
225	Other Material and Material Compounds	Modified organic natural materials	wood	1
226	Other Material and Material Compounds	Other compounds(e.g. friction linin	silicate	0
227	Other Material and Material Compounds	Other compounds(e.g. friction linin	steel	0
228	Polymer Materials	Duromer	smc	0
229	Polymer Materials	Duromer	smc	1
230	Polymer Materials	Elastomers	s1	0
231	Polymer Materials	Elastomers	sbr	0
232	Polymer Materials	Elastomers	tape	0
233	Polymer Materials	Elastomers	teo	0
234	Polymer Materials	Elastomers	teo	1
235	Polymer Materials	Elastomers	tes	0
236	Polymer Materials	Elastomers	tpe	1
237	Polymer Materials	Elastomers	tpo	0
238	Polymer Materials	Elastomers	tpo	1
239	Polymer Materials	Elastomers	tpr	1
240	Polymer Materials	Elastomers	tpu	0
241	Polymer Materials	Polymeric compound	shoddy pad	0
242	Polymer Materials	Polymeric compound	silicone	0
243	Polymer Materials	Polymeric compound	srim	0
244	Polymer Materials	Polymeric compound	vinyl	0
245	Polymer Materials	Thermoplastics	san	0
246	Polymer Materials	Thermoplastics	san	1
247	Polymer Materials	Thermoplastics	sma	0
248	Polymer Materials	Thermoplastics	sma	1
249	Polymer Materials	Thermoplastics	smc	1
250	Polymer Materials	Thermoplastics	smma	1
251	Polymer Materials	Thermoplastics	src	1
252	Polymer Materials	Thermoplastics	srim	1
253	Polymer Materials	Thermoplastics	te	0
254	Polymer Materials	Thermoplastics	teo	0
255	Polymer Materials	Thermoplastics	teo	1
256	Polymer Materials	Thermoplastics	teoc	0
257	Polymer Materials	Thermoplastics	tpe	1
258	Polymer Materials	Thermoplastics	tpo	0
259	Polymer Materials	Thermoplastics	tpo	1
260	Polymer Materials	Thermoplastics	up	1
261	Polymer Materials	Thermoplastics	ve	0
262	Polymer Materials	Thermoplastics	vinyl	0
263	*Process Polymers*	*Adhesives, sealant*	*sealant*	*0*
264	*Process Polymers*	*Adhesives, sealant*	*silicone*	*0*
265	*Process Polymers*	*Adhesives, sealant*	*tape*	*0*
266	*Process Polymers*	*Lacquers*	*tape*	*0*
267	Steels and Iron materials	Cast Iron	steel	0
268	Steels and Iron materials	Steels/Cast steel/Sintered steel	stainless steel	0
269	Steels and Iron materials	Steels/Cast steel/Sintered steel	steel	0
270	Steels and Iron materials	Steels/Cast steel/Sintered steel	up	0

Appendix II: Material Prices

Material type	Material Name	Price ($/kg)
Metals:		
Ferrous:	Iron	0.13
	Steel	0.13
Non Ferrous:	Aluminum	0.75
	Brass	1
	Bronze	1
	Copper	1.03
	Lead	0.14
Others:		
	ABS	0.55
	EPDM	0.09
	Foam	0.66
	Glass	0.04
	HCPP	0.44
	HDPE	0.55
	PC	0.66
	PC	0.14
	PE/PPE	0.44
	PEO	0.66
	PET	0.88
	PET	0.88
	POM	0.62
	PP	0.44
	PP	0.44
	PPO	0.10
	PUR	0.66
	PUR	0.66
	PVC	0.05
	Tires	($/tire)-1.10

Appendix III: Removal Times Calculation Inputs (Compact Car)

Part Location	Top Layer ? (1=yes,0=no)	Location Removal time (min)	Part Coefficient (A_i)	Weight Coefficient (B_i)	Number of parts per location	Total Location Parts Weight (kg)	Removal time (min/kg)
Air Cleaner	1	1	0.29	0.42	34.0	8.1	13.38
Air conditioning Compressor	1	1	0.01	0.05	27.0	6.6	0.11
Air Conditioning Refregerant System Parts	1	0	0.00	0.02	32.0	4.9	0.03
Battery and Lead	1	0	0.01	0.01	16.0	15.7	0.01
Battery Tray and Support	1	1	0.78	1.78	6.0	0.4	5.40
Body Assembly	1	1	0.60	0.44	6.0	2.8	4.83
Body Front Heat, Sound, Weather Sealing and Insulating	0	30	1.67	2.60	9.0	5.8	5.21
Body Front Ornementation	0	30	1.07	17.76	14.0	0.8	35.51
Body Front Structure	0	30	7.50	1.13	2.0	13.2	2.27
Body Front Trim and Upholstery		0	0.11	0.43	0.0	0.0	0.00
Body mounting	1	1	0.63	0.68	0.0	0.0	0.00
Body side and rear	1	4	0.84	0.64	0.0	0.0	0.00
Body Side and Rear heat, sound, Weather Sealing and Insulating	0	30	2.14	15.10	7.0	1.0	30.21
Body Side and Rear Ornamentation	0	30	1.67	10.76	9.0	1.4	21.52
Body Side and Rear Structure	0	1000	17.24	34.95	29.0	14.3	69.90
Body Side and Rear Trim and Upholstery	0	30	0.94	2.46	16.0	6.1	4.91
brake Anti-Lock Control System	0	30	0.07	0.16	226.0	96.4	0.31
Brake Lines	0	30	0.63	4.20	24.0	3.6	8.40
Brake Master Cylinder	0	30	1.07	20.35	14.0	0.7	40.71
Brake Pedal	0	30	1.67	6.07	9.0	2.5	12.14
Bumpers and associated parts	1	2	0.83	0.21	8.0	8.2	8.29
Computer and/or Multifunction Electronic Control Module and Related Sensor	1	0	0.13	0.43	19.0	2.7	3.53
Distributor and Electronic ignition	1	2	0.01	0.01	84.0	80.9	0.02
Electrical Wiring Harnesses, Fuses, Bulbs, and Circuit Breakers	1	0	0.00	0.01	218.0	16.4	0.02
End Gate, Rear Compartiment Lid and Rear Door heat, sound, we…	0	30	15.00	18.47	1.0	0.8	36.93
End Gate, Rear Compartiment Lid and Rear Door Operating Mechanism	0	30	0.47	10.58	32.0	1.4	21.16
End Gate, Rear Compartiment Lid and Rear Door structure	0	30	7.50	1.19	2.0	12.6	2.38
End gate,Rear Compartiment Lid and rear Door ornamentation	1	1	0.31	1.07	32.0	1.0	10.90
Engine Coolant Fan Shroud	1	1	0.47	0.53	0.0	0.0	0.00
Engine or Fuel Cell Exhaust Systems	1	3	0.14	0.06	10.0	23.9	0.11
Evaporative Emission Control System	1	3	0.05	1.65	30.0	0.8	3.30
External Window Cleaning component	1	2	0.67	1.30	65.0	5.5	50.82
Fan and drive	1	0	0.00	0.00	14.0	4.6	0.00
Frame	0	1000	27.78	11.53	18.0	43.4	23.07
Front and Rear Side Door Heat, Sound, weather sealing and ventilation	0	30	0.75	2.05	20.0	7.3	4.11
Front and rear side Door operating mechanism	0	30	0.09	1.49	159.0	10.0	2.99
Front and rear Side door ornamentation	0	30	1.67	23.46	9.0	0.6	46.91
Front and Rear Side Door Structure	0	30	1.00	0.29	15.0	51.2	0.59
Front and rear side door trim and upholstery	0	30	0.47	1.80	32.0	8.3	3.60
Front Axle and Front suspension less hub, Spring, Shock Absorber and Front Stabilizer	0	30	1.50	2.65	10.0	5.7	5.30
Front Bumper	1	5	0.43	0.49	6.0	5.2	0.99
Front Drive Final Drive, Differential and Axle Shafts	0	30	2.50	1.11	6.0	13.5	2.22
Front End Ornamentation	1	4	1.77	2.69	0.0	0.0	0.00
Front End Structural Components	1	2	0.06	0.42	17.0	2.3	0.84
Front Fender and Front End Exterior Components	1	3	1.33	0.64	12.0	8.8	21.65
Front Lamp and Turn Signal	1	1	0.28	1.00	54.0	4.0	19.21
Front Seat Ornamentation	1	0	0.03	0.40	0.0	0.0	0.00
Front Seat Structure	1	1	0.52	0.60	92.0	38.8	70.96

Appendix III (continued):

Part Location	Top Layer ? (1=yes,0=no)	Location Removal time (min)	Part Coefficient (A_i)	Weight Coefficient (B_i)	Number of parts per location	Total Location Parts Weight (kg)	Removal time (min/kg)
Front Shock Absorber	0	30	0.58	0.79	26.0	19.0	1.58
Front Stabilizer	0	30	0.29	0.47	52.0	32.1	0.93
Fuel pump, Filters and lines	1	2	0.50	6.31	2.0	0.2	2.00
Fuel Storage System	1	3	0.10	0.11	14.0	12.7	0.21
Generator, Voltage Regulator and Other Battery Charging Equipment	1	3	0.07	0.27	21.0	5.5	0.54
Heater Water System and Heater Fuel System Parts	1	1	0.10	1.09	6.0	0.5	2.18
Heating, Ventilaition,m AC and Windows defrosting Air Control Parts	1	0	0.35	0.40	113.0	14.6	45.52
Hood	1	1000	16.67	22.88	30.0	21.9	45.76
Horn, Switch and Mounting	1	1	0.02	0.37	14.0	0.7	0.74
Instrument Panel	1	1	0.00	0.02	64.0	17.3	0.04
License carter	1	1	0.05	0.28	0.0	0.0	0.00
oil Pan	1	1	0.45	0.64	0.0	0.0	0.00
Parking Brake Mechanism	0	30	0.79	4.13	19.0	3.6	8.27
Power Brake Booster	0	30	0.75	3.49	20.0	4.3	6.98
Power Plant Mounting	0	5	0.15	0.24	17.0	10.6	0.47
Power Steering	0	30	0.71	11.13	21.0	1.3	22.27
Radiator assembly	1	0	0.12	0.26	12.0	3.9	2.39
radiator grille and Deflectors	1	3	0.61	0.45	4.0	1.1	2.95
Radiator mounting parts	1	0	0.10	0.09	6.0	1.2	0.71
Radiator Surge Tank	1	2	0.43	0.31	19.0	1.2	8.55
Radio, clock and Electrical Convenience Components	1	0	0.03	0.18	52.0	4.2	2.05
Rear Bumper	1	2	0.08	0.10	14.0	11.7	0.20
Rear lamp	1	0	0.24	0.52	40.0	1.5	10.56
Rear Seat operating mechanism	1	0	0.15	0.74	11.0	0.5	2.04
Rear Seat Ornamentation	1	0	0.15	0.74	0.0	0.0	0.00
Rear Seat Structure	1	0	0.06	0.09	37.0	15.4	3.50
Rear shock absorbers	0	30	0.94	1.09	16.0	13.8	2.18
Rear Stabilizer	0	30	1.07	4.25	14.0	3.5	8.49
Rear Suspension less hubm spring, shock absorber and stabilizer	0	30	0.83	0.61	18.0	24.5	1.22
Rear View Mirror	1	1	0.26	0.45	33.0	1.9	9.38
Restraints	0	30	0.15	0.97	97.0	15.5	1.93
Roof	1	0	0.10	0.35	4.0	0.8	0.69
Roof Structure	1	1	5.88	32.72	20.0	0.9	147.67
Roof trim and upholstery	0	30	7.50	8.71	2.0	1.7	17.42
Starting Device	1	3	0.03	0.40	44.0	3.8	0.80
Steering Column Support	0	30	3.75	11.54	4.0	1.3	23.09
Steering Gear and Column	0	30	0.17	0.97	89.0	15.5	1.94
Steering Wheel	0	30	1.67	9.68	9.0	1.5	19.36
Thermostat and Miscellanous Items	1	0	0.00	0.00	4.0	0.1	0.00
Throttle Control for accelerator Pedal operation	1	1	0.03	0.57	9.0	0.4	1.14
Tool Compartment and Kit	1	0	0.05	0.14	9.0	3.9	0.99
Transfer Case Control	1	0	0.14	0.45	14.0	1.8	2.72
Transmission Case, Converter Housing , and Extension	1	1	0.25	8.16	2.0	0.1	16.31
Transmission External Control	1	3	1.50	3.20	51.0	2.1	83.35
Transmission Fluid Cooling System	1	1	0.13	0.92	4.0	0.5	1.84
Underbody	1	1	0.01	0.01	0.0	0.0	0.00
Underbody Heat, Sound, Weather Sealing and insulating	0	30	3.75	1.52	4.0	9.9	3.03
Underbody Ornementation	0	30	7.50	17.88	2.0	0.8	35.75
Underbody Structure	0	1000	14.71	1.67	34.0	300.2	3.33
underbody Trim and Upholstery	0	30	1.67	1.19	9.0	12.6	2.39
Vehicle condition information Componetns	1	1	0.50	2.41	18.0	1.5	12.64
Water Pump and drive	1	0	0.00	0.00	9.0	1.3	0.00
Wheel and tire	1	2	0.27	0.05	14.0	85.6	7.99
windows	1	20	4.16	2.04	0.0	0.0	0.00

Appendix IV: Main Model Inputs

Exogenous Data		
Conversion Rate	**$1.20**	/euro
Electricity Price	**$0.06**	/KWh
Interest Rate	**14%**	
Overhead Burden	**20%**	
Building Recovery Life	**30**	yrs
Light Equipment Recovery Life	**7**	yrs
Heavy Equipment Recovery Life	**12**	yrs
Working Days per Year	**230**	days/yr.
Length of a shift	**8**	hours/shift
Pre-treatment/ Dismantling		
Number of shift per day	**3**	
Length of a shift	**8**	hours/shift
Unplanned downtime	**0.1**	hours/shift
Paid Breaks	**0**	hours/shift
Idle time	**0.8**	hours/shift
Planned Maintenance	**0.4**	hours/shift
Main Machine cost	**$ 40,000.00**	
Tooling Cost	**$ 50,000.00**	
Transportation/Pressing cost	**$11.0**	/ELV
Shredder		
Capacity	**40000**	tons/year
Number of shifts	**2**	shifts/day
Length of a shift	**8**	hours/shift
Unplanned downtime	**1**	hours/shift
Paid Breaks	**1**	hours/shift
Idle time	**0.3**	hours/shift
Planned Maintenance	**0.2**	hours/shift
Power consumption	**400**	kwH
Main Machine Cost	**$ 2,000,000**	
Tooling Cost	**$50,000**	

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