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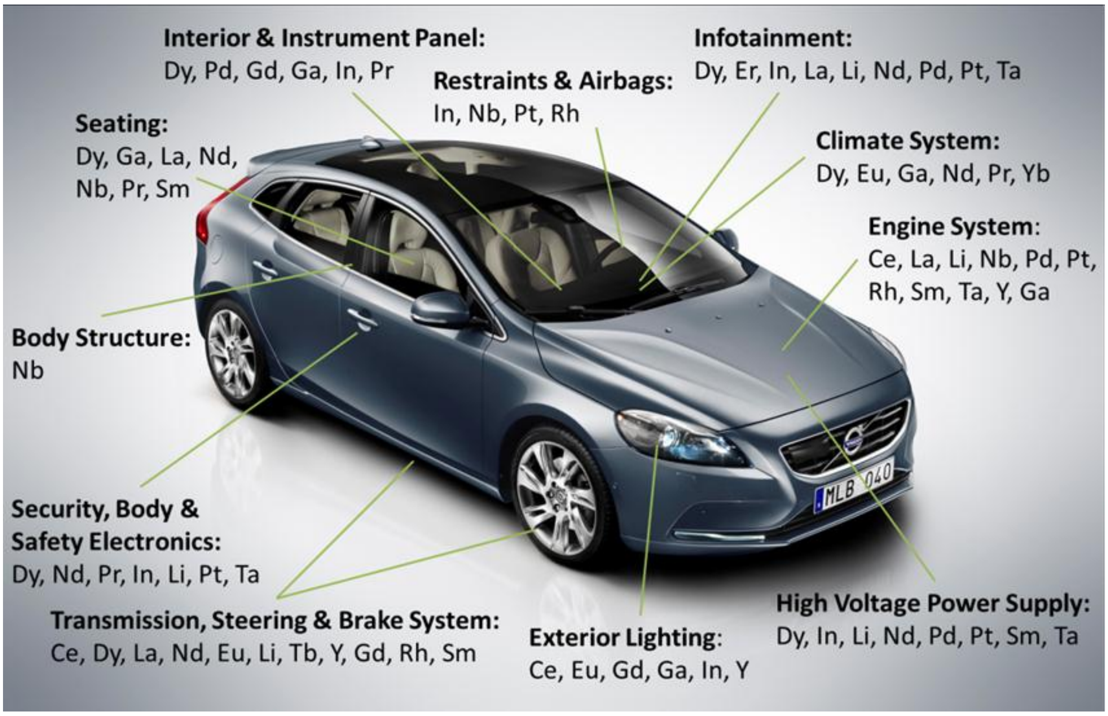

The Use of Potentially Critical Materials in Passenger Cars

KLAS CULLBRAND
OLOF MAGNUSSON

Department of Energy and Environment
Division of Environmental Systems Analysis
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Division of Environmental Systems Analysis
Department of Energy and Environment
Chalmers University of Technology
SE-412 96 GOTHENBURG
Sweden
Telephone +46(0)31-772 1000

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Abstract

High metal prices, increased demand for potentially critical minerals from growing economies, geographically concentrated production and environmentally unsustainable mining practices (Alonso, et al., 2012) have received increased political, research and business interest. The demand from competing technologies such as wind power turbines, nuclear power plants, solar panels, super alloys and technologies used in passenger cars such as catalysts, glass, information and communications technologies (ICT's), flat panel displays, permanent magnets and electronic equipment is fast growing (European Commission, 2010). This, along with the expected material needs of increased electrification of passenger cars, requires the automotive industry to monitor the use of potentially critical materials. In order to be able to plan for the future and develop sustainable environmental strategies for potentially critical materials, it is first of all important for the manufacturer to know if and if so, how much of the materials they use in their products. With this background, this thesis was initiated by the Volvo Car Corporation (VCC) and the division of Environmental System Analysis at Chalmers University of Technology.

The purpose of the thesis is to provide knowledge on the use of potentially critical materials in passenger cars. This involves screening relevant literature about critical materials in order to find materials to study and then analyzing which type of car parts that contains these materials. The use of the materials should be quantified and factors influencing the use should be analyzed. Data was to be gathered from the International Material Data System (IMDS) and the usability of the system was to be evaluated.

The thesis contains a material mapping of the use of 31 potentially critical materials in 4 different car models. The conclusions include:

- The largest quantities of the material mapped can be found in metallurgical, catalytic and electrical and electronic applications.
- Electrification of the powertrain increases the use of mainly neodymium, dysprosium, copper, samarium, silver, terbium, manganese and lithium but also palladium and platinum.
- Increased equipment level increase the use of mainly neodymium, dysprosium, copper, gallium, lithium, praseodymium and tantalum but also niobium, palladium and platinum.
- Increased size of the car could not be shown to directly increase the use. The reason for why the latter could not be shown is believed to be a consequence of other factors, such as year of design.
- The choice of catalytic exhaust treatment system is determined to influence the use of cerium, lanthanum, palladium and platinum.
- The IMDS offers the opportunity to access and create comprehensive and detailed information of the material content in vehicles. However, the system relies on the suppliers' own declaration of data, with reporting time lags and only controlled by the automaker OEM's by random sampling.

Acknowledgement

This thesis has been carried out at the masters programme Industrial Ecology – for a Sustainable Society, at Chalmers University of Technology in cooperation with Volvo Car Corporation (VCC).

We would like to thank our supervisors Andreas Andersson at VCC and Maria Ljunggren Söderman at Chalmers University of Technology who have provided us with support and guidance throughout the work. We would also like to thank the people working at the environmental and weight departments at VCC for all the support and for the great working environment created for us.

Gothenburg, June 2012

Klas Cullbrand & Olof Magnusson

Glossary

AWD – All Wheel Drive
BLIS - Blind Spot Information System
CAS – Chemical Abstracts Service
EBA - Emergency Brake Assist
EoL – End of Life
FWD – Front Wheel Drive
GADSL – Global Automotive Declarable Substance List
ICT – Information and Communications Technology
IMDS – International Material Data System
PCB – Printed Circuit Board
PGM – Platinum Group Metals
PSS – Product System Structure
REM – Rare Earth Metal
VCC – Volvo Car Corporation

CML – Conventional Midsize Car, Low-Specified
CMH – Conventional Midsize Car, High-Specified
CLM – Conventional Large Car, Medium-Specified
HMM – Hybrid Midsize Car, Medium-Specified

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1. Introduction

1.1 Background

High metal prices, increased demand for potentially critical minerals from growing economies, geographically concentrated production and environmentally unsustainable mining practices (Alonso, et al., 2012) have received increased political, research and business interest. With a high expected impact on the European economy, 14 materials or material groups have been classified as critical by the EU Raw Materials Initiative. These include rare earth metals (REM's), platinum group metals (PGM's), indium, gallium, and cobalt (European Commission, 2010). Other studies further add to the list of potentially critical materials. For example, the Oeko Institute (2009) classifies tellurium, indium, gallium, REM's, lithium, tantalum and PGMs as critical. More studies (see e.g. U.S. Department of Energy (2010) or Moss et al (2011)) points out further materials and the list of potentially critical materials is long. However, it is important to understand that the term "critical" is dynamic and changes with perspective and prevailing circumstances and that there is no single fixed definition of the term. While it is also important to think critically about critical materials and question the results of material studies in order to avoid overstating their results (see e.g. Bujis & Sievers (2011)), it is just as important to understand what Rosenau Tornow, et al. (2009) puts forward as:

> *"For manufacturers, all currently used raw materials of the value chain are critical for the production."*

The demand from competing technologies such as wind power turbines, nuclear power plants, solar panels, super alloys and technologies used in passenger cars such as catalysts, glass, information and communications technologies (ICT's), flat panel displays, permanent magnets and electronic equipment are fast growing (European Commission, 2010). This, along with the expected material needs of increased electrification of passenger cars, requires the automotive industry to monitor the use of potentially critical materials. If the risks of supply shortage, significantly higher prices or increased environmental impact are perceived as large, the automotive industry needs to be prepared to reduce or substitute the use of these materials. As a response to the risks, several car manufactures have started to implement various strategies focused on critical materials. Volkswagen claims that they are looking into mining projects in Australia and Vietnam (Phys.org, 2010), Honda focuses on recycling of rare earth metals (REM's) from used nickel metal batteries (World Honda, 2012), Toyota tries to diversify the supply by investing in smelting plants over the world and researches substitution of REM's (Reuters, 2012) and Nissan tries to minimize the use of precious catalytic metals (Euractive, 2011) (see section 3.3).

It is evident that a wide range of strategies can be implemented and that a wide range of materials can be classified as critical. However, in order to be able to react fast to any kind of supply disturbances, change in legislations, develop recycling strategies and to make decisions on which strategy to choose based on solid information, it is first of all important for any manufacturer to know if and how much of the material in question it uses in their products and their production. On the basis of this, this thesis was initiated by the Volvo Car Corporation (VCC) and the division of Environmental System Analysis at Chalmers University of Technology.

1.2 Purpose

The purpose of the thesis is to provide knowledge on the use of potentially critical materials in passenger cars. This involves screening relevant literature about critical materials in order to find materials to study and then analyzing which type of car parts that contains these materials. The use of the materials should be quantified and factors influencing the use should be analyzed. Data was to be gathered from the International Material Data System (IMDS) and the usability of the system was to be evaluated.

1.3 Research questions

From the purpose, 4 research questions have been developed in order to structure the thesis and its conclusions. These are:

1. What types of parts contains potentially critical materials in a passenger car?
2. In what quantities are potentially critical materials used in passenger cars and how does the use differ between car models and specifications?
3. Which factors of the car design influence the quantities of potentially critical materials used?
4. What are the major pros and cons with IMDS as a tool for this kind of analysis?

1.4 Scope

The thesis includes detailed analysis of four different car configurations of three different Volvo car models, being produced currently or in the near future. The chosen models and configurations are:

- Conventional Midsize Car, Low-Specified (CML)
- Conventional Midsize Car, High-Specified (CMH)
- Conventional Large Car, Medium-Specified (CLM)
- Hybrid Midsize Car, Medium-Specified (HMM)

In total, 31 potentially critical materials are analyzed of which 24 are selected for a detailed analysis (see section 1.5). Table 1 shows the materials analyzed in this study and the color coding used in the table are used throughout the report. The materials are further described in section 3.2.

Table 1. Selected materials in this study

1. Cerium	8. Gallium	15. Magnesium*	22. Praseodymium	29. Thulium
2. Cobalt*	9. Gold*	16. Manganese*	23. Rhodium	30. Ytterbium
3. Copper*	10. Holmium	17. Molybdenum*	24. Samarium	31. Yttrium
4. Dysprosium	11. Indium	18. Neodymium	25. Scandium	
5. Erbium	12. Lanthanum	19. Niobium	26. Silver*	
6. Europium	13. Lithium	20. Palladium	27. Tantalum	
7. Gadolinium	14. Lutetium	21. Platinum	28. Terbium	

🟦 = REM 🟩 = PGM ☐ = Others * = Only total mass analysis

The study does not consider the degree of criticality for any specific material. Instead, potentially critical materials were selected based on a literature study where materials most commonly classified as critical were chosen. This angle of approach was chosen in order to cover as many materials as possible in the material mapping process. Even though the materials are potentially critical or only critical in a certain aspect, this study will henceforth refer to the materials only as “critical materials”. In addition to these, a few more materials of assumed special interest for the automotive industry have been added. Of the 31 critical materials studied, 24 are analyzed in detail. The reason for why 7 materials are excluded from detailed analysis is due to limitations in the computer software used to extract data from the IMDS. However, these 7 materials were selected due to special interest for the automotive industry and were not as commonly classified as critical as the other 24.

1.5 Delimitations

- The focus of the thesis is to make a comprehensive mapping of the materials chosen. Hence, the analysis has limited depth in terms of technical analysis of specific materials. For example, for materials with applications in Printed Circuit Boards’ (PCB), the application is termed as PCB’s although the materials actual use within the PCB might differ.
- The thesis focuses on current situations. No future or historical scenarios are analyzed.
- The thesis is limited to cars produced by VCC. No comparisons with other car manufacturers are made.
- The focus of the study is on the material content of the car when it leaves the production factory. No analysis of the materials required to produce the car is made. Also, consumables like fuel and lubricants are not included in the study.
- Most of the data were gathered from the IMDS. In rare cases, data were gathered manually from suppliers. No quantitative data from literature were used. Literature were however used to identify potential usage and from this, potential data gaps.
- Due to limitations in the computer system that is used to access data from the IMDS, 7 materials were not analyzed in as much details as the remaining 24 (see section 2).
- The work is limited to the approximate months available for master theses according to the Chalmers curriculum.

2. Methodology

2.1 Data collection and analysis

The first step of the study was to identify potentially critical materials to analyze. This was done through a literature study where relevant reports were studied in order to find the materials most frequently classified as critical and materials relevant for the automotive industry. A few materials were added due to that these materials are of special interest for the automotive industry and the literature study resulted in a list of a 31 materials with potential use in the automotive industry described for all the materials. From this point, two different analyses were carried out (see Figure 1). Out of the initial 31 materials, 24 materials were selected for detailed analysis (see section 3.2). The remaining 7 could not be analyzed in details due to limitations in the computer software (IPCA), used to access data from the International Material Data System (IMDS) (see section 2.2). These 7 materials were however initially selected for the study due to special interest for the automotive industry and not since they were commonly classified as critical.

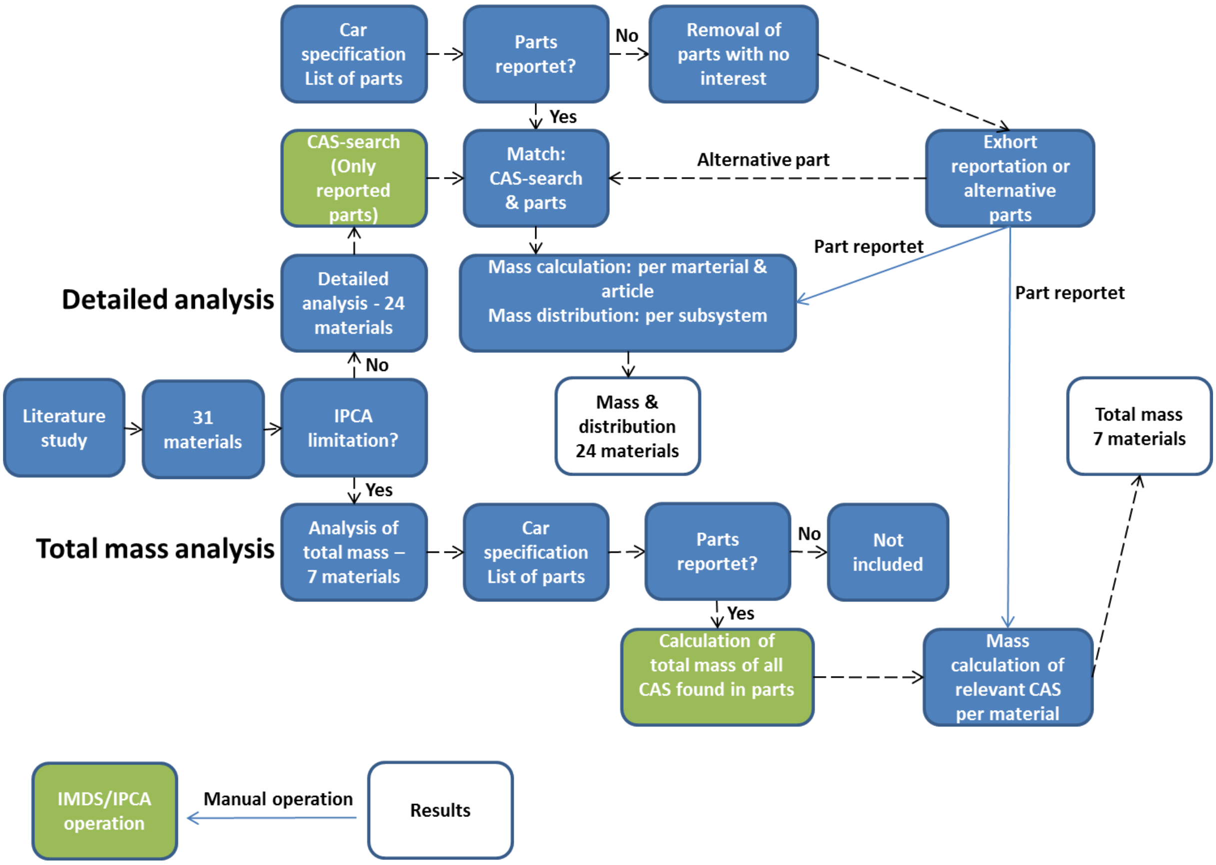

Figure 1. Flowchart illustrating the methodology used for data collection and analysis

Detailed analysis

The first step of the detailed analysis was to perform a search for all materials' relevant chemical abstract service numbers (CAS-numbers). This search resulted in lists with hundreds of thousands of matches of parts containing the materials searched for. These lists were then matched with the specification of each car, i.e. the parts numbers in the car list were matched with the parts numbers from the CAS-search in order to only include the parts that are found in each specific car. In this match, only the parts that were reported at the time the CAS-searched was performed could be matched. For all the materials, the mass of each CAS had to be calculated since the data from IMDS only gives the total percentage of that specific CAS although the relevant material might just be a compound of the CAS. This was done through the use of molar mass calculation. The part's mass was then distributed according to VCC's notations of vehicle subsystems (at VCC called Product System Structure (PSS), see Appendix II). A list of the non-reported parts were also created and from this list, parts not believed to be of interest were removed in order to avoid gathering manual data for a part that later could prove to have no influence on the results. This removal was done in close consultation with the VCC supervisor. For the remaining non-reported parts, the person or supplier responsible was contacted and asked to either state a part that was equivalent and reported or to report the datasheet in the IMDS. In rare cases, some parts material content were reported manually.

For all the materials, parts (both the reported and the non-reported) and cars, the total mass and distribution was calculated and compiled in a complete document containing mass of each material in each part, total masses and distributions by vehicle subsystem. Also, when a sufficient number of previously non-reported parts had been reported, the method was repeated in order to include as many parts as possible in the standardized operation of matching and calculating.

The analysis of the results was done by identifying the parts where the greatest mass of each material was found. Each part containing a large share of any of the studied materials was analyzed in detail the IMDS and the number of unique parts was calculated. In a single part, a material can have several applications. For example, if two different neodymium magnets are used in one part, neodymium has two applications in that part. Since the definition of a part can vary all the way from a complete gearbox to a single screw, the number of applications was also calculated and is presented in table 6-9 in section 5.3. Materials that were not found in any of the cars were excluded from further analysis and hence, also excluded from the detailed analyses in this report.

Total mass analysis

For the seven materials not analyzed through the detailed analysis methodology, the IPCA provides the alternative of calculating the total mass of each material found in the relevant car. The mass is calculated for all CAS-numbers found in the reported parts. However, this means that the non-reported parts are not included in the total mass calculation. From the list of total masses, all the relevant CAS-numbers were identified and calculated in the same way as in the detailed analysis but with the exception that the mass could not be related to any specific part or subsystem. During the detailed analysis, the parts that became reported but were initially non-reported, were also included in this total mass analysis and this analysis was also repeated as more parts were reported. As the detailed analysis meant that many of the non-reported parts were analyzed manually, some of the materials initially not analyzed in details were still analyzed to some degree if they were identified during the detailed analysis. This was especially relevant for the medium-specified hybrid midsize car (HMM) since this car has not yet gone into production and hence, fewer parts were initially reported. Since the HMM also contain parts that are specific for a hybrid, these parts also attracted special attention.

2.1.1 Methodology for factor analysis

In order to be able to answer research question 3, two hypotheses containing four factors believed to influence the use of critical materials were created:

- The quantity of potentially critical materials used is increased by *electrification*, *higher equipment level* and *size of the car.*
- The choice of catalytic exhaust treatment system influences the quantity and choice of potentially critical materials used.

The factors were evaluated according to a series of criteria that had to be met, in order for the hypotheses to be accepted (see Figure 2).

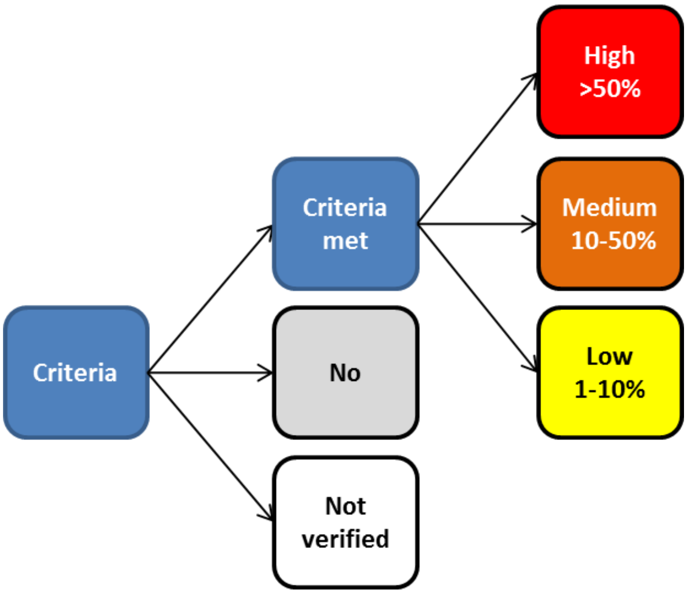

Figure 2. Methodology for evaluation of criteria

First hypothesis

For the first hypothesis, a series of criteria for each of the factors and materials was created. The criteria were:

Electrification: the total mass of a material in the HMM had to be at least 1% larger than the total mass of that material in the CMH and the majority of the mass difference had to be found in hybrid-specific parts such as e.g. the main battery, the main electric motor or the alternator. If the criteria were met, the hypothesis was accepted and the difference in mass compared to the CMH was calculated. The factor was graded as *high*, *medium* or *low* if the mass was more than 50%, 50-10% or

10-1% higher in the HMM than in the CMH. If the mass was smaller in the HMM than in the CMH, the criterion was not met and hence, the hypothesis was denied. If a mass increase of more than 1% could be identified but not definitely identified in hybrid-specific parts, the hypothesis was termed *not verified*.

Equipment level: the total mass of a material in the CMH had to be at least 1% larger than the total mass of that material in the CML and the majority of the mass difference has to be found in parts directly related to the additional equipment of the CMH, e.g. the premium sound system or electric seat adjustment. If the criteria were met, the hypothesis was accepted and the difference in mass compared to the CML was calculated. The factor was graded as *high*, *medium* or *low* if the mass was more than 50%, 50-10% or 10-1% higher in the CMH than in the CML. If the mass was smaller in the CMH than in the CML, the criterion was not met and hence, the hypothesis was denied. If a mass increase of more than 1% could be identified but not definitely identified in the additional equipment of the CMH, the hypothesis was termed *not verified*.

Size of car: the total mass of a material in the CLM had to be at least 1% larger than the total mass of that material in the CML and the majority of the mass difference has to be found in parts directly related to the size of the CLM, e.g. parts related to the chassis or the body structure. If the criteria were met, the hypothesis was accepted and the difference in mass compared to the CML was calculated. The factor was graded as *high*, *medium* or *low* if the mass was more than 50%, 50-10% or 10-1% higher in the CLM than in the CML. If the mass was smaller in the CLM than in the CML, the criterion was not met and hence, the hypothesis was denied. If a mass increase of more than 1% could be identified but not definitely identified in parts related to the increased size of the CLM, the hypothesis was termed *not verified*.

Second hypothesis

For the second hypothesis, the main criterion was that the total mass and choice of the catalytic material used had to vary in any of the cars' catalytic converters or particulate filters. For this hypothesis, the materials analyzed are those with catalytic properties, i.e. cerium, lanthanum, palladium, platinum and rhodium. If this criterion was met, the factor was graded as *high*, *medium* or *low* if the mass in the largest noted mass differed with more than 50%, 50-10% or 10-1% respectively, compared to the smallest noted mass for any of the cars. If no mass difference could be found, the hypothesis was denied. This factor could hence, not be termed *not verified.*

2.2 Tools – IMDS & IPCA

Most of the data were gathered from the International Material Data System (IMDS), containing hundreds of thousands reported data sheets of car parts. IMDS was created in a joint venture project involving Audi, BMW, Daimler Chrysler, Ford Motor Company, Opel, Porsche, Volvo and Volkswagen. This was in response to new legislations stating that 95% of each car should be recycled by the year 2015. To be able to meet this target and other legislations, such as REACH and ROHS, car manufactures need to have detailed knowledge about the materials the cars are built of. In IMDS, suppliers are required to report all substances that are covered in the global automotive declarable substance list (GADSL). In addition, all materials need to be specified to 100% by weight and type, but not necessarily specified by exact substance composition. For example, a non-GADSL substance may be specified only as REM or plasticizer. In IMDS, a part is described by a tree structure where the top node is the part itself, followed by sub-components and semi-components. The components are described by their material content and the substances within the materials. Substances are reported as weight percentage of the material they are found in. Figure 3 shows the general structure of a reported part in the IMDS (Enterprise Services HP, 2012).

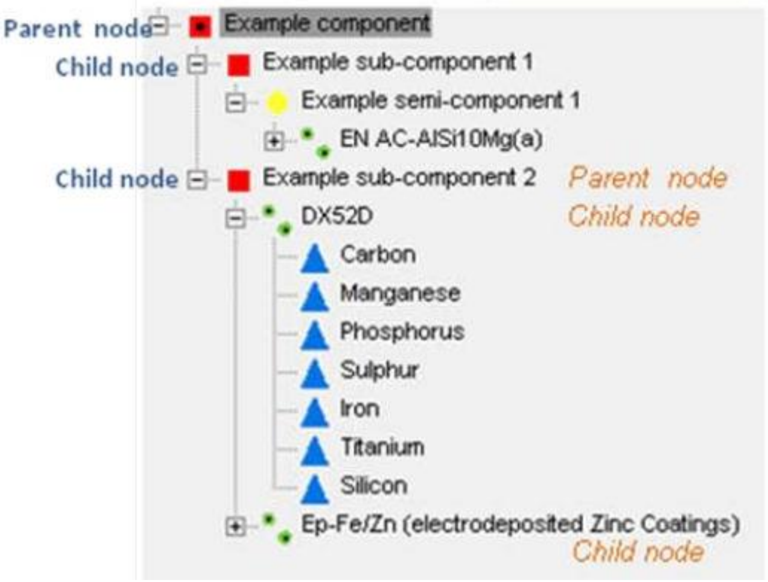

Figure 3. Tree structure of a reported part in IMDS (Enterprise Services HP, 2012)

Where data gaps were found in IMDS, suppliers and other relevant persons, such as technical experts at VCC, were contacted and asked to either fill the data gaps or present the required data manually. If the data was not available, alternative and equivalent parts were asked for. The data gaps could be in the form of non-reported datasheets, data marked as e.g. “confidential substances” or “miscellaneous” or REM’s or wrongly reported parts. Most of the communication with suppliers and persons responsible at VCC was carried out through e-mail and several hundreds of e-mails were sent in order to fill data gaps or to clarify ambiguous data. This required a substantial amount of effort and time. Meetings and phone calls were used when e-mail communication was considered insufficient.

At VCC, the computer program used to access the IMDS is called IPCA. IPCA provides the interface and enables VCC to only access VCC-relevant parts. During the study, pros and cons of using IPCA and IMDS for mapping critical materials were continuously observed and analyzed (see section 6). It should be noted that a prerequisite for IMDS is that there are restrictions on how data can be used. The data can only be used for environmental and health issues or to show governmental organs that VCC is following legislations. Data from IMDS cannot be used for price negotiations with suppliers and hence, only the environmental department at VCC can access the data and they are not allowed to spread the data to other departments within VCC, such as e.g. the department of purchasing. As a consequence, the names of the studied cars are anonymous and the results in this study are aggregated in order to avoid that the data are used for the wrong purposes.

3. Critical materials

A literature study was carried out in order to find which materials that are most commonly classified as critical and to identify their most common usage areas. This study will not contain any specific definition of a criticality and will instead present some of the definitions that were found during the literature study. These are presented in the first section of this chapter. In section 3.2, the results from the literature study are presented, i.e. the materials most commonly classified as critical are presented. These are also the materials in focus in the mapping process of this study. In addition to these materials, a few more have been added as they are believed to be of vital importance for the automotive industry.

3.1 Dimensions of criticality

This section presents a series of different dimensions and definitions of criticality in order to motivate this report's selected materials and to explain the term "critical". In order to do so, it is firstly important to make a distinction between the terms "critical" and "strategic". The European Commission (European Commission, 2010) states "….materials for military uses are called "strategic", while those materials for which a threat to the supply from abroad could involve harm to the national economy are considered "critical"." Committee on Critical mineral impacts of the U.S. Economy (U.S National Research Council, 2008) takes a similar stance and further adds that the term "critical" is a broader term that involves civilian, industrial and military applications. Hence, and in accordance with the definition from the European Commission (2011), a strategic material is always critical but a critical material may or may not be strategic depending on if it is used in military applications or not.

In literature, criticality is determined by evaluation of risks and impacts. The European Commission (European Commission, 2010) defines criticality by the material's economic importance and supply risk, i.e. a material is determined to be critical if the risks of supply shortage and their economic impact on the EU economy are higher than most materials. The commission also includes a third dimension in the form of environmental country risk that assesses the risk of a country taking environmental measures that may induce supply shortages. This dimension is however said to have no or very small impact on the results in the analysis presented. The Committee on Critical Mineral Impacts of the U.S. Economy (U.S National Research Council, 2008) takes a similar approach and evaluates criticality in terms of supply risk and impact of supply restriction as Figure 4 shows.

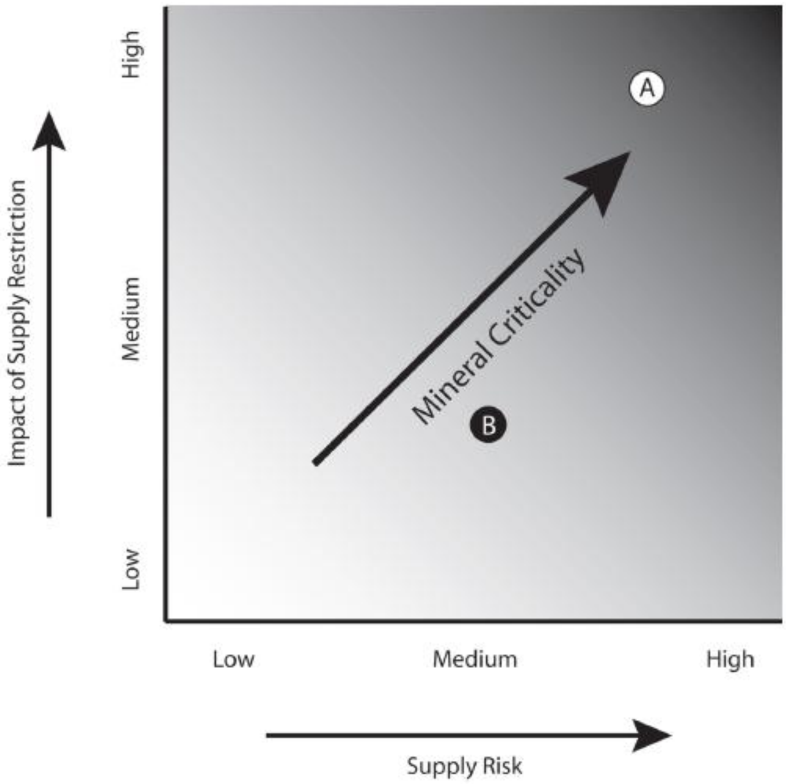

Figure 4. Evaluation of supply risk and impact of supply restriction. Material A is according to this methodology more critical than material B since it has a higher supply risk and the impact of a supply restriction is higher.

In order to evaluate the risks and impacts, it is necessary to break down the term “critical” into more easily assessable factors. Common means of analyzing the supply risks of a material are in terms of *substitutability, political risk, recycling potential, concentration of supply, by-product character, geological availability* (European Commission, 2010), *limitations/lead times to expand production* (Moss et al 2011)*, import dependence* (U.S National Research Council, 2008) and *competing demand* (U.S. Department of Energy, 2010). The different factors also interact to a varying degree according to each specific perspective and situation. Below follows a short description of what the different factors often refer to according to the literature studied**.**

- *Substitutability* refers to the degree to which a certain material can be substituted by another material. This means that the impact of the supply risks will only be fully realized if the material in focus cannot be substituted. (European Commission, 2010)
- *Political risk* refers to the political and economic stability of a certain country. It is commonly measured by making use of the World Bank “Worldwide Governance Indicator”. (European Commission, 2010)
- *Recycling potential* refers to the recycling rate of a certain material. The higher the recycling rate, the lower supply risk. This is since recycled materials (although secondary raw materials) are just another source of supply. The rate can be calculated in various ways with different assumptions, e.g. (European Commission, 2010).
- *Concentration of supply* refers to the level of concentration of production and is commonly measured by the Herfindahl-Hirschman Index (HHI). Increasing HHI-index indicates an increase in market power and hence, a decrease in the level of competition and vice versa. (European Commission, 2010)

- *By-product character* often refers to the supply risk arising from the fact that most critical materials are produced as a by-product from ores of primary materials. Hence, the economic incentive is derived from the mining of the primary material although extraction of by-products sometimes can generate additional revenue. A supply risk related to this is e.g. that it is not economic to raise the production of the primary material in order to meet an increasing demand of any of the by-products. (European Commission, 2010)
- *Geological availability* deals with the issue of heterogeneous distribution of mineral deposits and the availability of the Earth's resources. The potential for discovering new mineral deposits in the earth crust is vast and new resources and reserves are continuously discovered. However, the technical, economical and geological available reserves vary over time and are unevenly distributed over the crust. (European Commission, 2010)
- *Limitations/lead times to expand production* includes several different factors such as limitations due to that the existing production already are producing at full capacity, new production projects takes a substantial amount of time to implement and uncertainty linked to long-term investments in volatile markets. (Moss et al 2011)
- *Import dependence* includes e.g. political and economic risks arising from relying on foreign supply which may be disrupted or restricted by various reasons, depending on the specific situation. (U.S National Research Council, 2008)
- *Competing demand* deals with the issue of different technologies competing with one another for a material. E.g. an increase in the use of clean energy technologies will increase the demand for a number of critical materials already used by other technologies in e.g. the automotive industry. (US department of energy). For example, neodymium and dysprosium are widely used by the automotive industry but are at the same time required for wind turbines in wind power plants. (Alonso, et al. 2011)

The impact is then measured in terms of each risk's potential impact on e.g. a country's or a region's economy or environment or on the development of a certain technology. For example, the report presented by the European Commission (European Commission, 2010) measures the impact on the European economy for the coming ten years if the supply risks were to be realized whereas Moss et al (2011) measures the impact on the development of clean energy technologies, i.e. the impact changes with the perspective of the study. Competing and growing technologies such as wind power turbines, nuclear power plants, solar panels, super alloys and technologies used in passenger cars such as catalysts, glass, ICT, flat panel displays, permanent magnets and electronic equipment are fast growing (European Commission, 2010) and together with increased electrification of passenger cars, the demand for critical materials is increased, which in turn influence the supply risks. Table 2 shows a summary of the risks and perspectives considered in the reports studied.

Table 2. Supply risks and perspectives of the studied reports.

Study	US Department of Energy (2010)	European Commission (2010)	Oeko Institute (2009)	US National Research Council (2008)	Oakdene Hollins (2008)	Moss et al (2011)
Supply Risk	•Geological availability •Political risk •By-product character •Concentration of supply •Competing demand •Ability to substitute	•Political risk •Recycling Potential •Concentration of supply •Ability to substitute	•Geological availability •By-product character •Concentration of supply •Limitations/le-ad time to expand production	•Geological availability •By-product character •Import-dependence •Recycling rate	•Geological availability •Political risk •Concentration of supply •Vulnerability to climate change	•Political risk •Concentration of supply •Limitations/lead time to expand production
Perspective	•Impact on clean energy economy	•Impact on the EU economy	•Impact on future sustainable technologies and recyclability	•Impact on the US economy	•Impact on the UK economy	•Impact on low-carbon energy technologies

Evaluation of criticality is handled in different manners in different studies (see Table 2). Also, the perspective of the study changes the criticality indicators used, even though they appear to have the same meaning at first (European Commission, 2010). For example, economic importance is of course evaluated differently in a study performed by the EU than a similar study performed by China. However, since this report do not give any specific definition of the term “critical”, the various definitions and perspectives of criticality helps to cover more aspects than just one single definition. Also, depending on the time perspective, different materials will be classified as critical since the factors described in Table 2 obviously will change over time. For example, the Oeko institute (Oeko Institute, 2009) classifies REM’s as critical in a 10 year perspective but not in a 5 year perspective.

3.2 Selected critical materials

From the literature study, 31 materials were chosen for analysis. Out of these, 24 materials were selected for a detailed analysis (see section 2). Table 3 presents the selected materials and their main applications, annual production and spot price (see Appendix I for a more extensive description of the materials). The materials’ main applications were studied in order to receive knowledge of where in the cars the materials could be expected to be used.

Table 3. The selected materials and their applications according to the literature, annual production and spot prices.

Material	Selected Applications	Annual Production	Spot Price**
Cerium	Auto catalysts, alloys, glass manufacturing [2]	Total REM production: 124,000 t - China (97%) [1]	45.0$/kg [6]
Cobalt*	Li-ion batteries, super alloys, synthetic fuel [2]	87,400 t - DRC (53%), China (7%), Russia (7%) [1]	30.8 $/kg [5]
Copper*	Radiators, brakes, wiring, many other electrical and electronics applications[1]	15,427,000 t - Main producers: Chile, Peru, USA, Australia [1]	7.8 $/kg [5]
Dysprosium	Magnets, hybrid engines, nuclear reactors [1] [2]	Total REM production: 124,000 t - China (97%) [1]	1500.0 $/kg [6]

Erbium	Neutron absorber in nuclear reactors, phosphors [2]	Total REM production: 124,000 t - China (97%) [1]	350.0 $/kg [7]
Europium	Nuclear power stations, red light in TV and computer screens [2]	Total REM production: 124,000 t - China (97%) [1]	4000.0 $/kg [6]
Gadolinium	Phosphors, magnets [3]	Total REM production: 124,000 t - China (97%) [1]	163.0 $/kg [6]
Gallium	Integrated Circuits, laser diodes/LED, Solar cells [1]	78 t - Main producers: China, Germany, Kazakhstan, Ukraine [1]	405.0 $/kg [6]
Gold*	Jewelry, gold plating of electronic components, brazing alloy and photographs	Main producers: China, Australia, USA, South Africa and Peru (2,350 t) [4]	50190.0 $/kg [5]
Holmium	Limited usage areas but in some cases in magnets or glass coloring [2]	Total REM production: 124,000 t - China (97%) [1]	N/A
Indium	Flat screen panels, alloys for low temperature indicators, dental applications, glass [1]	N/A	785.0 $/kg [7]
Lanthanum	Alloys, phosphor lamp coating, optical glass, glass polishing [2]	Total REM production: 124,000 t - China (97%) [1]	36.0 $/kg [6]
Lithium	Alloys, high energy batteries, glass, ceramics, lubricants, medicine [2]	17,700 t - Main producers: Chile, Australia, China, Argentina [1]	5.0 $/kg [8] ****
Lutetium	Few commercialized application, one is to catalyze organic reactions [2]	Total REM production: 124,000 t - China (97%) [1]	N/A
Magnesium*	Pyro techniques, electronics, alloys in aerospace, automotive, medicine and truck construction [1]	30,190,000 t - China (56%), Turkey (12%), Russia (7%) [1]	3.1 $/kg [5]
Manganese*	Steel, aluminum, copper and nickel alloys. Some Li-ion batteries uses manganese as cathode [1]	9,664,000 t - Main producers: China, Australia, South Africa, Brazil [1]	3.4 $/kg [5]
Molybdenum*	Mainly metallurgical applications as an alloying agent [1]	202,000 t - Main producers: China, USA, Chile [1]	31.0 $/kg [5]
Neodymium	Alloys, glass coloring, auto catalysts, petroleum refinery, magnets [2]	Total REM production: 124,000 t - China (97%) [1]	160.0 $/kg [6]
Niobium	Metallurgical applications as an alloying agent, mainly in high-strength steel [1]	61,000 t - Brazil (92,4%) [1]	43.0 $/Kg [6] ***
Palladium	Auto catalysts, jewelry, dentistry, electronics, telecommunication [2]	195 t - Main producers: Russia (41%), South Africa (41%) [1]	19500.0 $/kg [5]
Platinum	Auto catalysts, jewelry, dentistry, electronics, other catalytic applications [2]	178 t - South Africa (79%), Russia (11%) [1]	45930.0 $/kg [5]
Praseodymium	Glass coloring, magnets	Total REM production: 124,000 t - China (97%) [1]	205.0 $/kg [6]
Rhodium	Alloys, hardening for platinum and palladium, electronics, jewelry, glass, auto catalyst, other catalytic applications [2]	N/A	42920 $/kg [5]

Samarium	Optical glass, capacitors, thermo ionic generating devices, lasers, carbon arc lightning, magnets [2]	Total REM production: 124,000 t - China (97%) [1]	138.0 $/kg [5]
Scandium	Used to create high intensive light [2]	Total REM production: 124,000 t - China (97%) [1]	18000.0 $/kg [7]
Silver*	Jewelry, coins, silverware, electronics, photographs, mirrors, catalysts [1[1]]	21,300 t - Main producers: Peru, Mexico, China, Australia [1]	891.7 $/kg [5]
Tantalum	Alloy in high-strength and heat resistant materials, capacitors, medicines, optical industry [1][2]	1,160 t - Australia 48%, Brazil (16%) [1]	400.0 $/kg [6]
Terbium	Phosphors, magnets [2]	Total REM production: 124,000 t - China (97%) [1]	3400.0 $/kg [6]
Thulium	Portable x-ray tools, dental diagnostics tools [2]	Total REM production: 124,000 t - China (97%) [1]	N/A
Ytterbium	Laser source, portable x-rays, additives in steel and glass [2]	Total REM production: 124,000 t - China (97%) [1]	N/A
Yttrium	Red color in televisions, fluorescent lamps, ceramics, alloys [2]	Total REM production: 124,000 t - China (97%) [1]	160.0 $/kg [6]

🟦 = REM 🟩 = PGM ☐ = Others

3.3 Strategies for managing critical materials

In order to secure access to and improve efficient use of critical materials, there are different measurers to be taken. However, no single measure fits all critical materials or all products using the materials. To understand what measure to be taken it is important for the concerned party to understand e.g. the drivers of criticality, product and material characteristics and the lifecycle of the product (European Commission, 2010). Depending on the perspective of the concerned party, the measures are more or less interdependent and address different types of risks and issues. On the national or EU level, policy intervention is crucial. The European Commission's (European Commission, 2010) recommendations on measures concerns:

- *Mining and access to primary resources:* even during closed loops with perfect recycling and re-use conditions, new primary materials will be needed. Especially in times of strong markets growth and or during introduction of new applications. Ensuring access to these resources should be done through promotion of exploration, research on mineral processing, extraction from old mine dumps and mineral extraction from deep deposits. It should also be done through improving relations with extractive industries in developing countries and foster good governance, capacity building and transparency.
- *Level playing-field in trade and investment and foster fair competition conditions:* make sure that fair competition and a level playing-field is established through e.g. maintaining trading policies, consultation with countries whose policies are causing distortion on the raw materials market, fostering of an exchange-of-view on certain policies and raising awareness of the impact of export restrictions.

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1. European Commission (2011). 2. Patnaik (2002). 3. Goonan (2011). 4. U.S. Geological Survey (2010). 5.infomine.com (2012). 6. metal-pages.com (2012). 7. mineralprices.com (2012) 8. Kushni, D., & Sandén, B.A (2012). *= Only total mass analys. **= The spot prices are metal prices and latest available update in year 2012. ***= Price for NeFb 65% Nb ****= Price is the extraction cost for lithium carbonate

- *Recycling:* alleviating supply risks of primary materials by efficient recycling of products and residues which also in many cases reduces the energy demand through energy savings. The more import dependent the involved party is on an individual metal, the more important recycling becomes. It becomes even more important if substitution or material savings in manufacturing are difficult to achieve. Increased recycling should be achieved through proper collection of End of Life (EoL) products, improving recycling chains through a system approach, prevention of illegal exports of EoL products and through promotion of research on technically challenging products and substances and system optimization.
- *Substitution:* substitution of critical materials is often difficult to achieve since it often means a change in the product quality, performance or economy. Substation of a critical material by an abundant one can be very beneficial but substituting a critical material with another critical material has no or little benefits. If material substitution proves difficult, substitution of product functions may be more beneficial, i.e. investigating the potential of achieving a key product function through a smarter product approach. Substitution should be encouraged through mainly promoting research activities on substitutes for critical materials.
- *Material efficiency:* using smaller amount of materials to produce products and extend the use loop for the materials is obviously important from a material scarcity perspective but also from a company perspective as material efficiency often goes hand-in-hand with economic and financial objectives like cost reductions and increased competitiveness. Material efficiency can be achieved in raw materials production, product manufacturing, use phase and in EoL. Efficient use of materials involves minimizing the amount of raw materials to produce a product but also material substitution, increased recycling rates and minimized material losses into residues.

On the company level, there are several available measures that are similar to those on the national level. The critical material issue has gained awareness throughout many industries. In the automotive industry, companies like Toyota, Volkswagen, Honda, Nissan, Renault and General Motors have taken different measures to handle the issue. Although most of the companies are focusing on REM's, strategies for other critical materials can be expected to be very similar. Volkswagen claims that they are carefully monitoring the trends in the REM market to be able to react as early as possible. The company further states that they are prepared to compensate for geological supply shortages in the form of new mining projects in Australia and Vietnam (Phys.org, 2010). Honda has taken another measure to ensure resource availability by starting the world's first process to extract REM's from used Honda parts in cooperation with Japan Metals & Chemicals Co. According to the company, the process is at first aimed to recycle REM's from nickel-metal batteries but will later also involve other car parts. The purity of the recycled metal should be as high as that of newly mined and refined (World Honda, 2012). Toyota is instead diversifying the supply of REM's through acquiring of mining rights and investing in smelting plants in different parts of the world, including India, Vietnam and Indonesia. The company is also researching in new ways of constructing hybrid and electrical cars without the use of REM's (Reuters, 2012). Nissan is reducing the usage of critical metals by e.g. setting a target to comply with emission regulations in each region with minimum use of catalytic precious metals. Renault claims that they are minimizing the use of REM's through technological advancement. The supply of lithium used in electrical car batteries is secured by agreements of guaranteed supply from suppliers (Euractive, 2011). General Motors takes a similar approach with agreements and technological advancement as the major strategies to mitigate supply risks.

To sum up and repeat what is mentioned in the first section of this chapter, no single measure fits all critical materials or all products using the materials. To understand what measure to be taken it is important for the concerned party to understand e.g. the drivers of criticality, product and material characteristics and the lifecycle of the product (European Commission, 2010).

4. Volvo Car Corporation and studied car models

Volvo Car Corporation (VCC) was founded in Gothenburg, Sweden by Gustaf Larson and Assar Gabrielsson and the first car was produced in 1927. VCC was then a part of Volvo Group until 1999 when the company was purchased by Ford Motor Company. In 2010, VCC was bought by the Chinese Zhejiang Geely Holding Group (Volvo Personvagnar AB, 2010).

VCC's global strategy is called "designed around you" which strives to understand human needs and to combine the feeling of luxury and the brand's historical legacy in terms of building safe cars (Volvo Cars, 2012). VCC's vision is "to be the world's most progressive and desired luxury car brand" and the core values are safety, environment, quality and design. The bullet list below show VCC in numbers for year the 2011 (Volvo Car Corporation, 2011):

- Revenue: 125,525 million SEK
- Gross profit: 22,066 million SEK
- Number of employees: 21,512
- Total sold cars worldwide: 449 255 cars
- Biggest markets in number of sold cars: U.S. 67 273, Sweden 58 463, China 47 140, Germany 33 167 and UK 32 770

4.1 Car model descriptions

This section gives a brief description of the four different car models and configurations studied in this report. All the cars are made for the Swedish market and have some sort of diesel engine. In IMDS, the cars are described in parts and the parts have varying complexity. For example, the gearbox can be considered as a part but a single screw can also be considered as a single part.

Conventional Midsize Car, Low-Specified (CML)

The low-specified midsize car has an automatic gear box, a diesel engine, front wheel drive (FWD) and weighs approximate 1500 - 1 700 kg. This version of the car does not have any extra equipment except the standard equipment. It should however be noted that even though the car is referred to as low-specified, it can still be highly equipped compared to other car models from other brands. In the IMDS, the car is described by 1552 pars and examples of standard equipment that comes with the CML are:

- Sound system, 5" front LCD and 6 speakers
- Electrically heated front seats
- Electrically heated/adjustable outer rear-view mirrors
- Electrified Climate Unit
- Air Bags, side air bags for front seats and inflatable air bag curtains
- ABS brakes with Emergency Brake Assist (EBA)
- City Safety Generation 2 -Collision prevention system

Conventional Midsize Car, High-Specified (CMH)

The conventional midsize, High-specified car has a diesel engine, an automatic gear box, All wheel drive (AWD) and weighs approximate 1500 - 1 800 kg. The car has most of the optional equipment available in a modern Volvo. In the IMDS, the car is described by 1660 parts and equipment in addition to the standard equipment is for example:

- Parking sensors
- Premium sound system, DVD player and 10 speakers with surround sound.
- Electrical adjustment of driver and passenger seats
- Park assist camera
- 7” front LCD display and two LCD’s in the back seat
- Rain sensors
- Sport exterior and wheels
- Blind spot information system (BLIS)

Conventional Large Car, Medium-Specified (CLM)

The conventional medium-specified large car (CLM) has a diesel engine, an automatic gearbox, FWD and weighs approximate 1800 - 2 200 kg. The CLM was designed several years earlier than the other three cars in this study. This version of the car has a medium specified equipment level with additional equipment compared to the CML but with less than the CMH. In the IMDS, the car is described by 1669 parts and equipment additional to the CML car is for example:

- Electrical adjustment of driver seat
- Sound system with 8 speakers

Hybrid Midsize Car, Medium-Specified (HMM)

The midsized hybrid (HMM) is a future car model with a combination of a diesel engine and an electric motor with Li-ion battery and weighs approximate 1 900 - 2 100 kg. It has an automatic gearbox and the diesel power output is distributed to the front wheels while the electrical output is distributed to the rear wheels. This version of the car has a medium specified equipment level with additional equipment compared to the CML but with less than the CMH. In the IMDS, the car is described by 1822 parts and equipment additional to the CML car is:

- Sound system, DVD player and 7” front LCD display
- Electrical adjustment of the driver seat
- Electrical heated back seats
- Parking sensors
- Rain sensors

The HMM also contains parts that are specific for a car with electrical powertrain. Examples of these parts are a high voltage battery, large electrical motor, voltage converter and charger.

5. Results and analysis

This chapter presents the results and the analysis of the material mapping. The first two sections contain results summary, a results comparison and an analysis of factors influencing the use of the studied materials. In section 5.3, the results of each individual studied car are presented separately and in more details.

5.1 Summary and comparison of results

The results of the material mapping process were, in terms of use, generally consistent with information found in the literature study (see section 3.2). For example, most of the materials analyzed were found in electronic and electrical applications, although in varying quantities depending on the characteristics of each study object. The largest total mass for all 31 materials was found in the hybrid car (HMM), the second largest in the high-specified conventional midsize car (CMH), the third largest mass in the low-specified conventional midsize car (CML) and the smallest mass in the medium-specified large conventional car (CLM). In the detailed analysis for the 24 selected materials, the order of CML and CLM are shifted while HMM and CMH remains in the same positions.

In this section, all 31 materials are included but the 24 materials selected for detailed analyses are analyzed in more depth than the other 7 (see section 2). The cars are compared in terms of total mass of each material in each car. Figure 5 shows a summarized picture of all four car models in terms of main subsystem distribution of the 24 materials analyzed in details. Each material is presented under its main subsystems, i.e. where most of that specific material's mass was located. However, many of the materials are found in a large number of subsystems (see section 5.3) and the number of subsystems is more than shown in the picture (see Appendix II).

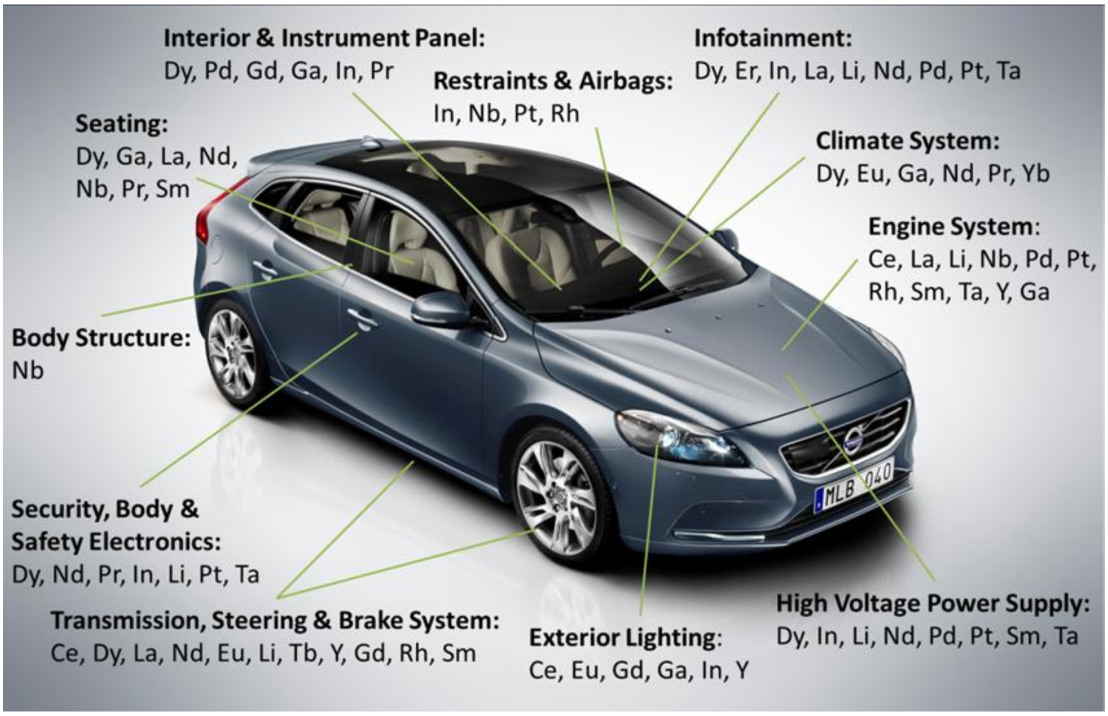

Figure 5. Summary of the results from the detailed analysis in terms of distribution by subsystem. Showing where the 24 materials' main masses where identified. The figure is a summary of all 4 analyzed cars.

Of the 31 materials analyzed, four materials were in at least one of the cars identified in mass over 1 kg. These are copper, manganese, magnesium and lithium (Figure 6). Copper is used in a large extent in mainly electronic and electrical applications and magnesium in mainly metallurgical ones. Lithium and manganese are both used in metallurgical and electronic and electrical ones. Figure 6 shows the total mass of these four materials in the different cars studied.

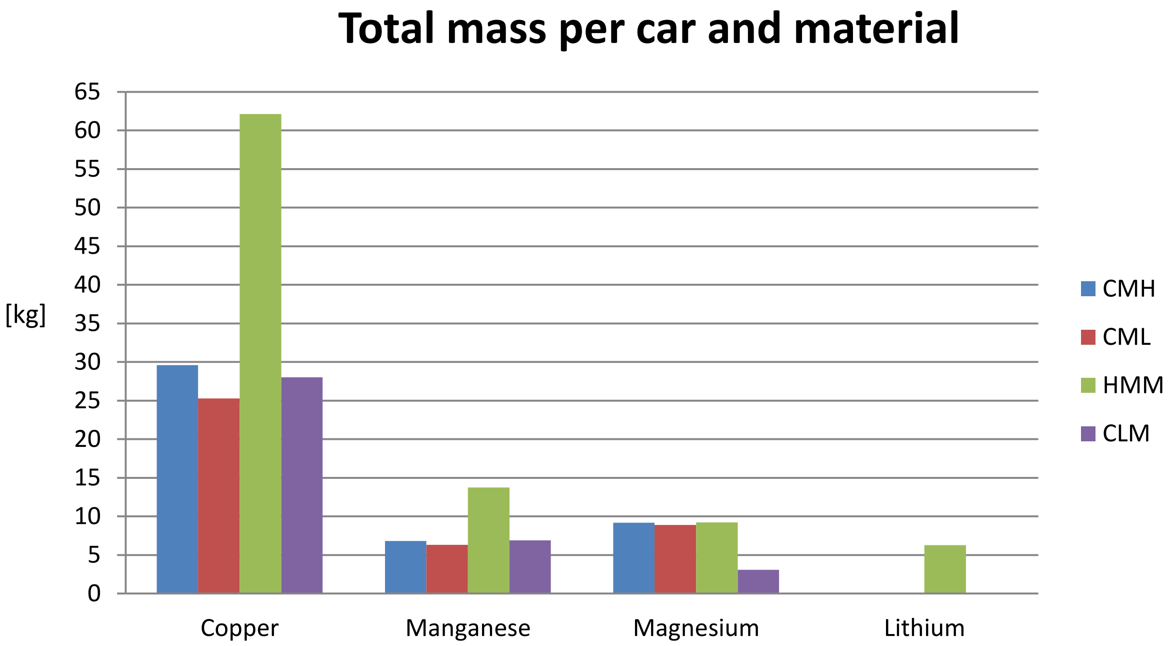

Figure 6. Total mass per car and material for materials with more than 1 kg identified in at least one of the cars.

The increased quantities of copper in the HMM, compared to the other three objects, is mainly since it is a hybrid with an electric powertrain using a high voltage power supply. As a consequence, substantial quantities of copper are used in e.g. the main Li-ion battery and the electric motor. Since copper are used in electronic wiring, electrification in general also contributes to increased use of copper. The increased quantities of manganese in the HMM is also mainly due to the electrification of the powertrain. The main share of the increase is located in copper and steel alloys in the main battery. The battery is also responsible for the single largest mass of lithium in the HMM. All the materials in Figure 6 are found in a large number of applications with metallurgical and electronic and electrical applications being the most common (see section 5.3). The reason for why less magnesium is used in the CLM than in the other three studied objects is difficult say without a detailed analysis. In the case of copper and manganese, indications from the detailed analysis of the HMM pointed out interesting parts for further analysis although no fully detailed analysis was conducted. Of the 31 materials, 6 materials were in at least one of the cars identified in masses larger than 45 g but less than 1 kg. These are molybdenum, neodymium, niobium, cobalt, dysprosium and silver (Figure 7).

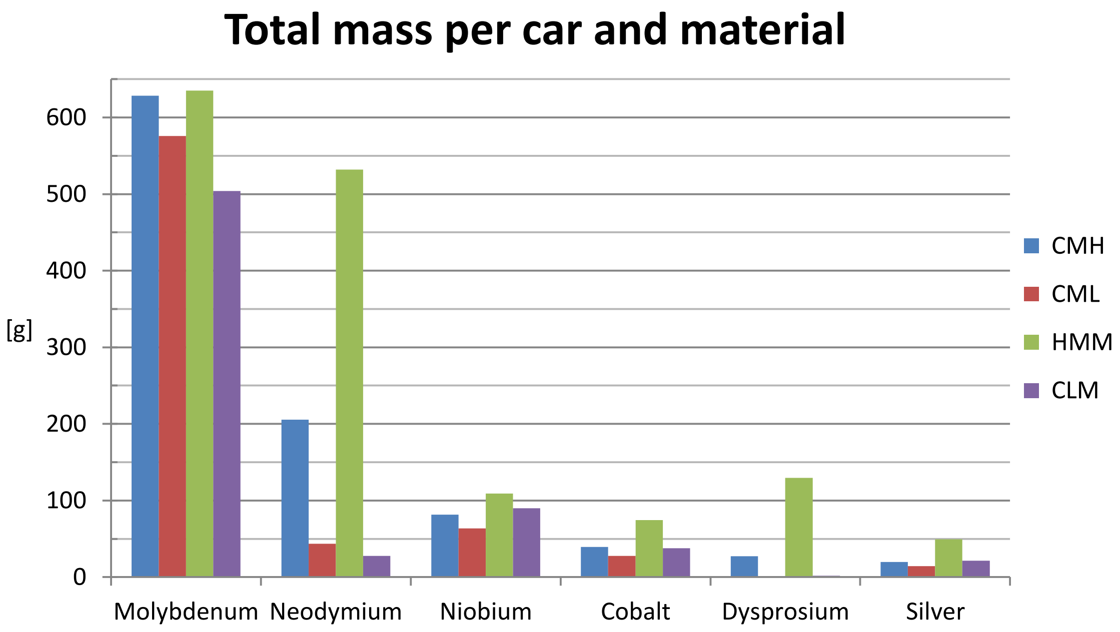

Figure 7. Total mass per car and material for materials with identified mass greater than 45g but less than 1kg in at least one of the cars.

The main use of molybdenum is in alloys, but since no detailed analysis was conducted for this material, it is not possible to say why the use varies between the cars. The relative variation is however considerably smaller than for many other materials analyzed, e.g. neodymium which shows large variations in mass. The use of neodymium was shown to be strongly correlated with the number and sizes of high-strength neodymium magnets. The CMH contains considerably more neodymium magnets than CML and CLM and hence, more neodymium. The largest mass of neodymium found in the CMH is located in the high-performance audio system but also in the steering system and in the electrical motors used to adjust the seats. The HMM contains even more neodymium, mainly as a result of the electrified powertrain containing relatively large and many neodymium magnets used in e.g. the alternator and the main electric motor. Dysprosium is mainly used to alter the characteristics of neodymium magnets and hence, the correlation between the number and size of neodymium magnets and the mass of neodymium is also true for the mass of dysprosium. The varying mass of niobium is however more difficult to explain, since niobium is used in small quantities in a large number of alloying applications. The more concentrated masses are however mainly found in certain high-strength steel applications, although to in varying amounts depending on the car model and specification. For cobalt and silver, no detailed analyses were carried out but general usage areas were identified. Silver is almost exclusively used in electrical and electronic applications such as printed circuit boards (PCB's) while cobalt can be found in a wide range of applications, e.g. pigments, alloys, electrical and electronics equipment and the large Li-ion battery used in the HMM. It is however believed that the battery contains more cobalt than identified because a large share of the battery's mass was not reported at the time of this study. Of the 31 materials analyzed, 10 materials were in at least one of the cars identified in masses larger than 0.5 g but less than 45 g (Figure 8).

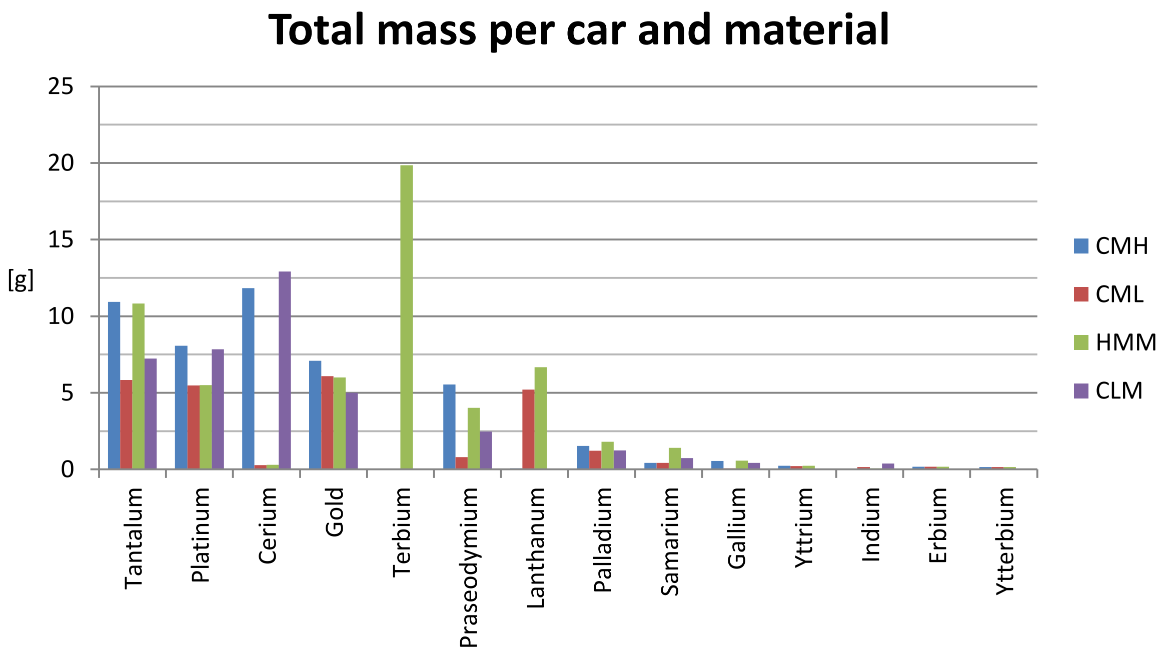

Figure 8. Total mass per car and material for materials with identified mass greater than 0.5 g but less than 45 g in at least one of the cars.

The largest shares of platinum, cerium, lanthanum and palladium were, as expected from the literature study, identified in catalytic converters and particulate filters. Depending on the specific catalytic converter or particulate filter, the use however varies. Platinum and palladium were always found in both the converters and filters while cerium only was found in these parts when lanthanum was not and vice versa. Platinum and palladium were also used in low concentrations in substantial numbers of electrical and electronic applications, mainly PCB's. Cerium was also unexpectedly found in elastomers, in e.g. rubber hoses. Terbium, lanthanum, praseodymium, samarium and gallium were all identified mainly in high-strength magnets used in e.g. electronic motors for electronic seat adjustment often the same magnets in which large amounts of neodymium and dysprosium were found). For terbium, the largest share in the HMM is found in the main electric motor while only trace amounts of terbium could be found in the other three cars. Tantalum is mostly used in electronic and electrical applications such as PCB's and since the HMM and the CMH contains more electronic applications with PCB's being a part of them, the use is also largest for these two cars. This is also likely to be the case for gold, although no detailed analysis was carried out for this material. Except use in PCB's, tantalum is also used in various alloys.

Of the 31 materials analyzed, 7 materials were not in any of the cars identified in masses larger than 0.5 g. However, although no large masses of these 11 materials could be identified, some of them were identified in large number of applications (see section 5.3). Materials with no identified use were holmium, lutetium, scandium and thulium (Table 4).

Table 4. Materials less than 0.5 g or with no identified usage

Yttrium	Indium	Erbium	Ytterbium	Gadolinium	Europium
<0,5 g	<0,5 g	<0,5 g	<0,5 g	<0,5 g	<0,5 g
Rhodium	Holmium	Lutetium	Scandium	Thulium	
<0,5 g	No Usage Found	No Usage Found	No Usage Found	No Usage Found	

🟦 = REM 🟩 = PGM ☐ = Others

Since no usage of holmium, lutetium, scandium and thulium, were identified, they are excluded from the detailed analyses in section 5.3.

5.2 Factor analysis

For all the materials, factors believed to influence the quantities used were evaluated with two hypotheses:

- The quantity of potentially critical materials used is increased by *electrification*, *higher equipment level* and *size of the car.*
- The choice of catalytic exhaust treatment system influences the quantity and choice of potentially critical materials used.

The factors are evaluated according to the criteria found in section 2.1.1 and their impact on the material use is presented in Table 5. The factor was graded as *high*, *medium* or *low* if the mass was more than 50%, 50-10% or 10-1% higher in the HMM than in the CMH (electrification), in the CMH than in the CML (equipment level) or in the CLM than in the CML (size). For the choice of catalytic exhaust system, the comparison is instead made between the highest and lowest identified mass in any of the cars. If the factors are graded as *not verified,* it means that an increase could be identified but not definitely identified in parts directly related to electrification, equipment level or the size of the car. If the factor is graded as *no*, no increase greater than 1% could be identified. Although the impact of the factors studied is true for this specific study and the chosen criteria, the outcome might change with a change of car model, specification or manufacturer.

Table 5. Factors influencing the use of materials, criteria for evaluation are found in section 2.1.1

Material/Factor	**Electrification (HMM vs CMH)**	**Equipment Level (CMH vs CML)**	**Size of the Car (CLM vs CML)**	**Catalytic Exhaust Treatment System (All cars)**
Cerium	No	No	Not Verified	High
Cobalt*	Not Verified	Not Verified	Not Verified	No
Copper*	High	Medium	Not Verified	No
Dysprosium	High	High	Not Verified	No
Gallium	No	High	Not Verified	No
Gold*	No	Not Verified	No	No
Lanthanum	No	No	No	High
Lithium	High	High	No	No
Magnesium*	No	No	No	No
Manganese*	High	Not Verified	Not Verified	No
Molybdenum*	No	Not Verified	No	No

Neodymium	High	High	No	No
Niobium	Not Verified	Low	Not Verified	No
Palladium	Low	Low	Not Verified	Medium
Platinum	Low	Low	Not Verified	Medium
Praseodymium	No	High	Not Verified	No
Samarium	High	No	Not Verified	No
Silver*	High	Not Verified	Not Verified	No
Tantalum	No	High	Not Verified	No
Terbium	High	No	No	No
Yttrium	No	No	No	No
Indium	No	No	Not Verified	No
Erbium	No	No	No	No
Ytterbium	No	No	No	No
Gadolinium	No	No	No	No
Europium	No	No	No	No
Rhodium	No	No	No	No
Holmium	No usage found	No usage found	No usage found	No usage found
Lutetium	No usage found	No usage found	No usage found	No usage found
Scandium	No usage found	No usage found	No usage found	No usage found
Thulium	No usage found	No usage found	No usage found	No usage found

🟦 = REM 🟩 = PGM * = Only total mass analysis

Increased **electrification** was identified to considerably increase the use of copper, dysprosium, lithium, manganese, neodymium, samarium, silver and terbium. These materials were found in large quantities in parts unique for the hybrid, such as the main electrical motor and the main Li-ion battery. The impact on palladium platinum, samarium and tantalum was determined to be low since small mass increases could be found, mainly as a consequence of that the number of low concentration applications increased. For cobalt and niobium, no clear evidence of increased use was found since the increase in mass could not be identified to parts specific for the HMM. For cobalt, the main reason for this is that no detailed analysis was conducted and it should be noted that the battery is believed to contain more cobalt than identified because a large share of the battery’s mass was not reported at the time of this study. Hence, the use of cobalt is expected to increase with electrification but based on only the data available, this could not be proven.

Increased **equipment level** was identified to considerably increase the use of dysprosium, gallium, lithium, neodymium, praseodymium and tantalum. The largest share of the increased use of dysprosium, gallium, neodymium and praseodymium is found in the magnets, mainly in the audio system and in the electrical seat adjustment. Lithium is increased mainly as a consequence of the use of a larger Li-ion battery in the car key in the CMH than in the CML and tantalum mainly as a consequence of an increased number of PCB’s. The use of copper, palladium and platinum is increased by the general increase of electrical and electronic applications such as electrical wiring and PCB’s. Niobium is increased due to its metallurgical use in the structure of the seats with electrical adjustment. Since no detailed analysis was carried out for cobalt, gold, manganese, molybdenum and silver, the increased use could not be identified in parts directly related to the equipment level.

Increased **size of the car** could not be identified to increase the materials classified as *no* since their total mass were smaller in the CLM than in the CML. For the materials classified as *not verified* the mass in the CLM was larger than in the CML but no clear evidence that it was a consequence of the larger size of the car could be found. However, for materials with mainly metallurgical applications, e.g. manganese and niobium, there is reason to believe that the increased size typically could influence their use in e.g. the body structure and the chassis. Difference in the year of design is here believed to influence the mass of the materials more than the size. Also, since a larger car means that longer and maybe larger wires need to be used, the increased use of copper might be a consequence of this. For copper and several of the materials with metallurgical applications, no detailed analyses were carried out and hence, it was difficult to confirm if the increased use was a consequence of the larger size of the car. For the all the materials classified as *not verified*, the increased use could be consequences of factors such as year of design of the car, choice of supplier or choice of technology rather than the size of the car (see section 7).

The choice of **catalytic exhaust treatment system** was shown to have largest impact on the use of cerium and lanthanum. Since in the specific catalytic converters or particulate filters analyzed, the materials are only used one at the time and hence, the choice of catalytic converter and particulate filter also means a choice of using either cerium or lanthanum. Palladium and platinum are however used for catalytic exhaust treatment in all cars analyzed but the choice of catalytic converter and particulate filter still influence the total mass used. The variations in use of palladium and platinum are although smaller than the variations off cerium and lanthanum.

For the materials classified as *not verified*, it is believed that other factors, not analyzed in this study, are influencing the use. Furthermore, all the materials are analyzed by how the use is influenced by the four factors studied in this report. This means that the study does not focus on finding factors for all materials that influence the use, but rather on mapping all the materials and then analyzing how the use is influenced by the factors chosen for the hypotheses. Hence, some materials may not be influenced at all by these specific factors but are influenced by factors outside the scope of this study (see section 7).

5.3 Detailed analyses

This subchapter presents the detailed analyses of the four cars studied. To simplify for the reader, the presentation of the analyses follows the same structure for all the cars. In a single part, a material can have several applications. For example, if two different neodymium magnets are used in one part, neodymium has two applications in that part. Since the definition of a part can vary all the way from a complete gearbox to a single screw, *number of applications* is, instead of number of parts, presented in the tables. *Main vehicle subsystems* represent the subsystems where most applications and largest mass were identified. *Main general usage area* describes the main applications in more general terms, e.g. applications such as magnets and PCB's are in general terms described as electrical and electronic. For descriptions of all the subsystems of the cars, see Appendix II.

5.3.1 Detailed analysis: Conventional Midsize, Low-Specified (CML)

The conventional low-specified midsize car (CML) has an automatic gear box, a diesel engine and front wheel drive (FWD). This version of the car does not have any extra equipment except the standard equipment (see section 4.1). The number of unique parts where the materials were found was 482 out of a total of 1552 parts and the materials were found in 1755 applications within these parts. Table 6 presents the results of the material mapping process for the low-specified midsize conventional car.

Table 6. Results from the detailed analysis of the Conventional Midsize car, Low-Specified (CML). See introduction to section 5.3 for interpretation of the table.

Material	Mass [g]	No. of Applications	Main Applications	Main Vehicle Subsystems	Main General Usage Areas
Cerium	0.29	5	Elastomers, LED, Zinc Alloys	Engine Cooling & Air Induction, Exterior Lighting, Steering	Elastomers, Electrical & Electronics, Metallurgical
Dysprosium	0.83	7	Magnets	Climate, Interior & Instrument Panel	Electrical & Electronics
Erbium	0.18	1	LCD	Infotainment	Electrical & Electronics
Europium	< 0.01	2	LED	Exterior Lighting	Electrical & Electronics
Gadolinium	< 0.01	11	Aluminum Alloys, LED	Brake System, Exterior Lighting	Electrical & Electronics, Metallurgical
Gallium	0.08	29	Magnets, LED	Climate System, Driver Controls	Electrical & Electronics
Indium	0.15	107	Glass, PCB's	Infotainment, Restraints & Airbags	Electrical & Electronics, Glass
Lanthanum	5.22	3	Magnets, Particulate Filters	Engine System, Steering	Catalytic Reactions, Electrical & Electronics
Lithium	5.18	1000	Batteries, Lubricants, Screws	Security & Body Electronics, Transmission	Electrical & Electronics, Metallurgical
Neodymium	43.38	28	Magnets, PCB's	Climate System, Steering	Electrical & Electronics
Niobium	63.39	336	Nickel Alloys, Steel Alloys	Body Structure, Engine System, Seating	Metallurgical
Palladium	1.22	58	Catalytic Converters, Particulate Filters, PCB's	Engine System, Brake System	Catalytic Reactions, Electrical & Electronics
Platinum	5.48	74	Catalytic Converters, Particulate Filters, PCB's	Engine System, Infotainment	Catalytic Reactions, Electrical & Electronics
Praseodymium	0.81	4	Magnets	Climate System, Driver Controls	Electrical & Electronics
Rhodium	< 0.01	2	Electronic Wiring	Restraints & Air Bags	Electrical & Electronics
Samarium	0.43	2	Magnets	Engine System	Electrical & Electronics

Tantalum	5.83	72	PCB’s	Engine System, Infotainment	Electrical & Electronics
Terbium	< 0.01	1	Doping Agent	Special Equipment	Electrical & Electronics
Ytterbium	0.16	1	Ceramics	Climate System	Electrical & Electronics
Yttrium	0.22	12	Ceramics, LED	Engine System, Exterior Lighting, Transmission	Electrical & Electronics
Total	**132.84**	**1755**			

The largest mass of critical materials in the CML car is represented by niobium (63.39 g). The high niobium content is mostly due to the its use as an alloying agent in high-strength steel and nickel alloys used in *Body Structure*, *Engine System* and in structural components of the seats in the subsystem *Seating*. Niobium was also found in second most applications (336) but unlike most of the other materials in the study, no use of niobium was found in electrical or electronic applications. The second largest mass of critical materials is represented by neodymium (43.38 g) and the most common use is in high-strength neodymium magnets and PCB’s. The largest portion of the mass is distributed to magnets in the servo system in *Steering* but significant amounts were also found in PCB’s and magnets used in *Interior & Instrument Panel* and *Climate System*. The third largest mass is represented by tantalum which is almost exclusively used in small concentrations in PCB’s. The largest mass of tantalum in a single part was approximately 1 gram.

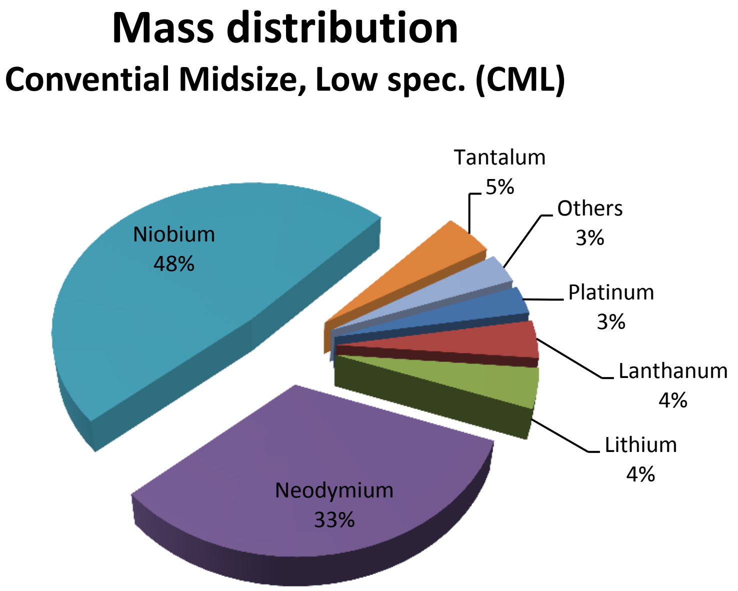

Figure 9. Mass distribution for materials in the Conventional Midsize, Low spec. (CML)

Three of the materials mapped were found to be used for the purpose of exhaust treatment in the CML; lanthanum, palladium and platinum. This is in line with the literature but cerium and rhodium, which also are commonly used for exhaust treatment (see Appendix I. Materials in this study), was not found to be used for that purpose in this model. However, and unexpectedly, cerium was found in small concentrations in elastomers. Palladium and platinum were also found to be used extensively in PCB's, although in small concentrations.

The materials with the largest number of applications were found to be lithium (1000), niobium (336) and indium (107). The large number of lithium applications is mostly due to that the material is used extensively as an alloying agent in mounting parts like screws and nuts. Larger concentrations of lithium could only be found in small lithium-ion batteries used in e.g. the remote car key. For indium, most of its use is electrical or electronic since it is mostly used in PCB's but minor use in glass could also be found. Similarly to lithium, no high concentrations of indium could be found.

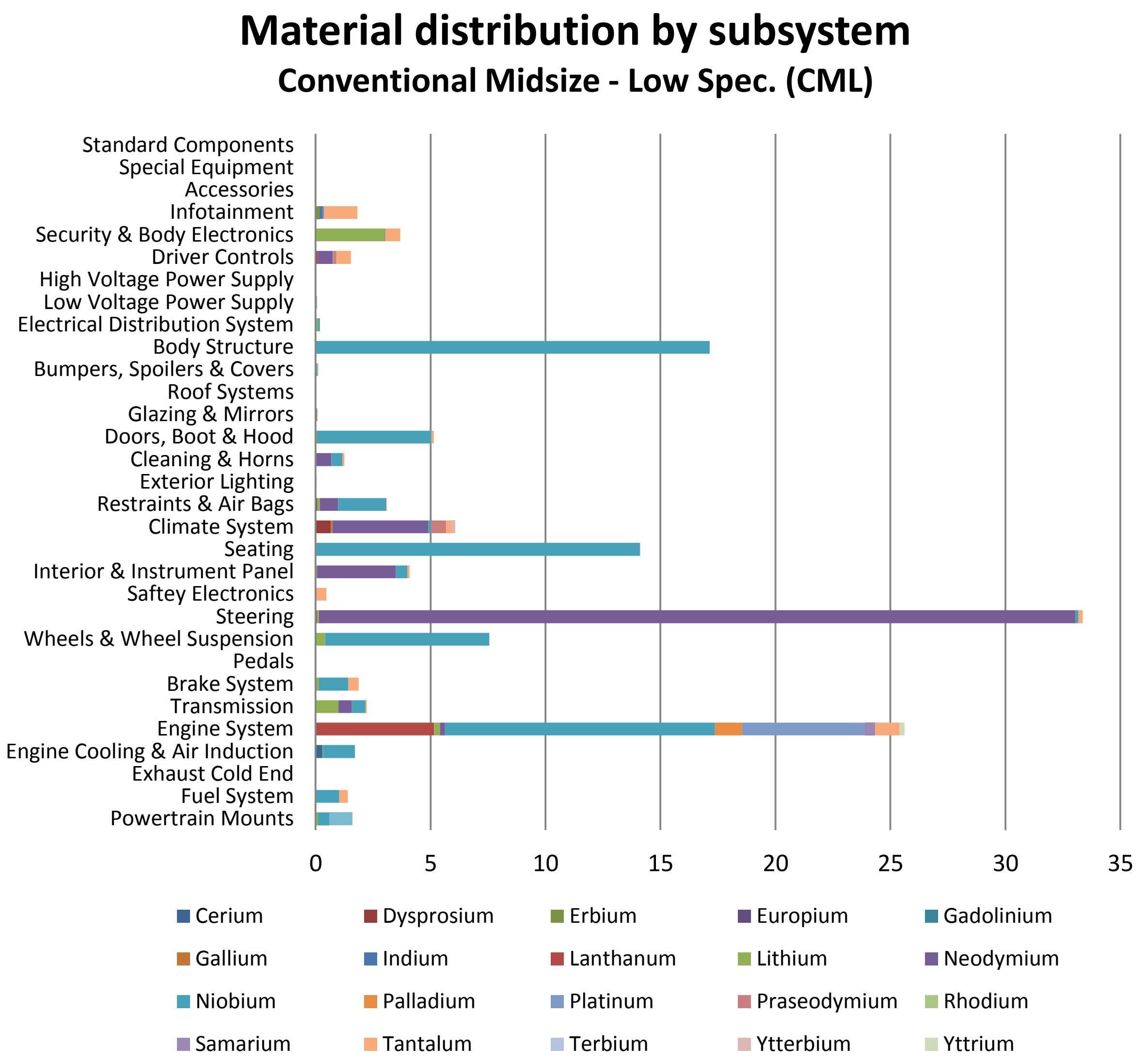

Figure 10. Material distribution by subsystem for the Conventional Midsize - Low Spec. (CML)
Y-Axis = Subsystem, X-Axis = Mass [g]

The largest mass of critical materials was located in the *Steering* subsystem of the CML. This is mainly explained by the steering systems' use of neodymium magnets. Other large portions of the materials were found in *Body Structure*, *Seating* and *Engine System*. This is mainly explained by the use of high-strength steels where niobium is used as an alloying agent. A large share of the subsystem *Engine System* is also represented by lanthanum, palladium and platinum, used for catalytic exhaust treatment. In Figure 11, the y-axis has been changed to represent elements instead of subsystems, which means that it shows the same information as Figure 10 but presented in a different manner.

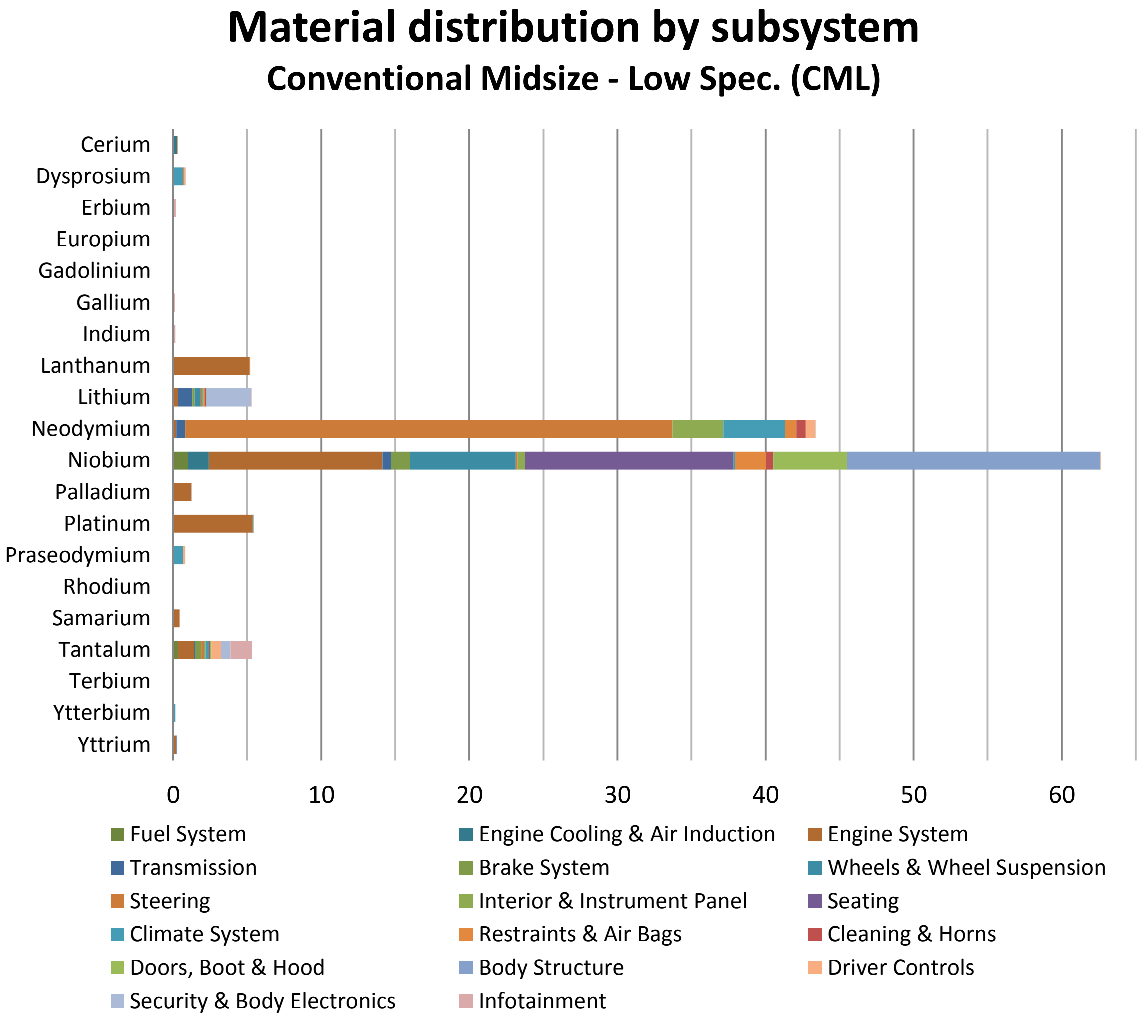

Figure 11. Material distribution by subsystem for the Conventional Midsize - Low Spec. (CML). Subsystems with less than 1 g of materials have been removed for illustrational purposes, Y-axis = element, X-axis = mass [g]

5.3.2 Detailed analysis: Conventional Midsize, High-Specified (CMH)

The conventional high-specified midsize car (CMH) has a diesel engine and an automatic gear box. It has the same engine used in the low-specified midsize car but with AWD instead of FWD. The car also has most of the optional equipment available in a modern Volvo car (see section 4.1). The materials analyzed were found in 2318 applications in 535 unique parts out of a total of 1660 parts. Table 7 presents the results of the material mapping of CMH.

Table 7. Results from the detailed analysis of the Conventional Midsize Car, High-Specified (CMH). See introduction to section 5.3 for interpretation of the table.

Material	Mass [g]	No. of Applications	Main Applications	Main Vehicle Subsystems	Main General Usage Areas
Cerium	11.83	7	Particulate Filters, LED, Zinc Alloys	Engine System, Exterior Lighting, Steering	Catalytic Reactions, Electrical & Electronics, Metallurgical
Dysprosium	27.14	21	Magnets	Infotainment, Seating, Steering	Electrical & Electronics
Erbium	0.18	1	LCD	Infotainment	Electrical & Electronics
Europium	< 0.01	3	LED	Exterior Lighting	Electrical & Electronics
Gadolinium	< 0.01	11	Aluminum Alloys, LED	Brake System, Exterior Lighting	Electrical & Electronics, Metallurgical
Gallium	0.56	47	Magnets, LED	Climate System, Seating	Electrical & Electronics
Indium	0.05	174	Glass, PCB’s	Infotainment, Restraints & Air Bags	Electrical & Electronics, Glass
Lanthanum	0.07	5	Ceramics, Magnets, Zinc Alloys	Infotainment, Seating, Steering	Electrical & Electronics, Metallurgical
Lithium	10.09	1105	Batteries, Lubricants, Screws	Infotainment, Security & Body Electronics, Transmission	Electrical & Electronics, Metallurgical
Neodymium	205.68	70	Magnets, PCB’s	Climate System, Infotainment, Seating, Steering	Electrical & Electronics
Niobium	81.42	380	Nickel Alloys, Steel Alloys	Body Structure, Engine System, Seating	Metallurgical
Palladium	1.54	227	Catalytic Converters, Particulate Filters, PCB’s	Engine System, Infotainment, Special Equipment	Catalytic Reactions, Electrical & Electronics
Platinum	8.08	106	Catalytic Converters, Particulate Filters, PCB’s	Engine System, Infotainment, Restraints& Air Bags	Catalytic Reactions, Electrical & Electronics
Praseodymium	5.55	13	Ceramics, Magnets	Climate System, Seating	Electrical & Electronics
Rhodium	< 0.01	2	Electronic Wiring	Restraints & Air Bags	Electrical & Electronics
Samarium	0.43	2	Magnets, PCB’s	Engine System	Electrical & Electronics

Tantalum	10.93	119	PCB’s	Engine System, Infotainment, Security & Body Electronics	Electrical & Electronics
Terbium	< 0.01	1	Doping Agent	Special Equipment	Electrical & Electronics
Ytterbium	0.16	1	Ceramics	Climate System	Electrical & Electronics
Yttrium	0.23	23	Ceramics, LED	Engine System, Exterior Lighting, Infotainment	Ceramics, Electrical & Electronics
Total	**363.94**	**2318**			

The largest mass of critical materials in the CMH car is represented by neodymium (205.68 g). The increased mass of neodymium compared to the CML is mostly due to the choice of speaker system. The CMH includes a high-performance speaker system which contains a substantial amount of high-strength neodymium magnets. Another notable change from the CML is that this version includes electrical adjustment of seats and hence, more neodymium magnets are found in the electrical motor adjusting the seats. Overall, the CMH contains substantially more electronic equipment than the CML and hence, more PCB’s and, in particular, more neodymium magnets. As a consequence, it also contains higher amounts of dysprosium (27.14 g) and praseodymium (5.55 g) used to adjust the properties of neodymium magnets.

The second largest mass of critical materials is represented by niobium (81.42 g) used in nickel and high-strength steel alloys. The largest portions of the mass can be found in the subsystem *Engine System* where metallurgical use in the exhaust treatment system contributes the most. The subsystems *Seating* and *Body Structure* also contain substantial amounts of niobium alloyed high-strength steel. Figure 12 presents the mass distribution of critical materials in the conventional high-specified midsize car.

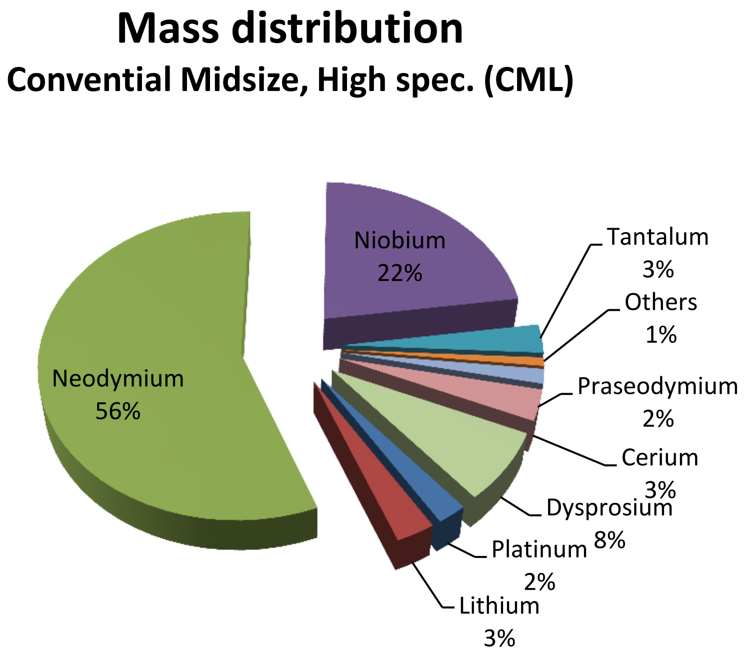

Figure 12. Mass distribution for materials in the Conventional Midsize, High spec. (CMH)

Tantalum is, as for the CML, used almost exclusively in small concentrations in PCB's in many different subsystems of the car. The largest mass was located in *Infotainment* subsystem. The main applications for platinum and palladium are catalytic exhaust treatment and PCB's. Cerium is also mainly used for the purpose of catalytic exhaust treatment, but no use of lanthanum or rhodium could be found for this purpose in this model.

The materials with the largest number of applications were found to be lithium (1105), niobium (380) and palladium (227). As for the CML, lithium is most commonly used for mounting purposes and the only higher concentrations of lithium are found in small lithium-ion batteries. The metallurgic use of niobium in this model is also similar to the use in the CML (see section 5.3.1). The large number of PCB applications for palladium can be traced to the large amount of electronic equipment in this model. Both lithium and palladium are most commonly found in small concentrations while niobium can be found in higher concentrations, mostly in alloying applications within the subsystem *Engine System*. With the exception of niobium, almost all the materials mapped were found to have electronic or electrical use, most commonly in applications such as PCB's and magnets.

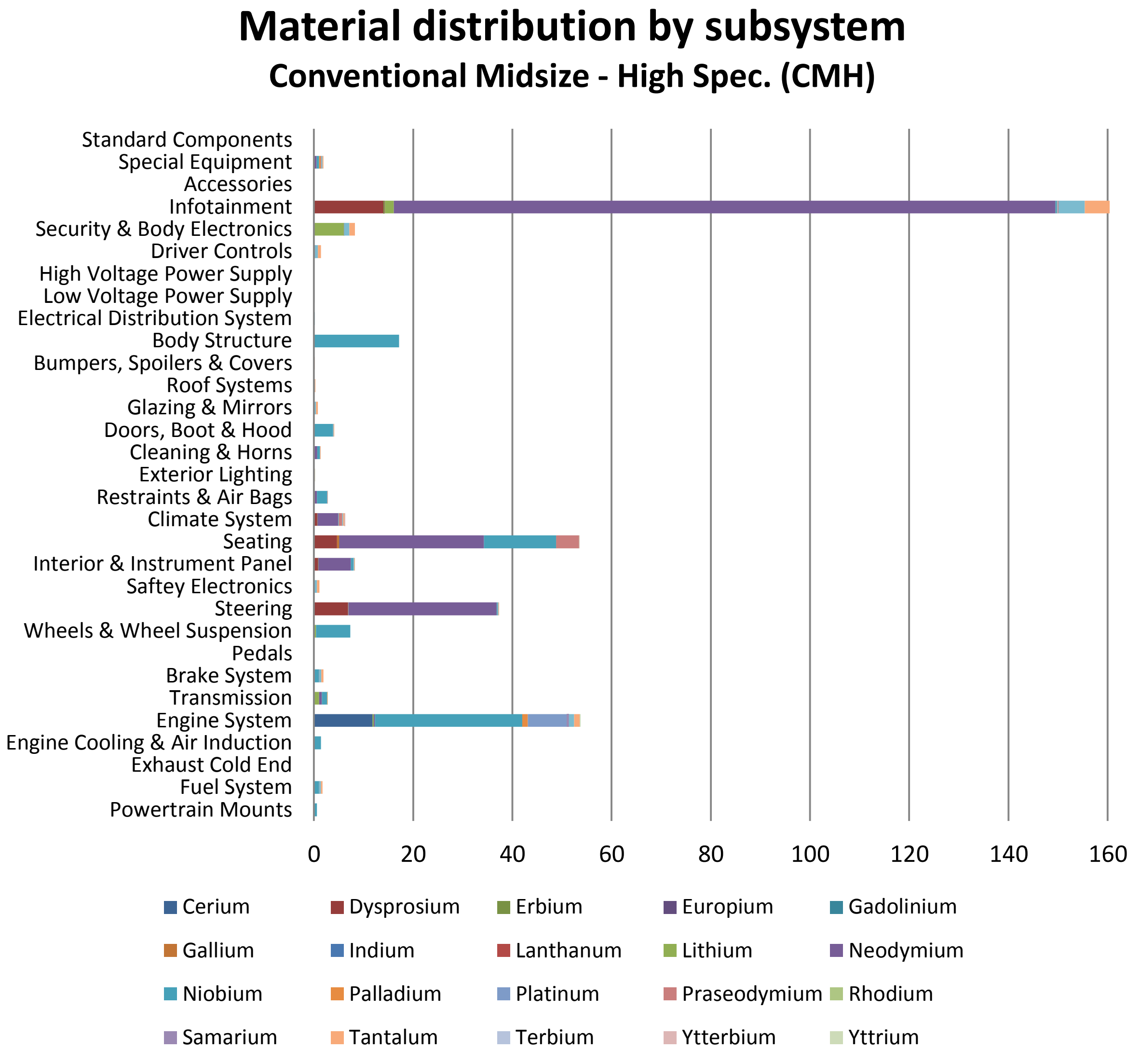

Figure 13. Material distribution by subsystem for the Conventional Midsize - High Spec. (CMH)
Y-axis = subsystem, X-axis = mass [g]

As Figure 13 shows, the *Infotainment* subsystem represents the single largest mass of critical materials. This is a direct result of the optional choice of a high-performing speaker system with neodymium magnets but also due to other optional electronic equipment like LCD displays and navigation system containing large amounts of PCB's. The choice of electronic seat adjustment also results in an increased amount of neodymium magnets within the *Seating* subsystem. The steering system of the car is similar to the steering system of the low-specified midsize car and hence, no substantial increase of critical materials could be traced to the subsystem *Steering*. From Figure 13, it is also possible to see that niobium is represented in considerable mass in a large number of subsystems with the subsystems *Engine System* and *Body Structure* being the most prominent. In Figure 14, the y-axis has been changed to represent elements instead of subsystems. It basically shows the same information as Figure 13 but presented in a different manner.

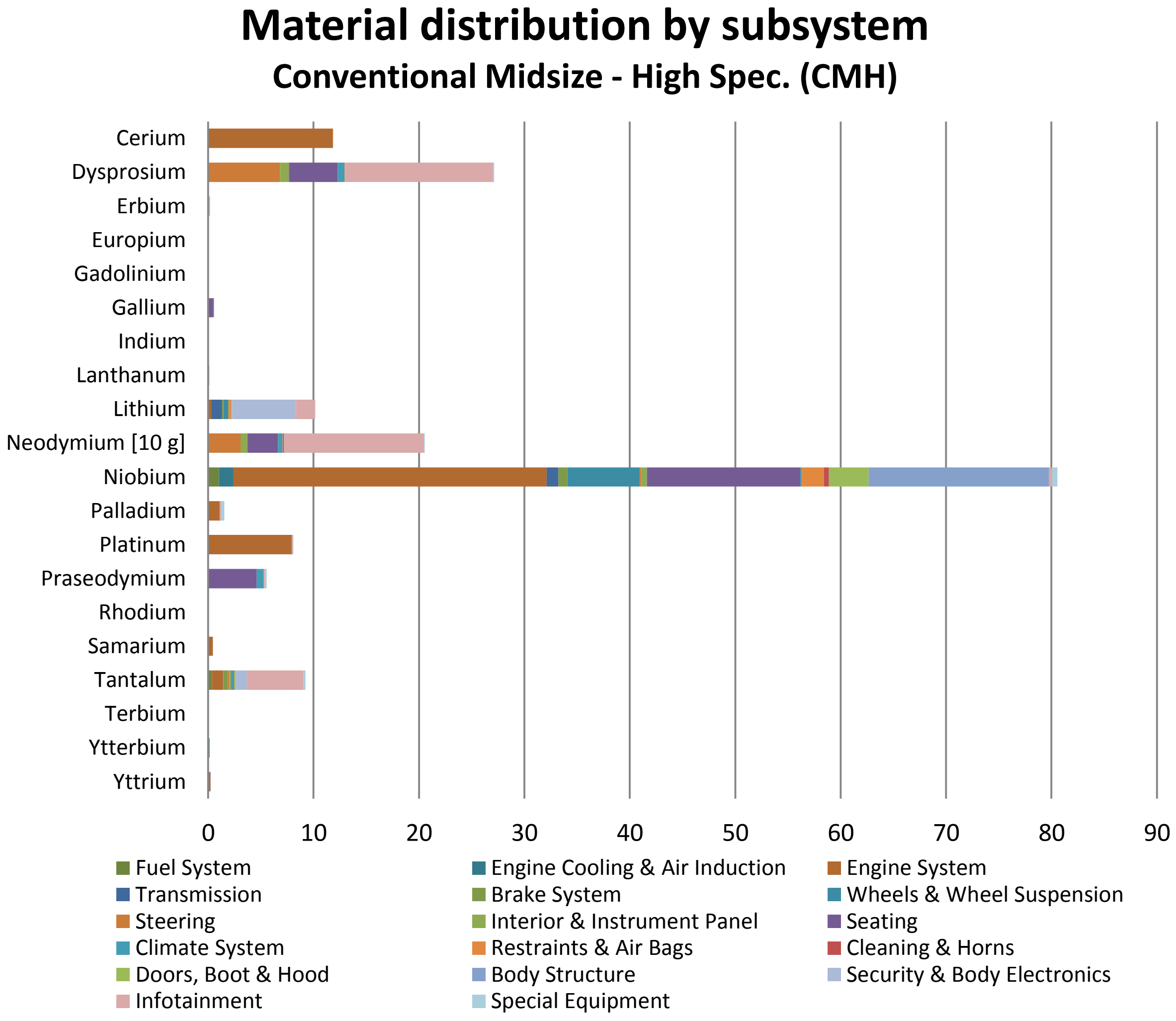

Figure 14. Material distribution by subsystem for the Conventional Midsize - High Spec. (CMH). Subsystems with less than 1 g of materials have been removed for illustrational purposes. Y-axis = element, X-axis = mass [g]

5.3.3 Detailed analysis: Hybrid Midsize, Medium-Specified (HMM)

The midsized hybrid car (HMM) studied has a powertrain with a combination of a diesel engine and an electric motor with Li-ion battery. It is specified with more equipment than the CML but less than the CMH (see section 4.1). The materials were found in 555 unique parts out of a total of 1821 parts and the materials had a total of 2379 applications within these parts. Table 8 shows the results of the material mapping process for the HMM.

Table 8. Results from the detailed analysis of the Hybrid Midsize Car, Medium-Specified (CMH). See introduction to section 5.3 for interpretation of the table.

Material	Mass [g]	No. of Applications	Main Applications	Main Vehicle Subsystems	Main General Usage Areas
Cerium	0.31	10	Elastomers, LED, Zinc Alloys	Engine Cooling & Air Induction, Exterior Lighting, Steering	Elastomers, Electrical & Electronics, Metallurgical
Dysprosium	129.66	20	Magnets	Climate System, High Voltage Power Supply, Transmission	Electrical & Electronics
Erbium	0.18	1	LCD	Infotainment	Electrical & Electronics
Europium	< 0.01	3	LED	Exterior Lighting, Transmission	Electrical & Electronics
Gadolinium	< 0.01	12	Aluminum Alloys, LED	Brake System, Exterior Lighting	Electrical & Electronics, Metallurgical
Gallium	0.57	43	Magnets, LED	Engine Cooling & Air Induction, Seating	Electrical & Electronics
Indium	0.08	182	PCB's	Driver Controls, High Voltage Power Supply, Security & Body Electronics	Electrical & Electronics
Lanthanum	6.68	5	Magnets, Particulate Filters, Zinc Alloys	Engine System, Fuel System	Catalytic Reactions, Electrical & Electronics, Metallurgical
Lithium	6256.55	1188	Batteries, Lubricants, Screws	High Voltage Power Supply, Infotainment, Security & Body Electronics	Electrical & Electronics, Metallurgical
Neodymium	531.88	74	Magnets, PCB's	Climate System, High Voltage Power Supply, Transmission	Electrical & Electronics
Niobium	109.14	401	Nickel Alloys, Steel Alloys	Body Structure, Exhaust Cold End, Seating	Metallurgical
Palladium	1.81	194	Catalytic Converters, Particulate Filters, PCB's	Bumpers, Spoilers & Covers, Engine System, High Voltage Power Supply	Catalytic Reactions, Electrical & Electronics
Platinum	5.51	92	Catalytic Converters, Particulate Filters, PCB's	Engine System, High Voltage Power Supply, Infotainment	Catalytic Reactions, Electrical & Electronics
Praseodymium	4.01	10	Ceramics, Magnets	Climate System, Seating	Ceramics, Electrical & Electronics

Rhodium	< 0.01	2	Electronic Wiring	Restraints & Air Bags	Electrical & Electronics
Samarium	1.40	4	Magnets, PCB’s	Brake System, Engine System, High Voltage Power Supply	Electrical & Electronics
Tantalum	10.83	109	PCB’s	High Voltage Power Supply, Infotainment, Security & Body Electronics	Electrical & Electronics
Terbium	19.86	3	Magnets	Transmission	Electrical & Electronics
Ytterbium	0.16	1	Ceramics	Climate System	Electrical & Electronics
Yttrium	0.23	25	Ceramics, LED	Engine System, Exterior Lighting	Ceramics, Electrical & Electronics
Total	**7078.86**	**2379**			

Of the materials studied, the largest masses in the HMM are represented by lithium (6255.55 g), neodymium (531.88 g) dysprosium (129.66 g) and niobium (109.14 g). The remarkable mass of lithium is explained by the use of Li-ion batteries, in particular the main battery used in the electric powertrain of the car. The large masses of neodymium and dysprosium are explained by a substantial amount of high-strength neodymium magnets used in the car, in particular in the main electric motor and the alternator. A large part of the mass of terbium (19.86 g) can also be assigned to these magnets. The largest concentrations of niobium are found in high-strength steel alloys in the subsystems *Exhaust Cold End* and *Body Structure*, similar to the use in CML and CMH but with additional mass found in alloying applications in the exhaust system. Figure 15 shows the mass distribution of the materials studied.

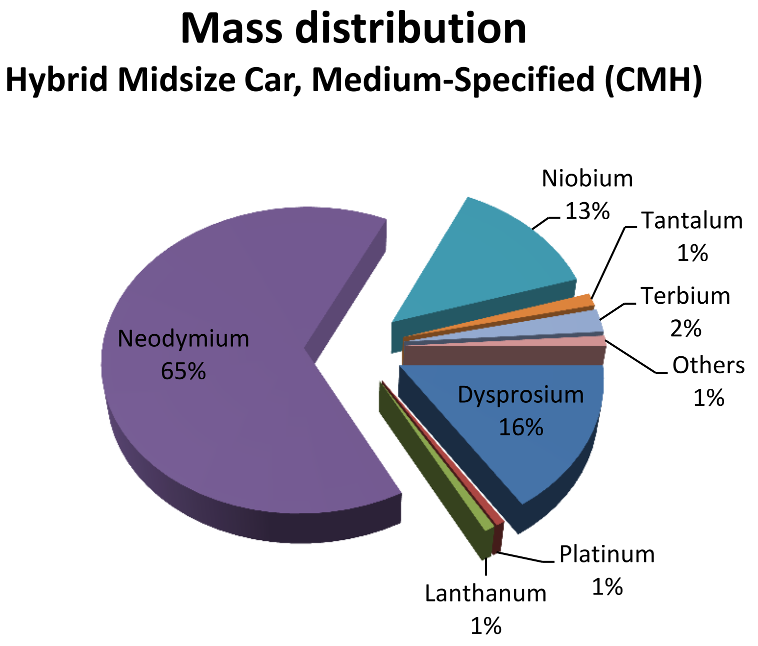

Figure 15. Mass distribution for materials in the Hybrid Midsize car, Medium spec. (CMH)
Lithium is excluded for illustrational purposes

As Table 8 shows, lithium has the most applications (1188). This is mostly due to its use as an alloying agent in mounting parts such as screws and nuts. The material with the second most applications is niobium (401). As with lithium, niobium is used in alloys, in particular in high-strength steel and in nickel alloys. Other materials with relatively large number of applications are indium (182), palladium (194), tantalum (109) and platinum (92).This is mainly due to their electronic and electrical use, mainly in applications such as PCB's.

In the HMM, lanthanum, palladium and platinum were all used in catalytic applications. Unlike in the CMH or the CLM, cerium had no catalytic applications. However, as in the CMH, cerium was found in elastomers. Figure 16 shows how the materials are distributed over the different subsystem of the car.

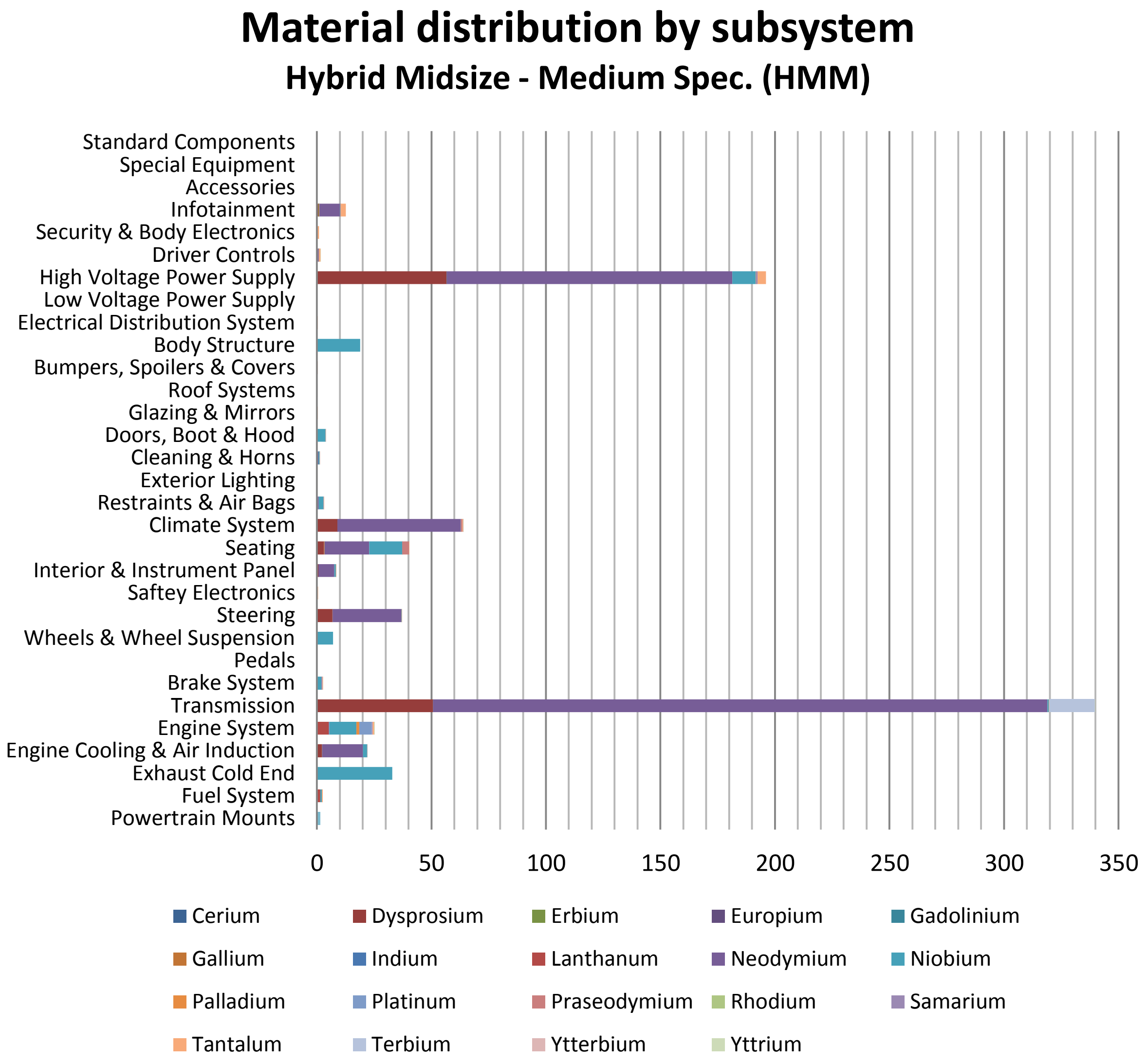

Figure 16. Material distribution by subsystem for the Hybrid Midsize - Medium Spec. (HMM) Lithium (6257 g) is excluded for illustrational purposes. Y-axis = subsystem, X-axis = mass [g]

With lithium excluded, the subsystem that represents the largest mass of materials is *Transmission* and it is mainly explained by the electric motor with considerable amount of high-strength neodymium magnets, containing neodymium, dysprosium and terbium. Second largest mass is found in the *High Voltage Power Supply* subsystem, where among others, the alternator, containing neodymium magnets, is found. This subsystem also contains the large Li-ion battery and if lithium would be included, this subsystem would instead represent the single largest mass of materials (almost 6.5 kg). Large or several high-strength neodymium magnets are also found in the *Climate System*, *Seating*, *Steering* and *Engine Cooling & Air Induction* subsystems, which explains that reasonable large masses are located in these subsystems. Niobium adds a considerable mass to several subsystems, in particular the subsystem with need for high-strength steel, i.e. *Body Structure* and *Exhaust Cold End*. In Figure 17, the y-axis has been changed to represent elements instead of subsystems. It basically shows the same information as Figure 16 but presented in a different manner.

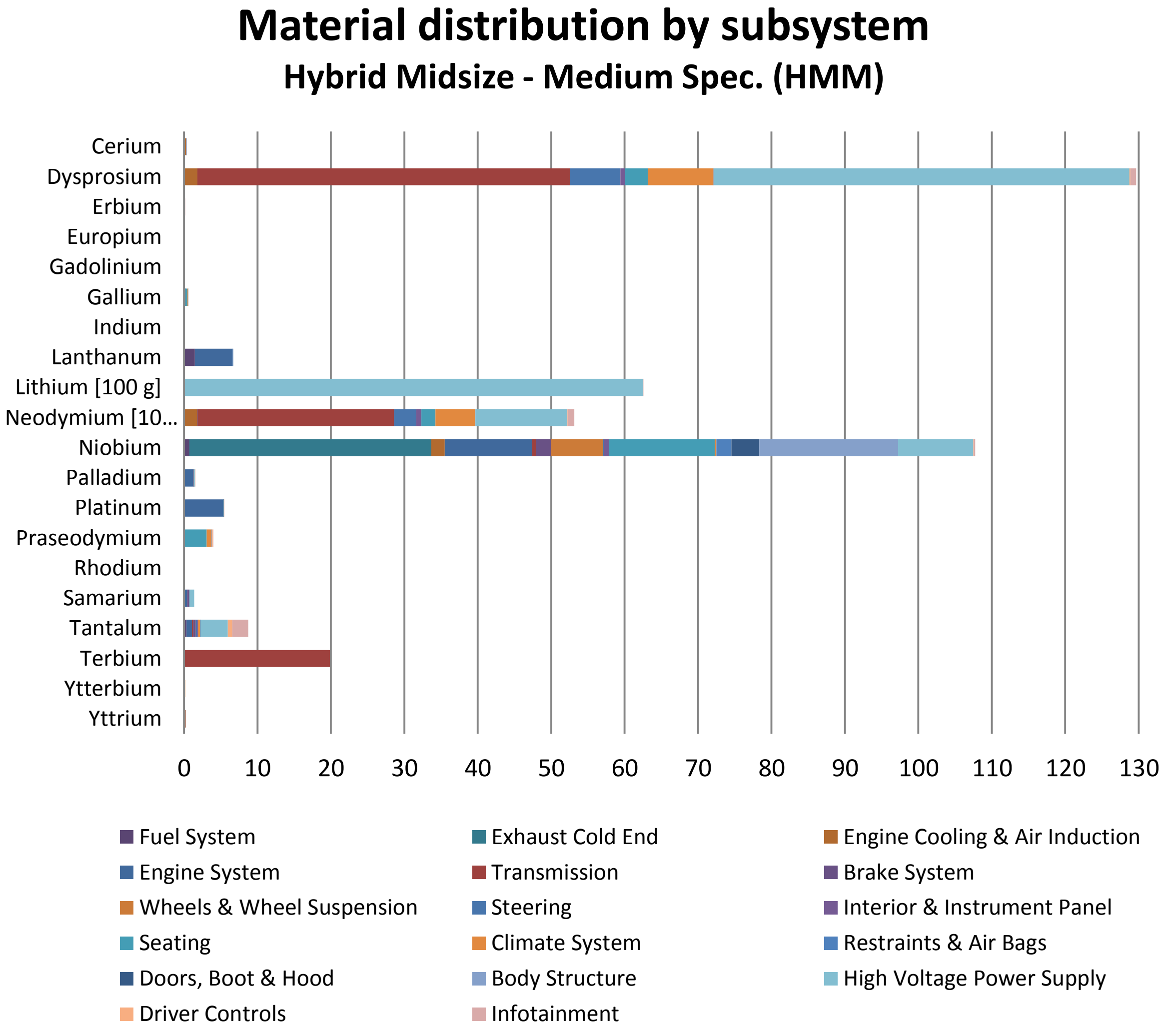

Figure 17. Material distribution by subsystem for the Hybrid Midsize, Medium Spec. (HMM), Subsystems with less than 1 g of materials have been removed for illustrational purposes, Y-axis = element, X-axis = mass [g]

5.3.4 Detailed analysis: Conventional Large, Medium-Specified (CLM)

The large conventional medium specified car (CLM) has an automatic gearbox, a diesel engine and FWD. It is specified with more equipment than the CML but less than the CMH and equal to the HMM. This car was designed several years earlier than for the others (see section 4.1). The materials were found in 425 unique parts out of total 1668 and had a total of 1762 applications within these parts. Table 9 presents the result of the material mapping process for the large conventional medium specified car.

Table 9. Results from the detail analysis of the Conventional Large Car, Medium-Specified (CLM). See introduction to 5.3 for interpretation of the table.

Material	Mass [g]	No. of Applications	Main Applications	Main Vehicle Subsystems	Main General Usage Areas
Cerium	12.91	4	Particulate Filters, Glass, PCB's	Engine System, Exterior Lighting	Catalytic Reactions, Electrical & Electronics, Glass
Dysprosium	1.96	9	Magnets	Climate System, Infotainment, Safety Electronics	Electrical & Electronics
Erbium	0	0	No Usage Found	No Usage Found	No Usage Found
Europium	< 0.01	1	Doping Agent in Ceramics	Climate System	Ceramics
Gadolinium	< 0.01	8	Aluminum Alloys, LED	Brake System, Driver Controls	Electrical & Electronics, Metallurgical
Gallium	0.42	21	Aluminum Alloys, Magnets LED	Exterior Lighting, Seating	Electrical & Electronics, Metallurgical
Indium	0.38	82	PCB's	Exterior Lighting	Electrical & Electronics
Lanthanum	0	0	No Usage Found	No Usage Found	No Usage Found
Lithium	1.36	873	Batteries, Lubricants, Screws	Engine System, Powertrain Mounts, Wheels & Wheel Suspension	Electrical & Electronics, Metallurgical
Neodymium	27.60	26	Magnets, PCB's	Climate System, Infotainment, Safety Electronics	Electrical & Electronics
Niobium	89.81	426	Nickel Alloys, Steel Alloys	Engine System, Restraints & Air Bags, Seating	Metallurgical
Palladium	1.24	89	Catalytic Converters, Particulate Filters, PCB's	Engine System, Special Equipment, Interior & Instrument Panel	Catalytic Reactions, Electrical & Electronics
Platinum	7.85	69	Catalytic Converters, Particulate Filters, PCB's	Engine System, Infotainment, Security & Body Electronics	Catalytic Reactions, Electrical & Electronics
Praseodymium	2.47	6	Magnets	Climate System, Safety Electronics	Electrical & Electronics
Rhodium	< 0.01	2	PCB's	Brake System, Engine System	Electrical & Electronics

Samarium	0.73	2	Magnets, PCB’s	Engine System, Seating	Electrical & Electronics
Tantalum	6.99	60	Nickel Alloys, PCB’s	Exhaust Cold End, Infotainment, Security & Body Electronics	Electrical & Electronics, Metallurgical
Terbium	0	0	No Usage Found	No Usage Found	No Usage Found
Ytterbium	0	0	No Usage Found	No Usage Found	No Usage Found
Yttrium	0.02	15	Ceramics, LED, Nickel Alloys	Engine System, Exterior Lighting	Ceramics, Electrical & Electronics, Metallurgical
Total	**153.74**	**1762**			

The largest mass of the materials studied is represented by niobium (89.81g), mainly used as high-strength steel and nickel alloys in *Seating* and *Engine System*. The second largest mass is represented by neodymium (27.6 g), mainly used in high-strength neodymium magnets in electric motors and infotainment applications such as the speaker system. The third and fourth largest masses are represented by cerium (12.91 g) and platinum (7.85 g) with the largest concentrated masses located in catalytic applications within the catalytic converter and the particulate filter. Figure 18 shows the mass distribution for materials found in the CLM.

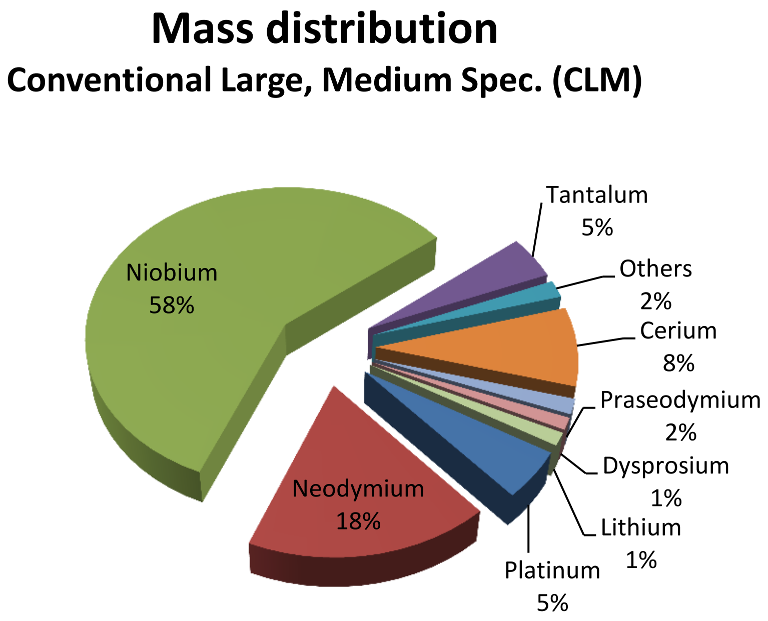

Figure 18. Mass distribution for materials in the Conventional Large, Medium spec. (CLM)

As for the three other studied objects (see e.g. section 5.3.2), lithium has the largest amount of applications (928) and is mainly used in mounting parts and batteries. Niobium was found in second most applications (426) and palladium in third most (89). The latter was mainly found in small concentrations in PCB’s, even though the largest single portion of mass is located in catalytic the catalytic converter. Materials with no usage were erbium, lanthanum, terbium and ytterbium. Figure 19 shows how the materials are distributed over the subsystems of the car.

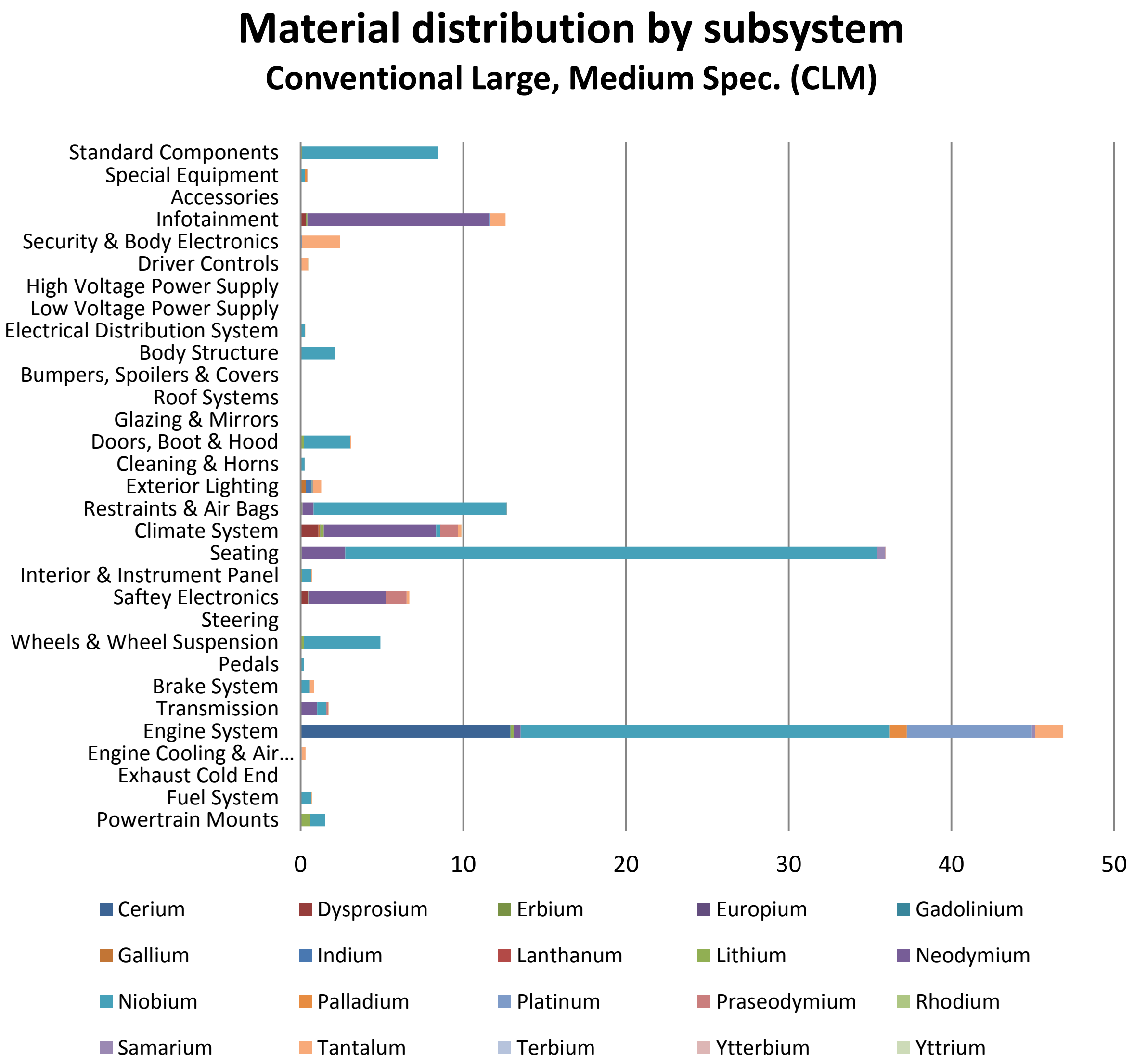

Figure 19. Material distribution by subsystem for the Conventional Large, Medium Spec. (CLM)
Y-axis = subsystem, X-axis = mass [g]

The subsystem representing the largest mass of the materials studied is *Engine System*. The largest shares of the subsystem are represented by niobium, cerium, platinum and, to a limited extent, palladium and tantalum. Second largest mass is found in *Seating* with niobium in the frames of the seats contributing to the largest mass. Also, neodymium magnets used in the electric motors for the purpose of electronic seat adjustment contributes to a small share. Other subsystems with relatively large masses of niobium used in alloys are *Standard Components*, *Restraints & Air Bags* and *Wheels and Wheel Suspension*. Compared to the other studied objects, only small concentrations of mass could be found in *Body Structure*. Largest masses in subsystems containing more electronic and electrical applications, such as *Infotainment*, *Security & Body Electronics*, *Climate System* and *Safety Electronics* are mainly represented by neodymium, tantalum, praseodymium and dysprosium. In Figure 20, the y-axis has been changed to represent elements instead of subsystems. It basically shows the same information as Figure 19 but presented in a different manner.

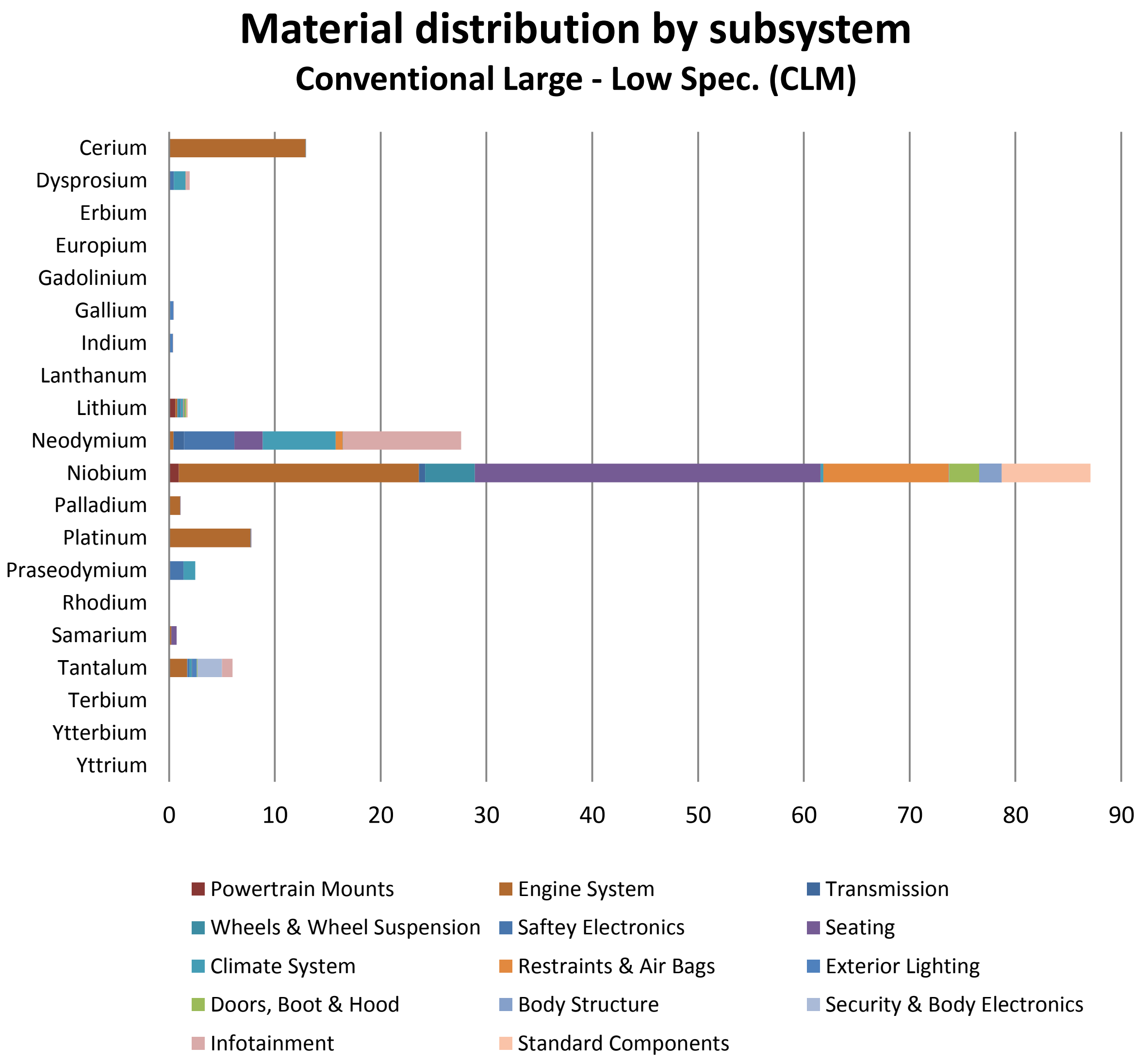

Figure 20. Material distribution by subsystem for the Conventional Large, Medium Spec. (CLM), Subsystems with less than 1 g of materials have been removed for illustrational purposes, Y-axis = element, X-axis = mass [g]

6. Evaluation of IMDS as a tool for mapping critical materials

One of the research questions in this study is: What are the major pros and cons of the IMDS as a tool for this kind of analysis? This question will be answered in this section and shortly in the conclusions.

The IMDS provides vast amounts of detailed information which would be considerably more time consuming to obtain without the system. Also, the level of details available for the user would maybe be almost impossible to obtain manually. However, although the system simplifies the data collection and provides detailed information, the work is still time consuming and even more so if the datasheets searched for have not been reported. A large share of the time spent on data collection was spent on exhorting suppliers and the persons responsible for a specific part to either report the missing data sheet or to state an equivalent and reported part. The following sections of this chapter contain identified pros and cons of the IMDS. This section also evaluates the computer software IPCA, used to access the data in the IMDS.

Pros

The main advantage of the IMDS is that it contains vast quantities of detailed data that is easily accessible for an IMDS user. The data is, at VCC, accessed through the computer software IPCA which provides a variety of search alternatives such as searching by CAS-number, the article number of a part or the name of a part. The search can also be narrowed down by e.g. telling IPCA to only show parts reported after a certain date. This was shown to be helpful in order to narrow down the number of hits and hence, decrease the time needed for the search itself and the interpretation of the search results. Although IPCA provides an easily understandable interphase and access to the information in the IMDS, there are some problems with the software (see below).

The level of detail of the data available in IMDS is high and provides information for every step from the relevant part itself down to the smallest substance (see section 2.2). Mapping material content at the level of detail in this study would probably be impossible without a system like IMDS. In addition to the material, substance and component composition of the part, the user also gets important and useful information about e.g. name of supplier and contact information of the supplier.

Although the following section presents several cons for using the IMDS for a material mapping such as the one performed in this study, the vast amount of detailed data available in the IMDS is such a huge pro in itself that it singly outweighs all the cons, i.e. the cons are small in comparison to the pros.

Cons

The main con with the IMDS is that it is common that suppliers do not report data sheets in time, e.g. before production start or any other deadline. In some cases, data sheets do not become reported at all. The most time consuming work when using the IMDS for this kind of study is to exhort reporting of these non-reported data sheets. In the short term, suppliers are not punished for delaying the data sheets, although VCC might choose another supplier if a specific supplier continuously miss deadlines and report incorrectly.

The number of possible ways of reporting, at the substance level, makes in difficult and time consuming to map materials as done in this study. As it is possible for the supplier to sometimes report substances as e.g. “confidential substances”, “misc. not to declare” or as substance groups such as “REM”, all these posts need to be evaluated separately. Since they do not automatically show up as a match in a search for a material or CAS-number, although they might actually contain the material searched for, they add to the margin of error of the material mapping process. To be able to know the actual substance or substances contained within these posts, the responsible persons or suppliers need to be contacted. This proved to be time consuming and the actual content was seldom known by the responsible person at VCC or the first-tier supplier. This meant that the request had to be passed on through the supply chain until it reached the relevant supplier. In many of the cases, this was considered to be too time consuming.

The information in the IMDS is based on the supplier’s self-declaration and consequently based on trust between the car manufacturer and the supplier. Few controls of the material content of a part is made and the only standardized control is made on each parts total mass. This means that it is possible for the suppliers to report incorrectly, either on purpose to hide information or by mistake.

The computer software IPCA, used to access the IMDS was in many cases delaying the work. The most time consuming error in IPCA was a software bug that meant the initial CAS-searches performed failed, often after several hours. This meant that all materials’ CAS-numbers had to be split up and sometimes searched for one by one and e.g. year by year. When the problem finally was solved, the searches instead required substantially longer time and it was not uncommon that they went on for 24 hours. The main con with IPCA was however that the system could not handle large enough data amounts. Hence, the more common materials of the study, e.g. copper, could not be analyzed in details since it would have meant numerous system failures to perform searches for them. This was the reason for why 7 materials only were analyzed in terms of total mass.

It should be noted that a prerequisite for IMDS is that there are restrictions on how data can be used. The data can only be used for environmental and health issues or to show governmental organs that VCC is following legislations. Data from IMDS cannot be used for price negotiations with suppliers and hence, only certain people at VCC can access the data and they are not allowed to spread the data to other departments within VCC, such as e.g. the department of purchasing. As a consequence, the names of the studied cars are anonymous and the results in this study are aggregated in order to avoid that the data are used for the wrong purposes.

7. Discussion

If a certain part had no reported data sheet and was believed to not contain any of the materials studied, the part was excluded from further analysis. This screening was done in close consultation with the VCC supervisor to ensure that no parts that were expected to contain any of the studied materials were excluded. The goal of the screening was to be as time efficient as possible within the time available for data collection, i.e. making sure that time was not wasted on getting a part reported and later find out that it in fact did in not contain any interesting material. It is however believed that this has no or only limited impact on the overall results. Furthermore, the number of parts excluded compared to the total number of parts analyzed is small. The main materials that believed to be affected by this in any degree are niobium and the seven materials for which no detailed analysis was carried out. This is since most of them have mainly metallurgical applications and hence, can be found in many different parts although you might not expect them to.

This study does not consider the degree of criticality of a material or how critical one material is in relation to another. The identified masses do not tell which material is most critical, e.g. 1 g of gold cannot be compared to 1 g of copper. One way of simplifying the comparison of criticality is to add a rough cost estimation of the materials found. This is since the cost of a material often roughly reflects how critical it is. Figure 21 shows the material costs per material and studied object and the price used for the estimation is found in Table 3. It should however be mentioned that the materials are not often bought on a open market but rather through long contracts with fixed prices and therefore, the absolute values do not tell much. The idea with the figure is only instead to show the relation between the materials and relate the masses identified to something that is maybe easier to grasp for the reader. Note that materials with identified masses less than 0.01 g and materials with no available price information are excluded.

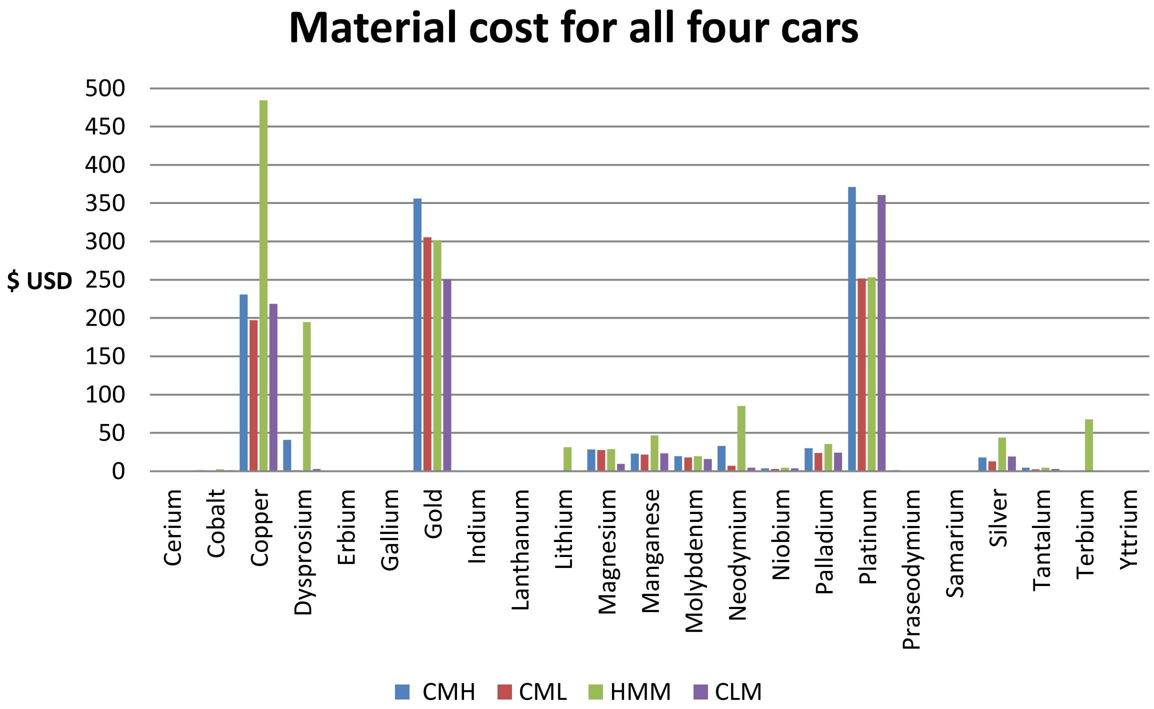

Figure 21. Material cost for materials with identified use over 0.01 g and available price information (see Table 3)

The degree of criticality of a material is influenced by the availability of the material and as a consequence of varying availability, material prices are often greatly fluctuating. Dysprosium can be used as an example of this. The spot price of dysprosium was in the end of 2003 roughly 30 $/kg (Alonso, Field, Roth, & Kirchain, 2011) and the price information from 2012 used in this study states a price of 1500 $/kg (Table 3), i.e. the dysprosium price has increased with approximately 5,000 % in 8-9 years. Since dysprosium is commonly classified as critical in the reports studied in this study, the correlation between price and criticality seems strong in this particular case. It should be noted that since the materials are used in greatly varying masses, the total price of a material (figure 21) should be interpreted carefully in terms of criticality.

To enable comparison between the different car models, the total material cost per car was also roughly calculated (Figure 22).

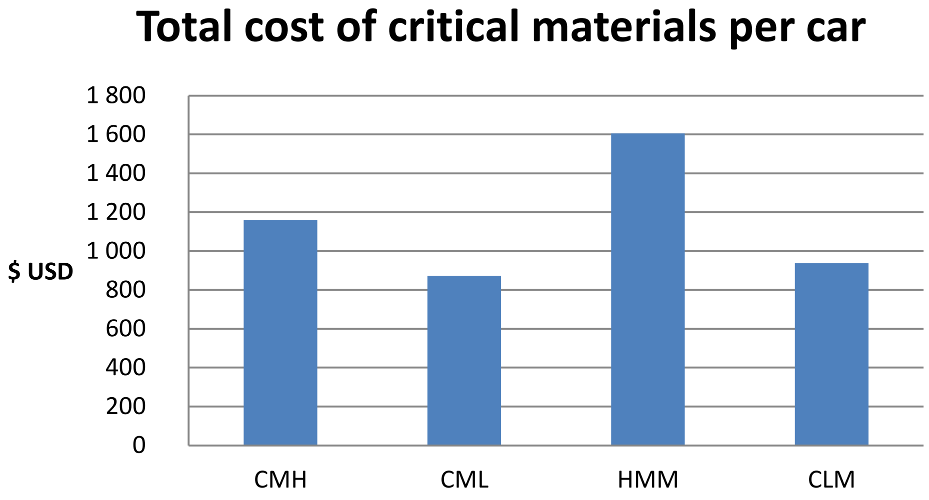

Figure 22. Total cost of materials per car

The material managing strategies that VCC should use depend on how critical a particular material is for VCC. This study can be used as background information to enable that environmental strategy decisions are focused on materials that are both potentially critical and in fact are currently used, i.e. critical for VCC. As shown in section 3.3, there are a large number of strategies that can be implemented but there is no single strategy that easily can be applied for all materials or all cars. For example, implementing a strategy to recover REM’s from EoL parts, as Honda is doing, might be the right way in the case of hybrid electric cars while substituting the REM’s might be the right way for conventional cars.

In this study, four factors believed to influence the use of potentially critical materials have been analyzed. However, there are several other factors that might influence the use as well, e.g. year of design, regulations, choice of supplier and intended market. In this study, the CLM has a considerably earlier year of design than the midsize cars studied. This is believed to influence the use of the studied materials although no analysis was carried for this factor. Some of the materials and technologies used in the CLM are no longer used in the other three cars and it is reasonable to believe that the CLM would have had the same technologies and materials choices as the other if it had had the same year of design. As a consequence, it is expected that the use of some of the materials studied would increase, e.g. the car might use high-strength neodymium magnets instead of ferrite magnets and more light-weight and high-strength alloys. The technical specification also changes with the market the cars are intended for since the demand differs between the markets. Also, the markets are also often regulated in different ways. For example, the emission regulations in place are not the same for all countries and hence, it is reasonable to expect that the regulated emission level in turn influence the use of catalytic materials in catalytic converters and particulate filters. It is evident that more than four factors influence the use of potentially critical materials but it is outside the scope of this study to further analyze this.

The choice of diesel engines in all the cars was made to simplify comparison between the cars and to be able to analyze the particulate filters only present in diesel cars. The particulate filter was from the literature study believed to contain several interesting materials. In further works it would also be interesting to analyze cars with petrol engines, although factors such as equipment level is expected to be unaffected by the choice of engine.

In the literature study, the potential uses of the materials were identified from the studies referred to in the literature section. Another report that was used to identify potential use and possible magnitude of masses of REM's to be found was the study by Alonso et al. (2012). Although the study is not referred to in terms of potential use and the study does not have any real car to base the data on, the study guided in pointing out certain parts in which to expect certain magnitudes of masses of REM's. The study helped to e.g. identify that the CMH's car list did not initially contain any speakers at all since the matching did not result in any substantial masses of neodymium or dysprosium in the infotainment subsystem. When the error had been corrected for, i.e. the initially missing speakers and other equipment had been added, neodymium and dysprosium were found in substantial masses. Although the study is based on data from a different market, no actual car and another methodology, the study is one of the first of this kind and was shown to be of great help for general knowledge of the use of REM's in passenger cars.

8. Conclusions

The conclusions answers the four research questions created from the purpose.

1. **What type of parts contains potentially critical materials in a passenger car?**

The largest mass and number of applications of the materials studied were found in electrical and electronic, metallurgical and catalytic applications. For materials with electrical and electronic applications, the largest masses and largest number of applications were identified in high-strength magnets used in electrical motors and audio systems, PCB's, batteries and in electronic wiring. For materials with metallurgical applications, the largest masses and largest number of applications were identified in parts containing alloys of steel, aluminum, nickel and zinc. These parts were mainly found in areas with high-strength or heat resistance requirements. Materials with catalytic properties are found in catalytic converters and particulate filters.

2. **In what quantities are potentially critical materials used in passenger cars and how does the use differ between car models and specifications?**

The materials studied are most extensively used in the medium specified midsize hybrid (HMM), mainly as consequence of the electrified powertrain. Next to the HMM is the high-specified conventional midsize car (CMH) with the main use in electronic equipment such as high-performance audio system and electronic seat adjustment. The low-specified conventional midsize car (CML) and the low-specified conventional large car (CLM) were identified to use considerably less of the materials studied. This was identified to be mainly a consequence of the relatively low specification of equipment level and no use of electrified powertrain. The main use for CML and CLM were identified in metallurgical applications.

For the 24 materials analyzed in detail, the quantities found in the studied objects are:

Table 10. Total quantities for the 24 materials analyzed in detail for all four cars studied

Model & Specification	Total mass	Applications	Unique parts
Conventional Midsize Car Low-Specified (CML)	132.84 g	1755	482
Conventional Midsize Car High-Specified (CMH)	363.94 g	2318	535
Conventional Large Car Low-Specified (CLM)	153.74 g	1762	425
Hybrid Midsize Car Medium-Specified (HMM)	822.31 g (6257 g Li excluded)	2379	555

For all the 31 materials analyzed, the total masses found in the studied objects are:

Table 11. Total quantities for the 31 materials analyzed for all four cars studied

Model & Specification	Total mass
Conventional Midsize Car Low-Specified (CML)	41259.7 g
Conventional Midsize Car High-Specified (CMH)	46589.5 g
Conventional Large Car Low-Specified (CLM)	38663.3 g
Hybrid Midsize Car Medium-Specified (HMM)	92900.4 g

3. Which factors of the car design influence the quantities of potentially critical materials used?

In order to answer this research question, the two hypotheses created will be answered. The first hypothesis is:

- The quantity of potentially critical materials used is increased by *electrification*, *higher equipment level* and *size of the car.*

Electrification: Yes, electrification increases the use of potentially critical materials. Since most of the materials studied are used in the electrical and electronic technologies used in the electrical powertrain of the HMM, electrification is the most influencing factor. Increased electrification mainly increases the use of neodymium, dysprosium, copper, samarium, silver, terbium, manganese and lithium but also palladium and platinum.

Higher Equipment level: Yes, higher equipment level increases the use of potentially critical materials. The use of the studied materials increased significantly by adding optional equipment such as high-performance sound system and electric seat adjustment. Increased equipment level was shown to be the second most influencing factor and increased the use of mainly neodymium, dysprosium, copper, gallium, lithium, praseodymium and tantalum but also niobium, palladium and platinum.

Size of the car: No, for the majority of the materials studied, the size of the car did not influence the use. No increased use could be identified in parts related to the size of the CLM compared to the other midsize cars studied. The use of materials used as alloys in the body structure was initially expected to increase as a consequence of the larger size but no evidence of this could be found. However, a possible explanation for why no evidence was found, was that the CLM was designed several years before the other cars

The second hypothesis is:

- The choice of catalytic exhaust treatment system influences the quantity and choice of potentially critical materials used.

Yes, the choice of catalytic treatment system influences the use of cerium, lanthanum, palladium and platinum but not rhodium which is commonly used in catalytic applications. The influence is largest for cerium and lanthanum but the use of palladium and platinum is also influenced. Rhodium was not used in any of the cars studied and hence, nu influence could be identified for the catalytic treatment systems studied in this report.

The study also found other possible factors that might influence the use of the materials studied, e.g. year of design, regulations, choice of supplier and intended market (see section 7). It is however outside the scope of this study to further analyze these.

4. **What are the major pros and cons with IMDS as a tool for this kind of analysis?**

This research question is answered shortly in the bullets lists below and more extensively in section 6. It should be noted that even though more cons are stated, the pros greatly overweighs the cons.

Pros:

- The vast amount of data
- The detail of the data

Cons:

- Insufficient reporting from suppliers
- Too many ways of reporting at the substance level and the possibility to report substances in ways that hide the actual substance
- Few controls of the details in reported data sheets are performed
- Limitations in IPCA in terms of the amount of data it can extract from IMDS during one search

9. Further research

The original idea behind this thesis was to identify the use of potentially critical materials in order for VCC to develop recycling strategies. Hence, VCC will use the information in this thesis to be able to communicate and develop recycling strategies in cooperation with the automotive recycling industry in several ongoing and planned recycling projects.

This study analyzes 24 materials in detail while 7 are analyzed in terms of total mass because of limitations in the computer software IPCA. If IPCA is upgraded, it would be interesting to perform detailed analyses for these 7 materials as well. Also, there are other types of materials that could be interesting to analyze, e.g. plastics.

Since this study only analyzes cars with diesel engines or a combination of diesel engine and electrical motor, further studies could include cars with petrol engines. Also, since the large car analyzed in this study is considerably older in terms of year of design and hence, probably use considerable older techniques and materials, further studies could include a large car with the same year of design as the medium sized cars.

As discussed in the discussion (section 7), there are more factors that might influence the use the materials studied. In further studies, it would be interesting to analyze other factors such as size, year of design, regulations, choice of supplier and intended market.

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Appendix I. Materials in this study

This section of the appendix describes the materials studied in short summaries.

Rare Earth Metals (REM's)

Rare earth metals (REM's) is a collective term that refers to the seventeen elements: cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, erbium, dysprosium, holmium, thulium, ytterbium, lutetium (the lanthanides) together with scandium and yttrium. Since no parts in IMDS were found to contain promethium, the material is excluded in this study. The mining activities are cost intensive and the elements can only be economically mined together, most commonly from the minerals bastnaesite and monazite. In 2009, the world production of REM's was 124kt and China alone stood for 97% followed by India (2%). However, since Chinas rapidly growing economy is expected to require all of its production of REEs in the near future, new mining projects have started in North America, India, Australia and Malawi (European Commission, 2010).

Cerium **[Ce]**

Is a grayish lustrous metal and the most abundant of the REM's with an estimated concentration of 66 mg/kg in the earth crust. It is most common in the minerals monazite, allanite, cerite, bastnasite and samarskite and often together with thorium and lanthanum (Patnaik, 2002). The main usage of cerium is in catalytic converters for the automotive industry, petroleum refining, metal alloys, glass manufacturing, polishing, ignition devices and gas lighters (Patnaik, 2002) (Humphries, 2011).

Dysprosium **[Dy]**

Is a silvery metal with an estimated concentration of 5.2 mg/kg in the earth's crust. It is most common in the minerals xenotime, gadolinite, euxemite and monazite, often as a by-product of yttrium production (Patnaik, 2002). The main usage of dysprosium is in magnets, hybrid engines, nuclear reactors and as fluorescence activator in phosphors (Patnaik, 2002) (Humphries, 2011) (European Commission, 2010).

Erbium **[Er]**

Is a silvery metal that are often found together with other rare earth metals and the concentration in the earth crust is 2.8 mg/kg. Erbium is used in phosphor that converts infrared light into visible light it is also used in nuclear reactors in the control rods as neutron absorber. (Patnaik, 2002)

Europium **[Eu]**

Is a soft silvery metal and one of the rarest of the REEs. It is most common in the minerals xenotime, monazite and bastnasite (Patnaik, 2002).The main usage of europium is in nuclear power stations and as red light for television and computer screens (Patnaik, 2002) (Humphries, 2011)

Gadolinium **[Gd]**

Is a colorless or light yellow metal with an estimated concentration of 6.2 mg/kg in the earth's crust. It is most common in the minerals bastnasite and monazite. The main usage is in magnets. (Humphries, 2011)

Holmium **[Ho]**

Is a soft shining silver like metal that can be found in the minerals monazite, gadolinite, xenotime, euxenite, fergusonite, and bastnasite. Holmium has an estimated concentration of 1,3mg/kg in the earth crust. Holmium has limited usage areas but are used to a small extent in magnets, glass coloring and in laser technologies (Patnaik, 2002).

Lanthanum **[La]**

Is a silvery white metal and are most commonly found in the rare-earth minerals monazite and bastnasite with a concentration of 15-20% in the minerals. In the earth crust lanthanum has an estimated concentration of 30mg/kg. The main use is in metal alloys, phosphor lamp coating, optical glass and in glass polishes (Patnaik, 2002).

Lutetium **[Lu]**

Is a silvery white metal and occurs in yttrium rich minerals in small amounts. Lutetium have few commercialize application, one is to catalyze organic reaction (Patnaik, 2002).

Neodymium **[Nd]**

Is a silvery-white soft metal that occurs with other rare earth metals and most commonly with cerium group elements. Its concentration in the earth crust is estimated to 24mg/kg. The main usage is in metal alloys together with cast iron, magnesium, aluminum, zirconium and titanium (Patnaik, 2002). It is also used in glass coloring, auto catalyst, petroleum refinery, laptop hard drives, headphones and in hybrid engines (Patnaik, 2002) (Humphries, 2011).

Praseodymium **[Pr]**

Is a pale yellow metal with an estimated concentration of 8.2 mg/kg in the earth crust. The main uses for praseodymium are in glass coloring and magnets (Patnaik, 2002).

Samarium **[Sm]**

Samarium is a yellow hard metal which is widely distributed in nature and the concentration in the earth crust is 7.05 mg/kg. Samarium is always found together with other rare earth metals in typically in minerals such as monazite and bastanasite. The uses for samarium is in optical glass, capacitors, thermoionic generating devices, lasers, carbon arc lightning and in permanent magnets. (Patnaik, 2002)

Scandium **[Sc]**

Is a silvery white metal which is soft and light. Scandium is widely spread in nature but in low concentration, the concentration in the earth crust is estimated to 22mg/kg. It can be found in most soils and in numerous minerals but in very low quantities. The uses for scandium are used to create very high intensive light. (Patnaik, 2002)

Terbium **[Tb]**

Is a silvery-gray soft metal that is found in the minerals xenotime, euxenite, cerite, monazite and in gadolinite. The concentration of terbium in the earth crust is 1.2 mg/Kg. Its limited usage can mostly be found in phosphor and permanent magnets (Patnaik, 2002).

Thulium **[Tm]**

Is a silvery lustrous metal and one of the least abundant rare earth metals in nature. Thulium can be found together with other rare earth elements in yttrium rich minerals. The concentration in the earth crust is approximate 0.52 mg/kg. The uses of thulium is few due to the high production cost, thulium are used in portable x-rays tools as medical and dental diagnostic tool (Patnaik, 2002).

Yttrium **[Y]**

Is a gray shining metal that is most commonly found in the monazite sand which consist of approximately 3% yttrium. The concentration in the earth crust is estimated to 33mg/kg and it has also been found in moon rocks. The main uses are as red color in televisions, florescent lamps, ceramics and metal alloy agent (Patnaik, 2002).

Ytterbium **[Yb]**

Is a silvery lustrous soft metal. Ytterbium occurs in different minerals such as euxenite, monazite, xenotime and in a complex titanium niobotantalate. The concentration in the earth crust is estimated to 3.2 mg/kg. The uses for ytterbium are; as a laser source, portable x-ray source, additives in steel, and in glass. (Patnaik, 2002)

Platinum Group Metals (PGM):

The Platinum group metals consist of six metals: ruthenium, rhodium, palladium, osmium, iridium, and platinum. The metals have similar chemical properties such as high melting point, low vapor pressure, high temperature coefficient of electrical resistivity, low coefficient of thermal expansion and strong catalytic activity. The reserves are distributed unevenly in the world with approximately 88.5% is in South Africa and 8.7% in Russia (European Commission, 2010). The three selected PGMs for this report are palladium, platinum and rhodium.

Palladium **[Pd]**

Is a silvery-white metal with an estimated concentration of 0.015 mg/kg in the earth crust. In nature it is always found together with other PGMs and it is three times more abundant than platinum. Important applications for palladium are in auto catalysts, electronics, dental care, jewelry and telecommunications (Patnaik, 2002). In 2009, the world production of palladium was 195 t where Russia and South Africa accounted for approximately 41% each (European Commission, 2010).

Platinum **[Pt]**

Is a silvery-white lustrous metal with an estimated concentration of 0.005 mg/kg in the earth crust. In nature, it occurs together with other PGMs. Important applications for platinum are e.g. in auto catalysts, jewelry, dentistry, electronics, as a catalyst e.g. hydrogenation and as coating for jet engines and missile parts (Patnaik, 2002).The world production of platinum was 178 t in 2009 where South Africa and Russia accounted for 79% and 11% respectively (European Commission, 2010).

Rhodium **[Rh]**

Is a grayish-white metal with an estimated concentration of 1 mg/kg in the earth crust. In nature it occurs in small quantities together with other PGMS. A large number of its application is as an alloying or hardening agent for platinum and palladium. Other important applications are in e.g. electronics, jewelry, glass manufacturing, auto catalysts and several other catalytic reactions. (Patnaik, 2002). In 2006, South Africa accounted for 89% of the world's supply of rhodium. (U.S National Research Council, 2008)

Other materials:

Cobalt **[Co]**

Is a silvery white metal, widely distributed in small concentrations in nature. Its concentration in the earth crust is approximately 0.0025% and it is most commonly found in rocks, coal and soils (Patnaik, 2002).Of the world production of cobalt, 85% arises from nickel and copper production and only 15% from pure cobalt production (European Commission, 2010). A large share of the usage of cobalt is in super alloys with high resistance to oxidation, corrosion and high temperatures (Patnaik, 2002). It is also used in high speed trains, lithium-ion batteries and synthetic fuels. Cobalt is considered to be have limited substitution options (European Commission, 2010).Figures from 2010 shows that 53% of the mine production comes the Democratic Republic of Congo, followed by China and Russia with around 7% each. In 2010, the world production of cobalt was estimated to 87,400 tones.

Copper **[Cu]**

Is a reddish brown metal. In nature copper can be found as sulfides, oxides, arsenides, arsenosulfides, carbonates and as native copper (100% copper). Copper have good characters especially for heat and electricity transfer and are therefore used in electric wiring, switches and electrodes. Other uses for copper are plumbing, piping, roofing, cooking, and electroplating protective coating. (Patnaik, 2002) The world production 2008 was 15,427,000 tones and the main producing countries were Chile (34.5 %), USA (8.5 %) and Peru (8.2 %). The demand in the future are expected to increase due to expansion of renewable energy that need more cables and generators than non-renewable electricity production also electrical vehicles requires significant more copper than conventional vehicles. Coppers good qualities make it hard to substitute in electrical application but copper that are used as construction material can be substituted with aluminum or non-metallic substances. (European Commission, 2010)

Gallium **[Ga]**

Is a silvery white metal similarly to aluminum but with a lower melting temperature of nearly room temperature 30 °C. The concentration in the earth crust is 19mg/kg and in the average concentration in the sea is 30ng/L. Gallium is found in ores of other metals and is being produced as a by-product from bauxite and zinc ores. In many of these ore the concentration of gallium is too low to be economical feasible to extract. The main primarily producing countries are China(75%), Germany, Kazakhstan and Ukraine. The main use of Gallium is in integrated circuits and in laser diodes/LED other uses of gallium is in photo detectors and solar cells. In the future the demand for gallium are predicted to double to year 2015 due to rapid increase of use of gallium in photovoltaic technologies. Gallium is not being recycled from old scrap due to there are almost no old scrap available yet but new scrap are being recycled. In future 40-50% of the produced gallium would come from recycling and that most of the recycled will take place in Japan. Substitution availability is available for most of the technologies but not in some integrated circuits for defense related systems. (European Commission, 2010)

Gold **[Au]**

Is a yellow metal. Gold is widely distributed in nature but in small concentration, the concentration on the earth crust is 4µg/kg. It occurs in its element form as metal or as an alloyed with silver often found in copper ores. (Patnaik, 2002) The world production 2009 was 2,350 tones, the main producing countries was China, Australia, USA, South Africa, Russia and Peru (U.S. Geological Survey, 2010). The main usage of gold is in jewelry, gold plating of electronics, brazing alloy and photographs.

Indium **[In]**
Is a silvery white soft metal, that is widely distributed in small concentrations. It is estimated to 0,1mg/kg in the earth crust and is found mostly in zinc sulfide ores and to a lesser extent in sulfide ores of iron and copper (Patnaik, 2002). The production depends on the production of lead and zinc since there is no primary production of the metal itself. The main end-use markets for indium are flat screen panels to an extent of 74% of the total end use. Other common applications are low melting point alloys for temperature indicators, minor alloys for dental application and architectural glass and windscreens. Less than 1% of indium scrap is being recycled (European Commission, 2010).

Niobium **[Nb]**
Is also known as Columbium and is a grayish soft metal. Its concentration in the earth crust is estimated to 20mg/kg and it can be found in several minerals often together with tantalum and rare earth metals. The World production in 2009 was 61,7kt with 92,4% of the production in Brazil and 7% in Canada. The amount of recycled niobium is not known but estimation from [USGS mineral Commodity Summaries 2011] states that up to 20% could be recycled with the right measures. The main usage for niobium is as metal alloying both for ferrous and non-ferrous metals. The main alloy is high-strength steel for construction of car bodies, off-shore platforms and pipelines but also as high-strength steel in aircraft and in the nuclear sector (European Commission, 2010).

Lithium **[Li]**
Is a silvery with metal and is the lightest metal. Lithium is widely distributed in nature and the concentration in the earth crust is 20mg/kg and in the sea 0.18mg/L. The use of Lithium is many such as medical uses, metallurgical as alloys in lead, magnesium, aluminum and other metals. Lithium is used in high energy batteries for electronics and in cars, it is also used in glass and ceramics and as lubricating grease for the automotive industry. (Patnaik, 2002)In the future Lithium car batteries is projected to be the dominant use for lithium to 2050. The main producers of lithium are Chile with 41.7 % of the total production in 2009 other large producing countries are Australia (24.8%), China (13.0 %) and Argentina (12.4 %). (European Commission, 2010)

Magnesium **[Mg]**
Is a silvery white metal. Magnesium is one of the most common metals in nature and the concentration in the earth crust is approximately 2.4% but it don’t exist in its element form it exist in different mineral forms. Magnesium can also be found sea water with a concentration of 1,350mg/L, Magnesium also occurs in all plants and are and are an important nutrient for humans and recommended daily intake for adults are 300mg/day. Magnesium are used in chemical, electro-chemical, metallurgy and electronic industries. Magnesium is alloyed with aluminum, zinc, copper, nickel, lead, zirconium and other metals as well. The alloys are used in almost all industries for example in the automotive industry. (Patnaik, 2002) The world production 2009 was 30,190,000 tones and the main producing countries were China (56.1 %), Turkey (12.0 %) and Russia (7 %). (European Commission, 2010)

Manganese **[Mn]**
Is a reddish grey metal. Manganese is the twelfth most abundance metal in nature and the concentration in the earth crust is 0.095% and the average concentration in sea water are 2µg/L.

Manganese exist mostly in the form of oxides, silicates and carbonate ores and are often found together with iron ores in small quantities. (Patnaik, 2002)The world production 2009 was 9,664,000 tones and the main producing countries were China (24.8 %), Australia (16.6 %), South Africa (13.5 %) and Brazil (10.2 %). Approximate 90% of the usage for Manganese is in steel metallurgy where it is used as a deoxidizing and desulfurizing agent. Other uses are in copper for same reason in steel, corrosion protection. (European Commission, 2010)

Molybdenum [Mo]

Is a silvery white metal. Molybdenum does not exist in nature in free element form. Molybdenite (MoS_2) is the most important ore and the one that are commercially mined. (Patnaik, 2002) The concentration in the earth crust is between 1-1.5 ppm and is mined both as primary production and as a byproduct of copper. The world production 2009 was 202,000 tones and the main producers were China (37.9 %), USA (24.6 %) and Chile (15.8 %). The main usages for molybdenum are in metallurgical used as an alloy manly in different steels but it is also used for catalysts, pigment, corrosion inhibitors and lubricants. (European Commission, 2010)

Silver [Ag]

Is a white metal with brilliant metallic luster. The estimated concentration of silver in the earth crust is 0.075mg/kg and in sea water the concentration is 0.014µg/L. Silver can be found in its element form commonly together with gold and can be found in most lead and copper ores. (Patnaik, 2002) The world production in 2008 was 21,300 tones and the main producing countries were Peru (17.3 %), Mexico (15.2%) and China (13.1%). The main usages for silver are in the jewelry, electrical and photograph industries. It is also used as catalysts, clothing, dental, solar panels, water treatment and plasma displays. Recycling of silver depends on where it has been used, silver that been used as jewelry are recycled up to 90% but silver that has been used in electronics are only been recycled up to 10-15%. (European Commission, 2010)

Tantalum [Ta]

Is a grey heavy and hard metal. The concentration in the earth crust is estimated to 2mg/kg and are never found as a free element form, tantalum is occurs most often in the mineral columbite-tentalite $(Fe, Mn) (Nb, Ta)_2 0_6$. The properties of tantalum and its alloys are high melting point, high-strength, ductile and high resistance to chemical attacks. Due to the properties tantalum are used in alloys for high-strength and heat resistance materials for aircraft, missile, automotive and gas and steam turbines industries. Tantalum is also used in capacitors, medicine and optical industries. (Patnaik, 2002) There are few countries that produces tantalum in 2009 Australia stood for 48,3% and Brazil for 15,5 % of the world production other countries that produced tantalum is Canada, Democratic Republic of Congo and Rwanda. Recycling of tantalum exists from cemented carbide and alloys sectors where tantalum is recovered in mixed or alloy form. Recycling from capacitors which is the main usage of tantalum does not exist due to it is difficult and expensive. For many technologies tantalum can be substituted or there is work in progress for substitutions but when tantalum is substituted most of the applications loose in effectiveness. (European Commission, 2010)

Tellurium [Te]

Is a silvery white lustrous metal. Tellurium occurs in nature in vary small concentration and can be found together with gold, silver, lead, nickel minerals and less common as tellurite (TeO_2). The estimated concentration of tellurium in the earth crust is 1µg/kg. (Patnaik, 2002) The tellurium primary producing countries are China (33%), Belgium (33%), Philippines (16%), Japan (12%), Canada (4%) and Russia (2%) of the world production in total. The world capacity for production of tellurium is high and is 74-78%. The main usages for tellurium are as alloy element in steel, copper, lead and cast iron. Other uses are in chemical and pharmaceuticals, electronics and in photovoltaic thin-films technologies but the use of tellurium in photovoltaic are predicted to decrease due to other materials are used instead. The recycling of tellurium exists in small amounts but is growing. (European Commission, 2010)

Appendix II. Tables

Table 12. Subsystem description

PSS	Subsystem	Explanation and/or examples of parts
10	Powertrain Mounts	Parts to mount e.g. engine & gearbox
20	Fuel System	Fuel filter, fuel lines & fule tank
30	Exhaust Cold End	Cold end of the exhaust system, i.e. not near the engine
40, 50	Engine Cooling & Air Induction	Air inlets, engine cooling fan & radiator
290,291,320	Engine System	Engine, catalytic converter & particulate filter
300,301,310,380	Transmission	Parts that transfer power from motor to drive shafts, e.g. gearbox & propeller shaft
60	Brake System	Brake pipes, brake disks & hydraulic unit for ABS
70	Pedals	Accelerator pedal & brake pedal
80, 90	Wheels & Wheel Suspension	Link arms, suspensions, subframes & wheels
100	Steering	Servo, steering column & steering gear
360	Saftey Electronics	Sensors for air bags & ABS sensor
120,14	Interior & Instrument Panel	Various visible panels and in some cases also the electronics behind the panels, e.g. door anels, instrument panel, arm rests, floor carpets
130	Seating	Seats, seat frames, seat heater & electrically adjustable seats
150	Climate System	Air condition, air ducts & climate unit
160	Restraints & Air Bags	Air bags, seat belts & load net
170	Exterior Lighting	Front-, position- and rear lights
180	Cleaning & Horns	System for cleaning windows and exterior lightings e.g. wipers, washer fluid reservoir & horns
190,220,230,240	Doors, Boot & Hood	Doors, boot & hood
200	Glazing & Mirrors	Glass, mirrors and other glazed surfaces, e.g rear view mirrors & door glass
210	Roof Systems	Roof hatch & roof rails
250,260,570	Bumpers, Spoilers & Covers	Bumpers, spoilers & covers
270,271,280	Body Structure	The car's structure above the chassis, e.g pillars & crossmembers
330	Electrical Distribution System	Mainly cables
332	Low Voltage Power Supply	12V battery, starter motor & alternator
334	High Voltage Power Supply	Battery for the hybrid, voltage converter & alternator
340	Driver Controls	Buttons and switches that the driver can control, e.g. cruise control start button & light switch

350,361	Security & Body Electronics	Electronic door locks, sirens, rain sensors & pressure sensors
370	Infotainment	System to both inform and entertain, e.g. speakers, amplifiers & microphones
990	Accessories	Accessories such as roof box & bicycle holder
980	Special Equipment	Special equipment such as sport steering wheel & 18" aluminum wheels
0	Standard Components	Clips, plugs, screws, sealing & nuts

Table 13. CAS-numbers found in the cars and used for molar mass calculations

CAS-numbers						
Rhodium	**Dysprosium**	**Erbium**	**Samarium**	**Silver**	**Ytterbium**	**Gold**
7440-16-6	7429-91-6	7440-52-0	7440-19-9	7440-22-4	1314-37-0	7440-57-5
Gadolinium	**Lanthanum**	**Tantalum**	**Terbium**	**Manganese**	**Cobalt**	**Praseodymium**
12064-62-9	7439-91-0	7440-25-7	7440-27-9	7439-96-5	7440-48-4	7440-10-0
7440-54-2	1312-81-8	12031-66-2	102110-19-0	1313-13-9	1308-06-1	12037-29-5
Palladium	**Platinum**	**Copper**	**Neodymium**	**Europium**	**Molybdenum**	**Cerium**
7440-05-3	7440-06-4	7440-50-8	12058-94-5	1308-96-9	7439-98-7	1306-38-3
1314-08-5	68478-92-2	12158-75-7	1313-97-9	374783-70-7	1317-33-5	102110-19-0
7647-10-1	12035-82-4	22205-45-4	7440-00-8	68585-82-0	68412-26-0	12014-56-1
						7440-45-1
Niobium	**Yttrium**	**Gallium**	**Indium**	**Magnesium**	**Lithium**	
7440-03-1	1314-36-9	12063-98-8	1312-41-0	7439-95-4	12031-63-9	
68611-43-8	12005-21-9	7440-55-3	1312-43-2	14807-96-6	12031-66-2	
1313-96-8	7440-65-5	25617-97-4	50926-11-9	1309-48-4	91001-47-7	
12031-63-9	68585-82-0	1303-00-0	7440-74-6	1309-42-8	7791-03-9	
			71243-84-0	329211-92-9	7620-77-1	
No CAS:				12125-28-9	7439-93-2	
Lutetium				12304-65-3	68649-48-9	
Holmium				1343-90-4	68604-46-6	
Scandium					4485-12-5	
Thulium					38900-29-7	
					12057-24-8	
					64754-95-6	
					1310-65-2	
					4499-91-6	
					10377-52-3	