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Energy and recycling implications of transitions towards light-weight passenger cars

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PREFACE

This research was completed in the spring of 2012 to fulfil the Industrial Ecology TVM4900 Master's Thesis requirement. It represents the culmination of the M.Sc. degree work in Industrial Ecology at the Norwegian University of Science and Technology (NTNU). I would like to express the highest gratitude to my supervisors Daniel Müller, Stefan Pauliuk and Roja Modaresi for their significant efforts in guiding this research throughout the semester. I would also like to thank Clare Broadbent from the World Steel Association for providing some valuable data for the research. Finally, I would like to thank my friends and family for supporting me in this venture. It is my sincere hope that this research will be useful to industry and future academic endeavours on this subject.

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ABSTRACT

The IPCC Fourth Assessment Report postulates that effective climate change mitigation requires global emissions to be reduced by at least 50% over the period of 2000-2050. At present, neither specific technological pathways nor internationally binding reduction targets for different sectors or countries have been established yet. With the rapid development of countries like India and China, the demand for passenger cars is going to increase rapidly. This would mean a steep rise in the demand for materials like steel and aluminium for the building of these cars. Primary aluminium is an energy intensive material whereas producing steel currently accounts for approximately 9% of all energy-related green house gas emissions. Having a greater car stock would mean a greater demand for the extraction and burning of fossil fuels like petrol and diesel, hence leading to a further rise in GHG emissions.

This model studies the global passenger car stock to compute the global direct and indirect CO_2 emissions and energy consumption until 2050 depending on population, car utilization, fuel consumption, material composition and material recycling rates. The model also studies the impact of light-weighting of the passenger car fleet by substituting the steel in the cars with aluminium. It also studies the effect of recycling materials from End-of-Life vehicles within the passenger car sector and on other sectors. The model performs these functions through the development of scenarios with single or multiple-varying parameters.

The results of the model show that it will not be possible to reach the targets put forth by the IPCC. In best case scenarios, the 2050 total emissions are still only 13-15% lesser than emission levels from 2000. It is shown that light-weighting of cars leads to a reduction of CO_2 emissions in the long run. The importance of recycling of aluminium and steel in passenger cars and other sectors (like Buildings) are also demonstrated from this model.

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List of Abbreviations Used:

IPCC = Intergovernmental Panel on Climate Change

IAI = International Aluminium Institute

LCA = Life Cycle Assessment

MFA = Material Flow Analysis

BIW = Body-in-White

Al = Aluminium

GHG = Green house gases

EOL = End of Life

ELV = End of Life Vehicle

1. INTRODUCTION

1.1. Climate Change and Transportation:

Climate change mitigation has become a major concern for the world in recent times. There is a general consensus among climate scientists that human activities, especially the extensive use of fossil fuels, have led to climate change – both local and global. To tackle this issue, the Intergovernmental Panel on Climate Change, IPCC, was created. The IPCC reports that in order to limit the global average temperature rise to 2° C above preindustrial levels, we need to reduce global emissions by at least 50% as compared to 2000 emission levels (IPCC, 2007).

Countries like India and China are developing rapidly and this can only imply a steep increase in their material use in all sectors. Solutions have to be created to allow for this development while, at the same time, trying to reduce the energy consumption and emissions due to this rapid development.

Figure 1 shows the total energy and process related emissions from all major sectors in 2006, as well as a breakdown of the same from the Industrial sector. 12% (or 121 Mt) of the steel from the Steel Industry and 27% (or 13 Mt) of the aluminium from the Aluminium Industry is used in the manufacture of vehicles (Allwood, Cullen, 2010). This demand is expected to, at least, double over the coming decades. This means, that we need to reduce the CO2 emissions per ton of material by a factor of 4 to be able to achieve the emission targets in 2050.

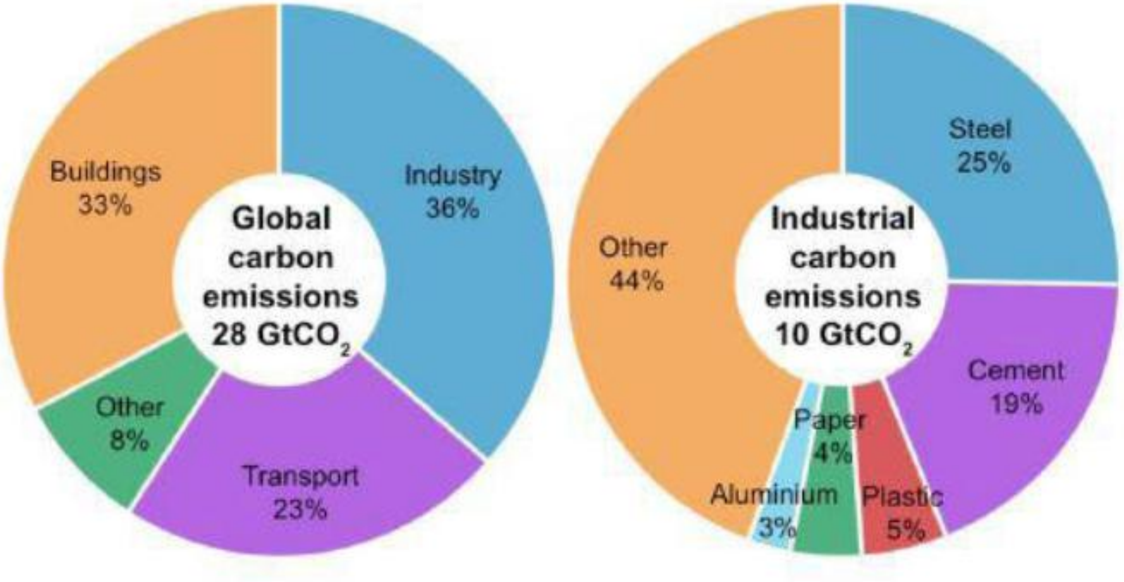

Figure 1: Global energy and process related emissions of CO2 by major sector, and broken down within industry

Figure 2 show the growing emissions from green house gases in vehicles over the next few decades as differentiated by the mode of transport. It can be seen that the overall emissions are more than doubling in this time. Further, road transport – cars, trains, trucks, buses, motorcycles, etc. – represent a major part of these emissions, both currently and in the future. Passenger cars represent a major share – 40-45% approx. (IPCC, 2007) – of road transport emissions. It is evident that reducing the emissions from the transportation sector is of utmost importance.

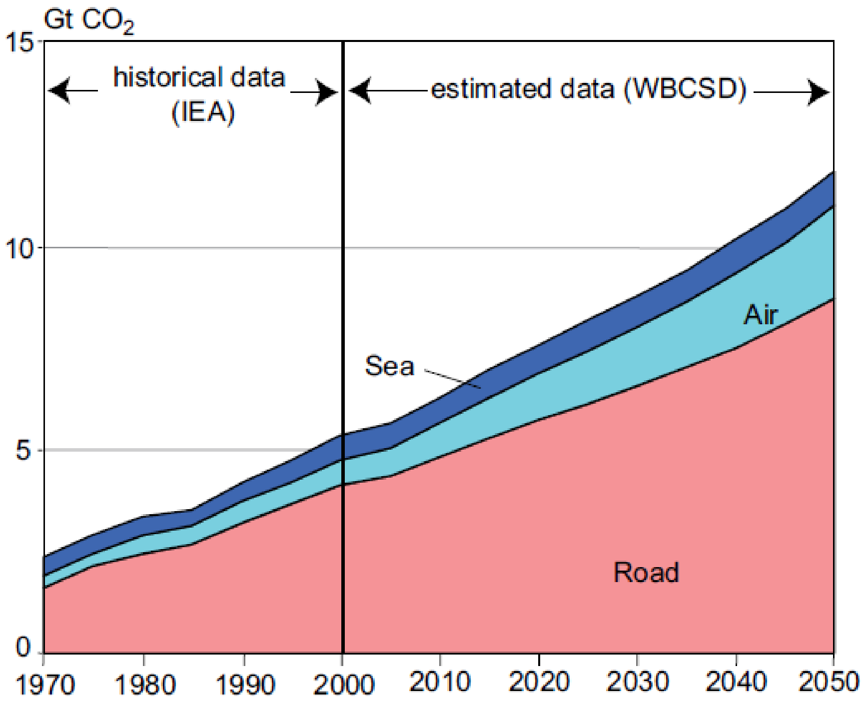

Figure 2: Historic and Projected CO2 emissions from transport by modes (IPCC, 2007)

1.2. Passenger Cars, Material Composition and Sustainability:

Passenger cars can by no means be standardized in terms of their material composition and fuel consumption. However, most of them have a ferrous metal composition ranging from 60-75% of the total car weight (GREET 2.7, 2006; Schweimer et al, 2000). The use of aluminium in passenger cars began around 1930 (Furrer et al., 2009). Typical material compositions of cars, as obtained from the Ward's Statistical data (Ward's Automotive Yearbooks, various years), are shown in the table below:

Table 1: Material Composition of a typical family vehicle

Year	Regular Steel	High Strength Steel	Stainless Steel	Other Steel	Iron	Plastic	Aluminum	Copper and Brass	Powder Metal Parts	Zinc Die Castings	Mg Castings	Fluids	Rubber	Glass	Other	**Grand Total**
1976	55.5%	3.2%	0.7%	1.5%	15.0%	4.4%	2.3%	0.9%	0.0%	1.2%	0.0%	5.1%	4.1%	2.3%	3.7%	100.0%
1977	54.4%	3.4%	0.7%	1.5%	14.7%	4.6%	2.6%	1.1%	0.4%	1.0%	0.0%	5.5%	4.1%	2.4%	3.5%	100.0%
1978	53.6%	3.7%	0.7%	1.5%	14.3%	5.0%	3.2%	1.0%	0.4%	0.9%	0.0%	5.5%	4.1%	2.4%	3.4%	100.0%
1979	53.1%	4.3%	0.8%	0.0%	14.3%	5.3%	3.4%	0.8%	0.0%	0.7%	0.0%	5.4%	4.0%	2.4%	4.7%	100.0%
1980	53.2%	5.4%	0.8%	1.7%	14.8%	6.0%	4.0%	1.1%	0.5%	0.6%	0.0%	5.5%	4.0%	2.6%	2.9%	100.0%
1981	49.6%	5.9%	0.8%	0.0%	14.6%	6.1%	4.0%	0.9%	0.0%	0.5%	0.0%	5.4%	4.1%	2.6%	4.7%	100.0%
1982	47.7%	6.4%	0.9%	1.5%	14.6%	6.5%	4.4%	1.3%	0.6%	0.5%	0.0%	5.8%	4.3%	2.8%	2.9%	100.0%
1983	47.3%	6.5%	0.9%	1.7%	14.8%	6.3%	4.3%	0.9%	0.0%	0.5%	0.0%	5.7%	4.3%	2.7%	3.4%	100.0%
1984	47.3%	6.8%	0.9%	1.4%	14.5%	6.6%	4.4%	1.4%	0.6%	0.5%	0.0%	5.7%	4.2%	2.8%	2.8%	100.0%
1985	46.5%	6.8%	0.9%	1.7%	14.7%	6.6%	4.3%	1.4%	0.6%	0.6%	0.1%	5.8%	4.3%	2.7%	3.1%	100.0%
1986	46.4%	7.1%	1.0%	1.5%	14.3%	6.9%	4.5%	1.4%	0.6%	0.5%	0.0%	5.9%	4.2%	2.8%	2.9%	100.0%
1987	45.9%	7.2%	1.0%	1.7%	14.5%	7.0%	4.6%	1.4%	0.6%	0.6%	0.1%	5.8%	4.3%	2.7%	2.7%	100.0%
1988	44.4%	7.6%	1.0%	1.5%	14.2%	7.3%	5.0%	1.6%	0.7%	0.6%	0.0%	5.9%	4.3%	2.9%	3.0%	100.0%
1989	45.1%	7.5%	1.0%	1.5%	14.6%	7.1%	5.0%	1.6%	0.7%	0.6%	0.0%	5.7%	4.3%	2.7%	2.6%	100.0%
1990	44.7%	7.6%	1.1%	1.3%	14.5%	7.3%	5.0%	1.5%	0.8%	0.6%	0.1%	5.8%	4.3%	2.8%	2.7%	100.0%
1991	43.8%	7.8%	1.2%	1.4%	14.1%	7.8%	5.4%	1.5%	0.8%	0.6%	0.1%	5.7%	4.4%	2.8%	2.6%	100.0%
1992	44.0%	7.9%	1.3%	1.3%	13.7%	7.8%	5.5%	1.4%	0.8%	0.5%	0.1%	5.6%	4.3%	2.8%	2.9%	100.0%
1993	43.7%	8.2%	1.4%	1.5%	13.1%	7.8%	5.6%	1.4%	0.8%	0.5%	0.1%	6.0%	4.3%	2.8%	2.8%	100.0%
1994	43.8%	8.3%	1.4%	1.3%	12.9%	7.7%	5.7%	1.3%	0.9%	0.5%	0.2%	6.0%	4.2%	2.8%	3.0%	100.0%
1995	43.6%	8.7%	1.4%	1.4%	12.4%	7.7%	5.8%	1.4%	0.9%	0.5%	0.2%	5.9%	4.2%	2.9%	3.1%	100.0%
1996	43.5%	8.9%	1.4%	1.2%	12.0%	7.6%	6.1%	1.4%	0.9%	0.5%	0.2%	6.1%	4.3%	2.9%	3.1%	100.0%
1997	43.4%	9.1%	1.5%	1.1%	11.6%	7.5%	6.4%	1.4%	1.0%	0.4%	0.2%	6.0%	4.3%	3.0%	3.1%	100.0%
1998	43.2%	9.8%	1.5%	1.0%	11.2%	7.5%	6.9%	1.4%	1.0%	0.4%	0.2%	6.1%	4.3%	2.9%	2.7%	100.0%
1999	42.7%	10.0%	1.5%	0.8%	10.9%	7.5%	7.2%	1.4%	1.1%	0.4%	0.2%	5.9%	4.3%	3.0%	3.1%	100.0%
2000	41.8%	10.3%	1.6%	0.7%	10.7%	7.6%	7.5%	1.4%	1.1%	0.3%	0.2%	6.0%	4.4%	3.0%	3.3%	100.0%
2001	40.8%	10.6%	1.6%	0.8%	10.4%	7.6%	7.8%	1.4%	1.1%	0.3%	0.3%	5.9%	4.4%	3.0%	4.0%	100.0%
2002	40.3%	11.3%	1.7%	0.8%	9.8%	7.6%	8.3%	1.5%	1.2%	0.3%	0.3%	5.9%	4.4%	2.9%	3.8%	100.0%
2003	40.3%	11.3%	1.7%	0.8%	9.8%	7.6%	8.2%	1.5%	1.2%	0.3%	0.3%	5.9%	4.4%	2.9%	3.8%	100.0%
2004	40.1%	11.6%	1.7%	0.8%	9.1%	7.6%	8.5%	1.5%	1.2%	0.3%	0.3%	5.9%	4.5%	2.9%	3.9%	100.0%

An interesting trend that can be noticed from the table is the increased use of aluminium and the decreased use of steel. The reason for this, as shown by many studies, is that aluminium can be classified as a 'light-weighting' metal. According to a report by the International Aluminium Institute (IAI, 2007),

"Aluminium is one of the most viable light-weighting options available to original equipment manufacturers in all areas of transport for weight reduction applications. Aluminium offers significant benefits in both the use stage and in the recycling stage of a vehicle."

The benefits aluminium offers in the use stage are indirect, and stem from the reduced fuel consumption from light-weighting. The recycling stage benefits are due to the fact that secondary aluminium creation requires only 5% of the energy for primary aluminium creation (IAI, 2009). Hence, this one of the aspects of this analysis is the increased use of aluminium in the car while also looking at its impact on the steel industry.

Allwood J.M. and Cullen J.M., in their book "Sustainable Materials: With Both Eyes Open" make a detailed analysis on how materials like aluminium and steel can be used efficiently in various sectors of the economy to reduce their global environmental impact (Allwood et al, 2012).

There are many studies on the potential of light-weighting. One of the early works regarding the use of Al in light-weighting is by Stodolsky (Stodolsky et al, 1995). It looks into the potential for energy and economic savings from light-weighting of vehicles. It has also been used in future analyses in the same field. Ungureanu (Ungureanu et al, 2007) uses a lot of values from this report for its Life Cycle Cost analysis. One study (Schmidt et al, 2004) performs a comparative Life Cycle Assessment (LCA) between light-and-recyclable cars (LIRECARs). It considers a reference car of weight 1000 kg and two light-weight cars of 750 kg and 900 kg and has material compositions for each of these cars (with the reduced weight cars having more Al in them). It shows positive results, thus supporting the case of light-weighting. The report, "On the Road in 2020" (MIT, 2000), also gives a comprehensive assessment of current and future car technologies. It has its own set of material compositions for cars and considers light-weight components in its analysis. Tempelman E. (Tempelman E., 2011) shows a comparison between various types of light-weighting materials using multiple parameters. This analysis also talks about how the material components of a car can be split into three types – primary, secondary and tertiary – based on their use and composition.

1.3. Using MFA to find a solution:

A lot of studies on the sustainability of the transport sector use LCA tools and methods in their analysis. One of the drawbacks of LCA studies is that they do not determine *when* in the entire lifetime of the car the emissions occur. Using a Dynamic Material Flow Analysis, one is able to find out the number of cars present at any particular time period and their emissions during that time period.

There are also some MFA studies which try to analyze the transport sector. Marlen et al (2009) gives a general overview of the use of MFA in the aluminium industry, whereas Cheah et al (2009) shows how recycling can be modeled when including different alloys of aluminium.

A stock driven dynamic MFA had been made for estimating material flows in buildings (Müller, 2006). The same method was modified to predict direct emissions of cars in China and come up with mitigation strategies (Pauliuk et al, 2009). Detailed studies (by Roja Modaresi) are also being done currently on the primary and secondary aluminium flows in cars on a global study.

One of the areas which has not been studied in detail is on how the rising stocks of passenger cars in the world would affect the emissions, energy consumption and recycling in the materials production industry.

This study tries to combine and improve upon the two works mentioned above by integrating aluminium, fuel consumption and adding an extra layer of interest – steel – into the analysis of passenger cars, on a global scale.

1.4. Study Aim and Scope:

The aim of this study is to develop a model for the total emissions from passenger cars and, by the development of some simple scenarios, show whether it is possible to reach the target emissions reductions by 2050. This study focuses primarily on the steel and aluminium used in cars as well as the fuel consumption from them.

By developing the model, the study essentially tries to answer these questions:

1. How can the direct and indirect energy use and emissions from the global car stock be minimized, and how are they related to each other?
2. How do different vehicle designs affect the material composition and fuel consumption of cars?
3. How do the secondary resources from End-of-Life Vehicles (ELVs) affect the recycling opportunities within the vehicle system and the other systems?

1.4.1. Scope:

To avoid issues of International Trade, the model has been designed on a global scale for the time period 1950-2050.

For the purpose of simplicity, passenger cars running on petrol and diesel have been combined. This situation is viable because we are looking at a global average car. Hence, fuel efficiencies and material compositions do not have to be calculated separately and the system becomes much simpler. Also, Electric cars have been neglected from this analysis due to their small share in the present world car mix.

It was decided that the model would look into the energy consumption and emissions from primary and secondary Wrought and Cast aluminium, as well as from primary and secondary steel for the global passenger car stock. The model would also calculate the total operation emissions and energy usage for the car stock. The model will also be able to incorporate light-weighting by substituting steel in the car with aluminium.

Next, the various parameters and scenarios for each parameter are chosen. These have been explained in detail in the following sections.

In the next section (Section 2) of this report, the various methods used to create the model are explained in detail. Section 3 presents the results of the model and provides an explanation of them. Finally, Section 4 discusses the implications of the results as well as the limitations of the model itself. It shows us how the results tie in with the central research questions and how this work can be continued in the future.

2. METHODS

In this section the rationale behind the modeling of the car has been explained. Next, the Passenger Car System has been described. Later, the general assumptions regarding the system and the car are put forth. Finally, the procedure for the model development has been explained in detail.

2.1. Modeling the Car:

One of the most important factors to consider for the passenger car is the weight of the car. Due to the wide variety of passenger cars weights, obtaining a global average is a very complex task. One approach to this is to not calculate the world average in the first place. Instead, the total weight of the car is assumed to be divided among three main components:

1. Body-in-White (BIW) or Primary Components: The BIW refers to the basic frame of the vehicle and includes 'closures' like the doors and the bonnet, as shown in Figure 3[1].

Figure 3: Components included in the Body in White of a car

2. Dependent or Secondary Components: The dependent components include all important components (engine, drive train, suspension and other main components) of the car whose weight depends on the BIW weight. This means that a change in the BIW weight of the car would affect the weight of the dependent components in order to maintain the same driving efficiencies and safety standards.
3. Independent or Tertiary Components: This set of components includes all the car subsystems which are not included in the first 2 sets of components. These include electrical system, windows, dashboard and controls, safety systems, interiors, etc. These subsystems are called independent because they are all necessary for the comfort and safety of the passenger. It is assumed that the change in the BIW weight will not affect the total weight of these components.

The various assumptions made in these components are explained in section 2.3.

The **second** important factor to be considered is the fuel efficiency/consumption of the car. The fuel consumption of the car depends on the weight of the car, the design and the speed at which the car is driven. The design and speed of the car are two very difficult components to incorporate while

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[1] Source: http://aluminium.matter.org.uk/content/html/eng/default.asp?catid=199&pageid=2144416949

calculating the fuel efficiency. If one is to ignore these factors, the fuel efficiency can be calculated from the weight of the car by using the formula (MSL MIT, undated):

Fuel efficiency in miles per gallon, $\boldsymbol{Fmpg = 8627.4 * (W) - 0.74584}$
Where W is the weight of the reference car.
Fuel Consumption, in L/100km (Feng An et al, 2004), $\boldsymbol{F = 235.2/Fmpg}$

2.2. System Definition and description:

For the purpose of this simplicity, the system has been shown separately for Aluminium and Steel. However, they are treated together in the program. In both cases, the upstream processes consist of Mining, Smelting, Semi-product Manufacturing and Car Manufacturing. The Use Phase of the car has been divided to include the Body-in-white (BIW), the dependant components and the independent components.

The Aluminium System is shown in Figure 4 and the Steel System is in Figure 5. Full size images of these figures are provided in Appendix A.

The main difference between the Aluminium and Steel systems is in the End-of-Life phase. In the Aluminium System, we have scrap aluminium from other sources (buildings, airplanes, etc.) entering into the system, whereas, in the Steel system, the scrap steel from EOL cars is leaving the system and going into other sources. This is because, currently, almost all the aluminium scrap from Buildings and other sectors is converted into secondary Cast Al (downgraded from Wrought if necessary), which is in turn used in the transportation sector. Steel on the other hand follows the opposite pattern. Steel scrap from vehicles is normally converted into secondary steel, to be used in the Buildings sector.

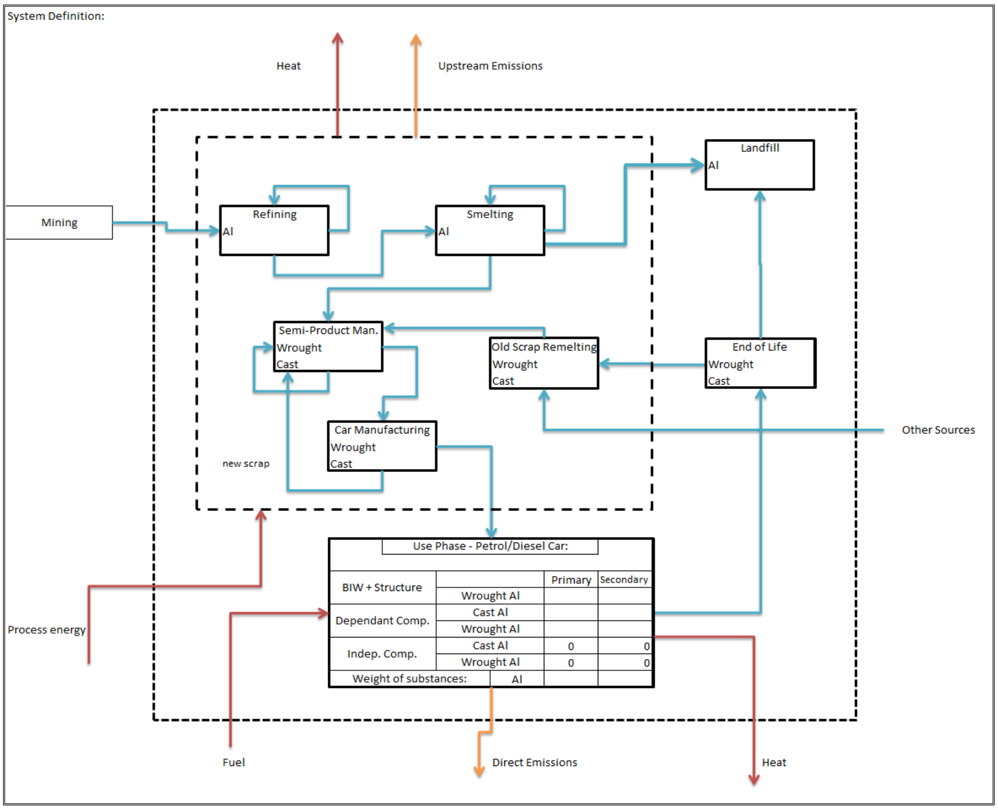

Figure 4: Aluminium System Diagram

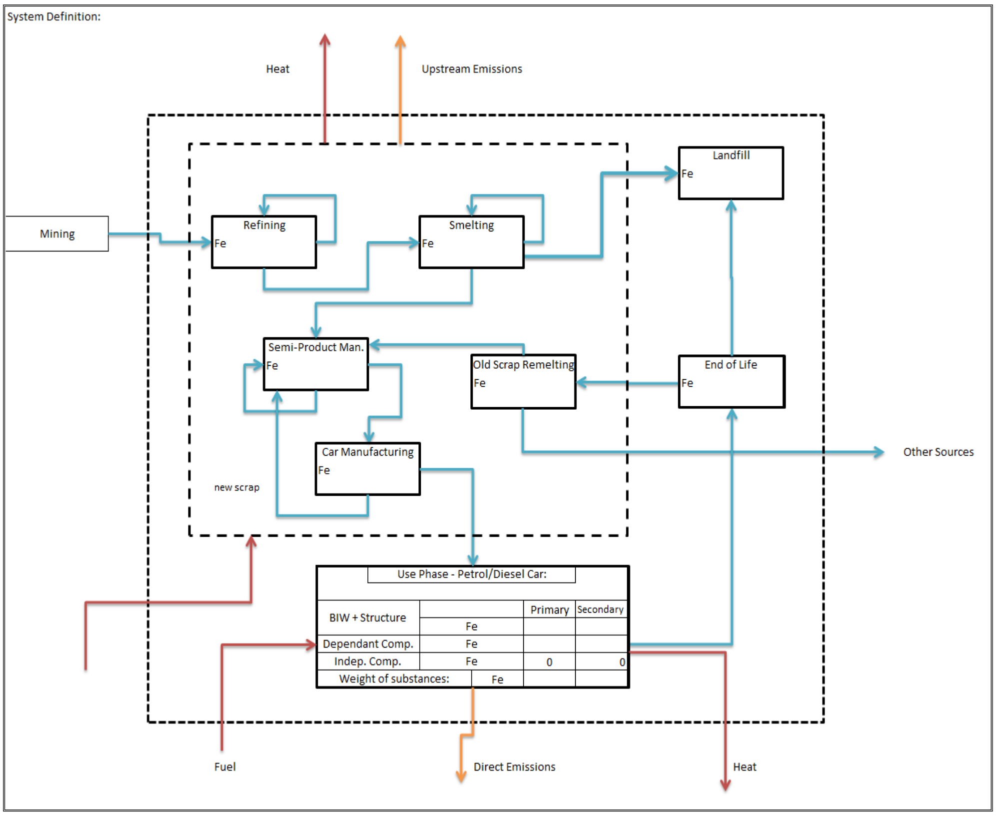

Figure 5: Steel System Diagram

2.3. General Assumptions:

2.3.1. System:

- **Combining of Upstream Processes** – In the program, the upstream systems have been combined with the Remelting of old scrap and made into one single subsystem. This subsystem's internal flows can now be neglected as all the data available from this subsystem accounts for all the processes within the subsystem. In this way, the only important material flows considered for this subsystem are the Primary and Secondary flows from the subsystem into the Passenger car and of the scrap entering into the subsystem from the End-of-Life (EOL) process.

- **Closed System** – From the Aluminium and Steel System diagrams, it is obvious that they represent Open systems, due to the fact that they have an external source of scrap import/export. However, modeling this would be very complex and time consuming. Hence a major assumption has to me made here that all the scrap that is available from the EOL process of the car is used within the Passenger Car System. Any excess or deficit of scrap is obtained or transferred to the Other Sources (which includes the Buildings Sector). These values are not calculated in the model and it is assumed that the manufacturing sector always has the required amount of secondary material as needed by the passenger car.

Another implication of having a closed system is that the model no longer takes into account the global total material flows of aluminium and steel. Instead it only takes into account the aluminium and steel which is used within the Passenger car sector. Combining this factor with the previous assumptions tells us that the internal processes will not be mass balanced. Instead, the focus of this study is on the direct and indirect emissions and energy consumption and on the showing whether there is enough scrap available for recycling within the Passenger car system.

2.3.2. Car:

- **BIW and Dependent Components** – As mentioned earlier, the total weight of the car has not been considered and instead, the car has been divided into the BIW, Dependent and Independent Components. An important assumption made here is that the BIW and Dependent Components are made only of steel and aluminium. It is assumed that the Dependent components only contain steel and Cast Al. The BIW is made up of only steel and Wrought Al. This assumption is made in order to simplify calculations and it is quite reasonable based on the fact that Cast Al is a major component of modern car engines whereas Wrought Al is used mainly in the outer body due to its material properties. In the Matlab model, the total steel from the BIW and Dependent components is combined into one parameter whereas the Wrought and Cast Al are treated separately.

- **Independent Components** – For the simplicity of the analysis, it is assumed that the independent components contain no steel and aluminium and instead contain all the other materials used in cars. In this way, the Independent components can be neglected from the analysis. This is a reasonable assumption due to the fact that these components include electrical and electronic systems (mainly copper, silicon and rare earths), tires (rubber), the dashboard and steering systems (wood, polymers), etc. For the purpose of the analysis, the energy and emissions from these components are also neglected. This would create a small error in calculating total emissions and energy consumptions but should not be much of a problem as they only account for less than a third of the car's weight.

- **Fuel Consumption** – During the course of the analysis, it was found that for a reference medium sized car weight of 1400 kg, the fuel consumption was ca. 10.9 L/100km. This value is much higher than most available data on fuel consumption of current medium sized cars – 7.69 L/100km in 2009 (IPCC, 2007). Hence, instead of making fuel consumption dependent on the weight of the car (the design and speed could not be considered anyway); it has been made independent of all parameters. In this way, more accurate values are obtained when compared to using the theoretical formula for the same. In some ways, this assumption might even account for the weight, design and speed of the car. Decreases in fuel consumption in the future could be accounted for by improvements in design and reduction in the total weight of the car.

2.4. Model development:

2.4.1. Parameter Estimation and Assumptions:

It can be seen from the previous figure that there are a lot of parameters to be taken into consideration. Some parameters are obtained and extrapolated from results of previous research done at NTNU, Trondheim. In the case of these parameters, the original sources and the method in which the parameters were derived will be mentioned along with the fact that the parameters have been extrapolated from the research. In the case of scenarios, unless it is specified, the Medium Scenario is always used as the Reference Scenario. The time period for the analysis has been chosen as 1950-2050. The various parameters and the involved assumptions are discussed below:

- **Population**: This data has been obtained from previous research, where historical population data from all countries were aggregated based on UN Population Statistics (Statistical Yearbook, 2010) and future scenarios were aggregated based on the UN Population Projection (World Population in 2300, 2003). There are 3 scenarios considered – the Low, Medium and High Population Growth scenarios. The 2050 estimates for the Low, Medium and High Population scenarios are ca. 7, 8.6 and 10.5 billion people respectively.

- **Cars/Capita**: This data has also been obtained from previous research, where historic numbers for global weighted-average vehicle ownership were calculated based on individual countries. Passenger car stock data were compiled for 1900-1979 (B.R. Mitchell, 2007a; B.R. Mitchell, 2007b; B.R. Mitchell, 2007c) and for 1980-2005 (Statistical Yearbook, 2010). These country data were used to estimate weighted-average vehicle ownership in a global weighted average. Future scenarios for car ownership are estimated based on regional IEA projections (IEA, 2010) and other studies (Joyce Dargay et al., 2007) for 2005 to 2050. All scenarios assume a logistic growth in car ownership with saturation around 2100. The saturation levels for the Low, Medium, and High scenarios were chosen to be 300, 450, and 600 cars per 1000 capita whereas the corresponding 2050 values are ca. 240, 320 and 402 cars per 1000 capita.

- **Lifetime**: These values were based on previous studies on the lifetime from the US, Norway and Japan (Müller et al., 2007; Scacchetti, 2009; Kagawa et al., 2011). For the global level, a constant lifetime is approximated using a normal distribution function with a mean (τ) of 14, 16, and 18 years. The standard deviation (σ) is assumed to be 30% of the mean value. We further assume that the lifetime of aluminium components in cars is the same as the lifetime of the cars.

- **Wrought and Cast Al weight**: This data was, again, obtained from previous research. Historic data for wrought and cast aluminium concentrations in vehicles were derived from estimates for the total aluminium content in vehicles and estimates for the share of wrought and cast aluminium. Ducker Worldwide (Ducker Auto and Light Truck Group, 2009) reports the global average total aluminium content of passenger cars for the

period 1978 (32 kg) to 2009 (149 kg). For the period 1930-1978, a linear growth is assumed under the condition that aluminium use in cars is negligible in 1930.
The average share of wrought and casting alloys employed in average passenger cars are reported for Europe at 10-year intervals beginning in 1978 (Kirchner G., 2009). It is assumed that these numbers are representative for gasoline vehicles in other parts of the world.

In the previous research, the amount of Cast Al was different for the petrol and diesel cars whereas the amount of Wrought Al was considered to be the same in these cars. Casting use began to differ by drive technology after 1978, when the use of aluminium engine blocks in gasoline vehicles started to become established. It is assumed that there is 20% less cast aluminium use compared to gasoline vehicles (Rosdiany, 2010) for diesel cars.

Most studies show that the growth potential for wrought aluminium in passenger cars is generally much higher than for castings, due to the high market penetration rate of Cast Al in engine parts and the current low level of Wrought Al application in BIW (Furrer, 2009; Hirsch et al., undated; Zapp et al., 2002).

On the basis of scenarios in the previous research, three scenarios for the Wrought Al content have been made – the Reference, High Wrought Al and Full Al BIW scenarios, with 2050 values of 90, 180 and 295 kg (IAI, 2007) respectively. Similarly, there are 2 Cast Al scenarios – the Reference and High Cast Al scenarios, with 2050 values of 100 and 120 kg respectively.

- **Steel weight**: The Steel weight value of the car is a tricky parameter. The values from 1976 to 2004 are obtained from Ward's statistical data (Ward's Automotive Yearbook, various years). Prior values are assumed to be the same as the 1976 value. Future values, on the other hand, are taken as dummy values equal to the 2004 value. They are later changed in the Matlab model to account for substitution of steel with aluminium. In this way, only one scenario has to be taken as an input but we get different steel values based on the different Wrought and Cast Al scenarios. For example, in the reference case, the 2050 value for steel weight becomes 883 kg whereas later scenarios have values like 684 kg (Best Realistic Case scenario) and 482 kg (Full BIW Best Case scenario).

- **Recycling Rates and Recovery Rates**: The Recycling Rate in this analysis is defined as the share of recycled steel or aluminium entering the passenger car out of the total steel and aluminium entering the car. There are 3 parameters here – Cast Al Recycling rate, Wrought Al Recycling rate and Steel Recycling rate. These parameters are taken as time series inputs, with an assumed constant value until 2009 obtained from various studies (Cheah et al, 2009; Ungureanu et al, 2007). These values are 80%, 10% and 25% respectively. For the future, 2 scenarios have been considered for each parameter. In the Reference Cases, the parameters stay the same till 2050. In the high Recycling rate scenarios, Cast Al and Steel reach a recycling rate of 95% by 2020 and stay constant afterwards; Wrought Al reaches a recycling rate of 80% by 2050. The Wrought Al high recycling rate scenario only reaches 80% because Wrought Al scrap is currently downgraded into Cast Al. This scenario assumes that in the future, technology would allow us to recycle most of it back into Wrought Al.

Recovery rate refers to the amount of material obtained from the End of Life stage, with respect to the amount of material entering it. In the analysis, a constant recovery rate of 90% (Ungureanu et al, 2007) for all materials is assumed. This parameter is not considered as a time series in order to simplify the model.

- **Vehicle Use**: The vehicle use has been derived from the assumption that an average car travels between 150,000 and 300,000 (IAI, 2007) kilometers in its lifetime. Based on the average lifetime of 16 years and an assumed total lifetime kilometers of 240,000km, a reference value of 15000 km/yr was arrived at. There are 3 scenarios for Vehicle Use taken into consideration – Low, Medium and High Vehicle Use scenarios, with constant values from 2010 to 2050 at 12000, 15000 and 18000 kilometers respectively.

  To account for the uncertainty in the lifetime and logical argument that cars will be driven for lesser kilometers/year later in its life, a simple mechanic was added to the program, where every successive year, the car is assumed to be used 4% less. In this way, a car which travels 15000 km in the first year will only travel 8000 km in its 16th year and if, by some chance, it is still in use for 25 years, it will only travel 5600 km that year.

- **Fuel Consumption**: This parameter was derived from previous research. In this research, there was a range of fuel consumption for passenger cars from various countries, ranging from 7 to 9 L/100km. Hence, the values until 2000 have been assumed as 8 L/100km. The average value for fuel consumption in 2001 was obtained from the IPCC report (IPCC, 2007). This value was used as the reference value for future fuel consumption values. Once again, 3 scenarios were considered here – Low, Medium and High Fuel consumption. These scenarios have some baseline values for 2030 and a final assumed value for 2050. In the Low Fuel Consumption scenario, the 2030 value is 4.78 L/100km (IPCC, 2007) and the 2050 value is assumed as 3 L/100km. In the Medium (reference) scenario, the 2030 value is 5.55 L/100km (IPCC, 2007) and the 2050 value is 4 L/100km. The High Fuel Consumption scenario follows a similar trend as the Medium scenario until 2030 but settles at a higher 2050 value of 5 L/100km.

  To account for engine efficiencies and to counteract possible data error in emissions from reducing the number of kilometers a car travels per year, the fuel consumption of the car has also been designed to increase every year by a constant factor of 1%. In this way, if the car has a fuel consumption of 8 L/100km in its first year, it would have a corresponding value of 9.3 L/100km in its 16th year.

- **Energy Intensities**: In this analysis, the energy intensities for steel and aluminium refer to the amount of energy required to produce 1 kg of the material. In the case of petrol, it is defined as the amount of energy available from burning 1 liter of petrol and has a constant value of 34.2 MJ/L.

Energy intensity data for steel was obtained from the World Steel Association (World Steel, 2012). The energy intensity for primary steel is 21.9 MJ/kg and that of secondary steel is 14.0 MJ/kg.

Energy intensity data for aluminium was obtained from previous studies (Cheah et al, 2009b). The values used are as follows:

  - Primary Wrought Al – 185.8 MJ/kg
  - Secondary Wrought Al – 48.0 MJ/kg
  - Primary Cast Al – 156.9 MJ/kg
  - Secondary Cast Al – 45.4 MJ/kg

The above values may seem to be higher than we would expect. One of the reasons for this could be that these values include the yield factor of aluminium production. In other words, creates 1 kg of primary Wrought Al would require more than 1 kg of primary Al in its upstream manufacturing processes and there will be some wasted Al whose energy requirements have to be accounted for.

All these values have been used as time series of constant values in the Matlab model. This has been done so that future studies in this area could incorporate technological improvements that decrease energy intensity of production.

- **Emission Intensities**: In this analysis, emission intensities are defined as the number of kg CO2 equivalents of emissions produced per unit of material – steel, aluminium or fuel. For petrol, petrol and aluminium, data was obtained using a Life Cycle Assessment (LCA) software developed at NTNU, called Arda. This software uses Ecoinvent data to calculate emissions and other impacts.

  For petrol, the value was found as 0.884 kg CO_2eq/MJ, which then had to be multiplied by the energy intensity to obtain the value in kg CO2/L of petrol.

  For Aluminium, there was no distinction available between Primary and Secondary Wrought and Cast Al. Hence the values for Primary Wrought and Cast were selected to have the general emission intensity value Primary Al – 12.232 kg CO_2eq/kg. Similarly, the value for Secondary Wrought and Cast Al was obtained as the value of Secondary Al – 1.379 kg CO_2eq/kg.

  For Steel, data was obtained directly from the World Steel Association. Primary Steel had and emission intensity of 2.311 kg CO_2eq/kg whereas Secondary Steel had a value one third that of Primary Steel. Both cases also had an additional 0.6 kg CO_2eq of emissions/kg from their product fabrication stage.

These values have not been chosen to be a time series for the purpose of simplicity and the fact that there is not much varying historic data or much change expected in the future.

2.4.2. Substitution of Steel with Aluminium:

One of the most important aspects of this model is the substitution of steel in the car with light-weight aluminium. Replacing steel with aluminium in order to keep the same driving performance leads to the car having lower weight, which in turn leads to lesser fuel consumption. This decreases the lifetime emissions and energy consumption of the car. Substitution creates a direct and indirect weight savings. For example, substituting a steel BIW of a car with an aluminium BIW would result in direct savings due to the substitution itself. It would also lead to indirect savings due to the reduced weight of the other components in order to maintain the same driving performance.

The substitution has been calculated in the Matlab model based on some reference data available in the IAI report (IAI, 2007). The method used is as described below:

Weight of Reference Al Component already present in car = $\boldsymbol{WAl,ref}$

Weight of Reference Steel Component already present in car = $\boldsymbol{WSt,ref}$

Direct Savings $\boldsymbol{Sd} = \boldsymbol{Wst,ref} - \boldsymbol{WAl,ref}$

Indirect Savings $\boldsymbol{Si} = \boldsymbol{Sd} * \boldsymbol{parameter}$

The parameter is the ratio between the indirect savings and direct savings. The value of this parameter is taken as 23% (IAI,2007).

Total Savings $\boldsymbol{St} = \boldsymbol{Sd} + \boldsymbol{Si}$

Ratio of Reference Al Component weight to the Total Savings, $\boldsymbol{R} = \boldsymbol{WAl,ref} \,/\, \boldsymbol{St}$

Weight of new Al component = $\boldsymbol{WAl,new}$

Extra Al added $\boldsymbol{WAl,ext} = \boldsymbol{WAl,new} - \boldsymbol{WAl,ref}$

Extra savings due to new component, $\boldsymbol{Sx} = (\boldsymbol{WAl,ext}) \,/\, \boldsymbol{R}$

Hence, Weight of new Steel Component $\boldsymbol{WSt,new} = \boldsymbol{WSt,ref} - \boldsymbol{Sx} - \boldsymbol{WAl,ext}$

In the model, this method has been used to incorporate the weight savings in the steel of the car from the extra Wrought and Cast Al added to the car since 2009.

2.4.3. Model Calculations:

Now that the parameters have been finalized, it’s time to look into how the model calculates various flows, stocks, energies and emissions. A set of codes were made which would help the model determine which parameter scenario to choose for each parameter. These codes are presented in Appendix B.

The total passenger car stock is calculated as:

$$\boldsymbol{Sc} = \boldsymbol{Population} .* \boldsymbol{Cars/Capita}$$

Note: All values in bold refer to vectors or matrices. Also, '.*' implies multiplying one element of a vector/matrix with the corresponding number in the other vector/matrix to get a new vector/matrix of the same dimensions.

This value is transferred, along with the lifetime, into a Matlab function previously developed at NTNU (MFA Dynamics Toolbox, Pauliuk, 2009), which calculates the number of cars bought and retired each year, the stock change, and also detailed car stocks and retired car flows based on the year (cohort) they were bought.

Once this is done, the model calculates the various aluminium and steel flows, and the energies and emissions. Aluminium and steel flows are calculated as follows:

$$\boldsymbol{Material\ Inflow} = \boldsymbol{Cars\ Bought} .* \boldsymbol{Material\ weight\ in\ car}$$

Where, the 'Material' will refer to Wrought or Cast Al or Steel. Secondary material flows would be calculated by multiplying this value with the corresponding recycling rates:

$$\boldsymbol{Secondary\ Material\ Inflow} = \boldsymbol{Material\ Inflow} .* \boldsymbol{Material\ Recycling\ Rate}$$

The material outflows are found out as shown:

$$\boldsymbol{Detailed\ Material\ to\ Waste} = \boldsymbol{Detailed\ Cars\ to\ Waste} * \boldsymbol{diag}\ (\boldsymbol{Material\ weight\ in\ car})$$

$$\boldsymbol{Material\ Outflow} = \boldsymbol{Rowaggr}\ (\boldsymbol{Detailed\ Material\ to\ Waste})$$

Where 'Detailed' refers to the year by year data and 'diag' is the diagonal matrix form of the vector in parentheses. 'Rowaggr' refers to the Row aggregation of the matrix in order to obtain a column vector.

The total aluminium or steel scrap entering back into the system from EOL is found out as:

$$\boldsymbol{Recyclable\ Material\ Flow\ =\ Material\ Outflow} * Recovery\ Rate$$

Once all the flows have been calculated, the direct and indirect energy consumption are calculated:

$$\boldsymbol{Prim.Material\ Energy\ Consumption = Material\ Inflow\ .*\ Energy\ Intensity\ .*\ (1 - Recycling\ Rate)}$$

$$\boldsymbol{Sec.Material\ Energy\ Consumption = Sec.Material\ Inflow\ .*\ Energy\ Intensity\ .*\ Recycling\ Rate}$$

$$\boldsymbol{Operational\ Energy\ Consumption\ =\ Vehicle\ use\ .*\ (Fuel\ efficiency)/100\ .*\ Petrol\ Energy\ Intensity}$$

Note: The Fuel efficiency is divided by 100 to change to units from L/100km into L/km.

Similarly, direct and indirect emissions are calculated as shown below:

$$\boldsymbol{Prim.Material\ Emissions = Material\ Inflow\ .*\ (1 - Recycling\ Rate) * Emissions\ Intensity}$$

$$\boldsymbol{Sec.Material\ Emissions = Sec.Material\ Inflow\ .*\ Recycling\ Rate * Emissions\ Intensity}$$

$$\boldsymbol{Operational\ Emissions\ = Vehicle\ use\ .*\ (Fuel\ efficiency/100)\ *\ Petrol\ Emissions\ Intensity}$$

Once all the results have been obtained, they are transferred into an Excel file and then for further analysis.

An easy way of visualizing the model is shown in Figure 6.1, along with its legend in Figure 6.2 below. The energy consumption is not shown in the model as it is analogous to the direct and indirect emissions.

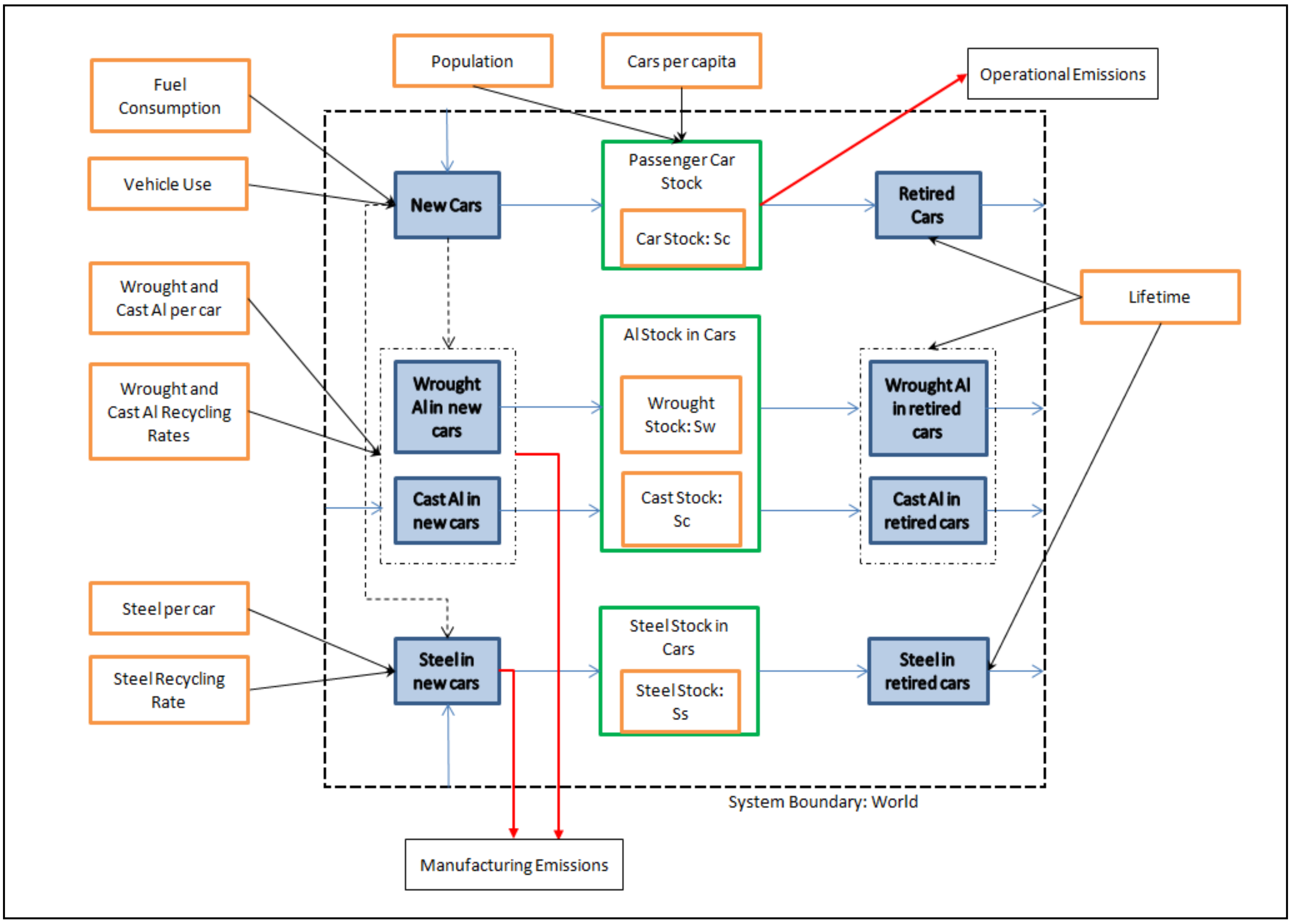

Figure 6.1: Model Working Procedure

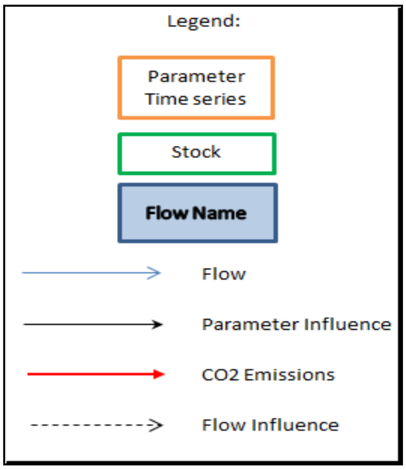

Figure 6.2: Legend for Figure 6.1

3. RESULTS

The results obtained from the model are shown in this section. First, the results of the Reference Case are explained. Next, the results of the Sensitivity Analysis of the various parameters are described. Finally, several multi-parameter scenarios have been explored and the findings explained.

3.1. Reference Case:

In this section, the Reference Case is first shown. This case represents all the default parameters used and shows what the possible energy consumption, emissions and the Al and Steel flows would be at Business as usual (BAU).

3.1.1. Energy:

As seen from Figure 7 below, the total energy consumption in 2050 is more than double as that from 2000. It can also be noted that the main cause of this is the fuel used from driving the car. The energy used for the production of Al and Steel have values of almost an order of magnitude less than the direct energy consumption. It may not be so clear from this graph, but the amount of energy being used in passenger cars from Al production has so far been less than that of steel production. However, in the future, the Aluminium industry will have a slightly higher energy consumption than the steel industry in the transportation sector.

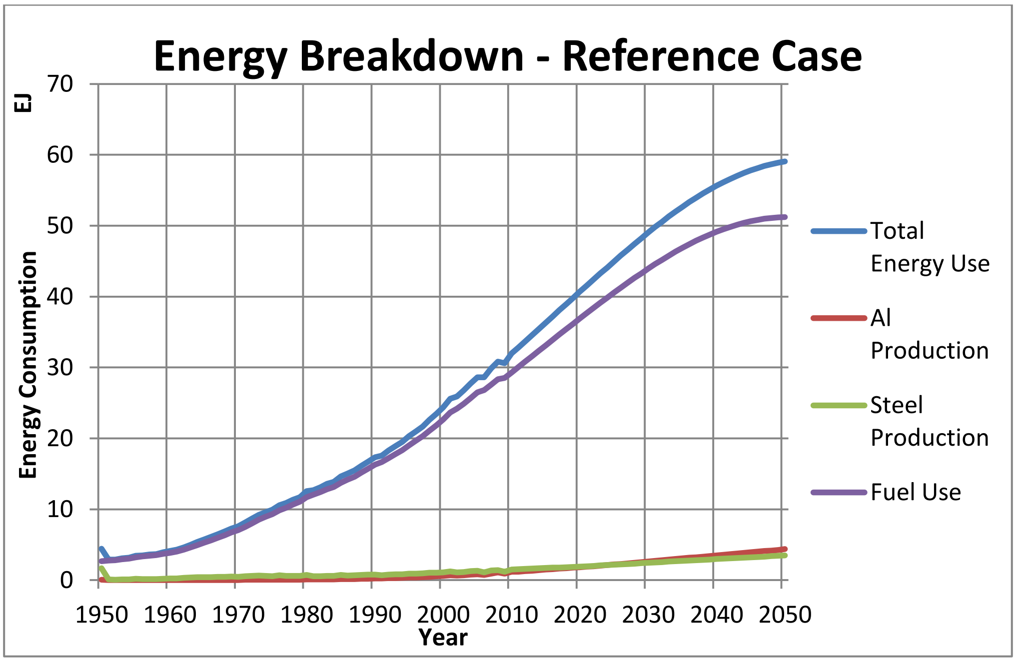

Figure 7: Energy Breakdown - Reference Case

3.1.2. Emissions:

The emissions in the BAU scenario follow a similar pattern to the energy consumption. The total CO_2 emissions in 2050 are more than 2 times that of the emissions in 2000. This result is almost the exact opposite of what we need in 2050 in order to restrict the Global average temperature rise to 2°C. Once again, the direct emissions are the most dominant factors for these values. The emissions from steel are consistently higher than those from aluminium. This is mainly due to the higher amount of steel in cars. The important thing to note is that unlike the energy case, the aluminium emissions do not exceed the steel emissions in the future. This is because aluminium is more energy intensive than steel.

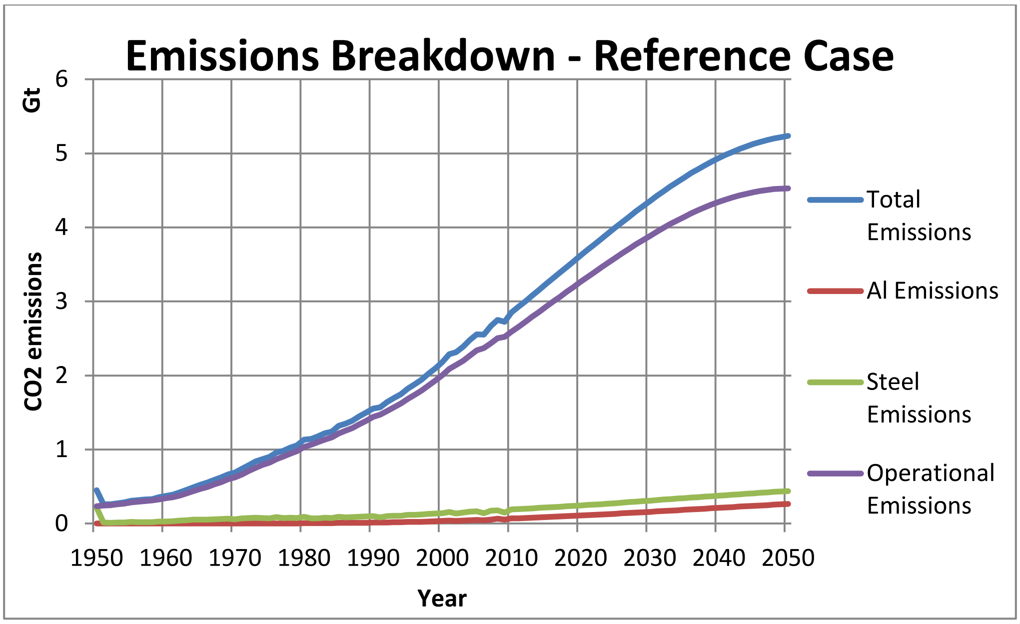

Figure 8: Emissions Breakdown - Reference Case

3.1.3. Aluminium Flows:

The following graph show the flows of secondary aluminium (Wrought and Cast combined) going into the car from the manufacturing industry and back to the manufacturing stage from EOL collection. It is observed that the amount of available Al scrap is exceeding the amount of secondary Al entering the car from 2030 onwards. This would create a problem in the future due to the unused scrap being generated, which cannot be used anywhere. It also means that the excess Al scrap coming from Buildings and other systems also cannot enter into cars in the form of recycled Al. This result hence substantiates previous studies in this area.

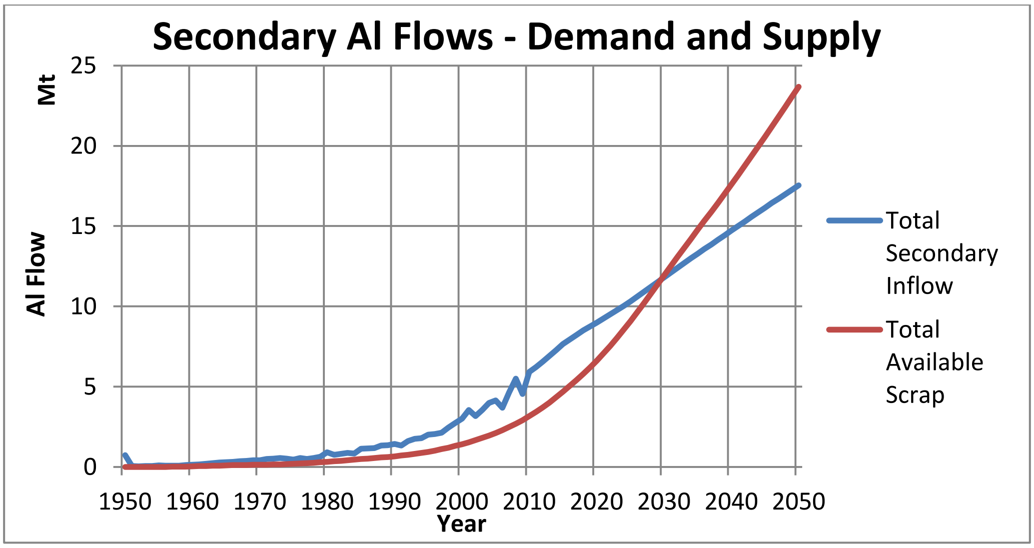

Figure 9: Secondary Al Flows - Demand and Supply

3.1.4. Steel Flows:

The following graph show the flows of secondary steel going into the car from the manufacturing industry and back to the manufacturing stage from EOL collection. As mentioned in the earlier assumption, all available scrap from the car is first used by the passenger car manufacturing industry itself and then sent to other industries in case of an excess. It is observed that only about half the scrap generated is reused by the Passenger car industry. Hence, there is a lot of excess steel available for the Building and other sectors.

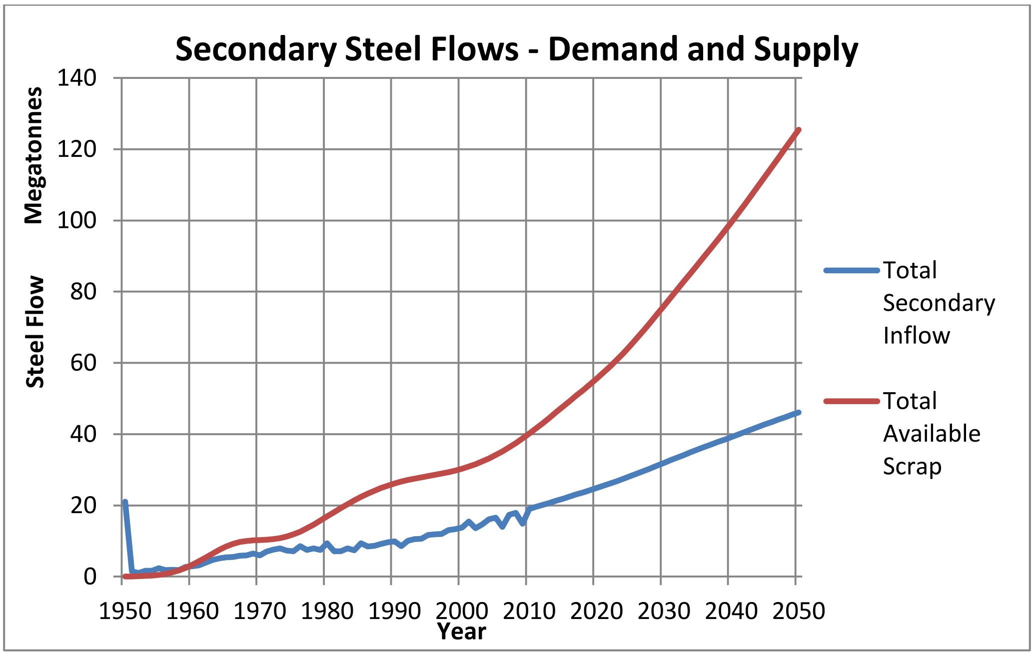

Figure 10: Secondary Steel Flows - Demand and Supply

3.2. Sensitivity Analysis / Single Parameter Scenarios:

As there are so many parameters to be taken into consideration for this study, a sensitivity analysis is of importance. However, this analysis has not taken into direct consideration the theoretical formulae. Hence the results obtained are more like single parameter scenarios than absolute and relative sensitivity values.

3.2.1. Population

As observed in the graph below, having a higher population increases the total Global CO_2 emissions and vice versa. Having a total population of ca. 10.5 billion in 2050 instead of the reference value of ca. 8.6 billion, creates a 23% increase in the total CO_2 emissions. On the other hand, having a population of ca. 7 billion in 2050 would create a 20% decrease in the total CO_2 emissions with respect to the reference case.

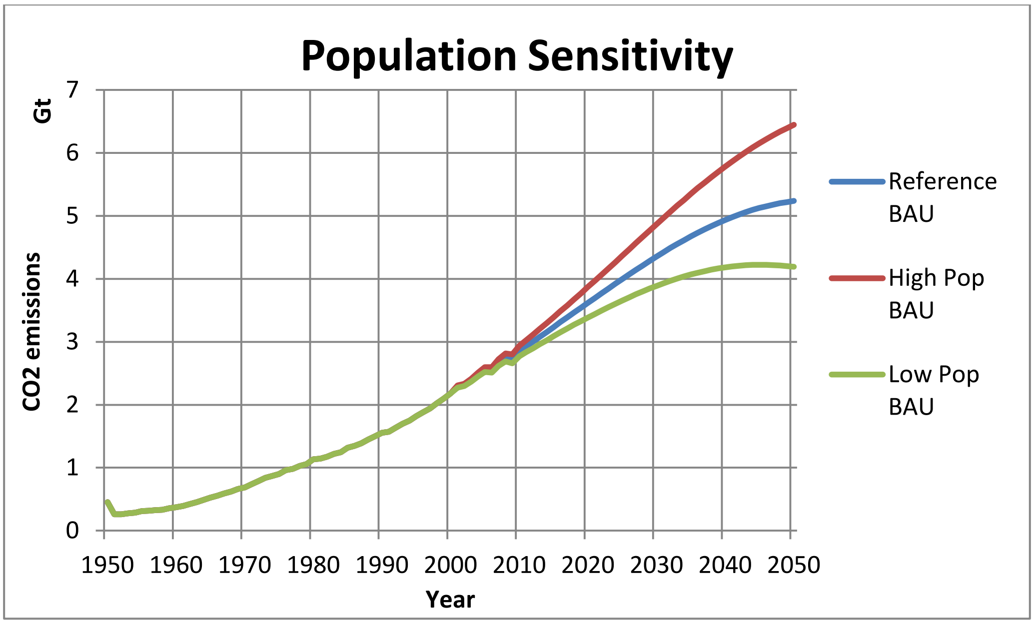

Figure 11: Population Sensitivity

3.2.2. Cars/capita

The Cars per capita follows a similar trend to that of the population. Increasing this value from 320 cars/1000capita in 2050 in the reference case to 402 cars/1000capita increases the total emissions by 26%. Decreasing this value to 240 car/1000capita decreases the total emissions by 25%.

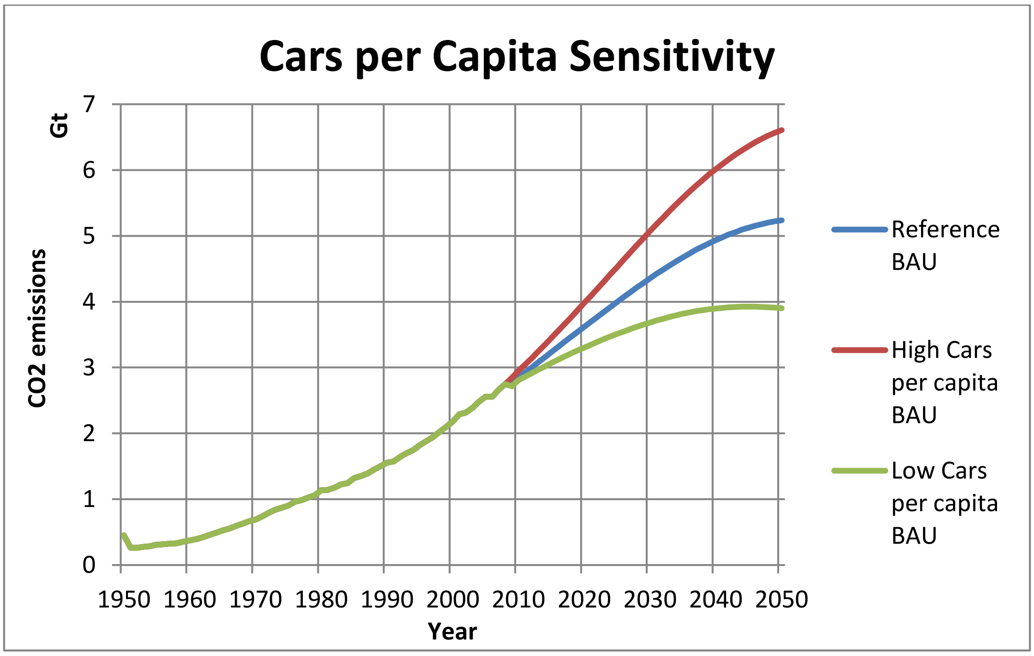

Figure 12: Cars per Capita Sensitivity

3.2.3. Lifetime

Changing the lifetime of the car seems to have a much lesser impact on the total emissions. An increase from 16 to 18 years in the lifetime of the car creates a 2.5% decrease in the total CO_2 emissions whereas a decrease to 14 years creates an increase in the total CO_2 emissions by 2.8%.

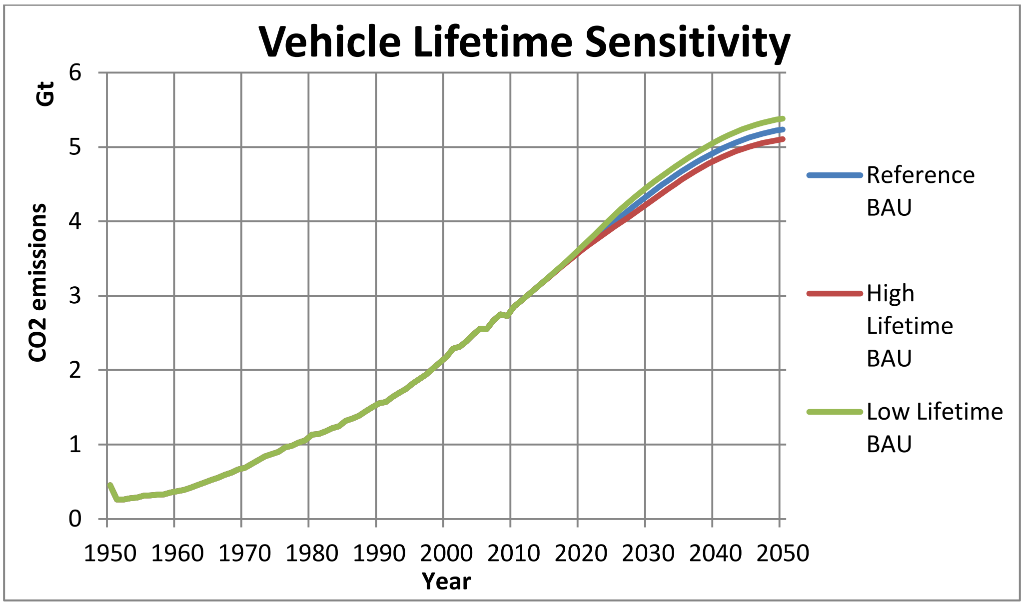

Figure 13: Lifetime Sensitivity

3.2.4. Vehicle Use

Changing the number of kilometers driven annually has a much higher impact on the total emissions than changing the lifetime of the car. Increasing the number of kilometers driven from 15000 km/year to 18000 km/year increases the total CO_2 emissions by 17.3%. Decreasing this value to 12000 km/year on the other hand creates a reduction in the total CO_2 emissions by 17.3%.

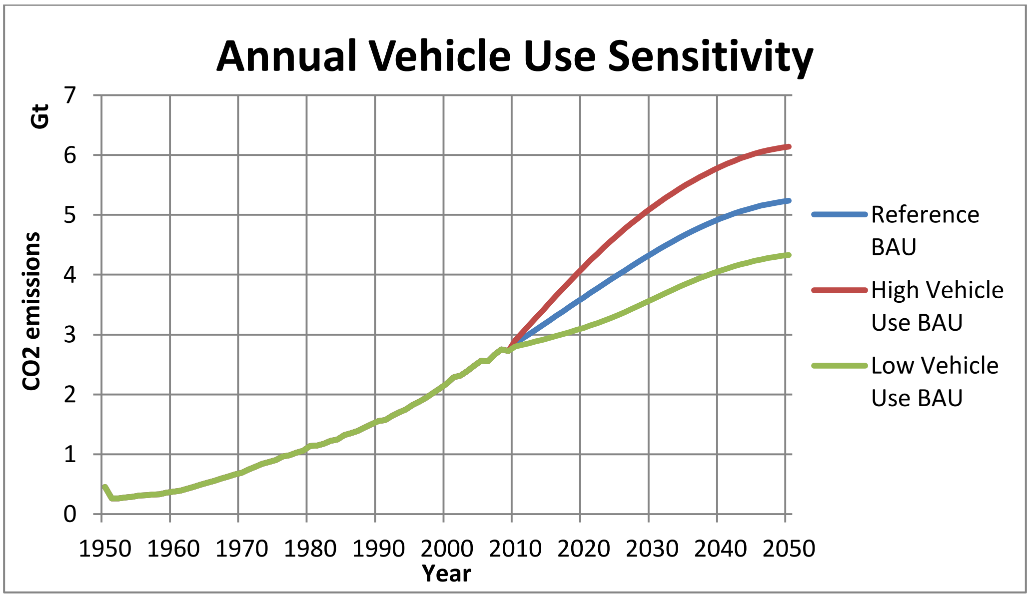

Figure 14: Annual Vehicle Use Sensitivity

3.2.5. Fuel efficiency

The fuel consumption has a slightly different pattern from the other graphs. This is because, in the case of the High Fuel consumption BAU scenario, the average fuel consumption is still decreasing from its value in 2001 and follows a similar pattern as the reference case until 2030 where the value is 5.5 L/100km (IPCC, 2007). From 2030 to 2050, the fuel consumption only decreases slightly to 5.0 L/100km whereas the reference case decreases to 4 L/100km. This is reflected in the following graph and shows that the High Fuel consumption scenario has 12.7% higher CO_2 emissions than the reference case. The Low Fuel consumption scenario, on the other hand, settles at 3 L/100km in 2050 and thus shows a 17.6% decrease in the total CO_2 emissions.

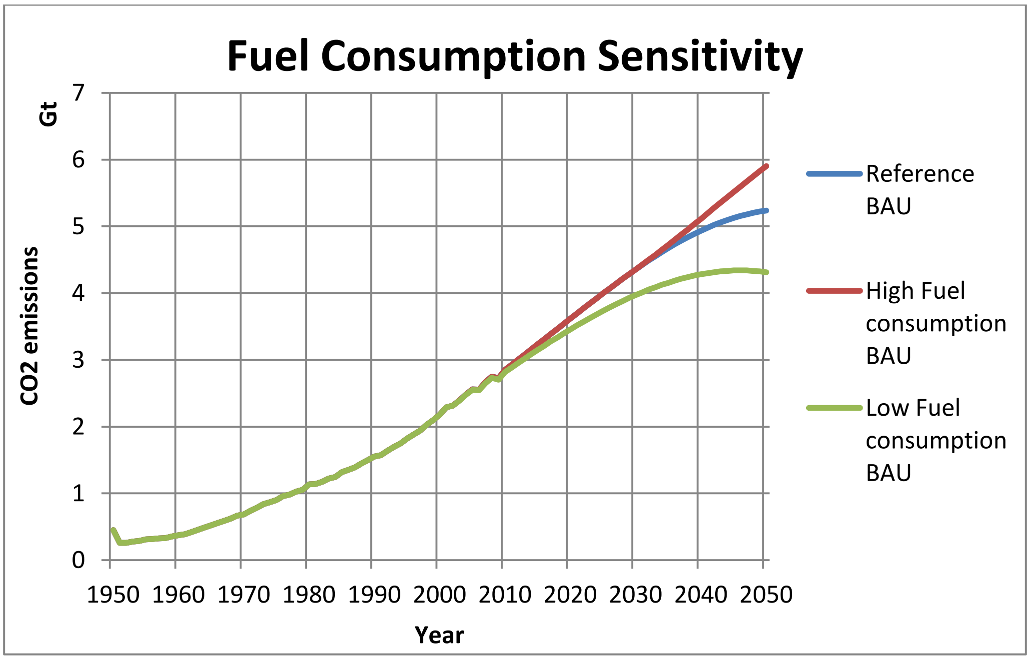

Figure 15: Fuel Consumption Sensitivity

3.2.6. Wrought and Cast Aluminum content

As seen from Figure 16.1, increasing the amount of Cast Al has a negligible impact on the total CO2 emissions, whereas increasing the amount of Wrought Al has only a small impact on total CO_2 emissions. In the latter case, the amount of wrought Al in the car is double that of the reference case in 2050. This doubling increases the total CO_2 emissions by 2.3% only.

Figure 16.2 shows the impact of these changes in the emissions from Aluminium Industry for passenger cars. Again, the increased Cast aluminium has a very small increase in the emissions from the car manufacturing industry. However, the doubling of wrought Al increases the emissions from this industry from ca. 275 Mt CO_2 in the reference case to ca. 475 Mt CO_2 .

It is also observed, however, that the increase in aluminium content in the car causes a decrease in the CO_2 emissions from the Steel Industry (Figure16.3). While the Cast Al creates a small reduction in the CO_2 emissions from the Steel Industry, the Wrought Al creates a larger reduction – ca. 20% -- from the Steel Industry.

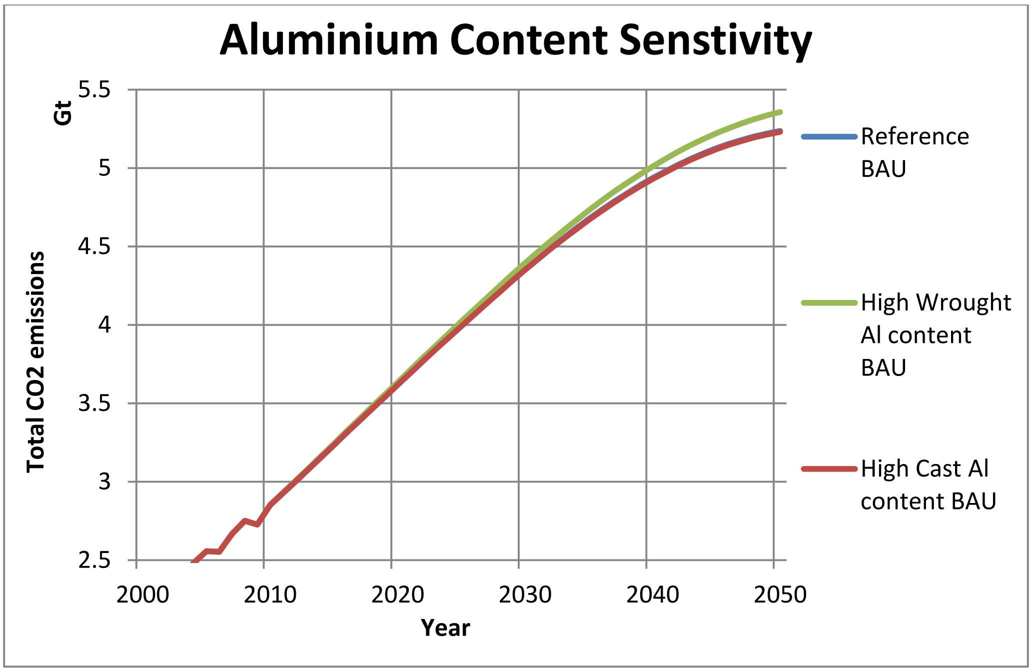

Figure 16.1: Aluminium Content Sensitivity – Total CO_2 emissions

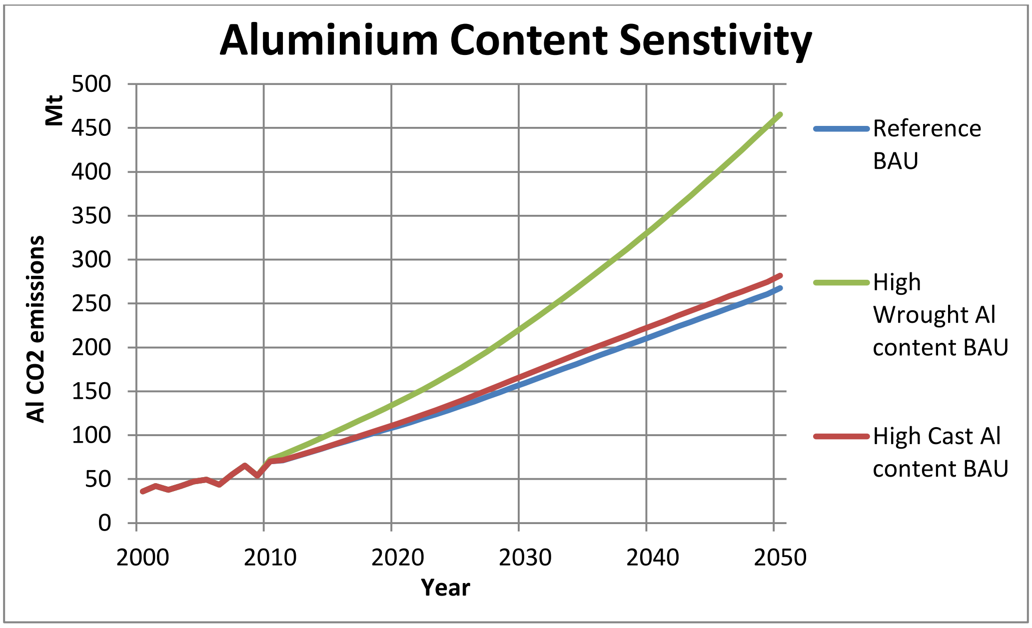

Figure 17.2: Aluminium Content Sensitivity – Al CO_2 emissions

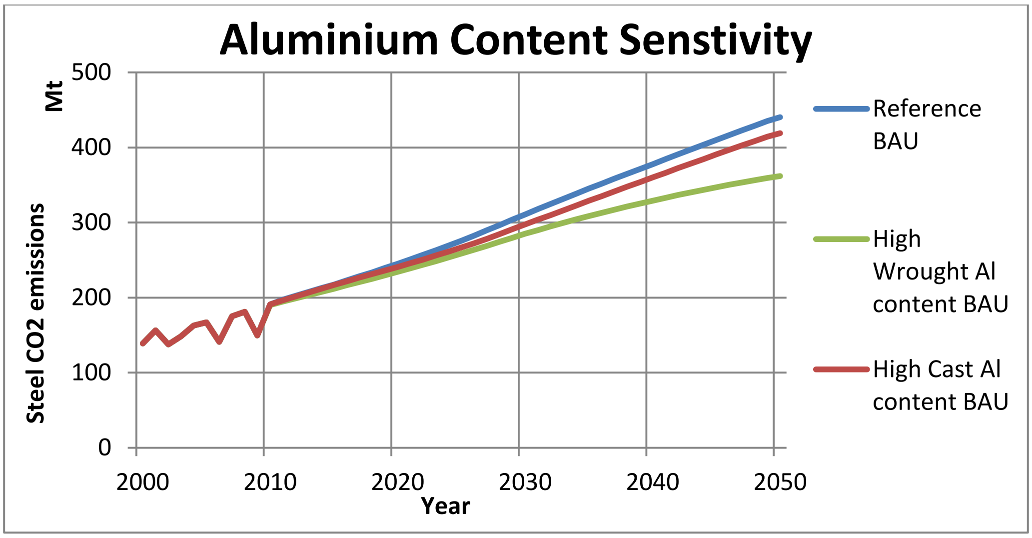

Figure 18.3: Aluminium Content Sensitivity – Steel CO_2 emissions

3.2.7. Recycling rates

It is observed from Figure 17.1 that increasing all the recycling rates only creates a slight reduction in the total CO_2 emissions. Increasing the steel recycling rate from 25% in 2009 to 95% in 2020 and having it stay at that level creates a 3.8% reduction in the total CO_2 emissions. Increasing the recycling rate for Cast Al from 80% in 2009 to 95% by 2020 provides only a 0.6% reduction in the total CO_2 emissions. This decrease is as expected due the already high recycling rates of Cast Al. In the case of Wrought Al, the recycling rate is made to increase from 10% in 2009 to 80% in 2050. This increase causes a 2.6% reduction in the total CO_2 emissions.

Looking into the individual industries provides us with a more optimistic view. In the case of the Aluminium Industry (Figure 17.2), increasing the Cast Al recycling rate creates a 15% decrease in the CO_2 emissions from car manufacturing with respect to the reference case. Increasing the Wrought Al recycling rate, on the other hand, creates an almost 50% reduction in CO_2 emissions with respect to the reference case. In the Steel Industry (Figure 17.3), the increase in the recycling rate of steel creates an approximate reduction in the CO_2 emissions of 45% with respect to the reference case.

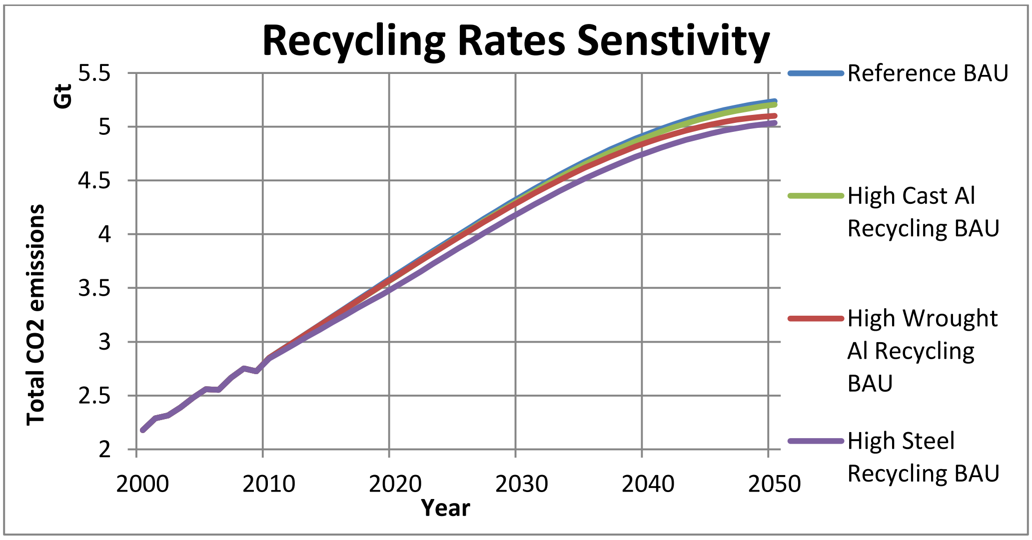

Figure 19.1: Recycling Rates Sensitivity - Total CO_2 emissions

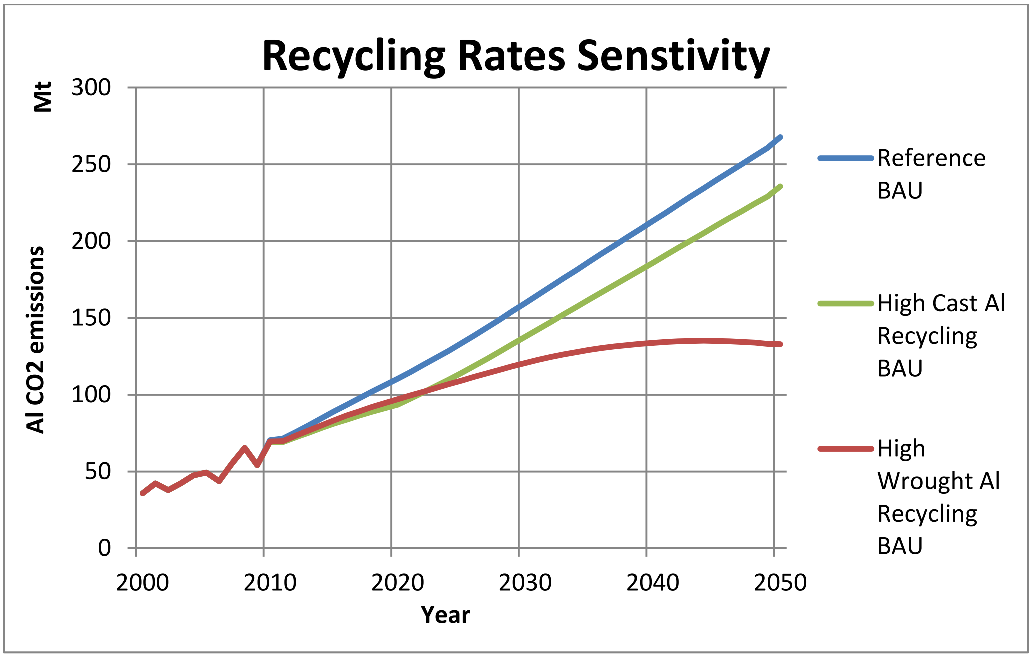

Figure 20.2: Recycling Rates Sensitivity - Al CO_2 emissions

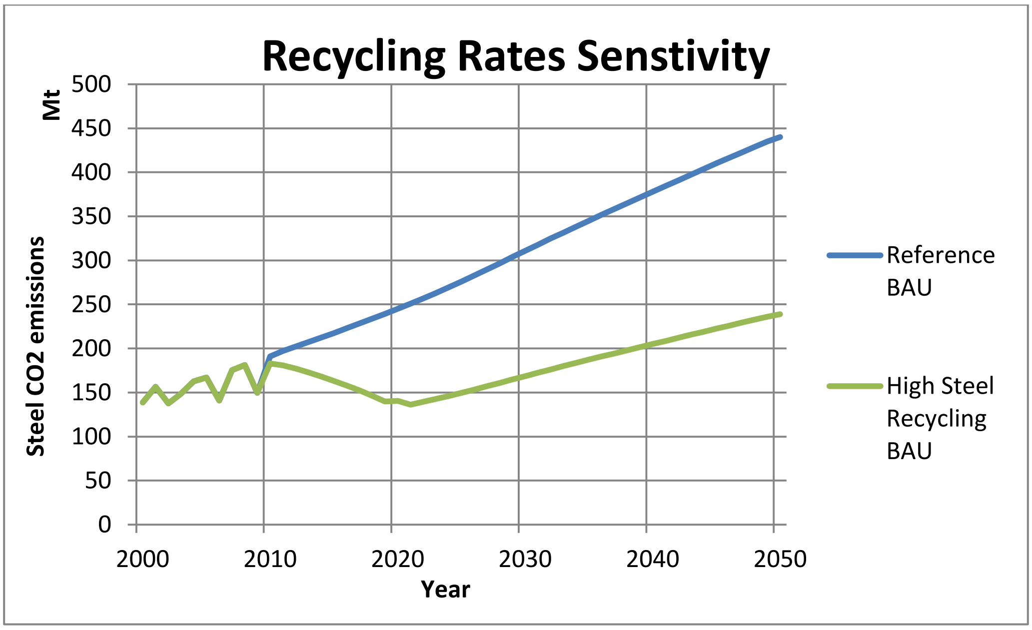

Figure 21.3 Recycling Rates Sensitivity - Steel CO_2 emissions

3.3. Scenarios:

By combining the above parameters in different ways, multiple scenarios have been made. They are shown in the table below.

Table 2: Scenarios and their descriptions

Scenario Number	Scenario Description
Scenario 1	Lifestyle change in vehicle use – This is achieved by reducing the average number of kilometers driven annually from 15000 to 12000 and by increasing the lifetime of the car from 16 to 18 years.
Scenario 2	Global Population reduction and reduction in car ownership
Scenario 3	Combination of scenario 1 and 2 – All non-technology oriented changes
Scenario 4	Implementing high recycling rates in Wrought and Cast aluminium only
Scenario 5	Implementing high recycling rates in aluminum and steel
Scenario 6	Focus on Cast Al – Implementing high recycling rates as well as having a higher amount of it in the car
Scenario 7	Focus on Al – Implementing high recycling rates as well as having a higher amount of Wrought and Cast Al in the car
Scenario 8	Implementing all material technology related changes i.e. high recycling rates of aluminium and steel as well as higher amounts of Wrought and Cast Al in the car
Scenario 9	Implementing all non-EOL changes i.e. higher amounts of Wrought and Cast Al as well as decreasing the fuel consumption of the car
Scenario 10	Implementing all technology oriented changes – Lower fuel consumption, higher recycling rates of Al and steel and higher amounts of Wrought and Cast Al in the cars
Scenario 11	Combination of Scenario 1 and 10 – combining technology and lifestyle changes
Scenario 12	Same as scenario 11 except for the further implementation of reduced vehicle ownership
Scenario 13 aka Best Realistic Case	Combination of all possible technological and lifestyle oriented changes i.e. combination of scenario 3 and 10
Full BIW Reference BAU	Implementing a full aluminum BIW while keeping all other parameters at their default value
Full BIW Best Case	Implementing a full aluminium BIW and combining it with all possible technological and lifestyle changes

Figure 18 shows all the scenarios related to lifestyle changes. It can be Scenario 1 provides a reduction of ca. 20% from the reference case, whereas Scenario 2 provides a much greater reduction, ca. 40%, from the reference case. It should be noted that scenario 2 is more difficult to achieve with respect to scenario 1 due to socio-economic reasons. Scenario 3, the combination of the two scenarios gives us a 52.3% reduction in the global total CO_2 emissions. The combination does not result in a 60% reduction because the parameters in scenario 1 are dependent on the population and car ownership and a reduction in the latter parameters creates a decrease in the reduction from the former parameters. On the bright side, the total CO_2 emissions in 2050 from Scenario 3 are now only 12.9% higher than the emissions from 2000.

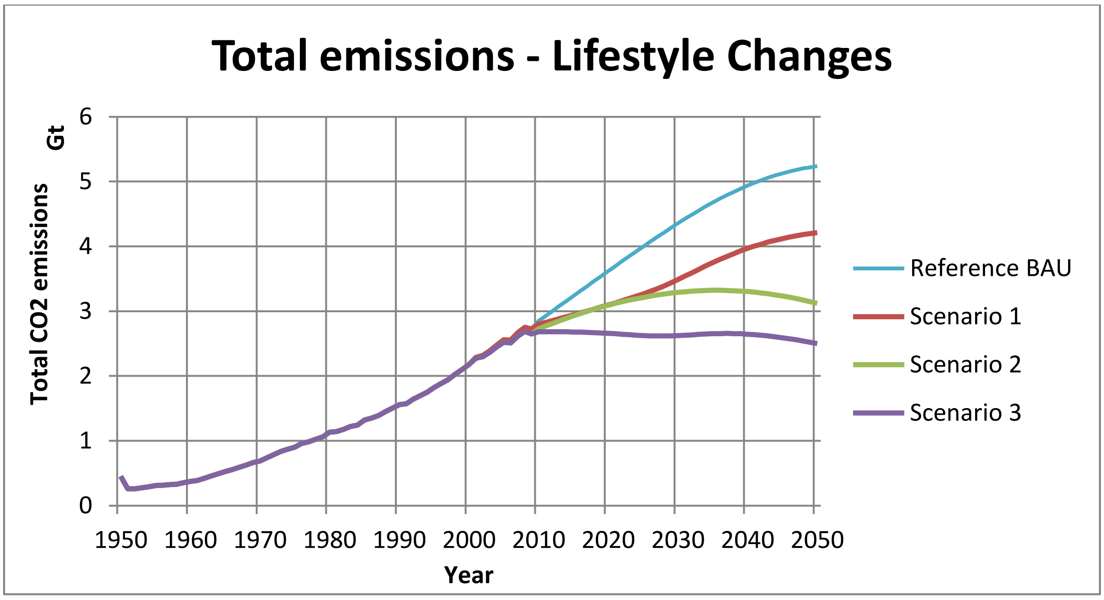

Figure 18: Total Emissions - Lifestyle Changes

When it comes to the scenarios related to technological changes, it is apparent from Figure 19 that Scenarios 4, 5, 6, 7 and 8 have the least impact on the total CO_2 emissions. This result is in agreement with the results for the individual parameters chosen for these scenarios. Among these scenarios, Scenario 8 has the highest reduction of CO_2 emissions – 6.7% with respect to the reference case.

Scenario 9 represents a reduced fuel consumption combined with an increase in the amount of Wrought and Cast Al in the car. This scenario leads to a 15.7% reduction of total CO_2 emissions with respect to the reference case. It can be observed that this reduction is less than that obtained by only reducing the fuel consumption (which was 17.6%). This is because the decrease in CO_2 emissions from fuel consumption is offset by the slight increase in CO_2 emissions from the increased use of Wrought and Cast Al.

Scenario 10 has the highest total CO_2 emissions reductions among all the technology change oriented scenarios, at 24.3%. The new 2050 value for total CO_2 emissions is still 45% more than the 2000 levels.

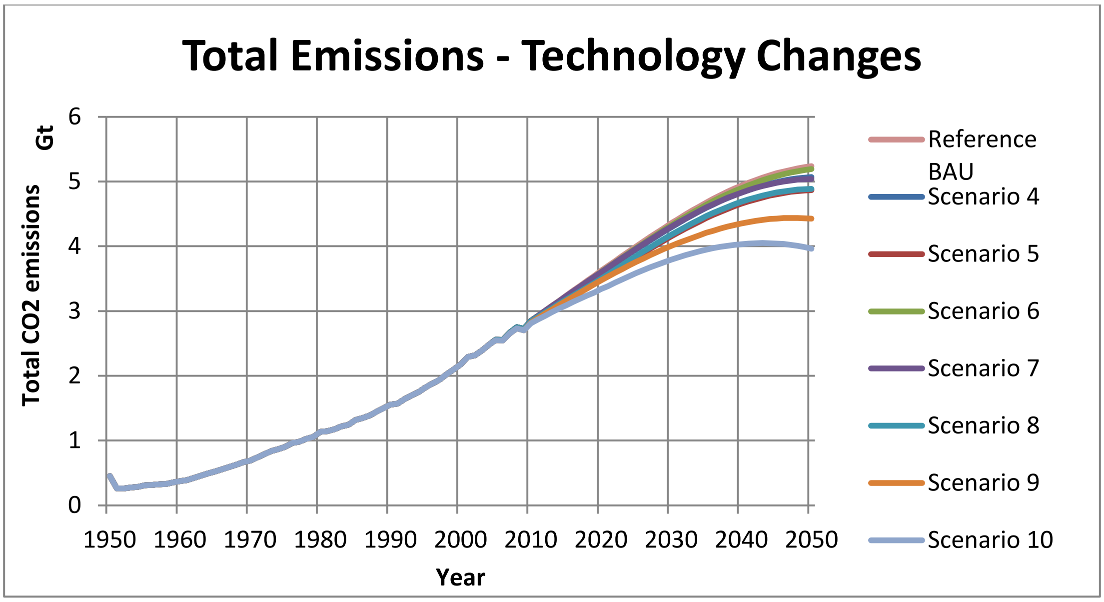

Figure 19: Total Emissions – Technological Changes

The combined scenarios present the most optimistic results. Scenario 11 represents a combination of all possible technology changes and a change in the way people use their car to reduce the annual kilometers travelled and increase the car's lifetime. This scenario leads to a total CO_2 emissions reduction of 39.2% with respect to the reference scenario.

Scenario 12 builds up on scenario 11 by including a reduction in car ownership. It has already been observed earlier that a reduction in car ownership had a strong impact on the CO_2 reduction. Here, the observed total CO_2 emissions reduction in 2050 is 54.7% from the reference case, which is still 8.2% higher than emission levels in 2000.

The Best Realistic Case scenario is a combination of Scenario 3 and Scenario 10. It represents all possible technology and lifestyle changes. Here, the total CO_2 emissions reduction in 2050 is 63.6% from the reference case. This value is now 14.5% below the 2000 levels and is the first scenario to have lower emissions in 2050 when compared with 2000 emissions.

The Full BIW Reference BAU scenario is a single parameter change scenario where the steel and aluminium BIW of the car is replaced with a purely Wrought Al BIW. This scenario is similar to the single parameter scenario where there is only an increase in the Wrought Al content of the car. Hence, the total CO_2 emissions here are slightly more than those from the reference case. However, when this scenario is combined with all the other parameters from the Best Realistic Case scenario, we get the Full BIW Best Case scenario. In this scenario, the total CO_2 emissions in 2050 is 63.4% lesser than the value of the reference case. This value is 13.7% lesser than that of the year 2000 and is the only other value to be lesser than the 2000 emission levels. It is interesting to observe that the values obtained in this scenario are very similar to those obtained from the Best Realistic Case.

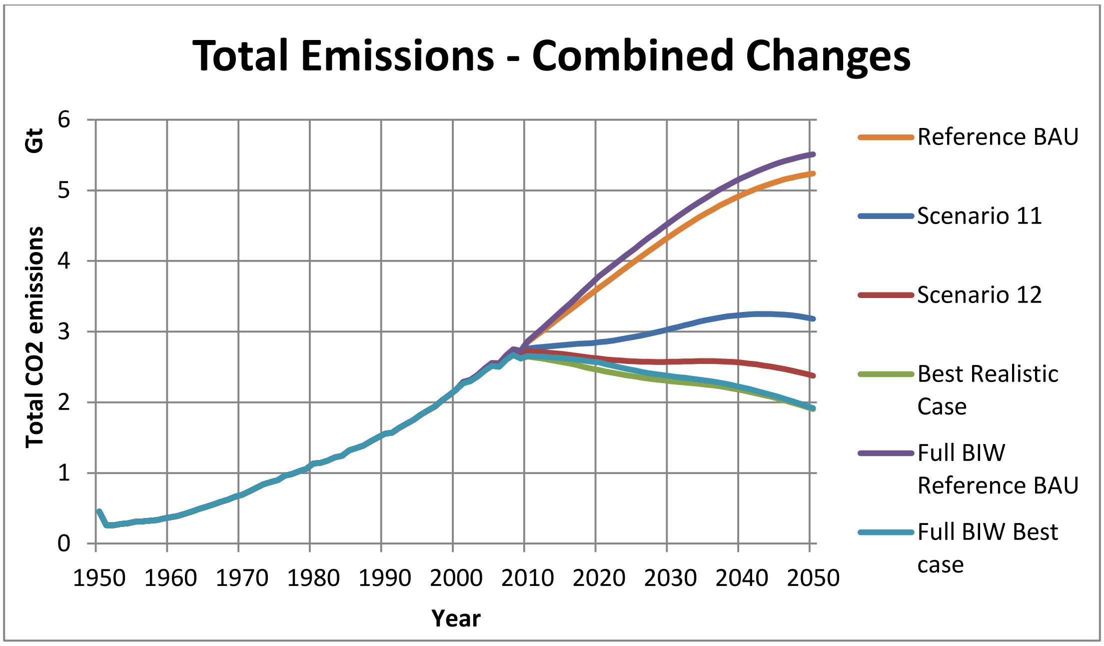

Figure 22: Total Emissions – Combined Changes

3.3.1. A Deeper Look into the 'Best' Scenarios:

Figure 21 shows the total emission levels from the Reference BAU, Best Realistic Case and the Full BIW Best case scenarios. The Best Realistic Case and the Full BIW Best Case have similar trends. However, if we look into their Emissions Breakdowns – as shown in Figure 22 – we can see that they differ quite a bit in the industry emissions. In the former case, the emissions from the Aluminium Industry and Steel Industry in the car manufacturing sector seem to be almost equal to each other after 2020. However, in the latter case, the Aluminium Industry emissions are much higher than the Steel Industry emissions in the near future but are heading towards equilibrium close to 2050. This trend is further clarified through figures 23 and 24. It is also clear that the emissions from the steel industry in the Full BIW Best case are consistently lesser than the same from the Best Realistic Case. **This is also the only industry and case where the emissions in 2050 are ca. 50% lesser than 2000 levels**.

It should again be noted that the fuel consumption is assumed to be independent from the weight of the car. This implies that the direct CO_2 emissions (Figure 25) from both these cases are the same. The direct emissions in 2050 are 61.9% lesser than the reference case values and 16% lesser than the same from 2000.

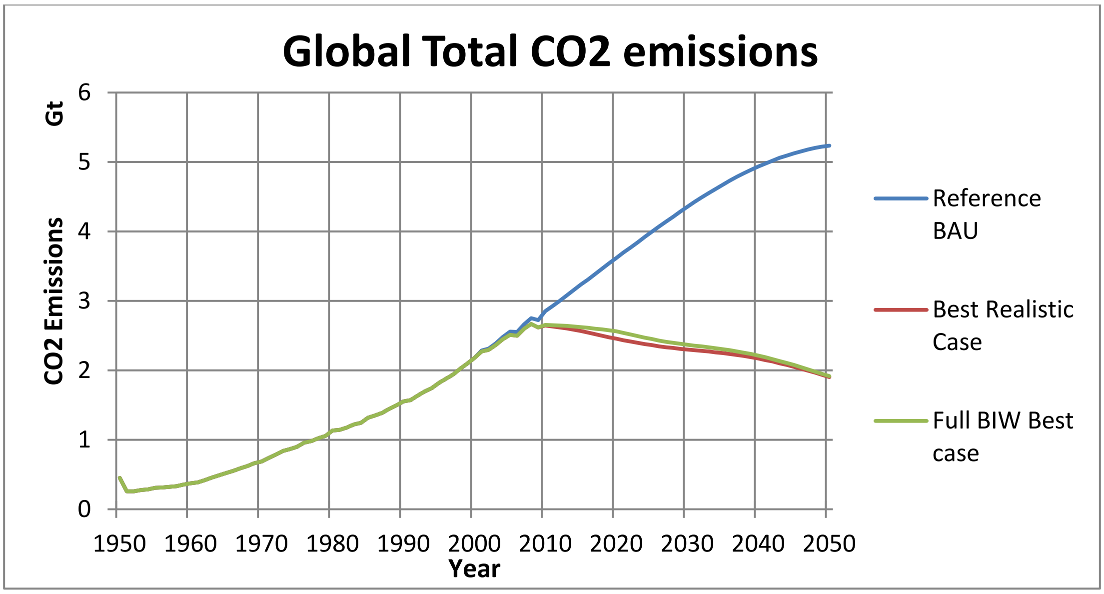

Figure 23: Global Total CO$_2$ emissions - Best Cases

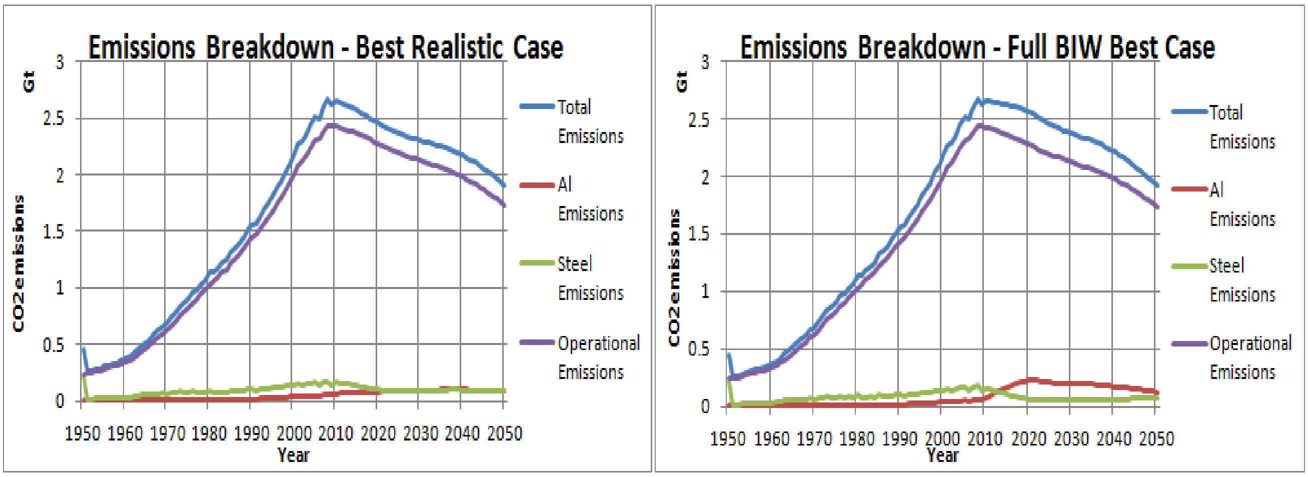

Figure 24: Emissions Breakdown - Best Cases

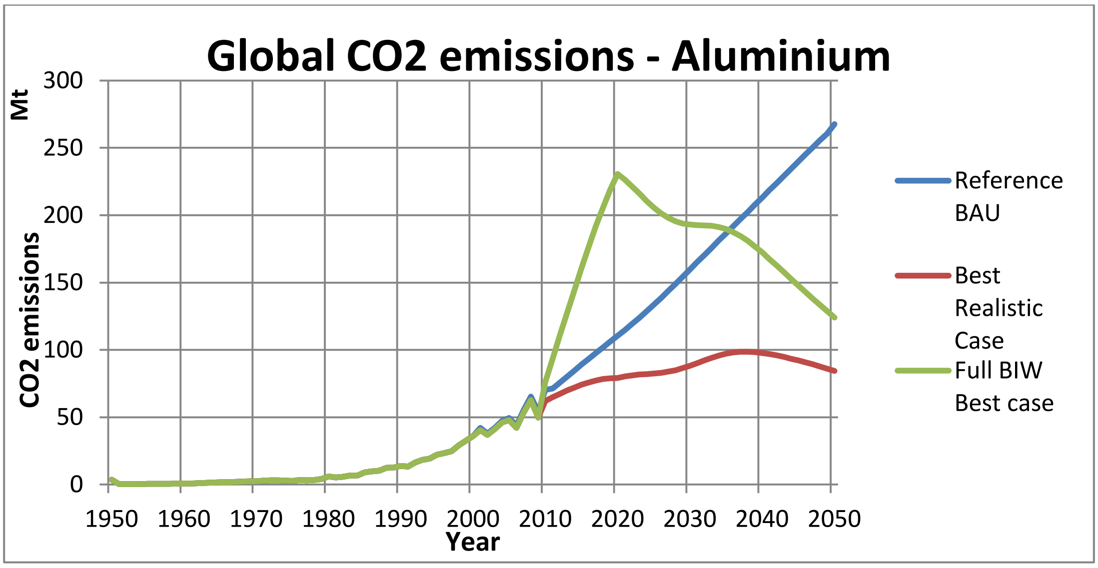

Figure 25: CO$_2$ emissions from Al - Best Cases

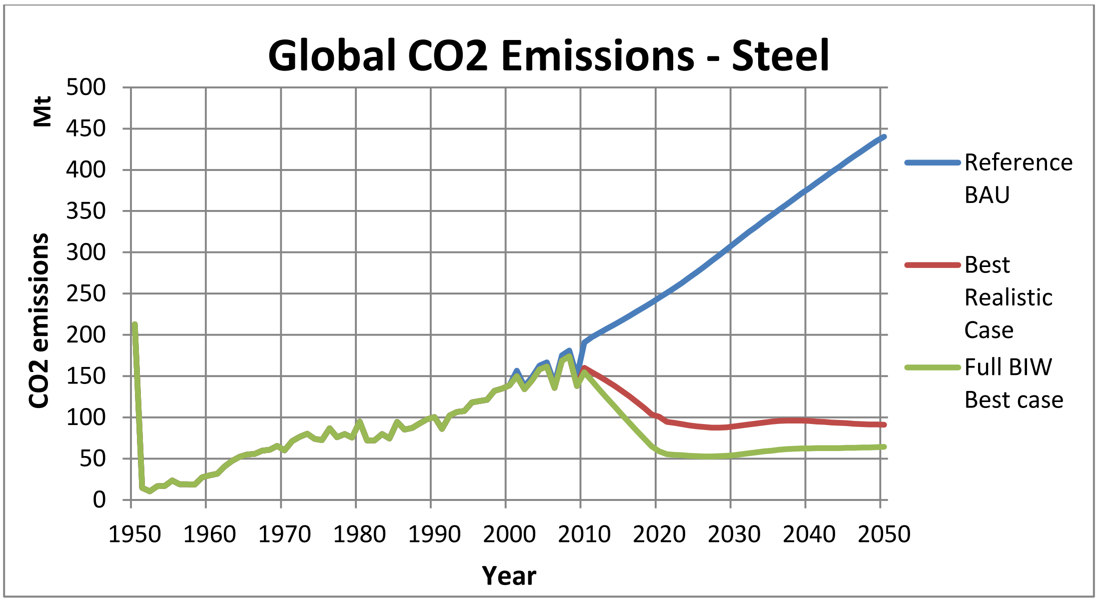

Figure 26: CO_2 emissions from steel - Best Cases

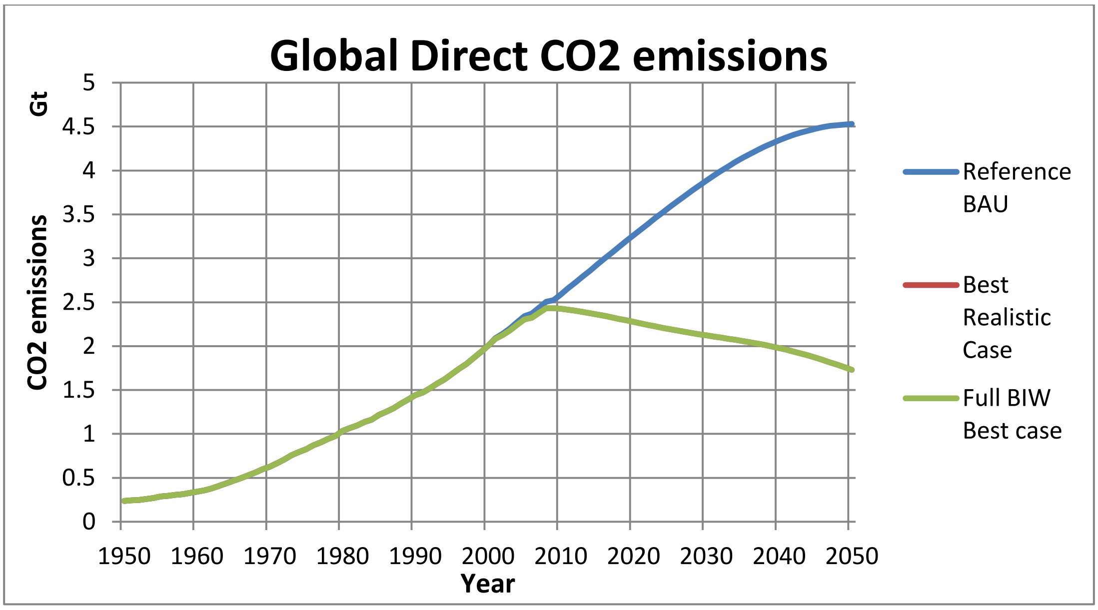

Figure 27: Direct CO_2 emissions - Best Cases

As expected, the total energy consumption (Figure 26) for the two ‘Best’ cases follows a similar trend to that of the total CO_2 emissions. Once again the Full BIW Best Case scenario is slightly more energy intensive than the Best Realistic Case scenario. A further look into the Energy Breakdowns from Figure 27 shows that in both cases, the direct energy consumption and the energy consumption from the Steel Industry are decreasing in the long run. In the Best Realistic case, the energy use from the Aluminium Industry is initially increasing slightly but then starts decreasing close to 2040. In the Full BIW Best Case, there is a steep increase in the energy consumption from the Aluminium Industry and then a slow decrease over the long run. However, the 2050 value for this is still quite high, accounting for ca. 13% of the total energy use.

It can also be observed from Figure 28 that the energy consumption in the Full BIW case from the Aluminium Industry is initially higher than that of the reference case and later becoming lesser than it, but the lowest among all the cases in the Steel Industry (Figure 29).

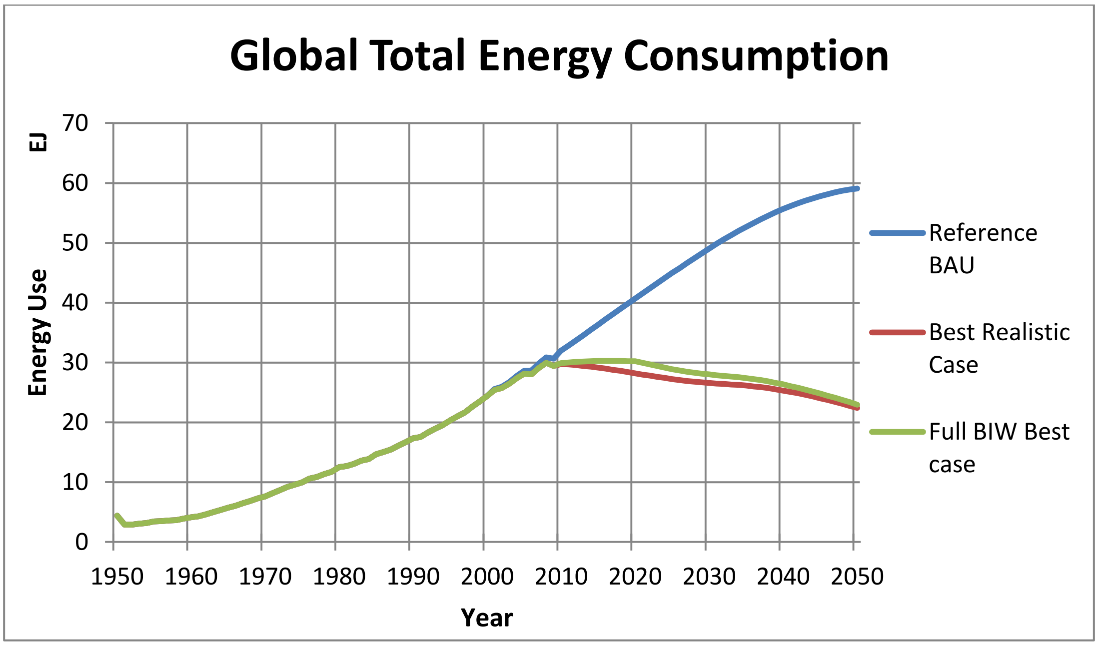

Figure 28: Global Total Energy Consumption - Best Cases

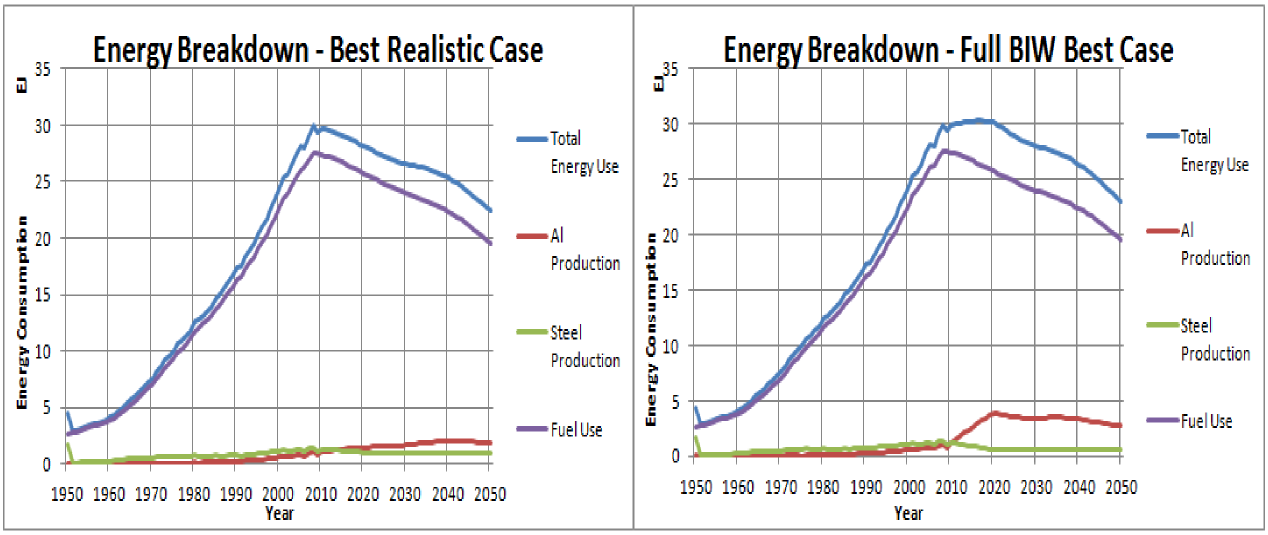

Figure 29: Energy Breakdown - Best Cases

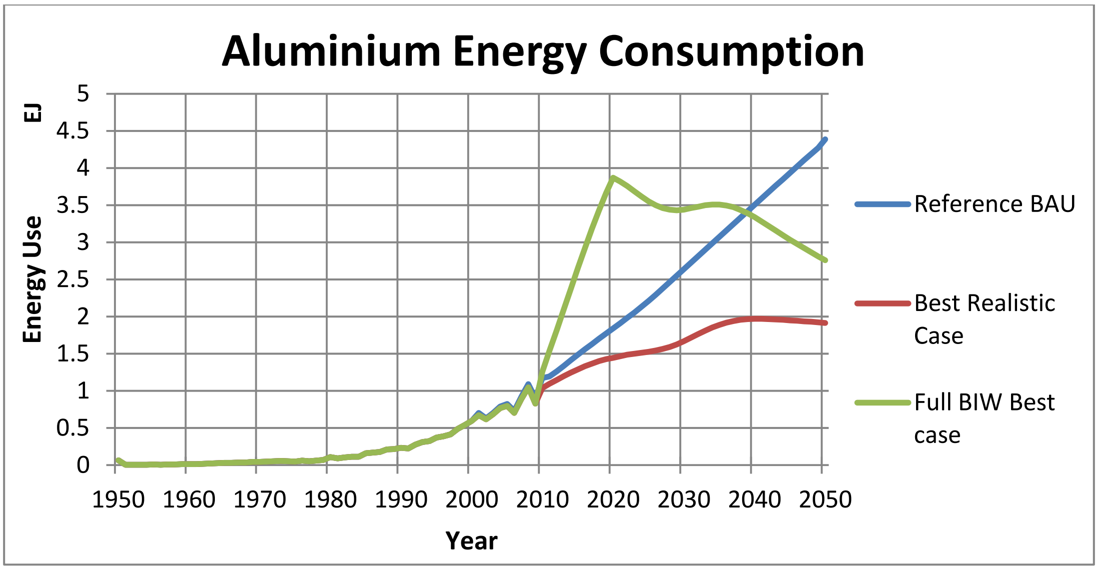

Figure 30: Aluminium Energy Consumption - Best Cases

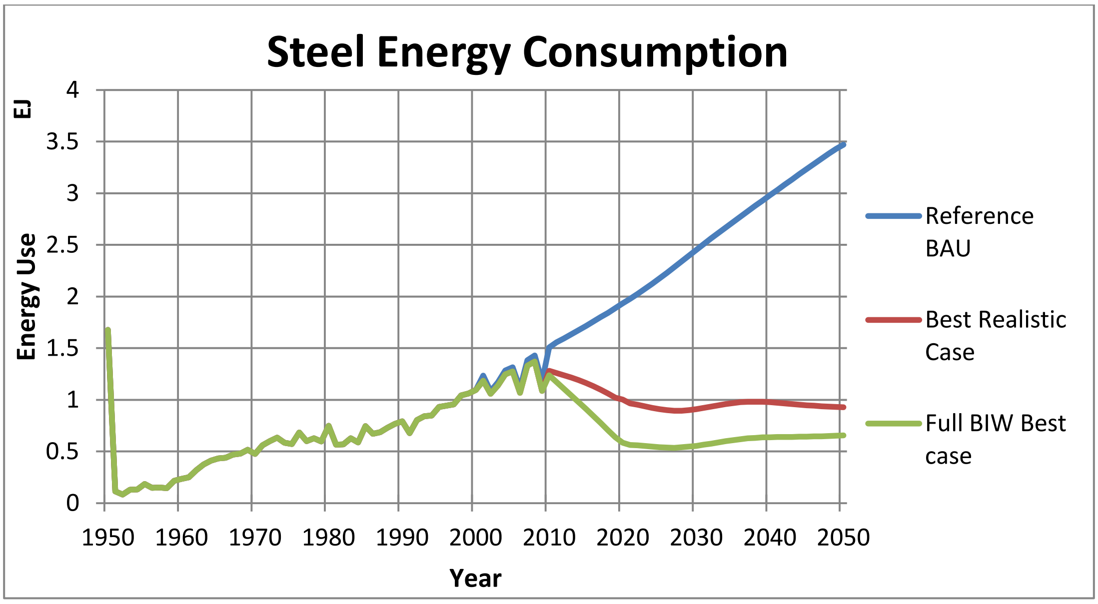

Figure 31: Steel Energy Consumption - Best Cases

In the secondary aluminium flows (Figure 30), it was already shown that the amount of available Al scrap exceeded the secondary Al demand in the car. This is not the case for the two 'Best' cases. In the Best Realistic Case scenario, there is quite a large deficit of scrap available from the passenger cars to be recycled into secondary Al for further use within the same sector. Hence, in 2050, almost 7 Mt of Al scrap has to be imported from other sectors to be used within the Passenger Car Manufacturing sector. In the Full BIW Best case, there is initially a large deficit of scrap available but this value decreases close to 2050. Hence the Al sector is almost self-sustainable in this scenario.

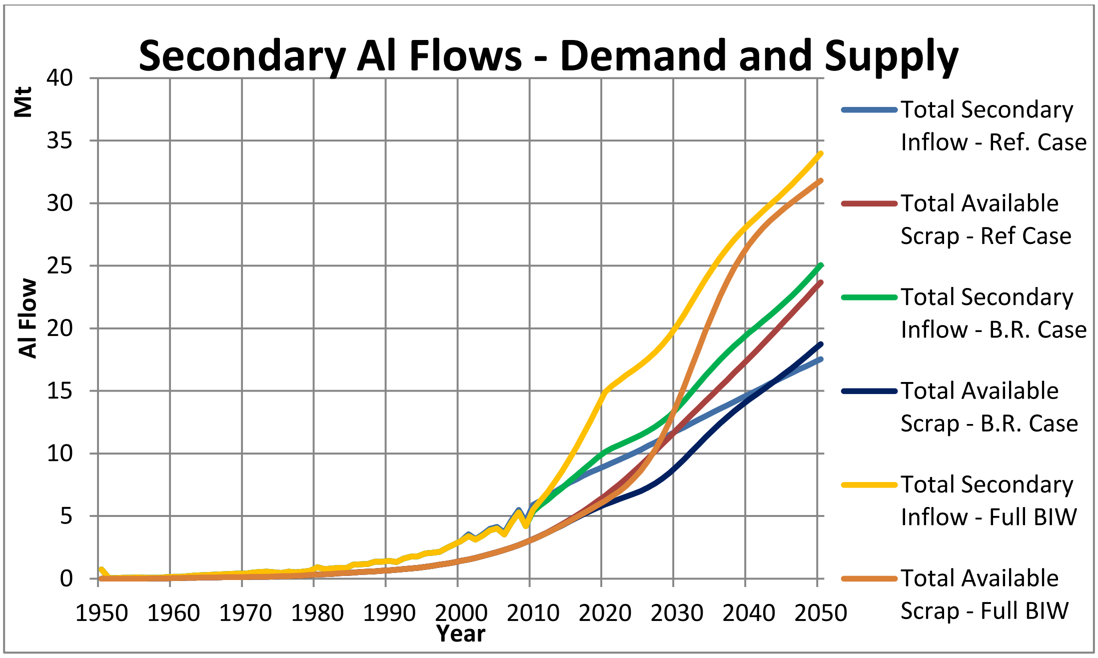

Figure 32: Secondary Al Flows - Best Cases

In the secondary steel flows (Figure 31), it was observed that there has always been an excess amount of steel scrap being produced. This is, again, not the case in the two 'Best' case scenarios. In the Best Realistic Case scenario, from 2015 onwards, the demand for secondary steel in the car manufacturing sector exceed the supply and thus needs to be obtained from other sectors. This deficit of 11-12 Mt in 2050 could be difficult to obtain because most other sectors (especially the Buildings sector) recycle most of their steel scrap within themselves. The Full BIW Best case scenario follows a similar pattern to the Best Realistic Case scenario and has similar deficits in 2050. The only difference is that the actual values of demand and supply are slightly lesser than those of the Best Realistic Case.

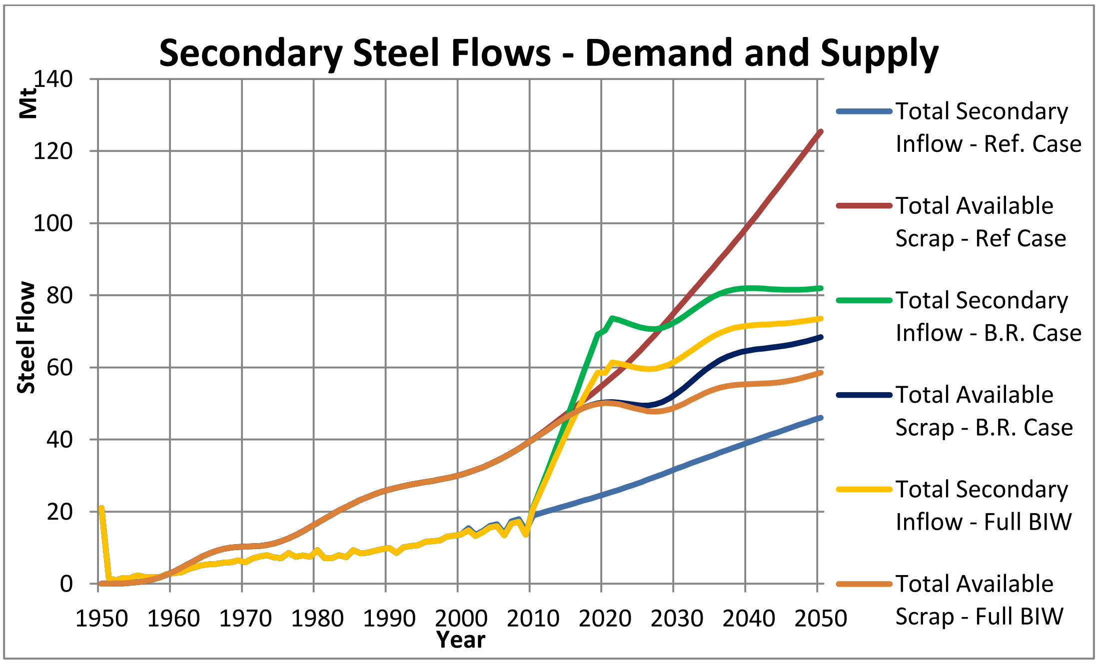

Figure 33: Secondary Steel Flows - Best Cases

4. DISCUSSION

This section first analyzes the results obtained from the previous section and how they tie in with the central research questions posed in Section 1.4. Next, the Policy Implications of the results are discussed. Finally, the accuracy and limitations of the model and results are discussed.

4.1. Model Results:

The model has produced some very interesting results in the light of climate change mitigation in the passenger car industry.

First, it is clear that the in-use car stock is driven by the rising demand for more cars in the future. Analyzing the various single and multi-parameter change scenarios (and the reference scenario) shows that it will not be possible to reach the target emission levels for 2050 set by the IPCC. Most of the scenarios have emissions above the 2000 levels. However, it is heartening to know that the Best Realistic Case Scenario and the Full BIW Best Case Scenario do show final emission levels 13-15% below the value from 2000. From the sensitivity analyses, it is evident that the aluminium and steel contents of the car, their recycling rates, and the car lifetimes have the lowest impact in climate change mitigation, whereas population, cars per capita, vehicle use and fuel consumption changes have much higher impacts on it. This means that most of the factors affecting the emissions from the passenger car stock have very little to do with the material composition of the car and more to do with the way the car is used. This is an important result as it gives an indication to policy makers as to where they have to focus in order to bring down emissions from the passenger car stock. So is it possible to achieve the 2050 IPCC target at all? That is a difficult thing to say. Solutions like electric/fuel cell cars, cleaner energy sources in material manufacturing for cars, and other such methods might help achieve this target.

Secondly, it was not completely possible to show how different vehicle designs could affect the material composition and fuel consumption of cars. Vehicle design can be interpreted in many ways. The conclusion of this analysis, based primarily on the single parameter material composition changing scenarios, is that light-weighting the vehicle through substitution of steel with aluminium slightly increases the lifetime emissions with respect to the reference case. This conclusion is only correct with respect to the emissions from within the aluminium industry. It does not give us an accurate prediction of how light-weighting affects the fuel consumption of the car. Many studies show that there is a connection between the total weight of the car and the fuel consumption (IAI, 2007; IPCC, 2007; Sivashankar, 2011). One way to solve this issue with the model would be to say that having higher amounts of Wrought and Cast Al in the car could automatically entail that the fuel consumption scenario would be the Low Fuel Consumption scenario. Hence, the emissions from Scenario 9 (section 3.3), would be a more accurate way of predicting the effects of light-weighting of a car on the fuel consumption. In this way, it effectively proves that light-weighting of the passenger car is of benefit to the Passenger Car Industry.

Finally, just because the material influences are not that high in climate change mitigation, it does not mean that they are not important. The 2050 emissions targets have to be achieved by all industries. Due to the increasing amount of aluminium entering cars in the future, there is going to be large demand for Al production. This does not mean that the demand for steel will be decreasing either. The increase in steel may not be as much as that from aluminium but it nevertheless be increasing. Hence, recycling of aluminium and steel becomes a very important factor. The results (section 3.3.1) of the two 'Best Case' scenarios show that, in the aluminium industry, there will no longer be a scrap surplus like in the Reference Case. This would mean that the Passenger Car Industry would still need some aluminium scrap from other sources. In this way the Passenger Car System can still act as a material sink for other sectors like Buildings. However, if the Buildings sector implements high aluminium recycling within their sector, it would be a problem for the Passenger Car System as it will not be able to meet its secondary Al demand. In the case of the steel industry, a similar problem is occurring, but on a higher magnitude. When the demand for recycled steel increases sharply (from Figure 30 in section 3.3.1), the steel scrap supply sector is only able to keep up with this demand for a few years. Afterwards, there is a lot of demand for steel scrap from other sectors. This creates a problem, because other steel intensive sectors, like Buildings, already implement high recycling rates (party from importing steel scrap from cars) already. This is a two-fold problem as it reduces the steel scrap available within the passenger cars sector while also decreasing the recycling rates in other sectors! This means that solving an environmental problem for one sector can have negative implications for other sectors. It is no longer possible to only concentrate environmental efforts in one sector. The scope of the efforts has to be increased to encompass all sectors where a material is present. This is an important issue that has to be looked into and solved by researchers and policy-makers in the future.

4.2. Policy Implications:

From the analysis, it is evident that a lot of effort has to be made to just bring the emission levels of passenger cars in 2050 below 2000 levels. Some changes might be easier to implement than other changes. Some changes might even create new problems for other sectors (as mentioned above). It becomes a difficult task for policy-makers to decide which changes to focus on. In the passenger car system, population and cars per capita have nothing to do with the car except for creating a demand for it. Reducing the growth in population is a global concern, which is already been looked into, not just due to the rising demand of passenger cars but due to the high demand of resources in general. The increase in car ownership is due to the lesser developed countries wanting to reach the higher standards of living present in the more developed countries. Car ownership is also a sort of social status symbol in some countries. Vehicle use is also an important factor which sort of ties in with car ownership. Methods like carpooling, increased use of bicycles and easier access to necessities can decrease the demand for cars as well as the daily distance travelled by them. Policy-makers have to come up with ways to incentivize lesser car use and ownership.

Fuel Consumption and the material composition of the car are technological issues. Fuel consumption has a high impact on reducing climate change mitigation. Hence, automobile technology has to be improved in order to decrease the fuel consumption of the car. One way, as shown from above, is to make material composition changes in the car, in order to reduce its total weight. Another macroscopic change that could be made is to improve the individual components of the car like the engine and drive train, to improve fuel energy conversion and recapturing energy losses, thus reducing the fuel consumption (IPCC, 2007). Lifestyle changes to improve fuel conversion include switching to hybrid electric cars (using electricity generated from renewable sources) or improving driving practices (simple changes like switching off the engine at traffic signals reduce fuel consumption). Hence, policy-makers have to implement both technological and social changes in order to decrease fuel consumption. One of the main deterrents to reducing the weight of the car is the safety concern. People buy bigger cars because they feel safer while driving them. Changing the mindset of people towards light-weight cars will be an important concern for policy-makers.

Increasing recycling rates of aluminium and steel is a difficult task. As mentioned earlier, currently, only about 80% of Cast Al and less than 10% of Wrought Al is made from recycled Al in the passenger car sector, whereas 25% of the steel in the car is obtained from recycled scrap. Currently, most Wrought Al scrap is remelted into recycled Cast Al. This is due to the alloying metals in Wrought Al alloys not being able to be separated to obtain pure Al. Cast Al on the other hand has more impurities and hence allows for the Wrought Al to be downgraded into it. Future technologies have to come up with ways to recycle Wrought Al back into Wrought Al. This is because primary Wrought Al creation is very energy and emissions intensive and most of the new Al entering the cars in the future is Wrought Al. Improving Wrought Al recycling can drastically decrease the GHG emissions from this sector, as shown above in figure 17.2 (Section 3.2.7). A similar GHG emissions savings can also be obtained from improving recycling within the steel sector (Figure 17.3, Section 3.2.7). Policy-makers will have to look towards scientists working these areas to come up with technologies to improve recycling. One possible way would be to design cars in such a way that they allow for easy dismantling of parts in order to improve recycling possibilities. Raising awareness among people about this is also important as it allows people to buy more environmentally friendly cars.

Making all these changes would require a drastic change in the way the people of the world think about transportation and climate change mitigation. A lot of effort has to be made by all the stake holders in the Passenger Car System. It will be a difficult task, but it is definitely achievable.

4.3. Methodological Reflections and Future Work:

According to the IPCC report, the total energy consumption from Light Duty Vehicles in 2000 was 34.2 EJ (IPCC, 2007). The value obtained in this analysis is 24.4 EJ. The main reason for this would be the fuel consumption assumed from 1950-2000. Having a constant average value of 8 L/100km prior to 2000 seems unreasonable as fuel consumption has been improving over time due to the decrease in the average weight of the cars over time. Similarly, direct emissions values from the IPCC report for cars can be seen as ca. 2 Gt CO_2 in 2000. These values are coinciding with the results obtained in the analysis, where the direct emissions in 2000 are also 2 Gt CO_2eq. It should be noted that the IPCC results would be slightly higher if they were expressed in CO_2 equivalents, which would include the other GHGs. It can be seen that for a model with so many assumptions and simplifications, the results obtained are in a comparable range with results from other studies.

The various limitations the model has and how they can be overcome in the future are discussed below:

- **Open System:** The model is currently a closed system and does not account for the steel and aluminium moving to and from other sectors but only for the materials involved within the Passenger Car sector. The model can be made able to account for the global material flows between various sectors. In this way we would be able to get a further insight into the relation between various sectors especially with regards to recycling of aluminium and steel. The recycling in the model can be improved so that the material flows in the car actually reflect the flows going out of the car, thus creating a mass balanced system.

- **Upstream Processes**: The model currently combines all the upstream processes into one sub-sector with the use of LCA data. This can be changed in the future, to show the individual flows of aluminium and steel in the various upstream processes

- **Detail level of Analysis**: The model currently combines petrol and diesel cars of various shapes and sizes into one average car and neglects electric cars completely. The model can be made to separate calculations for petrol, diesel and electric cars. The model can also be made to look into the different types of cars based on their size – micro cars, sedans, luxury cars, SUVs, etc. The model can also be made to include the other components of the car in its calculations. It can further distinguish between different alloys of aluminium and steel.

- **Fuel Consumption**: The model can be modified to in some way, incorporate the relation between the fuel consumption and the material composition. The independently studied fuel consumption scenarios can be shown side by side with the dependent fuel consumption scenario to show how much they differ.

- **Parameters**: Accurate historical values and robust future projections would also help improve the model.

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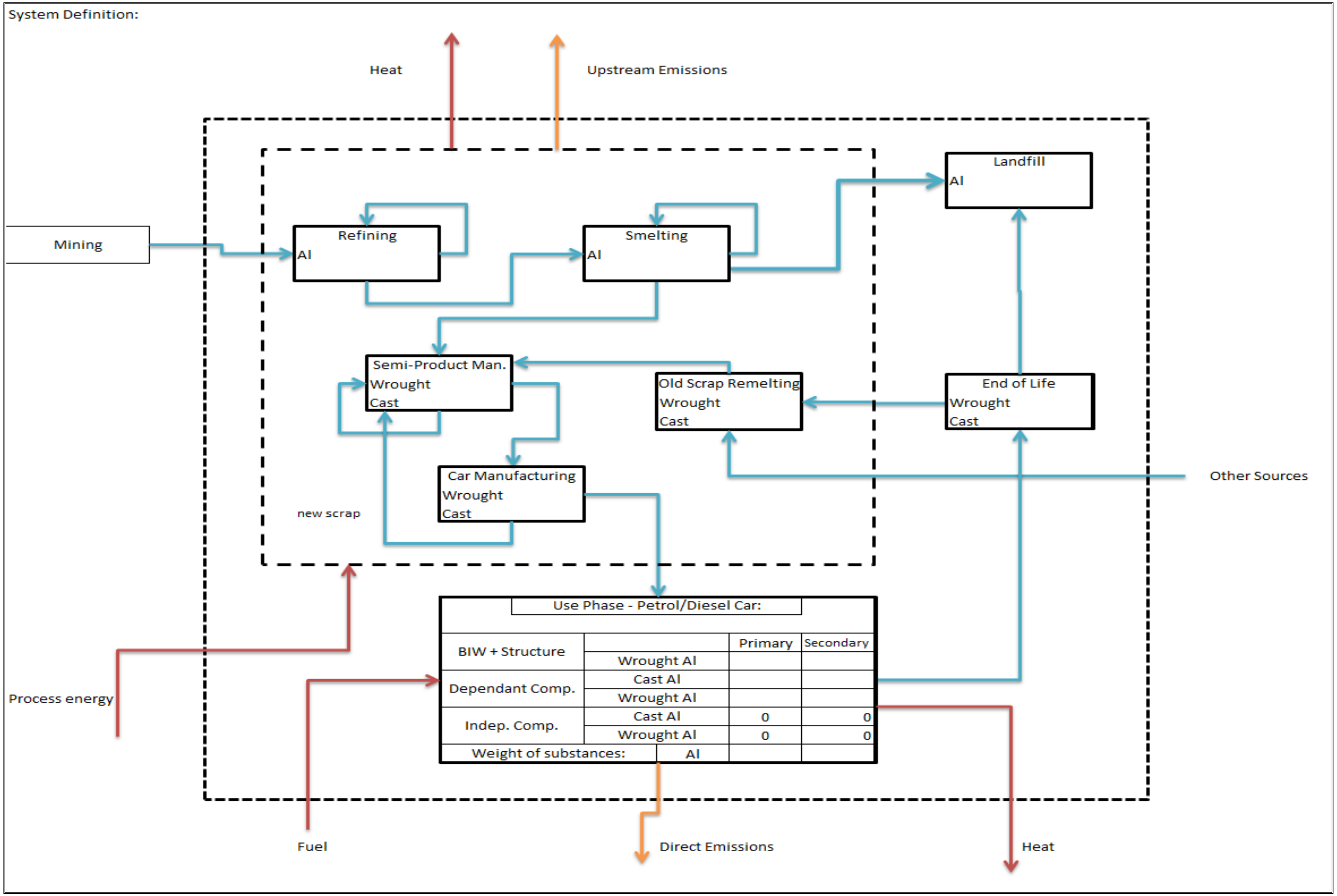
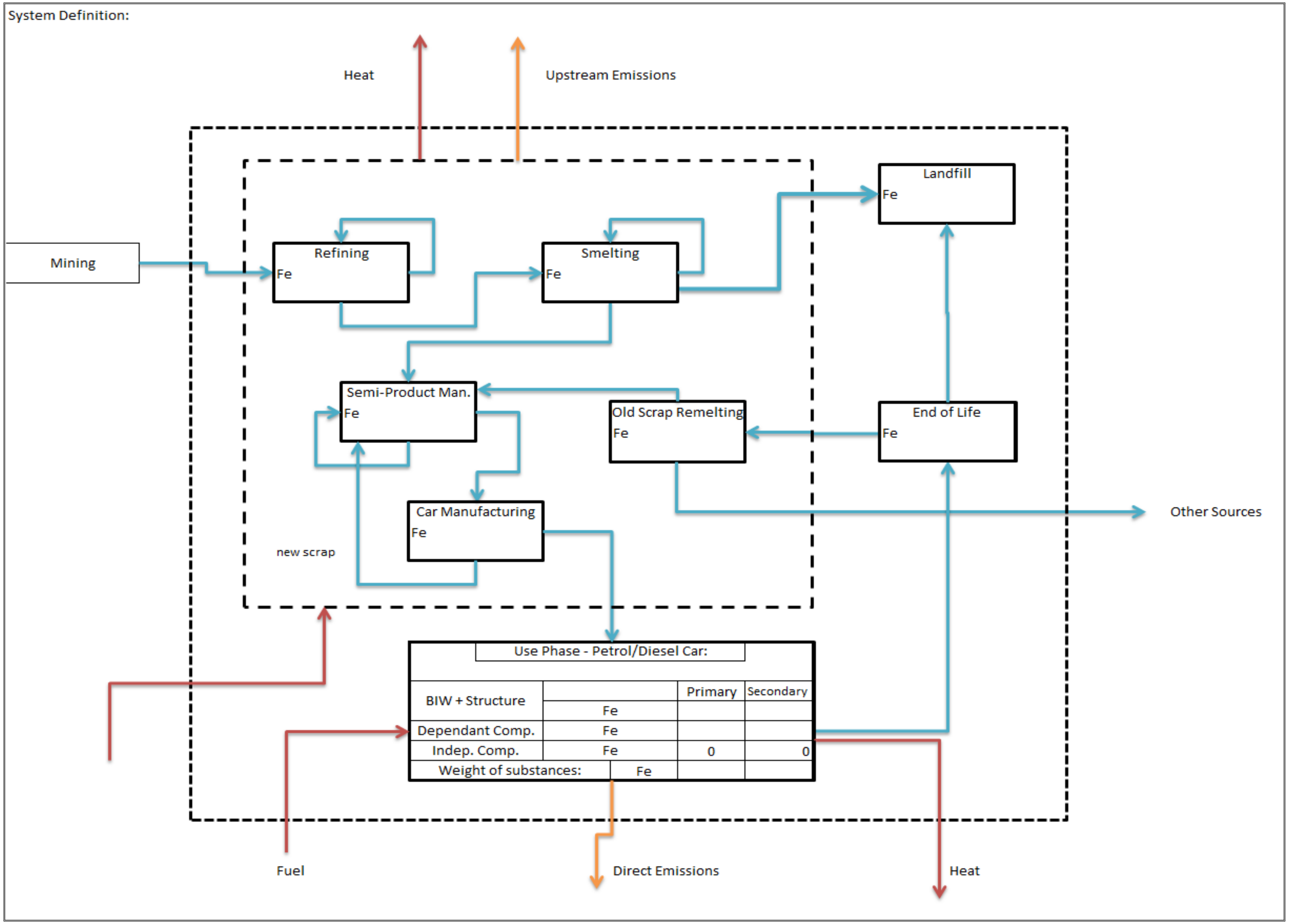
APPENDIX A: Full scale Flow Charts for the systems:

Aluminium System:



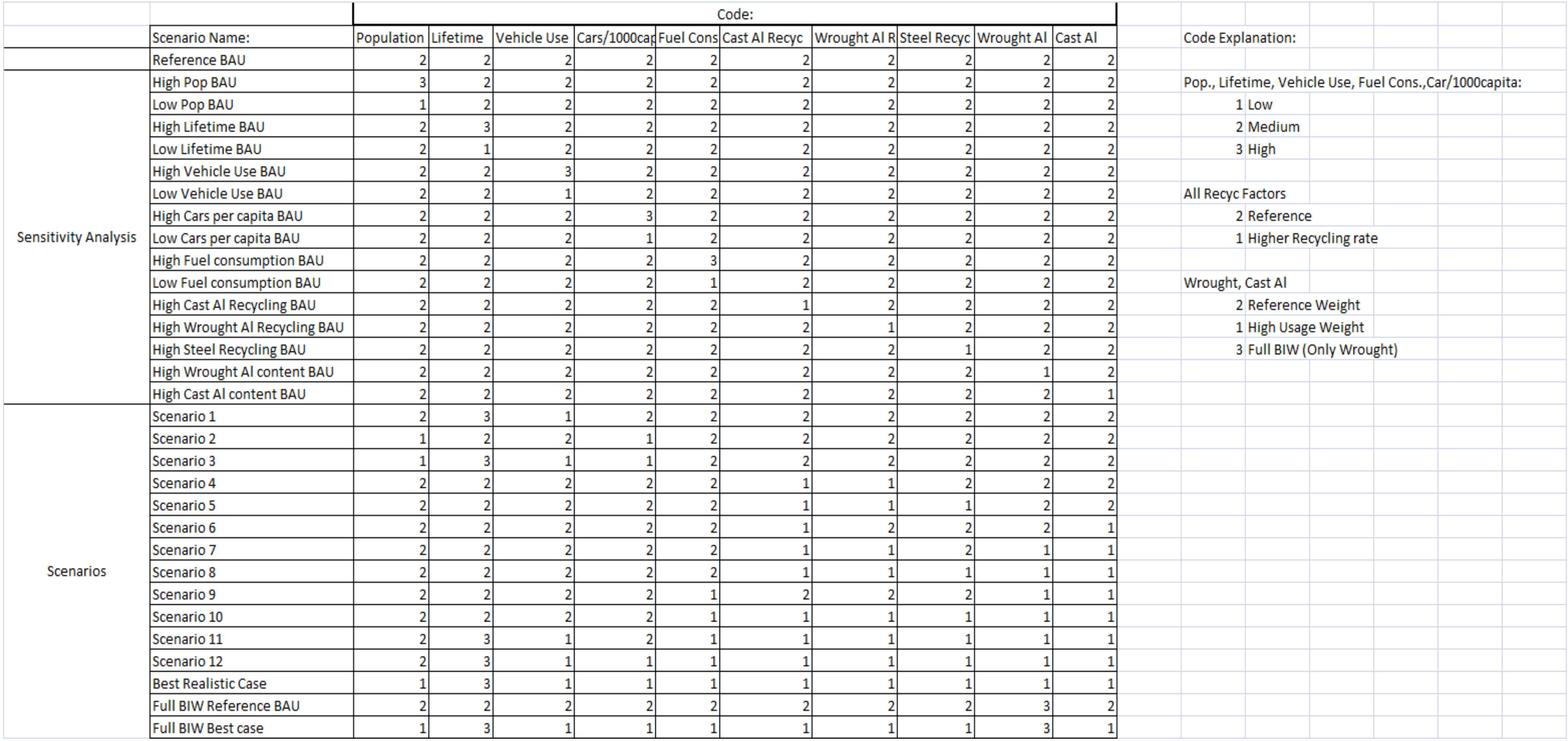
Steel System:



Use Phase - Petrol/Diesel Car:

		Primary	Secondary
BIW + Structure	Fe		
Dependant Comp.	Fe		
Indep. Comp.	Fe	0	0
Weight of substances:	Fe		

APPENDIX B: Scenario Codes:



		Code:									
	Scenario Name:	Population	Lifetime	Vehicle Use	Cars/1000cap	Fuel Cons	Cast Al Recyc	Wrought Al R	Steel Recyc	Wrought Al	Cast Al
	Reference BAU	2	2	2	2	2	2	2	2	2	2
Sensitivity Analysis	High Pop BAU	3	2	2	2	2	2	2	2	2	2
	Low Pop BAU	1	2	2	2	2	2	2	2	2	2
	High Lifetime BAU	2	3	2	2	2	2	2	2	2	2
	Low Lifetime BAU	2	1	2	2	2	2	2	2	2	2
	High Vehicle Use BAU	2	2	3	2	2	2	2	2	2	2
	Low Vehicle Use BAU	2	2	1	2	2	2	2	2	2	2
	High Cars per capita BAU	2	2	2	3	2	2	2	2	2	2
	Low Cars per capita BAU	2	2	2	1	2	2	2	2	2	2
	High Fuel consumption BAU	2	2	2	2	3	2	2	2	2	2
	Low Fuel consumption BAU	2	2	2	2	1	2	2	2	2	2
	High Cast Al Recycling BAU	2	2	2	2	2	1	2	2	2	2
	High Wrought Al Recycling BAU	2	2	2	2	2	2	1	2	2	2
	High Steel Recycling BAU	2	2	2	2	2	2	2	1	2	2
	High Wrought Al content BAU	2	2	2	2	2	2	2	2	1	2
	High Cast Al content BAU	2	2	2	2	2	2	2	2	2	1
Scenarios	Scenario 1	2	3	1	2	2	2	2	2	2	2
	Scenario 2	1	2	2	1	2	2	2	2	2	2
	Scenario 3	1	3	1	1	2	2	2	2	2	2
	Scenario 4	2	2	2	2	2	1	1	2	2	2
	Scenario 5	2	2	2	2	2	1	1	1	2	2
	Scenario 6	2	2	2	2	2	1	2	2	2	1
	Scenario 7	2	2	2	2	2	1	1	2	1	1
	Scenario 8	2	2	2	2	2	1	1	1	1	1
	Scenario 9	2	2	2	2	1	2	2	2	1	1
	Scenario 10	2	2	2	2	1	1	1	1	1	1
	Scenario 11	2	3	1	2	1	1	1	1	1	1
	Scenario 12	2	3	1	1	1	1	1	1	1	1
	Best Realistic Case	1	3	1	1	1	1	1	1	1	1
	Full BIW Reference BAU	2	2	2	2	2	2	2	2	3	2
	Full BIW Best case	1	3	1	1	1	1	1	1	3	1

Code Explanation:

Pop., Lifetime, Vehicle Use, Fuel Cons.,Car/1000capita:
1 Low
2 Medium
3 High

All Recyc Factors
2 Reference
1 Higher Recycling rate

Wrought, Cast Al
2 Reference Weight
1 High Usage Weight
3 Full BIW (Only Wrought)

APPENDIX C: Matlab Scripts:

B.1. **Model.m** –

```
% Pratulya Sivashankar, 2012
%
% Steps
%   1) Read paramaters from Excel ()
%   2) Save data as a .dat file
%   3) Call AlPassengerCars_Compute which gathers data and writes it back
%   to Excel
%

clear all
clc



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   1) Read data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% !!! Set path variable here so that Matlab knows exactly which
% Excel file to use:
path               = 'C:\Users\Pratulya\Desktop\Master Thesis\';
thisfilename       = 'Model Idea.xlsx';
datafilename       = strcat(path,thisfilename);
scenarios = xlsread(datafilename,'Scenarios','C3:L33');
[dummy, scenarionames] = xlsread(datafilename, 'Scenarios','B3:B33');
newpath            = strcat(path,'Scenario Results\');
mkdir(newpath);
resultfilename     = strcat(newpath,'Scenario Results.xlsx');

%% Read common technological data
datasheetname_in            = 'Basic Parameters';
GlobalTime = xlsread(datafilename,datasheetname_in,'C7:C107');
PopulationScenario   = xlsread(datafilename,datasheetname_in,'E7:G107');
CarsPerCapitaScenario   = xlsread(datafilename,datasheetname_in,'I7:K107');
LifetimeScenario   = xlsread(datafilename,datasheetname_in,'M7:O107');
Al_Cast_tot_Scenario  = xlsread(datafilename,datasheetname_in,'U7:V107');
Al_Wrought_tot_Scenario = xlsread(datafilename,datasheetname_in,'Q7:S107');
Al_Cast_recy_per_Scenario  =
xlsread(datafilename,datasheetname_in,'X7:Y107');
Al_Wrought_recy_per_Scenario =
xlsread(datafilename,datasheetname_in,'AA7:AB107');
Al_Cast_prim_ener  = xlsread(datafilename,datasheetname_in,'AF7:AF107');
Al_Wrought_prim_ener = xlsread(datafilename,datasheetname_in,'AD7:AD107');
Al_Cast_sec_ener  = xlsread(datafilename,datasheetname_in,'AJ7:AJ107');
Al_Wrought_sec_ener = xlsread(datafilename,datasheetname_in,'AH7:AH107');
Fuel_eff_Scenario = xlsread(datafilename,datasheetname_in,'AL7:AN107');
KilometrageScenario = xlsread(datafilename,datasheetname_in,'AP7:AR107');
Steel_tot = xlsread(datafilename,datasheetname_in,'AT7:AT107');
Steel_recy_per_Scenario =
xlsread(datafilename,datasheetname_in,'AV7:AW107');
Steel_prim_ener = xlsread(datafilename,datasheetname_in,'AY7:AY107');
Steel_sec_ener = xlsread(datafilename,datasheetname_in,'BA7:BA107');

%% General Parameters Used:
Petrol_Energy = 34.2; %MJ/L
```

```
%GWP_Petrol = 0.679374 * 0.74 ; %kg CO2 eq /L (kg Co2/kg * avg. density of
petrol)   Code:2378
GWP_Petrol = 0.0884 * Petrol_Energy ; % kg CO2 eq/MJ of petrol energy *
Petrol Energy intensity = kg CO2/L
GWP_Steel_prim = 2.311326 + 0.6; %kg CO2 eq/kg produced using cold rolling
+0.6 for fabrication
GWP_Steel_sec = GWP_Steel_prim/3 + 0.4; % a third of primary steel + 0.6
for fabrication (+0.4 here to include the +0.2 from the primary side)
GWP_Al_prim = 12.23226; % kg CO2 eq /kg produced   Code: 1755
GWP_Al_sec = 1.379254;  % Code: 1761
% Note: Aluminium GWP values do not include fabrication and semi-products

%% Variables to be used for computation and storing back to Excel
Results = zeros(101,1);
Header = cell(2,1);
Modellength = 101;
NoofScenarios = 31;



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   2) Save data as a .dat file
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

save('modeldata.mat');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   3) Call AlPassengerCars_Compute which gathers data and writes it back
%   to Excel
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

AlPassengerCars_Compute
```

B.2. **AlPassengerCars_Compute –**

```
% Script AlPassengerCars_Compute.m
%
% Dynamic MFA model for Al content of car stock
%
% Pratulya Sivashankar, 2012
%

% Load saved data so that it does not have to be read again from Excel

clc
load('modeldata.mat');

% Running the main section for all the scenarios:

for s = 1:NoofScenarios

    %% %%%%%%%%% Setting the Scenarios Parameters %%%%%%%%%%%%%%
    if scenarios(s,1) == 1
        Population    = PopulationScenario(:,1);
    elseif scenarios(s,1) == 2
        Population = PopulationScenario(:,2);
```

```
else
    Population = PopulationScenario(:,3);
end

if scenarios(s,2) == 1
    Lifetime    = LifetimeScenario(:,1);
elseif scenarios(s,2) == 2
    Lifetime = LifetimeScenario(:,2);
else
    Lifetime = LifetimeScenario(:,3);
end

if scenarios(s,3) == 1
    Kilometrage    = KilometrageScenario(:,1);
elseif scenarios(s,3) == 2
    Kilometrage = KilometrageScenario(:,2);
else
    Kilometrage = KilometrageScenario(:,3);
end

if scenarios(s,4) == 1
    CarsPerCapita    = CarsPerCapitaScenario(:,1);
elseif scenarios(s,4) == 2
    CarsPerCapita = CarsPerCapitaScenario(:,2);
else
    CarsPerCapita = CarsPerCapitaScenario(:,3);
end

if scenarios(s,5) == 1
    Fuel_eff    = Fuel_eff_Scenario(:,1);
elseif scenarios(s,5) == 2
    Fuel_eff = Fuel_eff_Scenario(:,2);
else
    Fuel_eff = Fuel_eff_Scenario(:,3);
end

if scenarios(s,6) == 1
    Al_Cast_recy_per = Al_Cast_recy_per_Scenario(:,2);
else
    Al_Cast_recy_per = Al_Cast_recy_per_Scenario(:,1);
end

if scenarios(s,7) == 1
    Al_Wrought_recy_per = Al_Wrought_recy_per_Scenario(:,2);
else
    Al_Wrought_recy_per = Al_Wrought_recy_per_Scenario(:,1);
end

if scenarios(s,8) == 1
    Steel_recy_per = Steel_recy_per_Scenario(:,2);
else
    Steel_recy_per = Steel_recy_per_Scenario(:,1);
end

if scenarios(s,9) == 1
    Al_Wrought_tot = Al_Wrought_tot_Scenario(:,2);
elseif scenarios(s,9) == 2
    Al_Wrought_tot = Al_Wrought_tot_Scenario(:,1);
else
    Al_Wrought_tot = Al_Wrought_tot_Scenario(:,3);
```

```
    end

    if scenarios(s,10) == 1
        Al_Cast_tot = Al_Cast_tot_Scenario(:,2);
    else
        Al_Cast_tot = Al_Cast_tot_Scenario(:,1);
    end

    %% %%%%%%%%%%%%%%%%%% Substituting the excess Steel with Al %%%%%%%%%

    % The reference values are obtained from the IAI report - Improving
    % Sustainability in the Transport Sector.

    % The substitution for Cast Al is done with the reference values for
    % the car's engine component.

    % The substitution for Wrought Al is done with the reference values for
    % the car's BIW.

    % In both cases, there is an indirect weight saving of 23%
    Ref_Engine_Cast = 16.4; %kg
    Ref_Engine_Steel = 31; %kg
    Ref_BIW_Wrought = 295; %kg
    Ref_BIW_Steel = 475; %kg
    Indirect_Savings = .23;

    % Finding the ratio of the amount of reference Al to the total savings
    % from lightweighting:
    Cast_Direct_Savings = Ref_Engine_Steel - Ref_Engine_Cast;
    Tot_Cast_Savings = Cast_Direct_Savings * (1 + Indirect_Savings);
    Cast_to_Tot_Savings = Ref_Engine_Cast/Tot_Cast_Savings;

    Wrought_Direct_Savings = Ref_BIW_Steel - Ref_BIW_Wrought;
    Tot_Wrought_Savings = Wrought_Direct_Savings * (1 + Indirect_Savings);
    Wrought_to_Tot_Savings = Ref_BIW_Wrought/Tot_Wrought_Savings;

    % Performing the substitution: Finding the savings from Cast and
    % Wrought Al and then modifying the amount of Steel in the car
    for i = 1:41

        Cast_diff(i) = Al_Cast_tot(60+i) - Al_Cast_tot(60);
        Steel_diff_Cast(i) = Cast_diff(i)/Cast_to_Tot_Savings;

        Wrought_diff(i) = Al_Wrought_tot(60+i) - Al_Wrought_tot(60);
        Steel_diff_Wrought(i) = Wrought_diff(i)/Wrought_to_Tot_Savings;

        % The first 2 subtaction terms represent the savings while the last
        % 2 terms represent the actual steel substituted with the Al
        Steel_tot(60+i) = Steel_tot(60) - Steel_diff_Cast(i) -
Steel_diff_Wrought(i) - Cast_diff(i) - Wrought_diff(i);


    end

    %% Finding the total car stock

    TotalCarStock =Population .* (CarsPerCapita/1000) ;
```

```
    % Now, we have to calculate the in-and outflows to the car stock, given
the
    % lifetime of the cars. This is done by calling the function
    % CalculateFullStock_Normal_DetailedWaste, which was developed by
    % Stefan Pauliuk



[DetailedCarStock,CarsBought,CarsToWaste,StockChange,DetailedCarsToWaste] =
CalculateFullStock_Normal_DetailedWaste(TotalCarStock,Lifetime,0.3*Lifetime
);

    %4.Now we want to calculate amount of aluminium, steel and energy
associated in Cars
    %inflows and outflows, in terms of Wrought and Cast Al, Steel and
Direct and Indirect energy.


    %% %%%%%%%%%%%%%%%%%% Aluminium %%%%%%%%%%%%%%%%%%%
    Castinginflow = CarsBought .* Al_Cast_tot;
    DetailedCasteToWaste = DetailedCarsToWaste * diag(Al_Cast_tot);
    Castingoutflow = DetailedCasteToWaste * ones(Modellength,1);
    Wroughtinflow = CarsBought .* Al_Wrought_tot ;
    DetailedWroughtToWaste = DetailedCarsToWaste * diag(Al_Wrought_tot);
    Wroughtoutflow = DetailedWroughtToWaste * ones(Modellength,1);
    AlOutflow = Castingoutflow + Wroughtoutflow;



    SecCastinginflow = Castinginflow .* Al_Cast_recy_per ;
    SecWroughtinflow = Wroughtinflow .* Al_Wrought_recy_per;
    Tot_Sec_Inflow = SecCastinginflow + SecWroughtinflow;



    FlowM = AlOutflow * 0.9;  % to account for losses in EOL

    Altotal= Al_Cast_tot + Al_Wrought_tot;
    detailedAlstock = DetailedCarStock *diag(Altotal);
    Alstock = detailedAlstock * ones(Modellength,1);
    Alpercapita =Alstock / Population *ones(Modellength,1);

    %% %%%%%%%%%%%%%%%%%% Steel %%%%%%%%%%%%%%%%%%%%

    Steelinflow = CarsBought .* Steel_tot;
    DetailedSteelToWaste = DetailedCarsToWaste * diag(Steel_tot);
    Steeloutflow = DetailedSteelToWaste * ones (Modellength,1);

    SecSteelinflow = Steelinflow .* Steel_recy_per;

    FlowS = Steeloutflow * 0.9;  % to account for losses in EOL

    %% %%%%%%%%%%%%%%%%%% Energy %%%%%%%%%%%%%%%%%%%

    % Operation Phase:

    % The number of kilometres driven per year in a car is decreased per
```

```
    % year, compounded at -4% and the fuel consumption of the car is 
assumed
    % to increase by 1% each year. Both these assumptions account for the
    % inefficiencies in the car.
    DynamicKilometrage = diag(Kilometrage);
    DynamicFuel_eff = diag(Fuel_eff);
    for i = 1:Modellength;
        for j = i+1:Modellength;
            DynamicKilometrage(j,i) = DynamicKilometrage(i,i)*0.96^(j-i);
            DynamicFuel_eff(j,i) = DynamicFuel_eff(i,i)*1.01^(j-i);
        end
    end

    DetailedKilometrage = DynamicKilometrage .* DetailedCarStock;
    DetailedOper_Energy = (DetailedKilometrage .* DynamicFuel_eff)/100 * 
Petrol_Energy;
    % FInding the total Operational Energy
    Eoper_tot = DetailedOper_Energy * ones(Modellength,1);

    %Production Phase:

    Eprod_Prim_Al_Wr = Al_Wrought_tot .* Al_Wrought_prim_ener .* 
(ones(Modellength,1) - Al_Wrought_recy_per) .* CarsBought;
    Eprod_Prim_Al_Ca = Al_Cast_tot .* Al_Cast_prim_ener .* 
(ones(Modellength,1) - Al_Cast_recy_per) .* CarsBought;
    Eprod_Sec_Al_Wr = Al_Wrought_tot .* Al_Wrought_sec_ener .* 
Al_Wrought_recy_per .* CarsBought;
    Eprod_Sec_Al_Ca = Al_Cast_tot .* Al_Cast_sec_ener .* Al_Cast_recy_per 
.* CarsBought;
    Eprod_Al_tot = Eprod_Prim_Al_Wr + Eprod_Prim_Al_Ca + Eprod_Sec_Al_Wr + 
Eprod_Sec_Al_Ca;

    Eprod_Prim_Steel = Steel_tot .* Steel_prim_ener .* (ones(Modellength,1) 
- Steel_recy_per) .* CarsBought;
    Eprod_Sec_Steel = Steel_tot .* Steel_sec_ener .* Steel_recy_per .* 
CarsBought;
    Eprod_Steel_tot = Eprod_Prim_Steel + Eprod_Sec_Steel;

    Eprod_tot = Eprod_Al_tot + Eprod_Steel_tot;

    %Combined:

    E_tot = Eoper_tot + Eprod_tot;


    %% %%%%%%%%%%%%%%%%%%%% Emissions %%%%%%%%%%%%%%%%%%%%%%%%

    Detailed_Emissions_Oper = (DetailedKilometrage .* DynamicFuel_eff)/100 
*  GWP_Petrol;
    Emissions_Oper = Detailed_Emissions_Oper * ones(Modellength,1);

    Emissions_Steel_prim = Steel_tot .* (ones(Modellength,1) - 
Steel_recy_per) .* CarsBought * GWP_Steel_prim;
    Emissions_Steel_sec = Steel_tot .* Steel_recy_per .* CarsBought * 
GWP_Steel_sec;
    Emissions_Steel = Emissions_Steel_prim + Emissions_Steel_sec;

    Emissions_Prim_Al_Wr = Al_Wrought_tot .* (ones(Modellength,1) - 
Al_Wrought_recy_per) .* CarsBought * GWP_Al_prim;
```

```
    Emissions_Prim_Al_Ca = Al_Cast_tot .* (ones(Modellength,1) -
Al_Cast_recy_per) .* CarsBought * GWP_Al_prim;
    Emissions_Sec_Al_Wr = Al_Wrought_tot .* Al_Wrought_recy_per .*
CarsBought * GWP_Al_sec;
    Emissions_Sec_Al_Ca = Al_Cast_tot .* Al_Cast_recy_per .* CarsBought *
GWP_Al_sec;
    Emissions_Al = Emissions_Prim_Al_Wr + Emissions_Prim_Al_Ca +
Emissions_Sec_Al_Wr + Emissions_Sec_Al_Ca;

    Emissions_Prod = Emissions_Steel + Emissions_Al;

    Emissions_tot = Emissions_Oper + Emissions_Prod;

    %% %%%%%%%%%%%%%%%%%%%%%% Graphs (My Favorite part!) %%%%%%%%%%%%%%
    %Plotting the Graphs

    %Energy
    plot(GlobalTime, Eprod_tot, GlobalTime, E_tot, GlobalTime,
Eoper_tot,'LineWidth',2,'LineWidth',2,'LineWidth',2)
    hold on;
    grid on;
    title('Yearly Energy Consumption');
    xlabel('Year');
    ylabel('Energy Consumption (MJ)');
    set(gca,'Xtick', [1950 1960 1970 1980 1990 2000 2010 2020 2030 2040
2050]);
    close gcf;

    %Emissions
    figure;
    plot(GlobalTime, Emissions_Prod, GlobalTime, Emissions_tot, GlobalTime,
Emissions_Oper,'LineWidth',2,'LineWidth',2,'LineWidth',2)
    hold on;
    grid on;
    title('Yearly Emissions (kg CO2 eq)');
    xlabel('Year');
    ylabel('Emissions (kg Co2 eq)');
    set(gca,'Xtick', [1950 1960 1970 1980 1990 2000 2010 2020 2030 2040
2050]);
    close gcf;

    %Al Flows
    figure;

plot(GlobalTime,SecCastinginflow,GlobalTime,FlowM,'LineWidth',2,'LineWidth'
,2);
    % Format plot:
    hold on;
    grid on;
    axis([1950,2050,0,9.e10]);
    set(gca,'Xtick', [1950 1960 1970 1980 1990 2000 2010 2020 2030 2040
2050]);
    axis 'auto_x';
    axis 'auto_y';
    x_label = xlabel('Year');
    set(x_label,'FontSize',18);
    y_label = ylabel('Al flow');
    set(y_label,'FontSize',14);
    set(title('Global Al demand and supply'),'FontSize',14);
    % save plot as png
```

```
    print(gcf,'-dpng', '-r150',strcat(path,'HistCarStock_Global_Al.png'));
    hold off;
    disp('Graph has been successfully saved.<br>');
    close gcf;

    %Steel Flows
    figure;

plot(GlobalTime,SecSteelinflow,GlobalTime,FlowS,'LineWidth',2,'LineWidth',2
);
    % Format plot:
    hold on;
    grid on;
    axis([1950,2050,0,9.e10]);
    set(gca,'Xtick', [1950 1960 1970 1980 1990 2000 2010 2020 2030 2040
2050]);
    axis 'auto_x';
    axis 'auto_y';
    x_label = xlabel('Year');
    set(x_label,'FontSize',18);
    y_label = ylabel('Steel flow');
    set(y_label,'FontSize',14);
    set(title('Global Steel demand and supply'),'FontSize',14);
    % save plot as png
    print(gcf,'-dpng', '-
r150',strcat(path,'HistCarStock_Global_Steel.png'));
    hold off;
    disp('Graph has been successfully saved.<br>');
    close gcf;




    %%   Save results from Workspace:
    disp('Export data as .mat-file.<br>');
    save(strcat(path,'Global.mat'));

    disp('Exporting data in Matlab style finished.<br>');




    % gather data:
    %Header:
    Header(1,1) = cellstr('Scenario');
    Header(2,1) = cellstr('Castingoutflow');
    Header(2,2) = cellstr('Wroughtoutflow');
    Header(2,3) = cellstr('Car inflow');
    Header(2,4) = cellstr('Car outflow');
    Header(2,5) = cellstr('casting inflow');
    Header(2,6) = cellstr('AlOutflow');
    Header(2,7) = cellstr('FlowM');
    Header(2,8) = cellstr('SecCastinginflow');
    Header(2,9) = cellstr('SecWroughtinflow');
    Header(2,10) = cellstr('Tot_Sec_Inflow');
    Header(2,11) = cellstr('Eoper_tot');
    Header(2,12) = cellstr('Eprod_Al_tot');
    Header(2,13) = cellstr('E_tot');
    Header(2,14) = cellstr('Steelinflow');
```

```
    Header(2,15) = cellstr('Steeloutflow');
    Header(2,16) = cellstr('SecSteelinflow');
    Header(2,17) = cellstr('Emissions_Oper');
    Header(2,18) = cellstr('Emissions_Steel');
    Header(2,19) = cellstr('Emissions_Al');
    Header(2,20) = cellstr('Emissions_tot');
    Header(2,21) = cellstr('Steel_tot');
    Header(2,22) = cellstr('FlowS');
    Header(2,23) = cellstr('Eprod_Steel_tot');


    %Body:
    Results(1:Modellength,1) = Castingoutflow;
    Results(1:Modellength,2) = Wroughtoutflow;
    Results(1:Modellength,3) = CarsBought;
    Results(1:Modellength,4) = CarsToWaste;
    Results(1:Modellength,5) = Castinginflow;
    Results(1:Modellength,6) = AlOutflow;
    Results(1:Modellength,7) = FlowM;
    Results(1:Modellength,8) = SecCastinginflow;
    Results(1:Modellength,9) = SecWroughtinflow;
    Results(1:Modellength,10) = Tot_Sec_Inflow;
    Results(1:Modellength,11) = Eoper_tot;
    Results(1:Modellength,12) = Eprod_Al_tot;
    Results(1:Modellength,13) = E_tot;
    Results(1:Modellength,14) = Steelinflow;
    Results(1:Modellength,15) = Steeloutflow;
    Results(1:Modellength,16) = SecSteelinflow;
    Results(1:Modellength,17) = Emissions_Oper;
    Results(1:Modellength,18) = Emissions_Steel;
    Results(1:Modellength,19) = Emissions_Al;
    Results(1:Modellength,20) = Emissions_tot;
    Results(1:Modellength,21) = Steel_tot;
    Results(1:Modellength,22) = FlowS;
    Results(1:Modellength,23) = Eprod_Steel_tot;


    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %   3) Write data:
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


    xlswrite(resultfilename,Header,char(scenarionames(s)),'A1');
    xlswrite(resultfilename,Results,char(scenarionames(s)),'A3');

end

%Program succesfully run
fprintf('Model calculations have been finished successfully!!\n');
```

B.3. **CalculateFullStock_Normal_DetailedWaste –**

```
%   MFA Dynamics Toolbox
%
%   function [FullStock,Demand,Waste,StockChange] =
CalculateFullStock_Normal_DetailedWaste(Stock,Tau,Sigma1)
%
```

```
%   Stefan Pauliuk, 2009
%
%   given a time series of a stock, this function calculates the time
series
%   of input and waste generation, assuming normally distributed lifetime
%   with sigma and tau.
%   In addition we split the stock into cohort so that we can trace each
%   vintage class.
%   Time is discrete with an intervall size of one year.
%
%   For further information, check with the manual of the MFA Dynamics
%   library.

function [FullStock,Demand,Waste,StockChange,DetailedCarsToWaste] =
CalculateFullStock_Normal_DetailedWaste(Stock,Tau,Sigma1)

% 0)  Check for Sigma. If the Tau/Sigma-Ratio is bad, we will get useless
% results because we only consider time steps of one year.
if mean(Sigma1) < 0.1 % The limit of 0.1 has been chosen rather
arbitrarily. The result of the function normpdf still sums up to 1 for such
a sigma and one year interval.
    disp('Standard deviation is too low! Function CalculateStock_Normal
cannot run.');
    FullStock = NaN;
    Demand = NaN;
    Waste = NaN;
    StockChange = NaN;
    return;
end

if sum((Sigma1 - 0.5 * Tau) > 0) > 0 % Here we would have considerable
negative distribution shares which are excluded from the outset. We cut of
the tail for negative lifetimes and normalise the remaining part to one
again.
    disp('Warning: Standard deviation/lifetime is larger than 0.5,
truncation probability measure is more than 2%.');
end


% 1) Calculate stock derivative
        nums = length(Stock); % This is the length of the time series.
        FullStock = zeros(nums,nums); % Define full stock table.

% Calculate the derivative of the stock:

        Stockdiff = zeros(nums,1);
        Stockdiff(2:end) = Stock(1:end-1);

        % StockChange = Stock(t) - Stock(t-1)
        StockChange = Stock - Stockdiff; % This is the discrete derivative.



% 2) Now, we build up the stock by its in- and outflows:
        Demand = zeros(nums,1);
        Waste = zeros(nums,1);

%get normally distributed values that we use as lifetime model:
        safetimelength = max(floor(max(Tau)+5*max(Sigma1)), nums);
```

```
        X = (1:1:safetimelength)'; % Make a long X to be shure to have a
very little tail cut.
        PDFs = zeros(length(Stock),safetimelength);
        for m = 1:1:length(Stock)
            PDFs(m,:) = normpdf(X,Tau(m),Sigma1(m)); % This is the only
place where Tau and Sigma1 enter explicitly
        end


% ! Negative lifetimes do not extist and limit the application of this
% model. If Sigma1 is more than a certain percentage of tau, the function
% will give a warning. However it may happen before that sum(PDF) is not
one. For
% these cases we correct the values:
        SumPDFs = sum(PDFs,2);
        PDFs = PDFs ./ repmat(SumPDFs,1,safetimelength);

% For each year, we calculate the hypothetical output first.
% This is done by multiplying all historic inputs with the PDF

DetailedCarsToWaste = zeros(nums,nums);

% 2.1) First year:

        Waste(1) = 0;
        Demand(1) = StockChange(1) + Waste(1);
        FullStock(1,1) = Demand(1);



% 2.2) All other years

        for n = 2:nums
            %Age = (n-1:-1:1)'; % Age of cohorts, seen from time step n
                thiswaste = 0;
                for m = 1:n-1
                    FullStock(n,m) =  FullStock(n-1,m) - (PDFs(m,n-m) *
Demand(m));
                    thiswaste = thiswaste + (PDFs(m,n-m) * Demand(m));
                    DetailedCarsToWaste(n,m) = (PDFs(m,n-m) * Demand(m));
                end
                Waste(n) = thiswaste;
            %FullStock(n,1:n-1) =  FullStock(n-1,1:n-1) - (PDFs() .*
Demand(1:n-1))';
            %Waste(n) = sum(PDFs(n,Age) .* Demand(1:n-1));

            % the initial stock as well as all other cohorts contribute
            if StockChange(n) < - Waste(n) % Check whether Stock is
decreasing too fast.
                disp('<b>Stock decreasing too fast! Function
CalculateFullStock_Normal cannot continue.</b><br>');
                Demand = NaN;
                Waste = NaN;
                StockChange = NaN;
                return;
            else
             Demand(n) = StockChange(n) + Waste(n); % calculate demand from
StockChange and Waste
             FullStock(n,n) = Demand(n);
           end
```

```
        end


disp('Function CalculateFullStock_Normal_DetailedWaste finished.<br>');

end
```