# Chapter Six

# Use of LCEM in LCA

## 6.1 Use of Results

Life cycle results for each of the fuel and vehicle combinations are subject to a procedure of normalisation and weighting within this Chapter. The Environmental Design of Industrial Products (EDIP) methodology, developed by Wenzel *et al* (1997, 1998), was chosen due to its holistic approach and ability to adapt to different situations and applications. The method also enables a user to compare any product on a common basis and weight the relative impacts.

The EDIP method has been used in an environmental diagnosis and impact assessment of televisions, refrigerators, high-pressure cleaners, pumps and electro-hydraulic activation units, see EDIP Volume 1, pages 319-514. To-date, the only study which applies the EDIP methodology in the assessment of alternative fuels, is that of Tan and Culaba (2003). They combine the EDIP methodology with the GREET model developed by Wang (1999a, 1999b), in the examination of air pollution and resource depletion of conventional and alternative fuels (biofuels and natural gas). In the present study an assessment is made on a per vehicle-km basis with three electricity generation scenarios envisaged. In total seven fuels were evaluated within a passenger vehicle on a life cycle basis. The main results, preceding normalisation and weighting, implied that the use of NG as an automotive fuel provides little or no environmental benefit.

The flexibility of the EDIP methodology enables small and large-scale impact assessments to be made at various levels of complexity.

## 6.2 The EDIP Method

### 6.2.1 Introduction

Alternative fuels are compared to other vehicle fuels on a life-cycle basis for three public service vehicles. A comparison is made based upon the potential environmental impact each vehicle has on society. The use of a vehicle produces emissions through the combustion of fuel and through the construction and use of the vehicle itself. Elements of an inventory of these fuel and vehicle cycles has been built, upon which an environmental impact assessment can be made. The combination of the cycles produces values that represent the total emissions from the use of a vehicle though its operational life, a so-called "cradle-to-grave" analysis. These total emissions can then be categorised against other fuel and vehicle cycles and against an average person's contribution to an environmental impact, such as Global Warming Potential (GWP) or Human Toxicity (HT). These are the processes of normalisation (see 6.2.2) and weighting (see 6.2.4), described in more detail below. The estimation of emissions is largely a technical matter and consideration of their impact on, for example, global climate change is relatively straightforward. The other impact chosen, as an example of procedures, is human toxicity and here the process is more complex. The problems of comparing "chalk and cheese" are more clearly illustrated.

Although local, regional and global pollution levels are increasing through the release and interaction of many compounds across micro and macro time periods, for the purpose of this study; the impacts to Global and Regional pollution are linked to GWP and HT respectively. No interactions over time or between the impacts are considered. The system boundaries of this LCA have to be drawn in order to limit the scope of investigation. Without boundaries a complete assessment can extend indefinitely.

A method for normalisation and weighting developed by Wenzel *et al* (1997, 1998) is used within this thesis. The EDIP system comprises of a methodology and a manual for the LCA of products, including examples of how industrial companies could use the method to design more environmentally friendly products.

**Note: For clarity the following format is to be used when referencing EDIP in this Chapter:**

EDIP **1** p.102 refers to (Book, Volume Number, Page Number) – see full reference as Wenzel *et al* (1997, 1998).

### 6.2.2 Normalisation

Basically there are two general goals in normalisation: Firstly, it assists the user in gaining an impression of the relative magnitudes of the calculated impact potentials. Evaluation of these against a common basis enables a comparison of magnitudes to be made. Secondly, the results are expressed in a form suitable for weighting. If the results are presented in a non-normalised form it is not possible to compare like-with-like. The results then become meaningless. For example, if the potential impacts for two different impact categories for two separate vehicle types are equally large on normalisation, this does not automatically mean that the two potential impacts are equally serious.

A normalised reference point must be chosen carefully in order for cross comparisons to be made. A normalised reference to the UK will differ from that of another country, depending upon population and national emissions inventories. A user must ensure that the same reference point is used within each comparison. This reference provides an appreciation of the relative seriousness of one impact compared to another is necessary. The EDIP methodology uses society's background impact for a given year as a normalisation reference point. This published approach has drawn on a wide range of databases. It is not appropriate to reproduce these fully during the current discussion.

The GWP environmental normalisation reference for Denmark is based upon 1990 global emission and population statistics. The total global emission of greenhouse gases was equivalent to $4.59*10^7$ kt $CO_2$/year and the total population was 5.29 billion, WRI (1990). Therefore the global person-equivalent for GWP based on actual emissions was 8.7 tonne $CO_2$ equivalent/person/year. This value has been taken to represent the normalisation reference value for GWP for an individual in Denmark. Due to the fact that GWP affects the global population it becomes nonsensical to calculate a normalisation reference based upon the total emissions and population for Denmark alone. However, a statistician may want to analyse the contributions made to this calculated average GWP from different countries. The Danish emission of greenhouse gases for 1990 was equivalent to $9.79*10^4$ kt $CO_2$/year and with a population of 5.135 million, Statistics Denmark (1992), a Danish GWP normalisation reference to a person in 1990 was equal to 19t $CO_2$ equivalent. This corresponds to an emission per Dane of more than double the average world person GWP in the form of man-made gases. For the UK, the total release of GWP gases in 1990 was equal to $7.8*10^5$ kt of $CO_2$ equivalent, DEFRA (2003), and the total UK population in 1990 was 57.8 million, Hicks and Allan (1999). Theoretically speaking, a person in the UK in 1990 contributed 13.49t of $CO_2$ equivalent GWP emissions i.e. an emission per UK citizen of 65% more the calculated world average.

In calculating the normalisation reference, the area and year of study need to be set and adhered to throughout the analysis for each impact under examination. For the global impact categories (see section 6.3.2) such as GWP, the whole world is affected; therefore a reference to the whole world is used. Regional and local environmental impacts only consider the region or local area where the impact occurs. The global and regional environmental impact categories do not constitute a common scale, obviously the global impacts are of a larger scale, therefore it becomes necessary to normalise all scales of impact. The EDIP method uses the population of people in the region for which the impact is assessed. This background impact is thereby expressed as **impact per person per annum** or **person-equivalent** abbreviated to **PE**. The normalised potentials are thus expressed in PE, i.e. fractions of the impact from an average person's contribution to the total. The EDIP method chose the year 1990 for the calculation of PE as the common reference year, because it is far enough away from the past to assess global and regional consequences since that time. The method considers emissions from all sources in a person's life, inclusive of domestic and industrial contributions. For example, an obscure gaseous or solvent-based emission as a result of a specific process in the manufacture of a vehicle, which is not commonly emitted by the average person, cannot be compared on a PE basis. In this specific case the PE would always equal one, independent of the absolute emission levels.

Normalisation provides an impression of the relative magnitude of the potential environmental impacts and also presents the data in a suitable form for weighting. The EDIP method has been developed to perform a normalisation and weighting methodology for any manufactured product. Some examples of this include: water pumps, televisions and refrigerators. The method has not yet been applied to an assessment of alternative fuels for public service vehicles.

The environmental impact potentials are listed in EDIP **1** p.106. The average person contribution to Global Warming (Global reference) accounts for 8700 kg $CO_2$-eq/year. This value is termed the normalisation reference for one year. In comparison the average Dane and UK citizen contributed to 19000kg and 13490kg CO2-eq respectively in 1990.

One can use (6.1) to calculate the potential environmental impact of the Global and Regional environmental impacts (GWP and HT). This potential impact value will then become normalised to the 1990 reference year.

The normalised impact potentials are calculated as follows:

$$NP_i = EP_i \times \frac{1}{T \times R_i} \tag{6.1}$$

where:

$NP_i$ - Normalised impact potential

$EP_i$ - Environmental impact potential (see below)

T - Time of service (years) – refers to the lifetime of the product

$R_i$ - Normalisation reference for one year

$i$ - The index of the various impacts considered (eg $i \equiv$ GWP or human toxicity)

**NOTE: $NP_i$, $WP_i$ and $R_i$ refer to Normalised and Weighted Impact Potential and Normalisation Reference for one year respectively, for resource consumption only. In the analysis of environmental impact, an addition letter is included (E), transforming ($NP_i$, $WP_i$ and $R_i$) to ($NEP_i$, $WEP_i$ and $ER_i$), specifying that the normalisation refers to environmental impacts only.**

### 6.2.3 Environmental Impact Potential ($EP_i$)

In order to find the $EP_i$ for use in (6.1), one needs to identify all of the pollutants that contribute, directly or indirectly, towards GWP. EDIP **2** p.26 details the pollutants that contribute towards GWP for the 20, 100 and 500 year time horizon. The 100-year time horizon was chosen for this study, as this is the standard time period used in the vast majority of studies and is universally agreed to be the standard time period to use in order to assess GWP. To find the total ($EP_{GWP}$), the GWP per substance needs to be found and then summed to find the total. To find the $EP_i$ one uses the following:

$$EP_i = \sum Q_i \times EF_i \qquad (6.2)$$

where:

$EP_i$ - Environmental impact potential

$Q_i$ - Quantity of substance (g)

$EF_i$ - Equivalency factor – potency in relation to a reference pollutant

To calculate the total contribution to the impact category (i.e. GWP) over the entire product life, the contributions are summed as in Example 1 (6.3), see EDIP **1** p.98.

In an LCA, the equivalency factors (for GWP) express a gases' potency relative to that of $CO_2$ over a 20, 100 and 500 year horizon as specified by ISO and SETAC. A time horizon of 100 years is commonly chosen in LCA studies as it reflects the medium time horizon (EDIP **2** p.22). The relative potency of gases depends on whether the contributions are viewed over a short or long time span. For some gases, e.g. $N_2O$ and $CH_4$, strength increases and decreases respectively with a longer time horizon. Therefore a medium time horizon is chosen. See EDIP **1** p.99. For the complete GWP equivalency factors see Table 1.5, EDIP **2** p.22.

**Example – calculation of EP**

For an emission of 550g of $CH_4$, 15,000g $CO_2$ and 10g CO, the GWP for a time horizon of 100 years is determined thus:

$$\begin{aligned}\sum EP_{GWP} &= (550 \cdot 25\text{g CO}_2 - \text{eq}) + (15{,}000 \cdot 1\text{g CO}_2 - \text{eq}) + (10 \cdot 2\text{g CO}_2 - \text{eq}) \\ &= 28{,}770\text{g CO}_2 - \text{eq}\end{aligned} \quad (6.3)$$

The 100-year equivalency factors (EF) for GWP of $CH_4$, $CO_2$ and CO are 25, 1 and 2 respectively. These values represent the impact factor of each compound in relation to the GWP contribution of $CO_2$. For example, when $CH_4$ has an impact factor of 25, it means that emission of 1g of $CH_4$ contributes as much to global warming as the emission of 25g $CO_2$ over a period of 100 years.

On completion of the summations for each impact category under investigation (GWP and HT), one can proceed to calculate the Normalised Impact Potential ($NP_i$) as in (6.1). The $NP_i$ is then weighted to a factor that reflects the seriousness of that impact.

### 6.2.4 Weighting

The normalisation phase provides information on which contributions are, in relation to each other, small or large. But just because a problem is large does not necessarily mean that it has a serious implication to human health or sustainability etc. With weighting, the relative seriousness of each individual environmental impact, in relation to the other impacts within the same category, can be expressed in a factor. In general terms the criterion for weighting address the probability that the impact will lead to an undesired consequence and the extent and duration of the consequences, Consoli *et al* (1993). On this basis the weighting factors are determined by a method called 'distance to target', a ratio between the actual impact and a target impact. A Weighting Factor (WF) of 1 means that the contribution in 1990 corresponds to the reduction target set for the year 2000.

$$WF = \frac{Actual\ impact}{Target\ impact} \tag{6.4}$$

The greater the difference between the actual and target impact, the higher the weighting factor. The Weighted Environmental Impact Potential (WEP) is expressed in the unit 'target person-equivalent', i.e. parts of that person-equivalent which correspond to the chosen target impact in the weighting.

In order to assess an impact, the environment's carrying capacity or legal and political targets are chosen in order to make an assessment. The carrying capacity is defined as the level of impact, which nature can absorb without the impact causing detectable effects in the short or long term i.e. a detectable effect on GWP would be an immediate or gradual increase in earth surface temperature. However, this only reflects how far society's current impact is from meeting the projected target reductions. The relative seriousness is not addressed. In contrast, EDIP **2** p.535 states that a sustainable impact may well cause certain environmental effects, but not any effects which endanger our own needs or those of future generations in the long term.

The EDIP method for calculating the weighted potential is:

$$\begin{aligned} & WP_i = WF_i \times NP_i \\ \Rightarrow \quad & WP_i = WF_i \times \frac{1}{T \times R_i} \times EP_i \end{aligned} \tag{6.5}$$

where,

$WP_i$ -Weighted impact potential

$WF_i$ -Weighting factor – see below

The Weighting Factor ($WF_i$) for an environmental impact reflects the seriousness of the potential effect being caused by the impact and the possible consequences of this effect relative to the other environmental effects, Wenzel *et al* (1997).

Depending upon the use of the LCA, the criteria for assessment will differ. The EDIP method is to apply weighting factors on the basis of political environmental targets set by the Danish Government or by various international protocols, Table 10.10, EDIP **1** p119. International and national agreements give reduction targets for many pollutants that it is felt required reduction due to the contribution to global and regional environmental damage to ecosystems. The EDIP method for environmental impact is based upon scientific, technical and political considerations. The method also suggests that many authorities prefer a product-oriented environmental policy as a means of achieving environmental reduction targets. Therefore the weighting factors should be and are based upon product consumption, so that authorities have an instrument to ensure that companies have the correct environmental priorities when developing new products. In reality, authorities and companies are legally obliged to conform with regulations set by the government and they are also prohibited by budgetary constraints and are constantly in conflict with operational performance. In the present context, Public Service Vehicle (PSV) operators are probably more amenable to adopting environmentally and socially responsible and sustainable policies with respect to their vehicle and fuel choices than the general public. As a result, the UK Government set up the Energy Saving Trust (EST) after the 1992 Rio Earth Summit which, in turn, established Powershift in 1996 with the aim of kick-starting the market for Clean Fuel Vehicles (CFVs) in the UK, through subsidies for public and private vehicle operators. As a result, Powershift's budget for 2000-2001 was £10.5 million, raised to £33 million for the period 2001-2004. Since the introduction of these subsidies, growth in UK CFVs has occurred.

The author considers that AF use in the UK is set to increase for the following reasons: The fiscal incentives are in place, generally operational characteristics are similar and with the introduction of congestion charging, car free days, tax and fuel reductions and pollution reduction, the future for AF is slowly expanding based upon scientific, technical and political considerations.

### 6.2.5 Weighting Methodology

The EDIP procedure chose the year 2000 as the common target year (at time of publication 1998), while 1990 was chosen as the normalisation reference year. Linear interpolation and extrapolation are used should the target year be before or after 2000 respectively. This becomes questionable when a LCA target year is a long way from the legislation target year.

The weighting factor expresses how much the normalisation reference must be reduced by, to be in accordance with the efforts expressed by the reduction targets set. The larger the factor, the larger the target. The Weighting Factor ($WF_i$) for the type of environmental impact category (i) is defined as the environmental impact potential of the emissions in the reference year 1990, ($ER_{i90}$) divided by the environmental impact potential of the target emissions in the year 2000, ($ERT_{i00}$).

$$WF_i = \frac{ER_{i90}}{ERT_{i00}} \tag{6.6}$$

where,

$WF_i$ -Weighting Factor

$ER_{i90}$ -Environmental impact potential of emissions in 1990

$ERT_{i00}$ -Environmental impact potential of target emissions for 2000

The decision to choose 1990 and 2000 as reference years for the ($ER_i$), are to some extent arbitrary and any reference year may be used. The sharper the reduction targets, the greater the weighting factor for the environmental impact. With the weighting factor, the weighting can be seen as a type of normalisation with the target emissions in the year 2000 as normalisation reference. The Weighted Environmental Impact Potential ($WEP_i$) is determined thus:

$$\begin{aligned} WEP_i &= WF_i \cdot NEP_i \\ \Rightarrow WEP_i &= \frac{ER_{i90}}{ERT_{00}} \cdot \frac{EP_i}{EP_{i90}} \cdot \frac{1}{T} \\ \Rightarrow WEP_i &= \frac{EP_i}{ERT_{00}} \cdot \frac{1}{T} \end{aligned} \qquad (6.7)$$

where:

$WEP_i$ -Weighted Environmental Impact Potential

NEPi -Normalised Environmental Impact Potential

$EP_{i90}$ -Environmental Impact Potential for 1990

**Example – Danish action plan to reduce pollution**

Denmark had an action programme to reduce pollution by certain percentages. The programme led to a reduction of 12% $CO_2$ from 1990-2000. The actual worldwide emissions of $CO_2$ in 1990 accounted for $2.71*10^{10}$ t. Therefore for the year 2000 a 12% reduction will result in emissions of $2.38*10^{10}$ t. One sums all of the pollutants and finds the GWP. This figure is $3.69*10^{10}$ t. This is the GWP for the target year 2000 ($ER_{i2000}$). If one reverts to Table 1.7, EDIP **2** p. 26, one can see that the total GWP emissions for 1990 equal $4.59*10^{10}$ ($ER_{i90}$). One can now use equation 6.7 to find the weighting factor applied to the Danish political reduction target for 2000.

The $WEP_i$ for a product is expressed as a percentage of the person-equivalent, which can be expected in the year 2000 if society's plans for reduction are achieved. The unit is person-equivalent target (PET) for the World and Denmark $_{(WDK)}$ $PET_{WDK00}$, based on the target emissions in the year 2000.

$$WEP_i = PET_{WDK00} \tag{6.8}$$

The subscript $_{WDK00}$ (World and Denmark reference for the year 2000) defines the weighting of global impact categories on the basis of the accepted global contributions in the year 2000, while the regional and local impact categories are weighted on the basis of the accepted contribution in Denmark.

**Example 3**

An LCA of a Bang and Olufsen (Beovision LX 5500) television sold to Germany, France, Sweden, Norway, Europe and the World is examined. The television is normalised and weighted relative to GWP as follows:

### 6.2.6 Normalisation

Consider a Bang and Olufsen television (EDIP **1** p.369) manufactured in Denmark with 2500 employees. The television weighs 42.7kg with the picture tube alone weighing 24.5kg. The television is ranked relative to a person's average contribution to each environmental impact (e.g. GWP), normalised relative to 1990. To be able to assess these normalised environmental impact potentials (NEP), weightings are applied. The weighting factors for each of the impact categories are listed in EDIP **1** p302/303.

The potential impact of one television over its lifetime of 10 years to GWP is 1340000g $CO_2$-eq, EDIP **1** p.386. The average person (World) contributes 8700000g of $CO_2$-eq per year. Using (6.1), the ($NEP_i$) can be found:

$$NEP_i = EP_i \cdot \frac{1}{T \times R_i} \Rightarrow NEP_i = 1340000 \cdot \frac{1}{10 \times 8700000} = 0.015 \tag{6.9}$$

Therefore the average PE contribution to GWP per year over the 10-year lifespan for the television is equal to 0.015. And the average milli-person equivalent (mPE) contribution equals 15. This value corresponds to 1.5% of a person's annual contribution to GWP.

### 6.2.7 Weighting

The $WF_{GWP}$ (weighting factor for GWP) is 1.3, EDIP **1** p.302 and is taken as a world reference for the year 1990. Specific to the environment, multiplying the normalised environmental potential impact ($NEP_i$) (above) by the $WF_{GWP}$ (see 6.6) produces a value of 19.5, which is the $mPET_{WDK2000}$ (one thousand person's-equivalent targeted emissions for the World and Denmark reference in 2000). This value of 19.5 is equal to 1.95% of a person's contribution to GWP as weighted against the targets set.

This weighting is necessary because not all environmental impacts are equally critical. They are weighted against the required reduction necessary to satisfy political and scientific targets between 1990-2000, EDIP **1** p.387.

Once a decision is made upon which global atmospheric exchanges (e.g. GWP, human toxicity) are to be considered a weighting factor can be calculated which could then be applied to (6.7) to calculate the total ($WEP_i$). One then uses (6.7) to find the contribution of the emission to a person-equivalent for the global and/or regional impact.

On completion of the normalisation and weighting, the EDIP method continues on to a stage of identification of the most significant impact potentials, preceded by an uncertainty and sensitivity analysis. In identifying the most significant environmental impacts, the user can review the impact in relation to the process and material used. The most significant impacts can then be altered or amended to reduce the overall environmental, economic or resource impact. Uncertainty within the data sources during each stage of the LCA can be simulated in order to make a robust assessment. Changes in resource use can be modelled over any specific time frame and the sensitivity of the output can identify key areas of interest (both problematic and where there is scope for improvement).

A final environmental diagnosis is performed to designate the most significant potentials for improvement and to discover where they reside in the product. On completion of this diagnosis, any new products are capable of adaptation and amendment, given that the environmental impact of the original products is known.

## 6.3 Applying the EDIP method to the LCA results

With knowledge of the EDIP process, the results from the LCEM for PSVs are used with the methodology of normalisation and weighting as defined above.

Each PSV, fuelled by the conventional and alternative fuels under examination, can be compared to the contribution made by an average person in the year 2000, and for the first time a comparison between the PSV types can be made. The results of which can be seen in Section 6.4.

An explanation of the development of the global impact categories, using the EDIP method, precedes the results section in this chapter in order for the user to fully understand the results presented.

### 6.3.1 Global Impact Categories

Most of the information to follow, pertaining to the description of GWP and HT is taken from Wenzel *et al* (1997,1998), with additional details taken from Delucchi (1991) and General Motors Corporation (2001)

### 6.3.2 Global Warming Potential (GWP)

The focus in the EDIP method is on "man-made greenhouse effect" i.e. the increase in temperature on top of the above natural greenhouse effect, cause by man-made emissions of substances or particles, which can influence the earth's radiation balance.

Many of the substances that are emitted to the atmosphere as a result of human activities (anthropogenic sources) contribute to this man-made greenhouse effect. The most important man-made emissions of greenhouse gases are, in order, the following:
Note: Some pollutants have a direct and indirect impact i.e. $CH_4$.

Direct

- $CO_2$
- $CH_4$
- $N_2O$
- Halocarbons

Ozone ($O_3$) is also a greenhouse gas, but the extent of its contribution is uncertain. A number of substances act indirectly as greenhouse gases by influencing the efficiency of one or more of the direct Greenhouse Gases (GHGs), as follows:

Indirect (via further oxidation, degradation and deposition)

- CO
- NOx
- NMHCs
- $CH_4$
- $SO_2$

The natural generation and maintenance of GHGs has led to life as it presently exists. In some senses man-made contributions of GHGs are small but these are potentially large enough to produce important climate changes. The average global temperature is believed to have risen between half and one degree over the last 100 years as a consequence of the man-made greenhouse effect, Albritton *et al* (1995). For further details on the basic formulae for the calculation of these direct and indirect effects, see Delucchi (1997), General Motors Corporation (2001), Lashof and Ahuja (1990) and Shine *et al* (1990).

Substances released into the atmosphere exert both direct and indirect effects on GWP. The direct effects are attributed to the fact that the substance absorbs infrared radiation from the earth and thus contributes to the temperature increase in the atmosphere. The indirect effects of GWP can be both positive and negative and are attributed to the influence of the substance on the presence of direct GHGs or the entry of solar radiation to the atmosphere. The calculation of these indirect effects is still burdened with a high degree of uncertainty and the Integrated Pollution Prevention and Control (IPCC) has only provided provisional quantification factors. Indirect contributions to GWP are therefore included only in the calculation of impact potentials for methane. For all other substances, only the direct contributions are computed.

Due to data availability and relative impact, the following compounds were considered within the present study:

- $CO_2$
- CO
- $CH_4$

Only direct effects plus (indirect $CH_4$) are considered within the analysis in agreement with the IPCC and EDIP methodology (EDIP **2** p.22). The equivalency factors for these compounds are taken from the IPCC guidelines, see EDIP **2** p.14-16.

### 6.3.3 Human Toxicity (HT)

The procedure for calculating the HT to air documented in Wenzel *et al* (1997, 1998) contains an error. The present author noted this error, which becomes apparent in the LCA examples listed in EDIP **1** p.341 and 386, and contact was made with the authors of the EDIP manuals; based at the Technical University of Denmark, see Appendix N. They confirmed the error and noted that the results presented in the books were incorrect. The procedure itself however is correct and works for each and every combination of impact assessments, therefore the present studies continues with the calculation in the same way as with GWP.

The EDIP report on the calculation of Human Toxicity (HT) openly admits the database should be treated sceptically and it will be several years before any international accepted methods are fully established. There is no previously accepted system of HT factors, which can simply be adapted for future use. The numbers of substances that contribute towards HT are very large and many substances are classified based upon their environmental hazard, i.e. the effect each substance has on human health relative to the ambient levels that currently exist in the air.

The HT impact involves many impact mechanisms, i.e. different basic toxicity mechanisms such as: damage to DNA, induction of allergy or inhibition of specific enzymes (EDIP **2** p.321). Humans are exposed to the impacts of pollutants in a number of different ways.

Direct exposure via inhalation of polluted air or ingestion of polluted groundwater, surface water or soil and indirect exposure via ingestion of plants, which can be exposed to pollution and ingestion of consumers (herbivores or carnivores) or their products (e.g. milk).

EDIP does not consider dermal absorption though this could be an important issue to the working environment as opposed to product use. Through these exposure pathways, the EDIP method calculates toxicity potentials for exposure to humans. This method was inspired by the EU Commission's technical guidelines for risk assessment of chemicals in the environment (EDIP **1** p.280). The toxicity potential is determined as the product of the quantity of substance emitted and the substance's equivalency factor for exposure through air, soil and water. The potential is expressed in ($m^3$) of air, soil or water and corresponds to the volume of the compartment (air, soil or water) into which the emission should be diluted for its concentration to be so low that no toxicological effects could be expected from the emission. Table 23.13, EDIP **1** p. 281-283 lists the equivalency factors for each compartment.

The compounds considered under the EDIP methodology for the calculation of HT to air are as follows:

- $SO_2$
- NOx
- $N_2O$
- NMVOCs
- CO
- Metals
    - Electricity production for the metals As, B, Cd, Hg, Ni, Pb and Se
    - All other human activities plus Pb, Hg and Cd

The following gases and compound were chosen in this study for the calculation of HT to the air compartment:

- $SO_2$
- NOx
- CO
- PM

The corresponding equivalency factors for the HT to air compartment are taken from EDIP **1** p.281-283, with the exception of PM, which is assumed to be $6.7*10^3$ $m^3/g$, taken from the implementation guidelines of the Philippine Clean Air Act, Tan and Culaba (2003). Alterations to the Normalisation Reference ($R_i$) value were necessary since only the four compounds listed were included.

The standard HT Ri value is calculated in EDIP **2** p.338 as $9.2*10^9$ $m^3$ air/person/year from a population of 5.133 million people in Denmark (calculated as EP (hta)/Population). Since all of the pollutants in EDIP Table 7.5 p.338 are not considered in the present study, the following alterations are made. A new Ri value of $\mathbf{6.6*10^8}$ $m^3$

air/person/year, results ($3.39*10^{15}/5.133*10^{6}$). Table 6.1 shows the standard HT Ri value and the new Ri value calculated in the present study. All metals have been omitted in the calculation of the new Ri value together with $N_2O$, NMVOCs and waste, dioxins. Metals are used in all vehicles types and to compare the impacts of metals with each vehicle is beyond the scope of the present study, which focuses upon the gaseous emissions releases to air only. However the impact of metals will not alter the emissions profiles because each fuel is compared using the same vehicle. The only impact would occur within the analysis of electric vehicles, where additional mass of metals is required for the batteries. However this additional mass would be included in the vehicle cycle and even with a larger percentage of metals and therefore HT, the electric vans normalised impact potential is still much lower than the liquid and gas fuelled vehicles. Moreover, additional volume to the Environmental Impact Potential of human toxicity to air EP(hta), decreases the NP value, see equation 6.1.

**Table 6.1 – Calculation of Human Toxicity**

| | EDIP 2 p.338 | Finnegan (2003) |
|---|---|---|
| **Activity** | **EP(hta) $m^3$ air/year** | **EP(hta) $m^3$ air/year** |
| $SO_2$ | $2.6*10^{14}$ | $2.6*10^{14}$ |
| NOx | $2.46*10^{15}$ | $2.46*10^{15}$ |
| $N_2O$ | $2.02*10^{13}$ | |
| NMVOC | $1.64*10^{15}$ | |
| CO | $6.7*10^{14}$ | $6.7*10^{14}$ |
| Cd, Pb, Hg | $4.21*10^{16}$ | |
| Other metals (as, Cr, Ni and Se) | $1.59*10^{13}$ | |
| Incineration of waste, dioxins | $1.37*10^{12}$ | |
| PM | | $1.3*10^{10}$ |
| | | |
| **Total** | **$4.71*10^{16}$** | **$3.39*10^{15}$** |

The calculation of PM emissions were not documented within the EDIP methodology, therefore an alternative dataset was used. The total PM released from all major sources in Denmark, in 2000 accounted for 67300t, http://www.dmu.dk/1_Viden/2_Miljoe-tilstand/3_luft/4_ADAEI/tables/PM.html. In comparison the total PM releases from Germany in 1994 was 805000t, EC (1997). The total emissions released are then multiplied by the EF (hta) in order to calculate the EP (hta). An EF(hta) for Denmark is assumed from Tan and Culaba (2003). Therefore the total EP (hta) $m^3$/year is calculated as $4.5*10^8$ (from the multiplication of the release of PM (67300t) and the EF(hta) from Tan and Culaba (2003). This number represent the total contribution to HT made by PM in Denmark.

The new Normalisation reference ($R_i$) value of $3.39*10^{15}$ was included in the calculation of the normalised impact potential ($NP_i$) that reflects the contribution of each pollutant to the HT total for Denmark in 1990. Subsequent weighting amendments were made to reflect the impact of these three compounds only.

## 6.4 Results

The weighted and normalised results presented in this chapter reflect the complete life cycle global and regional impacts of the PSVs, in relation to the impact from the average persons' contribution to GWP and HT in Denmark and the World, subject to the simplifications outlined during the discussion earlier.

Each vehicle and fuel combination can be compared and contrasted against each other and against the Normalisation Reference ($R_i$) point. The relative impact of each can then be investigated, together with the identification of the stage with the highest contribution to the impact in question.

### 6.4.1 GWP

The normalised GWP results for the Euro 4 Van, the HGV and the Bus are presented in Figure 6.1. The results show that the lowest contribution to GWP is from a Green Electric Van (15 years operation) with the highest impact from a diesel fuelled Euro 4 Bus (10 years operation), see Figure 6.1 and Appendix O. These results represent the percentage contribution from the average persons' total annual release of the gases that contribute to GWP in the World in 1990 i.e. the manufacture, use and disposal of a diesel fuelled bus operating for 10 years contributes to the equivalent GWP output of 5.8 people (per year) in 1990.

In comparison the following life cycle contributions are noted from the manufacture, use and disposal of three household products.

Low Energy Refrigerator in operation for 13 years (EDIP **1** p.319-346)

- 3% of the contribution to GWP from an average person in the World in 1990

Bang and Olufson television in operation for 10 years (EDIP **1** p.370-395)

- 1.5% of the contribution to GWP from an average person in the World in 1990

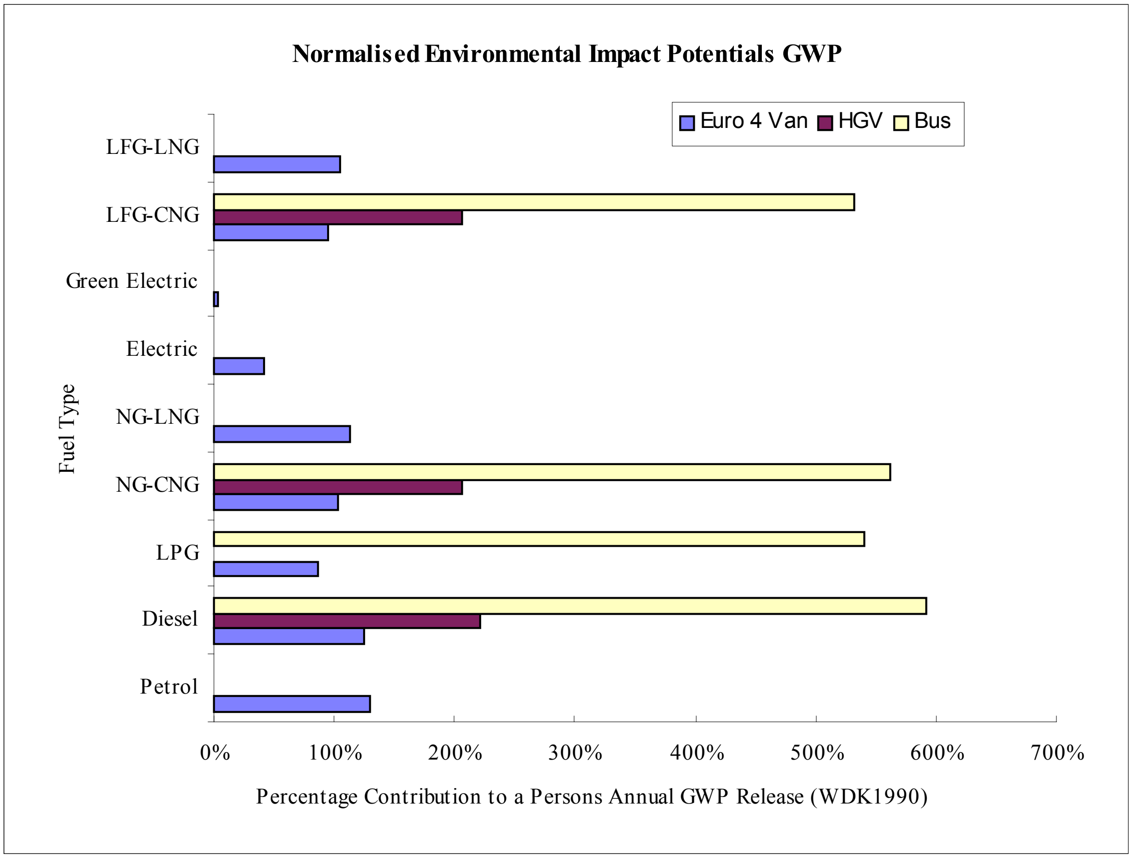
KEW High Pressure Cleaner in operation for 5 years (EDIP **1** p.415-438)

- 0.3% of the contribution to GWP from an average person in the World in 1990

The impact on GWP from a Green Electric van is less than that of the household products listed above, however the impact of a diesel van (~130%, see Figure 6.1), operating for fifteen years, is 128.5% greater, in relative terms, per annum, than a Bang and Olufson television (1.5%) manufactured and used in the 1990s and 1,928% greater over its life time use.

In comparison to a conventional petrol fuelled Euro 4 van, the results show, see Figure 6.1b, that diesel GWP emissions are reduced by approximately 5%, NG-CNG by approximately 30%, LPG by approximately 45% and electric vehicles by approximately 125%. In contrast, the work of Wang (1999b), on Light Duty Vehicles (LDVs) in the US, has revealed that GHG emissions in the use stage (F6 equivalent), in comparison to conventional gasoline in 1999, are reduced by approximately 27% for diesel LDVs, approximately 12% for LPG vehicles, approximately 10% for CNG vehicles and between 40-70% reductions are achievable with the use of electric vehicles (dependent upon the region of charging). Similarities between the two data sets are evident even with the numerous minor differences in UK and US vehicle design, use and size.

## Figure 6.1a – Normalised Environmental Impact Potentials for GWP




## Figure 6.1b – Calculation of NEP for GWP

| GWP (Av. Euro 4 Van) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Petrol | Diesel | LPG | NG-CNG | NG-LNG | Electric | Green Electric | LFG-CNG | LFG-LNG |
| EP | 169,177,223 | 162,581,611 | 112,038,230 | 134,667,945 | 148,180,050 | 54,022,718 | 3,529,663 | 124,566,052 | 137,740,277 |
| NP | 1.296 | 1.246 | 0.859 | 1.032 | 1.135 | 0.414 | 0.027 | 0.955 | 1.055 |
| mPE | 1,296 | 1,246 | 859 | 1,032 | 1,135 | 414 | 27 | 955 | 1,055 |
| Van % | 130% | 125% | 86% | 103% | 114% | 41% | 3% | 95% | 106% |
| HGV % | | 221% | | 207% | | | | 206% | |
| Bus % | | 592% | 540% | 562% | | | | 532% | |
| WP (Van) | 1.69 | 1.62 | 1.12 | 1.34 | 1.48 | 0.54 | 0.04 | 1.24 | 1.37 |
| WP (HGV) | | 2.87 | | 2.69 | | | | 2.68 | |
| WP (Bus) | | 7.69 | 7.02 | 7.31 | | | | 6.92 | |

The results show that the use of a petrol van for fifteen years contributes 130% per annum of the contribution to GWP from an average person in the World in 1990.

Therefore excluding all other GWP emissions, such as the use of household products, burning of fossil fuels, use of electricity, heating and general living, the use of a petrol van alone contributes to 130% above of the annual World average set for 1990. When all other possible GWP emissions from the average person are included this value increases further. Only a small percentage of the World population own and use a petrol van in this way. However with the annual increase usage of motor vehicles, it becomes clear to see that the use of a vehicle has an impact on the contribution to GWP, when compared to the output from an average person.

With the contribution to GWP from the average person established, one needs to investigate the relative impact against the international political reduction targets. The values are weighted to reflect the environmental impact potential for the target emission reductions.

The GWP weighted environmental impact potential results are presented in Figure 6.2. The smallest and largest weighted impact occurs from the manufacture, use and disposal of a Green Electric powered van (0.04%) and a diesel fuelled Euro 4 Bus (769%) respectively. Once again these results can be compared to the examples reproduced within the EDIP publications, as follows:

Low Energy Refrigerator in operation for 13 years (EDIP **1** p.319-346)

- 4% of the target reduction in GWP from an average person in the World or Denmark in 2000

Bang and Olufson television in operation for 10 years (EDIP **1** p.370-395)

- 1.8% of the target reduction in GWP from an average person in the World or Denmark in 2000

KEW High Pressure Cleaner in operation for 5years (EDIP **1** p.415-438)

- 0.4% of the target reduction in GWP from an average person in the World or Denmark in 2000

Therefore, the manufacture, use and disposal of a Green Electric powered van (0.04%) in operation for 15 years contributes much less to the targeted reduction percentages per person for the World or Denmark in the year 2000, whereas a diesel fuelled Euro 4 Bus (765%) used by an average person would result in their individual contribution being approximately 7.65 times greater than the acceptable level of targeted reduction (excluding the persons' annual general contribution through normal living) e.g. A petrol fuelled Euro 4 van (169% $PET_{WDK2000}$) contributes to 69% above the **maximum** contribution to GWP, which an average person should make in the year 2000 in order for the target reductions to be met.

Obviously, the average person will never own or operate a bus, however the results can be used to reflect the relative contribution made to that of the targeted reduction values.

**Figure 6.2 – Weighted Environmental Impact Potentials for GWP.**

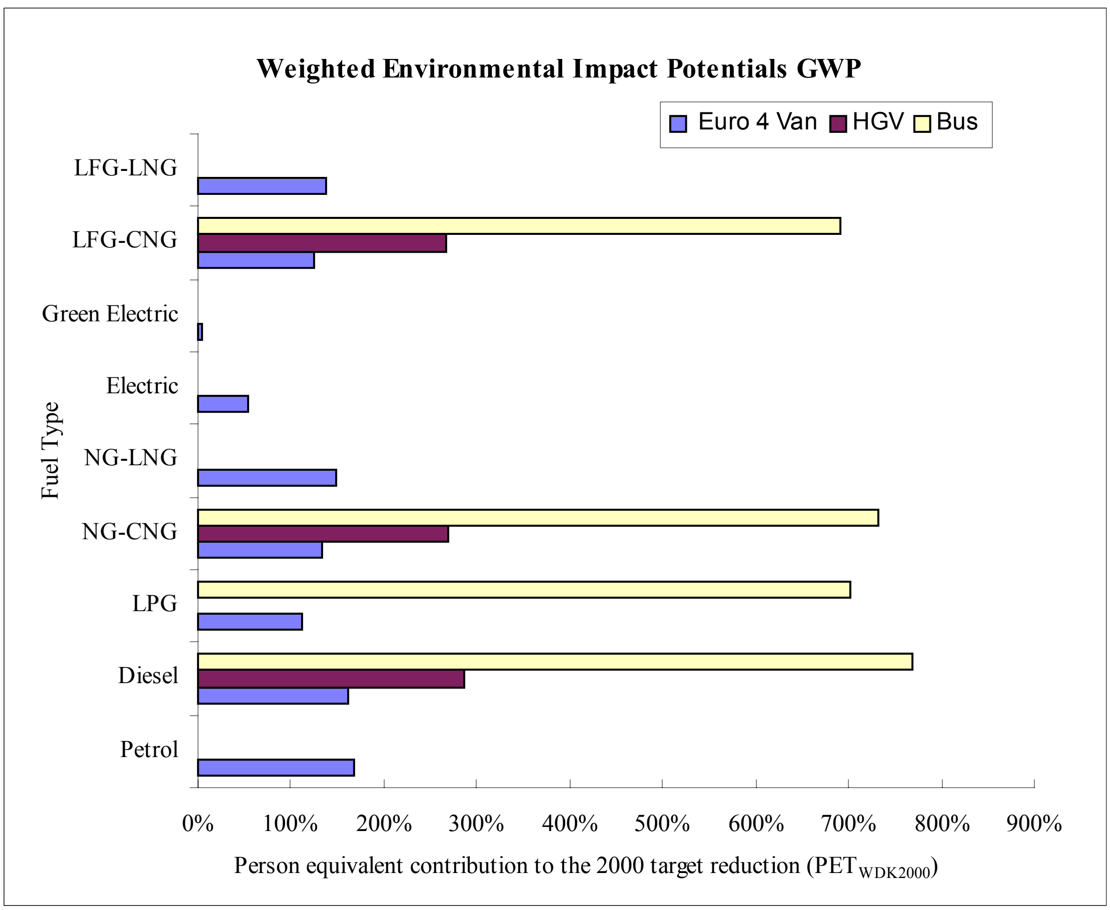


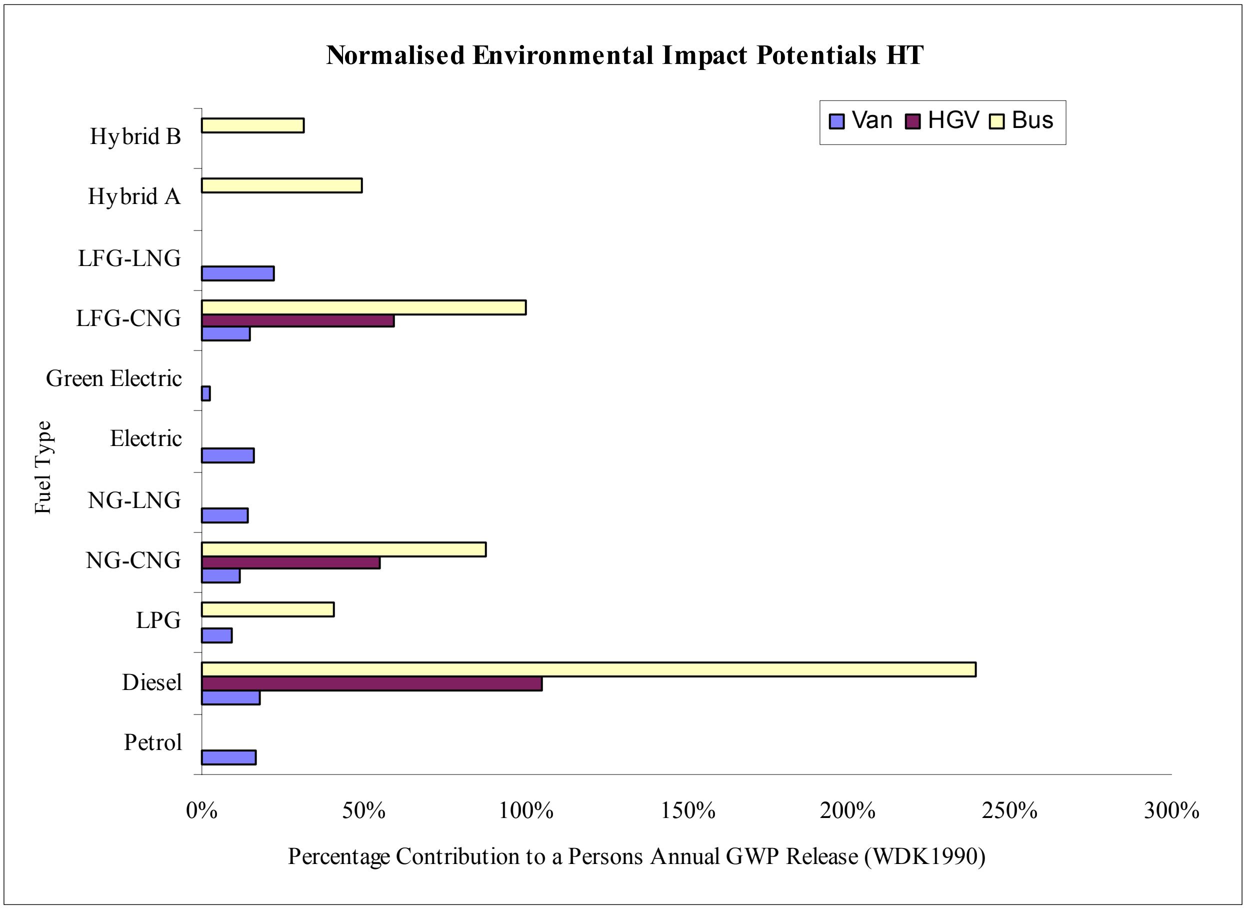
Figure 6.2 shows the relative impact each vehicle has on the targeted reductions set for the year 2000. It becomes clear to see that a bus has a much larger impact, for all fuel types, than a large van. This may seem obvious given the relative size of each vehicle. The electric and green electric vans show the lowest contribution to GWP on a relative scale, however within this LCA study a series of assumptions are made and only gaseous emissions are considered. If one were to consider metals and so-called auxiliary emissions, these results may alter, more so in the calculation of HT where metals contribute a great deal more than gaseous emissions to the total toxicity level.

It also becomes interesting to see that a change in fuel type for the same vehicle can lead to a significant reduction in contribution. A NG-CNG bus contributes to 731% of the average persons contribution to the target reduction. If one changes the fuel to LPG (702%) a reduction by 4% results. A significant reduction in targeted GWP reduction with large implications for a bus operator, concerned with pollution on a global scale.

### 6.4.2 Human Toxicity (HT)

The normalised HT results for the Euro 4 Van, the HGV and the Bus are presented in Figure 6.3. The results show that the lowest contribution to HT is from the Green Electric and NG-LNG Van (15 years operation), with the highest impact from a Diesel fuelled Euro 4 Bus (10 years operation).

**Figure 6.3a – Normalised Environmental Impact Potentials for HT**




The results presented in Figure 6.3 clearly show that the HT emissions associated with the operation of a bus are much higher then those of the large van. Not surprisingly, however the impacts of the bus and HGV CNG vehicles are similar, whereas in Figure 6.1 the GWP contributions for the CNG bus was much larger than that of the CNG HGV. Therefore if a public service vehicle operator had to make a choice of alternative fuel for a HGV fleet, in comparison to the fuel options available, it is globally beneficial (GWP) to operate using a LFG-CNG HGV and locally beneficial (HT) to operate a NG-CNG HGV. In this case the operator can confirm, on a purely environmental basis, that the CNG HGV provides the largest benefit, see Table below.

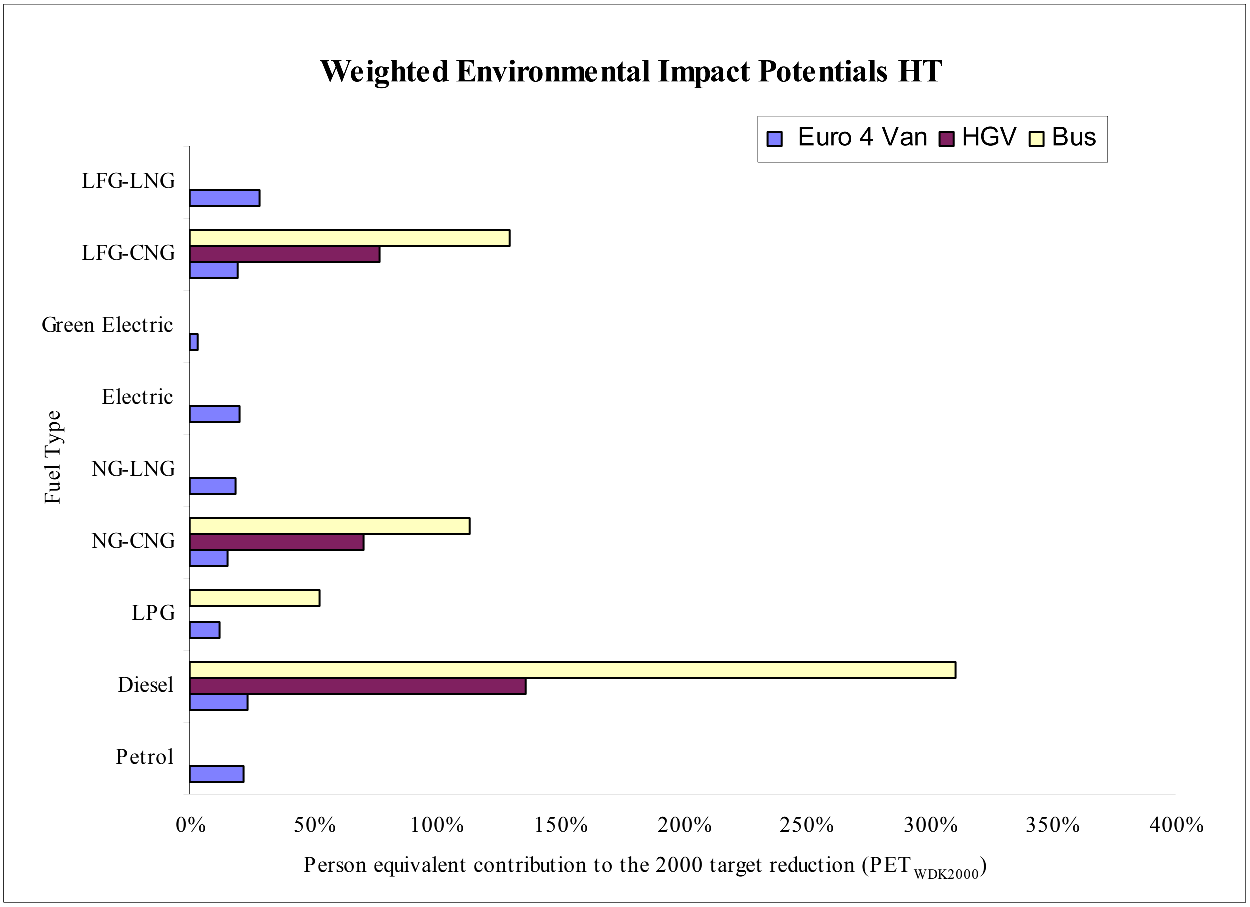
Figure 6.3b – Calculation of NEP for HT

| Human Toxicity (Euro 4 Van) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Petrol | Diesel | LPG | NG-CNG | NG-LNG | Electric | Green Electric | LFG-CNG |
| EP | 1,681,494,710 | 1,791,755,833 | 941,532,209 | 1,164,637,028 | 1,433,270,405 | 1,860,510,709 | 262,779,434 | 1,476,445,248 |
| NP | 0.170 | 0.181 | 0.095 | 0.118 | 0.145 | 0.188 | 0.027 | 0.149 |
| mPE | **170** | **181** | **95** | **118** | **145** | **188** | **27** | **149** |
| Van % | **17%** | **18%** | **10%** | **12%** | **14%** | **19%** | **3%** | **15%** |
| HGV % | | 105% | | 55% | | | | 60% |
| Bus % | | 240% | 41% | 88% | | | | 100% |

The electric vans at this stage have an impact on the levels of HT. The green electric van (3%) contributes the least to HT. Interestingly, the electric vans (19%) powered by the UK National Grid have a larger HT impact, on a per person contribution basis, than the LPG, NG-CNG, NG-LNG and LFG-CNG vans.

The relative impacts of the petrol and diesel vans, in comparison to the electric vans can now be seen, together with the impacts of the bus and HGV. On a relative scale a diesel van contributes 5 and 13 times less to HT than a HGV and bus. The same van also contributes to 18% of the average persons contribution to HT per year in Denmark in 1990.

**Figure 6.4 – Weighted Environmental Impact Potentials for HT**




In terms of the Person Equivalent Targeted (PET) reductions set for HT in the year 2000, the relative contributions can be seen in Figure 6.4. In the calculations of weighting impact potentials, targets are set for each of the compounds under investigation i.e. a 12% reduction in $CO_2$ was targeted in 2000 from the 1990 level, by the Danish Ministry of Energy. The Danes produced an action plan for sustainable development and reduction of many pollutants became necessary, see EDIP **2** p.23-30.

The $PET_{WDK2000}$ results are similar to the results presented in Figure 6.3, however a greater percentage reduction is required for each fuel and vehicle combination in order to achieve the target reductions. The relative contributions between each vehicle are unchanged as each is subject to the same weighting factor of 1.295. The addition of more compounds and/or metals to the calculation of HT would change the weighting factor and increase the percentage contribution.

A 100% $PET_{WDK2000}$ is equivalent to the contribution required by an average person in the World and Denmark in 1990 in order to achieve the targeted HT reductions set for the year 2000. On this basis, a NG-CNG HGV contributes to 82% of the target reductions. If the average person operated a HGV of this type, it is clear to see that the targeted 100% reduction could not be met as that person would have only a very small percentage (18%) of the total remaining for general living, fossil fuel use, work etc. A diesel bus contributes ~308% to the target reduction. However, if a bus transports 30 people then the targets, per person, are reduced to 10.3%. This demonstrates the sustainability of passenger transport.

### 6.5 Summary

The results presented in this Chapter are calculated from the methods described in EDIP, which are combined with the work of the present study. There are a series of assumptions made within and depending upon the goal and scope of the user, these may or may not be appropriate in particular cases. Individual users may have different viewpoints, draw their own conclusions and make their own assumptions. The results presented in this Chapter compare conventional and alternative fuels on a life cycle basis, with the EDIP methodology providing a basis upon which each fuel and vehicle combination can be compared.

The buses and HGVs are limited to certain fuels and in an ideal analysis each and every fuel and vehicle would be cross-compared. Moreover the inclusion of all process emissions, not only gaseous, would prove beneficial and may alter some results, although the GWP values would be unlikely to differ.

Each value used within the preceding Chapters represents a "snap-shot" in time for each fuel and vehicle combination. Changes in vehicle operation, percentage errors and probability distributions have not been included. It is the purpose of Chapter 7 to incorporate uncertainty in the results and simulate change within the systems. On completion, Chapter 7 will show the significance of each stage within the fuel and vehicle cycles, upon which the assumptions made within the present study can be reviewed.