Sensitivity in the operation of conventional and alternatively fuelled Public Service Vehicles on Merseyside

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Abstract

This paper compares the sensitivity in the operation of conventional and alternatively fuelled Public Service Vehicles (PSVs) in operation across Merseyside. Each fuel is compared on a life cycle assessment (LCA) basis, with the addition of landfill gas (LFG) as a viable alternative. On a complete life cycle basis, LFG powered vehicles compare favourably with gas-powered vehicles and generally cause less pollution than the liquid-fuel powered vehicles, with electric vehicles generally producing the least pollution overall. In the majority of cases, the sensitivity analysis has revealed that the most significant stage in the life cycles of each fuel and vehicle is the end-use (fuel combustion) stage. In some cases this stage alone contributes to 90% of the total life cycle emissions. Daily and annual changes in vehicle operation have a large influence on the amount of pollution released into the atmosphere.

Keywords: alternative fuels, public service vehicles, life cycle assessment, landfill gas, hybrid vehicle, sensitivity analysis.

1 Introduction

The majority of road vehicles in the UK today are either powered by petrol or diesel. Alternative fuels such as Liquified Petroleum Gas (LPG), Compressed and Liquified Natural Gas (CNG/LNG), Landfill Gas (LFG), Biofuels, Electric and Electric Hybrid vehicles account for around 2% of the current UK fleet.

Furthermore 80% of vehicles on the road in the UK are passenger vehicles and Light Goods Vehicles (LGVs) with the remainder consisting of Heavy Goods Vehicles (HGVs) and Buses, IEA [1]. As a result, the number of alternatively fuelled PSVs, of which the majority are HGVs and buses, in operation throughout the UK is very small. The majority of HGVs are diesel powered and their emission load on local and global air quality is well recognised, as are the improvements in diesel fuel and engine/exhaust systems. Global and local air quality worsens as more vehicles occupy our towns and cities. Levels of car ownership and use are set to escalate further as car dependency becomes more common. The European Union (EU), UK Government and Local Authorities are attempting to reverse this trend by numerous initiatives and incentives i.e. The Clean Accessible Transport for Community Health (CATCH) programme [2].
Implementing change and a modal shift in transporting people is proving difficult. A further problem arises then if people decide to use public transport and a modal shift occurs, the services provided must be efficient, cost effective, safe, punctual and environmentally friendly. This is the challenge that faces each Passenger Transport Executive and Authority (PTA/Es). The Life Cycle Emissions Model (LCEM) developed by Finnegan [3] uses the Life Cycle Assessment (LCA) approach to provide an Environmental Impact Assessment (EIA) of conventional and alternative fuels for PSVs, without the explicit need for expensive field trials. The model can be used as a decision making tool for fleet operators in the review and assessment of vehicle procurement. However the use of existing databases will date and the authors recognise that manufacturer/operator field data is important as technologies develop.

2 LCA and the LCEM

Life Cycle Assessment (LCA) is an environmental management tool used to understand and compare how a product or service is provided 'from cradle to grave', a term used to describe the life cycle of a product from its first derivatives to its end-use, Forbes [4]. The technique examines every stage of a product’s life, from material extraction, through manufacture, distribution, use, reuse/recycling and final disposal. A typical LCA consists of four stages: (1) Goal Definition and Scope (2) Inventory Analysis (3) Life Cycle Impact Assessment and (4) Interpretation, as defined by the International Standardisation Organisation (ISO14040). Details on the use of LCA studies in transport applications can be found within Finnegan [5], DETR [6], Rosselot and Allen [7] and Sheenan [8]. LCAs must be limited in scope and as a result it becomes common to define system boundaries. In theory a full LCA would include all upstream and downstream processes, in reality this ideal cannot be achieved and hence system boundaries are put in place. Within the LCEM model developed by Finnegan [3], two linked cycles exist: (1) Fuel Cycle (F1-F6) and (2) Vehicle Cycle (V1-V4). The fuel cycle consists of six stages (F1-F6) and the vehicle cycle contains four stages (V1-V4), further details can be found in Finnegan [3,4]. Other LCA studies world-wide use a similar approach as a template for their own work, see Deluchi [9], Gaines [10], General Motors

Corporation [11], Hackney [12] and Wang [13,14]. Much of the earlier work naturally concentrated on cars.

The LCEM is used to compare and contrast alternative fuels on a LCA basis. Within this paper the impacts of Global Warming Potential (GWP) and Human Toxicity (HT) are considered. Other impacts such as eco-toxicity and eutrophication could be added within the general framework.
In the assessment of conventional (petrol and diesel) and alternative fuels, ten life cycles are considered for vehicles in operation on Merseyside in 2004, see Figure 1.

Petrol	Petroleum Based Fuels
Diesel	
LPG	
NG to CNG	Natural Gas Based Fuels
NG to LNG	
Electric	Electric Based Fuels
Green Electric	
LFG to CNG	Landfill Gas Based Fuels
LFG to LNG	
Diesel/Electric Hybrid	Petroleum and Electric Based

Figure 1: Fuel Options

The following fuels are considered for the following PSVs:

Van	Petrol, Diesel, LPG, NG-CNG, NG-LNG, Electric, Green Electric, LFG-CNG and LFG-CNG
HGV	Diesel, NG-CNG, NG-LNG, LFG-CNG, LFG-LNG
Bus	Diesel, NG-CNG, NG-LNG, LFG-CNG, LFG-LNG, Diesel/Electric Hybrid

3 PSVs on Merseyside

PSVs in the present study are defined as Large Vans 1.8t Unladen Vehicle Weight (UVW), HGVs 18t UVW and Buses 10t UVW, although PSVs normally refers to buses. A complete LCA analysis of these PSVs has recently been completed by the first author, see Finnegan [3,4]. The Merseyside Passenger Transport Executive (Merseytravel) and Liverpool City Council operate vehicles of this type. This paper compares the sensitivity in operation of the conventional petrol and diesel vehicles across Merseyside. The alternative fuel vehicles are not in operation and the resultant emissions calculations are theoretical. The LCEM is capable of accurately predicting the emissions profiles of each alternative fuel, if in theory, the fuel was to replace petrol or diesel. It should also be noted that the alternative fuel emissions profile are based on the percentage addition/reductions when compared to a Euro 4 petrol/diesel vehicle. Any new vehicle registered after 2005 must comply with the EC Directive (98/69/EC), which sets emissions limits in g/km, dependent upon vehicle weight and class. Most PSVs on the road today comply with Euro 2 (1996) and Euro 3 (2000) standards.

4 CATCH and Hybrid Buses

The EC Life Environment CATCH project is being implemented in Liverpool (Merseyside), Succeava (Romania) and Potenza (Italy). There are seven objectives; the details of which can be seen on the CATCH website [2]. Objectives one and two involve applying emissions reduction technologies to 88 existing Euro 2 buses and procuring 6 new (diesel/electric) hybrid buses. This paper compares alternative fuels to Euro 4 standards, not Euro 2. This is because the LCEM developed by Finnegan [3] was intended for use prior to and proceeding 2005 to enable decision makers to choose between the procurement of new vehicles and alternative fuels next year and in the future. Moreover, the CATCH project is currently investigating the use of hybrid buses, which now quote emissions figures in comparison to the Euro 4 standards. Whether or not the alternative fuels are compared to Euro 4 or Euro 2 is inconsequential because the importance lies in the comparison of one fuel to another in the same vehicle and not the fuel used within different standards of vehicle.

This paper compares the hybrid buses (Type A and B) to other PSVs with the use of the LCEM. For the comparisons to be made, a number of assumptions are necessary. For the calculation of emissions and subsequently global and regional impacts, a large number of factors have been considered, see Finnegan [3]. Assumptions for the hybrid buses are as follows:

- Single-deck, series hybrid buses were chosen to represent the hybrid vehicle.
- A micro-turbine is used as the power source in Hybrid A with a turbo-diesel engine in Hybrid B, both running on Ultra-Low Sulphur Diesel (ULSD) to provide the power to charge the lead-acid batteries and operate the vehicle. Battery recharged occurs onboard the vehicle either through the operation of the combustion engine and generator elsewhere on the route, or by regeneration from braking.
- The vehicles operate on battery power through their operational cycles and the emissions associated with the use of each vehicle are calculated through independent testing at the Milbrook Proving Ground.
- Lead-acid batteries make up a large percentage of the UVW weight (21%) in Hybrid A (1400kg), a similar weight is assumed for Hybrid B.
- Arbitrary assumptions on fuel consumption are made; Hybrid A uses 20% more ULSD and Hybrid B uses 20% less ULSD in comparison to a Euro 4 bus. Emissions of hydrocarbons from both vehicles are considered to be negligible.

- Operational assumptions for this paper are best estimates. Each vehicle will cover 140km per day, be in operation for 6 days per week and 300 days per year for an assumed 10 year life.

5 Results

The life cycle emissions from the hybrid buses are compared with the other PSVs in operation across Merseyside with the use of the LCEM, see Figures 1 and 2. It must be noted that each PSV operates under different conditions and the comparisons are made with different fuels used within the same vehicle e.g. the van operates under very different conditions in comparison to the HGV or bus; average mpg, distance travelled, emission rates and speeds are very different for each vehicle. The results below are normalised to the percentage contribution to Global Warming Potential (GWP) and Human Toxicity (HT) made by each person in the world in 1990, based on the Environmental Design of Industrial products (EDIP) scheme, Wenzel [15,16]. Further details can be seen in Finnegan [3].

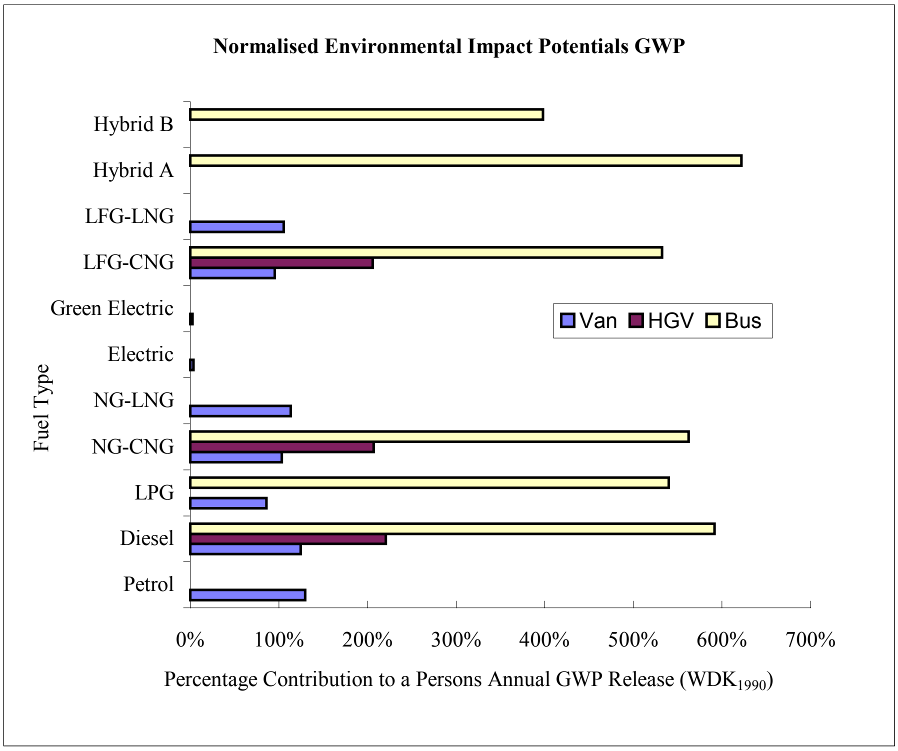

Figure 1: Normalised GWP for PSVs on Merseyside

NOTE: Direct comparisons between the different vehicle types presented in Figures 1 and 2 cannot be made. Comparisons of different fuels used within the same vehicle can be made. The Hybrid buses are compared to Euro 4 buses (any bus manufactured after 2006) and not the majority of buses in operation across the UK today, which meet lower emissions standards.

The results show the impacts made towards GWP by the PSVs on Merseyside. Hybrid bus A, powered by the micro-turbine and lead-acid batteries has the highest impact to GWP and the green electric van has the lowest impact (a fraction of a percent). It should be noted that these results represent the air emission of CO_2, CO and CH_4 (methane) scaled to their contributions to GWP only i.e. CH_4 is 25 times more potent than CO_2 as a GWP gas. The results represent the GWP contribution per person, this is to say that if 30 people travelled on the conventional diesel bus the percentage contribution to GWP from each person would decrease. Much lower than the contribution made per person driving a van powered by liquid and gaseous fuels. The results for the hybrid bus are not surprising given that Hybrid A consumes 20% more ULSD than a conventional Euro 4 bus. As Hybrid bus technologies develop, the amount of fuel required to charge the batteries onboard the vehicle will decrease.

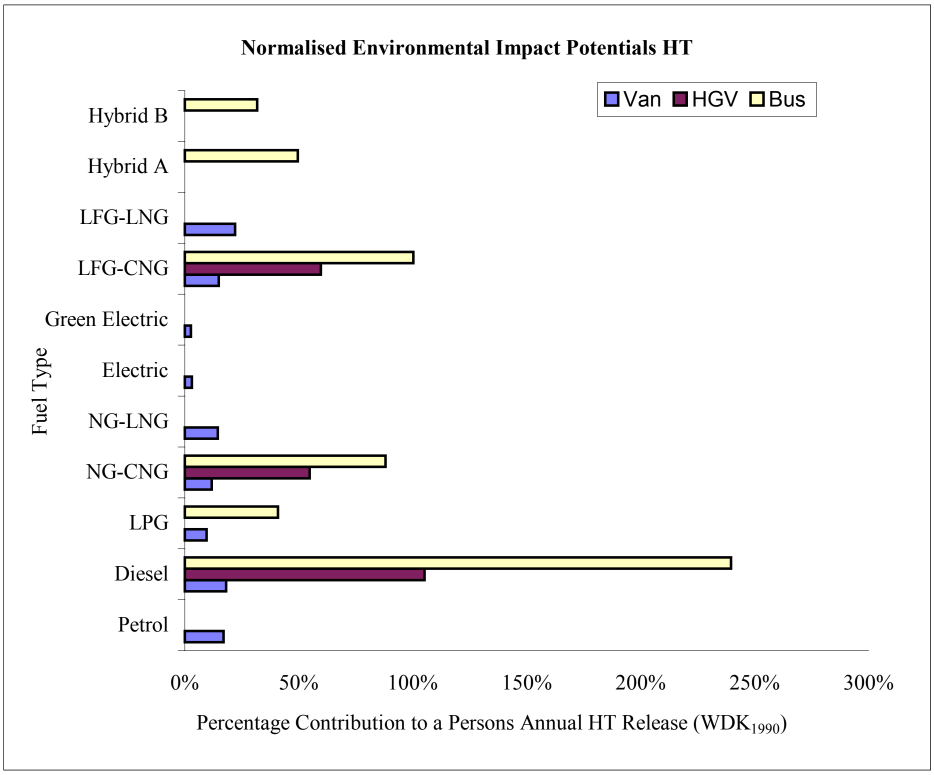

Figure 2: Normalised HT impacts for PSVs on Merseyside

The impacts on local air quality differ and if one considers the impacts of Oxides of Nitrogen (NOx), Carbon Monoxide (CO), Particulate Matter (PM) and Sulphur Dioxide (SO_2) as human toxicants; the results show, see Figure 2, that the green electric and electric vans contribute the least to HT with the diesel bus contributing the most to HT. The relative impacts of the hybrid buses are reduced in comparison to GWP; this is primarily because less HT related pollutants are released when the vehicle is in operation. Once again, should the bus, or indeed any vehicle have more than one occupant the percentage contribution per person is decreased. The average patronage on buses in Merseyside is 10. Reducing the percentage contributions by 10 for the diesel, LPG, NG-CNG, LFG-CNG and hybrid buses would indicate that the average persons contribution to HT would be approximately equal to that of a van occupied by one person. Hybrid bus B has the lowest contribution to HT from all buses sampled.

For any fleet manager deciding upon the procurement of conventional and alternative fuel vehicles, decisions have to be made on the significance of global and local impacts. Designated Air Quality Management Areas (AQMAs) require action plans, some plans suggest the use of alternative fuels, and others may stipulate that vehicles must be of Euro 4, 5 or Environmentally Enhanced Vehicle (EEV) standard. The LCEM model can be used as a useful tool in the decision making process, though the residual value of existing fleets and the availability of ‘green subsidies’ are among the many other factors to be considered.

6 Sensitivity Analysis

Following the estimation of the impacts each fuel and vehicle has on GWP and HT, a sensitivity analysis was used to identify the key stages in the life cycles of each vehicle, see Finnegan [3]. Results show that the end-use stage in the life cycle of each liquid and gaseous fuelled vehicle, has the greatest contribution to life cycle emissions. For the electric powered vehicle, the vehicle cycle stages play a more significant role in the formation of GWP and HT. Having identified the key stage in the formation of GWP and HT for each vehicle, a numerical simulation using the Latin Hypercube sampling technique was performed with the @RISK software. This type of sampling is used to investigate elements of uncertainty. The assumptions made in the LCEM for each fuel and vehicle combination are subject to varying degrees of uncertainty and by sampling it becomes possible to define some upper and lower limits for each GWP and HT output value i.e if the average speed of the bus is increased or decreased by 20% and/or the distance travelled per day increased or decreased the overall fuel cycle and hence life cycle results would change. The LCEM identified that the variables operational lifetime, distance travelled per day, average speed and total operational days per year, have the largest individual impacts related to the formation of GWP and HT for each of the liquid and gaseous fuels under examination. Figure 3, illustrates the bus correlation coefficient, representing the sensitivity of each of the output variables (listed above) to the input variable, which in the case of the bus is CO_2. The coefficient values identify the most 'critical' inputs in the model. A coefficient value of 1 refers to a perfect positive correlation between the variables x and y, conversely a value of –1 refers to a perfect negative correlation between the two variables e.g. a perfect correlation (±1) means that the value of y is totally dependent on the particular x variable considered.

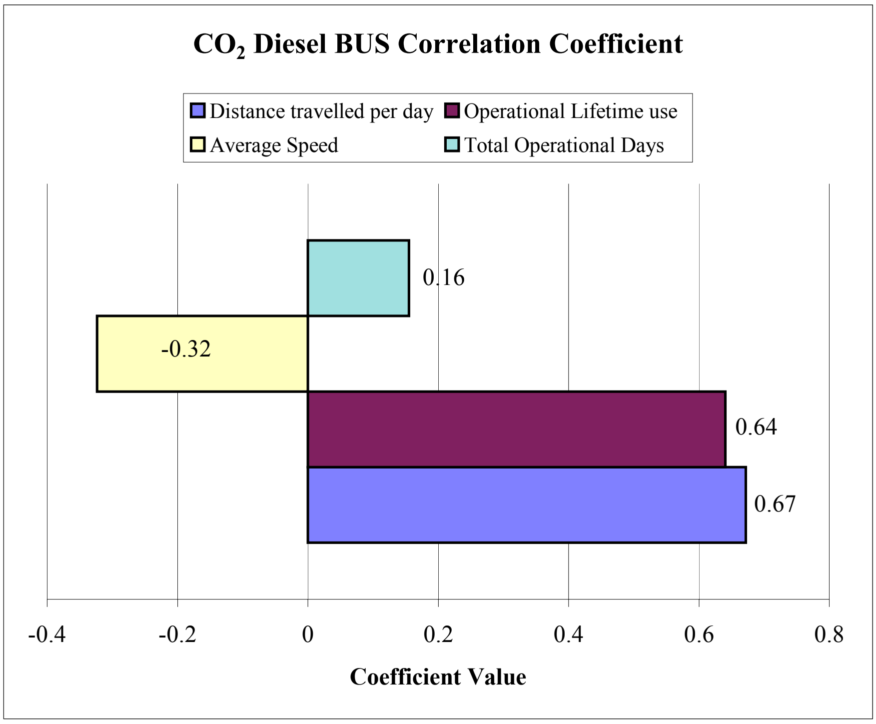

Figure 3: Diesel Bus Correlation Coefficient

The results show that the distance travelled per year is the most critical variable in the calculation of CO_2 and subsequently the formation of GWP. Similar trends are found for each pollutant under investigation and the distance travelled per day and operational lifetime use, have been identified as the most critical variables in the formation of GWP and HT. The average speed plays an important role but less critical role. These results show that changes in each variable can significantly alter the amount of pollutants released and therefore affect the contribution to GWP and HT. The LCEM has also shown that for all liquid and gaseous fuelled vehicles approximately 90% of the total life cycle emissions are derived from the fuel cycle (F6) end-use stage. The vehicle cycle contributes, on average, less than 10% to the total life cycle emissions, however, when electric or electric hybrid vehicles are in use the fuel cycle emissions are reduced and the impact of the vehicle cycle becomes more prevalent. Moreover, if the emissions during the end-use stage are reduced through exhaust after treatments, or via the use of a cleaner burning fuel, the total life cycle emissions can also be reduced.

Overall, and not surprisingly, the results show that fleet managers should concentrate their efforts on the operational use of their vehicles and the fuels used in powering them, for conventional and alternative fuel vehicles. However, as emissions in the end-use stage improve and battery, hybrid or even fuel cell vehicles become more common, the impacts of the other stages in the fuel and vehicle cycles may become more relevant.

7 Conclusion

The sensitivity analysis has shown that the most significant stage the life cycle of all vehicles, with the exception of the electric vehicles, is derived from the end-use stage. Furthermore the operational lifetime use, average speed, distance travelled per day and total operational days are the largest contributors to GWP and HT for all fuels and vehicles under investigation, again with the exception of the electric vehicles. To reduce the emissions of the compounds investigated, these four variables need careful consideration and future studies should focus upon them. However, as hybrid, electric and fuel cell vehicle technologies advance, the significance of the end-use stage will decrease. These vehicles (except hybrids) have zero emissions at point of use and for a true environmental impact assessment to be made; the whole life cycle of each vehicle must be considered.

8 References

[1] IEA. *Automotive Fuels for the Future: The Search for Alternatives*. International Energy Agency Advanced Motor Fuels Division, 1999.

[2] CATCH, www.cleanaccessibletransport.com

[3] Finnegan, S. A Life Cycle Assessment of Alternative Fuels for Public Service Vehicle. Ph.D. thesis, Department of Civil Engineering, University of Liverpool 2004.

[4] Forbes, M. White, P. Franke, M. Hindle, P. *Integrated Solid Waste Management: A Life Cycle Inventory*. 2nd Edition. Blackwell Science.

[5] Finnegan, S., Tickell, R.G. & Booth, K. A Lifecycle Assessment (LCA) of Alternative Fuels in Transport Operation. *Proceedings of the International Conference on Transportation Systems Planning and Operation,* **2** p.559-569. Indian Institute of Technology, Madras, India.

[6] DETR *Review of Work on Whole-Life Environmental Impacts of Vehicles* Cleaner Vehicles Task Force, London. 2002

[7] Rosselot, K and Allen, D. Life-Cycle Concepts, Product Stewardship and Green Engineering In: Allen, D and Shonnard, D. *Green Engineering: Environmentally Conscious Design of Chemical Processes*, Chapter 13, pp.419-459, 2002.

[8] Sheenan, J. Camobreco, V Duffied, J Graboski, M and Shapouri, H. *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*. NREL/SR-580-24089 UC Category 1503. US Department of Agriculture and US Department of Energy. National Technical Information Service (NTIS), US Department of Commerce, Springfield. 1998

[9] Delucchi, M. Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity. **1** ANL/ESD/TM-22. *Center for Transportation Research, Energy Systems Division, Argonne National Laboratory,* Argonne, Illinois 60439, 1991

[10] Gaines, L. and Singh, M. Energy and Environmental Impacts of Electric Vehicle Battery Production and Recycling. *Total Life Cycle Conference, SAE Paper 951865*, Austria. 1995.

[11] General Motors Corporation. Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems, *Argonne National Laboratory, Argonne, Illinois*. 2001

[12] Hackney, J. and Neufville, R. Life cycle model of alternative fuel vehicles: emissions, energy, and cost trade-offs. *Transportation Research* Part A **35** pp. 243-266, 2001

[13] Wang, M.Q. GREET Model 1.5a - Transportation Fuel-Cycle Model, Methodology, Development, Use, and Results ANL/ESD-39 **1** *Centre for Transportation Research, Argonne National Laboratory*, Argonne, Illinois 60439, 1999a

[14] Wang, M.Q. GREET Model 1.5a - Transportation Fuel-Cycle Model, Appendices of Data and Results ANL/ESD-39 **2** *Centre for Transportation Research, Argonne National Laboratory*, Argonne, Illinois 60439. 1999b

[15] Wenzel, H; Hauschild, M and Alting, L. Environmental Assessment of Products: Methodology, tools and case studies in product development **1** Chapman and Hall. 1997

[16] Wenzel, H; Hauschild, M and Alting, L. Environmental Assessment of Products: Scientific background **2** Chapman and Hall. 1998