Robustness of Materials Selection Decisions Using Various Life-Cycle Assessment Methods

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Abstract

The use of alternative materials to reduce vehicle mass is a tactic often promoted as improving the fuel efficiency and environmental performance of vehicles. However, a growing array of materials candidates confronts today's designer. While life-cycle assessment methods are available to provide quantitative input into this selection decision, their implementations are evolving and distinct. This paper explores the robustness of materials selection decisions when using different LCA methods. Specifically, this paper surveys the major analytical variations of LCA implementations and explores the implications of several of these variants when applied to an automotive materials selection case study. This case study examines analytical variations in: valuation method, secondary weight savings, and treatment of recycling. Preliminary results indicate that, although the choice of analytical method can have real impacts on individual metrics, there are sets of analytical variation over which strategic results are not strongly affected.

Introduction: The Challenge of Environmentally Informed Materials Selection

Industries, manufacturing and otherwise, are currently confronted with a range of pressures to produce products and conduct operations in ways that protect the natural environment, human health, and societal interests – ways that are sustainable. Included among these pressures are corporate regulations, resource availability, ethical responsibility, and consumer demand for environmentally-beneficial products and services [1]. Meeting these challenges will depend upon a wide range of actions, but fundamental to any such action will be the development of approaches to evaluate environmental performance, both as a way to monitor current practice as well as to establish goals for the future. Sustainability will not be successfully incorporated into firm actions until there are effective ways to measure progress toward it [2]. The proliferation of such approaches provides manifest evidence of the increasing intensity of the pressure being placed on firms to improve their environmental footprint. One such example comes in the form of firm-wide environmental evaluation and reporting. A growing number of firms file public reports on their environmental performance based on both in-house measures of performance as well as a host of institutionalized measurement schemes such as the Global Reporting Initiative indicators [3], the EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts [4], financial indicators including the Dow Jones Sustainability Index [5], and FTSE4Good Indices [6].

Irrespective of the specific metrology selected to evaluate firm performance, for a firm to improve they must be able to evaluate the implications of specific decisions they make about the products they produce and the production methods they utilize to realize those products. Within the family of decisions about product and production, no single decision has greater fundamental impact on environmental performance than the selection of materials. Materials influence the choice of production technology, product form, and, ultimately, the configuration and distribution of the supply chain. As such, materials not only establish the environmental characteristics of their associated extraction and refining, but also the characteristics of transformation into product, the performance of the product during use, and the potential for recovery at end-of-life. Effective tools to inform on the environmental implications of materials selection decisions are critical.

Of the methods available to incorporate environmental information into the materials selection process, the most general and broadly discussed method is life cycle assessment[1]. To comprehend the broad set of events and consequences that determine environmental performance, LCA requires the analyst to extensively characterize each of the stages of a product's or process' life. This presents a challenge for typical materials selection decisions that occur early in the product development cycle, when options are ample, but data is scarce. As a result, a critical question emerges concerning the effectiveness of LCA to support materials selection decisions: Is the LCA effective in supporting results robust to the magnitude of uncertainty endemic to materials selection?

The analyses in this paper will attempt to explore this question in the context of a case of materials choice for automotive structural materials. Specifically, robustness to four issues outside of the specification of material will be explored: (1) variation in the method of inventory evaluation, (2) uncertainty in product specification, (3) uncertainty in product use, and (4) uncertainty in end-of-life processing. Before detailing the results of these analyses, the following sections will briefly review the LCA method and describe the specific case study that will be explored.

Background: Life Cycle Assessment

The LCA framework is widely used to evaluate the environmental performance of product systems, offering a way to explore options that potentially will reduce life-cycle environmental impact. Increasingly, the LCA method has been used by firms as a tool for decision-making, product communication, and identification of product improvement opportunities. The International Organization for Standardization (ISO) LCA framework is depicted in Figure 1, showing the major conceptual stages of the LCA process. The Goal and Scope Definition stage is used to outline study objectives and necessary system boundaries. The next stage, Inventory Analysis, quantifies all material and energy inputs and outputs. The Impact Analysis stage then translates this inventory into impacts on ecological and human health. However, many LCA studies stop short of the Impact Analysis step due to its subjective, controversial nature and instead focus on assembling and analyzing life-cycle Inventory Analysis data.

[1] The key elements of LCA will be detailed in the following section.

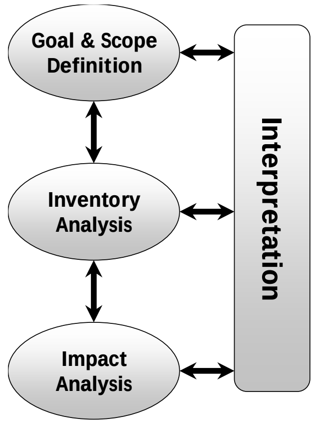

Figure 1. ISO 14040 framework for LCA [7]

Decision theory indicates the partitioning and weighting required to translate a LCA inventory into a measure of environmental performance is critical from a framing perspective [8]. Analysts approach the “Interpretation” phase of LCA using a variety of methods to weigh the results of the phases of the process, and each method for weighting relies on its own distinct, embedded assumptions regarding environmental valuation. Often this leads to a mindset where there exist “right” and “wrong” weighting methods, creating a dualistic way of thinking from which a “best” indicator must be chosen [9]. Fundamentally, determining the appropriate method to apply depends on consistency with strategic intent of the LCA study, and is therefore a task relegated to the LCA decision-maker. It is this notion of explicit and implicit trade-offs that occur when apportioning and weighting an inventory in terms of environmental effects that serves as motivation for testing the robustness of the LCA methodology.

Impact Assessment Methods

The impact assessment frameworks surveyed in this paper include Eco-indicator 99, Environmental Priorities System (EPS) 2000, and Cumulative Energy Demand (CED). Eco-indicator bases its damage assessment through an evaluation of impacts on human health, ecosystem quality, and damage to resources. These damage categories were weighed by an expert panel based on three different viewpoints --- individualist, egalitarian, and hierarchist --- each with distinct assumptions regarding cultural perspectives and impact timeframe [10]. EPS correlates environmental impacts with financial consequences by estimating a social “willingness to pay” for effects on human health, biodiversity, resource depletion, ecosystem productivity, and recreational and cultural values. CED calculates the total primary energy use through a life cycle and weighs results by type of resource consumed.

Methods

Understanding Metrological Effectiveness: Robustness

To date, indicators of environmental performance capable of informing the decisions of those effecting change in products, processes, and policy have not been specifically evaluated for their practical and effectual merit. General efforts within the literature to define the dimensions of merit for environmental metrics have resulted in criteria that can be summarized in a framework specifying that a successful metric must be (1) useful, (2) feasible, and (3) robust [11-14]. The focus of this paper is characterizing the robustness of LCA results.

In order to test the robustness of materials selection decisions when using different LCA methods, a vehicle materials selection case study was developed to provide a complete and detailed bill of materials for analysis. Environmental impact assessment results were computed using SimaPro 7.0 LCA software and the Eco-invent and ETH-ESU 96 databases. Results were then permuted to test for change in result due to: (1) variation in the method of inventory evaluation, (2) uncertainty in product specification, (3) uncertainty in product use, and (4) uncertainty in end-of-life processing. The figure of merit will be the extent of change required to change the elected materials selection decision.

Case Study

Base Case Selection

To evaluate the robustness of LCA to analytical variation in support of materials selection decisions, an automotive materials selection case study was developed. Specifically, the case involved vehicle life cycle considerations ranging from material production, operation, maintenance and repair to end-of-life. Burdens associated with vehicle part manufacturing and assembly were omitted due to limited information availability and their relatively small life cycle contribution compared to material production and vehicle operation [15]. Development of a novel, complete description of a vehicle at the level necessary to conduct a LCA was beyond the scope and resources of this study. Four candidate vehicle descriptions were identified in the literature. The composition of these candidates are compared in Figure 2 [15-18]. Although the distribution of materials is similar across all four designs, the vehicle description provided by the USAMP Life Cycle Inventory for the USCAR Generic Family Sedan Study was selected to serve as a Base Case for this study because of its comprehensive bill-of-materials [17].

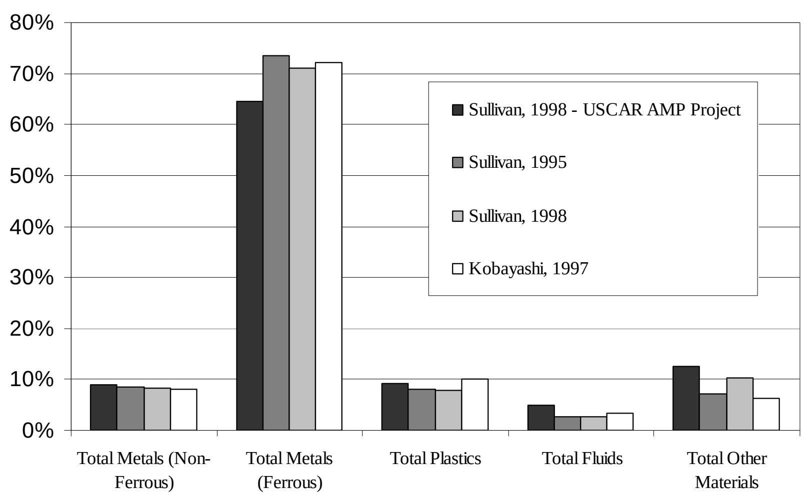

Figure 2. Comparison between material compositions used in vehicle LCA studies

Alternative Materials Comparator: Mass Reduction Using Aluminum Closures

To understand the robustness of the LCA method to support materials selection decisions, it was necessary to develop and analyze an alternative materials comparator. The selected comparator differs from the Base Case in that it is modeled to have closures with all structural components made from aluminum. Conceptually, this differs from the USAMP Base Case which used mild steel closure structures. To create the Comparator bill-of-materials, the Base Case bill-of-materials was modified by reducing the mass of steel and increasing the mass of wrought aluminum, each by a quantity equivalent to the mass of a full set of closures (four doors, hood, decklid, and fenders) made of the respective materials. Table 1 summarizes baseline vehicle and vehicle use assumptions. Specifically, the Base Case was modeled as containing 108 kg of mild steel associated with the closures. The Comparator was modeled to have a primary mass savings of 40 kg from substituting an assumed 68 kg of aluminum closures. Both values were based upon closure designs provided by a major US automaker. Notably, this mass differential would be expected to be less for many current vehicles due to the increased utilization of high strength steels. Because the focus of this work is not the case itself, but rather the robustness of the method, the Base Case vehicle was modeled as having mild steel closures to maintain consistency with the source study.

For the Base Case vehicle, fuel economy is 23.6 mpg with a vehicle mass of 1532 kg [17]. Total vehicle miles traveled was assumed to be 120,000 miles over an 11 year period for both alternative designs. For the Comparator vehicle, industry data was applied to calculate fuel economy savings due to weight savings at a rate of 6% reduction in fuel consumed per mile driven to a 10% reduction in vehicle mass [19].

Material substitution can lead to vehicle mass reduction directly (i.e., primary mass savings), but is also expected to enable corresponding secondary mass savings. Although total mass savings associated with materials substitution is ideally an iterative process that evaluates specific mass reduction candidates, in general, automakers use secondary weight savings factors from 1.3-1.75 [20]. For example, a factor of 1.5 indicates 100 kg of primary mass savings yields 50 kg of derived secondary weight savings. This analysis explores the implications of allocating secondary weight savings to mild steel, and compares performance with the Base Case. Sensitivities around secondary weight savings factors were also explored. Eco-indicator 99, EPS 2000, and CED, discussed above, were used to explore the effects of different impact assessment methods on the Base Case and secondary weight savings scenarios.

Table 1. Baseline vehicle assumptions

Design	Use	End of Life
• Base case: 108kg mild steel panels • Comparator: 68kg aluminum panels (40kg primary mass savings, 20kg secondary mass savings)	• 11 years • 23.6 mpg • 10,909 miles/yr	• High value/hazardous components removed • 95% ferrous metals recovered • 90% non-ferrous metals recovered • ASR land filled

Results

Table 2 compares the baseline results for the Base Case and Comparator vehicle evaluated using both the Eco-Indicator 99 method and Cumulative Energy Demand (CED) method. As a point of reference the reported life-cycle energy values for the USCAR AMP study vehicle are included. Total life cycle energy results (i.e., the CED method) for the Base Case vehicle differ from the USCAR AMP study by 2%. Notably, results for vehicle production and use differ from reported USCAR AMP value by 20% and 3%, respectively. Although the USCAR AMP study discusses the application of end-of-life credits, the positive value reported for end-of-life activities suggests that such credits were accounted for elsewhere in values reported in that work. As such, a more appropriate comparison likely comes from comparing the total of production and end-of-life: 142 MJ for Base Case versus 136 for USCAR AMP. These values differ by about 4%.The relative distribution of production and use impacts (i.e., use phase accounts for approximately 85% of the total) in these results is consistent with the studies mentioned above.

The Comparator results differ from the Base Case with an 11% higher vehicle production value and an 82% larger end-of-life credit. Use phase impacts for the Comparator vary by 2.4%, indicating a lower lifetime fuel consumption.

As shown in Table 2, when applying an environmental impact assessment method, such as Eco-Indicator 99, the overall distribution of results can shift significantly with use accounting for 75% of total impact. Nevertheless, the rank order of the Base Case and the Comparator design are unaffected.

The goal of this study has not been to evaluate the specific environmental merits of the two options being compared. Instead the question at hand is how sensitive is the result to changes in underlying analytical assumptions. To that end the following section will explore the impact of such changes on the relative standing of the two materials alternatives being considered: Base Case and Comparator. The figure of merit for that comparison will be the percent difference in the life-cycle result between the two alternatives, defined as:

$$\%\,difference = \frac{(Comparator - BaseCase)}{BaseCase} \qquad (1)$$

Looking at Table 2, the Comparator has a life-cycle impact approximately 2% less than the Base Case when evaluated under the baseline conditions.

Table 2. Base case results showing Eco-Indicator 99 (EI 99) and CED by vehicle life cycle stage

	Metric	Production	Use	End-of-Life	Total
USCAR AMP (GJ)	CED	133.7	838.6	2.7	975.0
Base Case (GJ)	CED	160.8	815.4	-18.4	957.8
Comparator (GJ)	CED	178.4	796.0	-33.4	941.0
Percent Difference:		10.9%	-2.4%	-81.5%	-1.8%
Base Case (Eco)	EI 99	1007	2458	-172	3293
Comparator (Eco)	EI 99	1080	2401	-231	3250
Percent Difference:		7.2%	-2.4%	-34.3%	-1.3%

Sensitivity Analysis

The life-cycle literature is full of discussions about various inherent uncertainties within the LCA method. These include core issues such as incomplete or inappropriate inventory data, insufficient or inconsistent data on the translation of releases into environmental harm, and the incorporation of human values to establish the relative importance of specific harms. The authors feel that for LCA to be broadly applied, the above issues will either need to be solved fundamentally or those firms that continue to apply LCA will have to implicitly or explicitly accept these limitations.

However, even when this happens, there still remains a question as to whether LCA is able to support materials selection decisions at the early design stages when they happen; is the LCA result able to resolve the performance of key technological alternatives, and, is that resolution robust to the extent of uncertainty present at early design. To that end, the focus of this work is to understand the impact of uncertainty in the way the problem is specified on the underlying result. This section details three preliminary analyses to examine this question, the robustness of the LCA result to 1) changing the impact assessment method; 2) uncertainty in product use characteristics, and 3) uncertainty in product specification.

Variation in the Impact Assessment Methodology

Figure 3 compares differences in the life-cycle result between the two materials alternatives when evaluated using the three valuation methods being studied: CED, Eco-indicator, and EPS. Since it is not appropriate to compare absolute results across such methods, the results of each have been normalized such that the difference in impact of materials production is 100 points.
The first clear observation from these results is that for the baseline conditions, all three methods indicate material production for the Base Case vehicle leads to lower impact, while the Comparator is associated with a lower impact during the vehicle use phase. Specifically, CED indicates a lower Base Case material production by 11%, Eco-Indicator by 7%, and EPS by 2%, while all three methods show a 2% impact reduction during the vehicle use phase. Probably the most notable difference among the results emerges in the evaluation of the impacts associated with end-of-life. While Eco-indicator and CED attribute a significantly larger credit (i.e., more negative points) to the Comparator, the EPS suggests that end-of-life activities associated with both alternatives lead to a nearly identical impact.

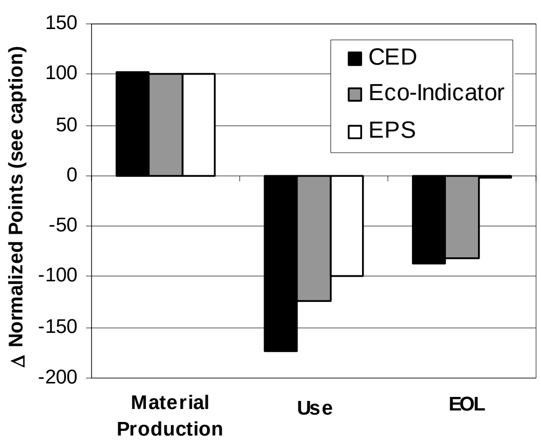

Figure 3. Normalization factor: CED = 172, Eco-Indicator = 0.72, EPS = 8.9

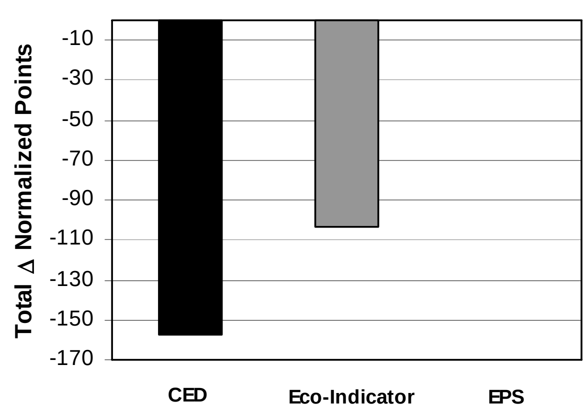

Figure 4. Total life cycle Eco-points for CED, Eco-Indicator, and EPS

Uncertainty in Product Use

Figure 5 and Figure 6 show the impact of changing the underlying assumptions about vehicle use on the percent difference between the Base Case and Comparator analysis as defined by Equation (1). Specifically, these plots show how percent difference changes with variation in vehicle lifetime, vehicle fuel economy (expressed as gallons per 100 miles) of the Base Case vehicle, and average driving distance per year. Analysis results represent changes to any one of these values, while holding the others constant at baseline conditions. Since all three of these factors convolve to determine use phase impact (in the form of fuel consumption), it possible to represent their impact on this triple axis plot.

Each of the results in Figure 5 exhibit a distinct pattern, beginning at a positive value at the y-axis and then declining sub-linearly until eventually becoming negative as the quantity being varied increases. This behavior derives directly from the structure of the life-cycle burdens associated with the two materials alternatives. The Base Case vehicle utilizes materials with lower impacts during production, while the Comparator vehicle creates less impact during use. As the use phase becomes more intensive (as is the case when all variables are increased), the Comparator provides a relative decrease in impact (i.e., its use phase impact grows more slowly than the Base Case).

The implications of the analytical differences exhibited by the three impact assessment methods (as discussed in the previous section), are shown clearly in Figure 5. Specifically, from the y-intercept it is clear that both the CED and Eco-Indicator methods place similar relative value on the production of the two alternatives. However, the higher value placed on production relative to use that emerges from the Eco-Indicator method leads to its more gradual slope in Figure 5. The consequence of this difference is that the use phase must be more intense (i.e., longer or more miles traveled per year), before the Comparator is able to offset its higher impact production. In a similar fashion, the large value placed on production impacts by EPS 2000 leads to both a high intercept and gradual slope.

In the end, it would appear that CED and Eco-Indicator results are very robust for automotive materials selection in this case. Although both exhibit a sign change (i.e., the preferred material changes) across the range of analysis, those conditions leading to a preferred Base Case are significantly outside of the range of modern consumer automobiles. Although a baseline lifetime was selected of 11 years to maintain consistency with the USCAR AMP study, evidence suggest that vehicle lifetimes are exceeding 15 years [21]. Similarly, miles driven per year continues to grow [22]. The EPS 2000 result presents more challenge. Although the Comparator exhibits net lower environmental impact for the baseline conditions, that benefit is small. Furthermore, the preferred technology inverts for conditions only slightly less intense than the baseline.

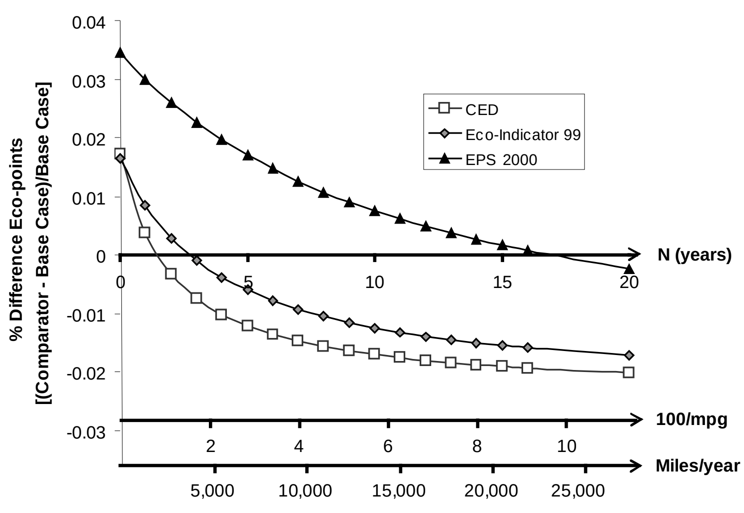

Figure 5. Comparison of Comparator and Base Case vehicles using Eco-Indicator, EPS, and CED varied across intensity of use (i.e. measured in terms of vehicle life, fuel consumption, and miles/year) – includes production, use, maintenance, and end-of-life

Figure 6 differs from Figure 5 insofar as it excludes the results of the end-of-life phase from the analysis. Given the small impact of end-of-life processing, the dominant effect of this is to change the allocation rules for dealing with the benefits of recycling end-of-life materials. Currently ISO 14040 standards do not explicitly address the issue of EOL accounting in open loop recycling and there exists a diverse set of methods to address recycling benefits or “credits” and burdens at product end-of-life. One method is to employ system boundary expansion to include all products affected by the secondary material flow of the original product, which can be overly cumbersome or infeasible in terms of data collection [23]. Furthermore, for metals that can be reused many times, boundary expansion can introduce a large source of uncertainty. A conceptually robust method, developed by Franklin Associates, that does not require specific analysis of subsequent life-cycle application of recover materials, requires the LCA analyst to assume recovery rates and predict the total number of times recycling will occur, given the incarnation of future products [24]. Other explorations in treatment of recycling in LCA include the elimination of all recycling credits associated with end-of-life, thereby only associating environmental burden with all materials that are not recycled [25]. For all results other than those presented in Figure 6, this study assumes a recycling credit for avoided primary material production and also ascribes an environmental burden to the collection, sorting, processing, and remelting of metal scrap. This method provides a result mid-way among the above strategies.

In the end, although excluding any benefit for end-of-life recovery has a strong effect on the absolute magnitude of the total material related impacts (cf. the y-intercepts of Figure 5 and Figure 6), ultimately the robustness of the results is only slightly changed. The CED and Eco-Indicator results show continued preference for operating conditions much less intense than the baseline and current prevailing trends. Similarly, the EPS 2000 result provides less resolution both in terms of the size of the benefit for intense use applications and the small change in relative result across the range of inquiry.

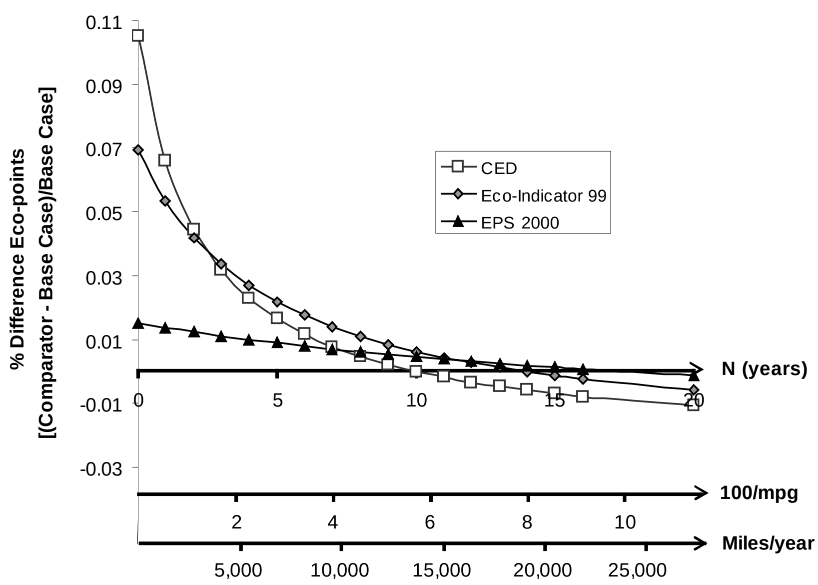

Figure 6. Comparison of Comparator and Base Case vehicles using Eco-Indicator, EPS, and CED varied across intensity of use (i.e. measured in terms of vehicle life, fuel consumption, and miles/year) – includes production, use, and maintenance (excludes end-of-life)

Secondary Weight Savings
Realized secondary weight savings is strongly affected by the specifics of the particular vehicle being altered as well as the magnitude of primary weight savings. As such, the actual amount of secondary weight savings is not known at the early strategic stages of product development when materials choices are made. To understand the impacts of this uncertainty, Figure 7 explores the effects of secondary weight savings and fuel intensity on the relative LCA result for the two technology alternatives (as defined in Equation (1)). The environmental "benefit" attributed to secondary weight savings varies with vehicle fuel intensity, or conversely, fuel economy. As fuel intensity rises, the opportunity to achieve greater environmental savings becomes more sensitive to secondary weight savings. Nevertheless, this analysis would suggest that the LCA result (for the Eco-Indicator method) is robust to secondary weight savings assumptions across the range of values investigated for this case. A similar result was observed for the CED method.

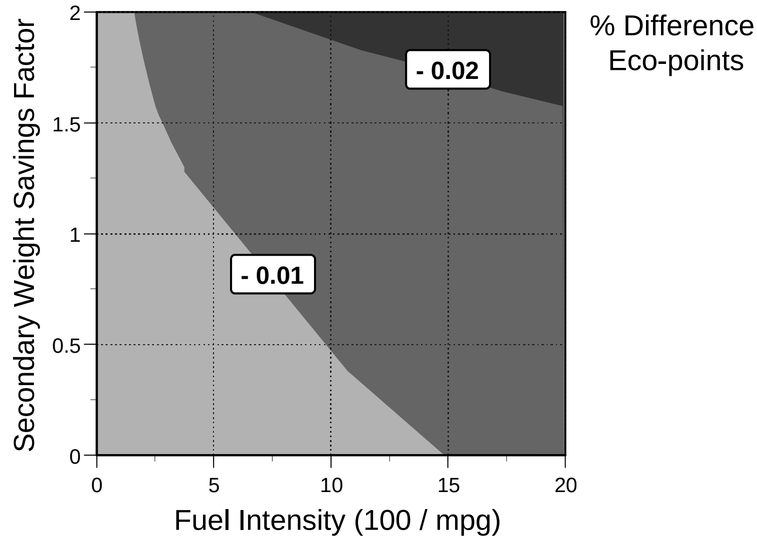

Figure 7. Relationship between secondary weight savings, fuel intensity, and percent difference in eco-points (Eco-Indicator 99)

Conclusions

One of the key engineering challenges of the 21st century will be creating products with substantially lower environmental burden. Any fundamental solution to this challenge will require careful selection of materials and the processes used to fashion material into product. Life Cycle Assessment is a broad, flexible analytical framework to map the environmental consequence of a range of design decisions including the selection of materials. For LCA to be effective in informing materials decisions, it must provide reasonably robust answers when applied against the uncertain data endemic to early-stage design.

This paper provides a preliminary exploration into the robustness of LCA result in response to variation in (1) the method used for evaluating environmental impact, (2) the characteristics of the intensity of vehicle use, and (3) the specification of the product in the form of secondary weight savings. This assessment was carried out in the context of a specific materials selection case that would lead to a lighter vehicle.

For the case presented herein, the EPS 2000 evaluation method provided a significantly different distribution of relative burden for the two alternative designs compared to either the CED or

Eco-Indicator methods. Nevertheless, all three methods maintained consistent choice order, with the lighter weight Comparator technology leading to lower environmental impact under baseline conditions.

For both of the latter methods, this choice order was not strongly sensitive to assumptions made about vehicle driving life or secondary weight savings for conditions similar to those for most personal vehicles in the US today. The EPS 2000 method showed stronger sensitivity to intensity of use. Nevertheless, across all of these results the intensity of use required to lead to Comparator preference was well below that of the average vehicle life within the United States.

For LCA to become widely accepted, practitioners need to develop confidence in the information that is provided. The result of this study indicates that for both secondary weight savings and assumptions about vehicle lifetime, the result of this materials comparison – in the form of preferred material – is stable across a broad range of relevant conditions particularly for two popular evaluation methods. Further study will be needed to continue to build confidence in LCA methods, but the limited results presented here hold promise that it to may become a tool used confidently by materials decision-makers in the future.

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