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Sustainability metrics for vehicles*

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Abstract: The public has growing concerns about the effects of human activity on the environment for both themselves and future generations. The concept being developed to address these environmental concerns, along with economic and social-equity considerations, is called "sustainable development". The business community has already started to address their contribution to environmental issues through collaborative efforts under organizations such as the World Business Council for Sustainable Development. That work has focused primarily on industrial and corporate environmental and economic performance through the development of eco-efficiency metrics, which are a measure of resources and materials consumed per unit output of product, sales, or value-added. While this development is important, it is not enough. Clearly, the environmental performance of the entire product system must also be elucidated. Otherwise, one might forget, for example, the power plant emissions of his or her so-called "zero-emission" vehicle. The metrics required to characterize sustainable practices and systems have yet to be developed. The set will include economic, environmental, and social-equity metrics. Because of their system-oriented environmental performance representation, life-cycle assessment metrics are certainly going to be included in such a set. A discussion of some potential life-cycle metrics follows.

INTRODUCTION

Sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. In short, it is desirable that current development not diminish Earth's carrying capacity, given expected rates of population growth and social, economic, and technological evolution. It is generally conceded that sustainable development should endeavor to balance economic, environmental, and social-equity considerations in new development initiatives. For all three areas, metrics are required and are being developed. The focus here is on the use of life-cycle inventory (LCI) metrics, with their cradle-to-grave representation, to provide a more holistic perspective on the environmental performance for product systems.

Life-cycle assessment (LCA) is becoming more widely accepted as the method of choice for determining the holistic environmental performance of a product system over its entire life, from cradle to grave. This entails the assessment of the environmental consequences of material production, part and product manufacture, product use, maintenance, repair, and, finally, end-of-life disposition. It is the broad scope of LCA that makes it an ideal source for sustainable development metrics. The method has undergone considerable evolution, highlighted by the recent issuance of a series of four standards developed by the International Standards Organization. During this development period, numerous studies have been conducted on a wide range of product systems, including the vehicle product system. Actually, these studies are life-cycle inventories (LCIs), the stage of LCA where burdens are quantified.

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The purpose of this paper is to advance a set of LCI metrics and apply them to a series of LCI studies on various vehicles. Not included in this discussion are cost analysis results, due to the lack of such information in those studies.

METRICS FOR COMPARISON OF STUDY RESULTS

The total life-cycle burden vector for an arbitrary product is:

$$\{\mathrm{B}\}_{tot} = \{\mathrm{B}\}_{mp} + \{\mathrm{B}\}_{assm} + \{\mathrm{B}\}_{op} + \{\mathrm{B}\}_{mntn} + \{\mathrm{B}\}_{EOL} \tag{1}$$

where subscripts *tot*, *mp*, *assm*, *op*, *mntn*, and *EOL* denote total, material production, part and product manufacture and assembly, operation, service and maintenance, and end-of-life, respectively. In order to facilitate the analysis of the life-cycle burdens for vehicles, we defined life-cycle burden per vehicle mile driven, which is comprised of two components, the fixed and variable per mile burdens. This is equivalent to fixed and variable cost metrics typically employed in cost analysis. Mathematically, we write these burdens as:

$$\overline{\{B\}}_{tot} = \overline{\{B\}}_{fxd} + \overline{\{B\}}_{\mathrm{var}} \tag{2}$$

where

$$\begin{aligned}\overline{\{B\}}_{tot} &= \{B\}_{tot}/LTDST \\ \overline{\{B\}}_{fxd} &= \frac{\{B\}_{mp} + \{B\}_{assm} + \{B\}_{mntn} + \{B\}_{EOL}}{LTDST} \\ \overline{\{B\}}_{\mathrm{var}} &= \{B\}_{op}/LTDST\end{aligned} \tag{3}$$

In eqs. 3, LTDST is the lifetime drive distance for the vehicle. We normalize the LCI burden vector by LTDST, as it is the measure of service rendered, i.e., the reason for the product to exist in the first place. We have defined these terms for two reasons: (1) to help reconcile and interpret seemingly different results and (2) to partition vehicle life-cycle burdens into product system service rendered and compositional categories, i.e., variable and fixed burdens, respectively. This leads to a better understanding of the origin of the various life burdens.

RESULTS

All LCI data presented herein have been extracted from the literature, and a more thorough review of them has been discussed elsewhere [2]. An example of a complete vehicle LCA can be found in ref. 3; there, a discussion of the ideal vehicle LCI system boundaries is given. Results for spark-ignited (SI), compression-ignited (CI), and electric vehicles (EV) have been included.

An inspection of Figs. 1 and 2 offers a unifying perspective of the results. Firstly, each data point on the graph represents either the variable or fixed life-cycle energy for a different vehicle, each identified by its weight. All of the studies show that variable energy results are reconcilable on the basis of vehicle mass. This, of course, is not surprising. After all, vehicle operating energy per lifetime mile driven, which is just the inverse of the fuel efficiency, is expected to vary proportionately with vehicle mass. In Fig. 1, there appears two families of curves, one for SIs and another for CIs and EVs. However, notice that the CI curve appearing in Fig. 1 for the per mile energy consumed demonstrates a lower level of energy and has a lower rate of change with mass. This is related to the higher operating efficiency of the CI and EV vehicles. Overall, results in Fig. 1 reflect the underlying physics of vehicle propulsion, i.e., the energy required to move a vehicle through a drive cycle is dependent on vehicle mass and powertrain efficiency. One clear conclusion that can be drawn from Fig. 1 is that a pound of weight saved for CIs and EVs has less energy reduction potential than that for the SI vehicles. Another result of this

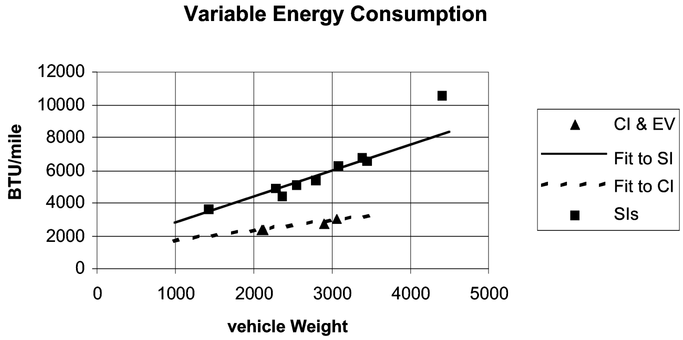

Fig. 1 Variable life-cycle energy results for 13 different vehicles.

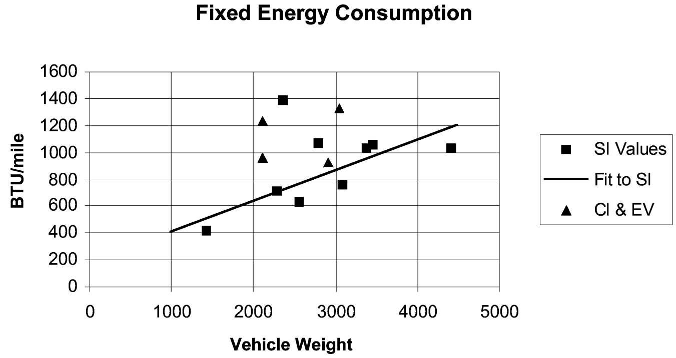

Fig. 2 Fixed life-cycle energy results for 13 different vehicles.

analysis is that both lines in Fig. 1 have very similar intercepts (1111 and 1076, respectively, for SI and CI), indicating that both vehicle classes have similar parasitic losses such as aerodynamic drag. While the agreement is probably fortuitous given the wide range of performance likely covered in those studies, it does reflect that most of those vehicles do not radically depart from today's conventional aerodynamic design. In Fig. 1, the variable values for SI-6B (4400-lb. vehicle) seem inordinately high relative to the trend line. We have no explanation for this other than it is apparently a very inefficient vehicle.

Figure 2 shows the dependence of fixed energy on vehicle mass. Despite the apparent scatter in the results, the authors believe that there is structure in the figures and that much of the scatter can be reconciled. The trend lines in the figures, admittedly judgment calls, represent what we believe to be the fixed burden behaviors for SI vehicles of conventional composition. It is clear that as a group, the EV and CI vehicles have higher fixed energy values than those for the SIs. Two potential reasons why fixed burdens are larger for one vehicle class versus another are: (1) the use of significant amounts of energy-intensive materials and (2) a significantly lower LTDST. Because for the EV a beta-alumina sodium/sulfur battery was used and for the lightweight CIs an extensive amount of aluminum was employed, their fixed-energy terms are expected to be larger compared to the other vehicles. These particular alternative materials are energy-intensive. On the other hand, SI-3, a 2800-lb. vehicle comprised of conventional materials, appears considerably above the lines in Fig. 2. The reason for this is due to its inordinately low LTDST.

There are some other exceptions appearing in Fig. 2 that merit comment. Notice that CI-4A (2900 lbs.) has a fixed-energy value quite similar to that of conventional SI vehicles. The reason for this is that, despite its high-efficiency powertrain, it has a conventional material composition. Also note in the figures that SI-7 (2360 lbs.) appears to have an inordinately high fixed energy. This is apparently due to what seems to be inordinately high material production and maintenance energies. We have no explanation.

CONCLUSION

A new set of environmental metrics based on life-cycle inventory results has been advanced to characterize the environmental performance of product systems. They are, namely, the fixed and variable life-cycle burden per vehicle lifetime mile driven, and they have been successfully used here to compare and reconcile seemingly disparate results from different whole vehicle LCIs. These two metrics represent two aspects of a product system, i.e., service rendered by the product and the materials and associated burdens required to provide the product.

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