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Energy-Consumption and Carbon-Emission Analysis of Vehicle and Component Manufacturing

Energy Systems Division

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ACRONYMS AND ABBREVIATIONS

AIV	Aluminum-intensive vehicle
C_{vm}	CO_2 emissions during the VMA stage
E_{vm}	Energy consumption during the VMA stage
EPI	Energy performance indicator
EV	All-electric vehicle
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
HEV	Hybrid electric vehicle
ICV	Internal-combustion vehicle
LCA	Life-cycle assessment
LCB	Life-cycle burden
LCE	Life-cycle energy
LCI	Life-cycle inventory
LHV	Low heat value
OEM	Auto manufacturer
PHEV	Plug-in hybrid electric vehicle
PNGV	Partnership for a New Generation of Vehicles
USAMP	U.S. Automotive Materials Partnership
USCAR	U.S. Council for Automotive Research
VMA	Part manufacturing and vehicle assembly

ENERGY-CONSUMPTION AND CARBON-EMISSION ANALYSIS OF VEHICLE AND COMPONENT MANUFACTURING

J.L. Sullivan, A. Burnham, and M. Wang

ABSTRACT

A model is presented for calculating the environmental burdens of the part manufacturing and vehicle assembly (VMA) stage of the vehicle life cycle. The approach is bottom-up, with a special focus on energy consumption and CO_2 emissions. The model is applied to both conventional and advanced vehicles, the latter of which include aluminum-intensive, hybrid electric, plug-in hybrid electric and all-electric vehicles. An important component of the model, a weight-based distribution function of materials and associated transformation processes (casting, stamping, etc.), is developed from the United States Council for Automotive Research Generic Vehicle Life Cycle Inventory Study. As the approach is bottom-up, numerous transformation process data and plant operational data were extracted from the literature for use in representing the many operations included in the model. When the model was applied to conventional vehicles, reliable estimates of cumulative energy consumption (34 GJ/vehicle) and CO_2 emission (2 tonnes/vehicle) were computed for the VMA life-cycle stage. The numerous data sets taken from the literature permitted the development of some statistics on model results. Because the model explicitly includes a greater coverage of relevant manufacturing processes than many earlier studies, our energy estimates are on the higher end of previously published values. Limitations of the model are also discussed. Because the material compositions of conventional vehicles within specific classes (cars, light duty trucks, etc.) are sensibly constant on a percent-by-weight basis, the model can be reduced to a simple linear form for each class dependent only on vehicle weight. For advanced vehicles, the material/transformation process distribution developed above needs to be adjusted for different materials and components. This is particularly so for aluminum-intensive and electric-drive vehicles. In fact, because of their comparatively high manufacturing energy, batteries required for an electric vehicle can significantly add to the energy burden of the VMA stage. Overall, for conventional vehicles, energy use and CO_2 emissions from the VMA stage are about 4% of their total life-cycle values. They are expected to be somewhat higher for advanced vehicles.

1 INTRODUCTION

Light-duty vehicles such as cars and trucks are an essential part of our economy, satisfying a broad range of consumer mobility needs. Though they provide tremendous value to their owners, these vehicles are, nevertheless, conspicuous consumers of materials and energy, which has led to a great deal of effort to improve their efficiency and overall environmental performance. While much of this work has focused on improved vehicle technology, there has also been considerable effort devoted to characterizing the life-cycle performance of the vehicle product system. The objective of life-cycle assessment (LCA) is to develop an environmental "picture" of product systems, one where life-cycle burdens (LCBs), such as energy, CO_2 emissions, and raw materials, are quantified and evaluated over all stages of a product's life cycle. Hence, tradeoffs between life-cycle stages can be accounted for, resulting in more holistic assessments of product systems and often illuminating improvement opportunities. For example, vehicles made lighter by substituting materials like aluminum and composites for steel do indeed have higher fuel economy (operational stage), but at the same time a part of that benefit is offset by the generally higher production energies of alternative materials (material production stage). While electric-drive vehicles use less energy during operation than their spark-ignited counterparts, the energy required to make constituent materials and assemble them into batteries may offset a major portion of the benefit.

These examples and many others show the merit of LCA, and illustrates it as a method that focuses not just on the product (or process) and its use but also the infrastructure needed to make, maintain, and dispose of it. Indeed, for automobiles, considerable resources (materials and energy) are consumed and emissions (environmental burdens) generated during their production. The life cycle of vehicles and most other products is comprised of five stages: 1) raw material extraction and material production, 2) product manufacture and assembly, 3) product use, 4) maintenance and repair, and 5) end of life. For vehicles, the burdens for the material production and vehicle operation stages are the largest and best understood, though some additional work needs to be done for a few advanced materials beginning to be used to a greater extent on vehicles. Though less understood, the burdens for the part manufacturing and vehicle assembly (VMA) stage are the next largest in magnitude, and hence the focus of this report.

Argonne National Laboratory has developed a vehicle-cycle module for the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model. The vehicle-cycle module (GREET 2) evaluates the energy and emission effects associated with material recovery and production, vehicle component fabrication, vehicle assembly, and vehicle disposal/recycling. The focus of the GREET model was to examine material production, as the research showed it accounts for the largest burden with respect to the vehicle life cycle. With respect to vehicle assembly, the Argonne analysis used data from an energy use survey of U.S. assembly plants that contained body welding, painting, and assembly operations. The survey collected three years of data from 35 plants, with the American affiliates of GM, Ford, Honda, Toyota, and Subaru participating (Boyd, 2005). The assembly burdens in GREET are based on the per-vehicle fossil energy and electricity use factors developed from the survey; the data take into account many factors, such as plant utilization, capacity, and local climate.

This top-down approach was used in the GREET analysis along with separate data on other processes excluded from the survey, like stamping and casting. For well-understood materials, such as steel and aluminum, all the processes from raw material extraction to vehicle component fabrication were coupled to calculate the burdens of finished components. For example, all the individual steps from transforming the raw material (taconite) into a stamped steel part were examined together, accounting for the amount of each intermediate material needed for each succeeding step. This approach eliminated double counting between part manufacture and vehicle assembly stages in the vehicle cycle analysis. However, since the focus was on material production, the transformation processes for parts manufacture were not examined in depth. Therefore, it was decided to fully examine VMA from the bottom up, in order to fill the gaps in GREET. This approach would allow us to fully compare the burdens of this stage and to take the pieces not already included in GREET and incorporate them in an updated version of the model. Specifically, by reexamining the system boundaries in GREET, we will add a new VMA module that allows a more complete examination of the vehicle cycle.

The purpose of this report is to introduce the VMA model, which represents a simplified approach for calculating the environmental burdens of VMA stage of the vehicle life cycle. A special focus is placed on quantifying energy consumption and carbon emissions. The intended application of the model is for use in the GREET 2 model. First, a mathematical representation of the model is presented, the formulation of which is based on a bottom-up approach. Next, results are generated using a vehicle with a very well-defined material composition and associated material transformation process distributions. These results, based on grand averages and range data, are compared and contrasted to literature values discussed below. From generalized material composition and associated transformation process distributions derived from the "well-defined" vehicle, more results are presented for both conventional and advanced powertrain vehicles. Finally, an analysis is conducted on the overall significance of VMA-stage burdens relative to those of the total vehicle life cycle, on both an overall and incremental basis. Sufficient data is presented for readers to either populate the VMA model or develop their own models.

2 SCOPE AND LITERATURE REVIEW

We denote the vehicle manufacturing and assembly stage of the vehicle life cycle as VMA, which also includes part manufacturing and assembly. This stage does not include raw material extraction and material production. Our analysis of this stage is from gate-to-gate of the facilities manufacturing parts and vehicles. The environmental burden vector for this stage is written {VM}, which has numerous components (burdens) such as fuels, power, greenhouse gases, criteria air pollutants, and various product compositional and process ancillary material flows. Two burden components of special interest here are stage energy consumption (E_{vm}) and CO_2 emissions (C_{vm}). For this discussion, the latter represents CO_2 gas emissions only and not total greenhouse-gas-equivalent emissions. Owing to the commonality of energy consumption and carbon emissions to virtually all products, processes, and services, their quantification for any life-cycle stage is customarily done from cradle (of the fuel) to point of consumption, which in this case is within the confines of manufacturing facilities. This means that all upstream energies consumed and emissions generated in association with the production of energy products (fuels or power) have been added in. Henceforth, to avoid confusion, these "cradle-to-gate" energy burdens are referred to as stage cumulative energy and CO_2. The cumulative energy E_{vm} is the sum of primary energies, which are made up of purchased (direct) energy products, such as kWh of electricity, gallons of gasoline, m^3 of natural gas, etc., that are expressed in a common energy unit after being adjusted for the production of each fuel. From a process or product life cycle characterization point of view, direct energies are preferable to primary energies for three reasons: 1) they are gate-to-gate quantities and as such more representative of the process or stage in question; 2) they provide more detail, instilling a greater confidence in the assessment and potentially illuminating process improvement opportunities; and 3) E_{vm} and C_{vm} are readily computed from them. Unfortunately, many life-cycle studies found in the literature report only primary energies, a situation often motivated by a desire to protect confidential or proprietary information.

As noted by a number of LCA investigators (Keoleian et al., 1998; Kobayashi, 1997; Sullivan et al., 1998b), vehicles are comprised of thousands of parts and components, each of which is generally composed of a number of constituent materials. Complicating the process of tallying up the various burdens of numerous vehicle parts and components is the fact that some are made by the vehicle manufacturer and others outsourced to suppliers (Tier 1, Tier 2, etc.). An assembly made by a Tier 1 supplier and purchased by an auto manufacturer (OEM) likely contains components made by Tier 2 suppliers. For example, a dashboard assembly produced by a Tier 1 supplier includes a speedometer made by a Tier 2, which in turn contains subcomponents made by other suppliers. In addition, the burdens incurred in the production of any product at a facility are often difficult to attribute or allocate to that particular product, as more than one product is commonly made there. Finally, these burdens include both fixed (overhead) and variable components (the latter being dependent on production volume), which likely vary from one manufacturer to another. Hence, it is clear that tracing VMA burdens through a maze of automaker and Tier 1 and 2 operations is at best an onerous task, the result of which is certain to contain considerable uncertainty. For the VMA stage of the vehicle life cycle, numerous studies have generated estimates of E_{vm}, but with widely varying results. For a listing, see Table 1. However, for the reasons just stated, such variation should not be surprising.

TABLE 1 Literature Values of VMA Life-Cycle Energy Consumption and CO_2 Emissions for the Average Vehicle

Source	Energy (GJ)	CO_2 (tonnes)
Berry and Fels (1972)	23.2	
Brown et al. (1996)	52.8	
Galitsky et al. (2008)	15.1	
Kobayashi (2007)	19.9	1.04
Schuckert et al. (1997)	24.1	1.43[a]
Sullivan and Hu (1995)	30.6	
Sullivan et al. (1998b)	39.9	2.61
Boyd (2005)	13.5[b]	

[a] Estimated from data in reference

[b] Does not include plants with stamping, machining, and casting

Berry and Fels (1972) were among the first to calculate the VMA primary energy consumption, E_{vm}. Their approach uses financial, material, and energy data from the Census of Manufacturers. They reported a value of 23.2 gigajoules (GJ), which appears as a single entry in one of their tables. Unfortunately, their approach using these data is neither well documented nor (by their own admission) straightforward. To our knowledge, no other estimate of E_{vm} for vehicles has been made based on this approach. Further, their estimate was intended to characterize the "representative U.S. produced vehicle," i.e., an average for all cars and light-duty trucks.

In 1993, Ford Motor Company reported direct vehicle production energy of 16.9 GJ per vehicle produced by the company. Adjusting for all upstream energy consumption, Sullivan et al. (1995 and 1998a) estimated a primary energy consumption of 30.6 GJ per vehicle produced. However, they did not report it in this form. Instead, they divided it by the average vehicle weight for the fleet sold that year to yield a simple mass-based algorithm for E_{vm}. As we argue below, E_{vm} is comprised of both fixed and variable terms and hence is not solely dependent on vehicle mass. Irrespective of how the 30.6-GJ value was reported, its accuracy is questionable, as adjustments should have been made to it. Because outsourcing was not considered, this number would likely need to be adjusted upward. On the other hand, a downward adjustment would also be needed, since auto companies routinely make spare parts for current and past vehicle models and in some cases parts for competitors. Unfortunately, because quantitative values for these two adjustments were not available, the impact of their sum on the Ford 1993 value for E_{vm} is not known, and hence its accuracy is unknown.

Kobayashi (1997) itemized the components of a vehicle life-cycle inventory (LCI), including VMA. He reports E_{vm} to be 19.9 GJ for a 1270 kg vehicle. His study does identify key processes employed in VMA, including stamping, casting, welding, heat treatment, forging, painting, molding, machining, plating, and body and part assembly. Unfortunately, unit process information for each of these operations is not given, though some can be estimated from figures in the report. Outsourcing was apparently considered for parts provided by suppliers. For that, he used Japan's Ministry of International Trade and Industry statistics for parts provided by suppliers, though the accuracy of that information is not known for LCA purposes. Unlike the two other studies just discussed, he provided an estimate of C_{vm} (see Table 1).

Schuckert et al. (1997) also estimated VMA cumulative energy and CO_2 emissions for a 1040-kg European sedan. They found E_{vm} to be 24.1 GJ. Their paper, like Kobayashi (1997), omits detailed unit process energy information; some articulation of a few processes is given in one of the figures. Though VMA-stage CO_2 emissions were not explicitly given, by simple proportionality we estimate C_{vm} to be 1.43 tonnes (see Table 1) from the energy and CO_2 emissions data given in their paper for vehicle production.

A value for E_{vm} has also been extracted from the work of Brown et al. (1996). Three listings related to motor vehicles are given in that reference, including details which are given in terms of "per pound of product output." Using energy and mass values from three of their modules, "Motor Vehicles and Car Bodies," "Parts and Accessories," and "Gray Iron Foundries," we estimated a cradle-to-gate energy use rate of 33.4 MJ per kg of car produced. When scaled to a 1500-kg vehicle, an E_{vm} value of 52.8 GJ results. As seen in Table 1, this value is high. Though their modules provide some detail, it is not sufficient for one to conclude that an adequate representation had been made for E_{vm}. Some transformation processes, like sheet metal stamping and vehicle painting, have been included, but others, like plastics and rubber molding, metal forgings, etc., are not mentioned. Even "metal casting" appears to be generic, apparently treating zinc, iron, and aluminum castings as the same. Hence, our estimated E_{vm} value must be considered a course approximation.

In a recent report, Galitsky and Worrell (2008) discussed energy efficiency improvement opportunities available to the auto assembly sector. Many energy efficiency improvement opportunities are identified, but also listed in the document are some representative energy consumptions for processes of interest to us, as well as overall vehicle assembly energy. Regarding the latter, they reported a value of 15.1 GJ per vehicle for the year 1994. When compared to other energy values in Table 1, this value of E_{vm} seems low. However, their treatment only considers assembly plants and not part manufacturing facilities, which we will see contribute a large component of VMA burdens.

A very comprehensive vehicle LCI study of the generic American family sedan was conducted by the U.S. Council for Automotive Research, (Sullivan et al, 1998b). Study participants included Ford Motor Company, Daimler Chrysler, and General Motors Corporation, with participation from the American Plastics Council, the Aluminum Association, and the American Iron and Steel Institute. Detailed quantifications of many environmental burdens, including primary energy resources (oil, natural gas) consumed, process and combustion emissions generated, and resources consumed (e.g. iron ore) were done for all the life-cycle stages. The USCAR study approached VMA burden estimation in terms of three simplified process types: part fabrication, subassembly manufacture, and vehicle assembly. The USCAR study reports E_{vm} as 39.9 GJ for a 1530-kg vehicle; a value of C_{vm} is also given (see Table 1). A more detailed discussion of the approach for calculating the {VM} vector has been given by

Keoleian et al. (1998). However, they argue that their VMA burden estimates might be too owing to data omissions for 1) some subassemblies; 2) part fabrication processes such as welding, and painting; and 3) some OEM plant processes. Though the data used in the development of the USCAR VMA stage analysis were based on values provided by the OEMs as well as generic processing data, those results and data unfortunately remain buried in their model and are not publicly available, making them generally unavailable for use in other models. However, some very useful non-proprietary information on materials and transformation processes is available from the study and is used by us in our model development.

Through the support of the Environmental Protection Agency's ENERGY STAR program, Argonne National Laboratory worked with U.S. assembly plants to develop plant-level energy performance indicators (EPIs) (Boyd, 2005). For consistency and data availability reasons, it was decided that the EPIs would be based on assembly plants that contained body welding, assembly, and painting operations, while excluding those facilities that also included activities like stamping, machining, and casting. It was stated that of the nearly 60 automotive manufacturing plants operating in the U.S., a majority included only welding, assembly, and painting. This set of plants was regarded as substantial and would ensure confidentiality to the five auto company affiliates participating in the project. Plants that included other operations like stamping, casting, etc., were excluded if the energy data from those operations could not be isolated. Using three years (1998-2000) of data for 35 plants, Boyd (2005) calculated the mean purchased (direct) energy consumption per vehicle to be 7.8 GJ, which corresponds to E_{vm} equal to 13.5 GJ/vehicle. Again, keep in mind that sites used in his study are automotive assembly plants and do not include part manufacturing facilities.

3 THE VMA MODEL

Figure 1 depicts the GREET vehicle-cycle stages, which include raw-material extraction from earth, material production, part production, vehicle assembly, and finally vehicle end of life (shredding, recycling, and landfilling). Note that vehicle use (or operation) is omitted from the vehicle-cycle stages; however, it is accounted for in the fuel-cycle stages (feedstock extraction, fuel production and use). As our focus here is on VMA, a more detailed representation of this life-cycle stage is given in Figure 2. During the VMA stage, production-ready materials in the form of ingots, billets, sheet stock, pellets, rods, etc., are delivered to factories where parts are fabricated and ultimately assembled into a vehicle. As stated above, this is a gate-to-gate analysis of the VMA stage; material production is not included here. However, there is one exception, float glass production. Because of the lack of data for the float process alone, we include the total process, i.e. both making the glass and "floating" it for auto window applications.

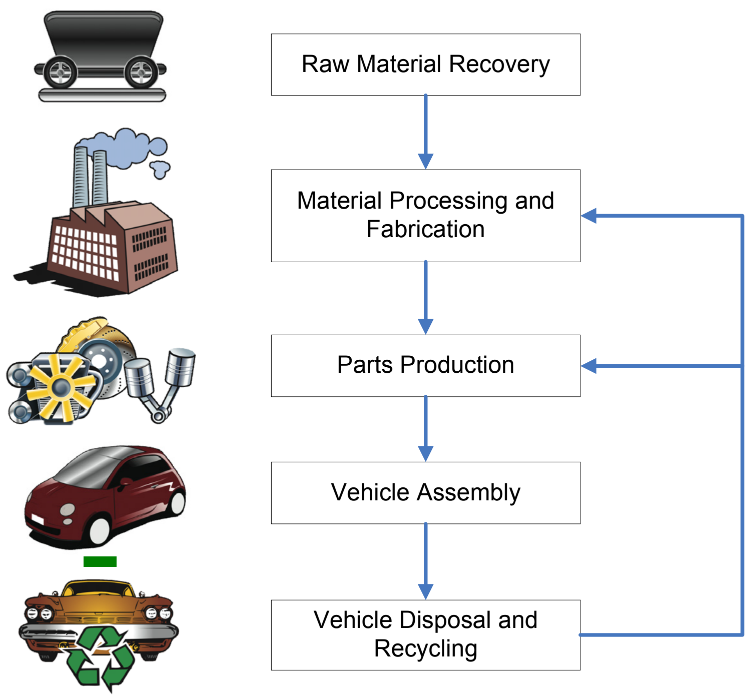

FIGURE 1 GREET Vehicle-Cycle Stages

Though our approach is bottom-up, we start at the top and imagine disassembling a vehicle and all of its components until only raw materials remain. Then we consolidate the materials into their respective types, identify the transformation processes (molding, stamping, calendaring, etc.) required to form them into shapes, and finally add in assembly processes. On a more approximate basis, we include the energy needed to both operate a plant and provide an acceptable plant working environment (heat, light, and air conditioning). Because VMA

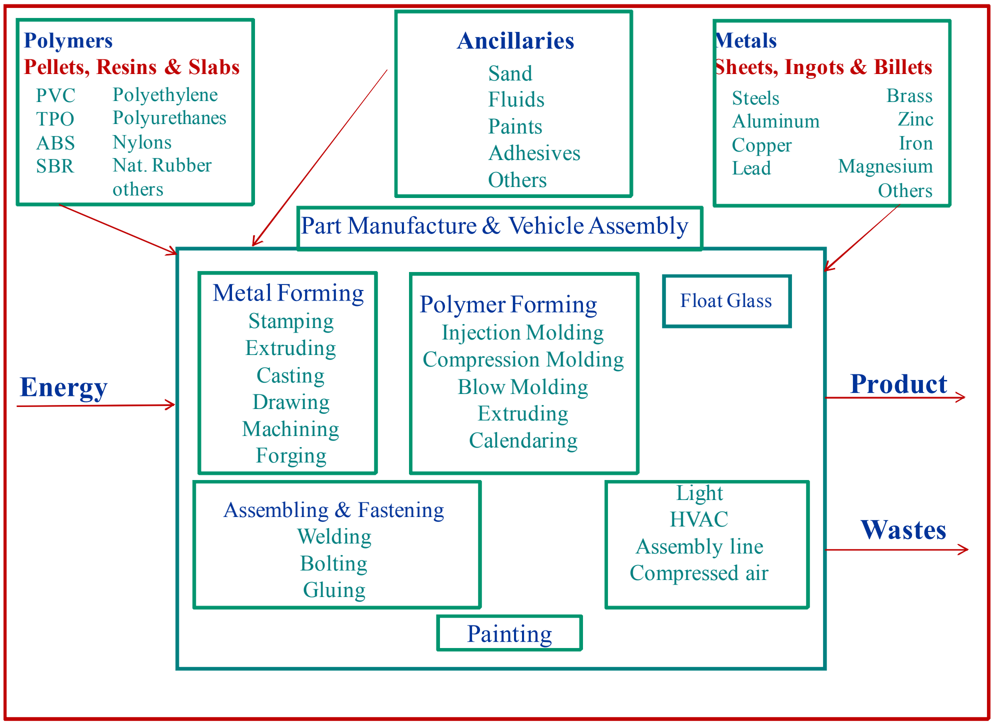

FIGURE 2 Activities in the VMA Stage of the Life Cycle

processes are generally conducted at a number of facilities, including those of vehicle manufacturers and suppliers, we feel that the bottom-up approach is a more accurate and reliable method. It is generally difficult to get consistent and reliable data across multiple organizations.

From the top, one can write an expression for the gate-to-gate burdens for automobile production and assembly as follows:

$$\{VMA\} = \sum_{j=1}^{n} \{VM\}_j + \{VM\}^* \quad (1)$$

where {VMA} is the burden list for both part manufacture and vehicle assembly, {VM}j is the burden vector for vehicle component j, n is the number of components or parts that are assembled into a complete vehicle by an OEM, and {VM}* is the burden vector for the assembly and finishing operations at an OEM's assembly plant. {VM}* is comprised of two terms: 1) a per-vehicle contribution such as painting and welding and 2) a general overhead fixed term associated with factory heat, light and power for assembly plant operations (e.g., running assembly lines).

At this point our disassembled car is just parts and subassemblies, each of which is comprised of some combination of various basic auto materials (sheet aluminum and steel, various plastics, cast metals, etc.) and subassemblies. For example, an alternator is comprised of an aluminum cast housing, an armature with copper field windings, magnets, and other components such as bearings. Of course, the same argument applies to sub-subassemblies and so on. So we continue the disassembly process for each part until only basic auto materials remain and at the same time take into account the form they were in (ingots, pellets, bales, sheet stock, billets, etc.) prior to part manufacturing. At this point {VM}j can be rewritten as an expression comprised of two terms, one representing the transformation of various bulk materials (metals, plastics, elastomers, etc.) into an appropriate form (casting, extrusion, stamping, etc.) for assembly into components and the other representing an aggregation of all component assembly and subassembly burdens. The resulting expression is

$$\{VM\}_j = \sum_{k=1}^{m} \sum_{l=1}^{q} P_{jkl} \ \{T\}_{kl} + \{vm^*\}_j \tag{2}$$

where p_{jkl} is the mass of material k formed into a part via transformation process "l" for component j, $\{T\}_{kl}$ is the burden vector to transform bulk material k into form "l" for use in component j, q is the total number of transformation processes involved, and m is the total number of distinct materials on the vehicle; $\{vm^*\}_j$ represents the assembly of transformed materials k (welding, gluing, bolting, soldering, etc.) into component j along with general factory overhead burdens of the same type as those described for auto assembly, i.e. {VM*}. Because car parts are generally made by a number of Tier 1 and Tier 2 suppliers, the last term of eq. (2), $\{vm^*\}_j$, is an aggregation of burdens from multiple manufacturing operations and sites involved in producing part j.

If we have enough information about vehicle materials in parts and how they are each transformed, eqs. (1) and (2) can be readily used to compute {VMA}. Unfortunately, a complete listing of materials on a part-by-part basis along with information about their transformation is generally unavailable. Besides, there are 20,000 or more parts on a vehicle (Sullivan et al., 1998b), thus making it an onerous task to explicitly consider all parts and hence account for their manufacturing burdens.

The form of eq. (2) can be greatly simplified by consolidating terms in the summation across all parts along the lines of materials and transformation processes. This follows from the recognition that a particular material may be used in multiple applications within a vehicle and as such, depending on the application, might be transformed in different ways. For example, some aluminum on a car, such as in a hood, is derived from stamping sheet stock whereas other aluminum, as in an engine block, is derived from melting ingots followed by shape casting. Hence, substituting eq. (2) into eq. (1) and consolidating by materials and transformation processes over all parts, we have

$$\{VMA\} = \sum_{k=1}^{m} \left\{ \sum_{l=1}^{q} P_{kl} \ \{T\}_{kl} \right\} + \{VM_c^*\} + \ \{VM^*\} \tag{3}$$

where

$$P_{kl} = \sum_{j=1}^{n} P_{jkl} \tag{4}$$

P_{kl} is the sum of all material k transformed by process "l" over all parts j. In short, P_{kl} represents material/transformation pairings, examples of which include cast aluminum, cast iron, forged steel, stamped steel, blow-molded polyethylene, etc. $\{VM_c*\}$ is the sum of all overhead burdens for the production of all parts and components. The sum of all materials, P_{kl}, is just the curb weight of the vehicle.

Simplifying the double summation notation in eq. (3), we have

$$\{VMA\} = \sum_{i=1}^{b} P_i * \{T\}_i + \{VM_c^*\} + \{VM^*\} \tag{5}$$

where "i" now denotes specific material/transformation pairings, i.e., cast aluminum, stamped steel, etc., and "b" is the total number of them. Simply stated, eq. (5) represents {VMA} as the sum of three burden sources: 1) material transformation processes, 2) overhead burdens associated with assembling parts from transformed materials and 3) overhead burdens associated with overall vehicle assembly. Eq. (5) is the core expression of the VMA model, and through its use, we will estimate the cradle-to-gate values of E_{vm} and C_{vm}, the two components of {VMA} of interest here. Because reasonably complete information is available on the total amounts of materials in vehicles and the forms in which they appear, the determination of the first term in eq. (5), with the application of a few approximations, is shown to be straightforward. The last two terms of eq. (5) are estimated by using information from auto and supplier industries on generic energy use for manufacturing. Included here for these two terms are operational burdens only; burdens associated with the construction of the plant and the materials comprising it are not included.

There is one set of burdens not accounted for in our model, i.e., ancillary materials. These are materials used in product manufacturing that are not components of those products. These materials include greases, oils, acids, processing aids, liquid nitrogen, CO_2, solvents, wood, fluxes, packaging, and many others. These materials are important in the production of any product, including vehicles. However, because they are not expected to contribute more than 5% of the total burdens associated with the VMA stage and considerably less than that for the entire vehicle life cycle, they are not accounted for in the model. Besides, in order to account for them, a quantitative listing of the various ancillaries with amounts would be needed. Unfortunately, those data are not available.

4 DATA AND RESULTS

To gain a more detailed insight into the VMA stage of the vehicle life cycle, we have divided this section into three parts: 1) apply the VMA model to a vehicle with a very well-defined material composition and associated transformation processes, 2) apply the model to other vehicles using material composition/transformation process distributions derived in Part 1, and 3) use the model to quantify the significance of E_{vm} and C_{vm} to the total life cycle upon vehicle changes. These exercises are intended to quantify where burdens are generated during the VMA stage, their dependences, and how our results compare to those in published studies.

Significant transformation processes as well as the various vehicle assembly processes considered herein are listed in Table 2. Also included are e_{vm} and c_{vm}, for each process. These quantities are rates, and when appropriately weighted and summed over all VMA processes, E_{vm} and C_{vm} result. Where available, range information is also provided in Table 2. Because few LCA studies have been conducted in the automobile manufacturing area, we cannot reliably report average and standard deviation results for the processes listed. While Table 2 is not an exhaustive listing of all automotive material transformation processes, it includes the ones most frequently used in vehicle manufacturing and deemed to be the most important. For details on purchased energy consumption when available for the processes listed in Table 2, the reader is directed to Table A-2.

Unlike the case for transformation processes such as casting, the energy required to stamp metal is probably not best represented on a part weight basis. However, given that most published values represent it on such a basis, we do the same, recognizing that the range observed in the table likely reflects the imperfections of that approach. Because it seems likely that it takes more energy to stamp the steel for a large car than a small one, a flat rate per vehicle does not appear to be a better alternative. Hence, we have opted for the former approach.

4.1 WELL-DEFINED MATERIAL COMPOSITION

Table A-1 contains a listing of virtually all materials in the generic family sedan (U.S. Automotive Materials Partnership [USAMP], 1999) from the 1990s, the form in which they are typically shipped to part and component manufacturers, the processes used to shape those materials into forms suitable for their intended parts, their percent by weight of the total vehicle, and finally the surrogate processes used to represent them in our modeling exercise. The mass of this vehicle is 1532 kg, of which 99.4% has been itemized in the table. Materials not included are adhesives, graphite, sealants, hot melts, desiccants, etc., each of which is on the order of 0.01% of vehicle mass. Of the materials listed, 10% is plastic, 7% rubber, 6.4% aluminum, 1.7% copper and brass, 10% iron, 54% steel, 0.8% lead, 2.8% glass, and the balance (7%) other (fluids, sealants, carpet, etc.). Incidentally, it has been our experience that for most conventional light-duty vehicles, these percentages are sensibly constant. Hence, regarding the material production stage of the vehicle life cycle, all one needs for estimating that stage's energy and carbon emission burdens is a value from a previously characterized vehicle and the ratio of their curb weights.

TABLE 2 Material Transformation and Vehicle Assembly Process Data

Process	Energy consumption[a] (MJ/kg) Ave	Energy consumption[a] (MJ/kg) Range	CO_2 emission (kg/kg) Ave	CO_2 emission (kg/kg) Range	Source[b]
Stamping	5.1	0.59 – 9.69	0.31	0.03 – 0.44	5 values (Wheeler, 2009; Bauer, 1992, pgs. 16 and 30; Brown et al., 1996, Processes 1 and 2, pg. 305; Burnham et al., 2006; Galitsky and Worrell, 2008, Table 2)
Shape casting					
Aluminum	55.3	33.1 - 88.4	3.08	1.83 - 4.95	4 values (U.S. LCI Database: Secondary, Shape Casted; Semi-Permanent Mold Casting; Precision Sand Casting; Lost Foam Casting)
Iron	32.0	24.0 - 36.1	1.69	0.45 – 2.46	4 values (Boustead and Hancock, 1979, Appendix, Iron From Scrap and Ferro-Alloy, pg. 340; Burnham et al., 2006; U.S. LCI Database, Iron, Sand Casted; Ford Vehicle LCI Model, Iron)
Copper wire production	7.1		0.43		1 value (Boustead and Hancock, 1979, Appendix, Copper Wire, pg. 332, footnote 561)
Brass from scrap	7.4		0.42		1 value (Brown et al., 1996, Secondary Non-Ferrous, pg. 291)
Secondary lead production	8.5		0.49		1 value (Boustead and Hancock, 1979, Appendix, Lead from Scrap, pg. 343)
Machining	2.015	1.73 – 2.30	0.115	0.10 - 0.13	2 values (Brown et al., 1996, Process 4, pg. 295 and Process 9, pg. 309)
Forging	45.1		2.61		1 value (Brown et al., 1996, Iron and Steel Forging, pg. 297)
Glass pane forming	16.0		0.93		1 value (Brown et al., 1996, Flat Glass, pg. 246)
Welding	920	920 - 1093	62.0	62.0 - 73.6	2 values (Berry and Fels, 1972)

TABLE 2 (Cont.)

Process	Energy consumption[a] (MJ/kg)		CO_2 emission (kg/kg)		Source[b]
	Ave	Range	Ave	Range	
Painting	4167	2141 - 8175	268	123 - 472	7 values (Papasavva, 2002; Galitsky and Worrell, 2008, Table 2, plus 55% of plant fuel for painting; U.S. LCI Database, Automotive Painting)
HVAC and lighting[c]	3335	2587 - 3565	225	174 - 240	2 values (Galitsky and Worrell, 2008, Table 2)
Material handling[c]	690	690 - 805	39.5	39.5 - 46.1	2 values (Galitsky and Worrell, 2008, Table 2)
Heating	3110		195		1 value (based on Galitsky and Worrell, 2008, Table 2)
Compressed air	1380	920 - 1380	93	62 - 93	2 values (Galitsky and Worrell, 2008, Table 2)
Moldings					
Rubber	12.9		0.74		1 value (Brown et al., 1996, Tires and Inner Tubes, pg. 234)
Thermosets	4.79		0.27		1 value (Plastics Europe, PU Foams)
Injection mold					
PP	26.4		1.53		1 value (Boustead, 1997)
PVC	24.3		1.56		1 value (Boustead, 1997)
Blow mold					
HDPE	19.7		1.13		1 value (Boustead, 1997)
Calendaring					
PVC Sheet	6.25		0.36		1 value (Boustead, 1997)
Extrusion					
HDPE pipe	7.03		0.42		1 value (Boustead, 1997)

[a] All energy values are low heat values (LHV).
[b] In many cases, CO_2 was calculated from listed energy assumed to be natural gas and grid electricity
[c] Electricity only

Of the 99.4% of vehicle mass accounted for, 92.7% of it is operated on by one of the transformation processes identified in Table 2. The transformation processes incurred for the remainder of the material are assumed to be either a part of the material production stage (e.g. petroleum-based liquids [oils, greases, and fuels], sulfuric acid, antifreeze, etc.) or not known (e.g. carpeting). Most of the iron in a vehicle is ductile iron and is in the form of castings, though some iron forgings are also present. Most aluminum in today's vehicles is castings; very little sheet (wrought) aluminum is used at this time, owing primarily to cost considerations. Much of the steel in vehicles has been formed by stamping sheet stock, though between 15% and 20% of steel is high- to mid-strength alloy for applications like axles, shafts, connecting rods, brackets, springs, gears, cam shafts, etc. These systems are generally formed as extrusions, forgings, drawings, etc.. and subject to some machining (threading, milling, drilling, etc.). About 40% of all plastic components on vehicles are shape-formed by injection molding. Other plastic transformation processes employed in making plastic auto components include calendaring, blow molding, and extrusion. Rubber components are typically compression molded, though some extrusions such as door weather seals are present.

As the focus here is on the VMA stage of the life cycle, available processing data are essential for our analysis. Because we do not have specific transformation energy and emissions data for all materials, we have used surrogate representations where necessary. For example, in the case of injection molding of polymers, we only have process data for polyvinyl chloride (PVC) and polypropylene (PP) parts (see Table 2 for references). Hence, for the other injection-molded polymers, we resorted to using a representative and comparable process, in this case injection molding of polypropylene. We believe that this approach provides reasonable approximations for those specific material/transformations where data are not available. For instance, though the melt temperatures for PP and PVC are quite different (about 170°C and 80-90°C, respectively), their process energy and carbon emissions are nearly the same (see Table 2). Another important surrogate representation has been applied for metal stamping. Our primary data are for steel stamping, but we also applied it to aluminum and brass stamping. For a summary listing of vehicle materials by material groups and transformation process surrogates, see Table 3.

An inspection of Table 3 again highlights the distinction between our bottom-up approach and that employed by the USAMP study (1999) from which our material composition data set was taken. Our approach is transformation process-centric and is applied to materials from any vehicle subsystem. On the other hand, the USAMP study divided the vehicle into subsystems like body, powertrain, electrical, etc., and modeled the manufacturing of those components on the basis of a combination of models where necessary and OEM data from various parts and assembly plants. Admittedly, our approach does not include all manufacturing operations, just the ones that contribute to the preponderance of the manufacturing effort. For example, printed circuit boards are only partly covered by our approach, namely, we include the manufacture of glass fiber thermosetting resin circuit boards. However, printing the circuits onto those boards, mounting components, and finally washing them is not covered by our approach at this time. From an energy carbon footprint perspective, those missed operations contribute little, though from the point of view of water and air emissions, those same operations might be quite significant.

TABLE 3 Summary of Transformations and Materials by Group

Transformation	Material Group	Transformation Process Surrogate	% of Curb Wt.
Metal stamping	Steel	Steel stamping	37.7
	Aluminum	"	0.2
Castings	Iron	Iron	8.6
	Aluminum	Aluminum	4.7
	Brass	Brass	0.6
	Lead	Lead	0.8
Forgings	Iron and steel	Iron and steel	3.8
Extrusions	Aluminum	Aluminum	1.4
Machining	Steel	Metals	14.0
Wire forming	Copper	Copper wire	1.2
Glass pane forming	Glass	Float glass	2.8
Blow molding	Polymers	HDPE bottles	0.2
Compression molding	Plastics and rubber	Compression-molding rubber	7.4
Thermoset molding	Polymer resins	PU foams	2.6
Extrusions	Plastics	HDPE pipe	1.6
Calendaring	Plastics	PVC	0.2
Injection molding	Plastics and rubber	PP parts	4.7
Total			92.5

As indicated by Table A-1, a full material transformation process assessment for energy consumption and CO_2 emissions via eq. (5) would, in principle, include over 100 items. However, as a result of our use of appropriate surrogates for material/transformations where data are not available, this list shrinks considerably. As shown in Table 3, only 17 terms are now required. For example, using data from Tables 2 and 3, the energy consumption for the production of iron castings from ingot and scrap on our 1532-kg vehicle is

$$1{,}532 \text{ kg} * 0.086 \text{ (tbl. 3)} * 32.0 \text{ MJ/kg (tbl. 2)} = 4{,}216 \text{ MJ}$$

Applying the data in Tables 2 and 3 to eq. (5), we have estimated E_{vm} and C_{vm}; results are presented in Table 4. Two sets of values are given in the table. The "grand average" is simply based on average process energy and CO_2 emissions given in Table 2. The other set is derived from the range data given in the table, stochastically sampled over many model runs (typically 200) to yield a statistical set of total VMA energy and CO_2 results. The range data defined the bounds for each process and, during each run, samples were randomly taken between the bounds for each process using a uniform distribution function. It is clear from an inspection of the table that the differences between the "grand average" and stochastic values are negligible, given the statistics shown. The variation shown in the table for the stochastic set would likely be somewhat

TABLE 4 E_{vm} and C_{vm} Results Summary for a Generic 1532-kg Vehicle

Item	Grand Average	Stochastic		
		Average	Standard Deviation	Coefficient of Variation
Energy (MJ)	33,924	33,125	2,343	0.071
CO_2 (kg)	2,013	2,169	226	0.104

higher if we had range information for all entries in Table 2. Also notice the difference between the coefficient of variation for energy and CO_2. It is likely due to the different carbon intensities of common process fuels and electricity.

When compared to the energy values given in Table 1, our results are seen to be on the higher end and are probably reasonably estimates of the actual value. To reach this conclusion, we dismiss the highest value in Table 1, the coarse estimated based on Brown et al. data (1996). However, we again remind the reader that Keoleian et al. (1997) have argued that the Sullivan et al. (1998b) value (39.9 GJ) might be underestimated somewhat.

The cradle-to-gate energy value that we report in Table 5 is about 15% lower than that reported in the USCAR study (Sullivan et al., 1998b). The reason or reasons for the difference are unclear One might be study-to-study variation. On the other hand, their approach was somewhat different from ours. The USCAR authors conducted their study in terms of major vehicle subsystems (powertrain, electrical, body, interior, fluids, HVAC, suspension), whereas our approach focuses on major transformation and vehicle assembly processes, irrespective of what subsystem the various materials are intended for. Nonetheless, both approaches are bottom-up. Two potential reasons for the disparity in energy values are: 1) space heating, lighting and material handling are implicitly included in the USCAR part-manufacturing estimates, and 2) transportation of parts and assemblies between suppliers (approximately 1,700 MJ [Sullivan et al., 1998b]) and auto assembly plants are also included. We have not explicitly included either of these in our model, except for auto assembly plant support (overhead) energy. While we feel that the overhead burdens associated with auto assembly plants $\{VM^*\}$ (see eq. [5]) are quite reliable and well documented (Boyd, 2005; Galitsky and Worrell, 2008), there is some remaining uncertainty about the burdens for part manufacturing, i.e. $\{VM_c^*\}$. Firstly, we have no explicit reference for the overhead burdens incurred during part manufacturing. Secondly, owing to a general lack of information on process boundary conditions, what data we do have on transformation processes, which are key operations in part manufacturing, may or may not implicitly include overhead burdens. Nonetheless, we estimate that the potential shortfall of our $\{VM_c^*\}$ energy value might be as much as 4700 MJ. To arrive at this value, we took one-half the overhead burdens from Table 5 (HVAC and lighting, heating, material handling, welding, and compressed air). This assumes that overall overhead burdens for part manufacture are the same as those for vehicle assembly. We take only of that value by presuming that about half of the transformation process data already have overhead rolled in. Adding the 4700 value to those in Table 4 yields an estimate of E_{vm} in good agreement with the USAMP value (see Table 1).

TABLE 5 Detailed Life Cycle Energy and CO_2 Results by Major Processes for a Generic 1532-kg Vehicle

Components of VMA	Energy (MJ)	CO_2 (kg)
Material transformation	19,340	1,065
Machining	982	56
Vehicle painting	4,167	268
HVAC & lighting	3,335	225
Heating	3,110	195
Material handling	690	46
Welding	920	62
Compressed air	1,380	93
Total	33,924	2,013

One advantage of the bottom-up approach is that contributions to E_{vm} and C_{vm} , and other burdens (if tracked) can be identified for each class of processes that comprise VMA. Such detail might offer opportunities for environmental improvements. Results by class of processes are presented in Table 5. Of any single entry in the table, material transformation processes (including machining) are collectively the largest contributor, amounting to 59% of the energy burden. Of those (results not tabulated), 77% are associated with metal transformations, followed by polymer processing at 19%, and finally glass production at 4%. And of the metal transformations, over three quarters of the energy is associated with casting, extruding, and forging, with aluminum and iron casting constituting over half of that. While painting accounts for only 13% of E_{vm}, for an assembly plant alone it represents 31%. The next largest contributors to the cumulative energy of the VMA stage are HVAC and lighting followed by other minor entries such as material handling. The trends discussed above for E_{vm} are the same for C_{vm}, also listed in Table 5. There it is seen that material transformation processes account for 55% of CO_2 emissions and of those the percentages for metals, plastics, and glass transformation are essentially the same as discussed for energy.

Though we have elucidated the primary energy and carbon burdens associated with the various processes within part manufacturing and vehicle assembly, an even more informative analysis is to conduct a speciated energy assessment of the different types of energy resources (coal, natural gas, electricity, etc.) being used, i.e. energy purchased by the user. This not only informs us about how different processes are powered, especially useful in comparing manufacturing in different parts of the world, but also permits us to estimate more accurately cumulative energy consumption and carbon emissions, which can vary from region to region. Generally, upstream energy consumption and emissions associated with the production of energy are dependent upon the region where it is produced. For example, because much of the electricity generated in Europe is from nuclear plants, the same electrically driven processes in North America are likely to have a higher carbon burden owing to a lower use of nuclear power here.

Another advantage of a speciated energy analysis is that it provides an opportunity to identify potential energy efficiency improvements.

In Table A-2, we have amassed purchased-energy data for the various processes modeled herein. However, because that type of information is generally less available than roll-up numbers, fewer entries in Table A-2 than in Table 2 actually represent averages. Nonetheless, this is the best information available to us. From that data and values in Table 3, we recomputed the E_{vm} and $C_{vm}$for our system. Results are given in Table 6.

TABLE 6 Purchased Fuel and Electricity Use and Energy and CO_2 Summaries for the VMA Stage for a Generic 1532-kg Vehicle

Resource	Coal (kg)	NG (m^3)	Propane (L)	Gas Oil[a] (L)	Fuel Oil (L)	LPG (L)	Diesel (L)	Gasoline (L)	Process Oil (L)	Electricity (kWh)
Material transformation	43.0	209	0.302	0.005	1.83	0.129	0.094	1.536	1.908	763
Machining										85.1
Subtotal	43.0	209	0.302	0.005	1.83	0.129	0.094	1.536	1.908	848
Assembly plant operations										
Vehicle painting		66.3								134
HVAC & lighting										290
Heating		85.9								0
Material handling										60
Welding										80
Compressed air										120
Subtotal		152								684
Total purchased energy	43.0	361	0.302	0.005	1.83	0.129	0.094	1.536	1.908	1,532
Total in MJ	1,122	13,060	7	0	71	3	3	49	73	5,515
Purchased electricity	5,515 MJ									
Purchased fuel	14,389 MJ									
LCE electricity[b]	16,111 MJ									
LCE fuels	15,577 MJ									
Electricity CO_2	1,188 kg									
Purchased fuels CO_2	2,227 kg									

[a] Gas oil is distillate oil.
[b] Note that this energy value also includes contributions from nuclear and renewables, which are not explicitly listed in the table.

The table shows that E_{vm} is 31,688 MJ and C_{vm} is 2,227 kg. These values are about 7% lower and 10% higher, respectively, than their counterparts in Table 4. We attribute these differences to the limitations of the purchased fuels data set (Table A-2), which has few samples per entry. Table 6 also shows trends in the energy purchased to run VMA operations. It is clear from the table that the use of electricity, as expected, is extensive and the most significant fossil fuels employed are natural gas and coal. When electricity generation is considered, even more coal and natural gas are used. Note from the table that the electricity used by the industry to produce this vehicle is around 28% of total purchased energy, with fossil fuels representing 72%. However, when converted to LCE values, electricity represents 51% of E_{vm}, with fossil fuels representing 49%. This trend has been noted before by Galitsky et al. (2008) and Boyd (2005), though in both cases for automotive "assembly" plants only. We used the trend to estimate assembly-plant fuel use. However, because this trend is observed in our part-manufacturing modeling results as well, our overall results show the same trend.

4.2 GENERALIZED MATERIAL/TRANSFORMATION DISTRIBUTIONS AND OTHER VEHICLES

The results presented above are for a vehicle with a very well-defined material composition and, more importantly, a detailed material transformation listing for those materials. Information about the latter is critical for assessment of VMA burdens. Unfortunately, such detail for vehicles is rarely available. Generally, we must be content with much less detail such as the material composition data listed in Tables 10–14 of the GREET 2.7 report (Burnham et al., 2006). However, some generalizations can be made about the distribution of material transformation processes employed in making vehicles, both overall and within specific materials (e.g. iron), as long as the overall material composition of the vehicle does not depart significantly from average. If a significant departure in material composition is encountered, as is expected for electric drive technologies, some adjustments to transformation-process distribution must be considered.

Table 7 has a high-level listing of the material composition and associated transformation processes for those materials which are typical of most conventional vehicles being produced at this time. This table has been derived from Tables A-1 and 3. There is an important secondary transformation process not listed in the table, i.e., machining. This process is a finishing operation, which is applied to castings, forgings, rods, and bar stock. It turns out that about 32% of the mass of the vehicle is subject to some type of machining, all of those materials being metals.

Because of the similarity in material composition for most conventional internal-combustion vehicles (ICVs), one can expect that the distribution of material/transformation processes employed in their respective part and vehicle manufacture to also be quite similar. However, when vehicles like hybrid electric, plug-in hybrid electric, and all-electric vehicles (HEVs, PHEVs, and EVs, respectively) are considered, the material composition and associated distribution of transformation processes is likely to be at least somewhat different. Further, some materials continue to make application inroads on cars. For example, when either a conventional

TABLE 7 Generalized Material Composition and Primary Transformation Process Listing for Use in the VMA Model

Material	% of Curb Wt.	Transformation Processes
Iron	10.1	Cast (85%); forged (15%)
Steel	54.2	Stamped (70%); forged (4%)[a]
Aluminum	6.4	Cast (76%); extruded (23%); stamped (1%)
Copper/Brass	1.7	Drawn (68%); cast (32%)
Lead	0.9	Cast (100%)
Rubber	6.8	Compression molded (89%); Injection molded (11%)
Plastics	9.8	Injection molded (40%); thermoset (27%); extruded (16%); compression molded (13%); blow molded (2%); calendared (2%)
Glass	2.8	Float glass (100%)

[a] The remaining steel is machined only.

or alternative vehicle has considerably lower iron composition than is traditionally the case, this likely implies a reduction in iron castings and an increase in aluminum ones. Therefore, when it is desired to model the VMA stage of an unconventional vehicle, an effort needs to be undertaken to identify the material dissimilarities and potential changes in the transformation processes employed.

We now apply the VMA model to other vehicles (Burnham et al., 2006) with known material compositions using the generalized material and transformation process distributions given in Table 7. Results from those runs are shown in Table 8.

A number of details in Table 8 merit comment. Firstly, notice that the entries for the two ICVs are sensibly identical to one another. Although there were some transformation-process differences between the vehicle systems in the USAMP and Argonne (GREET) data sets, in the aggregate those differences have little impact. For example, though the GREET data set makes no reference to iron forgings and the USAMP set lists 15% of iron parts as forgings, their respective E_{vm} and C_{vm} values are sensibly the same.

When modeling advanced hybrid or all-electric vehicles, we applied the material/transformation process distribution of conventional vehicles to their material compositions minus that of the battery. The battery was treated separately. Given that at this time only one material/transformation process distribution for vehicles is at hand, this approach is deemed at least a reasonable approximation of the actual distribution of fully or partially electric vehicles. Based on this approach, E_{vm} and C_{vm} values for these vehicles are also given in Table 8.

TABLE 8 E_{vm} and C_{vm} Results for a Series of Vehicles

Vehicle	ICV	ICV[a]	HEV[a]	PHEV-20[b]	PHEV-40[b]	EV[b]
Data source	USAMP	Argonne	Argonne	Argonne	Argonne	Argonne
% by wt. covered by model	92.8	95.2	95.2	93.4	92.2	89.3
% by wt. from advanced battery	0	0	0.6	2.3	4.18	6.6
Vehicle mass (kg)	1,532	1,578	1,683	1,746	1959	2104
E_{vm} (MJ)						
From model	33,920	33,358	32,886	33,712	36,766	38,094
From advanced battery[c]	0	0	1,060	3,654	7,452	12,637
Total	33,920	33,358	33,946	37,366	44,218	50,731
C_{vm} (kg)						
From model	2,011	1,969	1,949	1,995	2,165	2,244
From advanced battery	0	0	84	289	590	1,000
Total	2,011	1,969	2,033	2,284	2,755	3,244

[a] Vehicles from Burnham et al., 2006
[b] Based on Burnham et al., 2006 and simulations from Argonne's Powertrain System Analysis Toolkit
[c] Based on Rydh and Sanden, 2005

Notice in the table that as advanced batteries comprise an increasing percentage of vehicle weight, both E_{vm} and C_{vm} are seen to increase considerably. Part of the increase is simply due to vehicle mass increase, but as seen in the table a significant increase in E_{vm} is also incurred from the production of the battery alone. On a per-unit-mass basis, the E_{vm} values for battery production are quite large, especially when compared to the overall VMA burden. Indeed, the incremental manufacturing energy rate is 13.3 MJ/kg of vehicle whereas the values are 91 MJ/kg of Li-ion battery and 105 MJ/kg of NiMH battery (Burnham et al., 2006). Though there is a dearth of battery assembly data, the values taken from GREET appear quite representative and certainly in line with data recently reported for the manufacture of similar batteries intended for stationary photovoltaic applications (Rydh and Sanden, 2005).

An inspection of eq. (5) shows that VMA LCBs are multi-linear functions of the various processes used to manufacture vehicle parts, components and finally the vehicle. Another way to write eq. (5) is

$$\{VMA\} = \mathrm{P_T} \sum_{i=1}^{b} F_i * \{T_r\}_i + \{VM_c^*\} + \{VM^*\} \tag{6}$$

where F_i ($=P_i/P_T$) is the mass distribution function for material/transformation process combinations employed in making vehicle parts and components and P_T is overall vehicle mass. As before, the last two terms of eqs. (5) & (6) are constants independent of vehicle mass and represent plant-wide per-vehicle burdens. In general, F_i can vary from vehicle to vehicle.

Special Case for Eq. (6): Because many conventional passenger cars on the road today have virtually the same components and very similar percent material compositions, they can be expected to have sensibly the same distribution of material/transformation processes, i.e., F_i. Hence, to describe the VMA burdens for a population of such vehicles, eq. (6) becomes a simple linear equation:

$$\{VMA\} \cong \{A\}P_T + \{B\}, \qquad (7)$$

where {A} and {B} are vector constant lists corresponding to the list of burdens in {VMA}. The implication of eq. (7) is that for a population of conventionally powered passenger cars, all that are needed to estimate the VMA burden of any one of those vehicles are the burdens determined for another vehicle of that population and the ratio of their curb weights. Of course, eq. (7) and associated reasoning can be applied to any other population of comparably comprised and configured vehicles, e.g. light-duty pickup trucks, SUVs, etc.

Based on the USAMP material composition and transformation process data for the generic family sedan and the results in Table 5, the constants in eq. (7) are: for E_{vm}, A_e = 13.3 MJ/kg of car and B_e = 13,600 MJ, and for C_{vm}, A_c = 0.74 kg CO_2/kg of car and B_c = 890 kg. This expression can now be applied to other vehicles. For example, using the eq. (7) energy constants, E_{vm} for the Argonne ICV is 34,568 MJ, whereas it is reported in Table 8 as 33,358 MJ. The difference is 3.6%. The values for C_{vm} are 2,044 kg calculated from eq. (7) and 1,969 kg from Table 8; the difference is 3.8%. Applying the same equation and constants to a mid-size European C/D class vehicle weighing 1,214 kg, we calculate E_{vm} to be 29,731 MJ whereas direct application of the VMA model yields 30,357 MJ. The difference is 2%. As a final example, we apply eq. (7) to an aluminum-intensive vehicle (AIV) from the Partnership for a New Generation of Vehicles (PNGV) program. In that case, a 1,033-kg vehicle has an E_{vm} of 30,425 MJ, whereas eq. (7) yields 27,339 MJ. In this case the difference is 10%.

Though simplifications like eq. (7) are quite useful in determinations of E_{vm} and C_{vm}, caution must be exercised in their application. For vehicles with disparate material/transformation process distributions, the expression does not work. It is not surprising that the PNGV estimate based on eq. (7) departs significantly from that based on the general model. After all, relative to a conventional vehicle, the PNGV vehicle is comprised of a significantly larger amount of aluminum, both wrought and cast, the latter having the most energy-intensive transformation process presently used for making vehicle components (see Table 2). Regarding stamped metal, the use of more wrought aluminum and less steel would have little impact on E_{vm} and C_{vm}, though the impacts would be much larger in the material production stage of the vehicle life cycle. Finally, another example of the influence of material/transformation process distribution on VMA burdens and the applicability of eq. (7) is highlighted in our discussion above on advanced-battery burdens.

4.3 SIGNIFICANCE OF E_{vm} AND C_{vm} TO THE TOTAL VEHICLE LIFE CYCLE

From the total-life-cycle studies reported in the literature (e.g. Berry and Fels, 1972; Kobayashi, 1997; Schuckert et al., 1997; Sullivan and Hu, 1995; Sullivan et al., 1998a; Sullivan et al., 1998b; USAMP, 1999), the contribution of the VMA stage burdens of E_{vm} and C_{vm} have been found to be relatively small. In fact, the USAMP study (1999) reported it to be around 4% for both total LCE and life cycle CO_2 emissions. Our results support this conclusion. However, when changes in vehicle material composition and/or powertrain are considered, it might be more significant under certain circumstances. To explore that possibility, we now conduct incremental analyses for a material substitution and an overall vehicle weight reduction, both at constant vehicle performance (0-60 mph time, gradeability).

The change in vehicle LCE upon a material substitution can be written as

$$\Delta LCE \cong \left[\frac{\Delta E_{mp}}{\Delta P_T} + \frac{\Delta E_{op}}{\Delta P_T} + \frac{\Delta E_{vm}}{\Delta P_T} \right] \Delta P_T \qquad (8)$$

where "mp" denotes material production, "op" vehicle operation, and "vm" as defined above. The other two terms of a vehicle life cycle, namely maintenance/repair and end of life, are quite small and can be ignored. It has been argued by one of us (Sullivan and Hu, 1995) that in cases where vehicle weight is reduced by material substitution, the change in vehicle LCE is dependent to a good approximation only on changes in material production energy and vehicle operational energy, i.e. the first two terms in eq. (8). The ΔE_{vm} term was considered negligible. Expressing eq. (8) in more detail, we have

$$\Delta LCE \cong \left[\frac{\frac{E'_i}{C_i} - f \frac{E'_k}{C_k}}{1 - f} + \frac{B * D * LHV}{\xi} + \frac{\Delta E_{vm}}{\Delta P_T} \right] \Delta P_T \qquad (9)$$

where E'_i is the production energy rate (MJ/kg) of material i, C_i is the production efficiency of the application of material i, f is the substitution factor of material k for material I, B is the inertial component (on a low-heat-value [LHV] basis) of the fuel consumed (gallons) per unit distance driven through the drive cycle (Sullivan and Cobas-Flores, 2001), D is lifetime distance (160,000 miles), LHV is the low heat value of a gallon of fuel, and ξ is the fuel production efficiency. The magnitude of the first term is dependent on the materials being displaced and substituted; the second term is related to the vehicle mass dependence of fuel consumption (B), and finally the last term can be quite variable. Below we discuss two cases for the application of eqs. (8) & (9).

Our first case is for the substitution of aluminum for steel on an existing vehicle model. For this calculation, the following is assumed: material production energies (E'i) for virgin steel and aluminum are 32 and 183 MJ/kg, respectively (USAMP), Ci are 0.98, f (substitution factor) for wrought aluminum displacing rolled steel is 0.55 (Sullivan and Hu, 1995), B = 1.58x10-5 gallons/kg-mile (from simulation model for a D class vehicle – curb weight 1532 kg), LHV = 121 MJ/gallon gasoline (GREET 1.8), and ξ is 0.800 (GREET 1.8). Regarding the VMA stage of the life cycle, exchanging one stamped metal for another yields $\Delta E_{vm}/\Delta P_T = 5.1$ MJ/kg, which is just the energy to stamp a kilogram of parts. Hence, eq. (9) on a term-by-term basis is

$$\Delta LCE \cong [-155 \quad + \quad 383 \quad + \quad 5.1]\ \Delta P_T$$

Clearly, the E_{vm} term makes a small contribution. Incidentally, notice that if we assume the production efficiencies, C_i, for the metals are 0.55, typical of stamping operations with offal rates of around 45%, the first term becomes closer to -280. Hence, from an LCE point of view, the benefit of reduced vehicle weight using virgin sheet aluminum in place of steel is reduced. Further, if this vehicle has a more efficient powertrain, like a compression-ignited engine, the "B" term in eq. (9) and hence the second term above becomes smaller (perhaps up to a third less), which further erodes the benefit of this particular weight reduction approach. Using CO_2 rates of 2.43 and 11.4 g/kg for steel and aluminum (USCAR), respectively, $\Delta C_{vm}/\Delta P_T = 0.31$ g/kg of stamped metal, 10,486 g/gallon of gasoline (GREET), and the same substitution and efficiency factors as above, we find

$$\Delta LC\_CO_2 = [-8.71 \quad + \quad 26.5 \quad + \quad 0.31]\ \Delta P_T$$

As far as relative contributions are concerned, this expression shows essentially the same relationship between the first two terms as does its LCE counterpart above. Further, the vehicle manufacturing term is again seen to be a small contributor.

If, on the other hand, a vehicle is simply made lighter without material substitution and at the same time retains a constant material composition distribution F_i, eq. (7) becomes, on a term-by-term basis,

$$\Delta LCE \cong [55.8 \quad + \quad 383 \quad + \quad 13.3]\ \Delta P_T$$

Again, it is seen that the VMA component is relatively small. In this case, we assumed that $\Delta E_{mp}/\Delta P_T$ is 55.8 MJ/kg (=85.5 GJ/1532 kg) (USAMP, 1999), i.e. an average material production for the vehicle. Similar results can be generated for life-cycle CO_2 emissions.

The original rationale for focusing less on part manufacturing or assembly was that those elements did not appear to account for a large part of the energy use associated with the vehicle life cycle. However, this idea had not been fully tested and that left life-cycle analysis open to surprises and potentially to exaggerations. By virtue of its detail, the treatment presented here puts bounds on the magnitude of energy and carbon VMA burdens, though clearly these burdens are relatively small compared to the rest of the life cycle. However, there are other LCA burdens where the VMA stage is likely to dominate, for example, waterborne emissions. The bottom-up methodology developed here provides a framework for future examination of VMA LCBs for different manufacturing processes and products.

5 CONCLUSIONS

A model representing the part manufacturing and vehicle assembly (VMA) stage of a vehicle life cycle has been developed. Data from numerous sources were used, but a source of critical value has been the material composition and process data from the USAMP generic-vehicle life-cycle study. Various transformation processes have been included in the model, such as metal stamping, casting, forging, machining, and extrusion as well as polymer extrusion, injection, compression molding, blow molding, and calendaring. Float glass has also been included. About 40% of the cumulative energy and CO_2 emissions for the VMA stage are fixed, i.e. they are apportioned to the vehicle life cycle on a per-vehicle rather than on a per-unit-mass-of-material basis (vehicle size). The fixed operations include heat and light, air conditioning, vehicle painting, plant material handling, welding, etc.

The model estimates the cumulative energy consumption and CO_2 emissions to be about 34,000 MJ and 2,000 kg, respectively. These results are on the higher end of previously published values, though still somewhat lower (by about 17%) than that reported in the comprehensive USAMP generic-vehicle study. This disparity, if real, might be due to a lack of data in the VMA for support operations in the part manufacturing facilities of suppliers, though some of the difference is due to the omission of transportation energy incurred in moving parts between suppliers and OEMs. Nevertheless, our results, like those reported before, indicate that these VMA-stage burdens represent around 4% of the corresponding total LCBs. The results presented are based both on process “grand average” energy and CO_2 data and on range data. For the latter, a stochastic sampling procedure was applied to the range data, yielding mean values for the cumulative energy consumption and CO_2 emissions and standard deviations of 7% for the former and 10% for the latter. Based on a more limited set of data from the literature, results are also generated using speciated purchased fuel and power data, e.g., kWh of electricity, gallons of diesel, and cubic meters of natural gas. The corresponding cumulative energy and CO_2 values are a little lower than reported for the full set of data, the difference being attributed to a smaller set of information.

From the USAMP material-composition and transformation-process information, we developed a general material composition/transformation process distribution for conventional vehicles. Based on this distribution, the model was readily applied to a number of conventional vehicles. It was also found that for conventional vehicles, a simplified linear expression, dependent only on vehicle mass, yielded VMA-stage cumulative energy consumption and CO_2 emission results that are in very good agreement with results from the general model application. However, when this linear expression was applied to an AIV, a departure of 10% was observed from the general model output, which had appropriate adjustments made to its material/transformation process distribution. This point illustrates that for successful application to advanced vehicles like AIVs, EVs, and PHEVs, the derived distribution needs to be altered. Model results also demonstrate that battery manufacturing burdens lead to comparatively large additional energy and CO_2 burdens for electric-drive vehicles relative to their conventional counterparts.

Finally, the dependence of VMA cumulative energy and CO_2 burdens on specific changes in the vehicle, i.e., material substitution and overall vehicle-weight reduction, was explored. In both cases, the contribution of VMA terms to the incremental total vehicle life cycle is small. This is consistent with assumptions made in the past regarding the impact of manufacturing-stage burdens on changes in the LCBs accompanying changes in vehicle materials. However, for advanced vehicle technologies with lower operational burdens and comprised of more energy-intensive materials, VMA-stage burdens can be expected to become relatively larger.

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APPENDIX

Table A-1 Material Composition and Process Information

Material	Typical Feedstock Form	Primary Transformation	Significant Secondary Process	Material % on Car	% of Curb Wt	Modeled as
Polymers						
Polyamide (PA 6)	Pellets	blow molded			0.04	Blow molded HDPE
Polypropylene (PP)	Pellets	blow molded			0.15	Blow molded HDPE
Polyurethane (PUR)	Pellets	blow molded			0.04	Blow molded HDPE
Polyvinyl chloride (PVC)	Pellets	calendered			0.24	Calendared PVC
PET	Pellets	compressed			0.04	Molded rubber
PET	Pellets	Compression molded			0.03	Molded rubber
Polypropylene (PP)	Pellets	compression molded			0.21	Molded rubber
Acetal	Pellets	molded			0.01	Molded rubber
Acetal	Pellets	molded			0.02	Molded rubber
Acrylic Resin	Pellets	molded			0.02	Molded rubber
ABS	Pellets	molded			0.15	Molded rubber
EPDM	Pellets	molded			0.22	Molded rubber
Polyamide (PA 6)	Pellets	molded			0.05	Molded rubber
Polyamide (PA 66)	Pellets	molded			0.23	Molded rubber
Polybutylene terephthalate	Pellets	molded			0.01	Molded rubber
Polycarbonate	Pellets	molded			0.05	Molded rubber
Polyethylene (PE)	Pellets	molded			0.1	Molded rubber
Polypropylene (PP)	Pellets	molded			0.04	Molded rubber
Polyurethane (PUR)	Pellets	molded			0.01	Molded rubber
Polyvinyl chloride (PVC)	Pellets	molded			0.02	Molded rubber
ABS	Pellets	extruded			0.11	Extruded HDPE pipe
EPDM	Pellets	extruded			0.19	Extruded HDPE pipe
Polyamide (PA 66)	Pellets	extruded			0.2	Extruded HDPE pipe
Polyester resin	Pellets	extruded	woven		0.36	Extruded HDPE pipe
Polypropylene (PP)	Pellets	extruded			0.03	Extruded HDPE pipe
Polyethylene (PE)	Pellets	extruded			0.04	Extruded HDPE pipe
Polyvinyl chloride (PVC)	Pellets	extruded			0.68	Extruded PVC pipe
ABS-PC	Pellets	injection molded			0.18	Injected molded PP
Acetal	Pellets	injection molded			0.28	Injected molded PP
Acrylic resin	Pellets	injection molded			0.14	Injected molded PP
ABS	Pellets	injection molded			0.37	Injected molded PP
EPDM	Pellets	injection molded			0.28	Injected molded PP
Phenolic resin	Pellets	injection molded			0.05	Injected molded PP

Table A-1 (Cont.)

Material	Typical Feedstock Form	Primary Transformation	Significant Secondary Process	Material % on Car	% of Curb Wt	Modeled as
Polyamide (PA 6)	Pellets	injection molded			0.02	Injected molded PP
Polyamide (PA 66)	Pellets	injection molded			0.24	Injected molded PP
Polybutylene terephthalate	Pellets	injection molded			0.01	Injected molded PP
Polycarbonate	Pellets	injection molded			0.19	Injected molded PP
Polyethylene (PE)	Pellets	injection molded			0.27	Injected molded PP
PET	Pellets	injection molded			0.07	Injected molded PP
PPO-PS	Pellets	injection molded			0.14	Injected molded PP
Polypropylene (PP)	Pellets	injection molded			1.2	Injected molded PP
Polypropylene (PP, foam)	Pellets	injection molded			0.11	Injected molded PP
Polyvinyl chloride (PVC)	Pellets	injection molded			0.39	Injected molded PVC
Polyurethane (PUR)	monomer resins	RIM			0.86	Thermoset PU foams
Polyurethane (PUR, foam)	monomer resins	RIM			0.07	Thermoset PU foams
Polyurethane (PUR)	monomer resins	RIM			0.26	Thermoset PU foams
Polyurethane (PUR, foam)	monomer resins	RIM			1.04	Thermoset PU foams
Phenolic resin	monomer resins				0.03	Thermoset PU foams
Polyester resin	monomer resins	glued			0.36	Thermoset PU foams
Polyester resin	monomer resins	woven			0.02	?
				9.9		
Rubber	Pellets, bails	calendered			0.04	Molded rubber
Rubber	Pellets, bails	compression molded			0.01	Molded rubber
Tire	Pellets, bails	compression molded			2.96	Molded rubber
Rubber	Pellets, bails	extruded			2.41	Molded rubber
Rubber	Pellets, bails	unknown			0.73	Molded rubber
Rubber	Pellets, bails	injection molded			0.71	Injection molded PVC
Thermoplastic elastomer	Pellets, bails	injection molded			0.02	Injection molded PVC
				6.9		
Metals						
Aluminum	ingots	shape cast			0.4	Al shape casting
Aluminum	ingots	shape cast	machined		4.3	Al shape casting
Aluminum	billets	extruded			1.4	Al extruding
Aluminum	billets	extruded	machined		0.05	Al extruding
Aluminum	rolled sheet	stamped			0.2	Steel stamping
Aluminum	rolled sheet	stamped			0.02	Steel stamping
				6.4		

Table A-1 (Cont.)

Material	Typical Feedstock Form	Primary Transformation	Significant Secondary Process	Material % on Car	% of Curb Wt	Modeled as
Copper	billets				0.01	?
Copper	billets	extruded			1.14	Cu wire production
Brass					0.47	Secondary non-Fe processing
Brass	ingot	shape cast			0.08	Secondary non-Fe processing
Brass	rolled sheet	stamped			0.003	Steel stamping
				1.7		
Iron	ingots, scrap	shape cast	heat treated		0.36	Fe shape cast
Iron	ingots, scrap	shape cast	machined		8.23	Fe shape cast
Iron	billets	forged	machined		1.48	Fe forged
				10.1		
Steel (cold rolled)	Flat, bar, rod	cold formed			0.59	Steel stamping
Steel (cold rolled)	Flat, bar, rod	cold formed	machined		0.02	Steel stamping
Steel (cold rolled)	Flat, bar, rod	cold formed	machined		0.05	Steel stamping
Steel (EAF)	Flat, bar, rod	cold formed			0.31	Steel stamping
Steel (EAF)	Flat, bar, rod	cold formed	machined		0.16	Steel stamping
Steel (galvanized)	Flat, bar, rod	cold formed			0.51	Steel stamping
Steel (stainless)	Flat, bar, rod	cold formed			0.001	Steel stamping
Steel (hot rolled)	Flat, bar, rod	cold formed			0.57	Steel stamping
Steel (cold rolled)	rolled sheet	stamped			2.83	Steel stamping
Steel (cold rolled)	rolled sheet	stamped	machined		2.1	Steel stamping
Steel (galvanized)	rolled sheet	stamped			22.75	Steel stamping
Steel (galvanized)	rolled sheet	stamped	machined		0.04	Steel stamping
Steel (hot rolled)	rolled sheet	stamped			6.23	Steel stamping
Steel (hot rolled)	rolled sheet	stamped			0.35	Steel stamping
Steel (stainless)	rolled sheet				0.02	Steel stamping
Steel (stainless)	rolled sheet	stamped			1.21	Steel stamping
Steel (cold rolled)	Flat, bar, rod		machined		1.79	Machined
Steel (cold rolled)	Flat, bar, rod		machined		0.08	Machined
Steel (EAF)	Flat, bar, rod		machined		11.99	Machined
Steel (EAF)	Flat, bar, rod		machined		0.09	Machined
Steel (EAF)	Flat, bar, rod		machined		0.01	Machined
Steel (hot rolled)	billets	forged			0.64	Iron and steel forging
Steel (hot rolled)	billets	forged	machined		0.04	Iron and steel forging
Steel (hot rolled)	billets	forged	welded		0.4	Iron and steel forging

Table A-1 (Cont.)

Material	Typical Feedstock Form	Primary Transformation	Significant Secondary Process	Material % on Car	% of Curb Wt	Modeled as
Steel (EAF)	billets	forged	machined		1.22	Iron and steel forging
Steel (EAF)	ingot, scrap	shape cast	machined		0.17	Iron casting
Steel (cold rolled)	sheet				0.01	?
				54.2		
Lead	ingots, scrap	shape cast			0.79	Secondary lead production
Lead	ingots, scrap	shape cast			0.06	Secondary lead production
Tin		coated			0.004	?
Tin		extruded			0	?
				0.8		
Other						
Glass	sand, cullet, etc.	Float glass			2.76	Float glass
	Total material/transformations accounted for				92.7	
Fiberglass		extruded			0.03	
Fiberglass		pressed			0.22	
Recycled textile fibers		compressed			0.78	?
Carpeting					0.7	?
Carpeting		compressed			0.03	?
Transmission fluid	Petroleum prod.				0.44	
Engine oil	Petroleum prod.				0.23	
Ethylene glycol	Petroleum prod.				0.28	
Glycol ether	Petroleum prod.				0.07	
Refrigerant (R 134a)	Petroleum prod.				0.06	
Sulfuric acid					0.14	
Unleaded gasoline	Petroleum prod.				3.15	
Water					0.59	
	Total percentage of vehicle mass included				99.4	

TABLE A-2 Speciated Purchased Energy for Part and Vehicle Production Processes

Resource	Coal (kg)	NG (m^3)	Propane (L)	Gas Oil (L)	Fuel Oil (L)	LPG (L)	Diesel (L)	Gasoline (L)	Process Oil (L)	Electricity (kWh)
					Per kg of Output					
Process										
stamping	0.000	0.035	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.292
Shape casting										
Aluminum	0	0.705	0	0	0	0	0	0	0	2.235
Iron	0.320	0.273	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.377
Lead from scrap	0.000	0.215	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Copper wire	0.001	0.000	0.000	0.000	0.025	0.000	0.000	0.000	0.000	0.524
Brass from scrap	0.000	0.099	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.301
Forgings	0.000	1.036	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.377
Flat glass	0.000	0.337	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.243
Machining	0	0	0	0	0	0	0	0	0	0.1745
					Per Vehicle					
Painting	0	66.3	0	0	0	0	0	0	0	134
HVAC & lighting	0	0	0	0	0	0	0	0	0	290
Heating	0	85.9	0	0	0	0	0	0	0	0
Material handling	0	0	0	0	0	0	0	0	0	60
Welding	0	0	0	0	0	0	0	0	0	80
					Per kg of Output					
Moldings										
Rubber	0.000	0.135	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.657
Thermosets	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.417
Injection mold										
PP	0.000	0.022	0.001	0.000	0.008	0.000	0.000	0.025	0.000	2.096
PVC	0.000	0.000	0.021	0.000	0.008	0.012	0.001	0.000	0.170	1.375
Blow mold										
HDPE	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	1.709
Calendaring										
PVC sheet	0.000	0.004	0.000	0.000	0.000	0.000	0.005	0.000	0.001	0.506
Extrusion										
HDPE pipe	0.000	0.001	0.000	0.000	0.016	0.000	0.001	0.000	0.000	0.540

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