Proceedings of the ASME 2011 5th International Conference on Energy Sustainability
ES2011
August 7-10, 2011, Washington, DC, USA

ES2011-54957

Developments in Light Vehicle Life Cycle Analysis with Application to Electric Vehicles

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ABSTRACT

An LCA tool first reported on at the ASME ES conference in 2007 has been expanded and improved as follows:

- More than 400 production vehicles from all over the world are now in the data base
- Conventional and renewable liquid and gas fuels are included
- Electric vehicles (EVs) and plug in hybrid electric vehicles (PHEVs) are included along with hybrid electric vehicles (HEVs) and conventional internal combustion engine vehicles
- The tool is now web-based

The LCA tool includes both fuel and vehicle life cycle coefficients in its data base.

To illustrate the LCA ranking of vehicles using electricity (EVs, PHEVs, and HEVs) vs. conventional vehicles this paper will report on greenhouse gas emissions, total life cycle energy use along with NO_x, SO_x and mercury emissions. It will be shown, for example, that EVs are not the cleanest solution contrary to claims of various commentators in the popular press and of EV enthusiasts who do not take the entire life cycle into account.

INTRODUCTION

With the current level of interest in the "greening" of technology, many companies are developing products and ad campaigns meant to highlight the environmental friendliness of their products. Unfortunately, along with this mindset comes the potential for misrepresentation of the true burdens. The life cycle analysis of a product must take into full account all materials and their production characteristics. For fairness of comparisons, the results of such studies should report both emissions and energy use from the full range of activities involved with the product from cradle to grave.

The range of activities includes many different stages. At a minimum the following should be considered:

- acquisition or harvesting of raw materials,
- refining of the raw materials into workable elements,
- combination and assembly of these elements into the product,
- actual consumer use of the product, including maintenance and repairs, and

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- disposal and recycling of the product at the end of its useful life

Clearly, most consumers are unable to understand the nuances of each of these stages, and are not in a position to render such analyses on their own.

The authors have developed a simplified tool that allows the rapid calculation of the environmental impacts for one of the largest consumer purchases made on a regular basis: the automobile. We recognize that a true, full life cycling accounting can be quite data intensive; indeed, the authors have participated in such research over the last decade [Curtiss & Kreider 2009a, Curtiss & Kreider 2009b, Curtiss & Kreider 2009c, and Kreider & Curtiss 2007]. The goal of this current work is not so much to provide an exact account but rather a tool to allow different vehicles to be evaluated on an equal footing. We have developed a database of hundreds of current- and recent-year vehicle models and the algorithms necessary to give rapidly and accurately estimate the emissions and energy consumption of the vehicle over its lifetime.

IMPLEMENTATION

The new version of the vehicle evaluation tool is based on a combination of Java^{tm} code and GoogleApps^{tm} databases. The motivation for using GoogleApps is to allow for easy update of the databases and assumptions by personnel who are not necessarily fluent in web applications.

The on-line databases are broken out into assumptions, emission values, electricity mixes by state, and over 400 automobiles including those fueled by gasoline, diesel fuel, biodiesel, ethanol, natural gas, electric, and hybrid engines (stand-alone and plug-ins).

<u>Changes from previous versions</u>

The previous version of the LCA tool required that the user select three locations: one for the acquisition of raw materials, one for the vehicle assembly location, and one for the vehicle use location. These locations were selected from a list of all the states or as a US-TOTAL (i.e., a US average). The material acquisition location box has been removed; there is really no one single location for the acquisition of materials and indeed this would be represented better by a national average. The selection combo box has been removed and the code has been hard-wired to use the national average electricity emissions when calculating the overall emissions from material acquisition. This new version of the input screen is shown in Table 1.

Assembly and use locations are required inputs to properly assess the electricity production (and associated emissions) for both the fabrication of the vehicle as well as the use of any plug-in hybrids or pure battery electrics.

Table 1 New LCATool main input screen

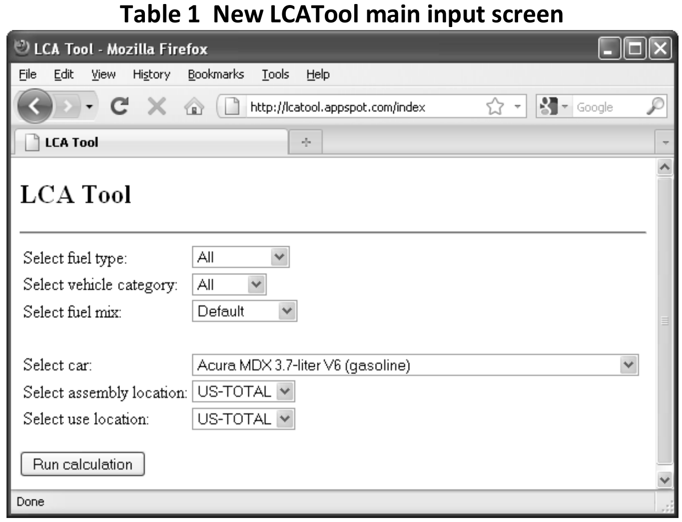

Table 2 shows the format of the new output screen.

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Table 2 New LCA Tool main output screen

LCA Tool Results

Vehicle:	Acura MDX 3.7-liter V6	**Use location:**	US-TOTAL
Type:	gasoline SUV	**Assembly location:**	US-TOTAL
Mileage:	11 city, 23 highway		

	Lifetime emissions (lbs)				Lifetime energy	
	CO2eq	SOx	NOx	Hg	MMBTU	% total
Material production	18248	72	32	0.00034	114	9
Vehicle assembly	8831	35	16	0.00016	22	2
Fuel production / transport	50244	41	47	0.00016	161	12
Vehicle operation	167717	16	155	0.00051	982	74
Vehicle maintenance	6781	27	12	0.00013	17	1
Vehicle disposal	11982	48	21	0.00022	30	2
Totals	260000	240	280	0.00153	1300	100

Changes have also been made to the code and databases. To understand these changes, we need to first look at some of the calculations that were in use.

<u>Reassessment of vehicle miles and use emissions</u>
The vehicle lifetime miles referenced by the LCA tool have been updated to reflect changes identified in recent work by the NHTSA [NHTSA 2008]. The numbers now used are

- 152,274 lifetime miles for cars and
- 178,824 lifetime miles for pickups and SUVs.

The addition of two new fuel classes to the LCA Tool input screen are to allow for users to select between the default values, fuels with lower carbon burdens, and fuels with higher carbon burdens. The default values are represented by the upstream and driving cycle emission values that are currently used in the tool.

Low carbon emissions are based on the idea of eventual legislation that would enforce cap and trade limits, implement carbon taxes, or mandate low carbon fuel sources. However, it is uncertain what actual reductions could be achieved when producing fuels. There is much speculation based on other life cycle analyses that the biofuels made from crops and crop residue could actually increase atmospheric carbon and that cap and trade would simply raise the prices of fuels without actually limiting the amount of carbon released.

For the purposes of the LCA Tool, the low carbon emission fuels will be assumed to apply only to upstream activities, since it is not feasible to reduce the amount of carbon emitted at the tailpipe for a given fuel. Rather, the low carbon emissions will be applied only for the upstream activities and will represent a 10 percent reduction of carbon emissions for both carbon dioxide and methane.

Similarly, the high carbon emission fuels – such as those derived from oil shales and tar sands – would see the increase of emissions in the upstream activities. Furthermore, these activities would be limited to the conventional liquid fuels produced by the bitumen-based source: gasoline and diesel. For the "high carbon" scenario the carbon dioxide and methane emissions are doubled for these two fuels.

<u>Reassessment of material acquisition energy</u>
Additional verification was performed on the energy required for the acquisition and refining of raw materials. Table 3 shows the values of energy requirements for extracting and producing raw materials currently used in the original LCA tool.

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Table 3 Raw material extraction / production energy consumption

Material	MJ / kg
Aluminum (recycled)	52
Aluminum (virgin)	231
Copper (recycled)	50
Copper (virgin)	125
Fluids	50
Glass (float)	13
Glass (recycled)	7
Glass (textile)	13
Glass (virgin)	13
Iron (recycled)	37
Iron (virgin)	37
Lead (recycled)	13
Lead (virgin)	25
Magnesium (recycled)	19
Magnesium (virgin)	63
Nickel (recycled)	50
Nickel (virgin)	100
Other	50
Plastics (misc)	68
Plastics (recycled)	45
Plastics (virgin)	90
Rubber (recycled)	12
Rubber (synthetic)	26
Rubber (virgin)	40
Steel (recycled)	52
Steel (virgin)	65

It is worth noting that many of the values in Table 3 were derived from a study performed at Argonne National Laboratory [Stodolsky 1995]. Additional research shows, however, that these numbers may be subject to revision. A recent study using GREET – also a product of Argonne National Laboratory – claims that "Each kilogram of primary aluminum ingot requires 160 megajoules (MJ) of energy to produce, a value that is about seven times that of steel, five times that of cast iron, and 2.5 times that of an average plastic" [Cheah 2009]. This implies that the aluminum value used in the current LCA tool should be corrected by a factor of about 0.7, while for steel, iron, and plastic the correction values are 0.4, 0.9, and 0.7.

But even here we must be careful. The International Aluminum Institute studies offer a glimpse into the uncertainty of any number involving aluminum production. They cite the values in Table 4 for the energy required to produce a kilogram of aluminum using the Bayer Hall Héroult route. Here we see variations amounting to differences of effectively over 100 percent between the various estimates. The report also shows global energy averages for the primary production of aluminum of 0.75 MJ/kg for mining, 30 MJ/kg for refining, and 124 MJ/kg for the anode and smelting processes, for a total of 155 MJ/kg, very close to the 160 MJ/kg cited in the ANL paper. We point out these details regarding aluminum to illustrate the uncertainties that even today plague LCA's.

Table 4 Energy consumption estimates for the production of aluminum

[Aluminium International Today 2010]

Source	MJ/kg Al	Notes
Norgate	211	Coal (35%)
Norgate	150	Gas (54%)
Norgate	120	Hydro (89%)
Cambridge	260	Coal (35%)
Aus Alu Council	182-212	Coal (35%)
Grant	207	Coal (35%)
Choate and Green	133	US average

At this point, we rely on the existing values for material acquisition energy. These can be easily updated as additional information is found. It is worth noting that the overall material acquisition energy is typically less than ten percent of the total vehicle lifetime energy, so even relatively large differences in the acquisition energy result in relatively small changes to the total vehicle life cycle energy consumption and emissions.

<u>Reassessment of vehicle assembly energy</u>

The current LCA tool uses an assembly energy factor of 4800 BTU per pound. This number has been in the database since the very first version of the tool. Research was initiated to assess this number to see if it is still accurate based on more recent studies.

Within the past two years, LBL, under work sponsored by the US EPA, issued a document discussing

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energy conservation in vehicle manufacturing and determined that

> *… the average specific electricity consumption per car has decreased from almost 1000 kWh/car in 1987 to 860 kWh/car in 1995. Although there are large variations between individual plants, this figure compares well to the 1998 average electricity use of Daimler Chrysler in 1999, estimated at 840 kWh/car… On a final energy basis, fuels represent 72% of the energy use, while on a primary energy basis fuels represent 45% of total energy use. In 1994, the specific fuel consumption is estimated at 6.5 MMBtu/car, while the primary specific energy consumption is estimated at 14.3 MMBtu/car, demonstrating the importance of electricity use in the fuel mix. [Galitsky & Worrell, 2008]*

Here the "final energy" is the energy purchased by the plant. Primary energy is calculated using the average efficiency (32%) for U.S. public power generation to estimate the fuels used to generate the power consumed by the automotive industry. The breakdown of their values for energy consumption per vehicle assembled is shown in Table 5.

Using the original LCA Tool value of 4800 BTU per pound, a 3000 pound car would require 14.4 MMBTU for assembly, or approximately 4200 kWh. Note that the 14.4 MMBTU assembly energy is essentially the same value as the 14.3 MMBTU primary specific energy requirement cited in the EPA study.

Similar to the material acquisition energy, we will preserve the current value used for vehicle assembly energy in the LCA Tool. The overall assembly energy is much smaller than even the material acquisition energy, so variations in this value are quite small compared to the overall lifetime vehicle energy consumption.

Table 5 Breakdown of electrical energy required per vehicle

End-Use	Share of electricity use (%)	Estimated typical electricity consumption (1995) (kWh/car)	Avg use in this study (kWh/car)
HVAC	11-20%	95-170	160
Paint systems (e.g. fans)	27-50%	230-320	260
Lighting	15-16%	130-140	130
Compressed air	9-14%	80-120	120
Materials handling/tools	7-8%	60-70	60
Metal forming	2-9%	20-80	30
Welding	9-11%	80-95	80
Miscellaneous	4-5%	35-45	20
Total	100%	730-1040	860

<u>Reassessment of vehicle database</u>

When the LCA Tool was first developed, little was known about the performance effects of different battery types and the nuances of electric vehicles (EVs) versus plug-in hybrid vehicles (PHEVs).

Table 6 shows typical battery state-of-charge (SoC) conditions for different types of electric vehicles. In this diagram, we see that hybrid electric vehicles like those on the road today (e.g., the Toyota Prius) maintain at least a 30 percent SoC at all times and rarely go above about a 70 percent SoC. Only a narrow range of the battery is normally used in charge sustaining (CS) mode and that about 40 percent of the mid range of the battery charge is used the rest of the time.

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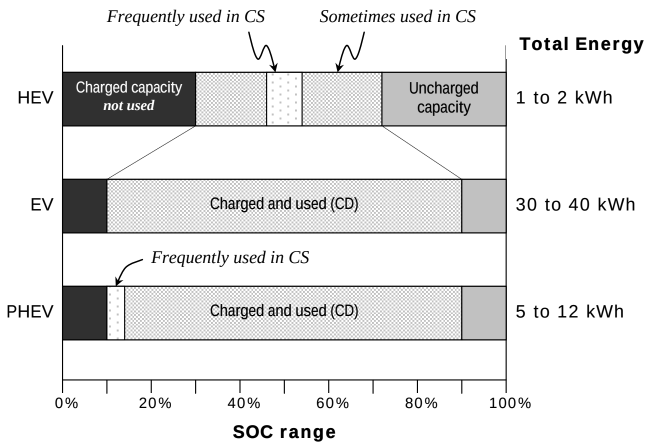
Table 6 Battery state-of-charge operating conditions for different types of electric vehicles

(*adapted from draft version of "A Sensitivity Study of Different PHEV Battery Electric Ranges: Implications for Battery Cycling, Battery Life, and Petroleum Fuel Use over the Vehicle Lifetime" by R. Devault and D. Smith at ORNL*)



Compare this to the pure electric vehicles and plug-in hybrids which use a considerably wider range of the available battery capacity in normal use, referred to as charge depleting (CD) mode. PHEVs and EVs allow for a far greater discharge of the battery to effectively substitute purchased electricity for gasoline.

The implication in this figure is, of course, the requirement for a large battery capacity in the HEVs even though less than half the capacity is ultimately used. This is important when considering the added weight of the batteries. NiMH battery packs have a specific energy of approximately 30 Wh/lb while li-ion batteries are about 45 to 70 Wh/lb. For example, the 2010 Prius has a curb weight of about 3000 lbs of which 100 lbs (3 percent) are 1.3 kWh of batteries. The Prius uses NiMH batteries, however, and are subject to narrower SoC limitations. It is entirely likely that the weight would be less in the case of a Li-ion battery used for the same purpose. For example, researchers at Argonne National Laboratory have recently performed experiments with actual vehicles using a 41-Ah Li-ion battery designed for PHEV applications. In these tests the vehicle all electric range was evaluated along with the temperature rise and battery performance in the CS mode at low states of charge (in the range of 20 to 35 percent). The results showed that CS operation at low SoC for an urban driving cycle had no effect on the fuel economy, indicating that the lower limits set for SoC is a "life" decision (greater SOC swing is generally associated with reduced battery life for NiMH batteries whereas the life of Li-ion batteries is more related to lifetime electricity throughput), not a "performance" decision. [Shidore, 2007].

It should also be pointed out that, although the ORNL report shows a charge range of 5 to 12 kWh for the PHEV, another recent study by the National Academy of Science claims that PHEVs will need to have storage capacities between 4 and 24 kWh to accommodate different all-electric ranges. [NAS 2010]

Another problem, not yet resolved, arises when trying to determine the overall fuel "efficiency" of electric vehicles and to derive metrics that are directly comparable to vehicles that use only liquid fuels. For the latter (including HEVs), the mileage numbers come from EPA dynamometer tests that follow a strict set of conditions to mimic city and highway cycles. The EPA has yet to determine, however, how to apply these tests to PHEVs. For pure electrics, however, there does appear to be a standard:

> *For all-electrics, the CAFE calculation begins with a gasoline-equivalent energy content factor in electrical terms: 12,307.3 Wh/gal, which equals approximately 41,994.3 Btu. The 12,307.3 Wh/gal figure is based on multiplying factors developed for fossil-fuel electricity efficiency (0.328) and electricity transmission efficiency (0.924), as well as the energy content of a gallon of gasoline (33,705 Wh/gal, or approximately 115,006 Btu). The result is divided by a factor for petroleum refining and distribution efficiency (0.830)…The electric vehicle is dynamometer-tested on the city and highway cycles,*

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producing electric power consumption numbers in Wh/mi. The numbers then are weighted 55% urban and 45% highway for an average. [SAE 2010a]

SAE International developed a testing standard (SAE J1711) for hybrid electric vehicles, including plug-ins. [SAE 2010b] However, the standard is already challenged and researchers from NREL have developed corrections to some of the techniques identified in this standard [Gonder & Simpson 2006]. The NREL researchers make a number of suggestions on how to change SAE J1711 including reporting the electricity use separately from the gasoline usage, improving the determination of the CD operating distance for the utility factor weighting, and changing the charging frequency assumption. In the first suggestion, the NREL researchers request that the tests

present a fuel economy and electricity consumption rating for the vehicle (such as providing a watt- hour-per-mile (Wh/mi) value in addition to the mile per gallon number). When combined with a distance driven over a period of time (that is representative of the typical daily distance distribution), these two numbers would provide an estimate of the volume of fuel used and the electrical charging energy that went into the vehicle over that operating period.

In summary, it would appear that there is still notable discrepancy on how to calculate the fuel efficiency of PHEVs.

Table 7 gives the EPA summary of for future electric vehicles although they did not publish equivalent gasoline mileage numbers. What is notable about this table is that all electric vehicles listed use lithium-ion batteries. The treatment of existing electric and plug-in vehicles in the existing LCA tool is based around NiMH batteries. This is the case with both the raw material energy as well as the vehicle weight.

Table 7 New and upcoming electric vehicles
Taken from http://www.fueleconomy.gov/feg/evnews.shtml

Vehicle	Seat	Top speed (mph)	Range (miles)	Battery	Availability
Tesla Roadster	2	125	245	Li-Ion	Currently available in U.S.
Nissan Leaf	5	90	100	Li-Ion	Limited production 2010; mass production 2012
Mitsubishi MiEV	4	82	70-100	Li-Ion	2009 in Japan; available in U.S. by 2011
CODA	n/a	80	90-130	Li-Ion	California by late 2010; other U.S. states by 2012
Ford Focus EV	4	85	100	Li-Ion	Currently in small test fleets in US & UK; on sale in N. America by 2011
smart fortwo EV	2	65	82	Li-Ion	250-vehicle U.S. pilot program in 2010; full-scale production by 2012.
Tesla Model S	7	120	160-300	Li-Ion	2012 in U.S.
Toyota RAV4 EV	n/a	n/a	n/a	n/a	2012 in U.S.
Volkswagen E-Up!	3+1	84	60-80	Li-Ion	Limited U.S. production by 2013; mass production by 2020

According to the NAS report, the Leaf has a storage capacity of 24 kWh. This is lower than the range suggested by Table 6 but also may be limited due to the relatively low range of this vehicle.

Both Mini Cooper and Audi are also looking at producing pure electric vehicles. The MiniE from Mini has a li-ion battery capacity of 35 kWh and a rated consumption of 0.22 kWh / mile. The charging time is rated at 3 hrs when charged from a 240 V circuit rated at 48 amps, or 4.5 hours at 240 V and 32 amps. The charging time increases to 26.5 hours when charged at 110 V at 12 amps. This vehicle is currently in field trials is rated at 150 kW (200 HP), weighs 3230 lbs, has a top speed of 95 mph and a range of 156 miles.

The Audi e-tron has four motors – one at each wheel – and can produce 313 HP. It uses a Li-ion liquid-cooled battery pack rated at 53 kWh with a usable portion of 42.4 kWh (80 percent of the full capacity) and has a range of 155 miles. The top speed is reported as 125 mph. They claim a charging time of 6 to 8 hours at 230 volts and 16 amps.

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The GM Volt uses a 16-kWh battery to meet the claimed all-electric range of 40 miles. Using a Li-ion battery, the Volt is designed to use only 8 kWh by operating from 80 percent to 30 percent SOC [NAS 2010]

In any case, it seems likely that the LCA Tool will soon need modifications to accommodate new battery chemistries. According to the NAS report, NiMH batteries are restricted to a 20 percent SoC range to preserve battery life and these batteries exhibit a high rate of self-discharge. The most advanced NiMH technology is in the Toyota Prius which uses 100 pounds of batteries with an energy capacity of 1.31 kWh – but only about a third of a kWh is available due to the SoC range restriction.

RESULTS

The new LCA Tool provides a very rapid estimate of the lifetime emissions of vehicles. The table below gives the estimated emissions and lifetime energy consumption for a large gasoline SUV with a 5.3 liter V8 engine rated at 10 / 21 MPG for city / highway mileage.

Table 8 Example LCA calculation for large, gasoline SUV

	Lifetime emissions (lbs)				Lifetime energy	
	CO2eq	SOx	NOx	Hg	MMBTU	% total
Material production	23570	93	42	0.00044	147	7
Vehicle assembly	11406	45	20	0.00021	28	1
Fuel production / transport	80421	66	75	0.00026	257	12
Vehicle operation - fuel	268448	26	247	0.00082	1572	76
Vehicle maintenance	12430	50	22	0.00023	31	2
Vehicle disposal	15476	62	28	0.00029	39	2
Totals	**410000**	**340**	**430**	**0.00230**	**2100**	**100**

The following table shows the results for a plug-in hybrid rated at 30 electric mile range and 3.0 liter, six cylinder engine rated at 24 / 37 MPG city / highway gasoline mileage. Note that in this case the values for the vehicle operation are spread across two different sources: liquid fuel and electricity. This split allows the user to determine the relative emissions depending on the state where the vehicle is operated. In the table shown below the vehicle is assumed to be used in California.

Table 9 Example LCA calculation for example plug in gasoline hybrid

	Lifetime emissions (lbs)				Lifetime energy	
	CO2eq	SOx	NOx	Hg	MMBTU	% total
Material production	15247	60	27	0.00028	95	19
Vehicle assembly	7111	28	13	0.00013	18	3
Fuel production / transport	12567	16	13	0.00008	22	4
Vehicle operation - fuel	23460	2	22	0.00007	137	27
Vehicle operation - electricity	55384	104	62	0.00059	199	39
Vehicle maintenance	6807	27	12	0.00013	17	3
Vehicle disposal	6764	13	8	0.00007	25	5
Totals	**130000**	**250**	**160**	**0.00140**	**510**	**100**

The bottom lines in these tables show values rounded to the appropriate significant figures and provide an easy way to compare different vehicles. These can be used to compare the environmental burdens imposed by different car fuels. The following table shows the relative effects of different types of fuels when used in vehicles with very similar body styles.

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Table 10 Comparison of Five Vehicle Classes

	Effective mileage			Emissions / Energy				
Category	***City***	***Hwy***	***Comb***	***CO2 eq.***	***SOx***	***NOx***	***Hg***	***MMBTU***
IC Engine	17	36	26	250000	180	260	0.0012	1278
IC Engine	23	39	30	210000	160	210	0.0011	1056
HEV	33	34	33	190000	180	200	0.0011	944
PHEV-20	35	51	42	130000	200	150	0.0011	611
EV-40	66	68	67	130000	330	170	0.0017	722
HEV with CNG	29	42	35	140000	150	140	0.0007	1000

CONCLUSIONS AND FUTURE WORK

The results in the previous table indicate that, while electric and plug in vehicles do indeed reduce carbon emissions, there are added sulfur and mercury burdens due to the use of grid electricity. It is worth noting that the PHEV-20 has the lowest energy footprint of all of these vehicles. Also notable is the natural gas hybrid that comes close to the carbon emissions of the electrics but at much reduced sulfur and NOx emissions. We do not include natural gas from fracked sources due to uncertain energy and emissions numbers.

The treatment of electric and plug-in electric vehicles in the current LCA tool is based mainly on NiMH battery chemistry. This is reflected in the material energy and material composition fraction allocation. To be better prepared for advances in the electric vehicle industry, it would make sense to include the vehicle battery type and mass for EVs, PHEVs, and HEVs. The implication here is that future versions of the LCA Tool must track and account for the battery type used in the vehicle. These changes will incorporate the type and capacity, which will in turn specify the minimum allowable state-of-charge and consequently the weight and composition. In turn, this will require changes and additions to the vehicle composition fraction tables and the algorithms that calculate raw material energy. Likewise, this will require an update of the raw materials table to include any necessary materials for different battery types.

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ANNEX A - ELECTRICAL VEHICLE COSTS

(*note added in proof*)

The question has been raised regarding the cost effectiveness of battery electric vehicles (BEV) by a reviewer. Although this was not within the scope of the original paper, we can offer some insights regarding capital costs for charging vehicles. Standard references provide the higher costs of the vehicle themselves. The third component of BEV cost is the societal, external cost of EVs. This is the subject of a paper in progress and uses as its input the LCA results for air pollutants given above.

Regarding the capital costs for vehicle charging we note that there is significant difference between residential charging (slow and often at 110 VAC) and commercial charging in parking garages and parking lots (faster and often at 240 VAC, so-called "Level 2" charging). Residential costs are expected to be under $2000[1] but commercial costs are significantly higher[2] because of often ignored expensive infrastructure retrofits in existing buildings.

In the 2011 study 25%, 50% and 75% of the parking spaces in an existing parking structure in downtown Boulder, CO were equipped with Level 2 Electric Vehicle Supply Equipment (EVSE). The construction documents for this work conformed to the US National Electrical Code 2011 in every respect. The plans and specs so generated were supplied to three large electrical firms in Denver, CO who submitted formal bids to do the retrofit installation.

The three sets of bids agreed within 10% and indicated an average cost per EVSE of $12,400. There were no economies of scale for the 25%, 50% and 75% cases. This prohibitively high cost results from electrical service upgrades (garages usually have light electrical loads only for lighting and plug loads), electrical equipment upgrades (panels and feeders), and hardscape work (core drilling, trenching, concrete repouring). One can imagine lower costs for new construction but no credible studies have been presented as of May 15, 2011. Many of the initial EVSE installations will necessarily be in existing buildings.

[1] Idaho National Laboratory, US Department of Energy Report INL/EXT-08-15058, 2008.

[2] Clanton and Associates, "Commercial Electric Vehicle Charging Station Study" prepared for Kreider and Associates, March 2011.

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