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Additional project information is available at www.sustainable-transportation.com.

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Abstract

Vehicle manufacturing effects are critical life-cycle components in the total costs of vehicle travel and future manufacturing processes should be evaluated for travel forecasts. With efforts to introduce lightweight materials, increased fuel economy, and new technologies such as electric vehicles, understanding the energy and environmental effects of these expected vehicles is critical. Current vehicle manufacturing energy use and greenhouse gas emissions are summarized from existing research for passenger (conventional gasoline vehicles, hybrid electric vehicles, aircraft, high-speed rail) and freight (trucks, trains, and ocean going vessels) modes. Future vehicle manufacturing effects are then determined incorporating the aforementioned modes as well as plug-in hybrid and battery electric vehicles.

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This white paper is intended to serve as background supporting information for an upcoming peer-reviewed journal publication on U.S. long-distance transportation futures. The methodology and results presented in this manuscript are subject to future updates during the peer-review process as we incorporate feedback. Before using the results in this white paper, we encourage the reader to visit our project website (🗗) for a listing of our latest publications and updated results.

1 Background

Some vehicle manufacturing direct and indirect processes have been shown to be significant energy and emissions contributors in the life-cycle footprint of transportation modes [Chester and Horvath 2010, Chester and Horvath 2009, Facanha and Horvath ES&T 2006, Facanha and Horvath IJLCA 2006, Chester and Horvath 2009]. For passenger transportation today, vehicle manufacturing accounts for 5-9% of the life-cycle energy and greenhouse gas (GHG) footprint of automobiles, 1-7% of rail modes, and 2-7% of air modes [Chester and Horvath 2009]. For other air emissions (specifically SO_2 and CO) the vehicle manufacturing life-cycle component can account for up to 29% of the life-cycle footprint showing the effects of supply chain energy use that may be less stringently regulated than the vehicle's direct fuel combustion [Chester and Horvath 2009]. Life-cycle inventorying of freight transportation reveals similar effects [Facanha and Horvath ES&T 2006, Facanha and Horvath IJLCA 2006].

Future travel life-cycle assessment (LCA) should consider changes in vehicle manufacturing processes, requirements (e.g., vehicle size, weight, and materials), and energy use that may transpire in the long-term. Some factors in future vehicle manufacturing may evolve independently of this life-cycle component. For example, a future electricity mix will affect the emissions profile of vehicle manufacturing processes but independently from this sector.

There is a dearth of vehicle manufacturing data constraining our ability to perform in-depth analyses across the myriad of energy and environmental questions that we would ultimately like to answer. However, a few exceptional resources exist that provide a basis for estimates. The results in this manuscript are based on analyses from GREET 2.7a (2007), Ecoinvent (2010), EIOLCA (2011), and SimaPro (2006) data. These tools and data are established in the LCA community and have been reviewed extensively by practitioners. While GREET 2.7a (2007), EIOLCA (2011), and SimaPro (2006) allow practitioners to specify and perform LCAs, it is important to recognize that their approaches and system boundaries are not necessarily consistent. These authors have reviewed these tools and data for this work and existing studies, and found that when commensurate system boundaries and energy profiles are established, the aforementioned sources produce fairly consistent results.

We present preliminary results for passenger and freight vehicle manufacturing energy use and GHG emissions of future transportation modes. These results can assist energy, sustainability, and climate policy makers and analysts in evaluating future scenarios for U.S. transportation systems.

2 Methodology

The vehicle manufacturing LCA establishes a consistent methodology for evaluating current and future automobiles, midsize aircraft, high-speed rail, freight trucks, and freight trains. The approaches detailed in the following subsections build upon those used by existing LCAs of passenger (specifically Chester and Horvath 2010 and Chester and Horvath 2009) and freight transportation (specifically Facanha and Horvath ES&T 2006 and Facanha and Horvath IJLCA 2006) by allowing for adjustment of critical factors to assess future lightweight and changing electricity mixes.

Energy use and GHGs are the focus of this white paper but the methodology is generalizable to other environmental indicators in life-cycle inventories and the authors plan to extend their results in future work. When reporting energy consumption of transportation modes, a challenge exists in responsibly conveying useful metrics. Energy can be reported as primary, secondary, or even end-use and can be further distinguished as fossil/non-fossil or even based on its physical interpretation (i.e., electrical, radiant, thermal, motion, sound, chemical, mechanical, nuclear, or gravitational). When comparing a gasoline-consuming car to an electricity-consuming train there are many characteristics that may be considered depending on the question being asked. For this white paper, we have chosen to report coal, natural gas, petroleum, and manufacturing electricity. GHGs are reported as CO_2, CH_4, and N_2O and normalized to CO_2-equivalence (CO_2e) using radiative forcing multipliers of 25 for CH_4 and 298 for N_2O for a 100 year horizon.

This report presents results for U.S. vehicles evaluated in current and future U.S. electricity mixes, resulting in U.S.-tailored data. The applicability and adaptation of results to non-U.S. travel is future work and not addressed here.

2.1 Electricity

Electricity is a common energy form in vehicle manufacturing for both direct and indirect (supply chain) processes, and its primary fuel mix is expected to change in the coming decades (Table 1) [EIA 2010]. Energy use and GHG emissions are established for relevant years from GREET 1.8d.1 (2010) and forecast to 2050 as the future year from extrapolations of expected U.S. primary fuel use reported by EIA (2010).

Table 1 – Electricity Mixes by Primary Fuels

Year	Oil	Natural Gas	Coal	Nuclear	Biomass	Others
1995	2.2%	14.8%	51.0%	20.1%	1.2%	10.7%
2010	1.0%	20.2%	46.7%	21.0%	0.3%	10.7%
2020	1.0%	15.6%	48.0%	20.6%	2.0%	12.7%
Future	0.6%	20.5%	41.5%	15.9%	2.0%	19.5%

Sources: years 1995, 2010, and 2020 are from GREET 1.8d.1 (2010);
future year mix is an extrapolation to 2050 of forecast's developed by EIA (2010) in Figure 73.

The percentage of primary fuels is then joined with electricity generation GHG emission factors reported by GREET 1.8d.1 (2010). These factors are shown in Table 2.

Table 2 – Electricity Generation GHG Emissions (grams/GJ)

GHG	Oil	Natural Gas	Coal	Nuclear	Biomass	Others
CO_2	251,752	152,416	327,694	-	-	1,166
CH_4	2.7	9.1	3.6	-	12.3	-
N_2O	1.1	3.6	3.2	-	35.3	-

Source: GREET 1.8d.1 (2010).

The electricity generation GHG emissions are ultimately used to adjust future vehicle direct and indirect electricity use effects with a customizable future mix. The future mix used assumes a business-as-usual electricity policy where renewables make small gains in the decades to come. However, the methodology presented here allows for the implementation of any forecasted future mix.

2.2 Automobiles

Conventional Gasoline Vehicle (CGV), Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), and Battery Electric Vehicle (BEV) manufacturing effects are determined with GREET 2.7a (2007). Modeling the CGV with GREET 2.7a (2007) instead of EIOLCA (2011) (the method used by Chester and Horvath 2010 and Chester and Horvath 2009) does not capture the supply chain but allows for materials-based changes in future work. HEVs are evaluated with both Ni-Mh and Li-ion batteries. GREET 2.7a (2007) allows for evaluation of both conventional and lightweight vehicles. A conventional CGV is specified as 3,330 lbs and lightweight 1,970 lbs, and a conventional HEV is specified as 2,810 lbs and lightweight 2,000 lbs (before batteries). The conventional weight vehicles are used for evaluating vehicles today and lightweight are used for evaluating future vehicles. GREET 2.7a (2007) evaluates three vehicle categories (ICEVs, HEVs, and FCVs) and HEVs serve as the foundation for PHEVs and BEVs with independent analysis performed for batteries.

Lead Acid, Ni-Mh, and Li-ion battery manufacturing is evaluated in GREET 2.7a (2007) for CGVs, HEVs, PHEVs, and the BEV with different configurations. For current vehicles, a CGV and HEV (with a Ni-Mh battery) are evaluated. For future vehicles, a CGV (with a lead acid battery), HEV with a Ni-Mh battery, HEV with a Li-ion battery, PHEV20 with a Li-ion battery, PHEV60 with a Li-ion battery, and BEV240 with a Li-ion battery are evaluated. A PHEV20 corresponds to a 20 kilometer all-electric range and a PHEV60 corresponds to a 60 kilometer all-electric range. The BEV240 corresponds to a 240 kilometer all electric range and is modeled with assumptions from Michalek et al. (2011). The PHEVs and BEV follow Michalek et al. (2011)'s study that evaluates Saft VL41M cells with a specific energy of 135 Wh/kg and material and process extrapolations for rated capacities of 4.6 kWh (PHEV20), 15.9 kWh (PHEV60), and 66.1 kWh (BEV240). The CGV conventional and lightweight vehicles carry 36 and 23 lbs of battery and require 2 replacements during the vehicle's life. A current HEV carries an 84 lb Ni-Mh battery and requires 1 replacement during the vehicle's life while a future HEV carries either a 51 lb Ni-Mh needing 1 replacement, or 21 lb Li-ion battery needing 2 replacements. GREET 2.7a (2007) allows for the evaluation of many battery performance factors and we defer to the model's baseline and time-series assumptions for many of these, which are discussed in additional detail in ANL (2010). GREET 2.7a (2007) evaluates battery manufacturing with current processes and future work will explore forecasting next generation technologies.

2.3 Midsize Aircraft

We define a midsize aircraft to have 130-seats similar to a Boeing 737 or Airbus 320 that captures the largest market share for mid-distance flights. This size aircraft has an average flight length of 1,300 km (840 mi) and is responsible for 60% of passenger-kilometers-traveled (PKT) on all U.S. domestic flights [Chester and Horvath 2009]. While it is important to consider other aircraft sizes (e.g., an Embraer 145 for short-haul and a Boeing 747 for long-haul, see Chester and Horvath 2009), here we focus on the midsize aircraft because of data availability for the updated methodology, and because the midsize aircraft plays a critical role in serving high-demand U.S. markets that are considering deployment of alternative long-distance modes such as high-speed rail. Chester and Horvath (2010) and Chester and Horvath (2009) developed current aircraft manufacturing estimates with EIOLCA (2011).

Current and future midsize aircraft are modeled from both EIOLCA (2011) and Ecoinvent (2010) data, and adjusted for electricity mixes, to develop multiple estimates of manufacturing emission profiles. Chester and Horvath (2010) and Chester and Horvath (2009)'s EIOLCA (2011) results capture the full U.S. supply chain for the manufacturing of an older generation Boeing 737 (i.e., the 400 to 600 series). Ecoinvent (2010) data reports aircraft manufacturing energy use and emissions for a 150-seat Airbus for direct manufacturing processes. While Ecoinvent (2010) data by itself does not capture supply chain processes, it is generally considered more accurate than EIOLCA (2011) for high-resolution processes because Ecoinvent data originates from primary data collection.

Current and future aircraft manufacturing energy use and emissions are determined from both EIOLCA (2011) and Ecoinvent (2010). A current aircraft is evaluated based on a Boeing 737-800 and future aircraft are evaluated as a Bombardier CS300-ER. Electricity emissions are adjusted to current and future mixes. This white paper does not present results for alternative materials (such as composites), a topic discussed in our Future Work section 4.

2.4 High-Speed Rail

Following the approach by Chester and Horvath (2010), high-speed rail (HSR) current and future vehicle manufacturing emissions are determined with SimaPro (2006) with appropriate electricity mixes. Chester and Horvath (2010) focused on California HSR and this report describes train manufacturing effects in 2010 and future U.S. mixes. Once again, the methodology described is generalizable so that current and future HSR considerations in any electricity mix for candidate corridors could be determined.

2.5 Freight Trucks and Trains

Building on the work of Facanha and Horvath ES&T (2006), energy use and emissions of freight trucks and trains are determined with EIOLCA (2011) and electricity emissions adjustments are applied for the desired current and future years.

Facanha and Horvath ES&T (2006) evaluated Class 8b trucks and we build upon their approach to also evaluate Class 6 and Class 5 trucks manufactured today and in the future. EIOLCA (2011)'s Heavy Duty Truck Manufacturing and Truck Trailer Manufacturing sectors match the direct process of interest and is therefore used instead of data from European sources such as Ecoinvent (2010).

Using EIOLCA (2011)'s Railroad Rolling Stock Manufacturing sector and Facanha and Horvath ES&T (2006)'s typical U.S. train with one locomotive and 70 railcars, current and future freight trains are determined.

Facanha and Horvath ES&T (2006) and Facanha and Horvath IJLCA (2006) provide in-depth assessment of energy use and emissions from freight modes and the results in this paper are intended to supplement their findings for assessment of future transport.

2.6 Freight Ocean Going Vessels

Ocean going vessels (OGV) are evaluated as either container or tanker using the Ship Building and Repairing sector in EIOLCA (2011), and similar to other vehicles, emissions are modified based on current and future electricity mixes. The cost of a container ship is roughly $\$_{1997}$59.9 million and a tanker $\$_{1997}$136 million [ACOE

2002]. OGVs are evaluated with bunker fuel engines and future ships will be evaluated with alternative fuel engines (e.g., natural gas), however, because the bulk of energy use and emissions are associated with non-engine component manufacturing it is not expected that results would change significantly.

3 Results

Results for energy use and GHG emissions for vehicle manufacturing in 2010 are shown in Table 3.

Table 3 – Results for Vehicle Manufacturing in 2010

Vehicle	CO_2 kg	CH_4 kg	N_2O kg	CO_2e kg	Coal GJ	Natural Gas GJ	Petroleum GJ
Passenger Modes							
CGV	7,600	13	88 (g)	7,900	38	41	21
HEV w/Ni-Mh Battery	8,000	13	95 (g)	8,300	40	41	21
Aircraft w/EIOLCA	16,000,000	72,000	970	18,000,000	57,000	100,000	66,000
Aircraft w/Ecoinvent	2,300,000	2,700	29	2,300,000	6,600	13,000	5,200
HSR	1,100,000	2,200	28	1,100,000	8,700	12,000	15,000
Freight Modes							
Truck Class 8b	54,000	5,300	1,100	500,000	160	370	110
Truck Class 6	32,000	3,200	630	300,000	95	220	66
Truck Class 5	30,000	2,900	580	270,000	87	200	61
Train	3,200,000	360,000	34,000	22,000,000	9,500	23,000	5,600
Container OGV	30,000,000	170,000	2,000	35,000,000	100,000	210,000	110,000
Tanker OGV	69,000,000	390,000	4,500	80,000,000	230,000	480,000	250,000

Notes: Aircraft based on a Boeing 737-800. All results rounded to two significant digits.
CO_2e may not match $CO_2 + 25 \times CH_4 + 298 \times N_2O$ due to rounding.

Midsize aircraft manufacturing is shown with results from two data sources: EIOLCA (2011) and Ecoinvent (2010). The energy use and emission results when using EIOLCA (2011) are roughly 7 to 33 times larger than when Ecoinvent (2010) data are used. This comparison is not commensurate as the system boundaries are different. Evaluation of midsize aircraft in EIOLCA (2011) captures the entire supply chain of the U.S. while Ecoinvent (2010) captures primarily direct manufacturing processes. When comparing only direct manufacturing GHG emissions, EIOLCA (2011) reports (before adjusting for electricity mixes) 1,060 Mg CO_2e per midsize aircraft compared to Ecoinvent (2010)'s 2,300 Mg CO_2e.

Results for energy use and GHG emissions for future vehicle manufacturing are shown in Table 4.

Table 4 – Results for Future Vehicle Manufacturing

Vehicle	CO_2 kg	CH_4 kg	N_2O kg	CO_2e kg	Coal GJ	Natural Gas GJ	Petroleum GJ
Passenger Modes							
CGV	7,200	12	87 (g)	7,600	28	38	31
HEV w/Ni-Mh Battery	7,900	13	96 (g)	8,300	32	41	32
HEV w/Li-ion Battery	7,400	13	89 (g)	7,800	28	39	31
PHEV20 w/Li-ion Battery	7,100	13	110 (g)	7,400	36	41	21
PHEV60 w/Li-ion Battery	8,400	17	170 (g)	8,900	53	49	22
BEV w/Li-ion Battery	17,000	33	370 (g)	18,000	130	86	39
Aircraft w/EIOLCA	14,000,000	72,000	1,000	17,000,000	42,000	110,000	65,000
Aircraft w/Ecoinvent	2,200,000	2,700	31	2,200,000	5,000	14,000	5,000
HSR	1,000,000	2,200	28	1,100,000	8,400	12,000	15,000
Freight Modes							
Truck Class 8b	51,000	5,300	1,100	500,000	130	370	110
Truck Class 6	31,000	3,200	630	300,000	79	220	65
Truck Class 5	28,000	2,900	580	270,000	73	200	59
Train	3,000,000	360,000	34,000	22,000,000	8,100	24,000	5,500
Container OGV	29,000,000	170,000	2,000	34,000,000	86,000	210,000	110,000
Tanker OGV	65,000,000	390,000	4,600	77,000,000	200,000	480,000	240,000

Notes: Aircraft based on a Bombardier CS300-ER. All results rounded to two significant digits.
CO_2e may not match $CO_2 + 25 \times CH_4 + 298 \times N_2O$ due to rounding.

The results in Table 4 capture weight changes for passenger modes and a 2050 forecast electricity mix for all modes, but not process improvements and materials, and should ultimately be normalized to an appropriate functional unit for the project goal. The per-vehicle results presented in Tables 3 and 4 do not capture the fundamental function of the passenger and freight modes. The goal of passenger modes is to provide PKTs and in an LCA manufacturing emissions should ultimately be apportioned to PKTs taking into account lifetime distance traveled and occupancy rates. Freight modes are generally considered as services for moving quantities of goods and are normalized per Mg-kms (or short ton-miles). A common functional unit allows for comparison internally and externally. LCA practitioners may be interested in comparing across life-cycle stages of a single mode (e.g., vehicle manufacturing, vehicle operation, infrastructure construction, fuel production) or across modes in consequential analysis to evaluate policies or decisions. Vehicle manufacturing results shown in Tables 3 and 4 do not provide a comprehensive picture for decision makers as they must ultimately be normalized and included with other life-cycle components.

4 Future Work

Several next steps have been identified for potential future work to improve the results. This working paper presents an effort to understand and evaluate the manufacturing requirements and effects of future vehicles. The methods that we use to evaluate future vehicle manufacturing are discussed and results are presented for energy use and GHG emissions. The following list discusses the next steps for this work identifying the expected highest-impact considerations:

1. The addition of conventional air emissions (carbon monoxide, sulfur dioxide, particulate matter, nitrogen oxides, and volatile organic compounds) is a necessary next step and work is underway by these researchers to develop the extended life-cycle inventories. Previous LCAs have shown that policies can exist that decrease the life-cycle energy consumption and GHG emissions of transportation modes while increasing conventional air emissions [Chester and Horvath 2010, Chester and Horvath 2009].
2. The focus of this research effort is future vehicles with light-weight materials in a conservative electricity mix, and future work will be focused on associated life-cycle process changes. Given the limited availability of vehicle manufacturing environmental data, we chose to evaluate the future vehicles in our first assessment pass with current manufacturing technologies. It is likely that manufacturing processes will change, particularly for next generation components (e.g., battery technology improvements for PHEVs is shown to be a critical life-cycle component by Michalek et al. 2011).
3. New materials are likely to enter the vehicle market, particularly for aircraft. The use of composites in aircraft structures requires an LCA by itself. This LCA will not be consistent with the one presented in this working paper which focuses on traditional aircraft structural materials.
4. With large-scale adoption of HEVs, PHEVs, or BEVs there are likely to be improvements in battery technology. As battery energy density improves, a given mass of battery will allow the vehicle to travel further on the same charge. The improvements in energy density will significantly reduce the life-cycle effects of HEVs, PHEVs, and BEVs [Michalek et al. 2011].
5. Engines are some of the most sophisticated components in vehicles typically accounting for a large share of total effects. Engine design varies by many parameters, the most critical being fuel input. The results in this working paper evaluate current engine design and this is not adaptable for alternative fuels. Future work will evaluate engine technologies by fuel for both current and future conditions.

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