LIFE CYCLE INVENTORY AND DATA FOR THE AUT

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Life Cycle Analysis (LCA) and Life Cycle Inventory (LCI) methods are used increasingly in the automotive industry to quantify the environmental impacts during vehicle manufacturing. Automotive coating processes are of particular interest as they contribute significantly to the environmental burden with emissions released to air, water, and land, along with the use of substantial amounts of energy and raw materials. Recently, the online NREL LCI Database was developed to characterize the environmental impacts of products and processes in the North American manufacturing sector, including automotive production. For automotive coatings, three unit processes represent the majority of environmental impacts: pretreatment, E-coat, and topcoat. The complexity of the automotive coating processes, however, poses a significant challenge for the practical application of LCI information. This article extends pretreatment LCI data previously presented at FutureCoat! 2007, with detailed LCI data for the E-coat and topcoat processes. Furthermore, an LCI data application protocol is proposed to allow LCI reference data to be used to estimate LCI results for a different manufacturing facility or scenario. The analysis examines several variables for their effect on extrapolating NREL reference data, including: coated surface area, paint process, production volume/cycle length, and vehicle type. For the coating process, the applicability of manufacturing LCI data is shown to depend primarily on coated surface area and production volume.

INTRODUCTION

The automotive manufacturing industry is one of the largest industrial sectors in North America, producing millions of vehicles annually for North American and international export markets. Efforts are currently being made to quantify and inventory the environmental impacts incurred during the various processes composing automobile manufacturing, including automotive paint and coating processes. Automotive paint and coating processes are of particular interest as they contribute significantly to the environmental burden with emissions released to air, water, and land, along with the use of substantial amounts of energy and raw materials.

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APPLICATION PROTOCOL

OMOTIVE

PAINT PROCESSES

Environmental impact data being collected for North American manufacturing facilities is being used to populate a public database of environmental impacts, known as the National Renewable Energy Laboratory (NREL) Life Cycle Inventory (LCI) Database, which will enable the use of Life Cycle Assessment (LCA) techniques for environmentally oriented decision making by both the private and public sector.[1]

However, the complexity of the contemporary automobile and the many different processes in its manufacture and assembly poses a significant set of challenges for completing a manufacturing LCI. Consequently, detailed and up-to-date LCI data does not exist for the majority of the manufacturing/assembly processes associated with the North American-based automotive industry, including the automotive coating processes. Previous studies of automotive coatings' environmental impacts have been comparative in nature (e.g., waterborne versus solvent paints,[2] powder coating[3]) and so discuss relative differences rather than focusing on absolute impact levels. As such, they have limited practical value for manufacturing and environmental decision-makers in other facilities or manufacturing scenarios.

For automotive coatings, three unit processes represent the majority of environmental impacts: pretreatment, E-coat, and topcoat. Detailed LCI data was recently published for the pretreatment processes by Prendi et al.[4]

This article extends the automotive coating LCI dataset, presenting detailed LCI data for the E-coat and topcoat processes. Furthermore, this article discusses some of the challenges of applying site-specific LCI data collected from one manufacturing facility (i.e., such as found in the NREL LCI Database) to other manufacturing facilities or scenarios, and investigates the effects of several key parameters on LCI estimates, including coated surface area, paint process, production volume/cycle length, and vehicle type. An LCI application protocol is accordingly developed and evaluated by scaling the NREL LCI materials data to another North American automobile manufacturing facility.

By providing both detailed LCI data and a practical LCI data application protocol, this article contributes valuable environmental impact information for an environmentally significant manufacturing process that is relevant to other LCI practitioners in automotive manufacturing and other industries (e.g., white goods manufacturing).

BACKGROUND

Life Cycle Inventory in the Automotive Industry

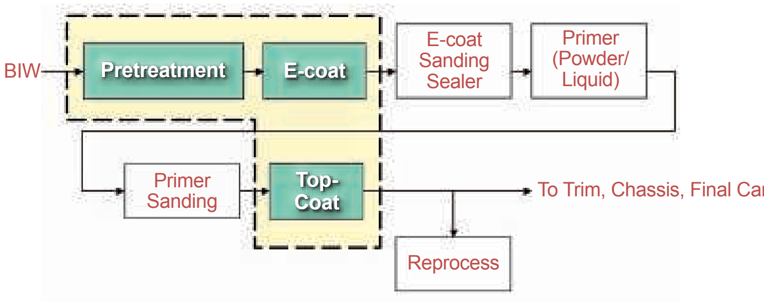
Life Cycle Assessment (LCA) techniques quantify the aggregate environmental impact of a product or process. As such, they can be useful for environmentally oriented decision making (e.g., identifying life cycle stages with more severe environmental impacts; quantifying trade-offs between alternatives).[3,5] The Life Cycle Inventory (LCI) portion of LCA is a systematic inventory of a product's or process' associated materials use, energy use, and emissions. Two considerable challenges that have restricted widespread use of LCA techniques, however, are: the resource-intensive data collection processes required to complete an LCI for a reference product or process; and the uncertainties associated with applying site-specific reference LCI data to processes at a different facility or manufacturing scenario.[6,7]

NREL LCI Database Project

The National Renewable Energy Laboratory (NREL), working with industry and academic research partners, is developing a publicly available database of LCI information for products, processes, and materials commonly used by North American-based industries and consumers.[7] The NREL LCI Database is intended as a reference data resource for completing LCAs relevant to the North American market. LCI data used to populate the database is ISO 14041-compliant, is developed in accordance with a common research protocol, and is critically reviewed before online publication. The database, currently in beta, can be found online.[8]

For the automotive industry, North American-based automobile manufacturers agreed to conduct LCIs on several prioritized manufacturing/assembly processes. Among these, the automotive painting process was selected due to its significant associated environmental impacts and its relevance to other industries that employ coating processes.[1] Additional background information on the NREL LCI Database project is provided in Prendi et al.[4]

Figure 1—Unit process flow for typical automotive paint process and scoped LCI system boundaries.



Automotive Paint Processes

The automobile painting process provides corrosion protection to a vehicle's body structure and a durable and decorative coating to the outer body panel surfaces.[9] Automotive painting in vehicle manufacture is a multi-step sequential process, typically involving the following unit processes: cleaning, pretreatment, E-coat, primer, and topcoat (i.e., basecoat and clearcoat). This is illustrated in *Figure* 1.

The vehicle body-in-white (BIW) goes through a waterborne pretreatment process, where it undergoes a number of dip and rinse stages.[10] This phase, also known as the phosphating stage, prepares the BIW for application of coatings. Then the BIW enters the E-coat and primer stage where anti-corrosion layers are applied. The BIW is now ready for application of color coat (basecoat). In this phase, the BIW is sprayed with either waterborne or solventborne basecoat. If the basecoat is solventborne, then a short flash time at ambient temperature is needed for evaporation of volatile solvents. Waterborne basecoats, however, need a longer flash time at elevated temperature; to accommodate this, a dehydration stage is added to the process. The dehydration oven includes convection and possibly infrared (IR) heating. Then the vehicle body is sent to the clearcoat application and curing stage. The clearcoat gives the glossy finish to the car, and it also adds protection to the other layers for longer durability of the finish.[10]

Previous studies have shown the environmental impacts associated with the automotive paint process to be significant relative to other automotive manufacturing processes.[11] Environmental impacts associated with automotive paint processes include releases to air (e.g., volatile organic emissions), wastewater (e.g., pretreatment chemicals, paint overspray in solution), and land (e.g., waste paint solids from overspray collected from downdraft booths as sludge). Further, materials used are highly varied and processed in large volumes (i.e., immersion tanks are large enough to submerge an entire vehicle body). Finally, substantial energy is required by the automotive paint process (e.g., maintaining immersion tank process temperatures, heating curing ovens, powering robotic spray equipment, etc.)

METHODOLOGY

Industry Partnership and ISO Compliance

The research was conducted over a two-year period through a partnership between the University of Windsor and a North American vehicle manufacturing facility. Subsidiary partnerships were also initiated with the partnered vehicle manufacturer's supplier organizations as required.

The research was carried out in compliance with relevant LCI protocols (i.e., ISO 14041) and referenced standardized LCI data collection tools.[1] Details of LCI goal definition, scoping, data sources, and process flow mapping are provided in Prendi et al.[4] The functional unit selected for presentation of LCI data and reporting to the NREL LCI Database is "per m^2 of painted BIW"; this is consistent with current industry environmental reporting practices.

LCI of E-coat and Topcoat Processes

The environmental impact parameters scoped for the automotive LCI of E-coat and topcoat processes include materials use, energy use, and pollutant emissions. The data collection targeted the 2003 calendar year because this was the most recent year during which two vehicle models were produced at the partnered OEM's assembly plant and for which complete data were consistently available. Where the identified data sources could not provide data for a particular environmental parameter, additional data sources were sought, including pre-2003 sources. Details of LCI scoping, assumptions, and data sources used are reported elsewhere.[4]

Development of LCI Data Application Protocol

The automotive paint process data in the NREL LCI Database is intended to be "scalable" across a range of North American market vehicle types and assembly facilities, allowing for practical application to new LCI and LCA activities.

Development of an LCI application protocol for the NREL automotive paint reference dataset involved scoping the quantitative analysis to LCI materials used in the E-coat and topcoat unit processes. This allowed a more manageable dataset while preserving two key automotive paint process types—immersion application (E-coat) and spray application (topcoat).

Model-specific materials use and production volume data for the two vehicle models painted at the NREL reference assembly plant were used along with the NREL paint LCI reference dataset. The two vehicle models share a single assembly line and single paint process, serving as a desirable analysis control. Quantitative comparisons are made between the two vehicle models with respect to their associated materials use at the unit process resolution level (e.g., materials use in E-coat, materials use in topcoat). The analysis examined several variables for their effect on extrapolating NREL reference LCI data: surface area, paint process, and production volume/production cycle length. Vehicle type effects on surface area were also examined.

LIFE CYCLE INVENTORY OF E-COAT AND TOPCOAT PROCESSES

E-coat

Materials Inventory: The materials inventory results for the E-coat process are summarized in *Table* 1. E-coat materials data were available from the internal *VOC Report* published annually by an environmental specialist at the partnered OEM. The *VOC Report* references the paint supplier's monthly reporting for its materials use data. Details about water use estimations for the E-coat process are reported elsewhere.[4]

Energy Inventory: The energy inputs identified were electrical and heat energy (i.e., steam). Data was not available for steam energy inputs. The calculated estimate of total annual electricity use for the E-coat process is reported in *Table* 1. Electricity is used to power the various motors, conveyors, and pumps associated with the E-coat process. Procedures used and assumptions made to estimate electrical energy for the E-coat process are similar to the ones used for pretreatment.[4] The only exception is that several pumps in the E-coat process are assumed to operate at full capacity for 24 hours per day and 365 days per year as opposed to 24 hours per day and 273 days per year. As previously reported,[4] the calculated estimate of electrical energy in E-coat is significantly different from metered usage data.

Emissions Inventory: Emissions released from the E-coat process are summarized in *Table* 2. Relevant emission fates included: emissions to air, solid emissions, and emissions to wastewater. Data sources, assumptions, and engineering estimates used to calculate emissions to air, water, and land are similar to those previously published for the pretreatment process.[4]

Table 2—Emissions to Air, Water, and Land for E-coat

Emissions to Air	/1000 m² Painted BIW
To air (NPRI reportable)	
None	0
To air (VOC)	
E-coat resin	410 g
E-coat pigment	41 g
Total VOC to air	**451 g**
Emissions to Water	**/1000 m² Painted BIW**
Wastewater to WWTP (NPRI reportable + non-reportable)	6.87 m³
To water (NPRI reportable)	
Carbon black	0.02 g
Total reportable compounds to water (g)	**0.02 g**
Emissions to Land	**/1000 m² Painted BIW**
Sludge to landfill (NPRI reportable)	
Carbon black	13.03 g
Total reportable compounds to land (sludge)	**13.03 g**
Filters to landfill (NPRI reportable)	
Carbon black	0
Total reportable compounds to land (filters)	**0**

Topcoat

Materials Inventory: Topcoat materials data are reported in *Table* 3. Similar to pretreatment and E-coat, topcoat materials data were available from the internal *VOC Report*. Materials use is reported for each individual paint color used in the topcoat process. Since production volume data was not available by color, individual color materials use cannot be reported using the functional unit. However, total production volume data (i.e., total annual vehicles painted) was available, allowing total materials use for the topcoat paint colors (i.e., all paint colors) to be reported using the functional unit.

As the assembly plant's various manufacturing processes do not consistently employ separate water meters, water use data was not available for individual unit processes (i.e., pretreatment E-coat, topcoat). Separate water metering was available for the plant's paint shop, however, which houses the primer and topcoat processes (i.e., basecoat and clearcoat). Metered water usage is reported by an environmental specialist at the assembly plant via an Excel spreadsheet, which was made available. Engineering estimates, developed with the plant's environmental specialist, were then used to apportion water use to the topcoat process. The calculations used to estimate water use for the topcoat process are summarized in *Table* 4.

Table 3—Materials, Water, and Energy Use Summary for Topcoat

Materials Use	L/1000 m² Painted BIW
Total basecoat materials used (all colors)	**35.24**
Clearcoat materials	
Clearcoat	16.83
Tinted clearcoat	2.54
Total clearcoat materials used	**19.36**
Water Use	**L / 1000 m² Painted BIW**
Water	706
Energy Use	**kWh / 1000 m² Painted BIW**
Energy	939

Table 4—Estimation of Water Use for Topcoat

Calculation Basis	/1000 m² Painted BIW
Annual total water use	1.058 m³
Estimate: primer	33.3 %
Estimate: topcoat (basecoat + clearcoat)	66.6 %
Annual total water use by primer	0.352 m³
Annual total water use by topcoat (rounded)	**0.706 m³**

Table 5—Emissions to Air for Topcoat

Emissions to Air	g/1000 m² Painted BIW
To air (NPRI reportable)	
Basecoat	
Carbon black	2.04E-04
1-Methoxy-2-propanol	0.11
Diethylene glycol butyl ether	8.15E-04
Ferric oxide	8.15E-04
Propylene glycol butyl ether	1.66
Copper compounds	2.26E-05
Stoddard solvent	0.28
Light aromatic solvent naptha	0.05
Heavy alkalide naptha	0.85
2-Butoxy-ethanol	0.01
Total reportable compounds (basecoat)	**2.96**
Clearcoat	
Acetone	0.67
N-butyl alcohol	0.79
1,2,4-Trimethyl benzene	0.58
Light aromatic solvent naptha	2.41
Total reportable compounds (clearcoat)	**4.45**
Total reportable compounds to air (topcoat)	**7.41**
To air (VOC)	
Basecoat	
Total VOC (basecoat)	**6520**
Clearcoat	
Clearcoat	7862.95
Tinted clearcoat	1184.98
Total VOC (clearcoat)	**9047.93**
Total VOC to air (topcoat)	**15567.88**

Energy Inventory: Energy inputs identified were electrical and heat energy (i.e., steam). Data was not available for steam energy inputs. The calculated estimate of total annual electricity use for the topcoat process is reported in *Table* 3.

Electricity use is not metered at the assembly plant by manufacturing process and apportioning total electricity use via engineering estimates is not recommended; the expertise to reasonably apportion energy use among the various manufacturing processes by estimation is not available in-house. As a result, electricity use was based on an audit of equipment associated with the topcoat process and then calculated using audited equipment power ratings. An audit of topcoat equipment was initiated by referencing the plant's preventive maintenance database and sorting the database for plant equipment associated with the paint process. The paint equipment list was then reviewed for equipment that uses electricity to operate. Emphasis was placed on equipment with more significant electrical energy use, similar to what was prepared by an outside energy consultant for the pretreatment and E-coat energy audits. Assumptions were similar to the pretreatment and E-coat energy calculations.

Emissions Inventory: Emissions released from the topcoat process are summarized in *Tables* 5 through 7. Relevant emission fates included: emissions to air, wastewater, and land (i.e., solid emissions). Data sources included the *NPRI Report* and the *VOC Report* for the 2003 calendar year. Since production volume data was not available by color, individual color VOC emissions cannot be reported using the functional unit. However, total production volume data (i.e., total annual vehicles painted) was available, allowing total VOC emissions for the topcoat paint colors (i.e., all paint colors) to be reported using the functional unit.

LCI DATA APPLICATION PROTOCOL

Painted Surface Area

Surface area was expected to be the dominant vehicle characterization parameter in the paint process, consistent with the per m^2 painted BIW functional unit and industry's use of surface area-based reporting for painting operations. For the two vehicle models assembled at the NREL reference facility, the percentage difference between painted surface area was compared against the percentage difference between materials use (i.e., E-coat, topcoat). It was expected that a straightforward LCI data application protocol using linear scaling would be demonstrated by a similar "scaling ratio" for both painted surface area and materials use.

It was noted from model-specific materials use data that slight differences existed between the two vehicle models. These are shown in *Table* 8. The difference was quantified by calculating the percentage difference in materials use between vehicle models for each of the paint processes (see *Table* 8). In reviewing the scoped processes, vehicle model-specific paint process materials were in close agreement and within a 5% difference (i.e., E-coat = 2.2%; topcoat = 4.8%). As well, total materials use (i.e., E-coat + topcoat), which would be used by an LCI practitioner interested in LCI scaling for the more inclusive automotive paint process, was within a 2% difference. These differences indicate that the well known "5% rule" can be applied, which states that environmental impact quantities less than 5% of the total can be omitted from an LCI except where they represent severe toxicities.[12,13] The results support the LCI research's assumption that the two vehicle models assembled at the reference assembly plant can be aggregated for the purposes of LCI data collection and reporting to the NREL LCI database.

The materials use difference was expected due to the differing as-reported BIW painted surface areas of the two vehicle models (i.e., 162 m^2 versus 152 m^2) and it was desirable to see if the vehicle model differ-

Table 6—Emissions to Water for Topcoat

Emissions to Water	/1000 m^2 Painted BIW
Wastewater to WWTP (NPRI reportable + non-reportable)	**669.63 L**
To Water (NPRI reportable)	
Basecoat	
Copper compounds	1.81E-04 g
Clearcoat	
None	0
Total reportable compounds to water (clearcoat)	**1.81E-04 g**

Table 7—Emissions to Land for Topcoat

Emissions to Land	g/1000 m^2 Painted BIW
Sludge to landfill (NPRI reportable)	
Basecoat	
Carbon black	19.55
1-Methoxy-2-propanol	0.11
Diethylene glycol butyl ether	0.84
Ferric oxide	81.70
Propylene glycol butyl ether	16.72
Copper compounds	1.99
Stoddard solvent	0.29
Light aromatic solvent naptha	0.05
Heavy alkalide naptha	0.84
2-Butoxy-ethanol	0
Total reportable sludge compounds (basecoat)	**122**
Clearcoat	
Acetone	0.68
N-butyl alcohol	0.79
1,2,4-trimethyl benzene	0.59
Light aromatic solvent naptha	2.40
Total reportable sludge compounds (clearcoat)	**4.46**
Total reportable sludge compounds (topcoat)	**253**
Filters to landfill (NPRI reportable)	
None	N/A

Table 8—Vehicle Model-Specific Material Use Data and Percentage Difference Between Vehicle Models at NREL Reference Assembly Plant (Q3, Q4 of 2003 Calendar Year)

Process	Model A Materials Use [L / Vehicle]	Model B Materials Use [L / Vehicle]	Diff |B – A|	% Diff |B - A| / A (%)
E-coat	5.88	6.01	0.13	2.2
Topcoat	9.22	8.78	0.44	4.8
Basecoat	6.10	5.69	0.41	6.7
Clearcoat	3.12	3.09	0.02	0.7
Total (E-coat + Topcoat)	**15.10**	**14.80**	**0.30**	**2.0**

ence in materials use (i.e., per vehicle) was comparable with the vehicle model difference in BIW surface area. This was assessed using a ratio of the materials use and comparing with the ratio of the BIW painted surface areas, as shown in *Table* 9.

A vehicle-model materials use ratio that equals the vehicle-model BIW surface area ratio exactly would indicate that the differences in material use between the two vehicle models could be explained entirely by their painted surface area differences. Examining the results in *Table* 9 shows that the topcoat (basecoat + clearcoat) vehicle-model materials use ratio did equal the vehicle model BIW surface area ratio exactly; as well, the topcoat vehicle-model materials use ratio was within 2% difference of the vehicle-model BIW surface area ratio. These results suggest that, for the two quarters of production for which model-specific materials data was available, basecoat and topcoat materials use can be scaled based on BIW painted surface area with minimal uncertainty in results.

E-coat, however, had vehicle-model materials use ratios that differed more compared with the vehicle-model BIW surface area ratio (i.e., E-coat = 8.4% difference). This suggests that LCI scaling based on painted surface area would have a larger results uncertainty for E-coat materials use relative to topcoat. Similarly, since E-coat is a significant component of total materials use (i.e., E-coat + topcoat), the resulting vehicle-model total materials use ratio (i.e., 1.02; 4.7% difference) also suggests that LCI scaling based on painted surface area would have a larger results uncertainty for total materials use.

Overall, since all vehicle-model materials use ratios were within 8.5% of the vehicle-model BIW surface area ratio, the painted surface area is likely the dominant vehicle-characterization parameter in the paint process. This is consistent with the choice of preferred functional unit (i.e., per m^2 painted BIW) as used in the NREL LCI Database.

Paint Process Type

An LCI practitioner will most typically perform an LCI scaling on the entire automotive paint process (i.e., inclusive of all unit processes). However, an LCI practitioner may wish to separately select the processes that best apply to a proposed manufacturing scenario. Thus, the effect of individual paint processes on the resultant LCI data was analyzed. E-coat and topcoat represented key paint process types: immersion tank coating application and spray booth coating application. The model-specific materials use dataset from the reference assembly plant was again used to examine the differences between unit processes (see *Table* 8).

It was noted that the difference in vehicle-model materials use was not consistent across the three assessed paint processes. Paint process materials use for the two vehicle models was very similar for the clearcoat process (i.e., 0.7% difference) and most different for the basecoat process (i.e., 6.7% difference); materials use for the E-coat process was within 2.5%. This suggests that LCI scaling is to some extent dependent on the paint process under consideration, with some unit process operations carrying greater associated uncertainty in the results (e.g., basecoat).

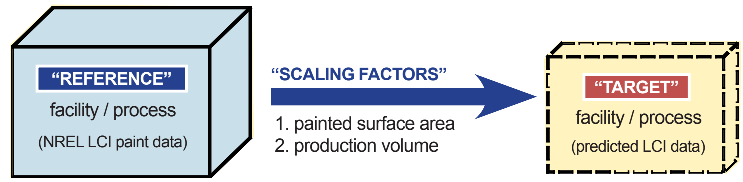
Examining the specific paint process materials applied in each of the unit processes is useful for understanding why some processes show larger percentage differences in usage quantities (e.g., basecoat) than others (i.e., clearcoat, E-coat). The first indicator considered in the analysis was the number of process products involved in each of the unit process operations. The E-coat and clearcoat operations each apply two paint products to every BIW; the basecoat operation applies one of nine different paint products (i.e., basecoat colors) to the BIW, depending on the color intended for each vehicle manufactured.

If the same quantity of basecoat were applied to each BIW, regardless of color, the number of available

Table 9—Vehicle Product Ratio for Material Use and Surface Area at NREL Reference Assembly Plant (Q3, Q4 of 2003 Calendar Year)

Process	Model A Materials Use [L / Vehicle]	Model B Materials Use [L / Vehicle]	A : B Materials Use	A : B BIW Surface Area	% Diff A:B Materials Use vs. BIW Surface Area (%)
E-coat	5.88	6.01	0.98	1.07	8.4
Topcoat	9.22	8.78	1.05	1.07	1.9
Total (E-coat + Topcoat)	**15.10**	**14.80**	**1.02**	**1.07**	**4.7**

Figure 2—Concept of LCI data application protocol.



basecoat colors would not be a factor in the LCI scaling. However, it was noticed in the paint supplier's monthly reporting that the quantity applied per vehicle was slightly different for each color. For example, a vehicle painted "black" received nearly 40% more quantity of basecoat than a vehicle painted "almond." This variation in materials use depending on paint color introduces greater variability to the LCI materials use data for the basecoat operation, and by extension to the topcoat unit process (i.e., topcoat = basecoat + clearcoat).

Further complicating matters is the fact that the NREL reference assembly plant does not produce equal numbers of each color vehicle. This adds further variability to the LCI materials use data and also explains the larger percentage difference shown between vehicle model materials use for the basecoat operation and topcoat unit process.

Thus, LCI materials data for the paint process exhibits process-dependency and paint processes can be broadly classified as either immersion processes (E-coat application) or spray processes (topcoat application). With this classification, it was observed that materials use in immersion processes is relatively independent of production volume compared with materials use in spray processes (e.g., immersion tanks must be sized to accommodate the BIW and must be kept filled regardless of BIW throughput).

Production Volume and Production Cycle Length

The research assumed that an NREL reference dataset aggregating a larger period of time would be preferable to one aggregating a smaller period of time. The paint process, in particular, contains some operations that are relatively independent of vehicle production volume.

Some paint process equipment must be operated continuously rather than only when a BIW is present. As an example, immersion tanks for pretreatment must be kept at an elevated operating temperature; since attaining the operating temperature requires time, their operation cannot be dependent on the presence or absence of a BIW on the moving assembly line. For this reason, the paint shop at most assembly facilities is kept running through weekends, even where no vehicles are scheduled for assembly. Other equipment items that run essentially continuously in an automotive paint shop include fans, blowers, and drying ovens. Scheduled shutdowns for equipment maintenance and process changes/model year changes are typically annual events and so require a suitable time period in data collection to ensure that they are quantitatively represented in the LCI.

It should also be noted that the effect of production cycle length on an LCI dataset may vary depending on which environmental impact parameter is examined. Materials, for example, largely tend to scale with vehicle production volumes (e.g., spray equipment only applies paint when a BIW is present to be painted; immersion tanks are depleted due at least partially to "dragout" as a BIW passes through them, etc.). The exception is water use, which runs continuously in systems such as the spray booth overspray collection system and so would not scale as directly with vehicle production volume as other materials. Since the bulk of paint shop emissions are created as a result of paint process materials use (e.g., VOCs from paint or solvents), emissions can be said to largely scale directly with vehicle production volume. Energy, however, is relatively independent of vehicle production volume, since much of the aforementioned equipment requiring continuous operation is electrically powered (e.g., fans, blowers, drying ovens) or steam powered (e.g., immersion tank heating).

This analysis suggests that LCI scaling to another facility or production scenario should be limited to a production cycle that is at least the cycle length of the source data (i.e., one year's production for use of the NREL reference LCI data). This allows "smoothing" of the operations that are relatively independent of vehicle production volume, such as continuously operated equipment or scheduled production shutdowns.

LCI Data Application Protocol

The LCI data application protocol, to be used for predicting paint process-associated environmental impacts at a given assembly facility from the NREL reference LCI data, is based on the preferred functional unit used in the reference LCI (i.e., per m^2 painted BIW) and incorporates variables for painted surface area and production volume. The LCI data application protocol (i.e., "data scaling") is conceptually illustrated in *Figure* 2.

The resulting linear scaling equation is written as:

$$LCI_{PREDICT} = LCI_{NREL} * [\text{BIW Painted Surface Area}_{PREDICT} * \text{Annual Vehicle Production}_{PREDICT}] \quad (1)$$

Table 10—Reference Surface Area Values for Use as Surrogate in LCI Scaling Equation

Vehicle Type	Overall Vehicle Dimensions L, W, H [m]	Reference Painted BIW Surface Area [m^2]
Sedan (large)	L = 5.3 W = 1. 9 H = 1.4	132.2 m^2
Sedan (large)	L = 5.0 W = 1.9 H = 1.5	151.9 m^2
Minivan/crossover	L = 5.1 W = 2.0 H = 1.7	154.6 m^2

As an initial contribution to future LCI data application scenarios, the authors submit surrogate painted surface areas, along with reference vehicle dimensions, for the minivan/crossover vehicle type and the sedan vehicle type. A reference table is provided in *Table* 10.

Test Case: Application of NREL LCI Paint Process Data to a Different Facility

The test case evaluated the proposed LCI application protocol's performance by applying the NREL paint materials use data to a "target" assembly plant as surrogate data and verifying the results against site-specific materials data collected at the "target" assembly plant. This represented an LCI practitioner applying the paint LCI dataset using the NREL LCI Database or OEM-selected LCI software (e.g., GaBi).

Table 11—Predicted Materials Using NREL Dataset and Painted Surface Area (Combined Vehicle Models; 2004 Calendar Year)

Paint Process Materials	NREL (Reference Assembly Plant) [L / 1000 m^2 Painted BIW)	PREDICTED (Target Assembly Plant) L	ACTUAL (Target Assembly Plant) L	% DIFF = (PREDICT-ACTUAL) / ACTUAL %
E-COAT	33.7	728,492	824,186	-12
E-coat resin	31.1	672,288	747,078	-10
E-coat pigment	2.6	56,204	77,109	-27
Basecoat	35.2	760,917	661,319	15
All colors aggregated	35.2	760,917	661,319	15
Clearcoat	19.4	419,369	385,472	9
Clearcoat	16.8	363,165	367,560	-1
Tinted clearcoat	2.5	54,042	17,913	202
Topcoat (Basecoat + Clearcoat)	54.6	1,180,286	1,046,791	13
TOTAL (E-coat + Topcoat)	**88.3**	**1,908,778**	**1,870,978**	**2**

Since the "target" assembly plant is a facility operated by the same OEM that partnered to provide the NREL reference LCI dataset, it uses a similar paint shop facility and also sources materials from the same paint supplier. The "target" assembly plant data was based on aggregate production of both vehicle models, January through August 2004 (i.e., nine months of data). Production volumes for the "target" assembly plant in the selected nine-month period were a combined 142,303 vehicles. Furthermore, it was assumed that the LCI practitioner had access to the BIW painted surface area for the vehicle models at the "target" assembly plant. Using the production volume and BIW painted surface area information, the production volume weighted BIW painted surface area was calculated, thereby aggregating the two vehicle models into a single representative model for the "target" assembly plant. This is analogous to what was done in preparing the NREL reference paint LCI dataset.

Equation (1) was used to predict the annual materials use at the "target" assembly plant for the E-coat and topcoat (i.e., basecoat, clearcoat) unit processes. A

An LCI practitioner may not know the BIW painted surface of the vehicle for which they wish to predict materials use, requiring use of the scaling equation with an appropriate surrogate BIW painted surface area value. A well-chosen surrogate painted surface area should consider both vehicle size (i.e., determined from readily available external vehicle dimensions) and vehicle type (i.e., basic structural configuration: minivan, sedan, pickup truck, etc.).

For situations where the BIW surface area must be approximated via a surrogate value, the linear scaling equation developed in this article is thus modified to:

$$LCI_{PREDICT} = LCI_{NREL} * [\text{Surrogate BIW Painted Surface Area}_{PREDICT} * \text{Annual Vehicle Production}_{PREDICT}] \quad (2)$$

comparison could then be made to the site-specific annual materials use data that were available from the "target" assembly plant (i.e., sourced from the *VOC Report*) and the percentage difference from that predicted by the linear scaling equation calculated. The results are shown in *Table* 11.

For the E-coat unit process, total materials use was underpredicted by approximately 12%; for the topcoat unit process, total materials use was overpredicted by approximately 13%. The net effect of the two differences, however, yielded a total materials use (i.e., E-coat + topcoat) that came very close to the true value, overpredicting it by only 2%. Additionally, the E-coat unit process, which is essentially an immersion process, underpredicted "target" assembly plant results for each E-coat material; the topcoat unit process, which is essentially a spray process, overpredicted the "target" assembly plant results for most materials.

The percentage difference in the E-coat materials use (i.e., −12%) can possibly be explained by the NREL reference LCI dataset being scaled down to a smaller predicted production scenario and by the observation that E-coat is primarily an immersion process with the total materials use relatively independent of production volume. Thus, immersion processes such as E-coat will approach a "lower limit" of materials use, corresponding to the reality of maintaining full tanks. The predicted materials use for the "target" assembly plant, representing a significantly lower production volume than the reference data (i.e., "target" assembly plant = 142,303 vehicles; NREL reference assembly plant = 285,875 vehicles), is likely to have scaled results below this "lower asymptote," resulting in an underprediction.

The percentage difference in the basecoat materials use (i.e., +15%) can be explained by considering the effect of aggregating the different colors. Although some basecoat colors are common with the vehicle product colors used at reference assembly plant in 2003, the "target" assembly plant used several different colors for the 2004 sedan models; as well, the production ratio for the vehicle colors at the "target" assembly plant is likely to differ significantly from that at the reference assembly plant. As previously stated, this can introduce uncertainty to the basecoat scaling compared with clearcoat scaling. This is confirmed by the observed percentage difference in the predicted "target" assembly plant results of approximately +15% for basecoat compared with only +9% for clearcoat.

A final factor in the observed percentage differences was that, since the "target" assembly plant data was aggregated from only nine months, it may have missed or inadequately represented factors such as scheduled production shutdowns or continuously operating equipment.

CONCLUSIONS AND RECOMMENDATIONS

The NREL LCI Database has been populated with up-to-date environmental impact data representative of painting practices in the North American automotive industry. Data is provided for three key unit processes: pretreatment, E-coat, and topcoat.

NREL paint LCI data exhibits process dependency. As an example, energy use in the paint process can be relatively independent of production volume due to the contributions of continuously operating equipment. The uncertainty of predicted results from a reference dataset will relate to any demonstrated process dependency, with materials/energy/emissions data representing some processes more reliably than others.

Aside from process differences between any two manufacturing facilities, differences in painted BIW surface area and differences in annual production volumes will affect results. For this reason, industry application of the NREL LCI database should use an appropriate data application protocol, if available. An example is the linear scaling equation (1) provided in this article. Painted BIW surface area data limitations can be overcome through the use of surrogate painted surface area based on vehicle type and vehicle size. CT

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