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Vehicle Remanufacturing: Economic and Environmental Expansion of the Life Cycle

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Abstract

Applying the Economic Input-Output Life Cycle Assessment (EIOLCA) method to the question of fielding newly manufactured or remanufactured vehicles provides an illuminating view of the economic and environmental advantages of remanufacturing. Sustained accomplishments of policy and engineering have reduced vehicle emissions such that current work has reached the point of diminishing returns. The macroeconomic, global, unprecedented, debt-supercycle-combined with increasing costs of natural resource extraction and vehicle production-demands improved asset and resource utilization. Expanding and exploiting the entire vehicle life cycle is a profitable and sustainable extension of work to date; such extension calls for remanufacturing to move from vehicle components to the entire vehicle. Stretching service lifetimes delay traditional end-of-life recovery practices while radically challenging the status quo. Mainstream remanufacturing will affect entire industries including insurance, licensing, and financing as they incorporate remanufactured vehicles in a new narrative and expanded life cycle. Objective decisions about production, acquisition, and regulation should include considerations for not only the life cycle but extending it as well. While there is much future work to be done in this area, this paper opens the discussion about the economic and environmental advantages of enterprise-level vehicle remanufacturing. In this work, the EIOLCA Method, with the United States 2002 Benchmark Producer Price Model, provides the mechanism to explore the economic and environmental impact of equal amounts of economic activity for traditional vehicle manufacturing and novel vehicle remanufacturing.

Introduction

Many and varying obstacles often hamper widespread adoption of novel ideas, products, and offerings; so it is with enterprise vehicle remanufacturing. Obstacles to adoption of vehicle remanufacturing include policy, legislation, and rule bias based on vehicle emissions. This is not surprising as policy and legislation have been the only tools for use against the environmental vagaries of automotive use. Current policy and legislation were born of a real health crisis in the various California metropolitan basins in 1965 [1].

Today, however, we are witnessing the declining marginal utility of technical advances in emission controls [2]. We are also witnesses to the revelation of considering the entire life cycle of manufacturing decisions and economics.

This paper is an investigation of a necessarily narrow aspect of these far-reaching topics to explore the question of whether wholesale, vehicle remanufacturing is ready for the mainstream by looking into mono-Nitrogen Oxide (NOx) emissions as a metric for responsible vehicle sourcing decisions. NOx and Volatile Organic Compounds (VOCs) are cited as motivations for emission reduction programs [3]. An objective analysis of at least one of these components should provide guidance for current and future policy action.

Method

There is no North American Industry Classification System (NAICS) code for vehicle remanufacturing; this is a clear measure of the novel nature of the activity. Accordingly, there is no industry or sector available in Carnegie Mellon's Green Design Institute's Economic Input-Output Life Cycle Assessment (EIOLCA) online tool. EIOLCA is a natural choice to evaluate the build phase impacts of manufacturing versus remanufacturing vehicles. While there is no sector for remanufacturing, we use the EIOLCA sector Automotive Repair and Maintenance, Except Car Washes as a proxy in this investigation. This EIOLCA sector is generally comprised of the NAICS sector 81111 Automotive Mechanical and Electrical Repair and Maintenance.

Sector 81111 is sufficiently broad to serve this purpose. To illustrate its breadth, consider Table 1 which lists each of the NAICS sectors included in the EIOLCA Broad Sector Group entitled "Other Services, Except Public Administration" and the EIOLCA Detailed Sector entitled "Automotive Repair and Maintenance, Except Car Washes."

Table 1. EIOLCA Detailed Sector constituent NAICS sectors included in the Other Services, Except Public Administration Broad Sector Group.

NAICS Sector Code	Sector Name	Sector Description
81111	Automotive Mechanical and Electrical Repair and Maintenance	This industry comprises establishments primarily engaged in providing mechanical or electrical repair and maintenance services for automotive vehicles, such as passenger cars, trucks and vans, and all trailers. These establishments specialize in, or may provide, a wide range of these services.
811111	General Automotive Repair	This industry comprises establishments primarily engaged in providing (1) a wide range of mechanical and electrical repair and maintenance services for automotive vehicles, such as passenger cars, trucks, and vans, and all trailers, or (2) engine repair and replacement.
811112	Automotive Exhaust System Repair	This industry comprises establishments primarily engaged in replacing or repairing exhaust systems of automotive vehicles, such as passenger cars, trucks, and vans.
811113	Automotive Transmission Repair	This industry comprises establishments primarily engaged in replacing or repairing transmissions of automotive vehicles, such as passenger cars, trucks, and vans.
811118	Other Automotive Mechanical and Electrical Repair and Maintenance	This industry comprises establishments primarily engaged in providing specialized mechanical or electrical repair and maintenance services (except engine repair and replacement, exhaust systems repair, and transmission repair) for automotive vehicles, such as passenger cars, trucks, and vans, and all trailers.
8111181	Carburetor Repair	Establishments primarily engaged in repairing carburetors and providing tune-ups.
8111182	Brake, Front End, and Wheel Alignment	Establishments primarily engaged in repairing, replacing, and adjusting brakes; performing front end and wheel alignment work; and installing springs, axles, and shock absorbers.
8111183	Electrical Repair Shops, Motor Vehicle	Establishments primarily engaged in performing electrical repair and maintenance services for motor vehicles.
8111184	Radiator Repair	Establishments primarily engaged in repairing, cleaning, and installing radiators and heater cores.
8111189	All Other Motor Vehicle Repair	Establishments primarily engaged in specialized repair of individual auto components (except radiator repair; brake, front end, and wheel alignment; carburetor repair; and electrical repair, motor vehicle). Included are auto repair shops specializing in air conditioning, clutch, and valve repair.
81112	Automotive Body, Paint, Interior, and Glass Repair	This industry comprises establishments primarily engaged in providing one or more of the following: (1) repairing or customizing automotive vehicles, such as passenger cars, trucks, and vans, and all trailer bodies and interiors; (2) painting automotive vehicle and trailer bodies; (3) replacing, repairing, and/or tinting automotive vehicle glass; and (4) customizing automobile, truck, and van interiors for the physically disabled or other customers with special requirements.
811121	Automotive Body, Paint, and Interior Repair and Maintenance	This industry comprises establishments primarily engaged in repairing or customizing automotive vehicles, such as passenger cars, trucks, and vans, and all trailer bodies and interiors; and/or painting automotive vehicles and trailer bodies.
8111211	Paint or Body Repair Shops	Establishments primarily engaged in repairing or painting car, truck, and trailer bodies.
8111212	Van Conversion Services	Establishments primarily engaged in customizing automobiles, trucks, and vans. Adapting vehicles for the physically handicapped or other special requirements are also included.
8111213	Upholstery and Interior Repair Shops	Establishments primarily engaged in repairing and replacing motor vehicle upholstery and interiors.
811122	Automotive Glass Replacement Shops	This industry comprises establishments primarily engaged in replacing, repairing, and/or tinting automotive vehicle glass, such as that in passenger cars, trucks, and vans.
811191	Automotive Oil Change and Lubrication Shops	This industry comprises establishments primarily engaged in changing motor oil and lubricating the chassis of automotive vehicles, such as passenger cars, trucks, and vans.
811198	All Other Automotive Repair and Maintenance	This industry comprises establishments primarily engaged in providing automotive repair and maintenance services (except mechanical and electrical repair and maintenance; body, paint, interior, and glass repair; motor oil change and lubrication; and car washing) for automotive vehicles, such as passenger cars, trucks, and vans, and all trailers.

There are at least two observations of note at this point. The first is that vehicle remanufacturing is a consolidation of all these activities and leverages the economies of scale offered in such a setting. The second is that vehicle remanufacturing certainly stands a chance at being recognized as a valid NAICS sector if we still track carburetor repair.

EIOLCA Model Description

We derive present day life cycle analysis from the work of Wassily Leontief, winner of the 1973 Nobel Prize in Economic Sciences. Leontief created the first input-output tables of the 1919 and 1929 American economy in 1932. These tables were processed using a large-scale mechanical computing machine in 1935 and the Mark I (the first large-scale electronic computer) in 1943 [4]. Leontief illustrates the approach by considering a simple economy comprised of two producing sectors-namely, Agriculture and Manufacture-and Households. Each of the two industries necessarily consumes some of its own output while supplying some of its output to the other; both sectors supply the balance of their output to the consuming Households. The input requirements for each unit of output, assembled in tabular form, represent the “structural matrix” of the economy [5].

Said another way, if sector *i* produces an amount that sector *j* requires, X_{ij} could represent this production. If x_i is the total output from sector *x* (say Agriculture) and y_i is the final demand from Households, then

$$x_i = y_i + \sum_j X_{ij} \tag{1}$$

Letting A_{ij} be the normalized production of each sector such that $A_{ij=}X_{ij}/x_j$ yields

$$x_i = y_i + \sum_j A_{ij} x_j \tag{2}$$

In vector notation,

$$\mathbf{x = y{+}Ax} \tag{3}$$

Or, using the identity matrix, I,

$$\mathbf{y = (I\text{-}A)x} \tag{4}$$

$$\mathbf{x = (I\text{-}A)^{-1}y} \tag{5}$$

Equation 5 states that knowing the final demand from a sector (y) and the normalized input-output matrix (A), the implied production from each sector in the economy (x) is known.

Going further, for any parameter associated with a given sector, say emissions (e), assembled in a matrix (E), it would follow that the change in emissions is represented by

$$\Delta e = E\,\Delta x = E(I\text{-}A)^{-1}\Delta y \tag{6}$$

This elegant representation allows the rapid determination of emissions (or other interesting parameters) for the entire supply chain (sector) required to produce a specific, final output demand.

The Green Design Institute of Carnegie Mellon University took Leontief's method and married it to an intensive computing capability in 1995. The National Science Foundation, the U.S. Environmental Protection Agency, and the Green Design Consortium funded this effort in part. The Pittsburgh Supercomputer Center hosts the EIOLCA on-line tool [6].

EIOLCA Model and Vehicle Remanufacturing

A review of the literature yields no discussion of the EIOLCA model and vehicle remanufacturing. Existing research examines energy, economics, emissions, remanufacturing components, life cycle analysis, and end-of-life activities. There are papers that include EIOLCA discussions on some of these topics. However, no known work views remanufactured vehicles as substitutes for newly manufactured products while considering both the economic and environmental impact in an input-output context.

The EIOLCA model has an interesting past; Leontief moved from Russia to the U.S. where his work was caught in post-World War II budget battles by those fearing centrally-planned models to be communistic. In 2005, Bezdek and Wendling used the model to show that the Corporate Average Fuel Economy (CAFE) program would save consumers money in automotive fuel consumptions and create jobs [7].

Gutowski et al. demonstrated, in 2011, that widely-held notions of remanufacturing did not save as much energy as previously thought. This work pulled the use-phase into consideration for several popular remanufactured products. A key conclusion was that for "products with no, or an unchanging, use phase energy requirement, remanufacturing can save energy [8]."

Using financial and design control incentives, Giuntini made the case in 2012 that the Original Equipment Manufacturers (OEMs) should offer remanufactured vehicles. This effort would see the "Big-3" create a new business model, but the primary motivation was a combination of market share, financial losses, and increasing irrelevancy in the financial investment community [9].

Using the EIOLCA Tool

There are five configuration steps for the tool. The first step is to choose the model. The EIOLCA model used for the current analysis is the U.S. 2002 Producer Price Benchmark Model, comprised of 428 sectors. There is a 1997 model; however, we selected the 2002 model because the 2002 model is closer to the light-vehicle model year likely considered a candidate for vehicle remanufacturing, and the 2002 model includes more categories of results for evaluation.

The next step is to specify the industry (labeled as the Broad Sector Group) and sector (listed as the Detailed Sector). For the manufacturing baseline, the choice is straightforward-the Industry selected was Vehicles and Other Transportation Equipment, while the selected Sector was Light Truck and Utility Vehicle Manufacturing.

The third step is to select the amount of economic activity for the sector. Our experience has shown, depending on the service level, a 50% reduction in the cost to the operator of the typical remanufactured vehicle. The vehicle is "reset" to a mission capable condition for half the cost of a newly manufactured vehicle. For round numbers, we selected $2 million economic activity for manufacturing such that 50% of that amount, $1 million economic activity, was applied for remanufacturing.

Selecting the category of results to display is the fourth step. The ten categories of results (hereafter referred to as result sets) for this model are the following:

- Economic Activity
- Conventional Air Pollutants
- Greenhouse Gasses
- Energy
- Resource Conservation and Recovery Act (RCRA) Hazardous Waste
- Toxic Releases
- Water Withdrawals
- Transportation
- Land Use
- TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) Impact Assessment

The last step is to run the model. The results in every EIOLCA model category were downloaded [10] and consolidated into one spreadsheet workbook.

With this data saved, we then configured the model for the remanufacturing proxy. The proxy Industry was Other Services, Except Public Administration and the Sector was Automotive Repair and Maintenance, Except Car Washes.

Edmunds lists the 2015 Chevrolet Silverado 2500HD dealer price as $40,695 [11]. Assuming the fleet buyer is successful at negotiating a discount, we can use $40,000 as a round number. Therefore, a remanufactured Silverado 2500 from model year 2002 would cost about $20,000. The $2 million manufacturing economic activity produces fifty vehicles while the $1 million remanufacturing yields the same fifty vehicles. With this amount of economic activity specified for remanufacturing, we ran the model again. The resultant data were likewise downloaded and consolidated into the spreadsheet workbook.

The output is too voluminous to report here, thus we only present the summary data. However, the reader is encouraged to learn more about the model at http://www.eiolca.net/; as well as the excellent treatment of interpreting the results at http://www.eiolca.net/Method/

Interp_Results.html. The example used in the online results interpretation is the EIOLCA tool using the 1997 U.S. Benchmark Model, selecting sector #336110 Automobile and Light Truck Manufacturing, and USD $1 million of economic activity. That this example exists is a fortunate coincidence for the current investigation as it assists the reader in understanding the EIOLCA method and increases the visibility of the topic in question.

As one would expect, the output, for each result set, is a table of sectors and constituent outputs for the category or result set under study. A dropdown box varies the number of top sectors displayed. Figure 1 is a screen capture of the table for Conventional Air Pollutants output for the top ten sectors for $2 million economic activity in vehicle manufacturing.

Sector		CO t	NH3 t	NOx t	PM10 t	PM2.5 t	SO2 t	VOC t
	Total for all sectors	*5.50*	*0.211*	*3.11*	*1.01*	*0.419*	*3.22*	*1.58*
331110	Iron and steel mills	1.19	0.003	0.177	0.049	0.040	0.132	0.040
33131A	Alumina refining and primary aluminum production	0.675	0.001	0.029	0.021	0.014	0.215	0.009
484000	Truck transportation	0.422	0.001	0.446	0.127	0.022	0.009	0.047
336300	Motor vehicle parts manufacturing	0.362	0.002	0.065	0.015	0.010	0.034	0.096
325182	Carbon black manufacturing	0.298	0.000	0.023	0.004	0.003	0.160	0.006
221200	Natural gas distribution	0.175	0.000	0.008	0.000	0.000	0.003	0.008
331200	Iron, steel pipe and tube manufacturing from purchased steel	0.171	0.000	0.025	0.008	0.007	0.019	0.011
532400	Commercial and industrial machinery and equipment rental and leasing	0.135	0.000	0.002	0.000	0.000	0.000	0.011
420000	Wholesale trade	0.129	0.000	0.127	0.035	0.007	0.009	0.068
211000	Oil and gas extraction	0.113	0.000	0.082	0.000	0.000	0.006	0.114

Figure 1. EIOLCA output for Conventional Air Pollutants.

A download button is available on the output page to save the data to a spreadsheet file. The first column is a list of sector NAICS codes, the second column is the sector name, and the other columns are the result set constituents. The first row is a header, the second row is the total for all sectors, and the remaining rows are the resultant sectors.

EIOLCA Tool Exposes the True Impact

Returning to the output from the EIOLCA model and using the results category "Conventional Air Pollutants" as an example, the manufacturing activity produces the following output for the top ten sectors (only Carbon Monoxide (CO) and mono-nitrogen oxides (NOx) are included for brevity and clarity):

Table 2. Selected EIOLCA results from Conventional Air Pollutants in $2 million Economic Activity in Vehicle Manufacturing.

Sector Code	Sector Name	CO ton	NOx ton
	Total for all sectors	*5.5*	*3.11*
331110	Iron and steel mills	1.19	0.177
33131A	Alumina refining and primary aluminum production	0.675	0.029
484000	Truck transportation	0.422	0.446
336300	Motor vehicle parts manufacturing	0.362	0.065
325182	Carbon black manufacturing	0.298	0.023
221200	Natural gas distribution	0.175	0.008
331200	Iron, steel pipe, and tube manufacturing from purchased steel	0.171	0.025
532400	Commercial and industrial machinery and equipment rental and leasing	0.135	0.002
420000	Wholesale trade	0.129	0.127
211000	Oil and gas extraction	0.113	0.082

The remanufacturing activity produces the following output for the top ten sectors (again, only Carbon Monoxide (CO) and mono-nitrogen oxides (NOx) are included for brevity and clarity):

Table 3. Selected EIOLCA results from Conventional Air Pollutants in $1 million Economic Activity in Vehicle Remanufacturing.

Sector Code	Sector Name	CO ton	NOx ton
	Total for all sectors	*1.38*	*0.929*
8111A0	Automotive repair and maintenance, except car washes	0.234	0.06
331110	Iron and steel mills	0.163	0.024
484000	Truck transportation	0.115	0.122
33131A	Alumina refining and primary aluminum production	0.087	0.004
492000	Couriers and messengers	0.082	0.086
336300	Motor vehicle parts manufacturing	0.051	0.009
532400	Commercial and industrial machinery and equipment rental and leasing	0.047	0.00
325182	Carbon black manufacturing	0.041	0.003
811400	Household goods repair and maintenance	0.041	0.00
221200	Natural gas distribution	0.04	0.002

EIOLCA Result Set Descriptions

Table 4. EIOLCA selected result set descriptions

Result	Unit	Description
Total Economic	$mill	The complete economic supply chain of purchases needed to produce the level of output ($mill = millions of dollars)
Total Value Added	$mill	The total value added by sector. Value Added represents the difference between output and supply chain purchases. VA includes labor costs, interests, rents, royalties, dividends, and profit payments; and excise and sales taxes paid by individuals to businesses.
CO	t	Emissions of carbon monoxide to the air from each sector.
NOx	t	Emissions of nitrogen oxides to the air from each sector.
SO2	t	Emissions of sulfur dioxide to the air from each sector.
VOC	t	Emissions of volatile organic compounds to the air from each sector.
N2O	t CO2e	Emissions of nitrous oxide (N2O) into the air from each sector (100-year GWP value is 310).
Fugitive	kg	Releases to air that do not occur through a confined air stream, including equipment leaks, evaporative losses from surface impoundments and spills, and releases from building ventilation systems. Sometimes called releases from nonpoint sources.
Stack	kg	Releases to air that occur through confined air streams, such as stacks, vents, ducts, or pipes. Sometimes called releases from a point source.
OzoneDep	kg CFC-11e	Ozone depletion air
HH Cancer (high)	kg benzene eq	Human health - cancer (high estimate)

In the current analysis, we transposed the results in each category to create a rank-ordered list to compare the impact of manufacturing and remanufacturing. The model output is voluminous; equally tedious is the description of each of the 60 result categories in ten result sets. In order to fully interpret the results, the reader will need to understand the description of each result category. As this detail is beyond the scope of this paper, please refer to the EIOLCA 2002 Impact Glossary (http://www.eiolca.net/tutorial/EIOLCA_Impact_Glos.html) [12]. Table 4 presents a sample of selected results to illustrate typical output.

Results

We normalized the results by the numbers of vehicles produced by each economic activity. Therefore, direct comparison of the result sets is allowed. In Table 5, the column labeled Mfg:Rmn shows the value obtained by dividing the manufacturing result by the remanufacturing result. We only present the first ten results for brevity and clarity.

For example, the first item in the table is the amount of air transportation required by manufacturing to produce fifty vehicles (8,810 ton-km) and that required in the remanufacturing process to produce the same fifty vehicles (988 ton-km); the manufacturing to remanufacturing ratio (Mfg:Rmn) is 892%. That is, manufacturing consumes almost nine times as much air transportation as remanufacturing. A ratio greater than 100% shows the category or result favors remanufacturing.

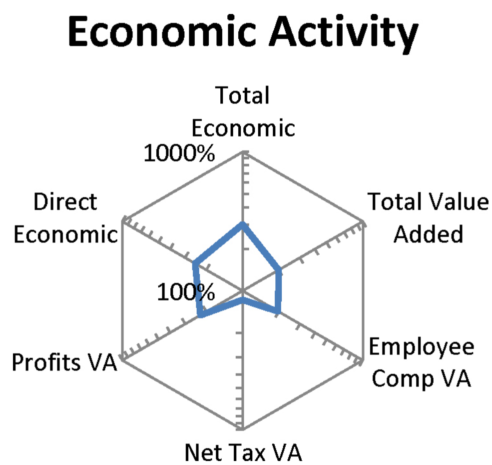
Table 5. Manufacturing compared to Remanufacturing using the EIOLCA model (top ten results).

Input	Parameter	Unit	Mfg	Rmn	Mfg:Rmn
Transportation	Air	ton-km	8,810	988	892%
Toxic Releases	POTW Metal	kg	3.42	0.39	868%
Transportation	Truck	ton-km	1,090,000	139,000	784%
Transportation	Rail	ton-km	1,140,000	148,000	770%
Toxic Releases	Fugitive	kg	59.20	8.22	720%
Land Use	Land Use	kha	0.12	0.02	700%
Toxic Releases	POTW Nonmetal	kg	101.00	14.50	697%
Transportation	Intl Air	ton-km	16,700	2,400	696%
Toxic Releases	Total Air	kg	378.00	54.50	694%
Toxic Releases	Stack	kg	318.00	46.30	687%

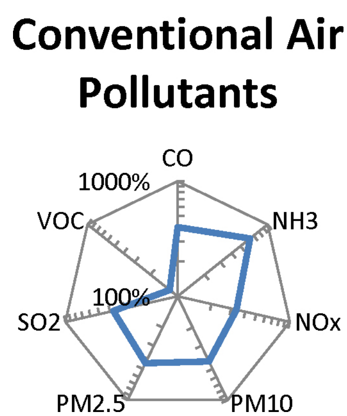
Having worked through this process, a comprehensive comparison between manufacturing and remanufacturing is now possible.

The following plots reduce the large volume of data to a depiction of each result set in order to visualize the entire output from the model. In general, the farther the data point from the center, the better the case for remanufacturing; all radar plots show parity or 100% in the center of the plot. See the appendix for an explanation of abbreviations used in the plots.

Only one result from sixty was favorable for manufacturing: Direct Economic Activity in percentage terms. One would expect this result because the analysis started with twice as much manufacturing economic activity. Surprisingly, the Direct Economic Activity in percentage terms result ratio was 82% instead of 50%; therefore, even in this one result, remanufacturing has the edge because the ratio exceeded 50%. We omitted this result from the plot to preserve uniformity. Direct Economic Activity in dollar terms does appear in the plot; refer to Table 6 for Carnegie Mellon's full description of this result set. The average ratio across all Economic Activity results was 195%.

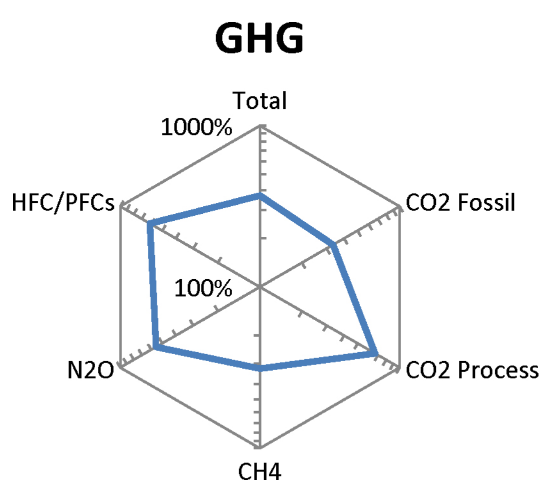


Graph 1. EIOLCA Economic Activity result set.



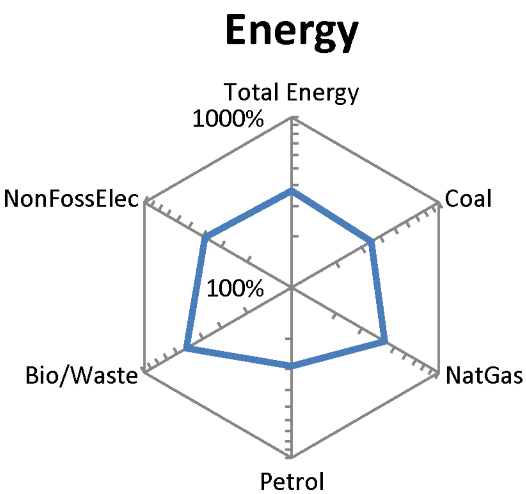
Graph 2. EIOLCA Conventional Air Pollutants result set.

The average ratio in Conventional Air Pollutants was 391%. An interesting result in this category was Volatile Organic Compounds (VOC), where the ratio was a close 122%. One possible explanation for this result is the amount of painting involve in vehicle repair, a prevalent activity in the proxy sector.



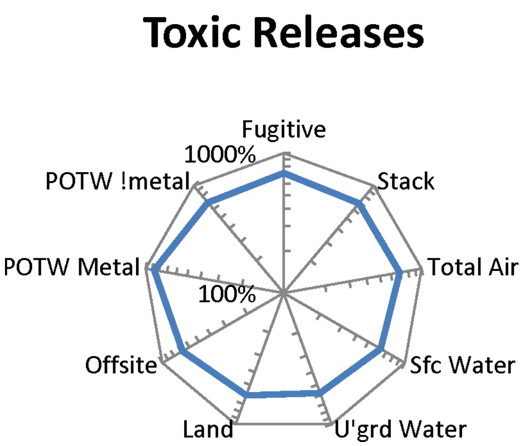
Graph 3. EIOLCA Greenhouse Gases result set.

The Green House Gas average ratio was 476%, which includes a 667% ratio for the CO2 Process. This is defined as "Emissions of Carbon Dioxide (CO2) into the air from each sector from sources other than fossil fuel combustion sources [12]."



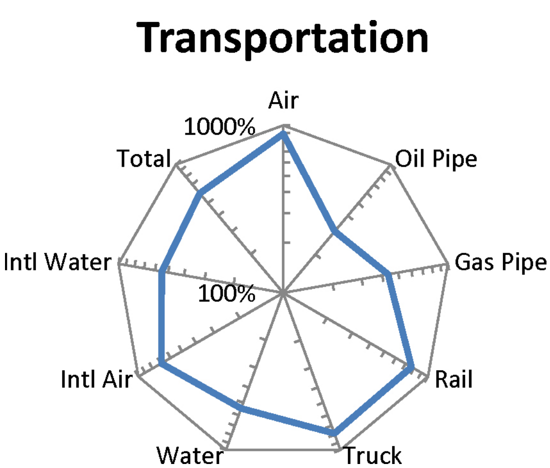
Graph 4. EIOLCA Energy result set.

Energy has been a topic often studied by the EIOLCA model applied to remanufacturing. This category average ratio was 390%. For those interested in biofuel and waste fuel use, the data reveals this use shows up better in remanufacturing with a ratio of 518%.



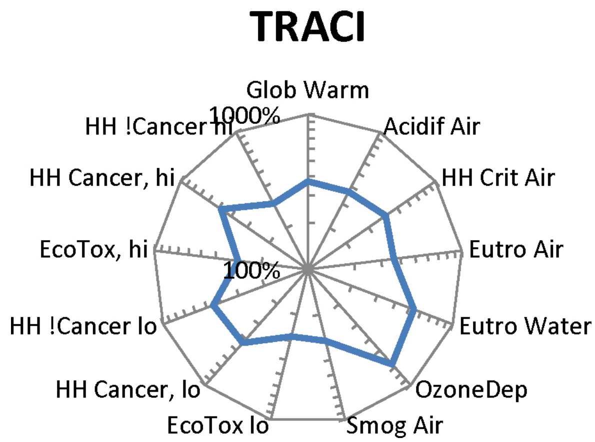
Graph 5. EIOLCA Toxic Releases result set.

Ratios were fairly uniform across Toxic Releases; the standard deviation was 79% with an average of 684%. Graphing software required using "!" to abbreviate the prefix "non."



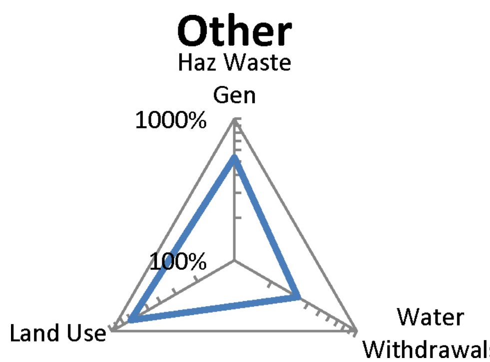
Graph 6. EIOLCA Transportation result set.

The Oil Pipeline result ratio in Transportation was somewhat of an outlier at 302% compared to an average of 618%. At present, no hypothesis for this difference has emerged.



Graph 7. EIOLCA TRACI Impact Assessment result set.

Remanufacturing is more ozone friendly with an ozone layer depletion ratio of 659% compared to manufacturing. The ozone layer depletion value "Represents the ozone depletion impacts of chemicals released into the air from each sector (kg CFC-11 equivalent). Values obtained from the US Environmental Protection Agency Ozone Depletion Potential List and Eco-Indicator 99." [12]. Graphing software required using "!" to abbreviate the prefix "non"; HH denotes "human health."



Graph 8. EIOLCA Water Withdrawals, Land Use, and Hazardous Waste Generation result sets.

Water Withdrawals (329%), Land Use (700%), and Hazardous Waste Generation (534%) are single-member result sets and are presented together to save space.

Discussion

To more pointedly illustrate how bias is built into policy decisions, we now turn to the specific issue of NOx emissions. From the results, the Conventional Air Pollutants result set, the NOx output for manufacturing, is 3.11 tons compared to 0.93 tons for remanufacturing or a Mfg:Rmn ratio of 335%.

With the reminder that we are using a 2002-vintage light truck in our analysis, we turn to the EPA's emission standards in place at the time. We find 0.4g/mi in Table A97-1 for the Intermediate Useful Life Standards For Light Light-Duty Trucks; the corresponding table A97-2 lists the Full Useful Life Standards For Light Light-Duty Trucks at 0.6g/mi [13].

As of 2007, the Tier 2, phased implementation was complete; the current levels of NOx emissions initially are 0.07g/mi (0-50,000mi) and 0.2g/mi for the remaining useful life [14].

With this information, we now can construct the NOx emissions for fifty new 2015 light duty trucks, over a useful life of 120,000mi, given by:

$$NOx_{50veh\,2015} = 50{,}000\text{mi} * \left(\frac{0.07\text{g}}{\text{mi}}\right) + 70{,}000\text{mi} * \left(\frac{0.2\text{g}}{\text{mi}}\right)$$
$$= 17{,}500\text{g} * 50 * \text{t}/1000000\text{g}$$
$$= 0.88\text{t} \tag{7}$$

The corresponding in-use NOx emissions for the fifty remanufactured 2002 light-duty trucks, over the same useful life of 120,000mi, is:

$$NOx_{50veh\,2002} = 50{,}000\text{mi} * \left(\frac{0.4\text{g}}{\text{mi}}\right) + 70{,}000\text{mi} * \left(\frac{0.6\text{g}}{\text{mi}}\right)$$
$$= 62{,}000\text{g} * 50 * \text{t}/1000000\text{g}$$
$$= 3.10\text{t} \tag{8}$$

The in-use phase reduction of NOx emissions for newly-manufactured vehicles is obvious. It is no surprise that governments, such as that of the state of Texas, are interested in reducing the number of older vehicles in service. However, this policy decision and the release of grant monies do not consider the build phase. The EIOLCA model suggests the build phase contribution for fifty newly-manufactured light-duty trucks is 3.11 metric tons, while the remanufactured NOx burden is only 0.93t.

Combining the build and the in-use phases shows that manufactured vehicles are responsible for 3.99t NOx, while remanufactured vehicles produce 4.03t NOx. However, remanufacturing saves $1 million over manufacturing. This $1 million otherwise would be available for direct investment. When one considers the tax monies diverted to grants and subsidies to retire older vehicles, the economic impact is even worse. In effect, the manufactured vehicle option not only loses $1 million, it wastes any tax revenue targeted for replacement grants or other reduction initiatives.

As the emission standards have become more stringent and original equipment manufacturers have repeatedly answered the call to reduce emissions, we are now entering a period of distinct, declining marginal utility, also known as the point of diminishing returns. For example, within the next several years, Tier 2 vehicles will no longer be candidates for remanufacture. The future cores used for remanufacture will have engines and systems with low emissions standards. Therefore, an analysis such as this one, performed ten years hence, will show a dramatic need for, and preference for remanufacturing the vehicle instead of building it new.

Conclusion

From an economic or environmental perspective, the preference for remanufactured vehicles is obvious. At present, “remanufacture” is not even in spell-check software. There are no governmental policies in place for serious consideration of remanufactured vehicles. NAICS does not yet list a code for remanufacturing. Government policy actions do not consider a remanufactured vehicle as a possible or logical substitute for a newly manufactured vehicle. Standard sourcing and purchase requests do not include remanufactured vehicles as options.

There is no fault with governmental policy or legislative actions - there has never been a serious, enterprise-level remanufacturing component in the industry.

At present, there are few to no enterprise-level vehicle remanufacturers. Perhaps UPS’s best-kept secret is its competitive advantage gained in repeatedly rebuilding its package cars (i.e., delivery vans) while they accumulate a million miles or more [15]. Less well known are the award-winning efforts by the Red River Army Depot near Texarkana, TX to “reset” High Mobility Multipurpose Wheeled Vehicles (HMMWVs or Humvees) and other vehicles [16]. The only known, large-scale, passenger vehicle remanufacturing activities, at present, are taxicab rebuilds undertaken by their owners.

The reality of declining marginal utility for in-use phase emissions will result in focusing environmental attention farther back in the life cycle. The EIOLCA build-phase results show that remanufacturing is a better economic and environmental alternative than manufacturing in every EIOLCA category. The time has come to take a serious look at enterprise-level remanufacturing as a safe, economical, and environmentally responsible alternative to newly manufactured vehicles.

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APPENDIX

Table 6. EIOLCA Economic Activity result set parameter descriptions.

EIOLCA Parameter	Acronym / Abbreviation Used	Unit	Parameter Definition
Total Economic Supply Chain Purchases	Total Economic	$mill	The complete economic supply chain of purchases needed to produce the level of output ($mill = millions of dollars).
Total Value Added	Total Value Added	$mill	The total value added by sector. Value Added represents the difference between output and supply chain purchases. VA includes labor costs, interests, rents, royalties, dividends, and profit payments; and excise and sales taxes paid by individuals to businesses.
Employee Compensation Value Added	Employee Comp VA	$mill	The portion of value added in the form of employee compensation, aka labor costs.
Net Tax Value Added	Net Tax VA	$mill	The portion of value added associated with taxes paid, minus any subsidies received, for example from agriculture subsidies.
Profits Value Added	Profits VA	$mill	The portion of value added in the form of profits.
Direct Economic Effects in dollars	Direct Economic	$mill	Direct Economic effects represent the purchases made by the industry being analyzed (as opposed to the total supply chain effects defined above that include direct and all indirect purchases).
Direct Economic Effects in percentage	Direct Economic	%	Direct Economic effects represent the purchases made by the industry being analyzed (as opposed to the total supply chain effects defined above that include direct and all indirect purchases).

Table 7. EIOLCA Conventional Air Pollutants result set parameter descriptions.

EIOLCA Parameter	Acronym / Abbreviation Used	Unit	Parameter Definition
Carbon Monoxide	CO	t	Emissions of Carbon Monoxide to Air from each sector.
Ammonia	NH3	t	Emissions of Ammonia to Air from each sector.
Nitrogen Oxides	NOx	t	Emissions of Nitrogen Oxides to Air from each sector.
Large Particulate Matter	PM10	t	Emissions of Particulate Matter (less than 10 microns in diameter) to Air from each sector. Value is Primary PM.
Small Particulate Matter	PM2.5	t	Emissions of Particulate Matter (less than 2.5 microns in diameter) to Air from each sector. Value is Primary PM.
Sulfur Dioxide	SO2	t	Emissions of Sulfur Dioxide to Air from each sector.
Volatile Organic Compounds	VOC	t	Emissions of Volatile Organic Compounds to Air from each sector.

Table 8. EIOLCA Greenhouse Gases result set parameter descriptions.

EIOLCA Parameter	Acronym / Abbreviation Used	Unit	Parameter Definition
Global Warming Potential	Total	t CO2e	Global Warming Potential (GWP) is a weighting of greenhouse gas emissions into the air from the production of each sector. Weighting factors are 100-year GWP values from the IPCC Second Assessment Report (IPCC 2001).
Carbon Dioxide from Fossil Fuels	CO2Fossil	t CO2e	Emissions of Carbon Dioxide (CO2) into the air from each sector from fossil fuel combustion sources.
Carbon Dioxide from other than Fossil Fuels	CO2 Process	t CO2e	Emissions of Carbon Dioxide (CO2) into the air from each sector from sources other than fossil fuel combustion sources.
Methane	CH4	t CO2e	Emissions of Methane (CH4) into the air from each sector (100-year GWP value is 21).
Nitrous Oxide	N2O	t CO2e	Emissions of Nitrous Oxide (N2O) into the air from each sector (100-year GWP value is 310).
Hydrofluorocarbons	HFC/PFCs	t CO2e	Emissions of all high-GWP gases such as hydrofluorocarbons, perfluorocarbons, and
/ Perfluorocarbons			sulfur hexafluoride into the air from each sector (100-year GWP values vary).

Table 9. EIOLCA Energy result set parameter descriptions.

EIOLCA Parameter	Acronym / Abbreviation Used	Unit	Parameter Definition
Total Energy from all fuels	Total Energy	TJ	Total energy use from all fuels and electricity from all sectors. Note that the total for each sector is the sum of all fuel sources plus only 31% of electricity to account for non-fossil fuel sources of electricity. Including all electricity would double count the fuel used to make the electricity, thus only the 31% that comes from non-fossil sources is included.
Coal	Coal	TJ	Coal used by each sector.
Natural gas	NatGas	TJ	Natural gas used by each sector.
Petroleum-based	Petrol	TJ	Petroleum-based fuels used by each sector.
Biomass / Biowaste fuel	Bio/Waste	TJ	Biomass/Waste fuel used by each sector.
Non-Fossil Fuel Electricity	NonFossElec	TJ	Non-fossil electricity used by each sector.

Table 10. EIOLCA Toxic Releases result set parameter descriptions.

EIOLCA Parameter	Acronym / Abbreviation Used	Unit	Parameter Definition
Fugitive Releases	Fugitive	kg	Releases to air that do not occur through a confined air stream, including equipment leaks, evaporative losses from surface impoundments and spills, and releases from building ventilation systems. Sometimes called releases from nonpoint sources.
Stack Releases	Stack	kg	Releases to air that occur through confined air streams, such as stacks, vents, ducts or pipes. Sometimes called releases from a point source.
Total Air Releases	TotalAir	kg	Total releases to air include all TRI chemicals emitted by a plant from both its smoke stack(s) as well "fugitive" sources (such as leaking valves).
Surface Water Discharges	SurfaceWater	kg	Releases to water include discharges to streams, rivers, lakes, oceans and other bodies of water. This includes releases from both point sources, such as industrial discharge pipes, and nonpoint sources, such as stormwater runoff, but not releases to sewers or other off-site wastewater treatment facilities. It includes releases to surface waters, but not ground water.
Underground Water Discharges	U'groundWater	kg	Underground injection releases fluids into a subsurface well for the purpose of waste disposal. Wastes containing TRI chemicals are injected into either Class I wells or Class V wells.
Land Releases	Land	kg	Land releases include all the chemicals disposed on land within the boundaries of the reporting facility, and can include any of the following types of on-site disposal:
Offsite Releases	Offsite	kg	The total quantity of TRI chemicals that were released to the environment or disposed of not at the facility.
POTW Metal	POTWMetal	kg	Publicly Owned Treatment Works wastewater treatment facility for metals.
POTW Non-Metal	POTWNonMetal	kg	Publicly Owned Treatment Works wastewater treatment facility for non-metals.

Table 11. EIOLCA Transportation result set parameter descriptions.

EIOLCA Parameter	Acronym / Abbreviation Used	Unit	Parameter Definition
Air Freight	Air	ton-km	Movement of inputs/freight via air.
Oil Pipeline	Oil Pipe	ton-km	Movement of inputs/freight via oil pipeline.
Gas Pipeline	Gas Pipe	ton-km	Movement of inputs/freight via gas pipeline.
Rail Freight	Rail	ton-km	Movement of inputs/freight via rail.
Truck Freight	Truck	ton-km	Movement of inputs/freight via truck.
Water Freight	Water	ton-km	Movement of inputs/freight via water.
International Air Freight	Intl Air	ton-km	Movement of inputs/freight via international air.
International Water Freight	Intl Water	ton-km	Movement of inputs/freight via international water (e.g., ship).
Total Freight	Total	ton-km	Total Movement of inputs/freight via all modes.

Table 12. EIOLCA TRACI Impact Assessment result set parameter descriptions.

EIOLCA Parameter	Acronym / Abbreviation Used	Unit	Parameter Definition
Global Warming Air	Glob Warm	kg CO2e	CO2 equivalent gases.
Acidification Air.	Acidif Air	kg SO2e	SO2 equivalent gases.
Human Health Criteria Air.	HH Crit Air	kg PM10e	PM10 equivalent gases.
Eutrophication Air	Eutro Air	kg Ne	Nitrogen equivalents.
Eutrophication Water	Eutro Water	kg Ne	Nitrogen equivalents.
Ozone Depletion Air	OzoneDep	kg CFC-11e	CFC-11 equivalents.
Smog Air	Smog Air	kg O3e	Ozone equivalent releases.
EcoTox (low)	EcoTox lo	kg 2,4D	Ecotoxicity (Low estimate); 2,4D (2,4-Dichlorophenoxyacetic acid) emitted to continental freshwater equivalent releases.
Human Health Cancer (low)	HH Cancer, lo	kg benzene eq	Human Health - Cancer (Low estimate); benzene emitted to urban air equivalent releases.
Human Health NonCancer (low)	HH !Cancer lo	kg toluene eq	Human Health - Non-cancer (Low estimate) ; toluene emitted to urban air equivalent releases.
EcoTox (high)	EcoTox, hi	kg 2,4D	Ecotoxicity (High estimate) ; 2,4D (2,4-Dichlorophenoxyacetic acid) emitted to continental freshwater equivalent releases.
Human Health Cancer (high)	HH Cancer, hi	kg benzene eq	Human Health - Cancer (High estimate) ; benzene emitted to urban air equivalent releases.
Human Health NonCancer (high)	HH !Cancer hi	kg toluene eq	Human Health - Non-cancer (High estimate) ; toluene emitted to urban air equivalent releases.

Table 13. EIOLCA Water Withdrawals, Land Use, and Hazardous Waste Generation result set parameter descriptions.

EIOLCA Parameter	Acronym / Abbreviation Used	Unit	Parameter Definition
Water Withdrawals	Water Withdrawals	kGal	Thousands of gallons withdrawn.
Land Use	Land Use	kHa	Thousands of hectares.
HazWasteGen	HazWasteGen	st	Estimated amount of RCRA Hazardous Waste Generated. RCRA is US EPA's Resource Conservation and Recovery Act, which seeks to assure that hazardous waste is properly managed. EPA manages which substances are subject to reporting to this Act. Source - EPA RCRA Subtitle C biannual report.

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