TRACI Assessment of Transportation Manufacturing Nexus in the U.S.: A Supply Chain-linked Cradle-to-Gate LCA

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Abstract

Sustainable transportation is an inevitable component of sustainable development intitiatives for mitigating the climate change impacts and stabilizing the rising carbon emissions thus global temperature. In this context, comprehensive analysis of the environmental impact of transportation can play a critical role towards quantifying the midpoint environmental and human health related impacts associated with the transportation activities triggered by manufacturing sectors. This study traces the life cycle impact of the U.S. transportation and manufacturing sectors' nexus using Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) in the context of the Economic Input-Output Life Cycle Assessment (EIO-LCA) framework considering the following midpoint impact categories: 'global warming', 'particulate matter', 'eutrophication', 'acidification', and 'smog air'. Both direct (onsite) and indirect (supply chain) industries' relationships with transportation industry are considered as the main scope. Results indicated that top ten contributor manufacturing sectors accounted for over 55% total environmental impacts on each impact category. Additionally, based on the decomposition analysis, food manufacturing sector was found to be the major contributor to smog air with an approximate share of 21% in the entire supply chain. Automobile related manufacturing sectors also have significant impact on all five life cycle impact categories that the environmental impact of transportation

is higher than on-site (direct) impact. Overall decomposition analysis of 53 manufacturing sector indicated that the environmental impact of transportation has severe effects on 'smog air', 'eutrophication' and 'acidification' with a share of 16.4%, 10.5%, and 6.0%, respectively. When we consider the average percentage share of transportation related environmental impact on the entire supply chain, U.S manufacturing sectors have a negative impact with a share of 18.8% of 'smog air', 16.8% for 'eutrophication', and 8.1% for 'acidification'.

Keywords: TRACI, EIO-LCA, Life cycle impact assessment, Sustainable transportation /manufacturing nexus

1. Introduction

Transportation industry is a critical sector which acts as a bridge between most of the remaining sectors for transporting goods and services in a national economy (Tseng et al., 2005). Especially for manufacturing industries, transportation sector is essential and critical since raw material, semi-finished goods and final products are carried through the industries within the supply chains to the end-users. In spite of its critical contributions to a country's economic sustainability, in fact, transportation industry also acts as a major driver for environmental impacts such as carbon emissions which effects global warming and human health issues significantly (Wakeland et al., 2012), because transportation activities are directy associated with green house gas (GHG) emissions, energy footprints, and dissemination of air pollutants, tbus severely affecting the Earth's sutainability (Huzayyin and Salem, 2013; Costanza and Mageau, 1999). Sustainable transportation is termed as the expression of sustainable development in the transportation sector (Ramani et al., 2009), and significant amount of work has been proposed on quantifying environmental impacts of transportation systems and developing policies towards sustainable transportation systems (Benjaafar and Savelsbergh, 2014). Especially, recent research focuses include invesitation of the interdependencies between economic, environmental and social aspects of transportation systems (Maheshwari et al., 2014). Numerous state of art practical and methodological contributions for the sustainable transporation issues of the U.S. exist in the literature, which include sustainability performance measure of transportation system (Paz et al., 2013), dynamic approach to quantify sustainbility performance of transportaiton systems (Maheshwari et al., 2014, Egilmez and Tatari, 2012), and sustainability footprint modeling for the U.S metropolitan areas (Amekudzi et al., 2009).

Regarding the environmntal impacts of transportation, World Health Organization (WHO, 1999) estimated air pollution generated from motor vehicles, and concluded that air pollution causes more death than all traffic accident. Furthermore, transportation in United States (U.S.) regrettably exacts dreadful toll in damaged health (NSTPRSC, 2007). Although the U.S. accounts for only five percent of world's total population, they contribute over 25 percent of Green House Gases (GHGs), due to rising motor vehicle emissions, fossil fuel consumption, and various industrial activities undertaken in the country's economy (Bell, 2009). According to Environmental Protection Agency's report (EPA, 2013), transportation activities account for 27% of the national total GHG emissions, while emissions from industrial sectors account for 20%. These statistics reveal that the inherent relationship between the manufacturing

industries and transportation activities is of importance to study comprehensively from an environmental and socio-economic sustainability perspective (Ewing et al., 2011, Egilmez et al., 2013, 2014). In this context, measuring and evaluating the environmental impact potentials of transportation activities associated with the manufacturing sectors and supply chains of the U.S. economy can be used as a practical approach to address the relationships from a supply chain-linked environmental impact assessment perspective.

While life cycle assessment is generally understood as the quantification of the environmental impacts (e.g. GHG emissions, energy use, water use, etc.) of products or processes, life cycle impact assessment takes the analysis to the next step where human-health (e.g. air pollution) and eco-system related (e.g. eco-toxicity) impacts, so called end-point impacts, are derived from the environmental impacts (Huzayyin and Salem, 2013). Even though, life cycle assessment needs to be performed comprehensively that consideres two dimensions of life cycle assessment: horizontal and vertical. In the horizontal dimensions, multiple environmental impact categories need to be addressed simultaneously, whereas the vertical dimensions need to go through from mid-point to end-point impacts. In fact, majority of the literature on deriving environmental sustainability impacts of transportation activities address the general environmental footprint categories such as carbon, energy and water footprint impacts, where the mid-point impacts are kept out of focus (Egilmez and Park, 2014; Park et al., 2015). In this study, transportation-related impacts of manufacturing activities and supply chains in the U.S. are studied comprehensively with an input-output-based LCA framework where the environmental impacts are traced to the mid-point dimensions such as global warming potential, particulate matter, eutrophication, acidification, smog air. The rest of the paper is organized as follows. Section 2 provides the literature review related to this study. Section 3 describes the economic input-output life cycle assessment (EIO-LCA) methodology. The results and analysis are summarized in Section 4. Finally, Section 5 provides the conclusions and future research.

2. Literature Review

Life cycle assessment (LCA) is a well- known and widely used tool to assess the environmental impacts considering the entire life cycle of products or production systems and supply chains, from raw material extraction through acquisition, production, manufacturing, to use and end-of-life and disposal (Hendrickson et al., 1998; Curran, 1996). LCA was firstly used in energy analysis for tracing the environmental burdens in the 1970s and then the full modeling was introduced in the 1980s and improved singnificantly in 1990s. In the last two decades, LCA has been gradually developed as a more comprehensive environment assessment tool (Guinee and Heijungs, 2010) by focusing on various environmental impact categories such as particulate matter, natural environment, resource consumption (renewable and nonrenewable), etc. (Finnveden et al., 2009). In the past decades, international corpoarates around the world started to adopt LCA tools in macro level decision making processes to measure and understand the overall environmental impacts of their processes and products towards realizing their environmental sustainability goals . A typical life cycle inventory (LCI) consists of the amount of all input(s)/output(s) related to the processes that compromises the life cycle of a product or system (Ewing et al., 2011). Among the LCA

techniques, process-based LCA (P-LCA) and economic input-output LCA (EIO-LCA) are widely used. P-LCA captures the environmental discharges by quantifying energy and material use from all life cycle processes (Ewing et al., 2011). P-LCA has been applied to various research fields such as ready meals (Calderón et al., 2010), fisheries (Vázquez-Rowe et al., 2010; Lozano et al., 2010), agriculture (Mohammadi et al., 2013; Vázquez-Rowe and Villanueva-Rey, 2012), dairy farm (Iribarren et al., 2011; Eide, 2002), energy (Iribarren et al., 2014; Barba-Gutiérrez et al., 2008) and construction (Tatari and Kucukvar, 2011). But these works pay specific attention to the limited phases of the life cycle such as onsite (process impacts) where the indirect impacts associated with supply chains were not considered. Recent literature promotes the use of EIO-LCA developed by Carnegie Mellon University (CMU, 2002), which provide an overview of direct and indirect environmental impact and identify the sectors that contribute most of the manufacturing sector's footprint (Huang et al., 2009). Application of EIO-LCA include estimation of the environmental impact of consumption and household type (Munksgaard et al., 2008), assessment of U.S. food and manufacturing sector's environmental impact (Egilmez et al., 2013), and wastewater for reuse in cooling system associated with tertiary treatment (Theregowda et al., 2014).

The transportation-related life cycle assessment literature is abundant with works which focus on specific phases, such as design or manufacturing process, operation, or end of life, of transportation systems or lack the national economy-wide impacts (Kaniut et al., 1997; Marheineke et al.,1998; Nocker et al., 2000; Facahna and Horvath, 2006; Mayeres et al., 1996; Delucci, 1997; Levinson et al., 1998; Cobal-Flores et al., 1998; Clark, 2003; Schipper, 2004). Only a few publications have provided life cycle impacts of transportation activities comprehensively (considering supply chain impacts) such as freight transportation (Facanha and Horvath, 2006), passenger transportation (Chester and Horvath, 2009; Chester et al., 2010). However, the previous works did not account for mid-point impacts (e.g. global warming, human health, smog air) and most of the time focus was kept limited to tailpipe emissions or conventional environmental impacts. In this study, EIO-LCA is utilized to assess the environmental impacts of transportation activities associated with the U.S. manufacturing sectors from cradle to gate point of view, where Tool for the Reduction and Assessment of Chemicals and other environmental Impacts (TRACI) module is utilized to quantify the mid-point impacts. Several environmental impact indicators are considered, namely: (1) Global warming (2) Acidification (3) Eutrophication (4) particulate matter (5) Smog Air. (For a more detailed discussion about mid-point impacts, see Bare et al. 2000)

3. Methodology

3.1 EIO-LCA Framework

The Economic Input-Output Life Cycle Assessment (EIO-LCA) is a well-known model that evaluates the environmental impacts of product and process of its entire life cycle. This method utilizes all industry transactions information such as purchasing materials from other industries by one industry, direct and indirect environmental emissions of each industry, in order to estimate the total emission throughout the entire supply chain (CMU, 2002). EIO-LCA was developed by Wassily Leontief in the 1970s based on the nation's economy

EIO table with environmental impact multipliers and linear algebra. The mathematical formulation is as shown in Equation 1 (Joshi, 1999) :

$$X = [(I\text{-} A)^{-1}]\,f \tag{1}$$

Where X denotes the total industry output, I refer to the diagonal identity matrix, and f represents the vector of total final demand of industry. In addition, the term $[(I\text{-} A)^{-1}]$ known as Leontief Inverse indicate the total requirement matrix (Leontief, 1986). The total requirement matrix is then multiplied by environmental impact multipliers, termed as E_{dir}. Thus, the total environmental output is expressed as shown in Equation 2 (Hendrickson et al., 2006; Egilmez et al., 2013):

$$r = E_{dir}\,X = E_{dir}\,[(I\text{-}A)^{-1}]\,f \tag{2}$$

Where r denote the total environmental outputs per unit of final demand, E_{dir} represents a diagonal matrix which consists of the direct environmental impacts per dollar output of each industrial sector.

3.2 Data Collection and Assessment

The aforementioned EIO-LCA framework was utilized for calculating direct plus indirect environmental impacts associated with transportation and manufacturing sector transactions. The scope of this study considers 277 manufacturing sectors and their relationships with the transportation industry. Direct and indirect environmental impact and economic output of entire manufacturing sectors was aggregated into 53 major manufacturing sectors. For example, the food manufacturing sector includes 33 sub sectors such as animal, grain, daily food, etc. and each sub sector has total environmental impact of four major transportation modes (truck, rail, air and water) (Egilmez et al.,2014). Economic input-output data from the U.S. Bureau of Economic Analysis (BEA, 2002) was used to calculate total economic output of transportation activity from each sector.

In this study, TRACI is used in EIO-LCA to collect data. TRACI is a midpoint oriented life cycle assessment tool which includes human and environmental impact category (Theregowda et al., 2014). This study used five environmental impact indicators that are available in EIO-LCA model, including global warming, acidification, eutrophication, particulate matter, and smog air, which are categorized as a midpoint impact in life cycle impact assessment (LCIA). Usually, LCIA translate the findings from the life cycle inventory (LCI) into 12 different environmental impact indicators such as Global warming, Smog formation, Acidification, Eutrophication, Human health cancer, Human health non-cancer, Human health criteria pollutants, Eco-toxicity, Land use, etc. (Bare et al., 2003; Saur, 1997).

4. Results

4.1 Analysis of Life Cycle Impact Inventory

The life cycle impact inventory of transportation activities betweeen the U.S manufacturing sectors and the final consumers is quantified using the EIO-LCA model. The descriptive

statistics of life cycle impact inventory for each impact categories are presented in Table 1. The mean of each indicator was founded 3E+09kg for GW, 3E+07kg for AC, 7E+06kg for PM, 1E+06kg for EU, 8E+08kg for SA and 2811.15 M$ for economic-output (EO). Moreover, since the interpretation of the LCA is the final phase, the researchers demonstrated the top ten contributors based on the each impact category related to freight transportation activity in Table 2.

Table 1. Descriptive statistics of life cycle impact category

Category	GW	AC	PM	EU	SA	EO
Mean	3E+09	3E+07	7E+06	1E+06	8E+08	2811.15
Standard Error	6.6E+08	7E+06	2E+06	3E+05	2E+08	618.484
Median	1.7E+09	2E+07	4E+06	8E+05	4E+08	1556.37
Std. Dev.	4.8E+09	5E+07	1E+07	2E+06	1E+09	4502.63
Kurtosis	34.344	35.48	35.97	34.71	34.685	34.1632
Skewness	5.41679	5.525	5.586	5.447	5.4452	5.39823
Range	3.4E+10	3E+08	9E+07	2E+07	1E+10	31721.9
Minimum	1.1E+08	1E+06	3E+05	49505	3E+07	100.851
Maximum	3.4E+10	3E+08	9E+07	2E+07	1E+10	31822.7
Sum	1.6E+11	2E+09	4E+08	8E+07	4E+10	148991
Count	53	53	53	53	53	53

4.2 Global Warming

Global warming (GW) is termed as the average temperature increase of the atmosphere near the surface of earth and in the troposphere, which in turn cause global and regional climate change (Bare et al., 2003; Brentrup et al., 2004). International Panel on Climate Change (IPCC) proposed the most-up-to-date methods for calculating greenhouse gases potency relative to carbon dioxide (CO_2) (Forster et al., 2007). For instance, "the Earth's average temperature rose about 0.6 °Celsius (1.1 °Fahrenheit) in the 20th century and "a projection of current trends as represented by a number of different scenarios gives temperature increases of about 3 ° to 5 °C (5 ° to 9 °Fahrenheit) by the year 2100 or soon afterwards. A 3 °C or 5 ° Fahrenheit rise would likely raise sea levels by about 25 meters (about 82 feet)" (Anon., 2015).

All possible direct and indirect CO_2 emissions from freight transportation activities associated with the economic activities among the U.S. manufacturing sectors are considered. From the Table 2, global warming potential are presented in terms of kilograms of CO_2 equivalents (kg CO_2.eq) for first top ten manufacturing sector, which has the highest transportation-related GW effect. It can be observed from Table 2 that food manufacturing sector is the dominating sector, which accounted for 21.3% share of total Kg CO_2-eq of carbon dioxide followed by motor vehicle manufacturing and motor vehicle body, trailer and part manufacturing with 5.8% and 5.5% share of total CO_2 respectively. The remaining manufacturing sector's potential to global warming ranges between 2.6% and 4.2%. Transportation of the top ten sectors accounts for 55.8% of the total global warming potential

which is over half of the total impact among 53 manufacturing sectors.

4.3 Particulate Matter

Particulate matter (PM) is the complex mixture of very small particles that is formulated from anthropogenic processes (e.g. Combustion, resource extraction). Particulate matter is made up of several different sizes such as PM_{10}, $PM_{2.5}$, $PM_{0.1}$ by emission of nitrate (NO_x) and sulphates (SO_2), organic chemicals, metal, and dust particles, etc. (Bare et al., 2003; Goedkoop and Spriensma, 2000). The PM can be categorized as human health criteria indicator because respiratory tract is a main effect from particle pollution. The PM is measured in μm (PM_x means particles with a size of X μm) and its unit is the kilogram. Total amount of PM_{10} related to transportation is utilized in this study due to the data availability from EIO-LCA. From the Table 2, similar results are obtained with the GW impact results, PM_{10} eq emissions are mainly from the food manufacturing sector with a share of 22.6%, followed by motor vehicle manufacturing (5.8%) and motor vehicle body, trailer and parts manufacturing (5.4%). Particulate matter that is related to transportation activity from top ten manufacturing sectors represents about 57.1% of the total human health impact.

4.4 Eutrophication

Eutrophication (EU) is the proliferation of chemical nutrients in an ecosystem which leads to abnormal productivity in an ecosystem (Bare et al., 2003). This causes foul odor, death of fish, reduction of marine mammals. Emission of phosphorous (P), nitrogen (N), and ammonia (NH_4) from various sources, including cars, truck, and power plants are the key impact to eutrophication within LCIA. Direct and indirect impact of nitrogen is included in the analysis. The unit of eutrophication is the kilogram of N equivalent (Kg N-eq). In terms of eutrophication, food manufacturing is still found to be as the dominant sector with 22.1%, which has same portion observed in smog air followed by motor vehicle manufacturing (5.5%) and motor vehicle body, trailer, and parts manufacturing (5.3%). The top ten sector's cumulative percentage is 58.0% of total eutrophication of transportation activity.

4.5 Acidification

The acidification (AC) is the concentration of hydrogen ion [H^+] within a local environment system (Bare et al., 2003). Acid substances travel through three routes (wet, dry, and cloud water deposition). This affects the ecosystem by reducing the alkalinity of lakes or corroding building materials, human-built structure, monuments etc (Norris, 2002). When fossil fuels are burned, they release sulfur dioxide (SO_2) and nitrogen oxides (NO_x) into the atmosphere. It has a fatal impact on the ecosystem change, plant and animal death. The total amount of SO_2 associated with transportation activity is obtained from EIO-LCA and it is presented in terms of the kilogram of SO_2 equivalents (kg SO_2 eq). It is noted that food manufacturing is the dominant sector, which has the highest responsibility on acidification associated with its transportation as shown in Table 2. It accounts for the 22.5% of total acidification. The second and third sectors that have the highest contribution on acidification are motor vehicle manufacturing and motor body (5.4%), trailer and parts manufacturing sectors (5.2%)

respectively. The total share of acidification of transportation of the first ten sectors is observed at 58.2%.

4.6 Smog Air

Smog Air (SA) refers to ozone (O_3) which is formed due to the interaction of volatile organic compounds (VOCs) and oxides of nitrogen in the presence of sunlight (Rani et al., 2011). Ozone is located in the upper atmosphere and at the ground level of the earth, which has severe effects on sensitivity vegetation and ecosystems, including forests, wildlife, trees and plants as well as it causes human health effects such as skin cancer, cataracts and serious breathing problem (Bare et al., 2003). Carbone monoxides (CO), sulphur dioxide (SO2), nitrogen oxide (NO) non-methane volatile organic compound (NMVOC) are included in the impact category. This study focused on the total amount of direct plus indirect O_3 that is released by transportation from cradle-to-gate manufacturing activity and its measure unit are presented in terms of kilogram of O_3 equivalents (kg O_3-eq). As shown in Table 2, the results associated with smog air indicate that the food manufacturing sector is the dominant area which has the highest share of smog air in terms of transportation activity. Food manufacturing by itself accounts for 22.1% of total smog air, which has a huge portion compared to other sectors. The remaining sectors impact range is between 3.0 % and 5.5 %, and top ten sectors account for 58.0% of the total share of smog air.

4.7 Economic-Output

Lastly, the economic output of transportation is analyzed for top ten manufacturing sector. According to Table 2, food manufacturing share 21.4% of total economic output followed by Motor vehicle manufacturing (5.7%) and motor vehicle body, trailer, parts manufacturing (5.5%) in economic output. Top ten manufacturing sectors are observed to have 56.2% share of total economic output related to transportation activity.

Table 2. Top Ten Sectors by Percent Shares in Total Transportation Related Impacts

Manufacturing Sectors	GW	PM	EU	AC	SA	EO
Food manufacturing	21.3	22.6	22.1	22.5	22.1	21.4
Motor vehicle manufacturing	5.8	5.8	5.5	5.4	5.5	5.7
Motor vehicle body, trailer, and parts manufacturing	5.5	5.4	5.3	5.2	5.3	5.5
Nonmetallic mineral product manufacturing	4.2	4.5	4.3	4.2	4.3	4.4
Plastics and rubber products manufacturing	4.2	3.8	4.4	4.3	4.4	4.2
Basic chemical manufacturing	3.3	3.2	3.6	3.7	3.6	3.3
Petroleum and coal products manufacturing	3.1	3.1	3.1	3.2	3.1	2.9
Wood product manufacturing	3.0	3.1	3.1	3.0	3.1	3.1
Iron and steel mills and manufacturing from purchased steel	2.9	2.9	3.6	3.6	3.6	3.0
Converted paper product manufacturing	2.6	2.6	3.0	2.9	3.0	2.7
Cumulative Impact	*55.8*	*57.1*	*58.0*	*58.2*	*58.0*	*56.2*

4.8 Supply-Chain Decomposition Analysis

Results related to decomposition of total impacts by onsite, supply chain and transportation

are also provided (See Fig. 1 and 2). The onsite impacts refer to the impacts that occurred during the manufacturing/production activites at the site, the transportation impacts refer to the impacts associated with the nexus between transportation and corresponding manufacgturing industries and supply chain impacts refer to the total impact minus (transportation+onsite) impact. It was evident that food manufacturing sector has the highest responsibility of environmental and economic impact from their direct and indirect life cycle perspective from the EIO-LCA results. Other sectors that are included in the top ten also have significant environmental impact associated with its transportation. In order to deal with policy making toward reducing environmental impact of transportation, it is very crucial to look at the proportional environmental impact of transportation from the supply chain perspective. Thus, decomposition analysis for onsite (direct), transportation, and supply chain (indirect) impact was performed as a robust analysis to provide an overall understating of each sector's environmental impact. First, we considered top three manufacturing sector, including food manufacturing, motor vehicle manufacturing, motor vehicle body, and total impact of these three manufacturing sectors for decomposition analysis in Figure 1. The transportation decomposition for 53 sectors by considering supply chain were also analyzed in Figure 2.

Among the five life cycle impact categories, food manufacturing and automobile related manufacturing sectors are more prone to smog followed by eutrophication and they are the predominant impact for top ten sectors. Figure 1 presents how each life cycle impact category's total impact is distributed among the supply chain industries, transportation industu and onsite manufacturing industry. In terms of the food manufacturing sector, the total environmental impact shares for supply chain are ranged between 63% and 89.7% for the each impact domain. The environmental impact range of transportation from cradle-to-gate point of view is between 1.8% and 20.7%. In terms of onsite impact, each environmental impact indicator ranges between 4.9% and 35.5%. Transportation in the food manufacturing sector shows higher percentage share on smog air accounting 20.7 % of the total. It has a relatively large impact share when compared to the economic output of the transportation activity.

Additionally, eutrophication is a significant impact affected by transportation showing 5.4% of the total share, which is also higher than the impact of onsite (4.9%). The impact of transportation on global warming and acidification is still noticeable, and particulate matter has negligible impact. Supply chain sectors are primarily responsible for all impact for the motor vehicle manufacturing sector ranged from 69.4% to 88.2% for each impact category. However, transportation has a potential environmental impact on each category in the motor vehicle manufacturing sector, which has a relatively large portion in life cycle impact when compared to its economic activity. The percentage share for each impact category of transportation accounted for a significant amount with 6.1% of global warming, 11.1% of acidification, 9.9% of particulate matter, 21.8 % of eutrophication, and 23.8% of smog air which also have a dominant impact than the impact from onsite. The environmental impact of motor vehicle body, trailer, and pars manufacturing sector show a similar pattern with the motor vehicle manufacturing sector. Supply chains are observed as the most dominant part

and the environmental impact of transportation has a greater share of an impact category than onsite as well, which are similar to the previous findings of Egilmez et al. (2013, 2014) and Kucukvar et al. (2015).

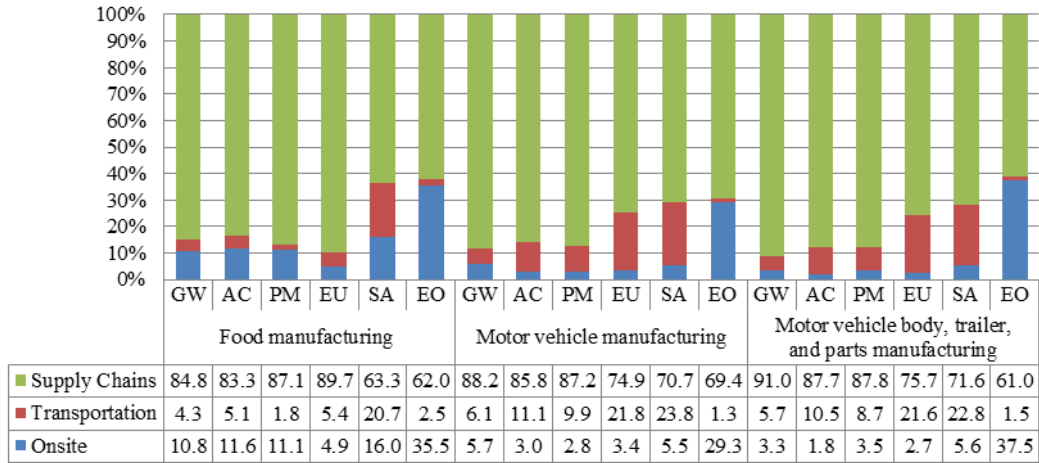|	GW	AC	PM	EU	SA	EO	GW	AC	PM	EU	SA	EO	GW	AC	PM	EU	SA	EO
	Food manufacturing						Motor vehicle manufacturing						Motor vehicle body, trailer, and parts manufacturing					
Supply Chains	84.8	83.3	87.1	89.7	63.3	62.0	88.2	85.8	87.2	74.9	70.7	69.4	91.0	87.7	87.8	75.7	71.6	61.0
Transportation	4.3	5.1	1.8	5.4	20.7	2.5	6.1	11.1	9.9	21.8	23.8	1.3	5.7	10.5	8.7	21.6	22.8	1.5
Onsite	10.8	11.6	11.1	4.9	16.0	35.5	5.7	3.0	2.8	3.4	5.5	29.3	3.3	1.8	3.5	2.7	5.6	37.5

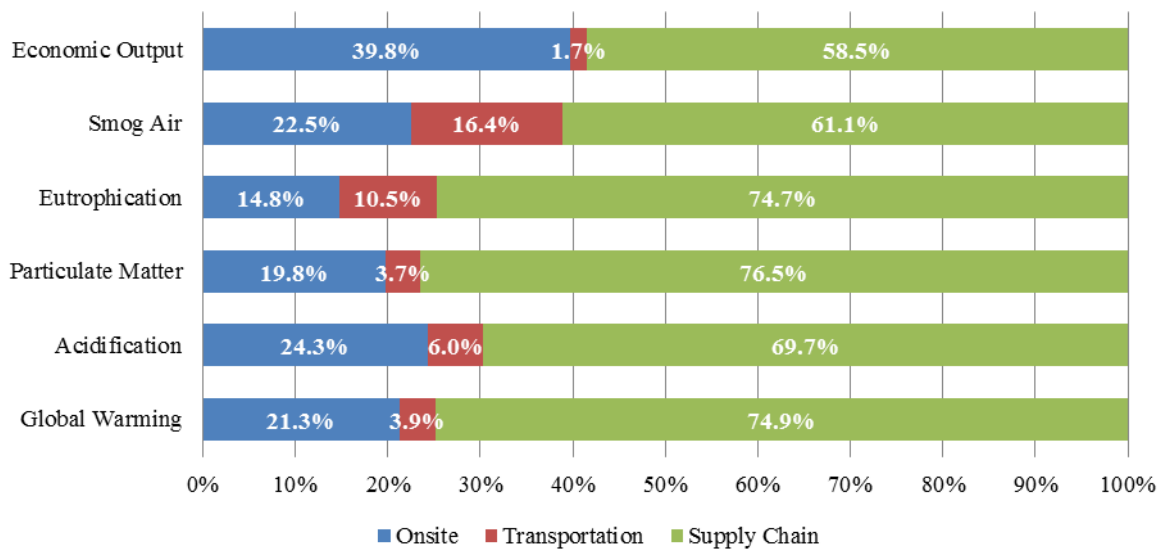Figure 1. Decomposition analysis result for top three sectors

Figure 2. Overall decomposition analysis of the 53 U.S. manufacturing sector's total impacts

From the results of the overall decomposition analysis of the total LCA impact for the 53 manufacturing sectors, the environmental impact of the transportation activities have severe effects on smog air, eutrophication and acidification with a share of 16.4%, 10.5%, and 6.0%, respectively. In the last part, the researchers also provided an average percentage share of transportation related impact when the entire supply chain for 53 manufacturing sectors is considered. The analysis shows that the smog air (SA) potential by transportation makes the highest contribution to total environmental impact with an average of 18.8%, followed by eutrophication (EU) with an average of 16.8%. The last but not least, transportation impact on global warming (GW), acidification (AC), and particulate matter (PM) has less than 10%

of the entire supply chain. It is also shown that the other miscellaneous manufacturing sector is the highest contributor with an average of 17.1% of five impact categories by transportation relative to supply chain. On the other hand, the basic chemical manufacturing sector has less environmental impact on the average of 3.9%.

Table 3. Average percentage share of transportation-related impacts in supply chain network

Manufacturing Sector	GW	AC	PM	EU	SA	Avg.	St. Dev.
Aerospace product and parts mfg.	7.6	11.4	9.6	24.0	24.7	15.5	8.2
Agricultural chemical mfg.	2.3	6.6	6.8	11.3	18.1	9.0	6.0
Agriculture, construction, and mining machinery mfg.	5.4	10.0	8.8	20.4	21.0	13.1	7.1
Apparel mfg.	5.5	6.9	6.2	12.0	18.9	9.9	5.6
Architectural and structural metals mfg.	4.5	11.4	9.0	23.1	23.4	14.3	8.6
Audio, video, and communications equipment mfg.	6.4	10.0	9.5	20.6	21.7	13.7	7.0
Basic chemical mfg.	1.3	1.9	1.7	7.2	7.6	3.9	3.2
Beverage mfg.	6.3	9.1	4.0	13.5	22.1	11.0	7.1
Boiler, tank, and shipping container mfg.	4.2	9.8	8.3	22.3	20.1	12.9	7.8
Commercial and service industry machinery mfg.	5.2	5.3	5.5	15.1	15.9	9.4	5.6
Computer and peripheral equipment mfg.	6.3	9.6	9.5	19.6	20.5	13.1	6.5
Converted paper product mfg.	5.2	8.0	6.2	16.6	17.0	10.6	5.8
Cutlery and handtool mfg.	4.0	8.9	7.5	20.5	21.2	12.4	7.9
Electric lighting equipment mfg.	4.6	8.3	7.6	16.7	17.0	10.9	5.7
Electrical equipment mfg.	4.8	9.9	8.6	22.0	22.5	13.6	8.1
Electronic instrument mfg.	6.0	9.1	8.5	19.5	20.5	12.7	6.8
Engine, turbine, and power transmission eqpt. mfg.	5.2	9.9	8.6	20.6	21.3	13.1	7.4
Food mfg.	4.3	5.1	1.8	5.4	20.7	7.5	7.5
Forging and stamping	3.9	10.3	8.4	22.1	22.6	13.5	8.5
Foundries	3.0	5.2	2.7	15.3	15.5	8.4	6.5
Furniture and related product mfg.	6.5	10.4	7.3	18.3	18.9	12.3	5.9
Household appliance mfg.	4.7	11.1	8.9	22.7	20.9	13.6	7.8
HVAC and commercial refrigeration equipment mfg.	5.2	10.4	8.7	22.2	22.9	13.9	8.1
Industrial machinery mfg.	5.1	8.8	8.2	17.7	17.4	11.5	5.8
Iron and steel mills and mfg. from purchased steel	2.4	10.1	7.0	20.0	20.3	12.0	8.0
Leather and allied product mfg.	3.6	3.8	4.0	3.9	21.9	7.5	8.1
Mfg. and reproducing magnetic and optical media	4.6	8.7	7.6	18.8	19.8	11.9	6.9
Medical equipment and supplies mfg.	6.4	9.0	9.0	20.9	22.6	13.6	7.6
Metalworking machinery mfg.	5.1	10.4	8.6	22.4	23.1	13.9	8.3
Motor vehicle body, trailer, and parts mfg.	5.7	10.5	8.7	21.6	22.8	13.9	7.8
Motor vehicle mfg.	6.1	11.1	9.9	21.8	23.8	14.5	7.8
Nonferrous metal production and processing	2.9	3.6	3.2	16.0	17.0	8.5	7.3
Nonmetallic mineral product mfg.	2.7	5.0	3.4	9.4	9.9	6.1	3.4
Ordnance and accessories mfg.	4.1	7.3	6.5	17.1	17.7	10.6	6.4
Other chemical product and preparation mfg.	3.7	7.0	5.0	17.5	18.4	10.3	7.1
Other electrical equipment and component mfg.	5.1	8.1	5.8	22.3	23.5	13.0	9.1
Other fabricated metal product mfg.	4.4	9.3	7.9	20.3	20.4	12.5	7.4
Other general purpose machinery mfg.	5.2	9.2	8.5	19.3	19.7	12.4	6.7
Other miscellaneous mfg.	8.3	12.2	11.6	25.5	27.9	17.1	9.0
Other transportation equipment mfg.	5.4	9.4	8.3	19.5	19.0	12.3	6.5
Paint, coating, and adhesive mfg.	4.7	11.1	6.7	21.3	23.2	13.4	8.4
Petroleum and coal products mfg.	1.7	3.0	2.4	8.7	8.5	4.9	3.4
Pharmaceutical and medicine mfg.	4.4	8.0	7.1	13.9	15.0	9.7	4.6
Plastics and rubber products mfg.	3.3	7.0	5.3	15.5	16.4	9.5	6.0
Printing and related support activities	5.9	7.3	6.7	15.4	15.5	10.1	4.9
Pulp, paper, and paperboard mills	2.9	4.3	2.9	9.2	10.4	6.0	3.6
Resin, rubber, and artificial fibers mfg.	2.2	5.1	3.4	10.1	12.0	6.6	4.3
Semiconductor and other electronic component mfg.	4.5	7.5	7.1	17.4	18.2	11.0	6.4
Soap, cleaning compound, and toiletry mfg.	4.0	7.6	4.8	15.2	18.1	10.0	6.4
Textile mills	3.5	4.5	2.9	7.9	12.8	6.3	4.1

Textile product mills	5.0	6.4	5.0	11.5	17.4	9.1	5.4
Tobacco mfg.	4.3	4.6	1.8	6.8	14.3	6.4	4.8
Wood product mfg.	6.4	7.9	3.4	10.6	13.0	8.3	3.7
Average	*4.6*	*8.1*	*6.5*	*16.8*	*18.8*	*10.9*	*6.4*

5. Conclusion and Future Work

In this study, EIO-LCA framework is used to determine the U.S. manufacturing sector's TRACI environmental impacts associated with transportation activities. It was a holistic method to quantify the environmental and human health related impact associated with transportation and manufacturing sector, which also enable an in-depth analysis of all life cycle inventories (LCI) by reducing its complexity. Conducting cradle-to-gate TRACI based environmental impact assessment also provided a comprehensive understanding of the end-point impacts, including global warming, particulate matter, acidification, eutrophication and smog air. The findings of the study revealed that the cumulative environmental impacts of top ten sectors accounted for over 50% of the total life cycle impacts from raw material extraction to manufacturing/production. The researchers identified that food manufacturing and motor vehicle related manufacturing sectors, predominantly affect the environment. Then, we performed decomposition analysis by looking into onsite (direct), transportation, and supply chain (indirect) impact as a robust method to provide proportional impact by each impact indicator for those hot spot sector.   Lastly, the overall decomposition analysis for 53 sector analysis shows that smog (16.4%), eutrophication (10.5%), and acidification (6.0%) were the key life cycle impact categories related to transportation activity. It is also noted that smog air (SA) potential by transportation makes the highest contribution to total environmental impact with an average of 18.8%, followed by eutrophication (EU) with an average of 16.8% when the entire supply chain is considered. It is also noted that smog air (SA) potential by transportation makes the largest contribution to total environmental impact with an average of 18.8%, followed by eutrophication (EU) with an average of 16.8% when the entire supply chain from cradle-to-gate is considered.

In the U.S, SO2, NOx, and NH3 release were the dominant sources that contribute to smog air and eutrophication, and acidification. Especially, the transportation sector was the most influential source for NOx and VOC emissions accounting for 53% and 51% of nation's total emission while NH_3 accounted for 4 % (Palmgren, 2004). These pollutants have both direct and indirect effects on human health and eco-system which not only accelerate human diseases, but also have significant impact on agriculture, wildlife, forests, etc. (WHO, 1999). In this regard, transportation policies, including reducing vehicle mile travel (VMT), promoting clean fuels and vehicle efficiency are recommended toward improvement of air quality (Schuster et al., 2004). Ultimately, this study could be a good reference for planners or policy makers for dealing with successful sustainable transportation practices and strategic mitigation with life cycle environmental impact. Current research can be extended towards various directions. First, EIO-LCA did not provide environmental intervention of product use and end-of-life phase (Gokhan Egilmez et al., 2013). Considering use and end-of-life would make the results more comprehensive. In addition, consideration of ecological impacts (Egilmez and Kucukvar, 2014; Kucukvar et al., 2014), land footprint associated with highway network, and inclusion of dynamic simulation models (Egilmez and Tatari, 2011) can be

critical extensions of current research.

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