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16. ABSTRACT

The freight system is a key component of California’s economy, but it is also a critical contributor to a number of externalities. Different public agencies, private sector stakeholders, and academia are currently engaged in the implementation of the California Sustainable Freight Action plan (CSFAP). This plan put forward a number of improvement strategies/policies. However, the freight system is so complex and multifaceted, with a great number of stakeholders, and freight operational patterns, that evaluating or assessing the potential impacts of such strategies/policies is a difficult task. To shed some light, this project develops a freight system conceptualization and impact assessment framework of the freight movements in the State. In doing this, the framework assess the impact of commodity flows from different freight industry sectors along supply chains within, originating at, or with a destination in the State of California. The conceptual framework analyzes the freight flows in supply chains, and the type of freight activity movements and modes. The framework uses a Life Cycle Assessment (LCA) Methodology. The framework could be extended to support multidimensional cost/benefit appraisals for both direct benefits (e.g., delays, costs, accidents, maintenance) and social benefits to non-users which include impacts on regional and national economies as well as environmental and health impacts. This report discusses the main components of the conceptual framework based on a comprehensive review of existing methodologies. The implementation is limited to the Life Cycle Impact Assessment (LCIA) following the Environmental Protection Agency’s Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI). The report describes the results from the LCIA implementation for a number of case studies.

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Development of a Freight System Conceptualization and Impact Assessment (Fre-SCANDIA) Framework

August 2018

A Research Report from the National Center for Sustainable Transportation

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National Center for Sustainable Transportation

ITS UC DAVIS INSTITUTE of TRANSPORTATION STUDIES

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A National Center for Sustainable Transportation Research Report

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Development of a Freight System Conceptualization AND Impact Assessment (Fre-SCANDIA) Framework

EXECUTIVE SUMMARY

The freight system is a key component of California's economy, but it is also a critical contributor to a number of externalities. Different public agencies, private sector stakeholders, and academia engaged in the development of the California Sustainable Freight Action Plan (CSFAP). This plan put forward a number of improvement strategies/policies. However, the freight system is so complex and multifaceted, with a great number of stakeholders, and freight operational patterns, that evaluating or assessing the potential impacts of such strategies/policies is a difficult task. To shed some light, this project develops a freight system conceptualization and impact assessment framework of the freight movements in the State. In doing this, the framework assesses the impact of commodity flows from different freight industry sectors along supply chains within, originating at, or with a destination in the state of California.

The conceptual framework analyzes the freight flows in supply chains, and the type of freight activity movements and modes. The framework uses a Life Cycle Assessment (LCA) methodology. The framework could be extended to support multidimensional cost/benefit appraisals for both direct benefits (e.g., delays, costs, accidents, maintenance) and social benefits to non-users which include impacts on regional and national economies as well as environmental and health impacts. This report discusses the main components of the conceptual framework based on a comprehensive review of existing methodologies. The implementation is limited to the Life Cycle Impact Assessment (LCIA) following the Environmental Protection Agency's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI).

The report describes the results from the LCIA implementation for a number of case studies. Specifically, the work estimated the impacts of moving a ton of cargo over a mile for various industry categories and commodity types. These results show the relative difference across industries and commodities and could serve to identify freight efficiency improvement measures in the state of California.

I. Introduction and Background

California has the largest State economy in the U.S. and is a major supplier of agricultural and high-tech manufactured products for the rest of the nation (Viljoen et al., 2014). The State's freight transportation system is critical to California's economy and to the economies of other States–20 percent of all U.S. foreign trade passes through California (California Department of Transportation, 2014). However, the vehicles, equipment, and facilities used by the different economic agents that conduct these freight operations generate a great deal of externalities including congestion, environmental emissions, and safety issues, among other impacts (Regan and Golob, 1999; Holguín-Veras et al., 2015; Jaller et al., 2016a).
For example, freight accounts for about half of toxic diesel particulate matter (diesel PM), 45 percent of the emissions of nitrogen oxides (NOx) that form ozone and fine particulate matter in the atmosphere, and six percent of the greenhouse gas (GHG) emissions in California (California Air Resources Board, 2015). These statistics, however, only include emissions from vehicles and the equipment used to move freight at seaports, airports, railyards, warehouses and distribution centers. The actual impacts from freight, including the necessary infrastructure, could be much higher. Different operational patterns, seasonality, lack of freight data, the multiplicity of economic agents, diverse supply chain structures and their interactions difficult the understanding of the freight system (Holguín-Veras and Jaller, 2014). These factors make the actual estimation of the full impacts a complex task (Jaller et al., 2016b). At the same time, public agencies are developing policies and methodologies to minimize the negative impacts of the system, while trying to maximize its benefits.

In order to take these policies from well-intentioned to effective, there is an urgent need to be able to evaluate the impacts of the freight transportation system (considering the supply chains that move the goods and services required for this vibrant economy). This requires the understanding and availability of a *system conceptualization* that characterizes the components and structural forms of the key types of supply chains active in the State, whether the policies are evaluated under horizontal or vertical equity considerations (Litman, 2009; Litman, 2016).

However, the freight system is so diverse that there could be a sheer number of inputs and outputs, thus defining a common measure to evaluate the system would be problematic (Barber and Grobar, 2001). Most supply chains are distributive networks, while others are performed in spoke and wheel patterns or corridors; some are defined within the boundaries of the state while others transcend its geographical and political limits (Rodrigue, 2013; SCAG, 2016). In some cases, products consumed, transformed, or exported in the State, may have already entered and exited the boundaries several times. Whilst some flows of cargo pass through urban areas, others have the urban areas as the destination. Therefore, evaluating the components inside the State or within specific geographic locations could foster some overall inefficiencies in the system. This is because supply chain optimization may be achieved when looking at the holistic chain/system, and not, when only optimizing specific components. Within the system, numerous market forces affect the way each individual player performs and their roles; each subset of each supply chain aims to maximize its own utility and efficiency, and to minimize its own cost of doing business. Consequently, having each individual player maximizing its own efficiency does not guarantee achieving system optimum.

The objective of this research is to help fill this gap by developing a Freight System Conceptualization AND Impact Assessment (Fre-SCANDIA) Framework of the freight movements in the State. The framework analyzes the main transportation flows of key supply chains and serves as an impact assessment tool. The framework can help identify the industry sector, or the commodity types that have the largest impacts, and potentially identify which economic agents' decisions or regulatory actions affect a particular impact category the most. The framework, and the results discussed in this report, can help agencies develop and understand appropriate performance measures by providing a methodology to estimate the baseline impacts of freight activity.

To achieve the objective, the research team developed a conceptual framework based on a Life Cycle Assessment (LCA) methodology considering the movement of goods within supply chains in different industries. The proposed LCA-based framework could be modified to support multidimensional cost/benefit appraisals for both direct benefits (e.g., delays, costs, accidents, maintenance) and social benefits to non-users as well as environmental and health impacts. The team conducted a number of case studies on different economic sectors and specific companies to illustrate the framework implementation and identify current methodological, data, and modeling gaps.

This report discusses the results of the research and contains the following sections. Section II provides a brief overview of the freight system, concentrating on the various modes of transport. Section III discusses key concepts from supply chain management that are important for the development of the proposed framework. Considering that the conceptual framework uses the LCA structure as a basis, Section IV is a comprehensive review of the state of practice of LCA. Section V discusses a wide range of impact assessment methodologies that range from general impact assessment tools, to specific environmentally (or economically) focused methods. Section VI reviews LCA implementations in transportation and the relationship with supply chain assessments. Section VII puts forward the Fre-SCANDIA framework. This section discusses the data and methodological gaps in the literature, which would be required for the development and implementation of the framework. Section VIII describes the basic implementation of the framework limited to the LCIA of freight flows. The section discusses a number of case studies. These include DELL as a leading computer hardware company, Nestlé as one of the largest food supply chains around the world, and Nike for its distinct third party logistics. The research team selected these case studies because of their representation of different industries and scope, and more importantly because of data availability to support modeling assumptions.

II. Brief Overview of the Freight Transportation System

Freight or cargo are the products or goods transported, usually for commercial benefit. The transport of goods can be done through a different set of modes: air, land (truck, rail), and water. However, besides the typical consideration of freight as the cargo itself, the freight system can also be understood as the movement of those cargoes; and, it could also be defined not only in terms of the commodity weight or value, but as the number of shipment and resulting vehicle trips generated (National Research Council, 2012). Usually, freight was associated with the large movement of break-bulk or containerized cargo, through large freight vehicles. It is now common to include in the freight definition, the movement of express, household goods, parcel, and other products that span the combinations of business and consumer interactions (Fitzpatrick et al., 2016). Overall, the freight transportation system is a complex system of systems, where a multiplicity of agents conduct a wide range of commercial activities related to a large number of commodities, services, or other economic transactions through different modes, vehicles, and operational strategies (Lamm et al., 2017).

In freight transportation, there are a number of terms that may have different understandings. For instance, while shipping may be associated with the action of sending-out goods by a "shipper" agent, shipping is also a general term originally used to refer to transport of goods by sea (Talley, 2014). The infrastructure and the companies (carriers) that move the goods support the supply of freight transportation. Receivers or consumers of the cargo could be the final consumption point or an intermediary destination that can transform the goods (Holguín-Veras and Jaller, 2014). Freight infrastructure includes the roadway system, railroads, airports, marine ports, locks and dams on rivers, pipelines, and other facilities such as warehouses, distribution centers, and intermodal yards, among others. In the U.S, the National Highway System (NHS) contains approximately 160,000 miles of the roads directly affecting the national economy and mobility (Rondinelli and Berry, 2000). The total road network in the US accounts for about 2.7 million miles of paved roads, and an additional 1.3 million miles of unpaved roads. Freight carriers are the owners or operators of the trucks, trains, ships, and airplanes that provides transportation to shippers. Other important private players in freight transportation include freight brokers, freight forwarders, and third-party logistics providers. Freight brokers assist shippers and carriers in assembling paperwork for international or complicated shipments. Freight forwarders consolidate multiple small shipments into larger shipments for transport (ICF International et al., 2011). The reader is referred Holguín-Veras et al. (2012) for a detailed description of agents' characteristics and interactions.

Cargo characteristics determine the type of transportation service demanded by shippers. Companies shipping high-value or perishable cargo tend to select truck or air transport to reduce transit time and gain higher levels of reliability. Airfreight carries high-value goods for which delivery within a few hours is often critical, such as express parcels and fresh flowers. Passenger and freight-only air carriers transport goods. Large freight-only carriers include Atlas Air, ASTAR Air Cargo, and Polar Air Cargo (Rondinelli and Berry, 2000). In the U.S., there are nearly 171,000 miles of railroad and hundreds of yards to assemble or dissemble the trains. Rail usually transports lower value, slow-moving bulk cargo, coal and other high-volume cargo through longer distances (more than 200-300 miles), thus it is popular for refineries, coal, and other large manufacturers. Trucks move a range of products, but they move a greater percent of higher value commodities like finished consumer products, computers, and pharmaceuticals (Bell and Iida, 1997). Domestic marine transport tends to carry low-value bulk cargo for which speed is not an important factor. Pipelines primarily transport petroleum products and natural gas.

The length of haul is also an important shipment characteristic that determines mode choice. Trucks tend to carry a larger percentage of short-haul movements. Trucking services can also be private or for-hire. Private services or private carriers are those that use their own fleets to move their cargoes. On the other hand, for-hire carriers offer their services to the open market. In the private sector, large companies such as Coca-Cola, Walmart, and Safeway, tend to use private fleets to move their cargo and maintain the reliability of service. Truck Load (TL) services provide truck transport to move cargo throughout the nation, while Less-than-Truck-Load (LTL) services move smaller shipments at the local level. These types of services can also incorporate consolidation of shipments, or can carry shipments to a specific terminals to be moved to their final destination (Crainic, 2003). Yellow Roadway, ABF, Con-way, Old Dominion Freight, FedEx Freight, and UPS Freight are examples of the largest U.S national LTL carriers. The network of LTL services requires terminals throughout the routes.

Rail, ocean, and air shipments tend to have a longer average shipment distance. Freight shipments often use more than a single mode of transportation. Trucks connect shippers to rail or maritime transportation modes or provide the “last mile” to the customer. “Intermodal” freight typically refers to freight moving in containers or trailers transferred between ships, railroads, and trucks. By reducing the cost of using multiple modes of transportation, intermodal freight movements allow shippers to use lower cost modes (such as rail or maritime) for long-haul movements and then switch to truck carriers to reach a final destination (Crainic, 2003). Some express carriers like Federal Express and UPS use their own multimodal transportation system to prove a door-to-door service (Rondinelli and Berry, 2000; PROTECTION, 2003). While maritime services move the bulk of the cargo using water-based modes, inland waterways also transport cargo in specific locations in the country.

Finally, the pipeline system carries specific cargo, usually petroleum products and other chemicals. The pipeline system includes collection pipelines, which are those used for moving natural gas or its products, and transmission pipelines, which transport over a far distance (e.g., moving natural gas to distant power plants, factories or distribution center). Additionally, distribution lines move cargos like natural gas shorter distances (Ganeshan and Harrison, 1995).

Although describing the system in terms of the cargo, modes, and the individual economic agents is important, the reality is that most of these economic agents comprise a number of supply chains. Some of these supply chains integrate the decision-making process, while others have independent agents. Nevertheless, understanding the freight system requires knowledge about supply chain structures, logistics, and management. In general, freight transportation results from economic and logistics decisions. Economic transactions between agents translate into the physical movement of the cargo, but the ultimate decisions of the mode, shipment size, vehicle size, and frequency of delivery come from logistics and supply chain management processes.

III. Supply Chain Management

A holistic supply chain includes processes and procedures to extract raw material, transport them to manufacturing facilities, produce final products, and distribute them to the consumers (wholesale or retail). Consequently, there are different stockholders involved such as suppliers, manufacturers, distributers, and retailers, among others. Supply chains flows include forward and reverse physical (e.g., returns), and information flows (Stadtler, 2005). At its highest level, a supply chain is comprised of two basic and integrated processes:

- The production planning and inventory control process; and,
- The distribution and logistics process.

The production planning and inventory control (first phase) consists of processes to gather raw materials and finally transform them into the final (or intermediary) products. Inventory control is embed into the manufacturing planning process and affects the procurement of raw material, defines the ordering schedule, and is part of the design and control of processes and products (Stadtler, 2005). The second phase determines the products' distribution among wholesalers, retailers, or the final consumer. That is, the distribution process determines the transportation of goods directly to retailers, or transporting all the cargo to a wholesaler or a facility in order to distribute them among retailers. According to these process, a supply chain can include all or some parts of these activities which define the specific structure of the supply chain (Beamon, 1998). For instance, Figure 1 shows a supply chain configuration involving five stages.

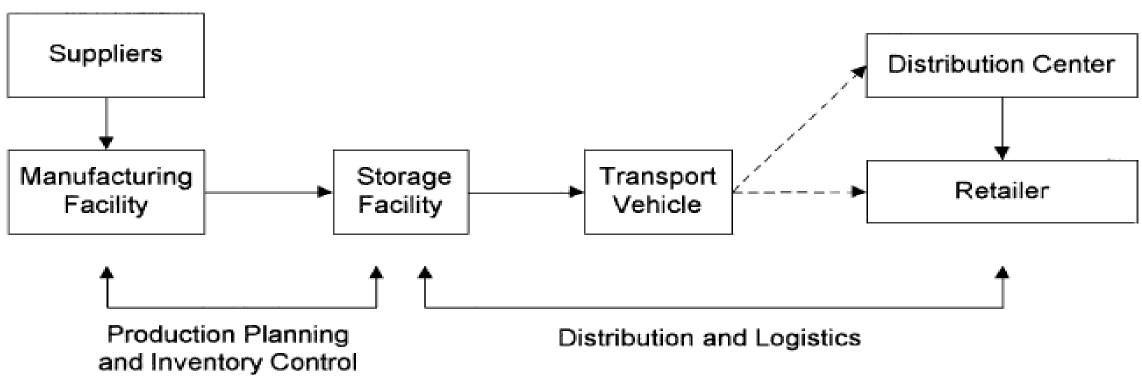

Figure 1. Supply Chain Process *(Beamon, 1998)*

Broadly, Supply Chain Management (SCM) focuses on the required processes to manage the supply chains. SCM includes decisions and evaluations at different levels and needs. Traditionally, the objective of SCM was to be cost effective across the whole system, including the transportation systems, inventory and raw material management, as well as finished goods and products. However, in recent years, the introduction of sustainable SCM considers other criteria such as social acceptability, efficiency, and environmentally beneficial aspects. Although there have been many methodological and technical advances during the last century, studying a supply chain is still a challenging task and there are multiple reasons for it. The study of supply chains usually focuses on specific products or services, as there are many interconnected dimensions as well as upstream and downstream supply chains. Designing and operating a supply chain needs to be cost-effective, thus requiring a service-level that guarantees the profitability of the business. Moreover, there are inherent uncertainties, risks, and disruptions that threaten supply chains.

Supply Chain Components

Manufacturing

Manufacturing refers to all the processes and facilities required to change the raw materials into intermediate or final products. Manufacturing facilities vary according to the number and type of their production processes.

Inventory

After the procurement or extraction of raw materials, supply chains have to manage the stocks or inventories of raw materials, work-in-progress and finished goods. Inventory systems consider various typologies with different numbers of echelons or stages. These echelons depend on the amount of products stored, the incoming supplies, production capacity, and the types of handled commodities. In most of cases, ensuring some level of demand satisfaction requires a safety stock because of the uncertainties associated with supply chains and demand. The main inventory and supply chain structure systems include single-echelon and multi-echelon (Siddhartha and Sachan, 2016). In a single echelon inventory system, a distribution center works as a hub between supplier and consumer. The distribution center or warehouse manages stocks and inventories (see Figure 2).

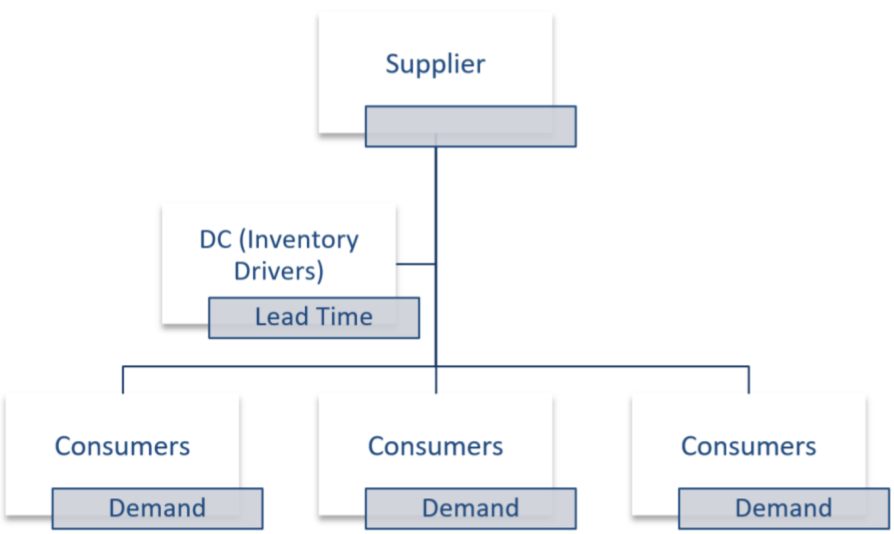

Figure 2. Single Echelon *(Hausman and Erkip, 1994)*

In contrast to the single-echelon inventory system, multi-echelon inventory systems include different layers along the supply from suppliers to consumers. The chain or network may have different distribution centers connecting suppliers to consumers. In a typical multi-echelon system, a central warehouse stores all the cargo; from there, the cargo goes to various smaller distribution facilities connected to the retailers and consumers (Figure 3). Many supply chains with multi-echelon inventory systems implement a hierarchical design with some regional larger distribution centers and some smaller facilities that service end customers. For instance, Nike, as one of the biggest supply chains around the world, distributes its products into seven major regional distribution centers and from there products send to different retailers (Sanyai, January 28, 2014).

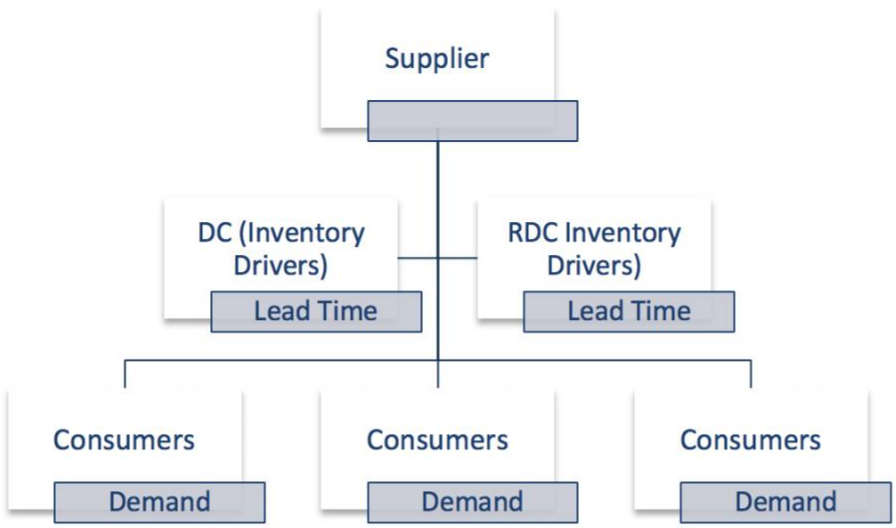

Figure 3. Multi Echelon *(Hausman and Erkip, 1994)*

Assembly and Distribution

Assembly takes place in supply chains with multi-echelon manufacturing systems in which parts from different suppliers comes to one place to finalize the product. For examples, the assembly of electronic devices happens at one place where the different parts coming from several sources merge. In these supply chains, the scheduling has a huge impact on the inventory level as well as the product distribution. A multi-echelon supply chain needs to manage the inventory in terms of fill orders and lead-time. These types of supply chain can maintain very high or very low operation and inventory cost depending on their service to their downstream supply chains. Strategies such as Just-in-Time (JIT) can have important implications for the inventory and distribution process (Whatis, 2014). In general, JIT have reduced inventory levels along supply chains; though have increased the frequency of distribution (resulting in more vehicle trips, and smaller shipments).

Supply Chain Models and Classification Systems

Generally, there are four main categories of supply chain models based on the modeling approach, the nature of the inputs and the objective of the study. The reader is referred to Beamon (1998) for a detailed description of these models:

- Deterministic analytical models;

- Stochastic analytical models;
- Economic models, and
- Simulation models.

Moreover, there are varieties of supply chain models, which address both the upstream and downstream processes, and can have different modeling objectives. Table 1 discusses descriptive and prescriptive models.

Table 1. Modeling Objectives

Descriptive Modeling	Demand forecasting using quantitative and qualitative models Activity based costing (ABC analysis) Collection of data and data mining Performance metrics
Prescriptive Modeling	Optimizations methods using simplex, duplex method of mathematical programming, and other advanced techniques

Source: (Beamon, 1998; Hartmut and Christoph, 2016)

Similarly, there are different approaches to evaluate the performance of supply chains. In 1996, the Supply Chain Council developed the Supply Chain Operations Reference (SCOR) (Huan et al., 2004). The main reason for developing this tool was customers' satisfaction through measuring, developing and improving supply chain services by embedding steps like planning, source finding, manufactory, delivery, and return (Stadtler, 2005; Latheef, 2011).
The SCOR model is a cross-functional model due to its four major pillars including process modeling and reengineering, skills, best practices, and performance measurements. In another effort, the Global Supply Chain Forum (GSCF) introduced a model to quantify and measure the performance of supply chains, in collaboration with the SCOR model. Their model is based on eight key factors that are both cross-functional and cross-enterprise. These factors include logistics, finances, production, purchasing, R&D, and marketing regarding each supply chain. According to this model, supply chain leaders need to fit these factors into the SCOR model (Stadtler, 2005; Latheef, 2011). The main objectives of these performance measurement models are to make sure that stakeholders are creating a beneficial and planned supply chain (Latheef, 2011).

Supply chains are also categorizes based on functional and structural attributes. These attributes are important for the management of supply chains, and the development of performance measures and criteria. Table 2 shows an example of a comprehensive classification system based on supply chain attributes.

Table 2. Supply Chain Attributes

Functional attributes		
Procurement Type	Number and type of products procured	Few Many
	Sourcing type	Single Double Multiple
	Suppliers' flexibility (Amounts to be supplied)	Low High
	Supplier lead time and reliability	Short (More reliable) Long (Less reliable)
	Material's life cycle	Short Long
Production Type	Organization of the production process	Flow shop Job shop
	Repetition of operations	Mass production Batch production One-of-a-kind Products
	Changeover characteristics	Fixed Sequence dependent
	Bottlenecks in production	Stationary and known Shifting
	Working time flexibility	Single shifts Multiple shifts
Distribution Type	Distribution structure	One-stage (one link between warehouse and customers) Two-stage (one intermediate layer, e.g. having central warehouse (CW) or regional warehouse (RW)) Three stage
	Pattern of delivery	Cyclic (fixed interval times) Dynamic (demand dependent)
	Deployment of transportation means	Routes (Standards, variable) Capacity (limited, unlimited) Loading requirement (full truck load, …)
Distribution Type	Availability of future demands	Unforeseen Forecasted
	Demand curve	Seasonal Sporadic Static
	Product's life cycle	Number of days, months, years
	Number of product types	Few Many
	Degree of customization	Standard Specific Highly specific

	Bill of materials (BOM)	Divergent (a single input product is disassembled (or split) and several output products are the result) Convergent (several input products are assembled (or mixed) to form a single output product) Mixture
	Portion of service operations	Tangible goods Intangible
Structural Attributes		
Typography of a supply chain	Network Structure	Serial Convergent Divergent Mixture
	Degree of globalization	Single country to Several continents
	Location of decoupling points	Engineer-to-order Manufacture-to-order Assemble-to-order Deliver-to-order
	Major constraints	Capacity of flow lines, critical materials, lack of capabilities
Integration and coordination	Legal position	Legally Separated Intra-organizational Inter-organizational
	Balance of power	Dominant partner (focal) Polycentric (Equals)
	Direction of coordination	Vertical Horizontal Mixture
	Type of information exchanged	Costs Material flows Any type of information

Source: (Hartmut and Christoph, 2016)

Supply Chain Performance Measures and Decision Variables

Performance measures or a set of performance measures can help determine the efficiency and/or effectiveness of an existing system, or help compare competing systems. The main types of measures include qualitative and quantitative. Qualitative measures involve no numerical measurements through the analysis, and assess performance using surveys or questionnaires. Some of these performance measures assess customer satisfaction, supplier performance, flexibility, and transaction satisfaction, among other criteria. On the other hand, qualitative measures use numerical methods to assess the performance (e.g., costs and benefits, customer's responsiveness) of supply chains. Cost-based measures include sales, profits, return on investments, operational costs, and inventory levels. Evaluation of responsiveness of customers can be through defining certain factors, which are dependent on the manufacture, inventory and distribution processes of the supply chain. These measures can be the lead-time of the distribution, lateness in deliveries, and customer response time (Marco Montorio, 2007).

Beamon (1998) proposes eight categories for the decision variables: inventory levels; number of echelons; production and distribution scheduling; distribution centers; number of product types held in inventory; relationships with suppliers; product differentiation; and, product assignment. Moreover, the author lists several performance measures with different focus criteria (see Table 3). Just until recently, performance measures did not include factors that were not direct impacts to the environment, even when other authors have defined a supply chain as "product life cycle processes comprising physical, information, financial, and knowledge flows whose purpose is to satisfy end-user requirements with physical products and services from multiple, linked suppliers" (Ayers, 2006).

Table 3. Performance Measures in Supply Chain Modeling

Basis	Performance Measures
Cost	Minimize cost Minimize average inventory levels Maximize profit Minimize amount of obsolete inventory
Customer	Achieve target service level
Responsiveness	Minimize stock out probability
Cost and customer responsiveness	Minimize product demand variance or demand amplification Maximize buyer-supplier benefit
Cost and activity time	Minimize the number of activity days and total cost
Flexibility	Maximize available system capacity

Source: (Beamon, 1998)

IV. Life-Cycle Assessment

The study of Life Cycle Assessment (LCA) began with the launch of the environmental Acts in 1970s. The Coca-Cola Company was the first one to study this concept to evaluate the environmental impact of containers in 1969. By that time, increasing concerns regarding resource availability and energy use highlighted the need for studies to measure the environmental impacts of processes and products (Curran, 1993; Dicks and Hent, 2014). After the initial studies (mostly by the Midwest Research Center), other institutes such as Battelle Frankfurt, EMPA in Switzerland and Sundström in Sweden, approached the topic. Early studies considered environmental dimensions regarding product packaging (Hunt et al., 1996a). Before the current LCA denomination, the studies were called resource and profile analysis (REPA) (Hunt et al., 1996b). In 2000, researchers started to investigate the similarities and differences between LCA and Partial model equilibrium (PE) models used to evaluate the effect of a policy on a specific market (Bouman et al., 2000; Guinée et al., 2001). Most of the partial equilibrium (PE) models concerns Multi-Market, Multi-Region Partial Equilibrium Models. Nevertheless, the Coca-Cola study set LCA as a tool for assessing environmental impacts. Furthermore, other initial experiences defined LCA as a toll for evaluating complex systems and a sustainability measure tool of products, processes, and companies. Table 4 briefly lists the evolution of LCA (Guinee et al., 2010).

Table 4. Evolution of LCA

The evolution of LCA is divided into four eras (Guinee et al., 2010)

- **1970-1990: "Decades of Conception"**

  "…Due to the increased awareness and public concerns regarding the pollutions, solid wastes, resources and energy efficiency, the first studies of LCA were conducted in late 1960s".

- **1990-2000: "Decade of Standardization"**

  "…Through this era, which is known for coordination of scientific activities around the world, a solid and holistic framework was provided both as SETAC and ISO's perspective for LCA studies. Through this period the main focus of LCA was packaging legislations" (Finkbeiner et al., 2006; Normalización, 2006).

- **2000-2010: "Decade of Elaboration"**

  "..During this period, the environmental policy decisions started to be made by life cycle analysis, and even the U.S. Environmental Protection Agency started supporting the use of LCA."

  In this era, many authors proposed several ways to perform LCA studies. These methods differed with respect to the system boundary and the allocation problem (Guinee et al., 2010). For instance:

  - Dynamic LCA,
  - Spatially differentiated LCA,
  - Risk-based LCA,
  - Environmental input-output based LCA (EIO-LCA), and

- Hybrid LCA.

- **The present day of LCA (2010-2020): Decade of Life Cycle Sustainability Analysis**
  In this era, the LCA studies consider all dimensions of sustainability: social, environmental and economical. The studies consider both products and sectors. Now, the Proposition of Life Cycle Sustainable Assessment (LCSA) is a framework comprised of models rather than a model itself.

Source: Adapted from (Guinee et al., 2010)

In general, a comprehensive LCA includes various stages and each directly affects the estimations and results. These stages include raw material acquisition, product manufacturing, usage and disposal, and the recycling of a product. There are different approaches for setting the boundary of the processes' in LCA studies such as Cradle-to-Grave, Cradle-to-Gate, Gate-to-Gate, Gate-to-Grave, or Cradle-to-Cradle (see Figure 4 and Table 5).

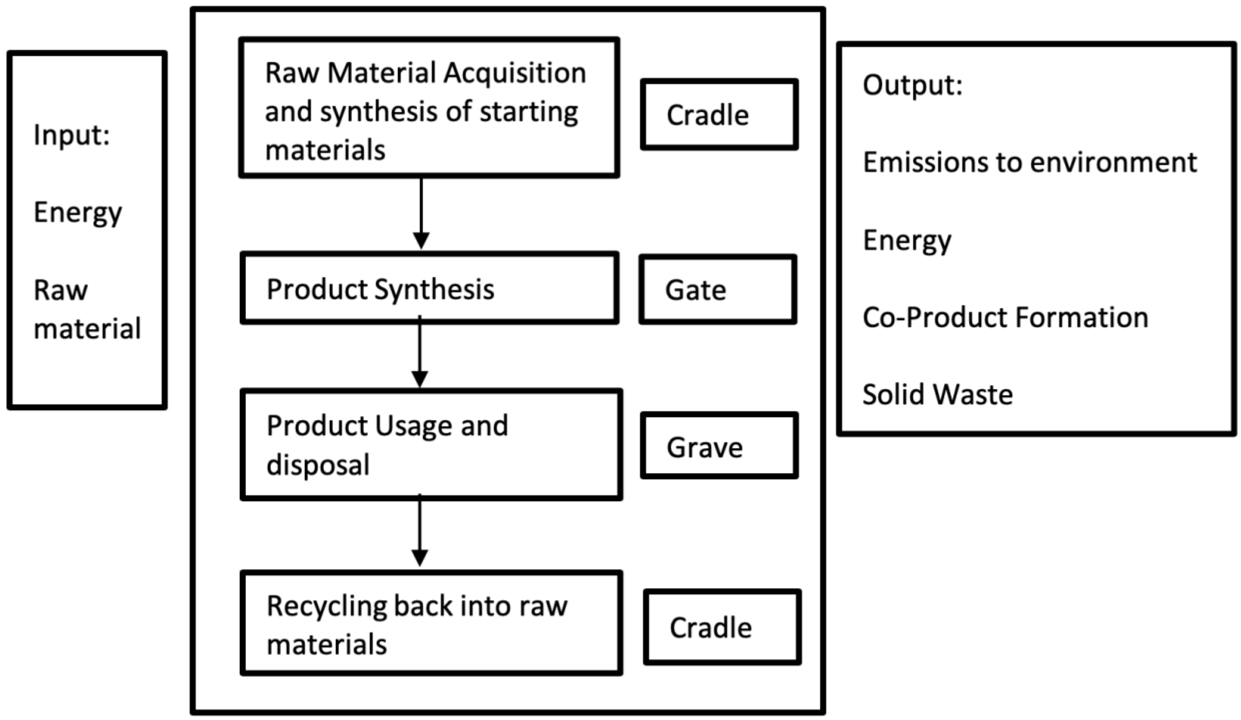

Figure 4. Life Cycle Stages ***(Dicks and Hent, 2014)***

Table 5. LCA Boundaries

Type of LCA	Definition of System Boundary
Cradle-to-Grave	Considers all life cycle stages: process from extraction of raw materials to their return to the earth. These stages include resource acquisition; product manufacturing; use; disposal; and, all intermediate transportation steps.
Cradle-to-Gate	Considers all stages from raw material production to the manufacture of the final product. Assumes stable downstream (post-manufacturing) steps for different processes.
Gate-to-Gate	Represents a partial life cycle excluding the raw material acquisition stage. The scope of the analysis generally considers a single process at a single manufacturing facility.
Gate-to-Grave	Only evaluate the life cycle found downstream of product manufacturing. These include product use, disposal, and recycling.
Cradle-to-Cradle	Often referred to as a closed-loop system. This scenario occurs when the end-of-life disposal step for the product is a recycling process. One can use this approach to evaluate products that circulate in cycles of production, use, recovery, and remanufacturing.

Source: (Dicks and Hent, 2014)

Generally, LCA consists of four phases: scope and boundary specifications; inventorying or Life Cycle Inventory (LCI), which measures the flows of resource inputs and emissions outputs; Life Cycle Impact Assessment (LCIA) that identifies the effects of the resource use and emissions; and interpretation, which incorporates the re-evaluation of the LCI and LCIA to reduce uncertainties. A traditional LCA contains all of these phases (Hellström et al., 2000). The International Organization for Standardization (ISO) has formalized the definition of LCA in its 14040 series indicating that an LCA process includes (Finkbeiner et al., 2006):

- Goal and scope definition;
- Inventory analysis;
- Impact assessment; and,
- Interpretation.

In some LCA cases, inventory analysis and impact assessment are treated the same or are jointly conducted. Moreover, although ISO introduces LCA as a framework to capture all the environmental effects, there are still limitations (Normalización, 2006; Curran, 2013).

According to the ISO 14044, LCA is a tool to evaluate the potential natural effects and assets used as part of an existing cycle of an item including crude material procurement, creation, use stages, and waste management, which incorporates both recycling and disposal (Finkbeiner et al., 2006). Practically, an LCA can be a comprehensive assessment of all attributes or aspects of the natural environment, human health, and resources (Finkbeiner et al., 2006). The exceptional characteristic of LCA is its attention on products/services in a life cycle point of view. The purpose behind leading a LCA lies in the definition of scope and goal of the project, the system boundaries, and its functional units. Quantitatively measuring the impacts of a good or service requires defining a functional unit.

The outcome of the LCI is a collection of the inputs (resources) and the outputs (emissions) from the item over its life cycle in connection to the functional unit. The LCIA analyzes and assesses the magnitude and significance of the potential natural effects of the contemplated framework (Finkbeiner et al., 2006). The estimation of impacts considers specific boundary conditions with a spatial and temporal dimension. For instance, the results allow a comparison of the emissions produced in past years with the ones emitted today and the ones at some point in the future.

Although much of the focus of LCA is to quantify emissions and outputs of a process, it may not fully consider the relationships and interdependencies of all the potential affected processes that fall outside the system under study. As a result, the analyses may require environmental risk assessment methodologies (Hertwich et al., 2002).

Generally, LCAs require large amounts of data, and the boundary setting and scope could limit and ease such requirements. In LCA, the very first step is the planning phase that define the objectives of the LCA and the required information. This step also specifies the level of details of the study (Consoli et al., 1993). After recognizing the system boundaries, the second step in an LCA process is the inventory analysis. This phase gathers the required data regarding mass, and energy requirements, among others, and builds the flow charts according to the system boundaries. Often, the analyses use quantitative data collected or estimated from approximations, assumptions, or from the literature. With the growing interests in LCA studies, there are now databases that can provide more quantitative information for each product or material.

The primary motivation behind the third phase is to evaluate the ecological effects as per the selected impact categories that may include human medical problems, air contamination, commotion contamination, sea-going poisonous quality, global warming, asset exhaustion, eutrophication, and so on. In addition, LCA could consider the social effects, costs, and other specific issues. The fourth stage requires interpreting the other stages. The fundamental explanation behind this sequential process is to introduce the ethics and scope of the proposed LCA analysis.

Attributional and Consequential LCA

Initial LCA studies focused on energy use and public environmental concerns in the 1970s. Later, in the 1980s and 1990s, LCA considered more a holistic assessment and introduced costing (McManus and Taylor, 2015). The first decade of the 21st century welcomed social LCA and the new consequential type of LCA (Guinee et al., 2010). One of the complexities regarding LCA studies is how to allocate impacts among different products, or processes. As a result, there are two common types of LCA: attributional and consequential. Attributional LCA (ALCA) considers the environmental consequences directly related to the physical flows regarding single or multiple product or process, while consequential LCA (CLCA) discusses how much environmental flows change with respect to possible changes or decisions (Earles and Halog, 2011). CLCA accounts for a broader spectrum compared to ALCA.

Differences between attributional and consequential LCA conditions the choice of methodology and data requirements for the LCI and LCIA phases (Finnveden et al., 2009a). LCA studies require extensive amounts of data. Consequently, in many cases, the nature of the data influences the results in both ALCA and CLCA. Usually, LCA requires information with respect to the generation costs, versatility of supply and more information according the end goal to extrapolate drifts in costs and yields (Searchinger et al., 2008; Curran, 2014). CLCA is a complex technique since it can require various economic models (Pesonen et al., 2000).

Weidema (1993) was among the first to discuss CLCA, which largely emphasized the need to consider market information in LCI data and analyses. CLCA is a modeling approach with a specific goal to show environmental effects and not only the physical direct impacts from ALCA. The first efforts to combine ALCA and CLCA use PE models and other heuristic approaches. Although researchers and practitioners used multi-Market, Multi-Regional PE and Computable General Equilibrium models in the past, new studies combine other economic concepts into CLCA. ALCA mostly uses information for each process in the life cycle evaluation, while CLCA portrays how physical streams can change as an outcome of an expansion or a limitation in the scope of the project, boundary, or any related policy (Earles and Halog, 2011). Moreover, LCA is developing into Life Cycle Sustainable Assessment (LCSA), which is a mix of models as opposed to one model in itself. In general, studies show that a significant share of the environmental impacts is not in the product usage but in its production, transportation, or disposal (Guinee et al., 2010).

Considering that most modeling efforts do not only want to replicate current conditions but also study future scenarios, Berglund and Börjesson (2006) suggested a typology based on the types of answers sought by the following questions:

- Predictive scenarios: What will happen?
- Explorative scenarios: What can happen?
- Normative scenarios: How to achieve a specific target?

The question on how and when to direct ALCA versus CLCA is not yet settled. Identification of influenced innovations, gathering of minor information, and related vulnerabilities are the issues of this question (Earles and Halog, 2011).

The Importance of Attributional and Consequential LCA

While attributional and consequential are now common names, they have also been referred to as descriptive versus change-oriented (Fichtner et al., 2004). Lundie et al. (2007) stated that decision-making should use CLCA when the difference between consequential and attributional LCA results are significant and when the uncertainties in CLCA do not exceed its benefits. Tillman (2000) considered that ALCA is a better approach due to its extensive application and when there are no future decisions that grant the need for a CLCA. Kløverpris et al. (2008)

contend that CLCA is more applicable for basic decision-making; nonetheless, they contend that it is also more relevant for expanding the comprehension of the product chain and for recognizing the procedures and relations which are most critical to make improvements (Tukker et al., 2006; Kløverpris et al., 2008).

CLCA can also evaluate the environmental effects regarding individual choices. However, ALCA concerns with separating systems and significant environmental impacts (Ekvall et al., 2005). The most distinctive difference between attributional and consequential LCA are the decisions between average and marginal data approaches (Tillman, 2000). Average data refer to those demonstrating the average environmental consequences resulting from producing a unit of a product/service. While marginal data demonstrate the environmental consequences resulting from a small change in a product/service. Essentially, ALCA uses average data, while CLCA uses marginal data to show the small relevant changes in the system (Ekvall et al., 2005). CLCA can also consider various marginal effects.

In summary, the case study requirements determine the LCA type. Rebitzer et al. (2004) proposed a five-step procedure to categorize the long-term marginal impacts. The longer the time horizon, the more uncertain the marginal effects. In case that the marginal effect time horizon is far into the future, the uncertainty is higher than the marginal effects themselves. Ekvall and Andrae (2006) propose five steps to deal with the CLCA. First is to make a list of predictable consequences, which are important to the environment. Second is to quantify those predictable consequences or costs as well as the benefits. Third, adequately find tools for the quantification of the consequences. The fourth step is to create a network of experts on each tool, and clearly analyze and define the consequences. Finally, make a synthesis description to have the methodology of the CLCA.

Generally, due to the use of economic concepts like marginal costs and elasticity, CLCA is a more complicated concept than attributional. The difference between these types shows how the decision on boundary, and goal and scope of the project affect the methodology and inputs used (Cherubini and Strømman, 2011).

Uncertainties in LCA

Uncertainty in the form of variability can be due to errors or data. Uncertainty analysis is the process of determining the variability of the data and the impact on the results. Uncertainty applies to both the inventory and the impact assessment indicators. However, the actual influence of uncertainty on decision-making has not been adequately studied (Nitschelm et al., 2016). In LCA, uncertainty is “the discrepancy between a measured or calculated quantity and the true value of that quantity’’ (Finnveden et al., 2009b).

LCA is a data driven approach to estimate environmental emissions, therefore, it is imperative to consider various types of uncertainty (Baker and Lepech, 2009). Sources of uncertainties generally address the inputs to the model and could typically be categorized as data (e.g., CO_2 emissions from a coal fired power plant), choices (regarding the system boundaries, time horizon in Impact assessment), and relations (like the dependency of traveled distance on fuel input). Uncertainty can also refer to lack of knowledge or randomness in any input originating from:

- Database Uncertainty (e.g., missing data)
- Model Uncertainty
- Statistical/measurement error
- Preferences Uncertainties
- Future Uncertainties related to the time and physical system

Summary

There are four main stages of an LCA, which follow a logical sequence of (Finkbeiner et al., 2006):

- Goal definition and scoping (outlining aims, methodology, and boundary conditions),
- Inventory analysis (data collection—determining inputs and outputs of materials, fuels, and process emissions),
- Impact assessment (determination of the life cycle environmental impacts for the predetermined inventory), and
- Interpretation (identification of hotspots, recommendations for improvement, and treatment of uncertainty) (Guinée, 2002).

There are many technical issues that need to be addressed during an LCA (Lifset and Graedel, 2002). In LCA studies and its application to different systems, the most important part of the study is the setting of the system boundaries and goal identification. The study could be limited to Cradle-to-Gate, Cradle-to-Grave, Gate-to-Gate, Gate-to-Grave, or Cradle-to-Cradle.

According to the type of the system and existing data, there are different databases that allow the inventory analysis. Annex A describes some of the databases and tools widely used in LCA studies. While LCA includes a holistic study of the system or the proposed process, it lacks enough flexibility to account for economic analyses, and this could be the main reason that most of the studies are focusing mostly on non-economic/financial approaches. Table 6 briefly describes some of the strengths and weaknesses of environmental LCAs.

Table 6. Strengths and Weaknesses of Environmental LCA

Strengths	Weaknesses
Holistic environmental appraisal	Static/Snapchat assessments
Established international standards	Variation in assessment due to value choice/methodological approaches
Procedural transparency	Only predefined environmental impacts assessed
Allows level playing field for comparison	A target for sustainable activity not specified only embodied impacts quantified
Pinpoints environmental inefficient hotspots	Data Quality
Springboard for communication	Inaccessible results

Source: (Hammond et al., 2015)

As mentioned earlier, there are different forms of LCA, some can include social aspects as well as economical (LCC) and some only focus on the environmental emissions. Over the past 10 years, LCA has also evolved to incorporate the two aspects of sustainability, i.e., economic (LCC) and social LCA (S-LCA), resulting in the Life Cycle Sustainable Assessment (LCSA) = LCA + LCC (Life Cycle Costing) + S-LCA (Social LCA) (Halog and Manik, 2016). Two main approaches exist (Earles and Halog, 2011).

(i) Life Cycle Sustainability Assessment (LCSA "Assessment[1]," LCSAs), and

(ii) Life Cycle Sustainability Analysis (LCSA "analysis[2]," LCSAn).

Finally, the researchers develop Table 7, which provides a summary classification of the various references discussed in this section based on the LCA classifications, the phases they consider, and their relationship to risk and uncertainties. Figure 5 provides a visual representation of the identified gaps.

[1] Assessment is a process to obtain information through surveying, characterizing, synthesizing, and interpreting primary data sources.

[2] Analysis is a process to search for understanding, by taking things apart and studying the parts.

Table 7. LCA Studies and Their Characteristics According to LCA Phases

			Year	2008	2003	1993	2004	2000	2008
			Authors	Weidema, B.	Weidema, B. P.	Weidema, B.	Weidema, B.,	Alberini, A.	Allen, S., G.
LCA Phases	Goal and Scope			√		√		√	√
	Inventory Analysis				√	√		√	√
	Impact Assessment Models	Environmental Design of Industrial Products (EDIP)	Weighting principle (Separate or non-separate)	Separate	Separate	Separate	Separate	None	Separate
			Spatial extension (Global and national)		√	√		√	√
			Normalized impact potentials (person equivalent)				√		
		Eco-indicator í99	Resources			√	√		√
			Ecosystem Quality				√		√
			Human Health				√		
		Impact Assessment of Chemical Toxics, version 2002	Abiotic Depletion Potential (ADP)				√		
			Photochemical Ozone Creation Potential (POCP)	√			√		
			Terrestrial and Aquatic Eutrophication				√		
			Particulate Matter (PM)				√		
			Eutrophication Potential (EP)				√		
		Environmental Priority Strategies in product design (EPS)	Aesthetic and cultural values				√		
			Resources (not renewable resources)				√		√
			Capacity of biological production (i.e. fertility)				√		
			Human Health				√	√	
			Biological diversity				√		
		USES-LCA	Terrestrial eco-toxicity	√			√		
			Marine sediment eco-toxicity				√		
			Marine aquatic eco-toxicity				√		
			Freshwater sediment eco-toxicity				√		
			Freshwater eco-toxicity				√		
	Interpretation of Results			√	√	√			√

				1995	1999	2011	2006	2011	2002	2016	2011
Year				1995	1999	2011	2006	2011	2002	2016	2011
Authors				Alting, L.	Bailly,	Bare, J.	Berglund,	Burnham, A.,	Burritt,	Cheng, X.	Cherubini, F.
LCA Phases	Goal and Scope			√	√	√	√	√	√	√	√
	Inventory Analysis			√	√	√	√	√	√	√	√
	Impact Assessment Models	Environmental Design of Industrial Products (EDIP)	Weighting principle (Separate or non-separate)	Separate	None	None	Separate	Separate	None	Separate	Separate
			Spatial extension (Global and national)		√		√	√		√	
			Normalized impact potentials (person equivalent)		√				√	√	
		Eco-indicator í99	Resources	√	√		√	√	√	√	
			Ecosystem Quality					√			
			Human Health				√		√		
		Impact Assessment of Chemical Toxics, version 2002	Abiotic Depletion Potential (ADP)								
			Photochemical Ozone Creation Potential (POCP)								
			Terrestrial and Aquatic Eutrophication								
			Particulate Matter (PM)					√			
			Eutrophication Potential (EP)				√	√			
		Environmental Priority Strategies in product design (EPS)	Aesthetic and cultural values								
			Resources (not renewable resources)	√			√				
			Capacity of biological production (i.e. fertility)								
			Human Health								
			Biological diversity								
		USES-LCA	Terrestrial eco-toxicity								
			Marine sediment eco-toxicity								
			Marine aquatic eco-toxicity								
			Freshwater sediment eco-toxicity								
			Freshwater eco-toxicity								
	Interpretation of Results			√	√		√	√		√	

Year				2010	2012	2004	2011	2009	2009	2009
Authors				Chester, M.	Chester, M.	Fichtner,	Favara, P. J., T.	Finnveden,	Finnveden, G., M. Z.	Goedkoop, M.,
LCA Phases	Goal and Scope			√	√	√		√	√	√
	Inventory Analysis			√	√	√		√	√	
	Impact Assessment Models	Environmental Design of Industrial Products (EDIP)	Weighting principle (Separate or non-separate)	Separate	None	Separate	None Separate	Separate	None Separate	Separate
			Spatial extension (Global and national)							
			Normalized impact potentials (person equivalent)		√			√		
		Eco-indicator í99	Resources			√		√		
			Ecosystem Quality							
			Human Health							
		Impact Assessment of Chemical Toxics, version 2002	Abiotic Depletion Potential (ADP)	√	√					√
			Photochemical Ozone Creation Potential (POCP)	√	√					√
			Terrestrial and Aquatic Eutrophication							√
			Particulate Matter (PM)	√	√					√
			Eutrophication Potential (EP)							√
		Environmental Priority Strategies in product design (EPS)	Aesthetic and cultural values							
			Resources (not renewable resources)	√	√			√		
			Capacity of biological production (i.e. fertility)	√	√					√
			Human Health							
			Biological diversity							√
		USES-LCA	Terrestrial eco-toxicity							√
			Marine sediment eco-toxicity							√
			Marine aquatic eco-toxicity							√
			Freshwater sediment eco-toxicity							√
			Freshwater eco-toxicity							√
	Interpretation of Results			√	√			√	√	√

			Year	1998	2000	2016	2002	2010	2001	2016
			Authors	Goedkoop,	Goedkoop,	Guinée, J.	Guinée, J. B.	Guinee, J.	Guinée, J.	Halog, A.
LCA Phases	Goal and Scope			✓	✓	✓	✓	✓	✓	✓
	Inventory Analysis			✓	✓	✓	✓	✓	✓	✓
	Impact Assessment Models	Environmental Design of Industrial Products (EDIP)	Weighting principle (Separate or non-separate)	None	None	Separate	Separate	Separate	Separate	Separate
			Spatial extension (Global and national)			✓	✓	✓		✓
			Normalized impact potentials (person equivalent)			✓	✓		✓	✓
		Eco-indicator í99	Resources	✓	✓			✓		
			Ecosystem Quality	✓	✓			✓		
			Human Health	✓	✓			✓		
		Impact Assessment of Chemical Toxics, version 2002	Abiotic Depletion Potential (ADP)							
			Photochemical Ozone Creation Potential (POCP)				✓			
			Terrestrial and Aquatic Eutrophication							
			Particulate Matter (PM)						✓	
			Eutrophication Potential (EP)							
		Environmental Priority Strategies in product design (EPS)	Aesthetic and cultural values							
			Resources (not renewable resources)						✓	
			Capacity of biological production (i.e. fertility)							
			Human Health				✓			
			Biological diversity							
		USES-LCA	Terrestrial eco-toxicity							
			Marine sediment eco-toxicity							
			Marine aquatic eco-toxicity							
			Freshwater sediment eco-toxicity							
			Freshwater eco-toxicity							
	Interpretation of Results			✓	✓	✓	✓	✓	✓	✓

LCA Phases	Impact Assessment Models		Year	2015	2005	1992	2013	1993	1993	1995
			Authors	Hammond,	Hauschild, M.	Heijungs,	Curran, M. A.	Curran, M. A.	Consoli, F., S.	Cobas, E., C.
LCA Phases	Goal and Scope			✓	✓	✓	✓	✓	✓	✓
LCA Phases	Inventory Analysis			✓	✓	✓	✓	✓	✓	✓
LCA Phases	Impact Assessment Models	Environmental Design of Industrial Products (EDIP)	Weighting principle (Separate or non-separate)	Separate	Separate	Separate	Separate	Separate	Separate	Separate
			Spatial extension (Global and national)		✓					✓
			Normalized impact potentials (person equivalent)		✓					
		Eco-indicator í99	Resources	✓					✓	✓
			Ecosystem Quality	✓						✓
			Human Health							
		Impact Assessment of Chemical Toxics, version 2002	Abiotic Depletion Potential (ADP)			✓	✓			✓
			Photochemical Ozone Creation Potential (POCP)			✓	✓			✓
			Terrestrial and Aquatic Eutrophication			✓	✓			✓
			Particulate Matter (PM)			✓	✓			✓
			Eutrophication Potential (EP)			✓	✓			✓
		Environmental Priority Strategies in product design (EPS)	Aesthetic and cultural values				✓			
			Resources (not renewable resources)	✓					✓	
			Capacity of biological production (i.e. fertility)				✓			✓
			Human Health							
			Biological diversity				✓			✓
		USES-LCA	Terrestrial eco-toxicity			✓	✓			
			Marine sediment eco-toxicity			✓	✓			
			Marine aquatic eco-toxicity			✓	✓			
			Freshwater sediment eco-toxicity	✓		✓	✓			
			Freshwater eco-toxicity	✓		✓	✓			
LCA Phases	Interpretation of Results			✓	✓	✓	✓		✓	✓

			Year	1995	1993	2016	2007	2004	2013	2006
			Authors	Christiansen,	Moriguchi,	Nahlik, M. J.,	Sandén, B. A.	Rebitzer, G., T.	Valdivia, S., C.	Tukker, A., G.
LCA Phases	Goal and Scope			√	√	√	√	√	√	√
	Inventory Analysis			√	√	√	√	√	√	√
	Impact Assessment Models	Environmental Design of Industrial Products (EDIP)	Weighting principle (Separate or non-separate)	Separate	Separate	Separate	Separate	Separate	Separate	Separate
			Spatial extension (Global and national)	√			√	√	√	√
			Normalized impact potentials (person equivalent)	√	√	√				√
		Eco-indicator í99	Resources				√	√		√
			Ecosystem Quality						√	
			Human Health		√	√	√			√
		Impact Assessment of Chemical Toxics, version 2002	Abiotic Depletion Potential (ADP)	√						
			Photochemical Ozone Creation Potential (POCP)	√	√	√	√			
			Terrestrial and Aquatic Eutrophication	√		√			√	
			Particulate Matter (PM)	√						√
			Eutrophication Potential (EP)	√	√	√	√	√		
		Environmental Priority Strategies in product design (EPS)	Aesthetic and cultural values						√	
			Resources (not renewable resources)		√	√	√	√		√
			Capacity of biological production (i.e. fertility)							
			Human Health		√	√	√		√	√
			Biological diversity							
		USES-LCA	Terrestrial eco-toxicity							
			Marine sediment eco-toxicity							
			Marine aquatic eco-toxicity						√	
			Freshwater sediment eco-toxicity							√
			Freshwater eco-toxicity							
	Interpretation of Results			√	√	√	√	√	√	√

				2007	1994	2000	2012	2015	2005	1999
Year				2007	1994	2000	2012	2015	2005	1999
Authors				Toffoletto, L.,	Tillman, A.-	Tillman,	Thoft-	Swart, P., R.	Steen,	Steen, B.
LCA Phases	Goal and Scope			√	√	√	√	√	√	√
	Inventory Analysis			√		√	√	√	√	√
	Impact Assessment Models	Environmental Design of Industrial Products (EDIP)	Weighting principle (Separate or non-separate)	Separate	Separate	None	Separate	Separate	None	Separate
			Spatial extension (Global and national)	√				√		
			Normalized impact potentials (person equivalent)	√			√			
		Eco-indicator í99	Resources	√					√	
			Ecosystem Quality						√	
			Human Health	√					√	
		Impact Assessment of Chemical Toxics, version 2002	Abiotic Depletion Potential (ADP)							
			Photochemical Ozone Creation Potential (POCP)							
			Terrestrial and Aquatic Eutrophication							
			Particulate Matter (PM)	√						
			Eutrophication Potential (EP)	√						
		Environmental Priority Strategies in product design (EPS)	Aesthetic and cultural values	√					√	
			Resources (not renewable resources)	√			√			
			Capacity of biological production (i.e. fertility)						√	
			Human Health	√						√
			Biological diversity						√	√
		USES-LCA	Terrestrial eco-toxicity			√		√		
			Marine sediment eco-toxicity			√		√		
			Marine aquatic eco-toxicity			√		√		
			Freshwater sediment eco-toxicity			√		√		
			Freshwater eco-toxicity			√		√		
	Interpretation of Results			√		√	√	√	√	√

Year			2004	2008	2007
Authors			Seuring, S.	Searchinger, T., R.	Schmidt, J.
LCA Phases	Goal and Scope		√	√	√
	Inventory Analysis		√	√	√
	Impact Assessment Models				
	Environmental Design of Industrial Products (EDIP)	Weighting principle (Separate or non-separate)	Separate	None Separate	None
		Spatial extension (Global and national)	√		
		Normalized impact potentials (person equivalent)			
	Eco-indicator í99	Resources			
		Ecosystem Quality			
		Human Health		√	
	Impact Assessment of Chemical Toxics, version 2002	Abiotic Depletion Potential (ADP)			√
		Photochemical Ozone Creation Potential (POCP)			√
		Terrestrial and Aquatic Eutrophication			√
		Particulate Matter (PM)			√
		Eutrophication Potential (EP)			√
	Environmental Priority Strategies in product design (EPS)	Aesthetic and cultural values			
		Resources (not renewable resources)		√	√
		Capacity of biological production (i.e. fertility)			
		Human Health			
		Biological diversity			
	USES-LCA	Terrestrial eco-toxicity			
		Marine sediment eco-toxicity			
		Marine aquatic eco-toxicity			
		Freshwater sediment eco-toxicity			
		Freshwater eco-toxicity			
	Interpretation of Results		√	√	√

Figure 5. LCA Studies Classifications According to Phases

LCA studies can be categorize according to many indices and factors (e.g., Table 7). The table shows that, in many cases, the work in the literature include the four LCA stages. Moreover, due to the inherent nature of the process, which is data driven, there are factors like risk and uncertainties that can affect the whole process. Table 8 summarizes the use of these factors in the reviewed literature.

Table 8. Classification of LCA Studies

Year	Authors	LCA Background	Attributional V.s. Consequential	Integration of LCA and RA (Risk Assessment)					LCA Uncertainties				
				Complementary Tools	LCA as a subset of RA	RA as a subset of LCA	Overlapped	Separated	Future Uncertainties (time and physical)	Preferences Uncertainties	Statistical/measurement error	Model Uncertainty	Database Uncertainty
2003	Weidema, B. P.	LCA for Market Segmentation	Attributional									✓	
2004	Weidema, B., T. Ekvall, H. Pesonen, G. Rebitzer, G. Sonneman and M.	SETAC Research on LCA	Attributional										✓
2000	Alberini, A. and A. Krupnick	Health Issues and Willingness to pay	Attributional									✓	✓
2008	Allen, S., G. Hammond and M. McManus	None Renewable energy Sources	Attributional								✓	✓	✓
1999	Bailly, H. and P. Brinckerhoff	Cost Benefit Analysis	Attributional					✓			✓	✓	✓

Year		2016	2004	2009	1998	2016	2005
Authors		Cheng, X.	Fichtner, W., M. Frank and O. Rentz	Finnveden, G., M. Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D.	Goedkoop, M., P. Hofstetter, R. Müller-Wenk and R. Spriemsma	Guinée, J.	Hauschild, M. and J. Potting
LCA Background		Fuzzy Logic in LCA	Cleaner Energy Production	LCA development	Impact assessment Methodology	LCSA	EDIP development
Attributional V.s. Consequential		Consequential	Attributional	Attributional	None	Attributional	Attributional
Integration of LCA and RA (Risk Assessment)	Complementary Tools						
	LCA as a subset of RA						
	RA as a subset of LCA						
	Overlapped						
	Separated	√					
LCA Uncertainties	Future Uncertainties (time and physical			√			
	Preferences Uncertainties	√					√
	Statistical/measurement error	√					√
	Model Uncertainty	√	√	√			
	Database Uncertainty	√		√	√	√	√

Year		1992	2016	2007	2006	2007	1994	2000
Authors		Heijungs, R., J. B. Guinée, G. Huppes, R. M. Lankreijer, H. A. Udo de Haes, A. Wegener	Nahlik, M. J., A. T. Kaehr, M. V. Chester, A. Horvath and M.	Sandén, B. A. and M. Karlström	Tukker, A., G. Huppes, J. Guinée, R. Heijungs, A. de	Toffoletto, L., C. Bulle, J. Godin, C. Reid and L. Deschênes	Tillman, A.-M., T. Ekvall, H. Baumann and T. Rydberg	Tillman, A.-M.
LCA Background		LCA development	LCA in Transportation	Consequential LCA	EIPRO	Canadian LCA (LUCAS)	LCA development	LCA Extensions
Attributional V.s. Consequential		Attributional	Attributional	Consequential	Attributional	Attributional	Attributional	Attributional
Integration of LCA and RA (Risk Assessment)	Complementary Tools							
	LCA as a subset of RA							
	RA as a subset of LCA							
	Overlapped							
	Separated							
LCA Uncertainties	Future Uncertainties (time and physical		✓	✓				✓
	Preferences Uncertainties		✓	✓		✓	✓	
	Statistical/measurement error			✓		✓		✓
	Model Uncertainty	✓				✓		
	Database Uncertainty	✓	✓	✓	✓	✓	✓	✓

Year		2015	1999	2016	2008	2007
Authors		Swart, P., R. A. Alvarenga and J. Dewulf	Steen, B.	Seuring, S.	Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid,	Schmidt, J. H., P. Holm, A. Merrild and P. Christensen
LCA Background		LCA development	LCA Extensions	LCSA	LCSA	LCA development
Attributional V.s. Consequential		Attributional	Attributional	Attributional	Attributional	Attributional
Integration of LCA and RA (Risk Assessment)	Complementary Tools					
	LCA as a subset of RA					
	RA as a subset of LCA					
	Overlapped					
	Separated					
LCA Uncertainties	Future Uncertainties (time and physical		✓			
	Preferences Uncertainties	✓				
	Statistical/measurement error					
	Model Uncertainty		✓			
	Database Uncertainty		✓	✓	✓	✓

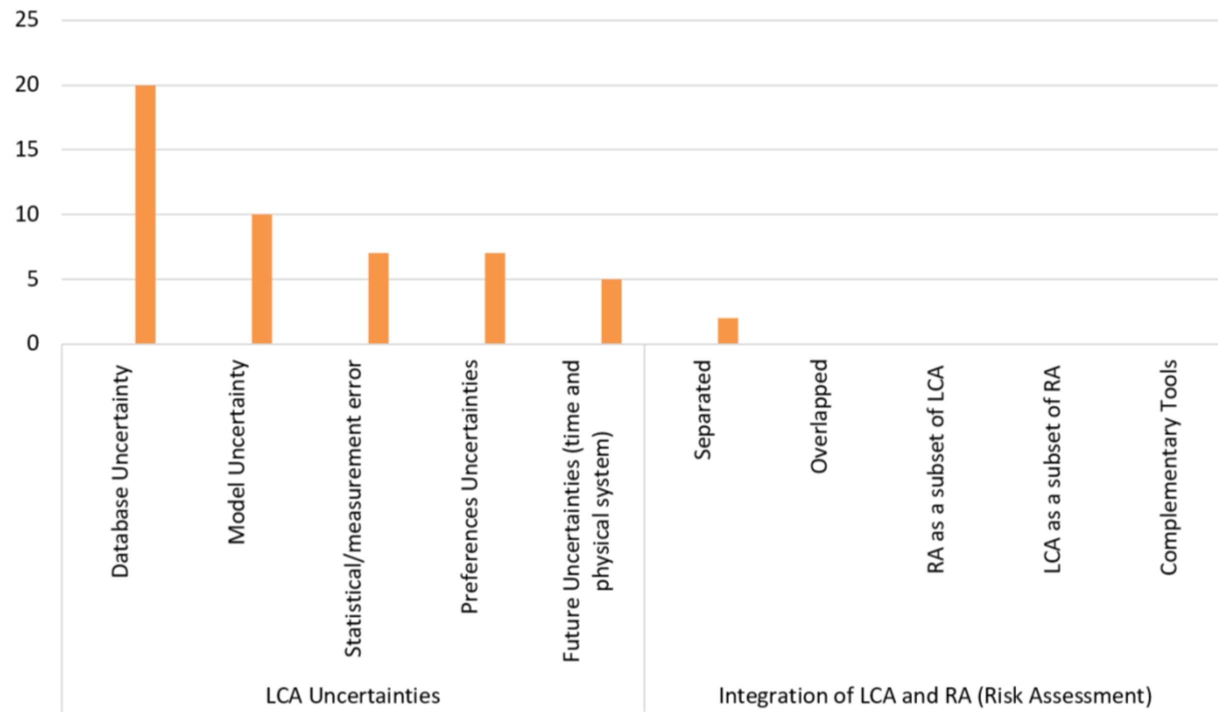

Figure 6. LCA Studies Classifications According to Uncertainties and Risk Factors

V. Impact Assessment Methodologies

Relevant to this report is the third phase of an LCA that refers to the assessment of impacts of the specific product or service (according to certain endpoints and midpoints). These impacts can be in the form of eco system quality, human health, and natural resources, among others. This phase evaluates all or some parts of these characterization factors (CFs) through defined and specific methodologies, and use weighting factors to aggregate life cycle impacts. The level of uncertainty and the coverage of impact categories are different depending on whether they are assessing mid-point or end-point indicators and contributes to different impact scores. Usually, equivalency factors express midpoint, while end-point indicators refer to the main factors of human health, ecosystem health, and resource availability. Social and Environmental Impact Assessment Methodologies are among the most common methods.

The international standard ISO14001:2004 defines an impact as "…any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's environmental aspects…" The ISO also define environmental aspect as the "…element of an organization's activities or products or services that can interact with the environment…" (Whitelaw, 2004; Finkbeiner et al., 2006).

Environmental Impact Assessment (EIA) Methodologies

EIA methodologies represent a wide variety of methods to trace back the environmental effects of a product or service. Considering the multitude of methods, the specific requirements of the study will help determine the most appropriate assessment to use. The most commonly used methodologies include the methods outlined below.

Ad hoc methods

These methods consider a qualitative index to assess environmental impacts, usually assessed by team of experts. The results are informed using simple terms without much detail on the specific parameter changes due to impacts. One of the major limitations is that these methods may not consider all the relevant impact factors, and there is a lack of normalization between different groups causing inconsistency in the analysis (Lohani et al., 1997).

Matrix methods

Matrix methods are among the popular methods for impact assessment due to their user-friendly representation of factors. The rationale for these methods is to identify the relationships and interactions between the processes (project actions) and the environmental impact factors. Early on, these methods compared in one axis, the list of project activities, and the environmental components on the other. The matrices provided a simple representation of the cause and effect relationship with either qualitative or quantitative values. However, these methods provide limited applicability to identify indirect impacts (Lohani et al., 1997).

Networks-based Methods

Matrix methods can also be categorized in many ways, one of which are network models, which incorporate long-term impacts of the project activity. One of the improvements from static matrix methods is the use of network-based conceptual models to represent the pathways or causal chains for the relationships between cause and effect. Several categories classify the impacts, e.g., primary, secondary or tertiary. The major strength of the network approach is its ability to indicate both direct and indirect environmental impacts.

Specifically, there are many methodologies to implement LCIA studies; Annex B summarizes these methodologies. Recently, Wolf et al. (2012) assessed the various EIA methodologies based on the included impact factors (see Table 9). In the table, “O” indicates if a specific impact is just considered in the methodology but not furthered investigated; “M” indicates that a midpoint value is available and furthered investigated; and, “E” refers to the availability of an endpoint value that is furthered investigated.

Table 9. Characterization Models for Impact Assessment

	Climate change	Ozone depletion	Respiratory inorganics	Human toxicity	Ionizing radiation	Eco toxicity	Ozone formation	Acidification	Tersest. Eutrophication	Aquatic Eutrophication.	Resource Consumption Others	Resource Consumption Others	Others
CML 2002 (Guinée, 2002)	O	O		M	O	O	M	M	M	M	O	M	
ECO-indicator 99 (Goedkoop and Spriensma, 2000)	E	E	E	O	O		E	E	E		E	E	
EDIP 2003/EDIP97 (Hauschild and Potting, 2005)	O	M	O	M	O	M	M	M	M	M		M	Work Environment Road noise
EPS 2000 (Steen, 1999)	E	E	E	E	O	E	E	O	O	O	E	E	
IMPACT 2002+ (Jolliet and Fantke, 2015)	O	O	E	M E	O	M E	E	M E		O	M E	E	
LIME (Itsubo et al., 2012)	E	E	M	E			O	M E	O	E	E	E	Indoor air
LUCAS (Toffoletto et al., 2007)	O	o		o		o	o	o	o	o	o	O	
MEEuP (Kemna et al., 2005)	O	O	M	M		M	M	M	M	M		Water	
ReCiPe (Goedkoop et al., 2009)	M E	E	M E	M E	O	M E	M E	M E	O	M E	M E	E	
Swiss Ecosacrcity 07 (Swart et al., 2015)	O	O	O	O	M E	M	O	O	O	O	M E	Water	Endocrine disruptors
TRACI (Bare, 2011)	O	O	M	M		M	M	M	O	M		O	
Specific methods to be evaluated	Ecological Foot Print			USETox		USETox					Ecological footprint		
Specific methods of potential interest (not to be evaluated)				Watson (Bachmann)	Eco toxicity of radiation (Laplace et al.)		EcoSense	EcoSense					Meijer indoor air UNEP Indoor air

Source: (Wolf et al., 2012)

Economic Cost-Benefit Analysis (CBA)

Cost-benefit analyses (CBA) are one of the common approaches to quantitatively assess the benefits of a project. This traditional approach evaluates economic factors such as welfare, resources, and public finance.

Table 10 provides an overview of the typical steps to conduct a cost-benefit analysis and the types of questions it addresses.

Table 10. Cost and Benefit Analysis

Steps	Questions?	Criteria
Preliminary Considerations	Problem statement	Which costs and benefits to consider?
		How to value them?
		What is the interest rate to discount them?
	Investigating the General Issue	
Main Questions	Enumeration of Costs and benefits (Examples)	Project definitions
		Externalities
		Secondary benefits
		Project Life time
	Costs and benefit evaluation	Relevant Prices
		Non-marginal Changes
		Market Imperfections
		Taxes and Controls
		Unemployment Ratio
		Collective Goods
		Intangibles
	Interest Rate	Time preference rate
		Opportunity cost rate
		Adjustment for uncertainties
		Interest Rate Calculations
		Principles, and practice
	Relevant Consideration	Distributional Constraints
		Budgetary Constraints
		Supply Chain Constraints
Final Considerations	Investment criteria	
	Policy vs. Decision making Consideration	

Source: (Prest and Turvey, 1965)

In general, a project is economically feasible and justifiable to do when the benefits outweigh its costs. An ideal cost benefit analysis evaluates all the aspects of the project including its desirability, social preferences, and the target policy. Logically, preferred projects are the ones with the highest net benefits compared to their net costs. The methods use a discount rate to estimate the value of future costs and benefits (Alberini and Krupnick, 2000).

Cost and Benefit Categories

In a cost benefit analysis, the costs are in the form of social costs, which refers to both direct and indirect costs to the agencies or stakeholders in the studied system. Therefore, the total social costs may differ from the private costs directly related to the project, policy, or strategy. Specifically, this social cost refers to the opportunities that the implementation of the new policy, services or goods provides. Common categories or costs include (Kuosmanen and Kortelainen, 2007):

- Government regulatory costs
- Social welfare losses
- Transitional costs
- Indirect costs

Theoretically, the total benefits regarding a project, policy or strategies equals to the benefits gained by each stakeholder and their willingness to pay for that specific potential policy. Table 11 provides example of benefits from environmental policies, their direct and indirect impacts, and the techniques used to do economic valuation of such impacts (Kuosmanen and Kortelainen, 2007).

Table 11. Categories of Benefits from Environmental Policies

Benefit Category	*Example of service flows affected by the policy*	*Possible Monetary Valuation Methods*
Human Health benefits: Morbidity and mortality risks	Reduced risk of cancer, Reduced risk of respiratory Symptoms	Averting behavior Contingent Valuation Hedonic pricing Methods Cost of illness
Amenities	Visibility affected by air Quality	Averting Behavior Contingent Valuation Hedonic Pricing Methods
Ecological Benefits: Market Products	Provision of food, fuel, timber, fiber, fur	Market approaches
Ecological Benefits: Recreation and aesthetics	Viewing, fishing, boating, swimming, hiking, etc.	Production Function Contingent Valuation Hedonic Pricing Methods Travel Cost methods
Ecological Benefits: Ecosystem Services	Flood moderation, climate moderation, water filtration, sediment trapping, groundwater recharge, soil fertilization, pest control.	Production Function Averting Behaviors Hedonic Pricing Methods
Ecological Benefits: Existence and banquet values	No associated services (passive use values)	Contingent Valuation
Material Damage	--	Averting Behavior Market Approaches

Source: (Alberini and Krupnick, 2000)

Environmental Cost-Benefit Analysis

CBA and LCA are decision-making tools regarding the impacts of projects, products and procedures; however, they may have different scopes and objectives. While CBA may consider a wide range of impacts, LCA mostly focuses on environmental and health impacts. Similarly, there are distinctions between Life Cycle Costing (LCC) and LCA (Finkbeiner et al., 2006; Lippiatt, 2017). LCC evaluates products, and procedures based on their monetary values, while LCA focusses on the environmental consequences resulting from a product. These distinctions contrast their degree and strategy of application (Lippiatt, 2017). LCC usually concentrates on the use phase, and could be considered a sub-category of a full LCA (Lippiatt, 2017). For instance, there are cases in which a LCC and a LCA differ in their consideration of the physical flows, processes, cash flows and their timing, as well as the risk of the costs. Despite the differences, there are models aiming at properly bonding LCA and LCC.

PTLaser

This method builds on the LCA stages and adds monetary values, measurements of time, and allocates capacities to the physical flow to properly account for the costs in the LCC (Norris, 2001). The major contribution of this model is the use of vulnerability and hazards concepts. This method builds on a chance-constrained framework to evaluate scenarios that can happen with some probabilities. (Norris, 2001).

TCAce

TCAce is another framework to integrate LCC and LCA with a decision making environment (Norris, 2001). Contrary to PTLaser, this method uses the outcome of a LCA and estimates the costs using conventional monetary examinations and considers the inconsequential costs (Norris, 2001).

LCA and Cost-Benefit Applications in Transportation

Transportation applications have used LCA and cost-benefit analyses to identify the most sustainable transportation mode, vehicle, or fuel pathway. Similar to the previous descriptions, LCA can evaluate the impacts of transportation processes from raw material extraction, and all the subsequent processes through its life cycle. Different stakeholders can use the methods for decision-making. Although general cost-benefits methods can evaluate a wide range of impacts, indirect environmental costs are sometimes ignored or could be the main focus of the method's implementation (Manzo and Salling, 2016). However, the traditional cost-benefit methods have not fully considered the ecological sustainability and the impact of the transportation systems on this aspect (Manzo and Salling 2016).

Chester et al. (2010) valuated passenger transportation systems including car, buses, trains and airplanes and their relative LCA. The study concluded that, inputs from life-cycle energy and GHG emissions will increase the operating costs from 31% (air) to 155% (rail). They also evaluated the energy consumption in transportation in three metropolitan regions and concluded that considering the environmental impact factors, the energy consumption and emissions increase up to 20 times.

In addition to the energy consumption and emissions, some of the studies incorporate the land use dimension. For instance, Kimball et al. (2013) show that the environmental impacts of the infrastructure construction, vehicle industries and energy consumption associated with public transportation are considerable.

Regarding the High-speed rail corridor in California, Chester and Horvath (2010) proposed an LCA analysis that showed high-speed rail transportation system in California may change travel behavior and travel demand in a way that results in environmental emissions reduction, while this system may also change the traffic dynamic and result in increased environmental emissions. Thoft-Christensen (2012) used LCA to analyze a motorway infrastructure investment and concluded that building the new infrastructure would impose higher expenses than the maintenance costs of the existing infrastructure. Chester and Horvath (2012) also evaluated the modal transfer from private vehicles to public transit modes. In this study, the authors believe that new technologies may help reduce environmental footprints, while results indicate that the lifecycle regarding the vehicle, infrastructure, and energy production may increase environmental emissions.

There are just a handful of studies combining LCA and Cost-Benefit Analysis (CBA) in transportation. These existing studies highlight the importance of evaluating the environmental impacts of transportation infrastructure and operations. Salling and Leleur (2015) developed a tool to analyze the transport infrastructure projects through CBA by incorporating a LCA module into the UNITE-DSS model (see Figure 7). The proposed UNITE-DSS model consists of two parts: deterministic and stochastic. The deterministic component deals with common socio-economic indicators using CBA approaches evaluating the Net Present Value (NPV), Benefit Cost Ratio (BCR), and the Internal Rate of Return (IRR). The stochastic component considers the uncertainty analysis of construction costs, in addition to the transport demand forecast, mostly based on Monte-Carlo Simulation (MCS).

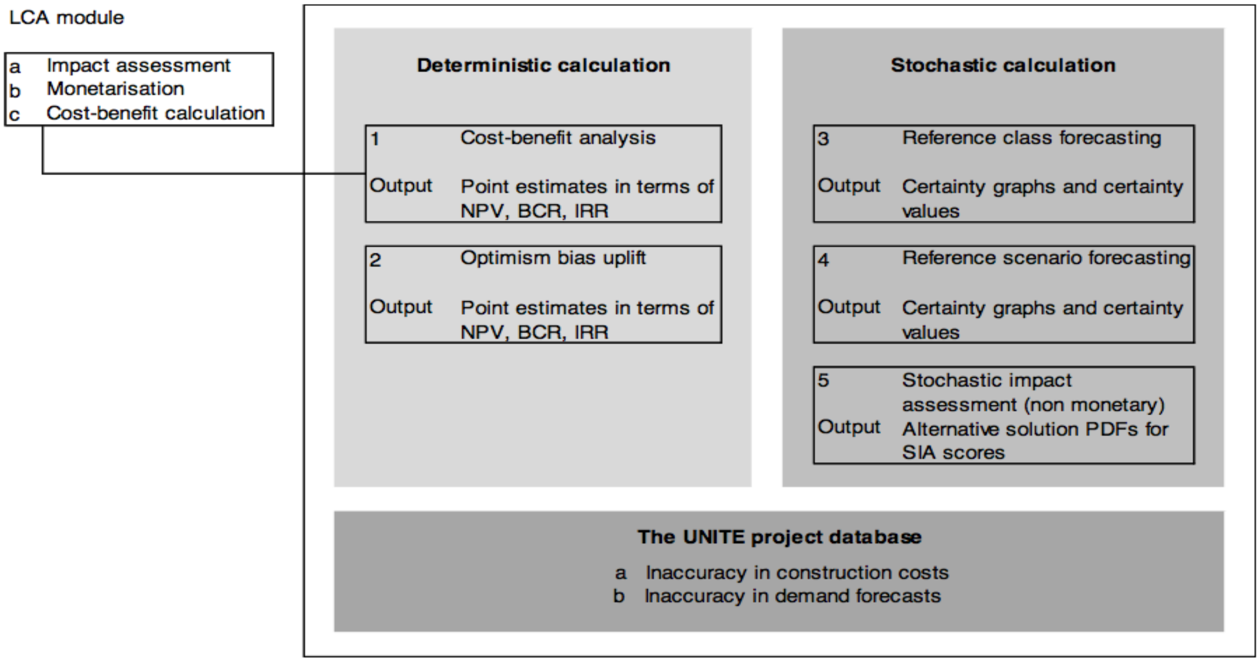

Figure 7. UNITE-DSS Model Framework *(Halog and Manik, 2016)*

Nahlik et al. (2015) proposed a LCA framework for freight transportation systems focusing on the flows originating from or destined to California. The freight transportation mode is limited to rail, Ocean Going Vessels (OGV), and road transportation, which divided into to medium heavy-duty vehicles (MHD), and Heavy-Heavy Duty vehicles (HHD). The study considers energy inputs and air emissions categorized as GHG, CO, non-methane volatile organic compounds (NMVOC), NOX, SO_2, PM_{10}, and $PM_{2.5}$. The study transferred the individual emission categories into carbon dioxide equivalent (CO_2eq) for ease of calculations. The study uses a number of databases to estimate the environmental impacts of the transport of goods using the various modes and the established boundaries. The LCA stages include vehicle operation/propulsion, vehicle manufacturing and maintenance, infrastructure, and energy production. The estimates use EMFAC and CARB data for assessing vehicle operations, CA-GREET for energy production and mix grids, PaLATE for infrastructure emissions, and SimaPro and Ecoinvent to calculate the emissions regarding vehicle manufacturing and maintenance. The study considers different scenarios to assess the movement of goods intrastate and the imports and exports. For intrastate transportation, the analyses consider rail and over the road transport, and consider combinations of modes (railway and use of trucks), and using (MHD and HHDO) trucks for intrastate transportation. The importing and exporting goods to/from the state is also considered through the rail, rail and trucks (MHD, HHD), trucks and the combination of trucks and ships) for imports and exports. Limiting to the transportation component, the study finds that truck movements (vehicle operations) contribute the largest amount of emissions. Moreover, the study concludes that ocean going ships are among the modes of transportation that have the lowest emissions (Nahlik et al., 2015). This study provides a general framework to estimate the environmental impacts of the entire transportation sector, whether in or outside California. Figure 8 provides an overview of the LCA results in the state (Nahlik et al., 2015).

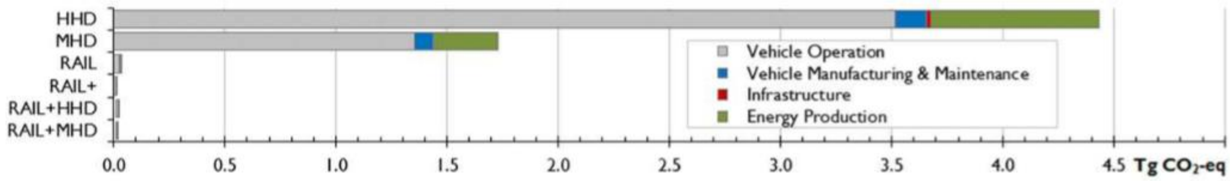

Figure 8. California Intrastate LCA results (Nahlik et al., 2015)

California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C)

One special method that combines LCA and CBA is the California Life-Cycle Benefit/Cost Analysis Model (CAL-B/C). This method provides a practical approach for economic evaluations regarding highways, and transit systems in the State of California (Bailly and Brinckerhoff, 1999). The California Department of Transportation (Caltrans) developed the Cal-B/C as a CBA for highway projects as a spreadsheet model. The model provides analyses based on annual transit ratios and average daily traffic in a highway. The benefits of the model are considered to be in four categories of time savings, reducing vehicle operation costs, and emissions reductions (CO, NOx, PM10, VOC). Cost categories consider annual operating costs and life cycle investment costs. Furthermore, the model incorporates different transportation modes including passenger, rail, light rail, and bus. The method estimates the impacts over the life of the project in the form of life cycle costs/benefits, cost-benefit ratio, projects pay back ratio, the investment return rate, and net present values (Langdon, 2006).

Typically, the factors that affect the cost of travel are wage rates, trip purposes, and the amount of time saved or lost. Regarding the value of time, this method incorporates different analyses dependent on mode, route, speed, and dwelling choices. The cost estimates also include congestion, the level of service, and waiting/walking time to destination (Bailly and Brinckerhoff, 1999). The model has capabilities to estimate the cost considering different vehicle types, driver behaviors, and passengers. The model builds on the HERS, StratBENCOST, and STEAM models.

Although there are many complexities regarding the evaluation of the cost-benefits in transportation models, models like StratBENCOST and STEAM, account for some environmental costs (Bailly and Brinckerhoff, 1999). On the other hand, the STEAM model estimates the environmental costs more holistically and takes external effects like global warming and noise into account. STEAM calculates the emissions more precisely by using changes in VMT and number of vehicle trips (Bailly and Brinckerhoff, 1999). Figure 9 displays an example flow of using the CAL-B/Co to estimate effects of a highway project on air pollution.

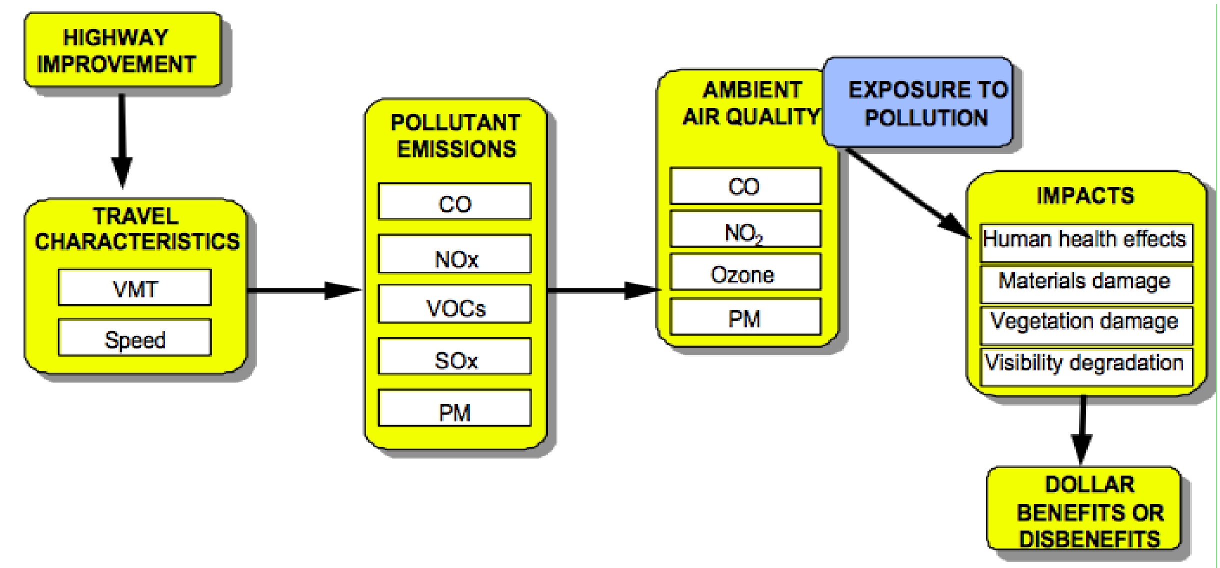

Figure 9. Dollar Value on the Air-pollution Effects of a Highway Project *(Bailly and Brinckerhoff, 1999)*

Summary

LCA provides a general system to recognize and assess the impacts of systems, products, and processes (Matthews et al., 2002). There has been an evolution of both LCA and CBA frameworks, and their combination have led to frameworks that could fully assess the various impacts. However, there are contrasting views and objectives for the selection and implementation of an assessment methodology. For example, Table 12 shows the differences between LCA and some supply chain management perspectives.

Table 12. Modeling Approaches for Life Cycle Assessment and Supply Chain Management

	Life Cycle Perspective	*Supply chain Management Perspective*
Objective of Study	Sustainability measurement in support of a decision	Supporting implementation of a decision or decision rule
Dependent Variable	Environmental impacts per functional unit	Performance (cost, profit, or other) per unit time
Scope of considered system	Broader system boundary including different life cycle stages	Often limited to the stages that are immediately related to the decision
Environmental Impacts Considered	Usually multidimensional	Often Single-Dimensional
Impact of Production Function	Linear in Volume	Nonlinear, Complex
Economic Structure od model	Usually single-agent	Multiple agents; incentives matter
Dealing with uncertainty	Confidence intervals for impacts	Robustness of decision

Source: (Matos and Hall, 2007)

A careful analysis of the scope of a methodology is imperative to define the set of impact categories to address. A sample of references from the literature can help highlight the focus or gaps in the type of impact categories receiving attention. Table 13 compares the references reviewed in this report regarding the following impact categories: environmental, financial/economic, and direct/indirect transportation cost/benefits. The table shows that LCA methods have a higher tendency to focus on the environmental aspects rather than the economic or social consequences.

Table 13. Classification of Studies According to Impact Assessment Categories

			Environment		
Attributional V.s. Consequential			Attributional LCA		
Type of Model			Based on Previous Studies (Action taken by companies towards life cycle engineering	Resource Prioritization	Chemical & Environmental impact Reduction
Year			1995	2009	2011
Authors			Alting, L.	Baker, J. W., &	Bare, J.
Environmental Factors	Human Health	Respiratory inorganics			✓
		Human toxicity			✓
		Ionizing radiation			
	Climate Effects	Climate change	✓	✓	✓
		Water Eutrophication			
	Terrestrial & Aquatic Impacts	Aquatic Eco toxicity			
		Terrestrial Eco toxicity	✓		✓
		Air Acidification	✓		✓
	Air Impacts	Photochemical Oxidation	✓		✓
		Ozone layer depletion	✓		✓
		Water Use			
	Natural Resource Depletion	Mineral extraction			
		Land Occupation/Use			✓
		Non-Renewable Energy			✓
Financial/Economic Factors		Internal Costs			
		External Costs			
		Social Costs			
		Variable/Fixed costs			
		Market costs			
		Non-Market Costs			
		Perceived Costs			
		Actual Costs			
		Direct Costs			
		Indirect Costs			
		Economic Transfers			
		Resource Costs			
		Taxes			
Transportation Costs/Benefits	User Costs and Benefits	Vehicle ownership and operating			
		Vehicle taxes and government fees, and			
		Road tolls and parking fees			
		Public transportation fares			
		Fitness (use of physically active modes,			
		Cost recovery and subsidies (portion of			
	External Impacts	Traffic congestion and risk an individual			
		Air, noise and water pollution emissions.			
		Barrier effect (delay that roads and			
		Transport of hazardous material and			
		Aesthetic impacts of transportation			
		Impacts on community livability.			
	Economic Impacts	Access to education and employment,			
		Impacts on business activity, property			
		Distribution of expenditures and			

Transportation Costs/Benefits															Financial/Economic Factors													Environmental Factors																			
Economic Impacts			External Impacts						User Costs and Benefits																			Natural Resource Depletion			Air Impacts			Terrestrial & Aquatic Impacts			Climate Effects		Human Health							
Distribution of expenditures and	Impacts on business activity, property	Access to education and employment,	Impacts on community livability.	Aesthetic impacts of transportation	Transport of hazardous material and	Barrier effect (delay that roads and	Air, noise and water pollution emissions.	Traffic congestion and risk an individual	Cost recovery and subsidies (portion of	Fitness (use of physically active modes,	Public transportation fares	Road tolls and parking fees	Vehicle taxes and government fees, and	Vehicle ownership and operating	Taxes	Resource Costs	Economic Transfers	Indirect Costs	Direct Costs	Actual Costs	Perceived Costs	Non-Market Costs	Market costs	Variable/Fixed costs	Social Costs	External Costs	Internal Costs	Non-Renewable Energy	Land Occupation/Use	Mineral extraction	Water Use	Ozone layer depletion	Photochemical Oxidation	Air Acidification	Terrestrial Eco toxicity	Aquatic Eco toxicity	Water Eutrophication	Climate change	Ionizing radiation	Human toxicity	Respiratory inorganics	**Authors**	**Year**	**Type of Model**	**Attributional V.s. Consequential**	
																																						✓				Bouman, M., Heijungs,	2000	Simulation		
																																	✓					✓				Curran, M. A.	2013	Environmental Assessment of a case study		
																												✓				✓	✓	✓	✓			✓				Curran, M. A.,	2006	Inventory Datasets		
																												✓		✓		✓	✓				✓	✓	✓	✓	✓	de Haes, H. A. U., Jolliet, O.,	1999	Impact Categories choosing methods		

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Attributional V.s. Consequential						
Type of Model			Introduction to LCA	Quantifying environmental metrics	Recent Development in LCA	A handbook for LCA
Year			2014	2011	2009	2002
Authors			Dicks, A., & Hent, A.	Favara, P. J., Krieger, T.	Finnveden, G., Hauschild,	Guinée, J. B.
Environmental Factors	**Human Health**	Respiratory inorganics	✓		✓	✓
		Human toxicity	✓		✓	✓
		Ionizing radiation	✓		✓	✓
	Climate Effects	Climate change	✓	✓	✓	✓
		Water Eutrophication	✓			✓
	Terrestrial & Aquatic Impacts	Aquatic Eco toxicity	✓			✓
		Terrestrial Eco toxicity	✓	✓	✓	✓
		Air Acidification	✓	✓	✓	✓
	Air Impacts	Photochemical Oxidation	✓	✓	✓	✓
		Ozone layer depletion	✓	✓	✓	✓
		Water Use	✓	✓	✓	✓
	Natural Resource Depletion	Mineral extraction	✓	✓	✓	✓
		Land Occupation/Use	✓	✓	✓	✓
		Non-Renewable Energy	✓	✓	✓	✓
Financial/Economic Factors		Internal Costs				✓
		External Costs				✓
		Social Costs				
		Variable/Fixed costs				
		Market costs				
		Non-Market Costs				
		Perceived Costs				
		Actual Costs				
		Direct Costs				
		Indirect Costs				
		Economic Transfers				
		Resource Costs				
		Taxes				
Transportation Costs/Benefits	**User Costs and Benefits**	Vehicle ownership and operating				
		Vehicle taxes and government fees, and				
		Road tolls and parking fees				
		Public transportation fares				
		Fitness (use of physically active modes,				
		Cost recovery and subsidies (portion of				
	External Impacts	Traffic congestion and risk an individual				
		Air, noise and water pollution emissions.				
		Barrier effect (delay that roads and				
		Transport of hazardous material and				
		Aesthetic impacts of transportation				
		Impacts on community livability.				
	Economic Impacts	Access to education and employment,				
		Impacts on business activity, property				
		Distribution of expenditures and				

		Attributional V.s. Consequential				
		Type of Model	Euthorofication Assessment	Framework for Social LCA	Quantifying environmental metrics	Sustainability Assessment
		Year	1999	2006	2001	2016
		Authors	Finnveden, G., & Potting, J.	Dreyer, L., Hauschild,	Guinée, J. B., Huppes,	Halog, A., & Manik,
Environmental Factors	**Human Health**	Respiratory inorganics		✓	✓	✓
		Human toxicity		✓	✓	✓
		Ionizing radiation		✓	✓	✓
	Climate Effects	Climate change	✓	✓	✓	✓
		Water Eutrophication	✓	✓	✓	✓
	Terrestrial & Aquatic Impacts	Aquatic Eco toxicity	✓	✓	✓	✓
		Terrestrial Eco toxicity	✓	✓	✓	✓
		Air Acidification	✓	✓	✓	✓
	Air Impacts	Photochemical Oxidation	✓	✓	✓	✓
		Ozone layer depletion	✓	✓	✓	✓
		Water Use	✓	✓	✓	✓
	Natural Resource Depletion	Mineral extraction	✓	✓	✓	✓
		Land Occupation/Use	✓	✓	✓	✓
		Non-Renewable Energy	✓	✓	✓	✓
Financial/Economic Factors		Internal Costs				✓
		External Costs				✓
		Social Costs				
		Variable/Fixed costs				
		Market costs				
		Non-Market Costs				
		Perceived Costs				
		Actual Costs				
		Direct Costs				
		Indirect Costs				
		Economic Transfers				
		Resource Costs				
		Taxes				
Transportation Costs/Benefits	**User Costs and Benefits**	Vehicle ownership and operating				
		Vehicle taxes and government fees, and				
		Road tolls and parking fees				
		Public transportation fares				
		Fitness (use of physically active modes,				
		Cost recovery and subsidies (portion of				
	External Impacts	Traffic congestion and risk an individual				
		Air, noise and water pollution emissions.				
		Barrier effect (delay that roads and				
		Transport of hazardous material and				
		Aesthetic impacts of transportation				
		Impacts on community livability.				
	Economic Impacts	Access to education and employment,				
		Impacts on business activity, property				
		Distribution of expenditures and				

Attributional V.s. Consequential						
Type of Model			GWP (quantifying environmental metrics)	GWP (quantifying environmental	Statistical analysis for weighting factor	Spatial differentiation
Year			2002	2001	1996	2016
Authors			Hertwich, E. G., Jolliet,	Hertwich, E. G.,	Hunt, R. G., Franklin, W.	Nitschelm, L., Aubin, J., Corson, M.
Environmental Factors	Human Health	Respiratory inorganics	✓	✓		
		Human toxicity	✓	✓	✓	
		Ionizing radiation	✓	✓	✓	
	Climate Effects	Climate change	✓	✓	✓	✓
		Water Eutrophication	✓	✓	✓	✓
	Terrestria l & Aquatic Impacts	Aquatic Eco toxicity	✓	✓	✓	✓
		Terrestrial Eco toxicity	✓	✓	✓	✓
		Air Acidification	✓	✓	✓	✓
	Air Impacts	Photochemical Oxidation	✓	✓	✓	✓
		Ozone layer depletion	✓	✓	✓	
		Water Use	✓	✓	✓	
	Natural Resource Depletio n	Mineral extraction	✓	✓	✓	✓
		Land Occupation/Use	✓	✓	✓	✓
		Non-Renewable Energy	✓	✓	✓	✓
Financial/Economic Factors		Internal Costs			✓	
		External Costs			✓	
		Social Costs			✓	
		Variable/Fixed costs				
		Market costs				
		Non-Market Costs				
		Perceived Costs				
		Actual Costs				
		Direct Costs				
		Indirect Costs				
		Economic Transfers				
		Resource Costs				
		Taxes				
Transportation Costs/Benefits	User Costs and Benefits	Vehicle ownership and operating				
		Vehicle taxes and government fees, and				
		Road tolls and parking fees				
		Public transportation fares				
		Fitness (use of physically active modes,				
		Cost recovery and subsidies (portion of				
	External Impacts	Traffic congestion and risk an individual				
		Air, noise and water pollution emissions.				
		Barrier effect (delay that roads and				
		Transport of hazardous material and				
		Aesthetic impacts of transportation				
		Impacts on community livability.				
	Economic Impacts	Access to education and employment,				
		Impacts on business activity, property				
		Distribution of expenditures and				

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Attributional V.s. Consequential					
Type of Model			LUCAS	GWP (quantifying environmental metrics)	GWP (quantifying environmental metrics)
Year			2006	2007	2007
Authors			Tukker, A., Huppes, G.,	Sandén, B. A., & Karlström, M.	Schmidt, J. H., Holm, P.,
Environmental Factors	**Human Health**	Respiratory inorganics	✓		
		Human toxicity	✓		✓
		Ionizing radiation	✓		
	Climate Effects	Climate change	✓	✓	✓
		Water Eutrophication	✓	✓	✓
	Terrestrial & Aquatic Impacts	Aquatic Eco toxicity	✓	✓	✓
		Terrestrial Eco toxicity	✓		✓
		Air Acidification	✓		✓
	Air Impacts	Photochemical Oxidation	✓		✓
		Ozone layer depletion	✓		✓
		Water Use	✓		✓
	Natural Resource Depletion	Mineral extraction	✓		✓
		Land Occupation/Use	✓		✓
		Non-Renewable Energy	✓		✓
Financial/Economic Factors		Internal Costs			✓
		External Costs			✓
		Social Costs			
		Variable/Fixed costs			
		Market costs			
		Non-Market Costs			
		Perceived Costs			
		Actual Costs			
		Direct Costs			
		Indirect Costs			
		Economic Transfers			
		Resource Costs			
		Taxes			
Transportation Costs/Benefits	**User Costs and Benefits**	Vehicle ownership and operating			
		Vehicle taxes and government fees, and			
		Road tolls and parking fees			
		Public transportation fares			
		Fitness (use of physically active modes,			
		Cost recovery and subsidies (portion of			
	External Impacts	Traffic congestion and risk an individual			
		Air, noise and water pollution emissions.			
		Barrier effect (delay that roads and			
		Transport of hazardous material and			
		Aesthetic impacts of transportation			
		Impacts on community livability.			
	Economic Impacts	Access to education and employment,			
		Impacts on business activity, property			
		Distribution of expenditures and			

Attributional V.s. Consequential					Consequential LCA
Type of Model			GWP (quantifying environmental metrics)	allocation, waste management, paper recycling, waste	Partial equilibrium model
Year			2008	1999	2006
Authors			Searchinger, T., Heimlich, R.,	Ekvall, T.	Ekvall, T., & Andrae, A.
Environmental Factors	Human Health	Respiratory inorganics			
		Human toxicity			
		Ionizing radiation			
	Climate Effects	Climate change	✓	✓	✓
		Water Eutrophication	✓		
	Terrestrial & Aquatic Impacts	Aquatic Eco toxicity	✓		
		Terrestrial Eco toxicity	✓	✓	
		Air Acidification	✓	✓	
	Air Impacts	Photochemical Oxidation	✓	✓	
		Ozone layer depletion	✓	✓	
		Water Use	✓	✓	
	Natural Resource Depletion	Mineral extraction	✓	✓	
		Land Occupation/Use	✓	✓	
		Non-Renewable Energy	✓	✓	
Financial/Economic Factors		Internal Costs	✓	✓	
		External Costs			
		Social Costs			
		Variable/Fixed costs			
		Market costs			
		Non-Market Costs			
		Perceived Costs			
		Actual Costs			
		Direct Costs			
		Indirect Costs			
		Economic Transfers			
		Resource Costs			
		Taxes			
Transportation Costs/Benefits	User Costs and Benefits	Vehicle ownership and operating			
		Vehicle taxes and government fees, and			
		Road tolls and parking fees			
		Public transportation fares			
		Fitness (use of physically active modes,			
		Cost recovery and subsidies (portion of			
	External Impacts	Traffic congestion and risk an individual			
		Air, noise and water pollution emissions.			
		Barrier effect (delay that roads and			
		Transport of hazardous material and			
		Aesthetic impacts of transportation			
		Impacts on community livability.			
	Economic Impacts	Access to education and employment,			
		Impacts on business activity, property			
		Distribution of expenditures and			

Attributional V.s. Consequential						
Type of Model			The Eco-indicator 99 Impact categories	The Eco-indicator 99 Impact categories	ReCipe Model	Bioenergy systems
Year			2000	1998	2009	2011
Authors			Goedkoop, M., & Spriensma, R.	Goedkoop, M., Hofstetter, P.,	Goedkoop, M., Heijungs, R.,	Cherubini, F.,
Environmental Factors	Human Health	Respiratory inorganics	✓	✓	✓	
		Human toxicity	✓	✓	✓	
		Ionizing radiation	✓	✓	✓	
	Climate Effects	Climate change	✓	✓	✓	✓
		Water Eutrophication	✓	✓	✓	
	Terrestrial & Aquatic Impacts	Aquatic Eco toxicity	✓	✓	✓	
		Terrestrial Eco toxicity	✓	✓	✓	
		Air Acidification	✓	✓	✓	
	Air Impacts	Photochemical Oxidation	✓	✓	✓	
		Ozone layer depletion	✓	✓	✓	
		Water Use	✓	✓	✓	
	Natural Resource Depletion	Mineral extraction	✓	✓	✓	
		Land Occupation/Use	✓	✓	✓	✓
		Non-Renewable Energy	✓	✓	✓	
Financial/Economic Factors		Internal Costs				
		External Costs				
		Social Costs				
		Variable/Fixed costs				
		Market costs				
		Non-Market Costs				
		Perceived Costs				
		Actual Costs				
		Direct Costs				
		Indirect Costs				
		Economic Transfers				
		Resource Costs				
		Taxes				
Transportation Costs/Benefits	User Costs and Benefits	Vehicle ownership and operating				
		Vehicle taxes and government fees, and				
		Road tolls and parking fees				
		Public transportation fares				
		Fitness (use of physically active modes,				
		Cost recovery and subsidies (portion of				
	External Impacts	Traffic congestion and risk an individual				
		Air, noise and water pollution emissions.				
		Barrier effect (delay that roads and				
		Transport of hazardous material and				
		Aesthetic impacts of transportation				
		Impacts on community livability.				
	Economic Impacts	Access to education and employment,				
		Impacts on business activity, property				
		Distribution of expenditures and				

		Attributional V.s. Consequential	Sustainable transportation			
			Attributional			
		Type of Model	GWP calculations for Transportation	The UNITE-DSS model	Long Haul Transportation	GWP calculations for Transportation
		Year	2016	2016	2003	2013
		Authors	Nahlik, M. J., Kaehr,	Manzo, S., & Salling, K.	Crainic, T. G.	Chester, M. V., Nahlik,
Environmental Factors	**Human Health**	Respiratory inorganics				✓
		Human toxicity	✓	✓		
		Ionizing radiation				
	Climate Effects	Climate change	✓	✓		✓
		Water Eutrophication				
	Terrestrial & Aquatic Impacts	Aquatic Eco toxicity				
		Terrestrial Eco toxicity				
		Air Acidification	✓	✓		✓
	Air Impacts	Photochemical Oxidation	✓	✓		✓
		Ozone layer depletion	✓	✓		✓
		Water Use				
	Natural Resource Depletion	Mineral extraction		✓		
		Land Occupation/Use		✓		
		Non-Renewable Energy		✓		
Financial/Economic Factors		Internal Costs		✓		
		External Costs		✓		
		Social Costs		✓		
		Variable/Fixed costs				
		Market costs				
		Non-Market Costs				
		Perceived Costs				
		Actual Costs				
		Direct Costs				
		Indirect Costs				
		Economic Transfers				
		Resource Costs				
		Taxes				
Transportation Costs/Benefits	**User Costs and Benefits**	Vehicle ownership and operating		✓	✓	
		Vehicle taxes and government fees, and		✓	✓	
		Road tolls and parking fees		✓	✓	
		Public transportation fares		✓		
		Fitness (use of physically active modes,		✓		
		Cost recovery and subsidies (portion of		✓		
	External Impacts	Traffic congestion and risk an individual		✓	✓	
		Air, noise and water pollution emissions.		✓		
		Barrier effect (delay that roads and		✓		
		Transport of hazardous material and		✓	✓	
		Aesthetic impacts of transportation		✓		
		Impacts on community livability.		✓		
	Economic Impacts	Access to education and employment,		✓		
		Impacts on business activity, property		✓		
		Distribution of expenditures and		✓		

						Cost Analysis
Attributional V.s. Consequential						
Type of Model			Energy Use (Private v.s. Public Transit)	Energy Consumption-GWP	Energy Consumption-GWP	LCC
Year			2010	2010	2012	###
Authors			Chester, M. V., Horvath,	Chester, M., & Horvath, A.	Chester, M., & Horvath, A.	Langdon, D.
Environmental Factors	**Human Health**	Respiratory inorganics				✓
		Human toxicity				
		Ionizing radiation				✓
	Climate Effects	Climate change	✓	✓	✓	✓
		Water Eutrophication				✓
	Terrestrial & Aquatic Impacts	Aquatic Eco toxicity				✓
		Terrestrial Eco toxicity			✓	✓
		Air Acidification	✓	✓	✓	✓
	Air Impacts	Photochemical Oxidation	✓	✓	✓	✓
		Ozone layer depletion		✓		✓
		Water Use				✓
	Natural Resource Depletion	Mineral extraction	✓			✓
		Land Occupation/Use				✓
		Non-Renewable Energy			✓	✓
Financial/Economic Factors		Internal Costs				✓
		External Costs				✓
		Social Costs				
		Variable/Fixed costs				
		Market costs				
		Non-Market Costs				
		Perceived Costs				
		Actual Costs				
		Direct Costs				✓
		Indirect Costs				✓
		Economic Transfers				
		Resource Costs				
		Taxes				
Transportation Costs/Benefits	**User Costs and Benefits**	Vehicle ownership and operating	✓		✓	
		Vehicle taxes and government fees, and	✓		✓	
		Road tolls and parking fees	✓	✓	✓	
		Public transportation fares	✓		✓	
		Fitness (use of physically active modes,			✓	
		Cost recovery and subsidies (portion of			✓	
	External Impacts	Traffic congestion and risk an individual	✓	✓	✓	
		Air, noise and water pollution emissions.	✓	✓	✓	
		Barrier effect (delay that roads and			✓	
		Transport of hazardous material and				
		Aesthetic impacts of transportation				
		Impacts on community livability.				
	Economic Impacts	Access to education and employment,				
		Impacts on business activity, property				
		Distribution of expenditures and				

Attributional V.s. Consequential						
Type of Model			UNITE-DSS model	GWP (quantifying environmental metrics)	Economic Input/Output Analysis	WTP & COI economic Model
Year			###	2007	1995	###
Authors			Salling, K. B.,	Kuosmanen, T., & Kortelainen, M.	Cobas, E., Hendrickson, C.,	Alberini, A., & Krupnick, A.
Environmental Factors	Human Health	Respiratory inorganics				✓
		Human toxicity				
		Ionizing radiation				
	Climate Effects	Climate change			✓	
		Water Eutrophication			✓	
	Terrestrial & Aquatic Impacts	Aquatic Eco toxicity			✓	
		Terrestrial Eco toxicity			✓	
		Air Acidification			✓	✓
	Air Impacts	Photochemical Oxidation			✓	✓
		Ozone layer depletion			✓	✓
		Water Use				
	Natural Resource Depletion	Mineral extraction			✓	
		Land Occupation/Use				
		Non-Renewable Energy				
Financial/Economic Factors		Internal Costs	✓	✓		✓
		External Costs	✓	✓		✓
		Social Costs		✓		
		Variable/Fixed costs				✓
		Market costs		✓		
		Non-Market Costs				
		Perceived Costs		✓		✓
		Actual Costs		✓		✓
		Direct Costs	✓	✓		✓
		Indirect Costs	✓	✓		
		Economic Transfers				
		Resource Costs				✓
		Taxes				
Transportation Costs/Benefits	User Costs and Benefits	Vehicle ownership and operating				
		Vehicle taxes and government fees, and				
		Road tolls and parking fees				
		Public transportation fares				✓
		Fitness (use of physically active modes,				
		Cost recovery and subsidies (portion of				
	External Impacts	Traffic congestion and risk an individual				
		Air, noise and water pollution emissions.				✓
		Barrier effect (delay that roads and				
		Transport of hazardous material and				
		Aesthetic impacts of transportation				
		Impacts on community livability.				
	Economic Impacts	Access to education and employment,				
		Impacts on business activity, property				✓
		Distribution of expenditures and				

Attributional V.s. Consequential					
Type of Model			cost-Benfit Models (HERS, StratBENCOST, STEAM)	Economic Input/Output Analysis	MEMA and PEMA
Year			1999	2001	2002
Authors			Bailly, H., & Brinckerhoff, P.	Norris, G. A.	Burritt, R. L., Hahn, T., & Schaltegger, S.
Environmental Factors	Human Health	Respiratory inorganics			
		Human toxicity			
		Ionizing radiation	✓		
	Climate Effects	Climate change	✓		
		Water Eutrophication			
	Terrestrial & Aquatic Impacts	Aquatic Eco toxicity			
		Terrestrial Eco toxicity			
		Air Acidification	✓		✓
	Air Impacts	Photochemical Oxidation	✓		
		Ozone layer depletion	✓		
		Water Use			
	Natural Resource Depletion	Mineral extraction			
		Land Occupation/Use			
		Non-Renewable Energy			
Financial/Economic Factors		Internal Costs	✓	✓	
		External Costs	✓	✓	
		Social Costs			
		Variable/Fixed costs	✓		
		Market costs	✓		
		Non-Market Costs			
		Perceived Costs	✓		
		Actual Costs			
		Direct Costs	✓	✓	
		Indirect Costs	✓	✓	
		Economic Transfers			
		Resource Costs	✓		
		Taxes	✓		
Transportation Costs/Benefits	User Costs and Benefits	Vehicle ownership and operating	✓		
		Vehicle taxes and government fees, and			
		Road tolls and parking fees	✓		
		Public transportation fares			
		Fitness (use of physically active modes,			
		Cost recovery and subsidies (portion of			
	External Impacts	Traffic congestion and risk an individual	✓		
		Air, noise and water pollution emissions.	✓		✓
		Barrier effect (delay that roads and	✓		
		Transport of hazardous material and	✓		
		Aesthetic impacts of transportation			
		Impacts on community livability.	✓		
	Economic Impacts	Access to education and employment,			
		Impacts on business activity, property			
		Distribution of expenditures and			

Transportation Costs/Benefits															Financial/Economic Factors													Environmental Factors														Authors	Year	Type of Model	Attributional V.s. Consequential	
Economic Impacts			External Impacts						User Costs and Benefits																			Natural Resource Depletion			Air Impacts			Terrestrial & Aquatic Impacts			Climate Effects		Human Health							
Distribution of expenditures and	Impacts on business activity, property	Access to education and employment,	Impacts on community livability.	Aesthetic impacts of transportation	Transport of hazardous material and	Barrier effect (delay that roads and	Air, noise and water pollution emissions.	Traffic congestion and risk an individual	Cost recovery and subsidies (portion of	Fitness (use of physically active modes,	Public transportation fares	Road tolls and parking fees	Vehicle taxes and government fees, and	Vehicle ownership and operating	Taxes	Resource Costs	Economic Transfers	Indirect Costs	Direct Costs	Actual Costs	Perceived Costs	Non-Market Costs	Market costs	Variable/Fixed costs	Social Costs	External Costs	Internal Costs	Non-Renewable Energy	Land Occupation/Use	Mineral extraction	Water Use	Ozone layer depletion	Photochemical Oxidation	Air Acidification	Terrestrial Eco toxicity	Aquatic Eco toxicity	Water Eutrophication	Climate change	Ionizing radiation	Human toxicity	Respiratory inorganics					
																		✓	✓							✓	✓															www.Ledvance.com	2017	Energy Input/Output Modeling		
																✓						✓						✓						✓		✓						Berglund, M., & Börjesson, P.	2006	Energy Input/Output Modeling	Attributional	Energy Systems
							✓																									✓	✓	✓	✓			✓				Allen, S., Hammond, G.,	2008	Energy Input/Output Modeling		

Category	Sub-category	Factor	Fichtner, W., Frank, M., & Rentz, O.	Hammond, G. P., Jones, C. I.,	Hauschild, M., & Potting, J.
		Year	2004	2015	2005
		Type of Model	: Combined investment and production planning	GWP (quantifying environmental metrics)	EDI2003 Methodology
		Attributional V.s. Consequential			Attributional
					Health Impacts
Transportation Costs/Benefits	Economic Impacts	Distribution of expenditures and			
		Impacts on business activity, property			
		Access to education and employment,			
	External Impacts	Impacts on community livability.			
		Aesthetic impacts of transportation			
		Transport of hazardous material and			
		Barrier effect (delay that roads and			
		Air, noise and water pollution emissions.			
		Traffic congestion and risk an individual			
	User Costs and Benefits	Cost recovery and subsidies (portion of			
		Fitness (use of physically active modes,			
		Public transportation fares			
		Road tolls and parking fees			
		Vehicle taxes and government fees, and			
		Vehicle ownership and operating			
Financial/Economic Factors		Taxes			
		Resource Costs			
		Economic Transfers			
		Indirect Costs			
		Direct Costs			
		Actual Costs			
		Perceived Costs			
		Non-Market Costs			
		Market costs			
		Variable/Fixed costs	✓		
		Social Costs	✓		
		External Costs	✓		
		Internal Costs	✓		
Environmental Factors	Natural Resource Depletion	Non-Renewable Energy		✓	✓
		Land Occupation/Use			✓
		Mineral extraction		✓	✓
	Air Impacts	Water Use			✓
		Ozone layer depletion			✓
		Photochemical Oxidation			✓
	Terrestrial & Aquatic Impacts	Air Acidification		✓	✓
		Terrestrial Eco toxicity			✓
		Aquatic Eco toxicity			✓
	Climate Effects	Water Eutrophication		✓	✓
		Climate change			✓
	Human Health	Ionizing radiation			
		Human toxicity			✓
		Respiratory inorganics			

NCST

Transportation Costs/Benefits															Financial/Economic Factors													Environmental Factors																		
Economic Impacts			External Impacts						User Costs and Benefits																			Natural Resource Depletion			Air Impacts			Terrestrial & Aquatic Impacts			Climate Effects		Human Health							
Distribution of expenditures and	Impacts on business activity, property	Access to education and employment,	Impacts on community livability.	Aesthetic impacts of transportation	Transport of hazardous material and	Barrier effect (delay that roads and	Air, noise and water pollution emissions.	Traffic congestion and risk an individual	Cost recovery and subsidies (portion of	Fitness (use of physically active modes,	Public transportation fares	Road tolls and parking fees	Vehicle taxes and government fees, and	Vehicle ownership and operating	Taxes	Resource Costs	Economic Transfers	Indirect Costs	Direct Costs	Actual Costs	Perceived Costs	Non-Market Costs	Market costs	Variable/Fixed costs	Social Costs	External Costs	Internal Costs	Non-Renewable Energy	Land Occupation/Use	Mineral extraction	Water Use	Ozone layer depletion	Photochemical Oxidation	Air Acidification	Terrestrial Eco toxicity	Aquatic Eco toxicity	Water Eutrophication	Climate change	Ionizing radiation	Human toxicity	Respiratory inorganics	**Authors**	**Year**	**Type of Model**	**Attributional V.s. Consequential**	
																															✓								✓	✓	✓	Board, T. R., National	2011	Health Impact assessment		
																																							✓	✓	✓	Jolliet, O., & Fantke, P.	2015	Health Impact assessment		

Figure 10 summarizes the results from Table 13 and shows that most studies focused on climate change and its impact indicators (CO_2eq in most cases). The next most used criteria in life cycle analysis is “Air acidification” and “photochemical Oxidation”.

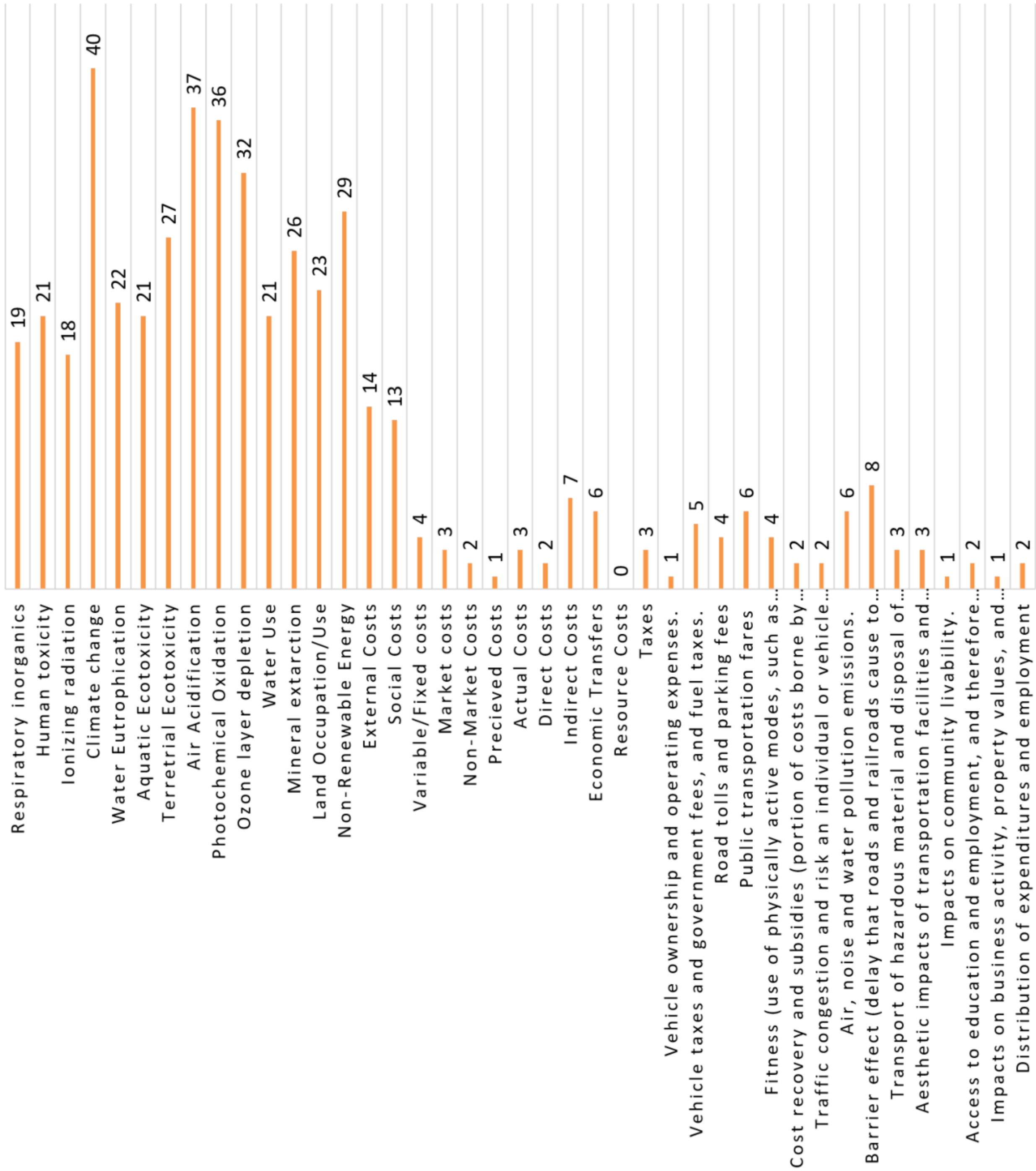


Figure 10. Classification of Studies According to Impact Assessment Factors

VI. Freight System Conceptualization and Impact Assessment Framework

The objective of the work is to develop a Freight System Conceptualization and Impact Assessment Framework of the freight movements in the State to identify the industry sectors and/or commodity types that have the largest impacts. The framework could assist in the decision-making process and the development of strategies to improve the system. The strategies could be in the form of regulatory actions, plans, or the implementation of specific infrastructure, operational, or technological projects. This is important considering that the California Sustainable Freight Action Plan (CSFAP) seeks to "… Improve freight system efficiency 25 percent by increasing the value of goods and services produced from the freight sector, relative to the amount of carbon that it produces by 2030..." (California Governor's Office, 2016). The metric considers the freight transportation sector as the establishments in the North American Industry Classification System (NAICS) codes 48 and 49 (minus transit and passenger transport). These industry sectors include establishments in the air, rail, water, truck, pipeline, and other transportation and support activities, as well as warehousing and storage. While these are the main transportation related establishments, there are a number of establishments not categorized in NAICS 48 and 49, which also transport cargo usually using their own fleets. These segments are not included in the defined CSFAP metric. Moreover, it is important to recognize that the transportation system, in many cases, does not add value to the products or services transported and is just the conduit between other components of supply chains and industries. The efficiency of the freight transportation system may not always result from the optimal selection of routes, vehicles and technologies, which directly relate to the transportation system, but from complex logistics activities (e.g., frequency of distribution, shipment size, and delivery options).

Consequently, the proposed framework must be consistent with the types of decisions and the scope of the analysis (e.g., system wide, corridor, specific project, policy), and the objective (e.g., cost minimization, return on investment, social and health impacts, emission reductions, comparison between alternatives, impact assessment, cost assessment). With this in mind, the research team proposes a conceptual framework based on a LCA methodology. Although, LCA has incorporated costing in the LCC, social impacts in the S-LCA, and a combination of models in the LCSA frameworks, it is not fundamentally a cost-benefit framework.

During the review process, the research team identified that Caltrans developed and uses the California Life-Cycle Benefit/Cost Analysis Model (CAL-B/C). At the project level (e.g., infrastructure investment, technology change), the tool is comprehensive (See Annex C for examples of model considerations). However, the life-cycle component of the tool may not incorporate the details of a complete LCIA framework. Moreover, the team found that California agencies have tested and used other benefit-cost tools such as TREDIS[3]. Therefore, the research team concentrated on developing the framework that expanded the LCA

[3] https://www.tredis.com/. TREDIS is a Benefit-Cost Analysis, Economic Impact Analysis, and Financial Impact Analysis tool for transportation planning.

capabilities, and could serve as an input to the CAL-B/C. In doing so, the team built upon the framework developed by Nahlik et al. (2015) for the California Air Resources Board and earlier work by Facanha and Horvath (2006); Facanha and Horvath (2007). These works also focused on the freight originated from or destined to California at the aggregate level. The proposed framework in this project, explicitly considers the flows for different industries and commodity groups. Nevertheless, the team adapted some sections from Nahlik et al. (2015) framework.

The proposed framework, as a stand-alone tool, seeks to produce impact assessments for the freight flows in the base case, and can estimate the impacts for a set of scenarios to do comparative analyses. Agencies could use other benefit-cost models to assess such scenarios.

Considering the scope and complexity of such a framework, this section illustrates the main components using a high-level logical framework (see Figure 11). This high-level logical framework includes three main components that resemble the LCA phases: problem definition, goals, and system boundaries; measurement indicators and data collection; and impact categories, and analysis of results. One particular characteristic of the framework is that is it envisioned to cover end-to-end supply chains (which could span over multiple geographic boundaries, various industry sectors, and commodity types). The team suggests the use of the supply chain characterization in Table 2 as a guide to understand the type of freight activities carried out by key supply chains in the study area. This would help understand the limitations of the framework implementation, and aid in the data gathering and collection process.

Figure 11. Logical Framework

Figure 12 illustrates the main considerations when defining the problem, and setting the goal and scope of the analyses. For instance, when analyzing supply chains, will the estimates include all components, or just the transportation related activities? The functional unit is another important decision, as it will determine its usability in other models such as the benefit-cost models. Previous research studies have used moving a metric ton of cargo over a mile distance as the functional unit. The boundary and scope would also affect the implementation of the framework.

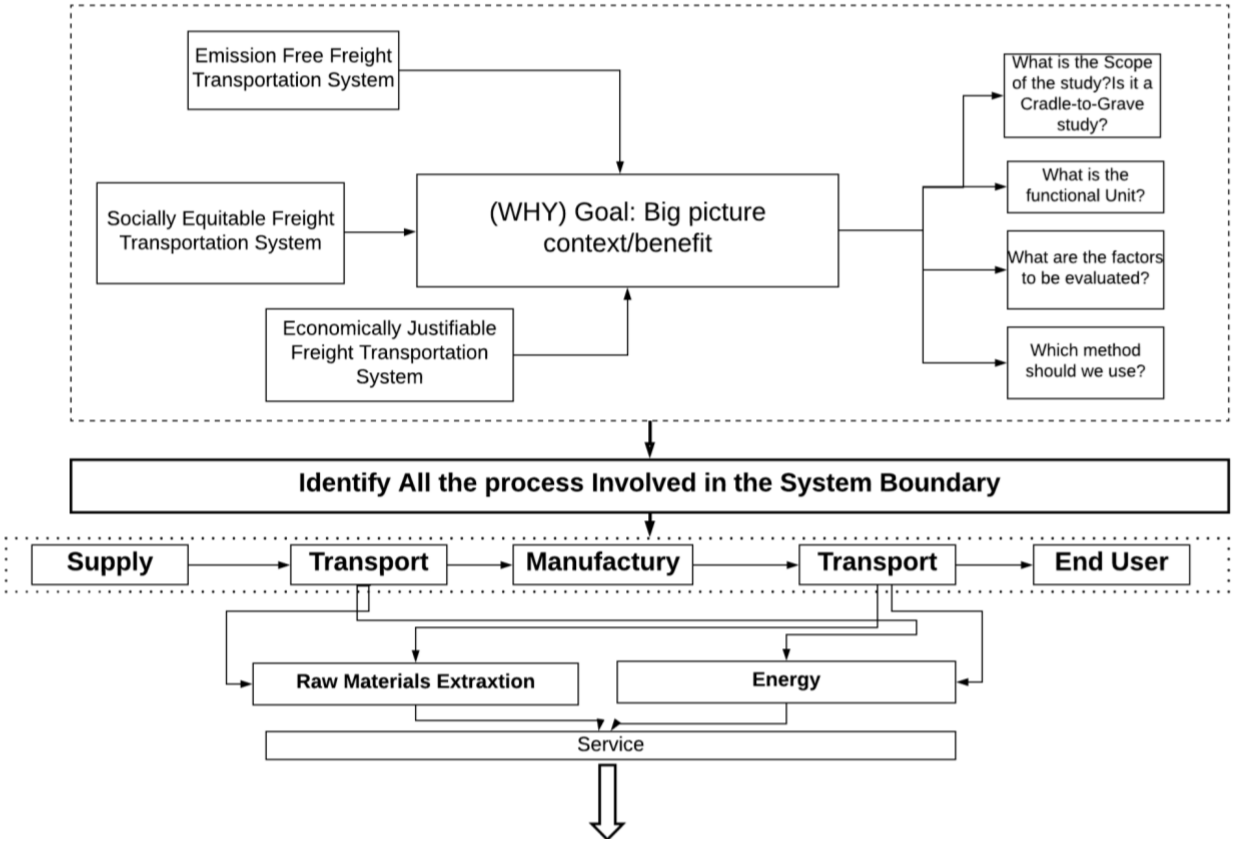


Figure 12. Goal and Scope

Recalling Section II in this document, several modes of transportation or services move freight such as trucking, air, rail, and water (inland waterways, ocean shipping). Therefore, the LCA must include life cycles over these modes, as well as the infrastructure used. Chester (2015) defines a number of life cycle groupings for freight (see Table 14). For each of the groupings, the vehicle and infrastructure could include manufacturing or construction, operation, maintenance and end-of-life (not included in Table 14) phases.

The research team found that there is a general lack of information and methods to consider all these phases, especially in terms of infrastructure. While there are databases (see Annex A) that provide some information for the use phases for the vehicle, and energy production, there is a lack of data and allocation methods for infrastructure, especially maintenance and pavement.

Figure 13 shows some examples of the freight transportation services, and the potential types of vehicles considered when conducting the analyses. Depending on the type of services and the type of analyses, the implementation of the framework requires further considerations in terms of measurement indicators for the transportation system (e.g., flows, costs, service reliability).

Figure 14 illustrates the type of data necessary as input to conduct the analyses, and potential data sources for process inventories for the various life cycle groupings. Data collection and assembly are very time consuming. In some cases, flow inventories exist for the various vehicles, or infrastructures; in other cases, the inventories have to be constructed based on individual flows. In California, the Air Resources Board have developed tools for emissions inventories (see https://www.arb.ca.gov/msei/categories.htm). For instance, CARB uses EMFAC model to assess emissions from on-road vehicles. Other commonly used models include the Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) Model.

Table 14. Freight Life Cycles

Life Cycle Grouping	TRUCKING	AIR	MARINE (OGV)	RAIL
Vehicle				
Manufacturing	▪ Truck Manufacturing ▪ Transport to Point of Sale	▪ Aircraft Manufacturing ▪ Engine Manufacturing	▪ Ship Manufacturing	▪ Train Manufacturing ▪ Transport to Point of Sale
Operation	▪ Propulsion ▪ Idling	▪ APU / Startup / Taxi Out / Takeoff / Climb Out / Cruise / Approach / Landing / Taxi In	▪ Line Haul ▪ Near port ▪ Hoteling	▪ Propulsion ▪ Idling
Maintenance	▪ Truck Maintenance ▪ Tire Replacement ▪ Battery Replacement	▪ Aircraft Maintenance ▪ Engine Maintenance	▪ Ship Maintenance ▪ Engine Maintenance	▪ Train Maintenance
Infrastructure				
Construction	▪ Roadway	▪ Airport ▪ Runway, Taxiway, & Tarmac	▪ Ports (Buildings and Facilities)	▪ Tracks ▪ Terminals
Operation	▪ Roadway Lighting ▪ Herbicide Use ▪ Deicing	▪ Airport Energy ▪ Runway Lighting ▪ Deicing Fluids ▪ Ground Support Equipment	▪ Ancillary equipment use ▪ Lighting ▪ Port energy use	▪ Track Lighting ▪ Herbicide Use ▪ Train Control ▪ Equipment
Maintenance	▪ Roadway Maintenance	▪ Airport ▪ Runway, Taxiway, & Tarmac	▪ Port infrastructure ▪ Port equipment	▪ Track Maintenance
Energy Production				
Extraction, Processing, & Distribution	▪ Gasoline/Diesel/Natural Gas Extraction, Processing, & Distribution	▪ Jet Fuel Extraction, Processing, & Distribution	▪ Heavy Fuel Oils Extraction, Processing, & Distribution	▪ Diesel Fuel Extraction and Processing, Electricity Generation, Transmission & Distribution

Note: APU = Auxiliary Power Unit
Source: (Chester, 2015)

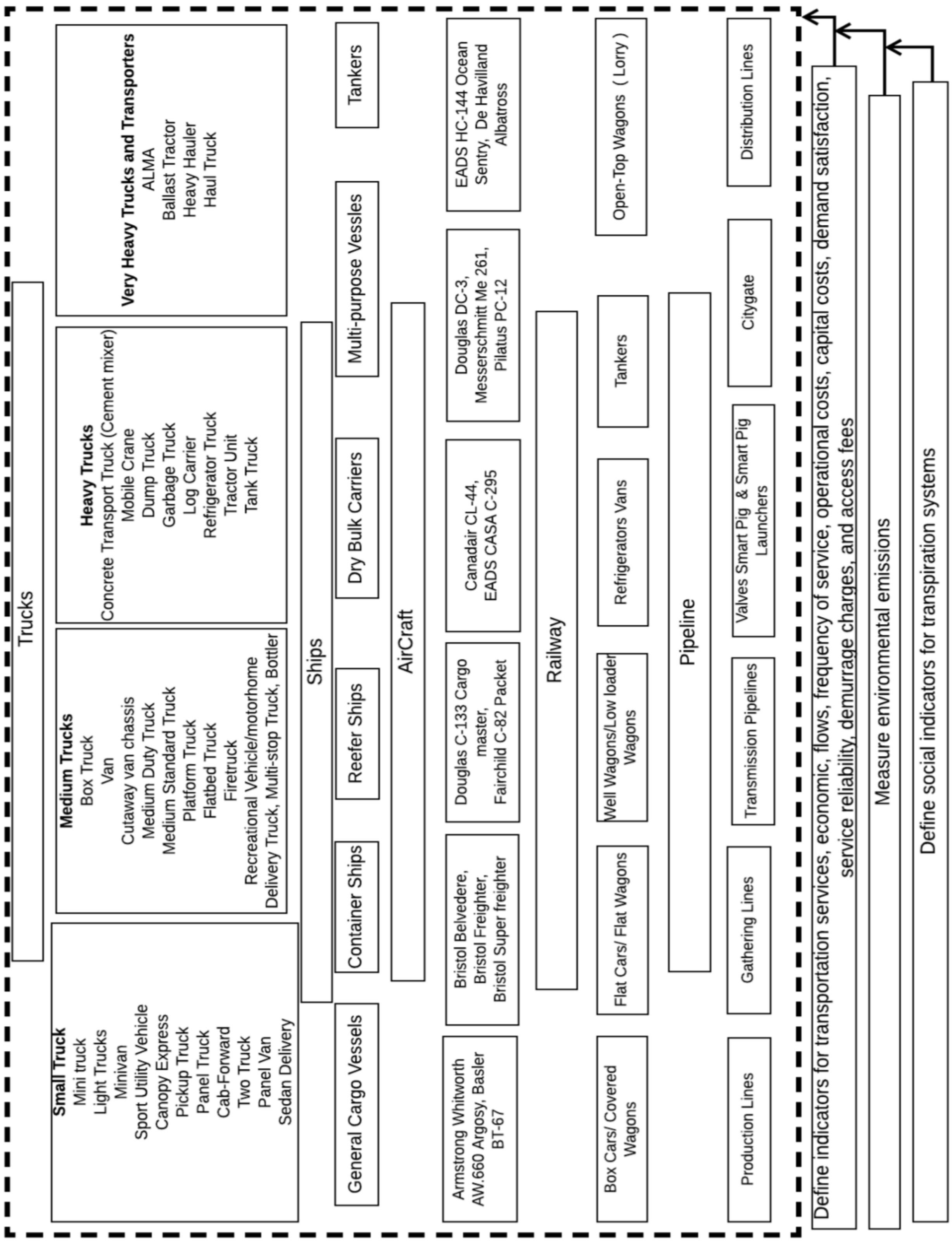


Figure 13. Examples of Services to Consider in Freight LCA (*Authors, adapted from Nahlik et al. 2015)*

The inventories and inputs generate a number of results such as atmospheric and waterborne emissions, solid waste, and if included, costs for the functional unit. The framework implementation also requires defining the impact categories; there are different models representing impact assessment methodologies and each of them may consider different factors (see Annex B for examples). The following are examples of frequently used impact categories.

Human Toxicity Potential (HTP)

The main goal of this category is to indicate the chemical and environmental consequences of a processor product to human health. Examples of this category are sodium dichromate, and hydrogen fluoride, mostly generated from electricity production from fossil fuels. Such chemicals can harm human race through inhalation, touch, and ingestion (Hertwich et al., 2001).

Global Warming Potential (GWP)

One of the most popular categories in order to represent impact categories is through Global Warming Potential (GWP). This factor indicates the amount of greenhouse gas emissions (e.g. CO_2, CH_4) released in to the environment from a product or process. This factor is calculated for a 100-year time horizon and its represented in a CO_2 equivalent (www.Ledvance.com, 2017).

Acidification Potential (AP)

This category of impact assessment refers to the lack of certain chemical nutrient in an ecosystem including calcium, magnesium, and potassium. Due to this loss, the acid elements are replaced and result in atmospheric pollution. Acid rain and its consequent effects on environment is an example of this category. The acidification Potential mostly happen due to the replacement of NO_2 and SO_2 and represents as SO_2 equivalent (www.Ledvance.com, 2017).

Eutrophication Potential (EP)

Due to the concentration of chemicals into an ecosystem eutrophication happens. These chemicals are mainly nitrogen and phosphorus, which mostly comes from sewage outlets and fertilizers. Eutrophication can be measured in terms of phosphate (PO43-) equivalents (www.Ledvance.com, 2017).

Photochemical Ozone Creation Potential (POCP)

Although Ozone is protective in the stratosphere, it is toxic at ground level. Especially in the presence of carbon monoxide (CO), sulfur dioxide (SO2), nitrogen oxide (NO), ammonium and NMVOC (no methane volatile organic compounds). POCP, also known as summer smog, is measured in ethane and NOx equivalents (www.Ledvance.com, 2017).

Abiotic Depletion Potential (ADP)

This impact category represents the level of extraction and scarcity of a substance. It is indicated through natural gas, crude oil, and hard coal and measured by antimony equivalent (www.Ledvance.com, 2017).

Particulate Matter (PM)

Particulate Matter are among the popular impact categories. It is usually represented as the PM10 equivalent. Particulate matters are a combination of small particles and in the presence of acid components, organic chemicals, metal, and soil particles are considered to be pollution for the environment (www.Ledvance.com, 2017).

Terrestrial and Aquatic Eutrophication

This impact category represents types of pollution, which considers both water and air (Finnveden and Potting, 1999; www.Ledvance.com, 2017).

The impact assessment step involves characterization of the impacts, which considers an impact score for the selected categories, and can be for example CO2 equivalent per functional unit. These are the main results of the LCIA, because they indicate the environmental, economic, or social impacts of the different processes or activities. An important step is to normalize the results, which define the impact for a common reference/unit. In some cases, weighting is necessary when evaluating scenarios.

Finally, and most important, is the process of analyzing and interpreting the results to derive robust conclusions and recommendations. The following section will concentrate on the implementation of the framework for a number of case studies. The process evidenced limitations, knowledge gaps, and other constraints when applying the conceptual characterization framework put forward in this study.

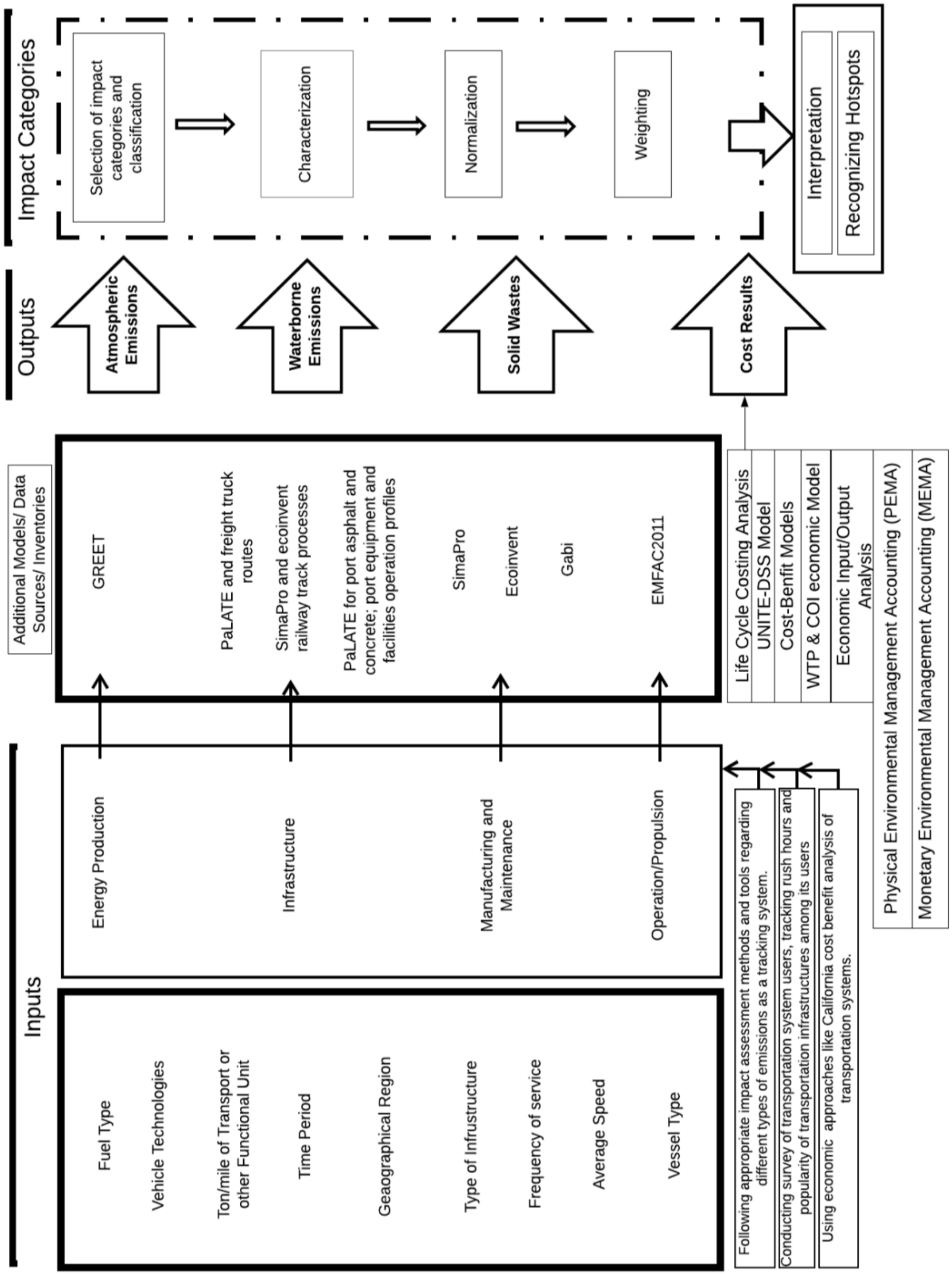


Figure 14. Defining Measurement Indicators, Data Collection, Impact Assessment Categories, and Analysis of Results

Data Availability

The implementation of the framework requires two main types of data: freight flows and LCIs. Freight flows refer to the flow transportation data such as freight tonnage, commodity type, vehicle used, transportation distance, fleet mix and type, geographic location, origins and destinations, speeds, and costs, among other variables. Additionally, it requires LCIs for the vehicles, infrastructure, energy, and other considered groupings. The level of specifications of the LCIs should match the variability of the flow data (e.g., vehicle type, geographic location).

Table 15. Data Availability

		Freight flows	Life cycle inventories	Life cycle costs
Freight Flows	Industry sector	Aggregate		
	Commodity type	Aggregate		
	Mode	Aggregate		
	Vehicle type	N/A		
	Vehicle characteristics	N/A		
	Road characteristics	N/A		
	Geographic Location	Aggregate		
	Origins and destinations	State/County		
	Speeds	N/A		
Vehicle	Truck manufacturing		Available	Minimal
	Truck operation		Available	Minimal
	Truck maintenance		Available	Minimal
	Truck end-of-life		Available	Minimal
	Airplane manufacturing		Generic	Minimal
	Airplane operation		Generic	Minimal
	Airplane maintenance		Generic	Minimal
	Airplane end-of-life		Generic	Minimal
	Rail manufacturing		Generic	Minimal
	Rail operation		Generic	Minimal
	Rail maintenance		Generic	Minimal
	Rail end-of-life		Generic	Minimal
	Vessel manufacturing		Only for Large	Minimal
	Vessel operation		Only for Large	Minimal
	Vessel maintenance		Only for Large	Minimal
	Vessel end-of-life		Only for Large	Minimal
Infrastructure	Construction		Available	N/A
	Operation		Available	N/A
	Maintenance		Allocation Problems	N/A
	End-of-life		Available	N/A
Energy	Extraction, Processing, Distribution		Available	Available

Models Availability

Similar to the data limitations, the team identified a general lack of freight models that could generate the required data. In California, Caltrans hosts the California Statewide Travel Demand Model[4]. The model analyzes freight flows through the short and long distance commercial vehicle models. However, the embedded models estimate the productions, attractions, and tours based on industry sectors and other variables (e.g., commodity growth factors), and the outputs are zonal level aggregates. Other similar models at the Regional and MPO level may produce even more aggregate results. Consequently, there are no models capable of considering supply chains as the unit of analysis. Another limitation refers to the infrastructure assessment. In many cases, the agencies will not build new infrastructure, and most of the impacts result in the rehabilitation and maintenance of existing infrastructure. Currently, for instance, there are no models to allocate pavement impacts and costs resulting from different types of freight vehicles and flows. The literature also revealed the need to develop models to assess the impacts of different vehicles and fuel technologies.

Considering the different modes, the data and models to estimate short haul and last-mile delivery traffic lack in comparison to the availability for long-haul movements.

[4] http://www.dot.ca.gov/hq/tpp/offices/omsp/statewide_modeling/cstdm.html

VII. Framework Implementation

The research team identified, as previously discussed, a general lack of data to implement the general framework. To overcome this limitation, the team made a number of assumptions and considerations, and conducted a number of case studies. The case studies include the freight flows generated from an apparel/shoes manufacturing company, a computer and electronics manufacturer, and a producer of food and beverage products, and the freight produced and attracted by various industry sectors and commodity types in the State of California.

Freight Flows Data

The team used the Commodity Flow Survey (CFS) data from 2012[5]. The CFS is a mandatary survey for companies to report shipments made in a week for every quarter of the survey year. The Bureau of Transportation Statistics and the U.S. Census Bureau surveys shippers every five years (see Table 16). The most recent survey was in 2017, though the results and data are available for the 2012 version. The Census collects information for about 100,000 establishments. The data includes information about the establishments' industry and for every shipment the tonnage, value, mode, origin, and destination, commodity type, and other characteristics.

Table 16. Industries Included in the CFS

NAICS	Description
212	Mining (except oil and gas)
311	Food manufacturing
312	Beverage and tobacco product manufacturing
313	Textile mills
314	Textile product mills
315	Apparel manufacturing
316	Leather and allied product manufacturing
321	Wood product manufacturing
322	Paper manufacturing
323	Printing and related support activities
324	Petroleum and coal products manufacturing
325	Chemical manufacturing
326	Plastics and rubber products manufacturing
327	Nonmetallic mineral product manufacturing
331	Primary metal manufacturing
332	Fabricated metal product manufacturing
333	Machinery manufacturing
334	Computer and electronic product manufacturing
335	Electrical equipment, appliance, and component manufacturing
336	Transportation equipment manufacturing
337	Furniture and related product manufacturing

[5] https://www.census.gov/econ/cfs/pums.html

NAICS	Description
339	Miscellaneous manufacturing
4231	Motor vehicle and parts merchant wholesalers
4232	Furniture and home furnishing merchant wholesalers
4233	Lumber and other construction materials merchant wholesalers
4234	Commercial equip. merchant wholesalers
4235	Metal and mineral (except petroleum) merchant wholesalers
4236	Electrical and electronic goods merchant wholesalers
4237	Hardware and plumbing merchant wholesalers
4238	Machinery, equipment, and supplies merchant wholesalers
4239	Miscellaneous durable goods merchant wholesalers
4241	Paper and paper product merchant wholesalers
4242	Drugs and druggists' sundries merchant wholesalers
4243	Apparel, piece goods, and notions merchant wholesalers
4244	Grocery and related product merchant wholesalers
4245	Farm product raw material merchant wholesalers
4246	Chemical and allied products merchant wholesalers
4247	Petroleum and petroleum products merchant wholesalers
4248	Beer, wine, and distilled alcoholic beverage merchant wholesalers
4249	Miscellaneous nondurable goods merchant wholesalers
4541	Electronic shopping and mail-order houses
45431	Direct selling establishments
4931	Warehousing and storage (includes 484)
5111	Newspaper, periodical, book, and directory publishers
551114	Corporate, subsidiary, and regional managing offices

Table 17 shows the Standard Classification of Transported Goods (SCTG) codes included in the CFS. Establishments in one specific industry may generate shipments of different types of commodities. Therefore, commodity-based analyses span multiple industries. Similarly, industry-based analyses span over multiple commodity types.

Table 17. Commodities Transported

SCTG	Description	SCTG Group
01	Animals and Fish (live)	01-05
02	Cereal Grains (includes seed)	
03	Agricultural Products (excludes Animal Feed, Cereal Grains, and Forage Products)	
04	Animal Feed, Eggs, Honey, and Other Products of Animal Origin	
05	Meat, Poultry, Fish, Seafood, and Their Preparations	
06	Milled Grain Products and Preparations, and Bakery Products	06-09
07	Other Prepared Foodstuffs, and Fats and Oils	
08	Alcoholic Beverages and Denatured Alcohol	
09	Tobacco Products	

SCTG	Description	SCTG Group
10	Monumental or Building Stone	10-14
11	Natural Sands	
12	Gravel and Crushed Stone (excludes Dolomite and Slate)	
13	Other Non-Metallic Minerals not elsewhere classified	
14	Metallic Ores and Concentrates	
15	Coal	15-19
16	Crude Petroleum	
17	Gasoline, Aviation Turbine Fuel, and Ethanol (includes Kerosene, and Fuel Alcohols)	
18	Fuel Oils (includes Diesel, Bunker C, and Biodiesel)	
19	Other Coal and Petroleum Products, not elsewhere classified	
20	Basic Chemicals	20-24
21	Pharmaceutical Products	
22	Fertilizers	
23	Other Chemical Products and Preparations	
24	Plastics and Rubber	
25	Logs and Other Wood in the Rough	25-30
26	Wood Products	
27	Pulp, Newsprint, Paper, and Paperboard	
28	Paper or Paperboard Articles	
29	Printed Products	
30	Textiles, Leather, and Articles of Textiles or Leather	
31	Non-Metallic Mineral Products	31-34
32	Base Metal in Primary or Semi-Finished Forms and in Finished Basic Shapes	
33	Articles of Base Metal	
34	Machinery	
35	Electronic and Other Electrical Equipment and Components, and Office Equipment	35-38
36	Motorized and Other Vehicles (includes parts)	
37	Transportation Equipment, not elsewhere classified	
38	Precision Instruments and Apparatus	
39	Furniture, Mattresses and Mattress Supports, Lamps, Lighting Fittings	39-99
40	Miscellaneous Manufactured Products	
41	Waste and Scrap (excludes of agriculture or food, see 041xx)	
43	Mixed Freight	
99	Missing Code	

Table 18 shows the different transportation modes used to move freight. The distinction between for-hire trucks and private trucks is very important for the analyses and the goal of this project. This is because, without loss of generality, a carrier company (NAICS 484: Truck Transportation) provides the for-hire trucks, while the individual establishment operates the private trucks. Similarly, in the U.S. Class I railroad carriers transport the vast majority of the rail movements, and belong to the NAICS 482: Rail Transportation; carrier airlines (freight and passenger) are in the NAICS 481: Air Transportation; and NAICS 483 is Water Transportation.

This distinction between the carrier and the shipper is an important consideration when designing transportation policies. As mentioned before, the carrier companies are the conduit between other economic agents, which are ultimately responsible for the cargo movements and the logistics decisions. However, most of the regulations only consider the vehicles and carriers' operations.

For many decades, the CFS only published aggregated results at the County, State, or MSA levels of the data (tabulations). In 2012, the Census Bureau published the first generation of the 2012 CFS Public Use Microdata (PUM). This experimental data contains information for approximately 4.5 million shipments from the 2012 CFS. The Bureau used a number of statistical tools and methods to create the synthetic shipment data to protect the confidentiality of individual business information. The research team developed a spreadsheet-based tool to manipulate the data. The tool can produce tabulations of shipment tonnage, ton-miles, value per industry sector, commodity type, mode or any other of the variables contained in the CFS-PUM. For the analyses, the team uses the CFS-PUM as the freight flow data.

Table 18. Transportation Modes in the CFS

Most Detailed Mode Codes		1st Collapsing		2nd Collapsing	
04	For-hire truck	03	Truck	02	Single mode
05	Private truck				
06	Rail				
08	Inland Water	07	Water		
09	Great Lakes				
10	Deep Sea				
101	Multiple Waterways				
11	Air (incl truck & air)				
12	Pipeline				
19	Other mode				
14	Parcel, USPS, or courier			13	Multiple mode
15	Truck and rail	20	Non-parcel multiple mode		
16	Truck and water				
17	Rail and water				
18	Other multiple mode				

CFS-PUM Freight Flows in California

The team estimated the ton-miles for different industries and commodities originating from or destined to California in 2012 using the different modes. Figure 15 shows the magnitude for the various industries. There is no symmetry in the freight flows, and it is evident that for the high-volume industries, the majority of the cargo shipped out uses rail, while most of the cargo destined to California (from U.S. establishments) arrives by truck. Looking at the 3-digit level NAICS codes, the State generates and attracts a large percentage of NAICS 311: food-manufacturing products. In terms of attraction, other significant industries include NAICS 4231:

Motor vehicle and parts merchant wholesalers, NAICS 312: Beverage and tobacco product manufacturing; NAICS 4244 Grocery and related product merchant wholesalers; and NAICS 551114: Corporate, subsidiary, and regional managing offices. For outbound shipments, NAICS 311, NAICS 325: Chemical manufacturing and NAICS 4245: Farm product raw material merchant wholesalers represent the largest shares.

Figure 16 compares the mode shares for the different industries. It is clear that for-hire trucks dominate the freight movements, with rail being significant for outbound cargo. For some of the industries, private trucking is important, though the industries tend to generate low ton-miles. For example, NAICS 45431: Direct selling establishments transport most of the cargo using private trucks. Some of these industries tend to have destinations at shorter distances. This is important aggregate information; however, no additional information translates the general modes to specific vehicles types or classes. California is an important consumption destination; Figure 17 shows the inbound and outbound ton-miles for different commodity groups. SCTG 7: Other prepared foodstuffs, and fats and oil represent the largest percentage of the inbound cargo. This is also an important commodity group for outbound shipments, as well as SCTG 2: Cereal grains (including seeds). Consistent with the industry-based picture from Figure 15, there is a higher share of rail outbound shipments. Figure 18 shows the mode shares per commodity. Almost all SCTG 2 shipments use rail, and all coal transport is by rail. In addition, about half of agricultural products (SCTG 3 and SCTG 4) shipments use rail. However, the majority of inbound and outbound shipments use truck (with for-hire trucks dominating). There are a number of commodity groups that use private fleets, and these tend to be commodities requiring specialized vehicles such as SCTG 10: Monumental or building stone, SCTG 11: Natural sands, SCTG 12: Gravel and crushed stone, SCTG 18: Fuel oils, and SCTG 25: Logs and other wood in the rough. These flows evidence different types of freight patterns resulting from the type of commodity. This is not clearly identified at the industry group level.

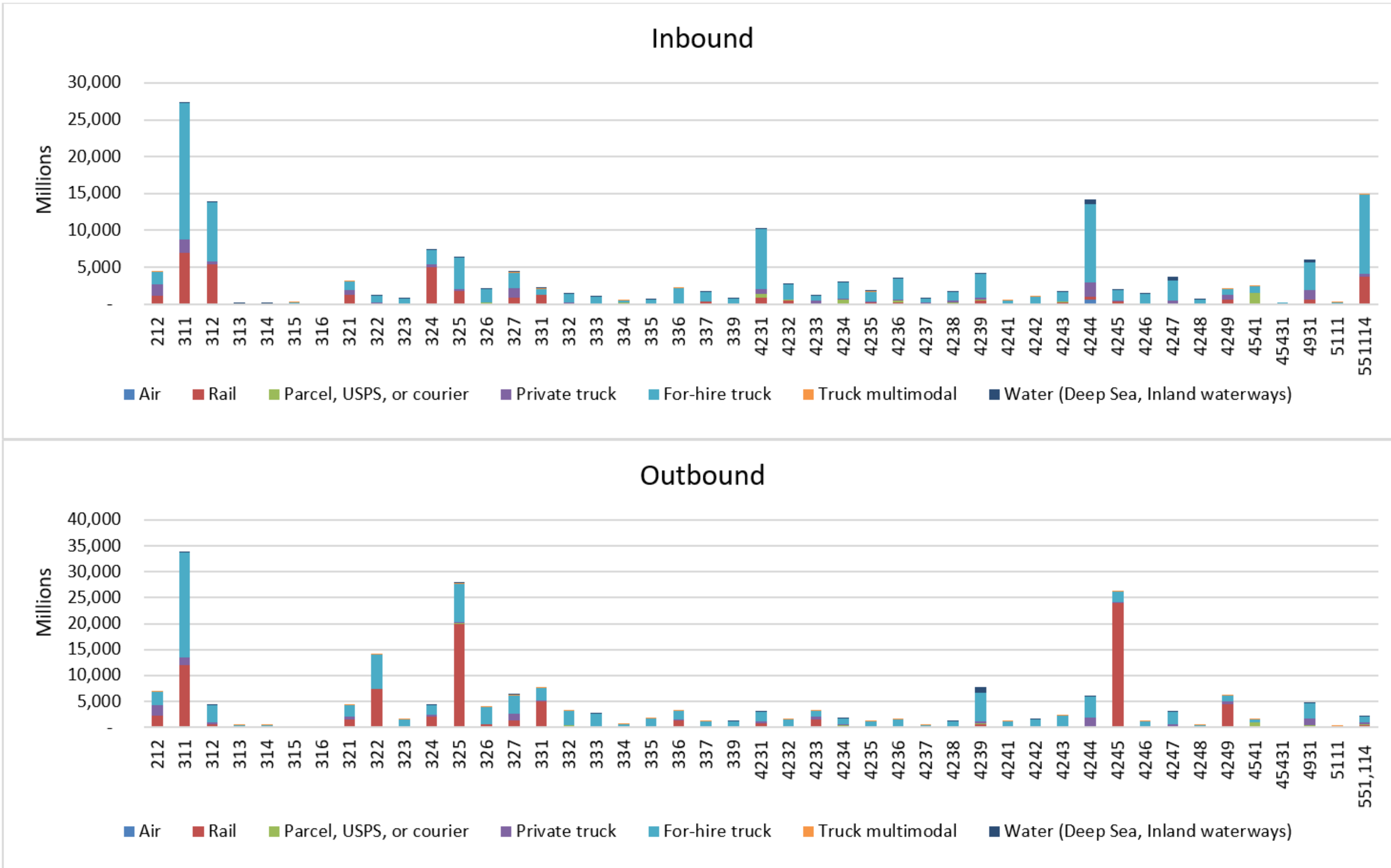


Figure 15. Ton-miles Originated from (Out) and Destined to (In) California in 2012 per Industry Sector per Mode of Transport

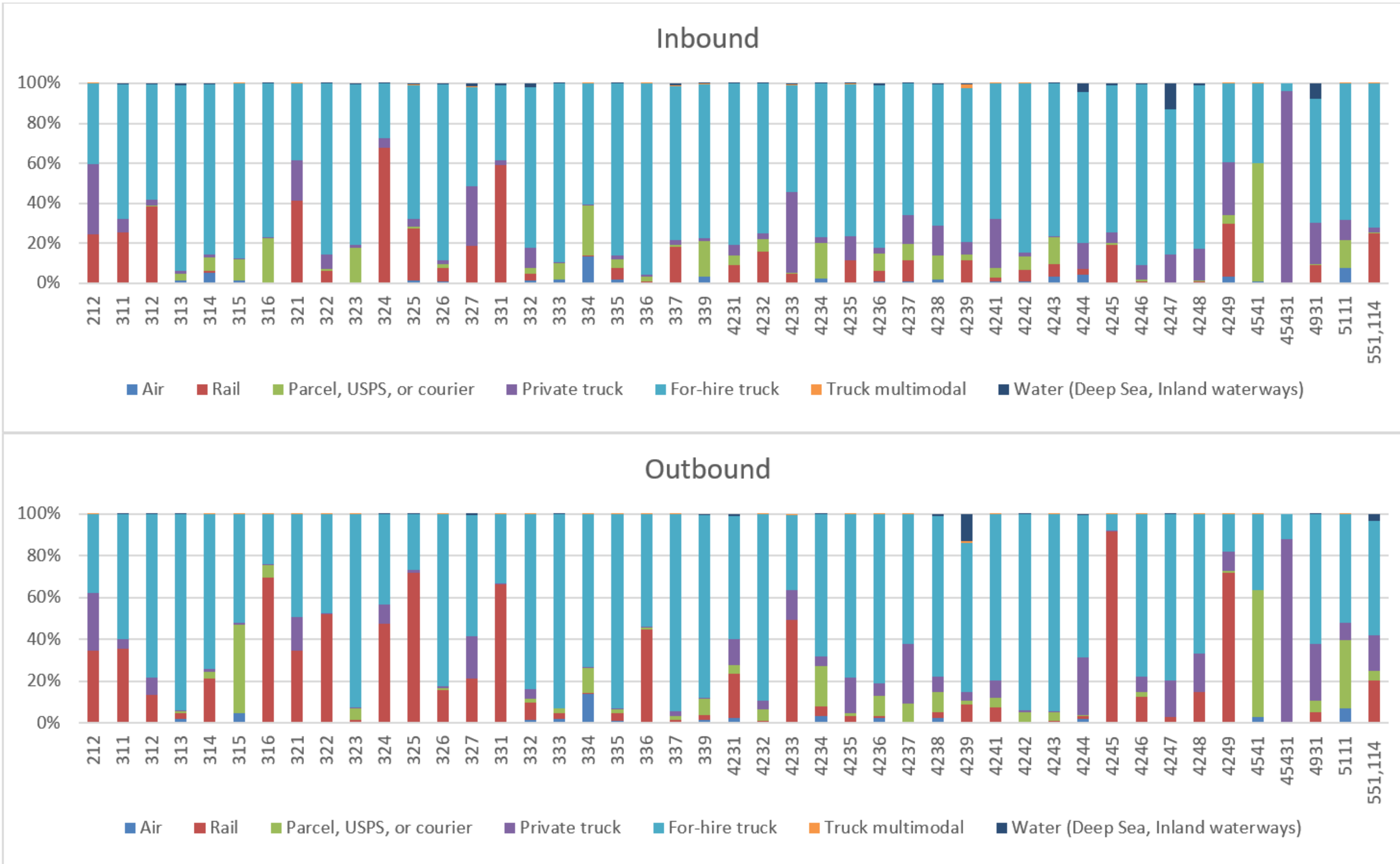


Figure 16. Comparative Mode Share for Ton-miles Originated from (Out) and Destined to (In) California in 2012 per Industry Sector

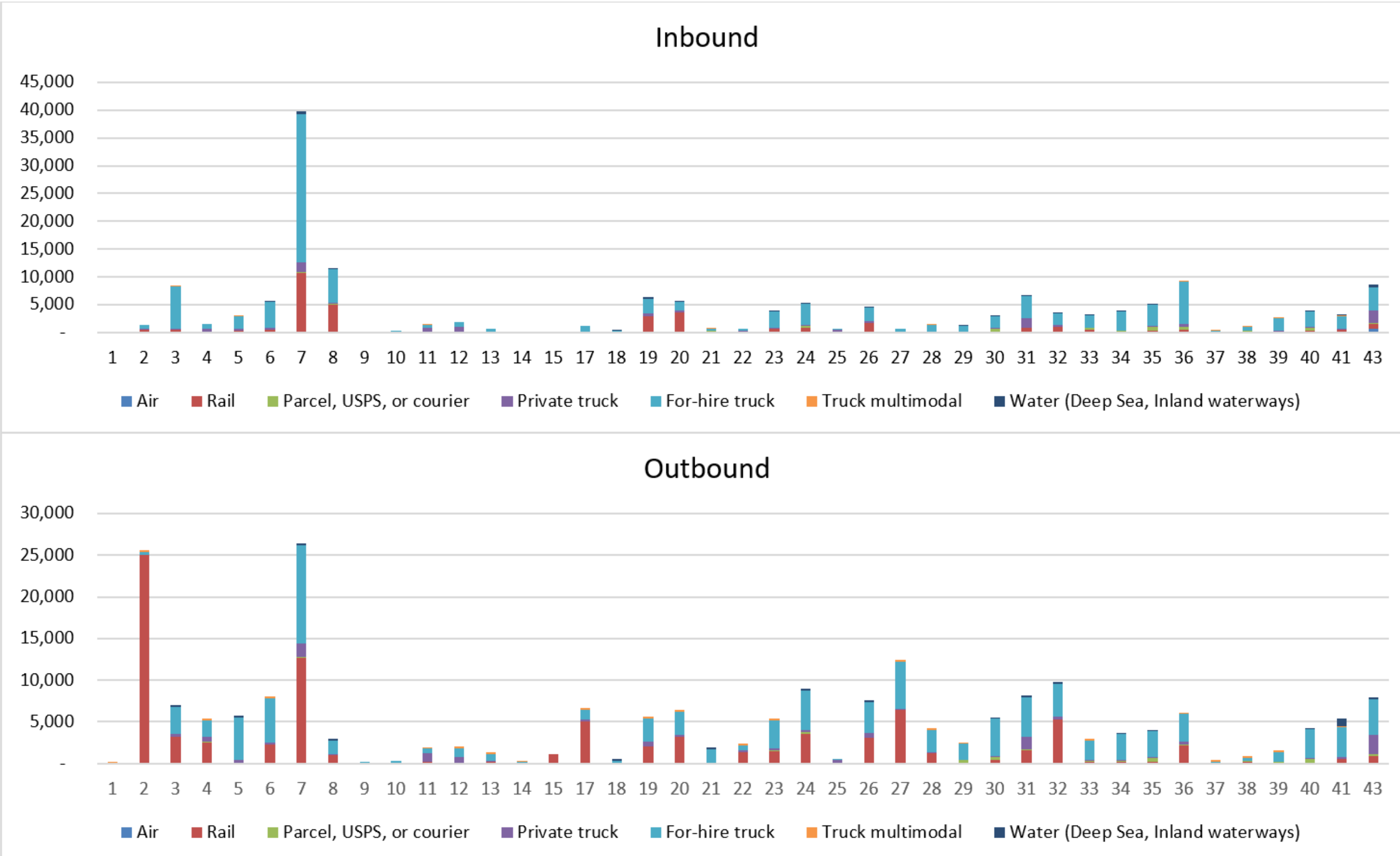


Figure 17. Ton-miles Originated from (Out) and Destined to (In) California in 2012 per Commodity Group per Mode of Transport

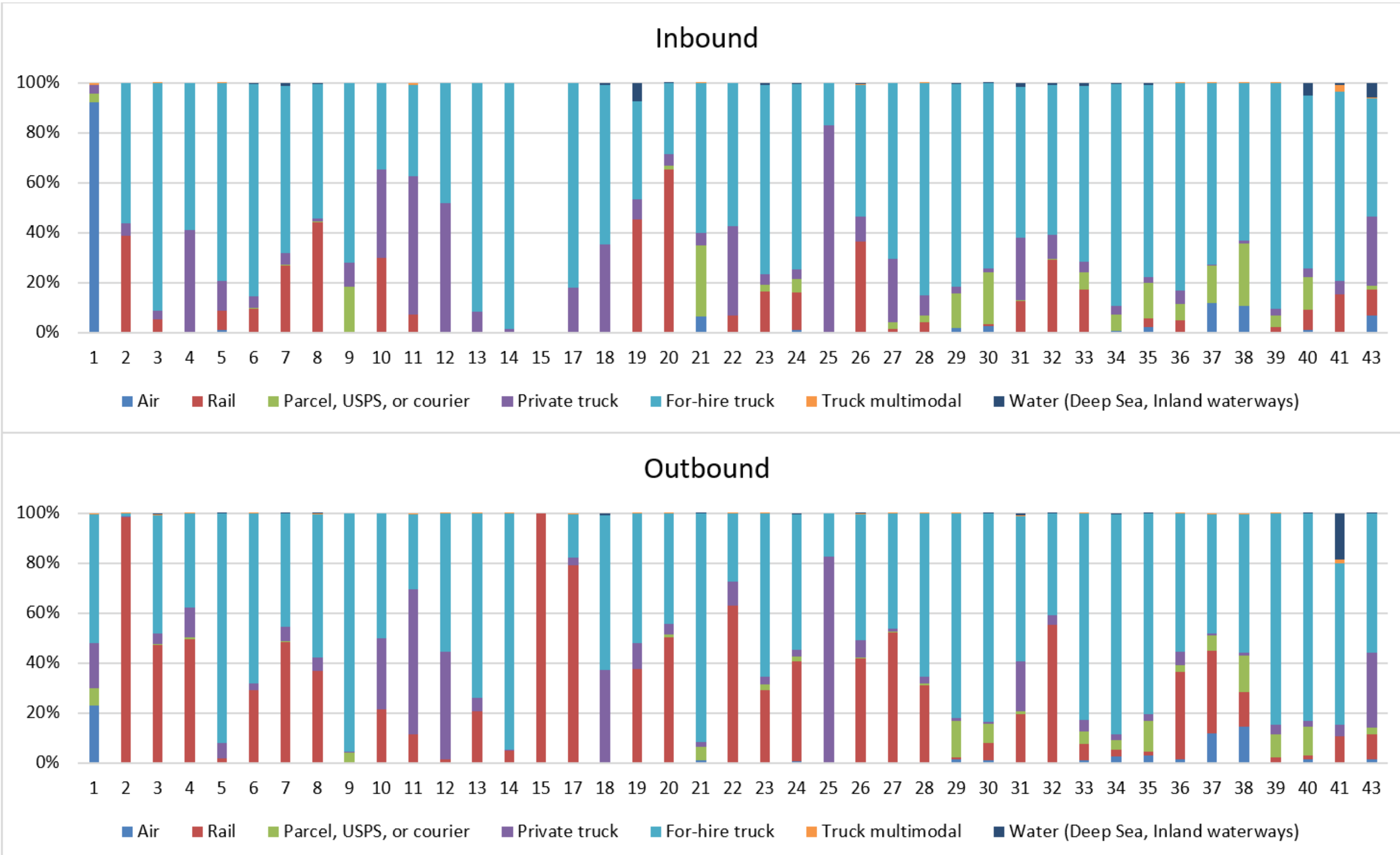


Figure 18. Comparative Mode Share for Ton-miles Originated from (Out) and Destined to (In) California in 2012 per Commodity Group

Life Cycle Inventory Data

For the LCI data, the team found various sources. For example, EMFAC provides life cycle data for various vehicle and technology types, and GREET assess the life cycle of energy sources. However, the available disaggregate data did not include all processes (e.g., production/construction, operation, maintenance) for the vehicles, and the infrastructure in particular. Considering the other databases (see Annex A), the team used Gabi to identify inventories for the implementation. Most of the available inventories in Gabi are from Ecoinvent 3.0 and may include global, regional or country data for specific or aggregate processes. The team selected U.S. or global inventories and sought inventories for the transport of goods related to the various modes under consideration. Table 19 shows examples of aggregate transport processes. From the available inventories, the team selected:

Rail:

- Market for transport, freight train

Water:

- Transport, freight, sea, transoceanic ship

Air:

- Market for transport, freight, aircraft

Truck:

- Transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO3, carbon dioxide, liquid refrigeration
- Market for transport, freight, lorry 3.5-7.5 metric ton, EURO3
- Transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO4, carbon dioxide, liquid refrigeration
- Market for transport, freight, lorry 3.5-7.5 metric ton, EURO4
- Transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO5, carbon dioxide, liquid refrigeration
- Market for transport, freight, lorry 3.5-7.5 metric ton, EURO5
- Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO3, carbon dioxide, liquid refrigeration
- Market for transport, freight, lorry 7.5-16 metric ton, EURO3
- Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO4, carbon dioxide, liquid refrigeration
- Market for transport, freight, lorry 7.5-16 metric ton, EURO4
- Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO5, carbon dioxide, liquid refrigeration
- Market for transport, freight, lorry 7.5-16 metric ton, EURO5

- Market for transport, freight, lorry 16-32 metric ton, EURO3
- Market for transport, freight, lorry 16-32 metric ton, EURO4
- Market for transport, freight, lorry 16-32 metric ton, EURO5

The team found that the transoceanic ship inventory does not completely reflect the flows for this process.

As previously discussed, the existing flow data (ton-miles) does not identify the type of vehicle (fleet mix) used. Therefore, using these inventories, team developed generic LCIs assuming the fleet composition in the 2012 EMFAC vehicle population data as the mix transporting the flows in the CFS-PUM.

Table 19. LCI Examples for Truck Freight Transport Processes

Process	Refrigeration	Capacity (metric ton)	V-Type	Emission Standard	Vehicle Manufacture	Maintenance	End of Life	Fuel	Input of fuel	Road/ infrustructure	Exhaust emissions	Non-exhaust emissions
transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspeci	Not-Specified	All	N/A	EURO4	I	I	I	I	I	I	I	I
transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO5, carbon dioxide, liquid ref	Refrigerated	3.5-7.5	Light	EURO5	I	I	I	I	I	I	I	I
transport, freight, lorry 3.5-7.5 metric ton, EURO3	Non-Refrigerated	3.5-7.5	Light	EURO3	I	I	I	I	I	I	I	I
transport, freight, lorry 16-32 metric ton, EURO3	Non-Refrigerated	16-32	Heavy	EURO3	I	I	I	I	I	I	I	I
transport, freight, lorry >32 metric ton, EURO5	Non-Refrigerated	>32	Heavy	EURO5	I	I	I	I	I	I	I	I
transport, freight, lorry 3.5-7.5 metric ton, EURO4	Non-Refrigerated	3.5-7.5	Light	EURO4	I	I	I	I	I	I	I	I
transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO3, R134a refrigerant, cooling	Refrigerated	7.5-16	Medium	EURO3	I	I	I	I	I	I	I	I
transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO4, R134a refrigerant, freezin	Refrigerated	3.5-7.5	Light	EURO4	I	I	I	I	I	I	I	I
transport, freight, lorry 7.5-16 metric ton, EURO3	Non-Refrigerated	7.5-16	Medium	EURO3	I	I	I	I	I	I	I	I
transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO5, carbon dioxide, liquid ref	Refrigerated	3.5-7.5	Light	EURO5	I	I	I	I	I	I	I	I
transport, freight, small lorry with refrigeration machine, EURO3, CO2 refrigerant, freezing to gene	Refrigerated	Small	Light	EURO3	I	I	I	I	I	I	I	I
transport, freight, lorry >32 metric ton, EURO6	Non-Refrigerated	>32	Heavy	EURO6	I	I	I	I	I	I	I	I
transport, freight, lorry, all sizes, EURO5 to generic market for transport, freight, lorry, unspeci	Non-Refrigerated	All	N/A	EURO5	I	I	I	I	I	I	I	I
transport, freight, lorry >32 metric ton, EURO5	Non-Refrigerated	>32	Heavy	EURO5	I	I	I	I	I	I	I	I
transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO5, R134a refrigerant, freezin	Refrigerated	3.5-7.5	Light	EURO5	I	I	I	I	I	I	I	I
transport, freight, lorry 16-32 metric ton, EURO5	Non-Refrigerated	16-32	Heavy	EURO5	I	I	I	I	I	I	I	I
transport, freight, lorry >32 metric ton, EURO5	Non-Refrigerated	>32	Heavy	EURO5	I	I	I	I	I	I	I	I
transport, freight, lorry 3.5-7.5 metric ton, EURO4	Non-Refrigerated	3.5-7.5	Light	EURO4	I	I	I	I	I	I	I	I
transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO3, R134a refrigerant, cooling	Refrigerated	7.5-16	Medium	EURO3	I	I	I	I	I	I	I	I
transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO4, R134a refrigerant, freezin	Refrigerated	3.5-7.5	Light	EURO4	I	I	I	I	I	I	I	I
transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO5, R134a refrigerant, cooling	Refrigerated	3.5-7.5	Light	EURO5	I	I	I	I	I	I	I	I
transport, freight, light commercial vehicle	Not-Specified	Small	Light	N/A	N	I	I	I	I	I	N	I

Note: I = Included, N= Not Included

EMFAC Vehicle Population

Considering Gabi presents the LCIs for the European context, the team created a crosswalk for the vehicle categories and considered light heavy duty, medium-heavy-duty, and heavy-heavy-duty vehicles from EMFAC. These are a combination of Class 3 – Class 8 FHWA classes. Moreover, the team used the vehicle model and class to assume EURO standard classifications for the EMFAC vehicle population. Table 20 summarizes the vehicle population in California from the EMFAC 2012, and Figure 19 shows the shares of EURO standards for these vehicles.

Table 20. EMFAC 2012 Vehicle Population

	Before Euro	Euro 0	Euro I	Euro II	Euro III	Euro IV	Euro V	Grand Total
Light	36,524		12,550	23,151	142,653	88,952	57,461	361,290
Medium	49,086		15,422	31,201	115,905	96,740	77,737	386,091
Heavy	23,487	12,816	11,891	20,460	51,916	39,590	49,671	209,831
Grand Total	**109,097**	**12,816**	**39,862**	**74,813**	**310,473**	**225,282**	**184,869**	**957,212**

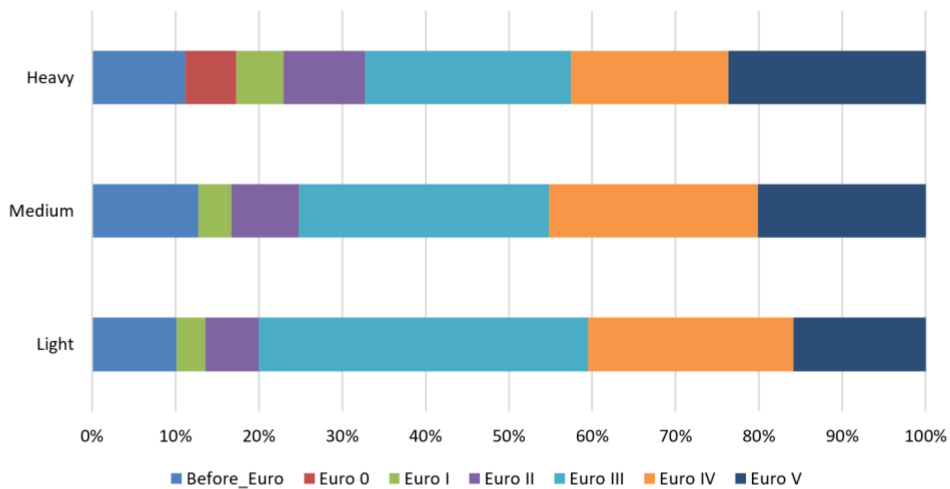


Figure 19. EURO Shares for Different Vehicles Types

Considering the availability of process inventories for truck transport for EUROs III to V, the team estimated the adjusted shares for the vehicle population using these vehicles as the entire population. Table 21 shows the adjusted factors.

Table 21. Adjusted EURO Standard Fleet Composition

	Euro III	Euro IV	Euro V
Light	49.35%	30.77%	19.88%
Medium	39.91%	33.31%	26.77%
Heavy	36.77%	28.04%	35.18%
Grand Total	43.08%	31.26%	25.65%

With these adjusted factors, the team generated the following generic vehicle type LCIs to use in the analyses:

- Transport, freight, lorry, all
- Transport, freight, lorry, non_refrigerated
- Transport, freight, lorry, refrigerated
- Transport, freight, small lorry, all
- Transport, freight, small lorry, refrigerated
- Transport, freight, small lorry, non_refrigerated
- Transport, freight, medium lorry, all
- Transport, freight, medium lorry, non_refrigerated
- Transport, freight, medium lorry, refrigerated
- Transport, freight, large lorry, all
- Transport, freight, large lorry, non_refrigerated

Impact Categories

The next step required defining the impact categories. The team selected the widely used *US. EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)*. Table 22 describes the various TRACI impacts.

Table 22. TRACI Impact Categories

Impact	Description
Global warming potential (GWP)	Mass of carbon dioxide (CO_2) equivalent emissions to air with the potential to contribute to global warming, combining emissions of CO_2, N_2O, CH_4, and other potent GHG emissions based on their relative contribution to radiative forcing on a 100-year time horizon
Acidification potential	Mass of emissions that contribute to acidic pollution expressed as equivalent hydrogen ions (H_+) from nitrogen and sulfur emissions to soil and water
Ozone depletion potential	Mass of substances released to air that could deplete stratospheric ozone reported in chlorofluorocarbon-11 equivalents
Eutrophication potential	Mass of emissions to air and water that can enrich freshwater and coastal water bodies with nitrates or phosphates represented in nitrogen equivalents. These pollutants can accelerate biological productivity (growth of algae and weeds) and deplete oxygen in aquatic ecosystems
Photochemical smog formation potential	Mass of air emissions of NO_x, VOCs, and other ground level ozone forming chemicals reported in units of ozone equivalence. TRACI uses the maximum incremental reactivity method to estimate the likely tropospheric ozone smog formation potential from VOCs, which have several chemical fate pathways
Resource depletion	Mass of fossil fuel, volume of water, or area land use; context is critical to this indicator as different places and resources have different availabilities
Human health - particulate	Mass of air pollution emissions including particulate matter consisting of inhalable coarse particles between 2.5 and 10 microns (PM_{10}) & fine particles less than or equal to 2.5 microns ($PM_{2.5}$) and their precursors
Human health - cancer comparative toxicity unit (CTU_{cancer}), human health non-cancer comparative toxicity unit ($CTU_{non\text{-}cancer}$), and Ecotoxicity comparative toxicity unit (CTU_{eco})	Metrics that represent the emissions of known carcinogens and toxics to urban air, nonurban air, freshwater, seawater, natural soil, and agricultural soil based on a chemical fate model. Human health cancer aims to provide information about emissions known to cause human cancer. Human health non-cancer represents contributions to other kinds of toxicity. Ecotoxicity estimates freshwater or marine toxicity or damage.

Source: Adapted from (Bare, 2011)

The team used TRACI and the LCIs to estimate the various impacts for the different modes (see Table 23). These impacts are per ton-kilometer.

Table 23. TRACI Impacts for the Different Modes

market for transport, freight/ transport, freight					
TRACI Category		Rail	Air	Transoceanic Ship	
Ecotoxicity	CTUeco/tkm	1.6508E-01	3.4619E-01	6.7480E-11	
HumantoxCAN	CTUcancer/tkm	5.1802E-09	5.6156E-09	0.0000E+00	
HumantoxNC	CTUnoncancer/tkm	8.4591E-09	2.7572E-08	0.0000E+00	
GWP	kg CO2 eq/tkm	5.8033E-02	1.1179E+00	2.6279E-10	
Resources		0.0000E+00	0.0000E+00	0.0000E+00	
Humanpartic	PM2.5eq/tkm	8.1106E-05	2.8981E-04	0.0000E+00	
ODP	kg CFC-11 eq/tkm	1.1368E-08	2.7340E-07	2.1599E-13	
Smog	kg O3 eq/tkm	1.6514E-02	1.1934E-01	3.7908E-13	
Accidification	kg SO2 eq/tkm	5.7409E-04	4.8835E-03	0.0000E+00	
Eutrophication	kg N eq/tkm	1.1649E-04	7.7583E-04	0.0000E+00	
transport, freight, lorry, all					
TRACI Category		All	Small	Medium	Large
Ecotoxicity	CTUeco/tkm	1.1471E+00	1.9317E+00	6.7691E-01	4.5925E-01
HumantoxCAN	CTUcancer/tkm	1.3866E-08	2.4175E-08	8.0006E-09	4.3660E-09
HumantoxNC	CTUnoncancer/tkm	1.4494E-07	2.1448E-07	1.0192E-07	8.2363E-08
GWP	kg CO2 eq/tkm	3.5490E-01	5.6604E-01	2.3634E-01	1.5053E-01
Resources		0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
Humanpartic	PM2.5eq/tkm	3.6035E-04	5.5823E-04	2.4377E-04	1.7725E-04
ODP	kg CFC-11 eq/tkm	8.2394E-08	1.2940E-07	5.5819E-08	3.6934E-08
Smog	kg O3 eq/tkm	4.1342E-02	6.5559E-02	2.7562E-02	1.8871E-02
Accidification	kg SO2 eq/tkm	1.7352E-03	2.7815E-03	1.1419E-03	7.5506E-04
Eutrophication	kg N eq/tkm	4.6276E-04	7.7116E-04	2.8889E-04	1.7213E-04
transport, freight, lorry, non_refrigerated					
TRACI Category		All	Small	Medium	Large
Ecotoxicity	CTUeco/tkm	1.3172E+00	2.1890E+00	7.5155E-01	4.5925E-01
HumantoxCAN	CTUcancer/tkm	1.3404E-08	2.2574E-08	7.4787E-09	4.3660E-09
HumantoxNC	CTUnoncancer/tkm	1.5093E-07	2.2097E-07	1.0366E-07	8.2363E-08
GWP	kg CO2 eq/tkm	3.3354E-01	5.1596E-01	2.1551E-01	1.5053E-01
Resources		0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
Humanpartic	PM2.5eq/tkm	3.4991E-04	5.2893E-04	2.3255E-04	1.7725E-04
ODP	kg CFC-11 eq/tkm	7.7976E-08	1.1895E-07	5.1336E-08	3.6934E-08
Smog	kg O3 eq/tkm	3.8446E-02	5.9933E-02	2.5220E-02	1.8871E-02
Accidification	kg SO2 eq/tkm	1.6187E-03	2.5374E-03	1.0427E-03	7.5506E-04
Eutrophication	kg N eq/tkm	4.2933E-04	6.9207E-04	2.6032E-04	1.7213E-04
transport, freight, lorry, refrigerated					
TRACI Category		All	Small	Medium	Large
Ecotoxicity	CTUeco/tkm	9.4148E-01	1.6743E+00	6.0226E-01	
HumantoxCAN	CTUcancer/tkm	1.4219E-08	2.5775E-08	8.5224E-09	
HumantoxNC	CTUnoncancer/tkm	1.2623E-07	2.0800E-07	1.0018E-07	
GWP	kg CO2 eq/tkm	3.5930E-01	6.1612E-01	2.5718E-01	
Resources		0.0000E+00	0.0000E+00	0.0000E+00	
Humanpartic	PM2.5eq/tkm	3.4493E-04	5.8753E-04	2.5499E-04	
ODP	kg CFC-11 eq/tkm	8.2253E-08	1.3984E-07	6.0302E-08	
Smog	kg O3 eq/tkm	4.0961E-02	7.1185E-02	2.9904E-02	
Accidification	kg SO2 eq/tkm	1.7392E-03	3.0255E-03	1.2410E-03	
Eutrophication	kg N eq/tkm	4.8117E-04	8.5025E-04	3.1747E-04	

Figure 20, Figure 21, and Figure 22 provide a visual comparison of the various modes/vehicles. The results show great variability, with refrigeration becoming an important contributing factor to, in general, larger impacts. However, it is important to recognize that these estimates are for generic vehicles using averages of the vehicle population and other assumptions. As discussed in this document, uncertainty and data quality are important aspects of LCA analyses. The variability in these inventories is an example.

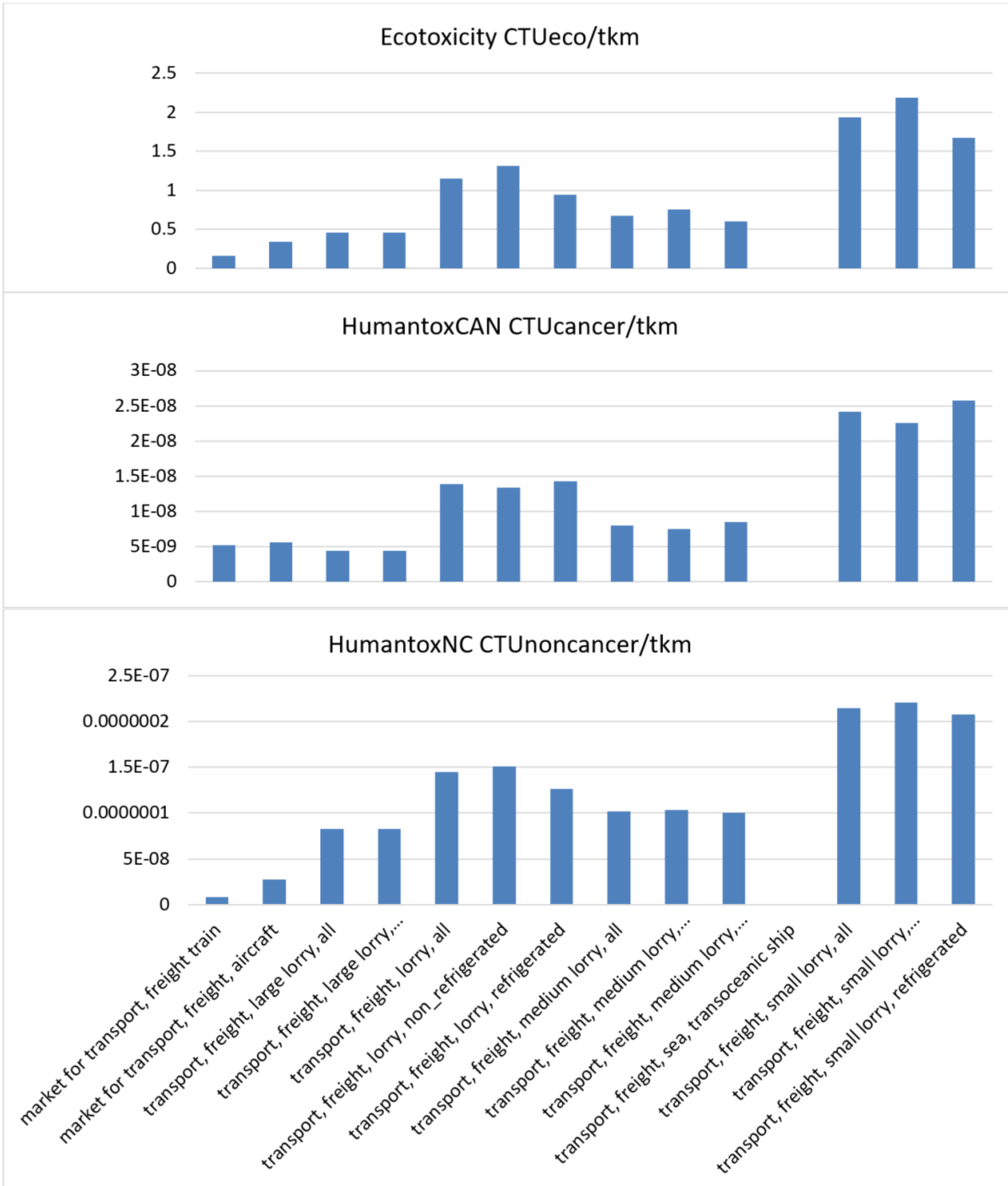


Figure 20. Ecotoxicity and Human Toxicity per Ton-Km

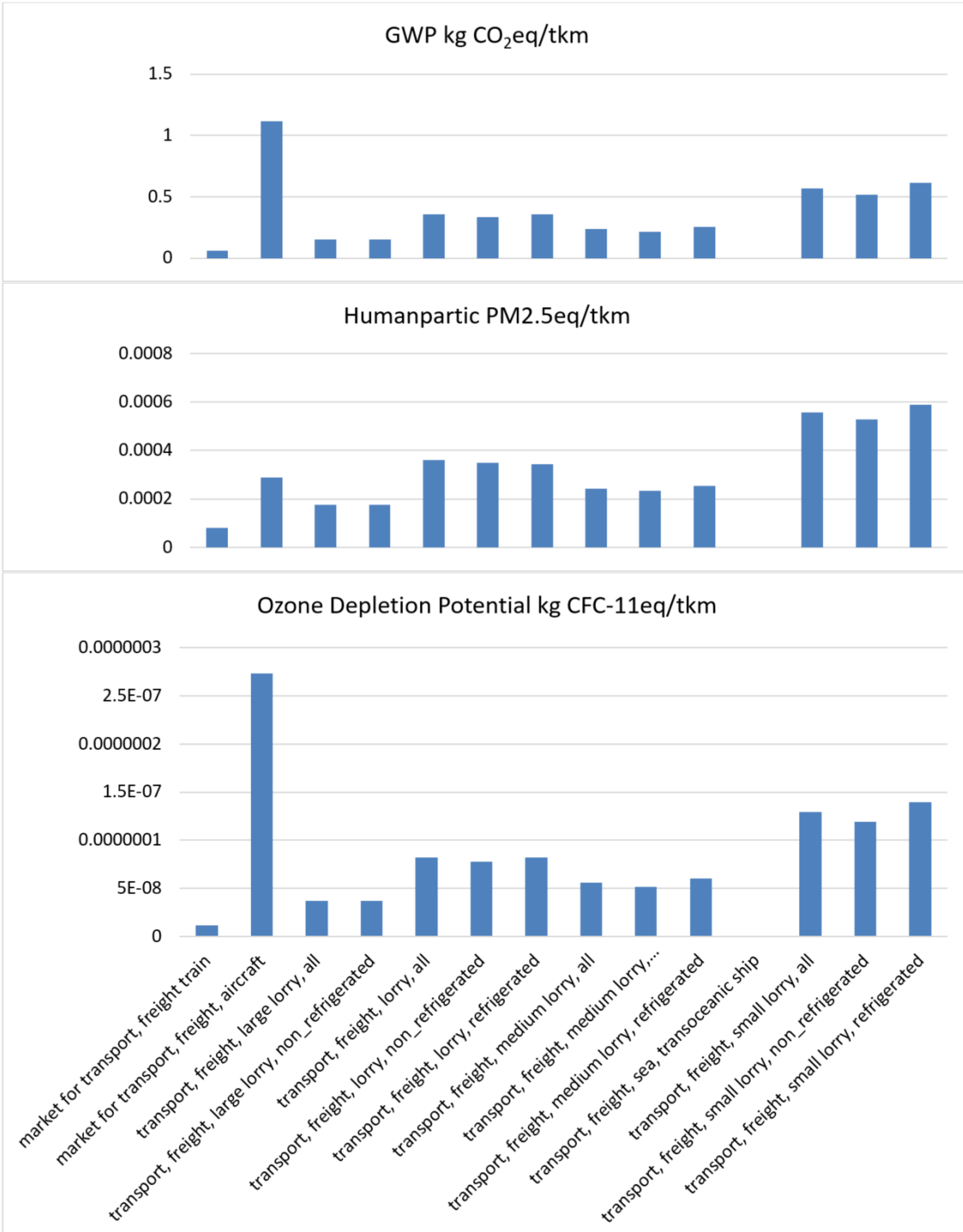


Figure 21. GWP, Human Particles, and Ozone Depletion Potential per Ton-Km

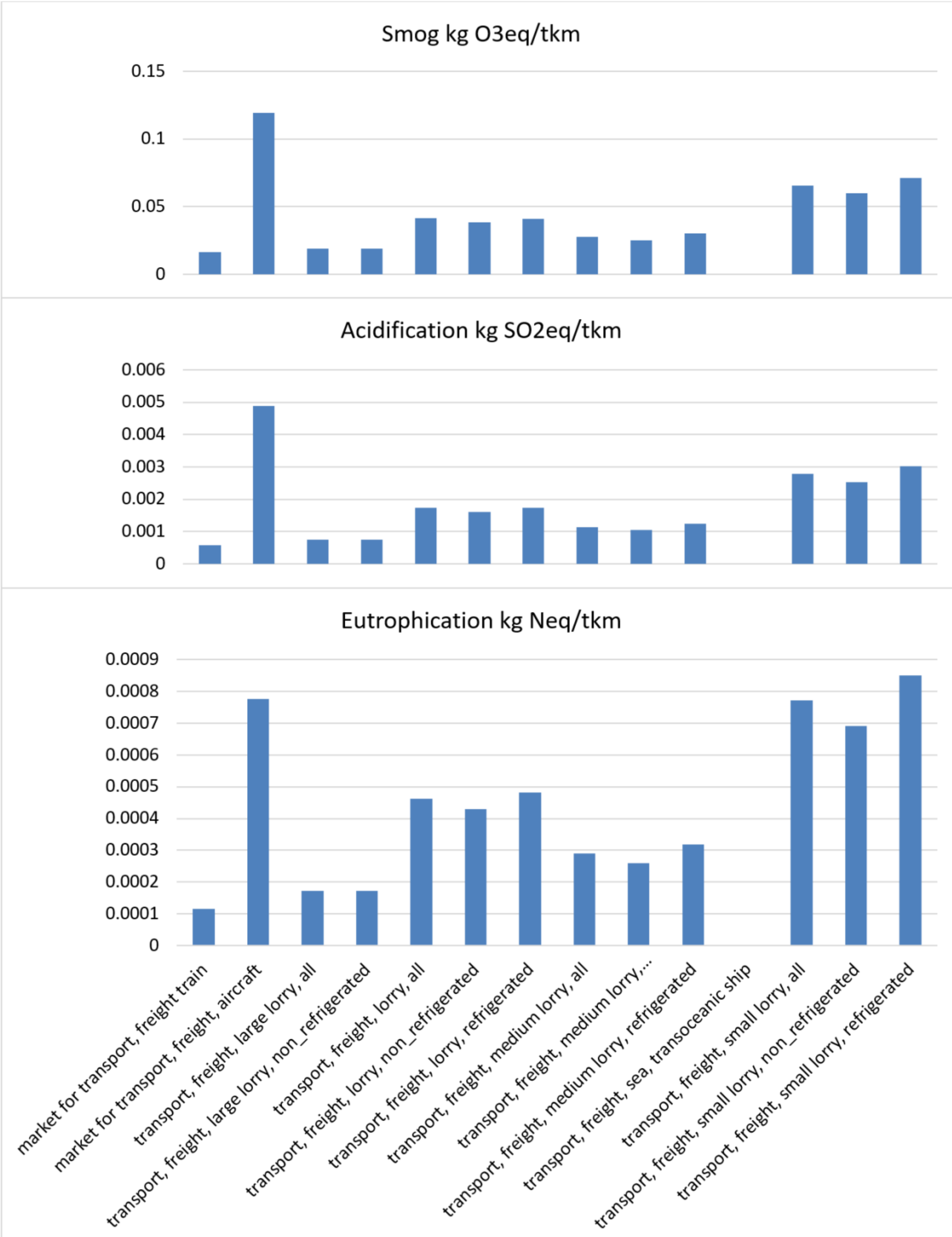


Figure 22. Smog, Acidification and Eutrophication Impacts per Ton-Km

VIII. Case Studies

The team conducted a number of case studies to show the framework implementation. These include:

- Inbound and outbound shipments to/from California for CFS-PUM industries and commodities
- Computer and electronics manufacturer (e.g., DELL) generated freight flows
- Apparel/shoes manufacturer (e.g., Nike) generated freight flows
- Food/beverage producer (e.g., Nestlé) generated freight flows

It is important to acknowledge the limitations of the case study implementations due to data availability. The research team considered a number of important assumptions when estimating the flows for the specific companies. These results are for illustration purposes of the framework implementation and may not represent complete or accurate depictions of specific companies' flows and impacts. The team made the best efforts to identify the specific flows based on aggregate market data. This section shows aggregate results. There are supplementary spreadsheet files for this report providing detailed estimates and models.

Freight Flows in California

Figure 15 to Figure 18 showed the inbound and outbound freight flows to and from California per NAICS industry group, and SCTG commodity group estimated from the 2012 CFS-PUM. The team converted the ton-miles to ton-km to estimate the TRACI impacts. The analyses consider:

- Total flow impacts and average impacts per ton-km per industry group per mode;
- Total flow impacts and average impacts per ton-km per commodity group.

Total Flow Impacts and Average Impacts per Ton-km per Industry and Mode

Figure 23 through Figure 31 show the results of the TRACI categories for each industry. The results show the impacts per mode, considering air; rail; parcel, USPS or courier; private truck; for-hire truck; truck multimodal; and, water modes. Moreover, these results compare the impact for the total industry flows, and for the average per ton-km. These are interesting results as they show the effect of the mode share characteristics of the industry. One example is NAICS 4245: Farm product raw material merchant wholesalers. Although this industry generates a significant amount of ton-miles, reflected in the total flow impacts, the average impact per unit of measurement is low resulting from the large share of rail mode. On the contrary, NAICS 334: Computer and electronic product manufacturing, generates a small amount of ton-miles, but uses air transport in a significant share of the shipments, resulting in larger unitary impacts compared to other industries. The analyses of the average impact per ton-km show evidence that despite the variability, the higher impacts tend to have a similar ceiling (with the exception of 334), whereas there is no common bottom for the lower average impacting industries.

Figure 32 shows the TRACI impacts for all (only including the CFS-PUM industries) freight flows in California. As expected, the majority of the impacts come from the ton-km using for-hire trucks because this mode transports most of the cargo. Rail is the second popular mode, and the impacts reflect this relationship and the lower per ton-km TRACI impacts. The results show that, for instance, the GWP impacts are about 150 million ton CO_2eq for the yearly flows, with almost 120 million of those generated by trucks.

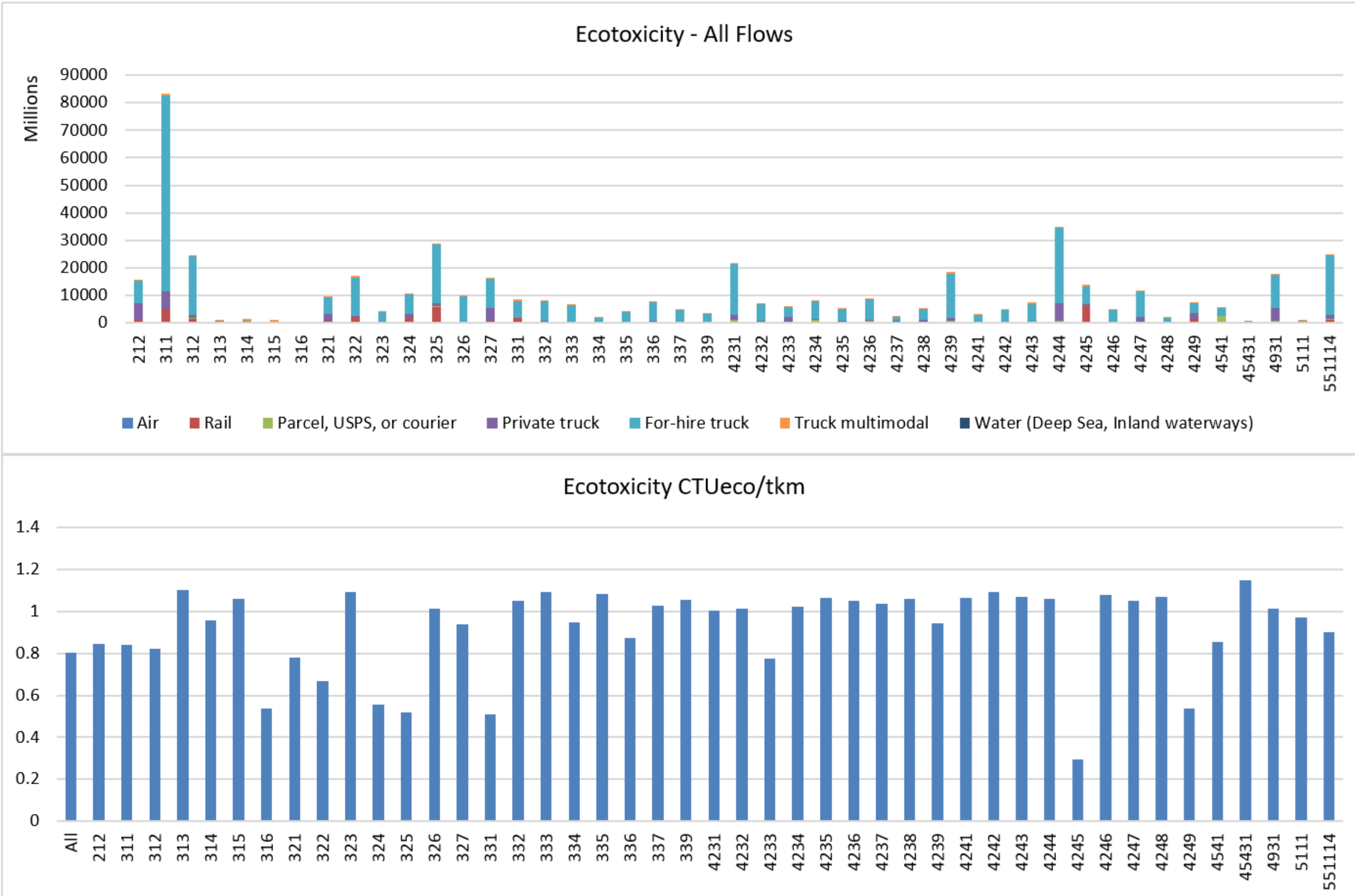


Figure 23. Ecotoxicity Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Industry Category

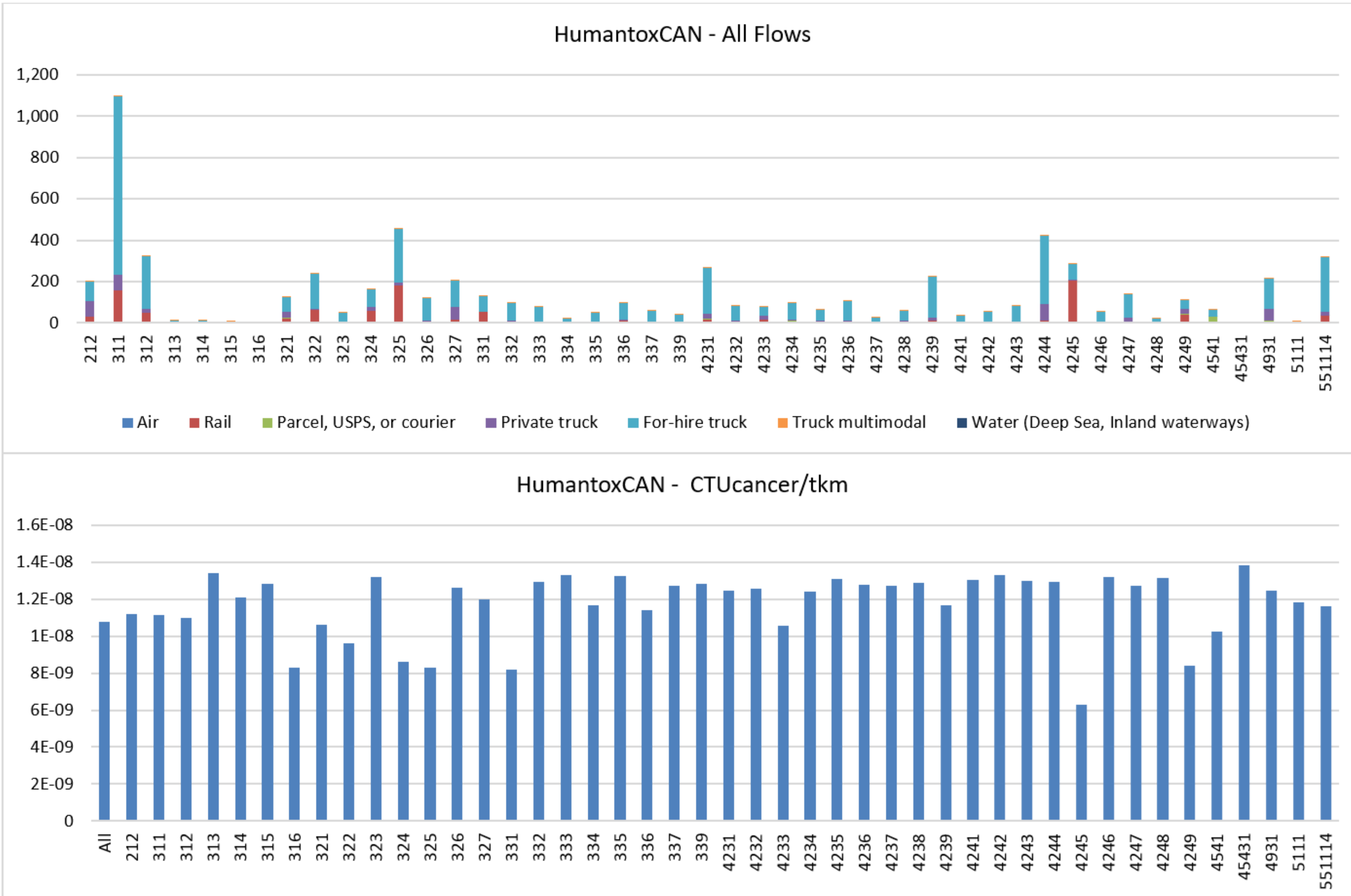


Figure 24. Human Health Cancer Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Industry Category

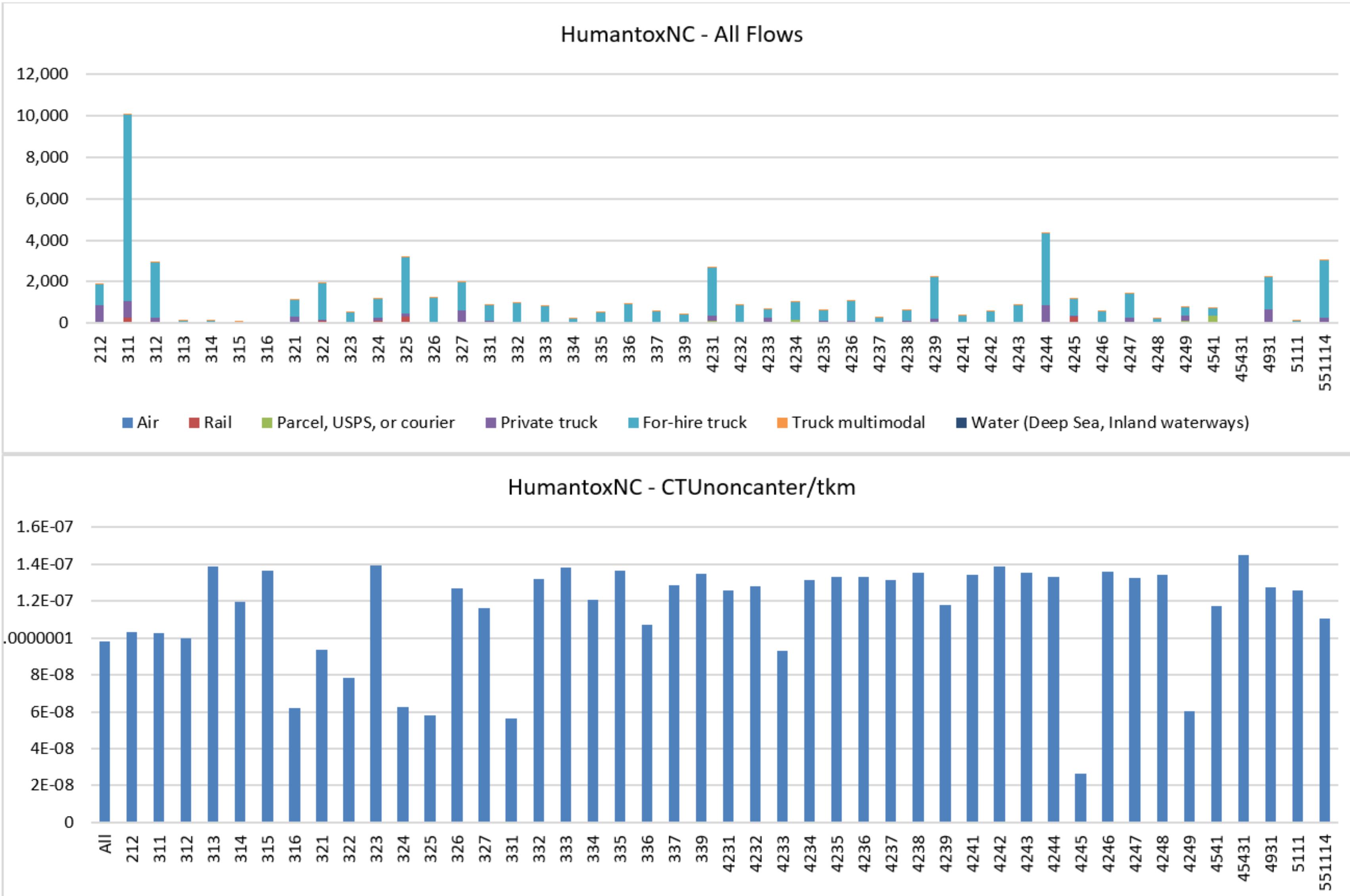


Figure 25. Human Health Non-Cancer Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Industry Category

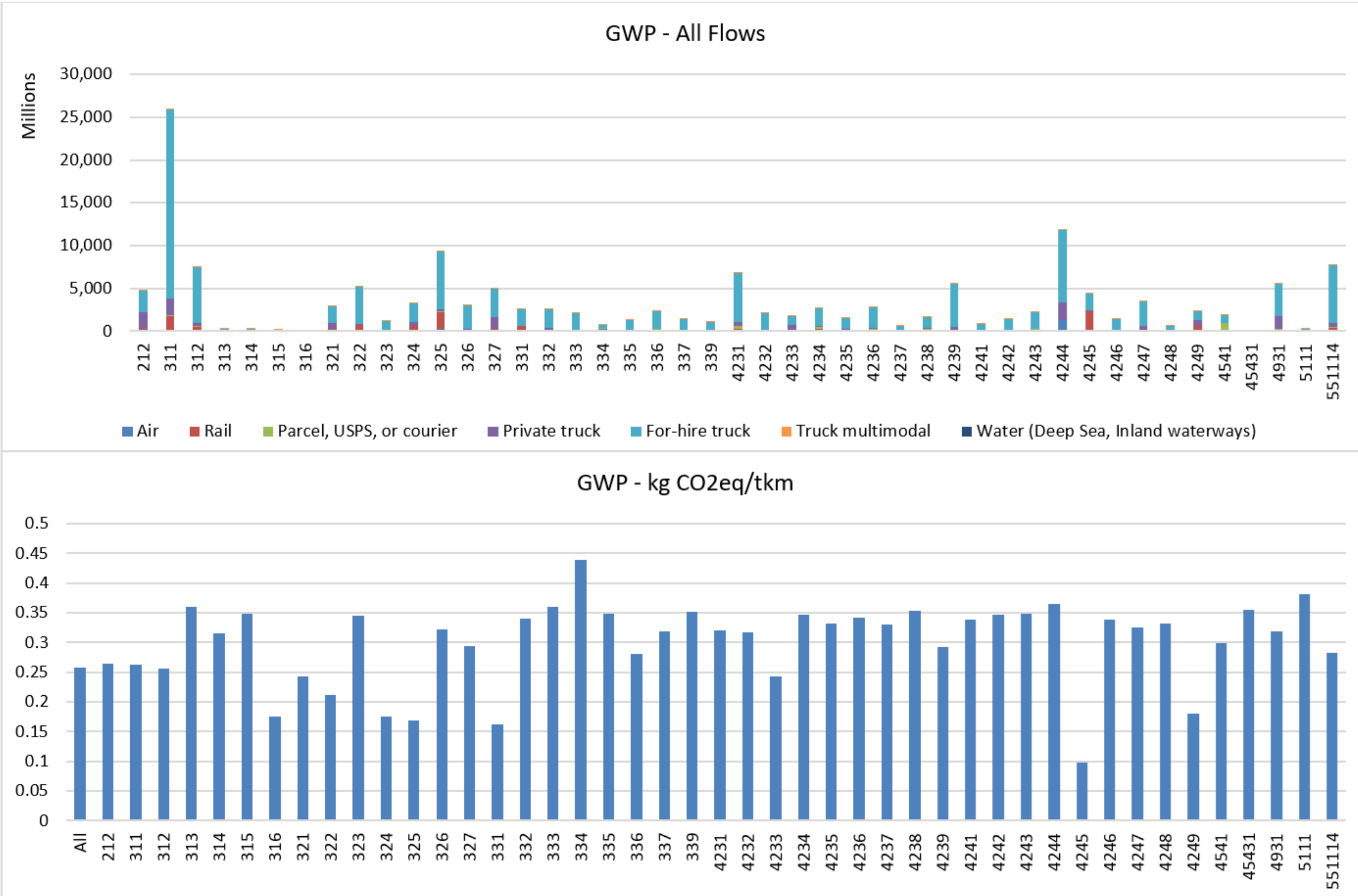


Figure 26. Global Warming Potential Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Industry Category

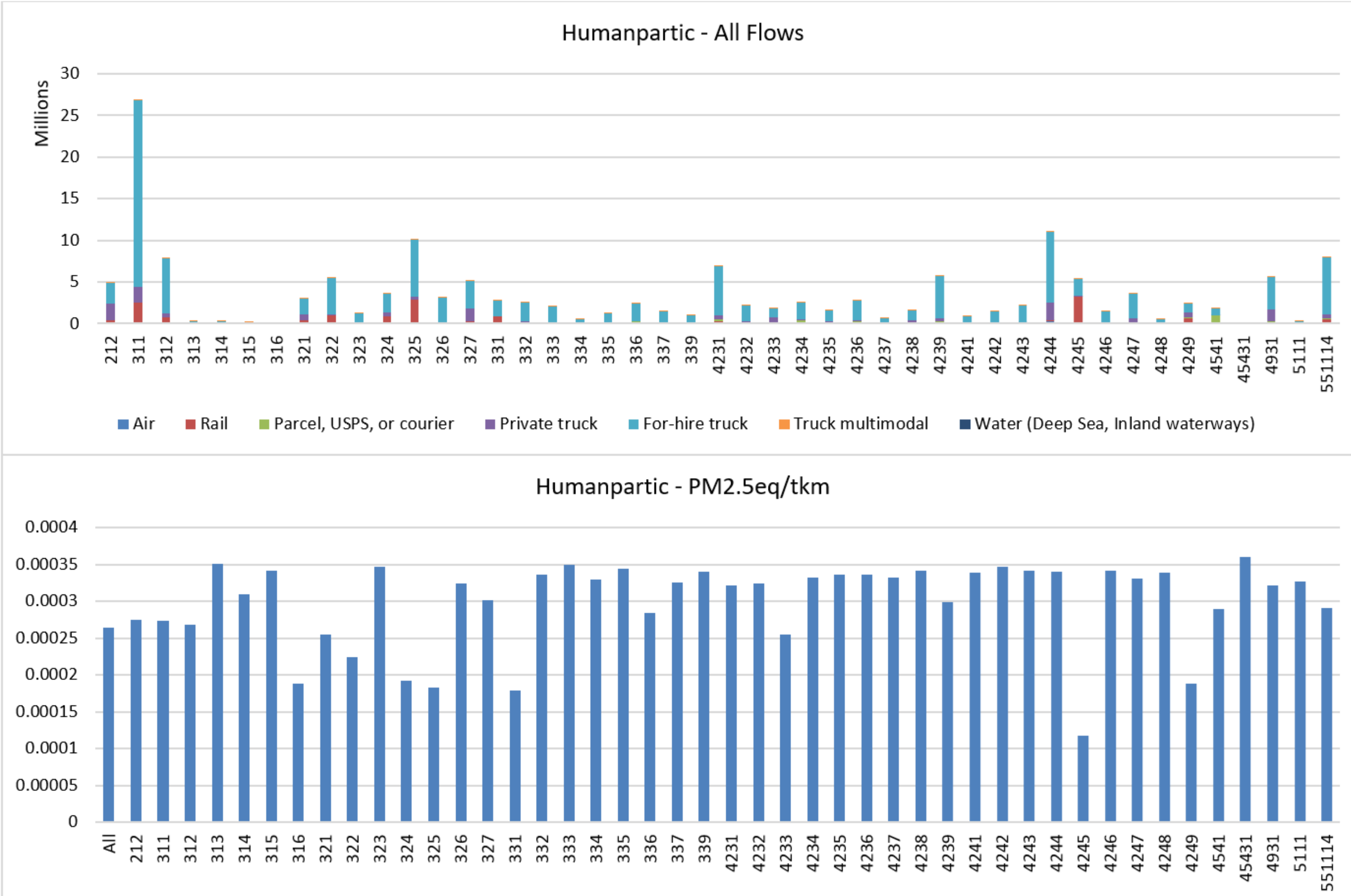


Figure 27. Human Health Particulate Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Industry Category

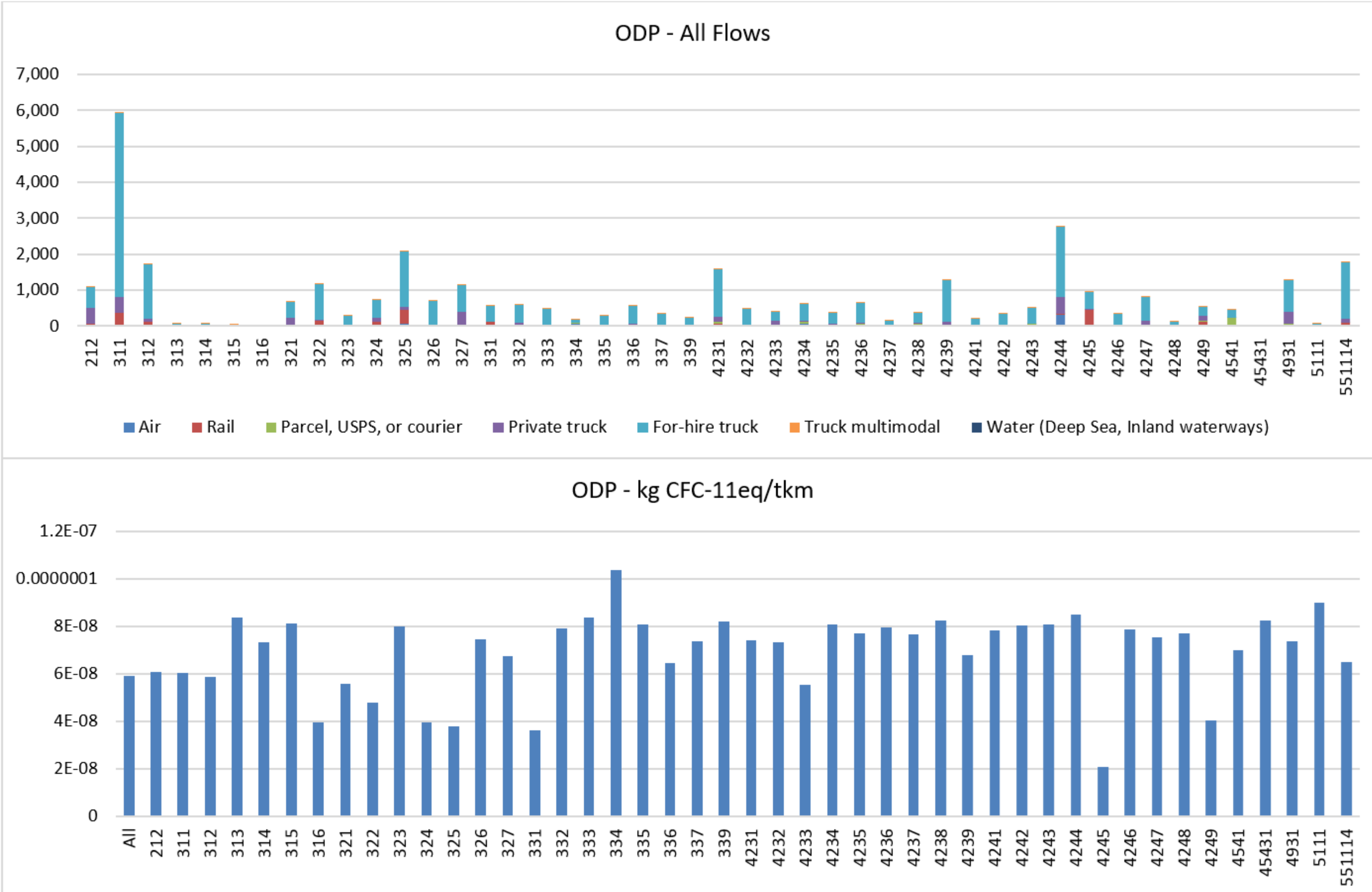


Figure 28. Ozone Depletion Potential Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Industry Category

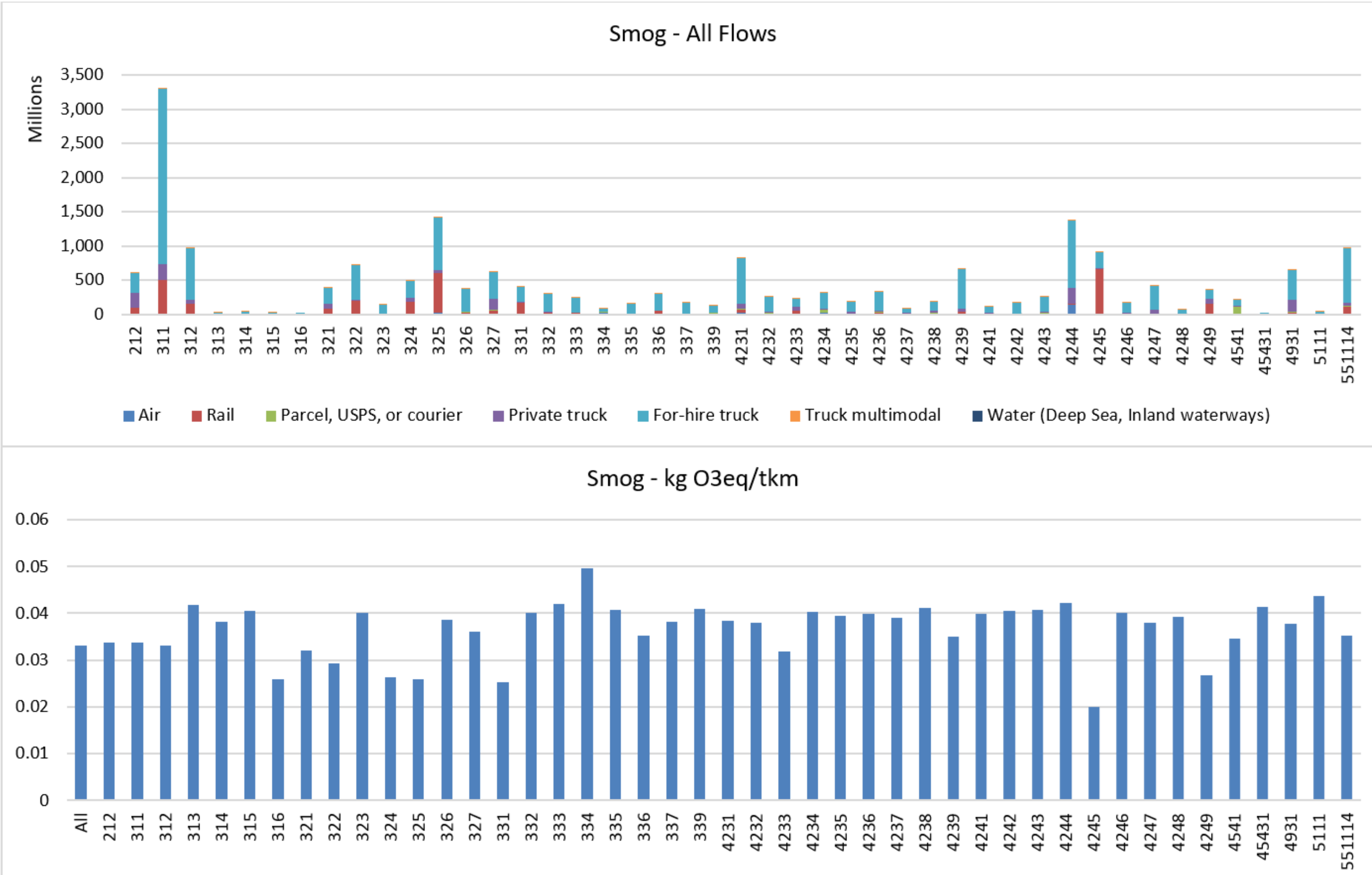
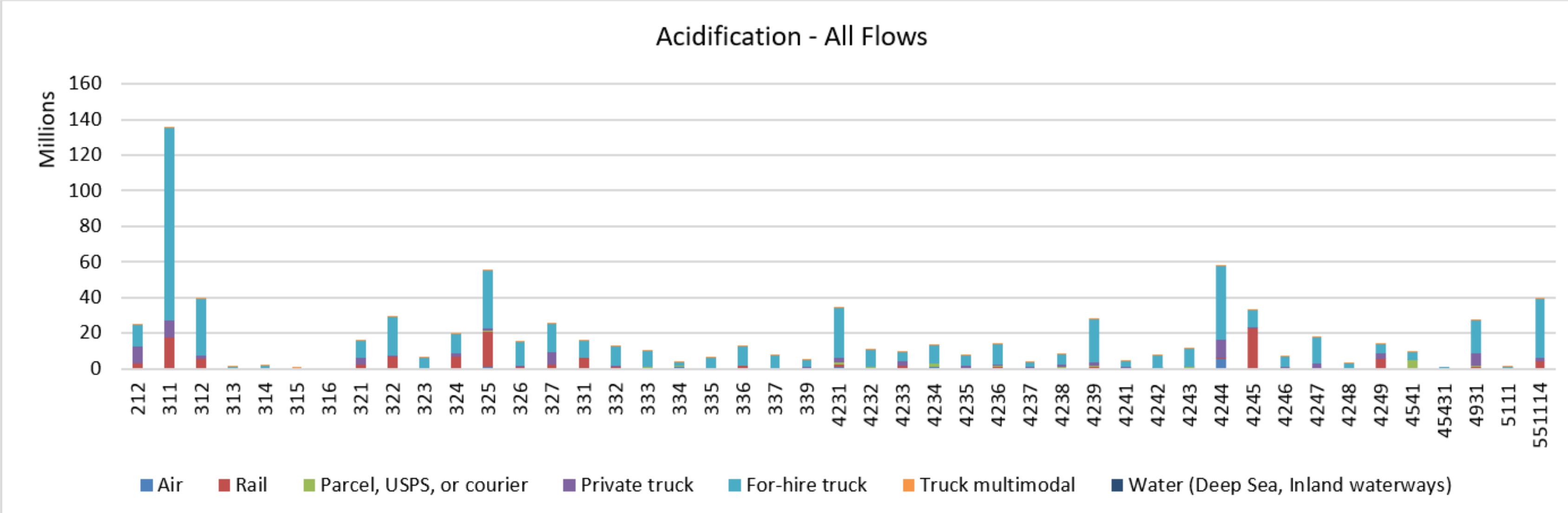


Figure 29. Photochemical Smog Formation Potential Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Industry Category



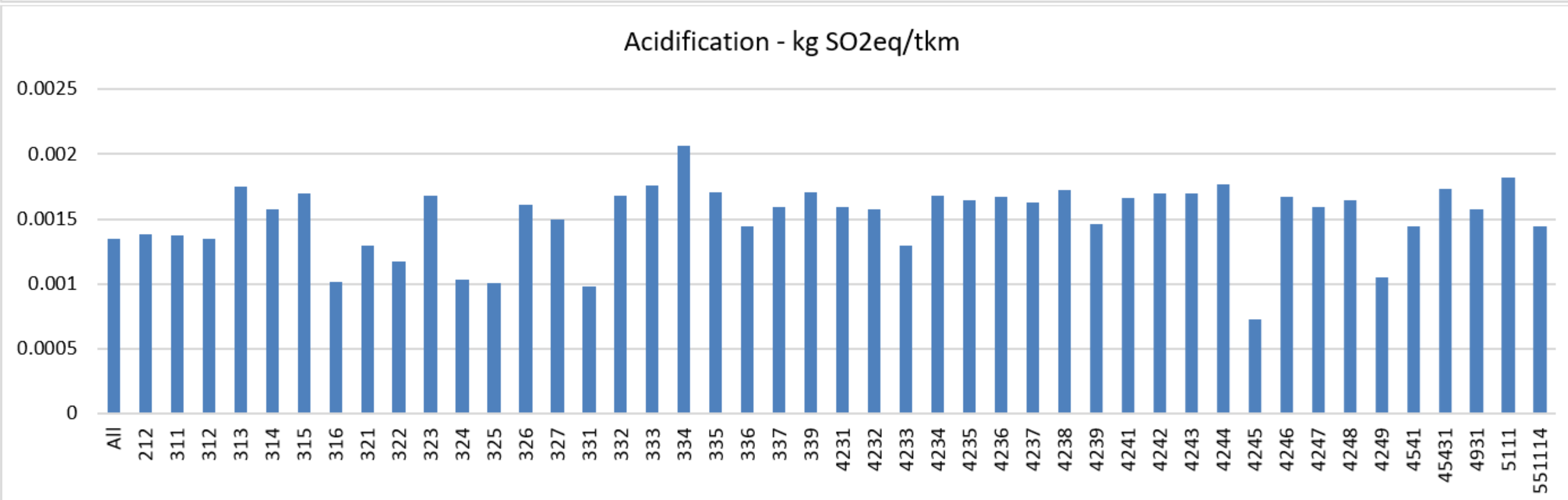


Figure 30. Acidification Potential Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Industry Category

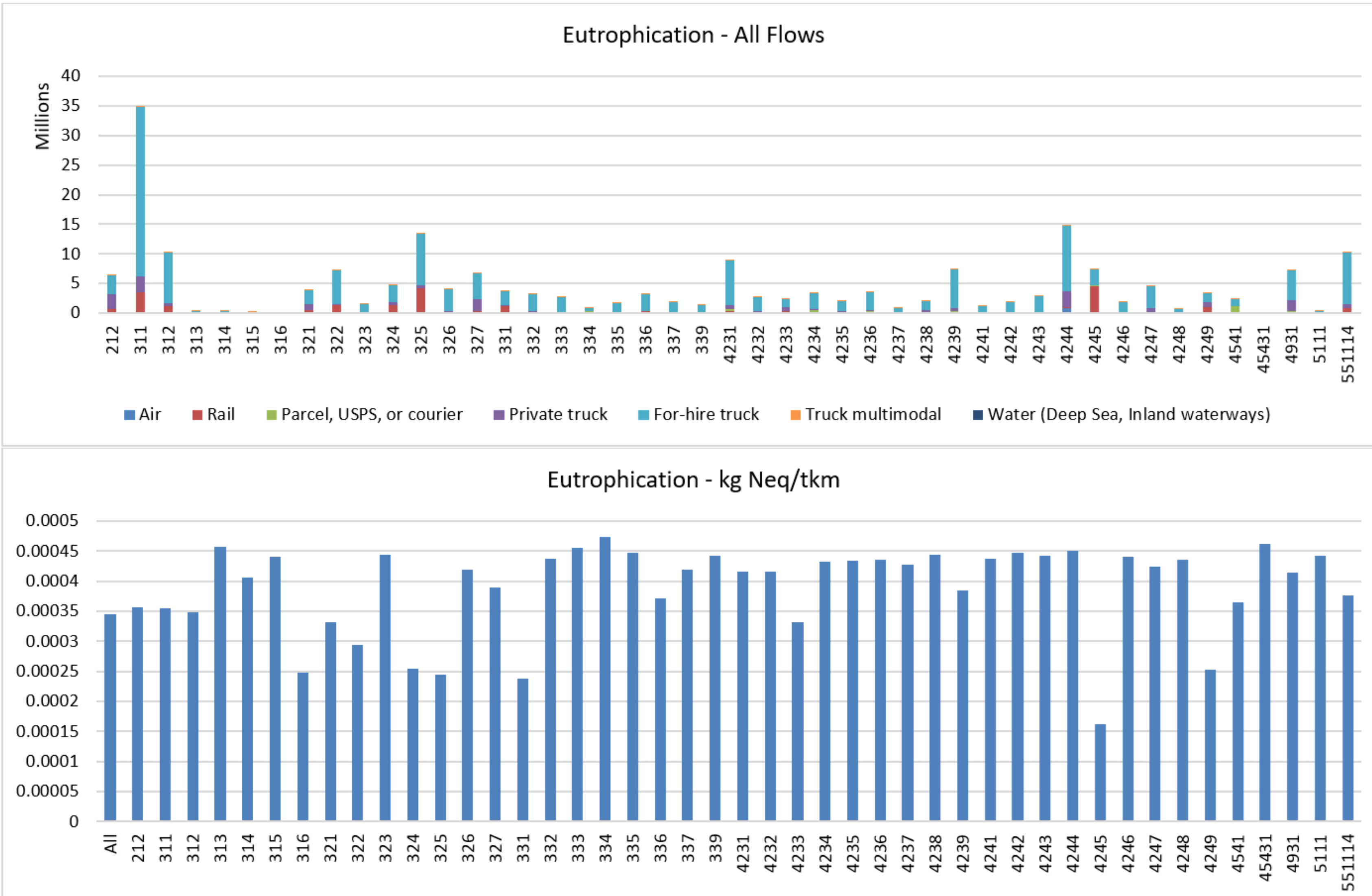
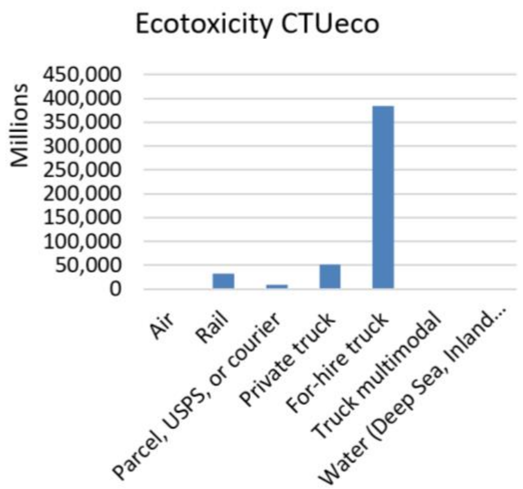
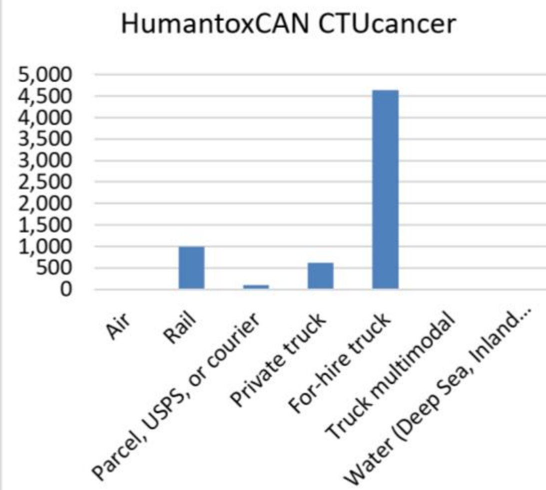
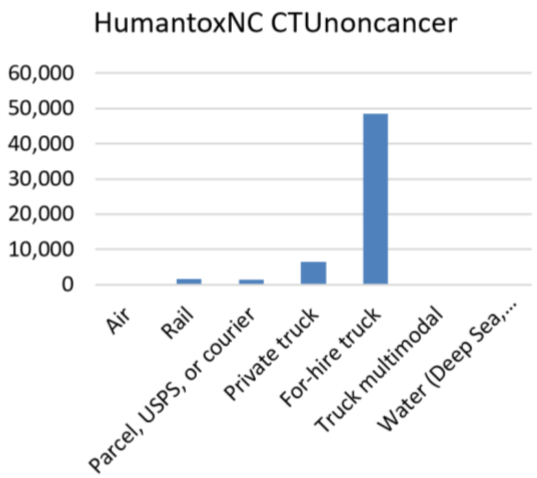
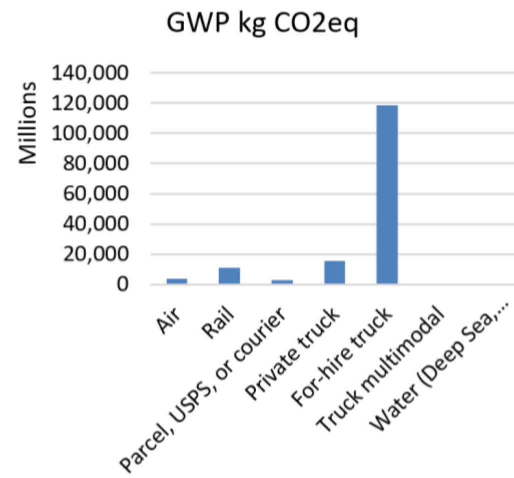


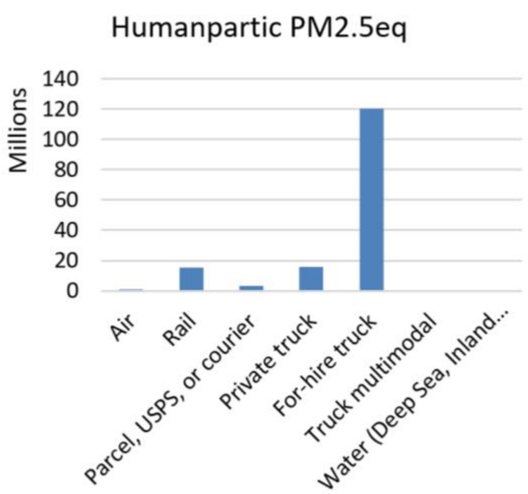
Figure 31. Eutrophication Potential Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Industry Category

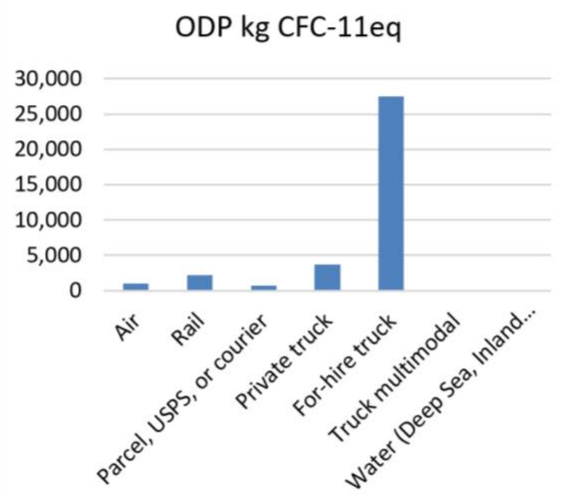

Ecotoxicity CTUeco
Millions
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Air
Rail
Parcel, USPS, or courier
Private truck
For-hire truck
Truck multimodal
Water (Deep Sea, Inland...


HumantoxCAN CTUcancer
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Air
Rail
Parcel, USPS, or courier
Private truck
For-hire truck
Truck multimodal
Water (Deep Sea, Inland...


HumantoxNC CTUnoncancer
60,000
50,000
40,000
30,000
20,000
10,000
0
Air
Rail
Parcel, USPS, or courier
Private truck
For-hire truck
Truck multimodal
Water (Deep Sea,...


GWP kg CO2eq
Millions
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Air
Rail
Parcel, USPS, or courier
Private truck
For-hire truck
Truck multimodal
Water (Deep Sea,...


Humanpartic PM2.5eq
Millions
140
120
100
80
60
40
20
0
Air
Rail
Parcel, USPS, or courier
Private truck
For-hire truck
Truck multimodal
Water (Deep Sea, Inland...


ODP kg CFC-11eq
30,000
25,000
20,000
15,000
10,000
5,000
0
Air
Rail
Parcel, USPS, or courier
Private truck
For-hire truck
Truck multimodal
Water (Deep Sea, Inland...

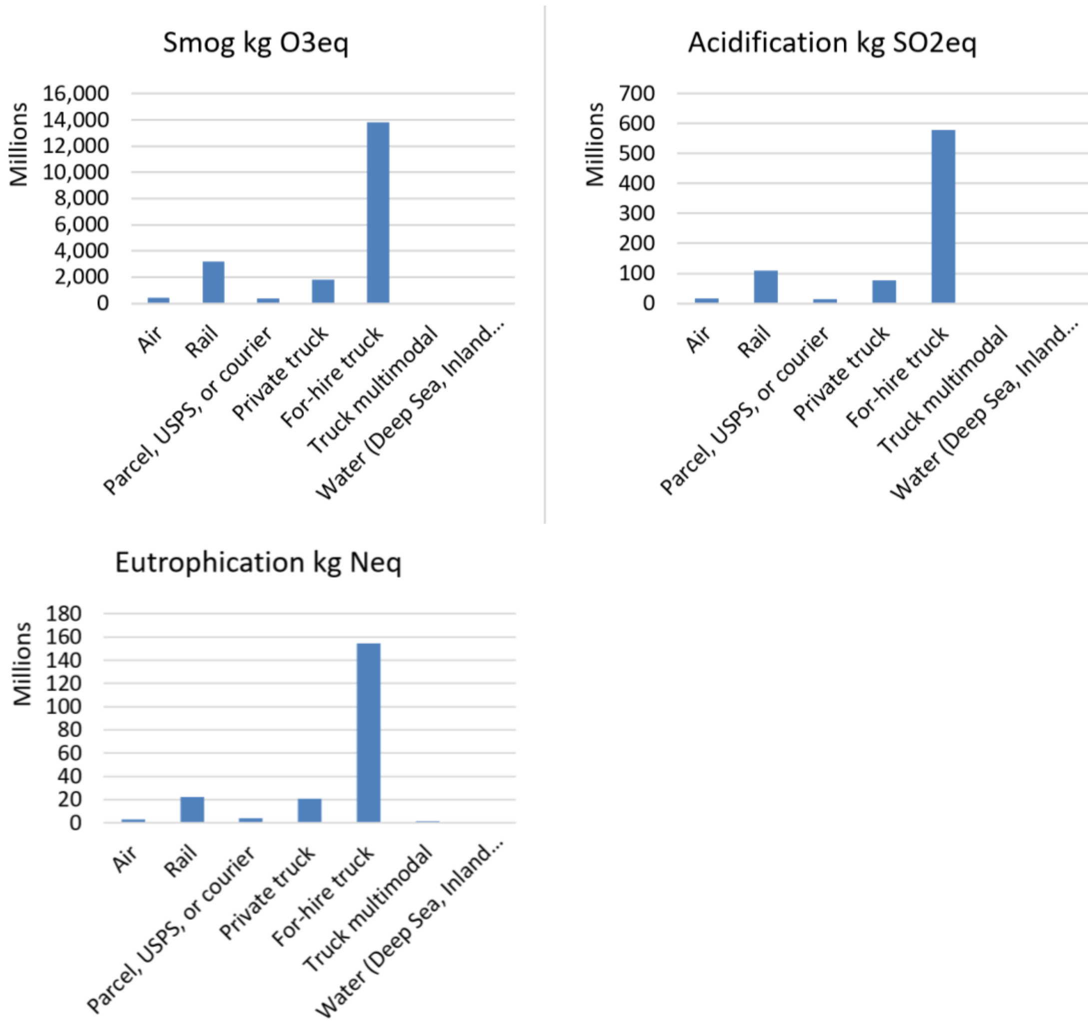


Figure 32. California Flow Total TRACI Impacts

Total Flow Impacts and Average Impacts per Ton-km per Commodity Group

Similar to the previous results, the team estimated the TRACI impacts for the freight flows categorized by SCTG commodity code. Figure 33 through Figure 41 show the results for all ton-miles per commodity, and the average per ton-km. As expected, the SCTG 07: Other prepared foodstuffs, and fats and oils are the largest because this commodity has the largest share of distribution. Interestingly, the per ton-km impacts are, in many cases, lower than the estimated average. Another important consideration are the cases of SCTG 15: Coal and SCTG 02: Cereal grains. These are mainly transported by rail, thus the per ton-km tends to be the lowest. When analyzing commodity flows, the impacts per unitary measure tend to have more variability than when resulting from industry categories. The selection of preferred modes per commodity could explain these results; on the other hand, the industries tend to transport multiple commodities.

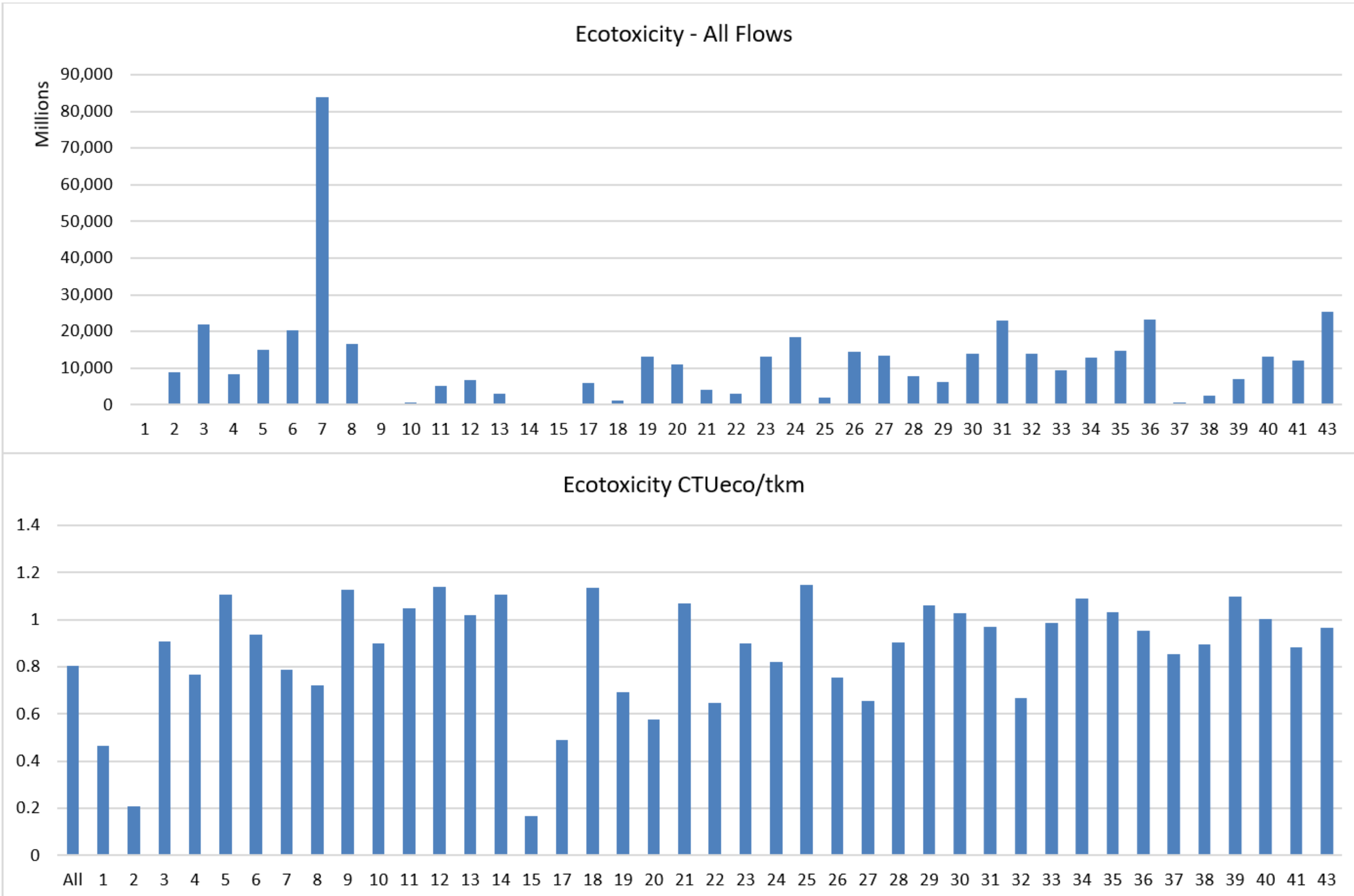


Figure 33. Ecotoxicity Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Commodity Group

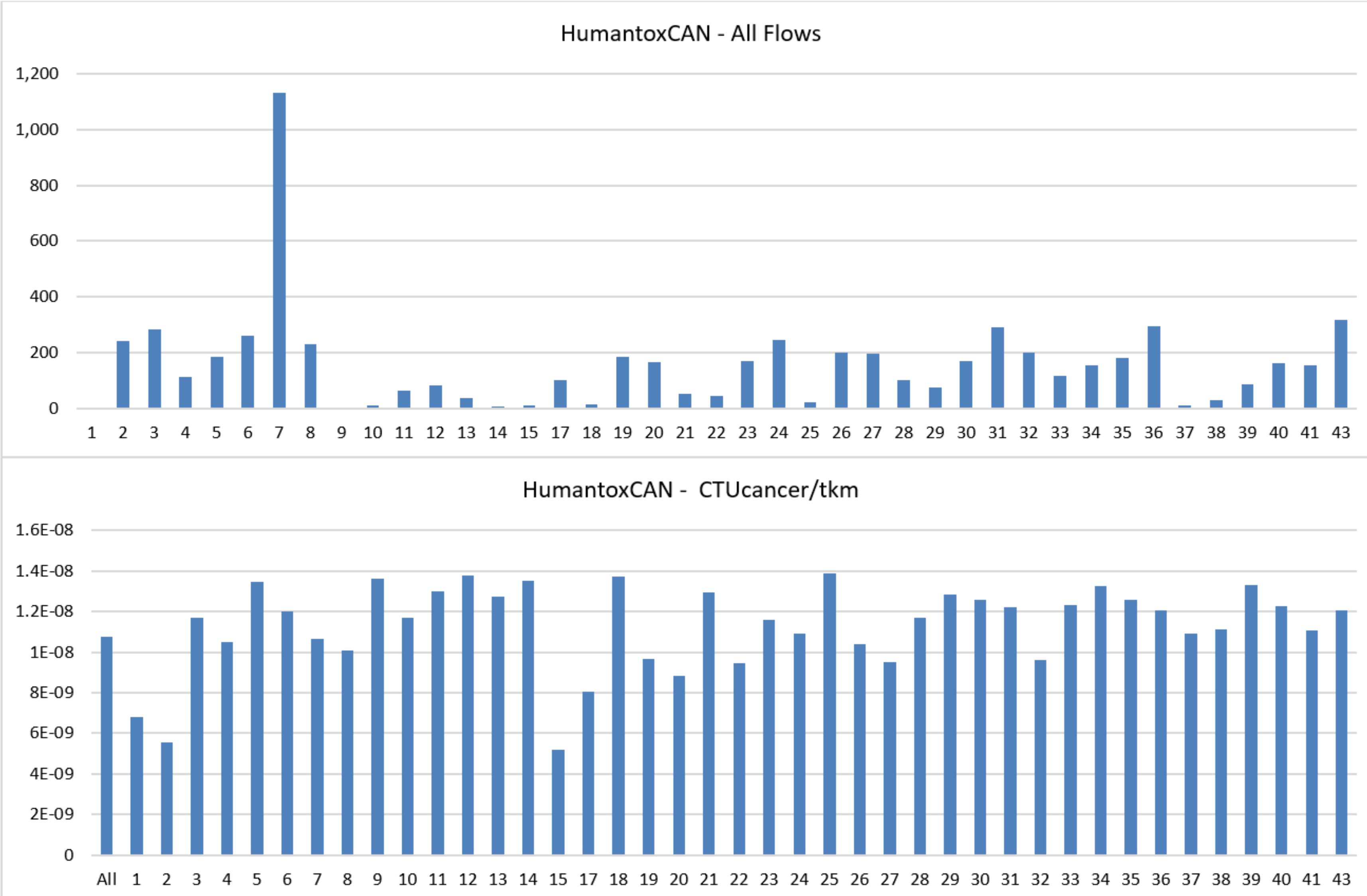


Figure 34. Human Health Cancer Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Commodity Group

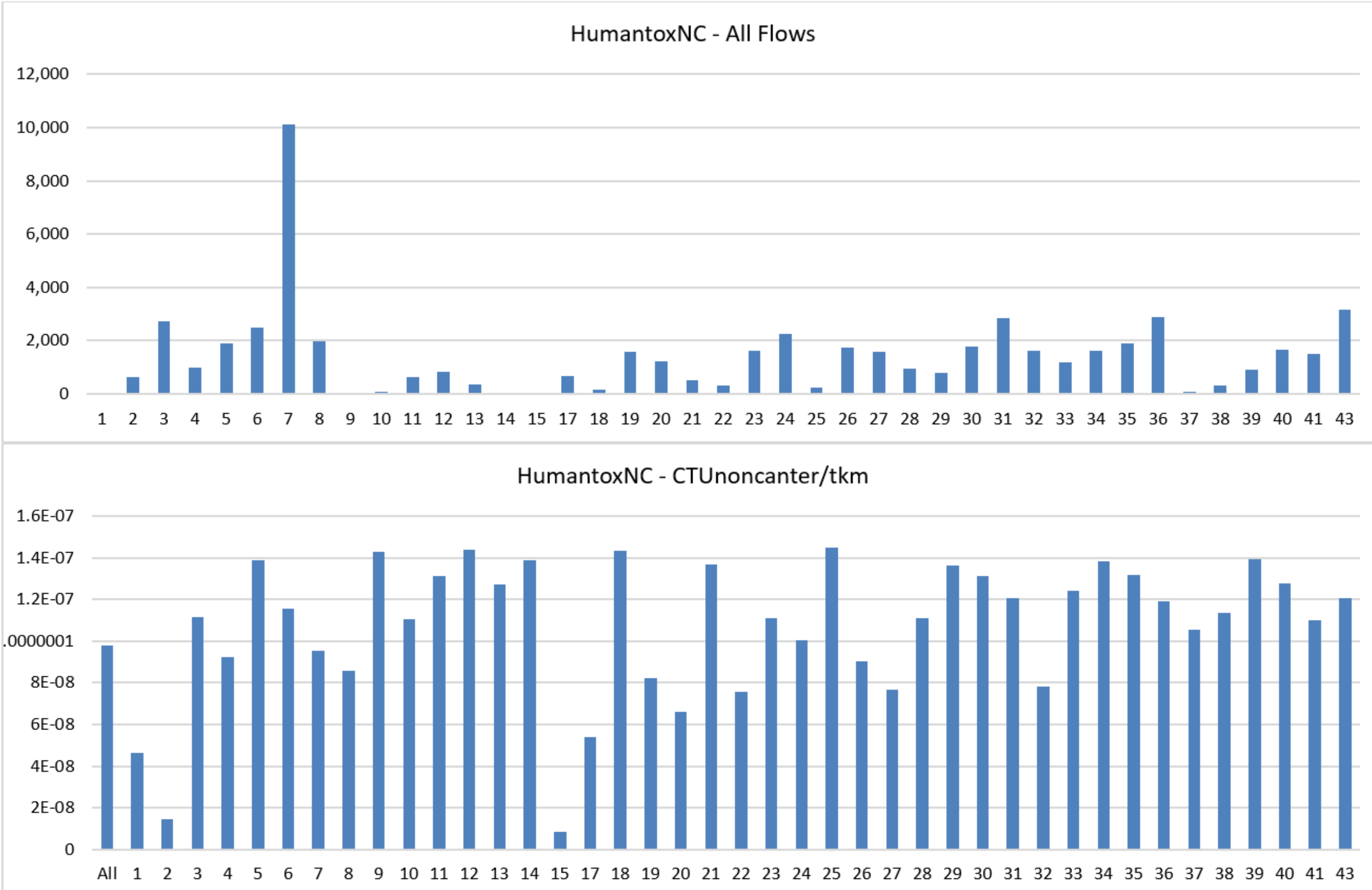


Figure 35. Human Health Non-Cancer Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Commodity Group

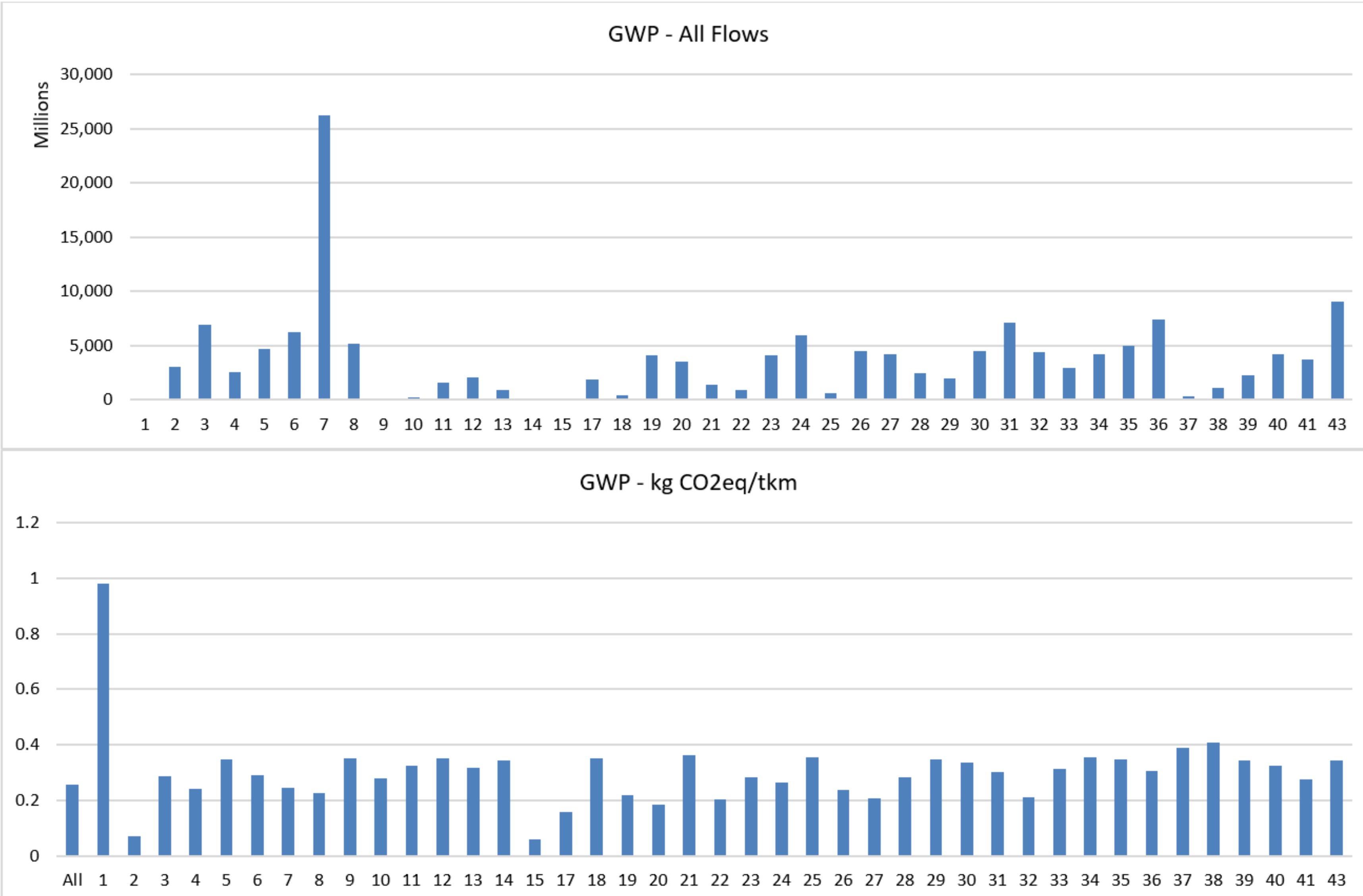


Figure 36. Global Warming Potential Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Commodity Group

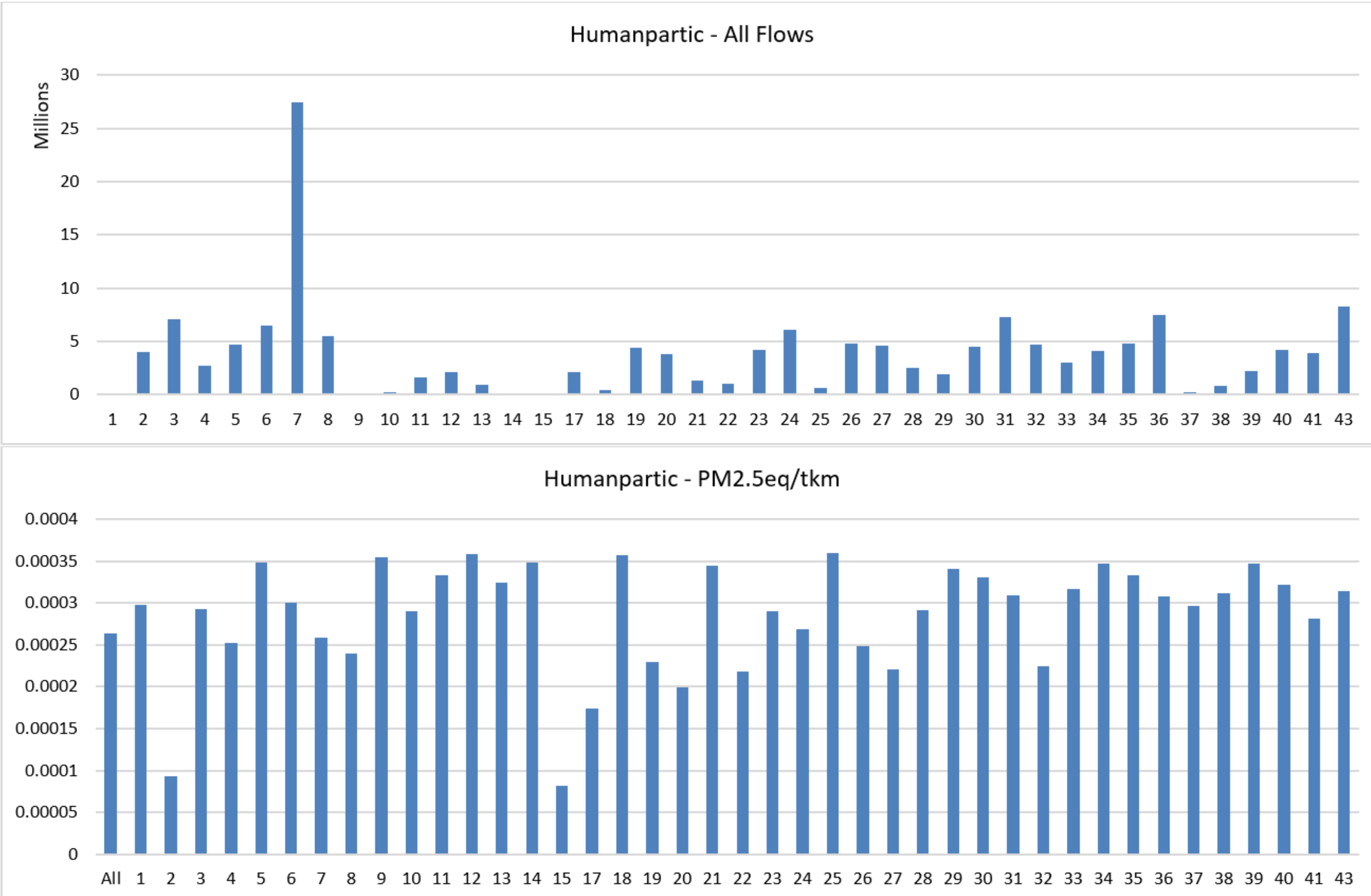


Figure 37. Human Health Particulate Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Commodity Group

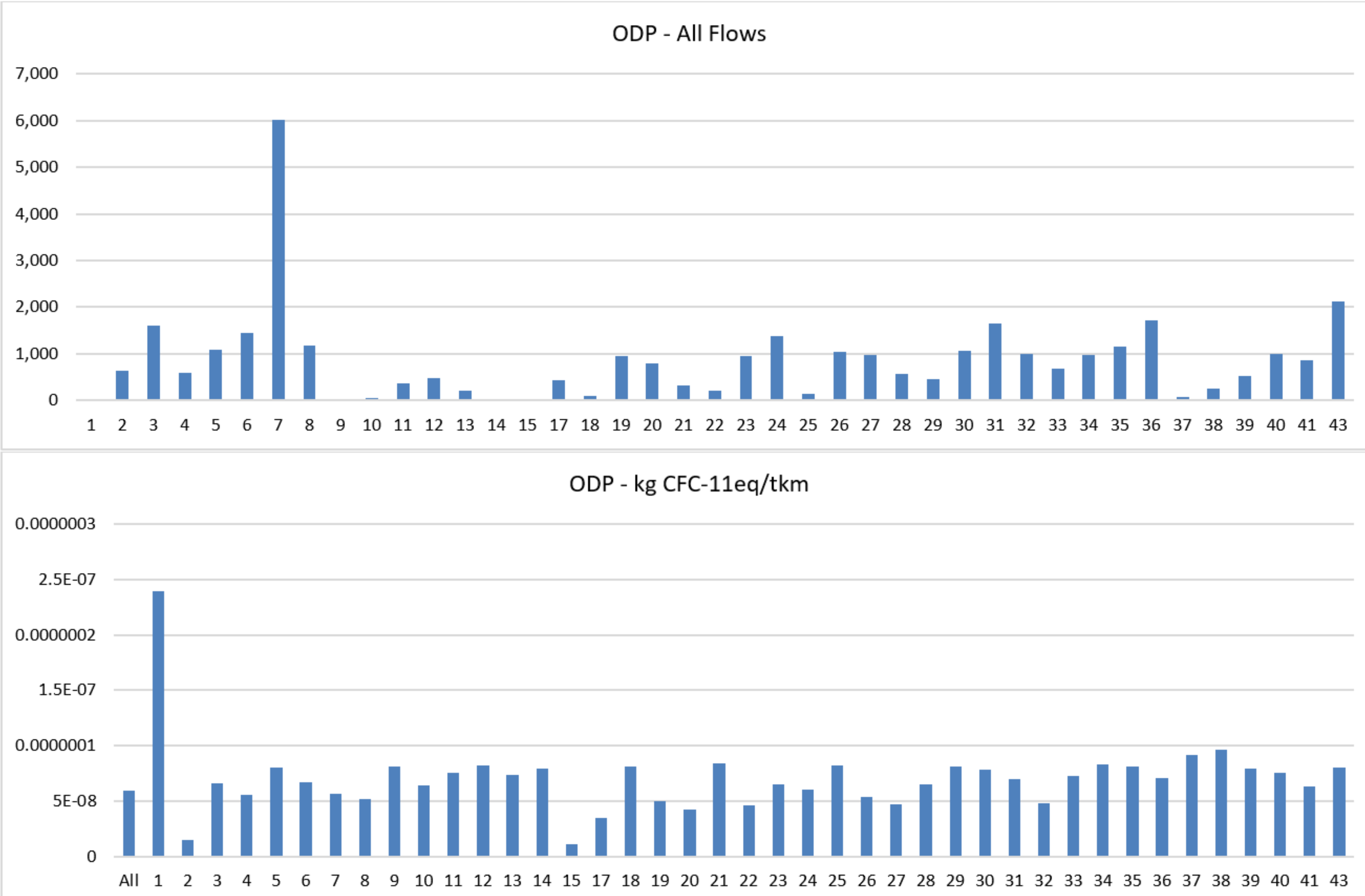


Figure 38. Ozone Depletion Potential Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Commodity Group

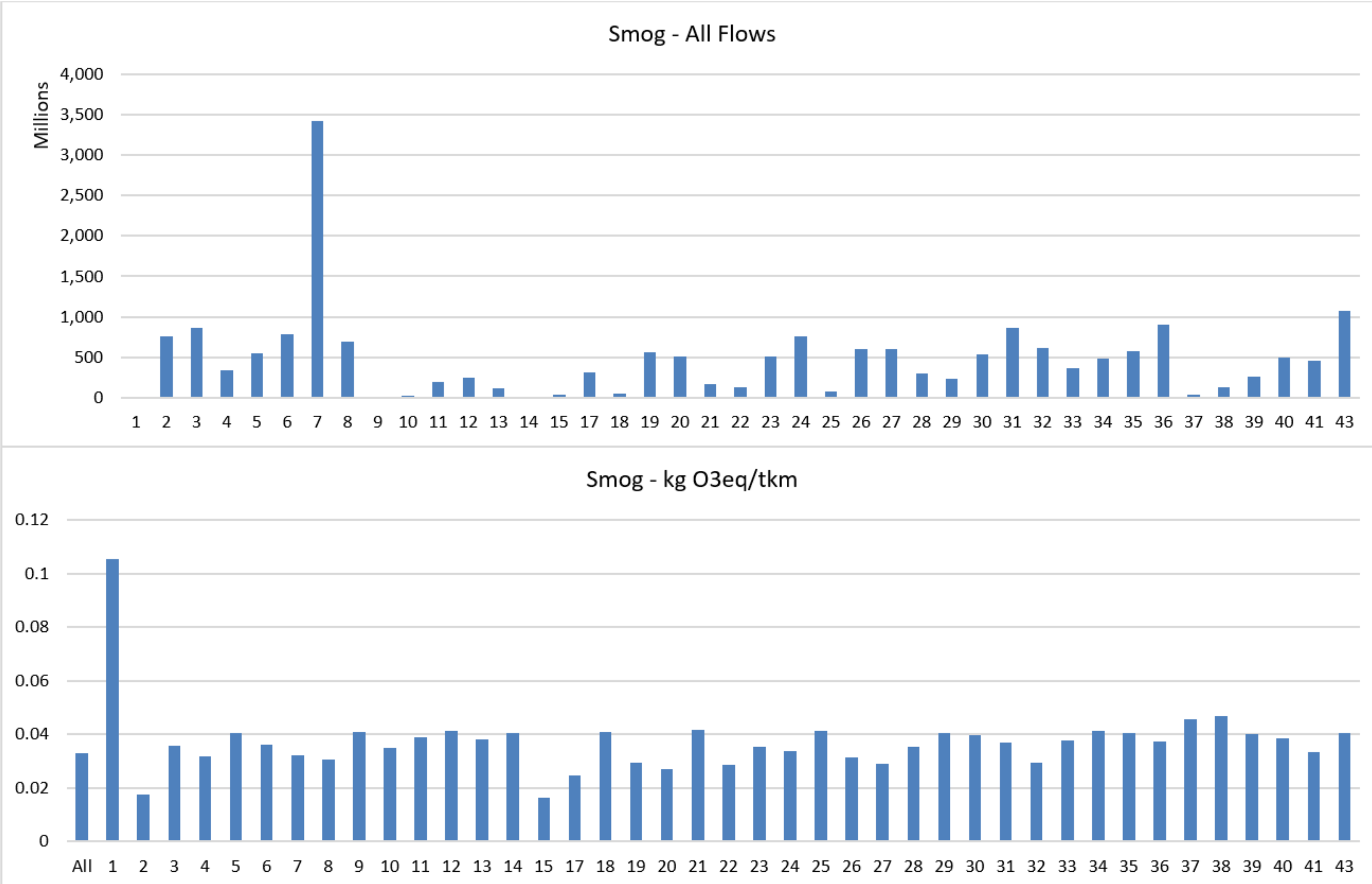


Figure 39. Photochemical Smog Formation Potential Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Commodity Group

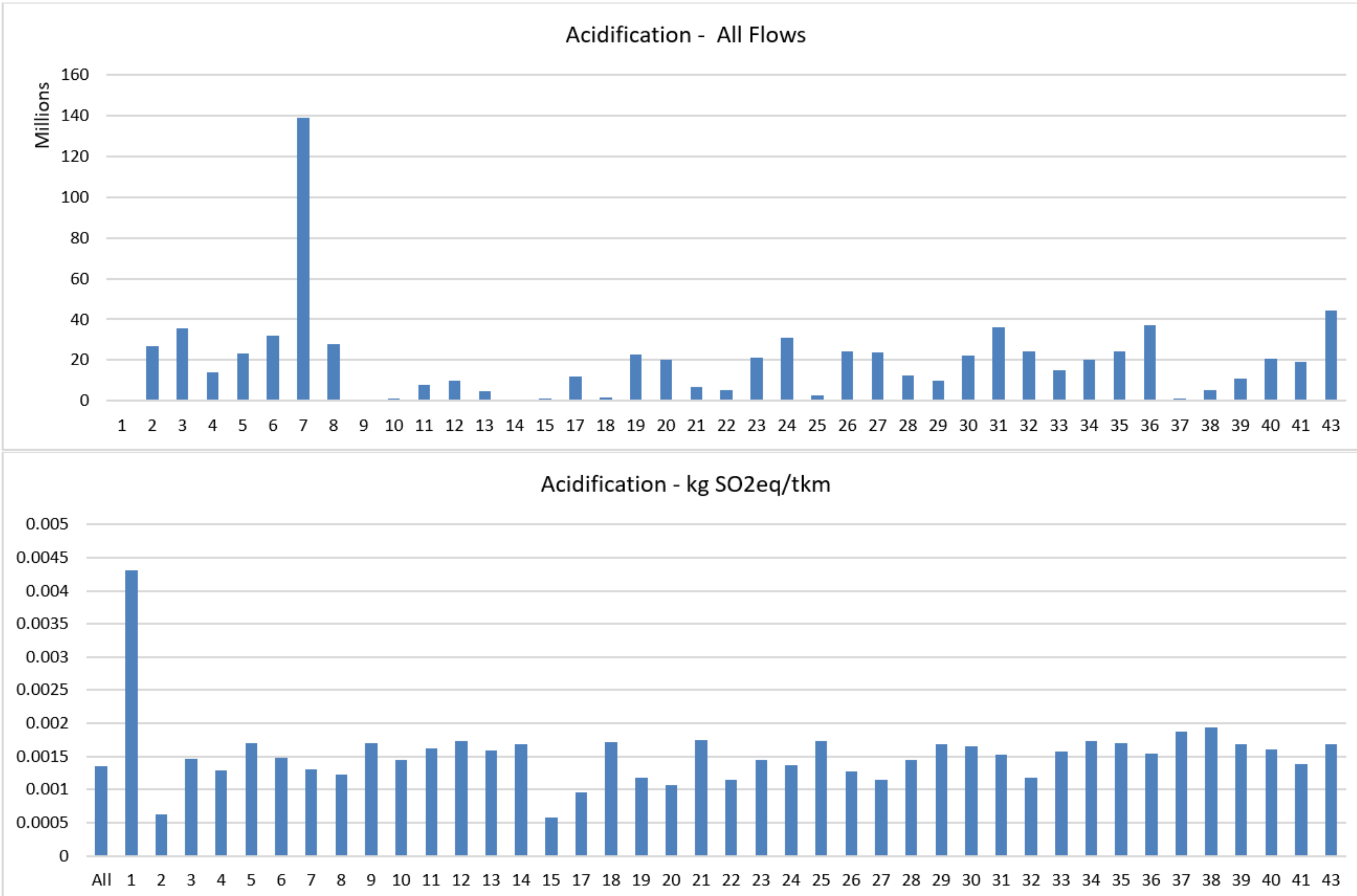


Figure 40. Acidification Potential Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Commodity Group

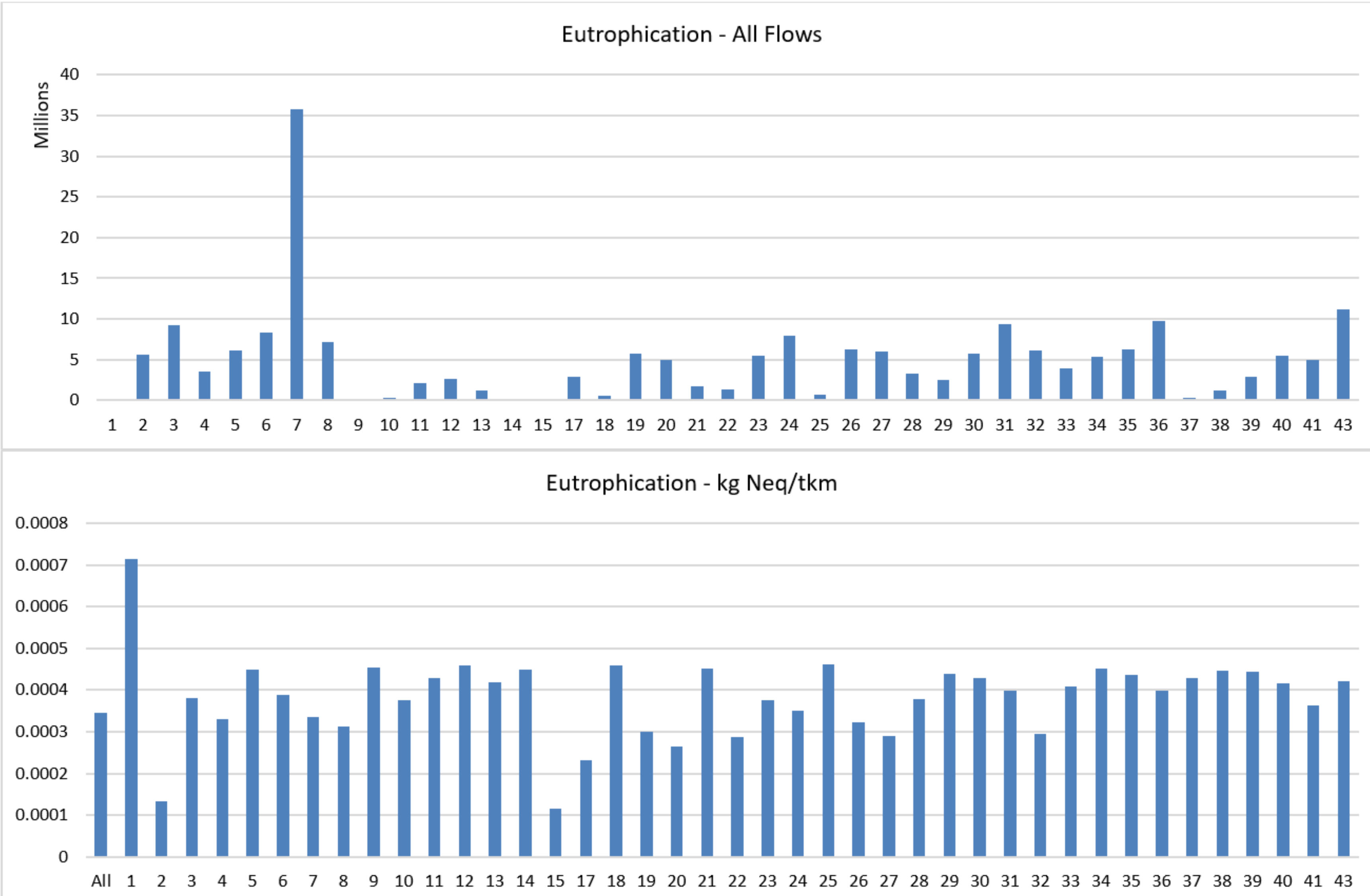


Figure 41. Eutrophication Potential Impacts from All California Flows (top) and Average per Ton-km (bottom) for each Commodity Group

Computers and Electronics Manufacturer's Supply Chain

For the computers and electronics manufacturers, the team selected a company similar to DELL Inc. as the case study. DELL is an American privately owned multinational computer technology corporation that develops, sells, repairs, and supports computers and computer related products. Named after its founder, Michael DELL, the company is one of the largest technological corporations in the world, employing more than 103,300 people worldwide. DELL sells personal computers (PCs), servers, data storage devices, network switches, software, computer peripherals, HDTVs, cameras, printers, MP3 players, and electronics built by other manufacturers. The company implements a direct-sales model and "build-to-order" or "configure to order" approach to manufacturing delivering individual PCs configured to customer specifications.

This strategy implies that the company does not have specific stores or PC/Laptop models to sell, but builds products according to customer's orders. DELL benefits from its small, yet worldwide, supply chain model, which for some logistics activities relies on third companies (see Figure 42).

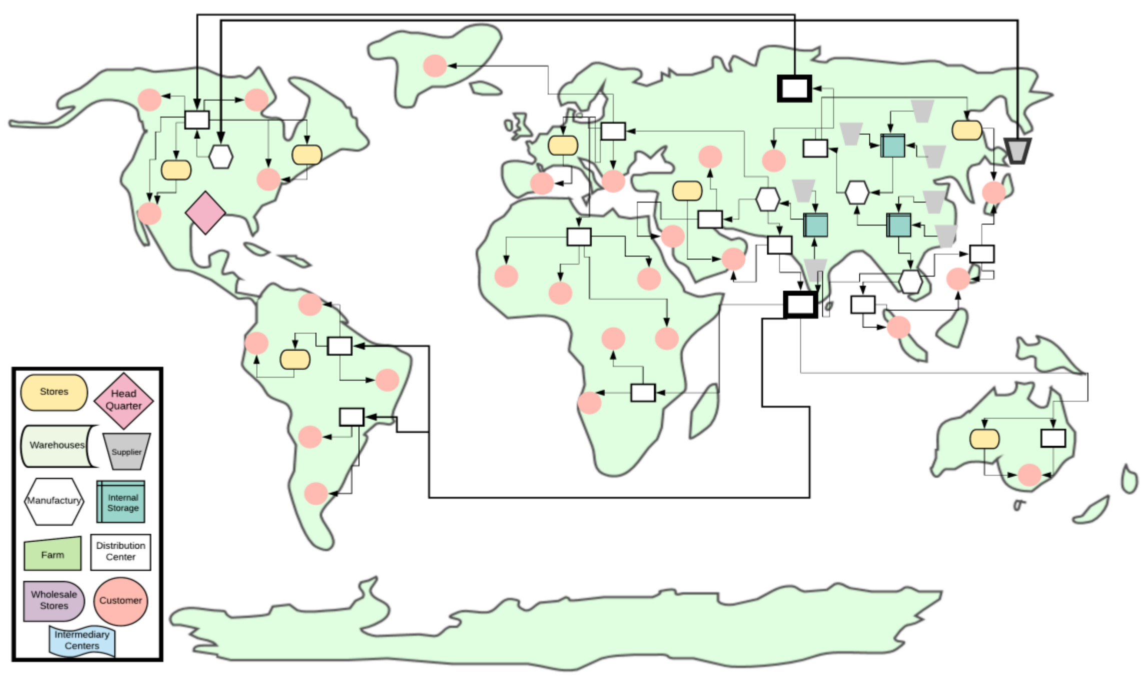


Figure 42. DELL World Map

DELL has 14 facilities in the U.S. and about 16 facilities abroad (see example in Figure 43). These connect directly with headquarters. The company performs research & development, manufacturing, customer service, and finance in the U.S. and India facilities. Moreover, the company is responsible for assembly, quality control check, and software installation (as mentioned, other activities in the supply chain are outsourced). Figure 44 shows an example of DELL operations along a schematic of electronic products' supply chain.

DELL has realized that supply chain is becoming more and more important for the success of today's business and they work accordingly to keep a competitive advantage in the market. The company has implemented supply chain management practices to develop an effective service from suppliers to consumers. Following the attributes discussed in Table 2, Table 24 shows the key aspects of DELL's supply chain.

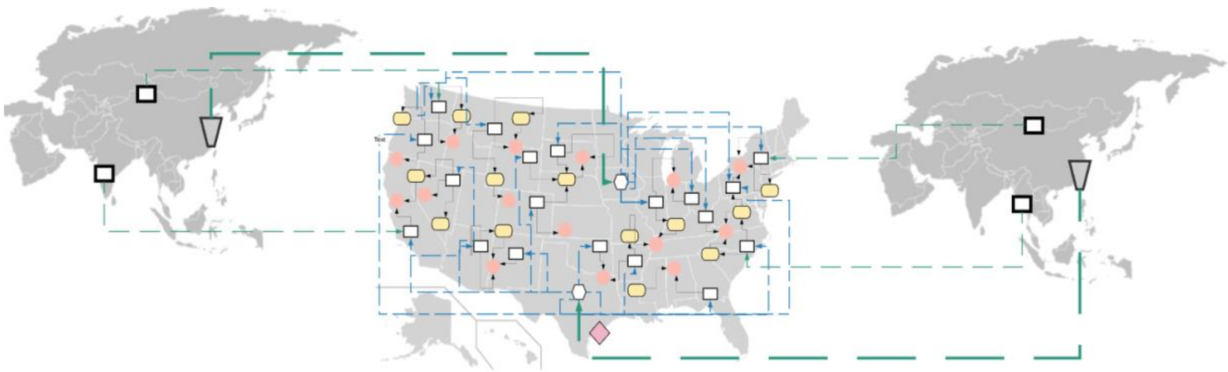


Figure 43. U.S. Map for DELL

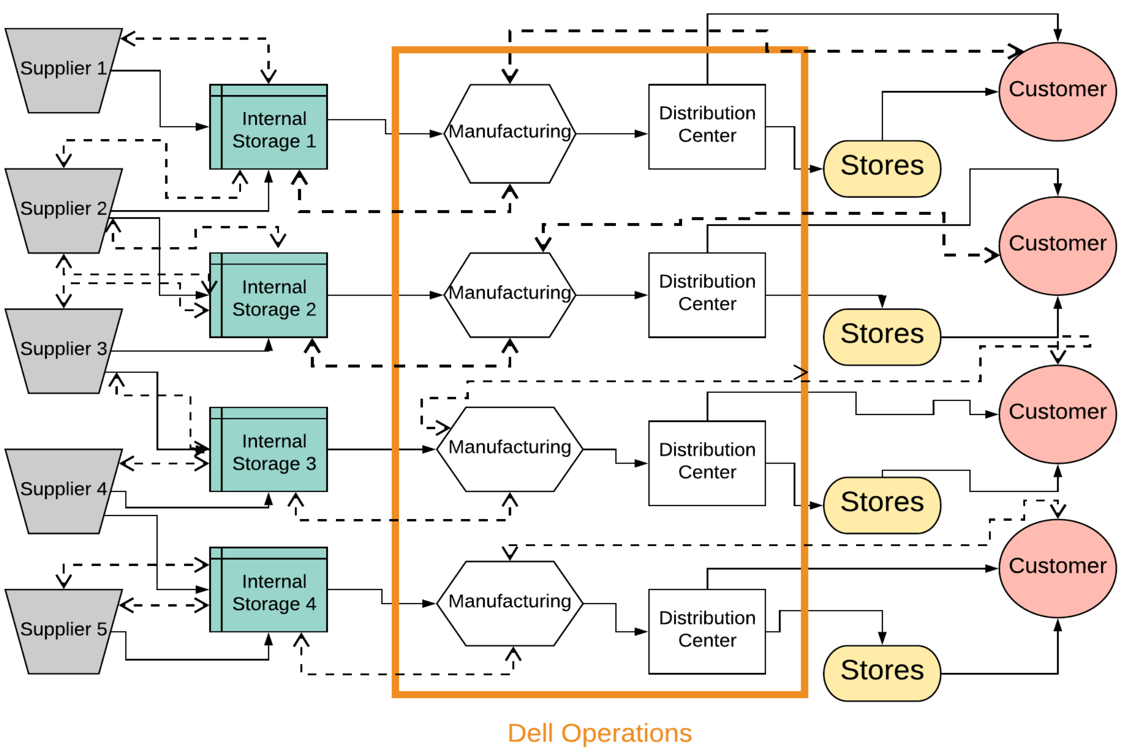


Figure 44. DELL's Supply Chain

Table 24. DELL's Supply Chain Attributes

Procurement Type	Number and type of products procured	Many (Sales over 62 billion $ in the first quarter of 2017)
	Sourcing type	Multiple (over 100 suppliers)
	Suppliers' flexibility (Amounts to be supplied)	Low
	Supplier lead time and reliability	Low (Very Reliable)
	Material's life cycle	Long
Production Type	Organization of the production process	Job Shop
	Repetition of operations	Batch Production
	Changeover characteristics	Sequence Dependent
	Bottlenecks in production	Could be both or none
	Working time flexibility	Multiple Shifts (Even 10h a day labor work)
Distribution Type	Distribution structure	One stage
	Pattern of delivery	Dynamic
	Deployment of transportation means	Routes: Both (Variable & Standards)
		Capacity: Limited
		Loading requirements: Applied for air and land transportation
	Availability of future demands	Forecasted
	Demand curve	Sporadic
	Product's life cycle	nearly 20 years (LCA Study File)
	Number of product types	21 Product Type
	Degree of customization	Specific
	Bill of materials (BOM)	Convergent
	Portion of service operations	Tangible Products
Typography of a supply chain	Network Structure	Mixture
	Degree of globalization	Worldwide
	Location of decoupling points	Manufacture-to-order (Build in -to-order)
	Major constraints	Supplier, JIT production procedure
Integration and coordination	Legal position	Inter-organizational
	Balance of power	Dominant Partner (Texas Headquarter)
	Direction of coordination	Vertical
	Major constraints	All

To estimate the impacts of DELL's freight flows, the research team conducted a comprehensive search for the specific company flows, but they were not publicly available. The team decided to conduct a market level analysis to allocate state flows (from the estimated CFS-PUM) to the company. In doing so, the team gathered information about market shares for PC makers around the world and in the U.S. Table 25 shows the global share of PC for six pioneering technological companies. These market shares only include desktop computers, laptops, and notebooks. The data shows that DELL has around 15% of total sales and ranks third worldwide.

Table 25. Global PC Market Shares

Rank	2011		2012		2013		2014		2015		2016	
1	HP	16.6	HP	16.1	Lenovo	16.9	Lenovo	18.8	Lenovo	19.8	Lenovo	20.7
2	Lenovo	12.5	Lenovo	14.9	HP	16.2	HP	17.5	HP	18.2	HP	19.4
3	**DELL**	**11.7**	**DELL**	**10.7**	**DELL**	**11.6**	**DELL**	**12.8**	**DELL**	**13.6**	**DELL**	**14.7**
4	Acer	-	Acer	10.2	Acer	8	Acer	7.9	Asus	7.3	Asus	7.6
5	Asus	5.7	Asus	6.9	Asus	6.6	Asus	7.2	Apple	7.2	Apple	6.9
Others	42.8		41.2		40.7		35.7		33.9		30.7	

Source:(https://www.gartner.com/newsroom/id/3568420)

Moreover, Table 26 shows DELL's worldwide quarterly market shares between 2011 and 2017. During the last year, the company increased the market in about half point.

Table 26. DELL'S Worldwide Market Share (2011-2017)

Market share (in %)	
Q1 '11	11.4
Q2 '11	12.1
Q3 '11	11.2
Q4 '11	12.2
Q1 '12	11
Q2 '12	11.3
Q3 '12	10.5
Q4 '12	10.4
Q1 '13	11.2
Q2 '13	11.9
Q3 '13	11.6
Q4 '13	11.8
Q1 '14	12.6
Q2 '14	13.3
Q3 '14	12.7
Q4 '14	13.1
Q1 '15	12.8
Q2 '15	14
Q3 '15	13.5
Q4 '15	13.5
Q1 '16	14.2
Q2 '16	14.7
Q3 '16	14.7
Q4 '16	14.8
Q1 '17	15
Q2 '17	15.6
Q3 '17	15.2
Q4 '17	15.2

Source: (https://www.statista.com/statistics/298976/pc-shipments-worldwide-dell-market-share/)

Although DELL's share worldwide is around 15%, in the U.S., the company has had a share ranging between 20% and 26.2% between 2010 and 2016. Considering the CFS data available, the team estimated an average market share for the company of 21.33% (see Table 27 for U.S. quarterly shares). Detailed data at the State level was not available.

Table 27. PC Unit Shipments in the U.S. - DELL's Quarterly Market Share 2010-2016

Market share (in %)	
Q1 '10	23.4
Q2 '10	23.7
Q3 '10	23.6
Q4 '10	22
Q1 '11	22.7
Q2 '11	22.2
Q3 '11	21.6
Q4 '11	22.4
Q1 '12	22.1
Q2 '12	22.5
Q3 '12	20.7
Q4 '12	20
Q1 '13	21.7
Q2 '13	24.3
Q3 '13	20.9
Q4 '13	21.9
Q1 '14	24.2
Q2 '14	25.4
Q3 '14	23.9
Q4 '14	23.1
Q1 '15	23.1
Q2 '15	24.1
Q3 '15	24.1
Q4 '15	23.9
Q1 '16	25.6
Q2 '16	25.8
Q3 '16	26.2

Source: (https://www.statista.com/statistics/311417/us-pc-unit-shipments-dell-market-share/)

Considering that the CFS-PUM data contained information about both the industry category and the transported commodities, the team identified DELL's NAICS and the type of products it sells and distributes. DELL's NAICS codes are 423430 and 33411 (DELL Inc. is also found in NAICS 443142: Electronic stores); however, the company distributes a range of commodities that may not be all commodities transported by establishments in this NAICS code. There was an additional limitation to the existing data. The NAICS code was restricted to 3- or 4-digits in the data, and the commodities only at the 2-digit SCTG. Overall, the company belongs to the following subsectors:

Sector 42: Wholesale Trade

- ✓ Subsector 423: Merchant Wholesalers, Durable Goods
  - Industry Group 4234: Professional and Commercial Equipment and Supplies Merchant Wholesalers
    - Industry 42343: Computer and Computer Peripheral Equipment and Software Merchant Wholesalers
      - 6 Digit Code(s) NAICS 423430: Computer and Computer Peripheral Equipment and Software Merchant Wholesalers

Sector 31-33: Manufacturing

- ✓ Subsector 334: Computer and Electronic Product Manufacturing
  - Industry Group 3341: Computer and Peripheral Equipment Manufacturing
  - Industry 33411: Computer and Peripheral Equipment Manufacturing
    - 6 Digit Code(s) NAICS 334111: Electronic Computer Manufacturing
    - 6 Digit Code(s) NAICS 334112: Computer Storage Device Manufacturing
    - 6 Digit Code(s) NAICS 334118: Computer Terminal and Other Computer Peripheral Equipment Manufacturing
    - 6 Digit Code(s) NAICS 33411A: Computer terminals and other computer peripheral equipment manufacturing
    - 6 Digit Code(s) NAICS 334220: Broadcast and wireless communications equipment
    - 6 Digit Code(s) NAICS 334290: Other communications equipment manufacturing

As mentioned, the data for these sectors were available at 3- and 4-digits. The team used information about the GDP share by NAICS industries to identify the share of DELL's subsectors from the total NAICS 334: Computer and electronic product manufacturing, and for the NAICS 423: Merchant wholesalers, durable goods. Table 28 shows the GDP shares for NAICS 334 subsectors. The shaded rows indicate DELL's sub-sectors.

Table 28. GDP NAICS 334 Computer and Electronic Product Manufacturing (Millions of Dollars)

						Year				
IO Code	**Description**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
334111	Electronic computer manufacturing	49273	39786	23304	12510	13471	14930	19319	18225	19975
334112	Computer storage device manufacturing	9234	7349	9906	10932	12223	14340	12859	12157	12598
33411A	Computer terminals and other computer peripheral equipment manufacturing	16088	12799	13123	13984	15857	16316	14741	15065	13184
334210	Telephone apparatus manufacturing	9813	9914	10756	10523	9589	10043	9293	10553	8522
334220	Broadcast and wireless communications equipment	44959	35182	31990	33039	30870	31983	30220	27716	26475
334290	Other communications equipment manufacturing	5480	5146	6277	6267	6122	6468	6732	6120	5570
334300	Audio and video equipment manufacturing	5392	4048	4304	5000	2923	2814	2816	3235	9112
33441A	Other electronic component manufacturing	31147	24470	26989	28968	30062	29706	30945	31069	32936
334413	Semiconductor and related device manufacturing	77399	63255	79905	88037	78877	73825	76480	76318	84049
334418	Printed circuit assembly (electronic assembly) manufacturing	23846	18228	21408	21596	19141	20296	19057	20213	22110
334510	Electro medical and electrotherapeutic apparatus manufacturing	25836	23592	25635	25781	29497	29968	29154	31144	31146
334511	Search, detection, and navigation instruments manufacturing	52422	52303	53358	54461	52796	50452	48873	50401	51619
334512	Automatic environmental control manufacturing	3451	2931	3249	3164	3196	3214	3315	3076	3259

IO Code	Description	2008	2009	2010	2011	Year 2012	2013	2014	2015	2016
334513	Industrial process variable instruments manufacturing	11008	9132	9662	10974	12858	12965	13481	12866	13641
334514	Totalizing fluid meter and counting device manufacturing	5942	5180	6050	6756	6964	5982	5565	5482	5774
334515	Electricity and signal testing instruments manufacturing	11989	9060	10111	10828	12892	12092	12050	11700	12176
334516	Analytical laboratory instrument manufacturing	14345	12877	14197	14666	15009	14939	17670	17938	19108
334517	Irradiation apparatus manufacturing	4499	4217	4307	4102	10548	12220	11814	13452	12986
33451A	Watch, clock, and other measuring and controlling device manufacturing	10588	8887	9480	10968	12821	13182	13109	12214	12890
334610	Manufacturing and reproducing magnetic and optical media	6945	5073	4691	3790	3611	3231	3391	3505	3027
	Total	19656	53429	68702	76346	79327	78966	80884	82449	400157
Share of Computer and electronics		**0.177**	**0.169**	**0.125**	**0.099**	**0.207**	**0.120**	**0.123**	**0.119**	**0.114**

Source: (Bureau of Economic Analysis, 2017)

According to the estimates, the share of computers and electronic in NAICS code 334 is about 20% of the GDP. Obviously, the share of DELL is much lower than this since the company is just one of many companies in the industry. Similarly, according to the total value of shipments, Figure 45 shows the 2012 share for different industries in GDP. The industries in the figure include all the NAICS sub-category codes, which means that for the computer and electronic products, the 7% also includes all 334 NAICS code, or even more.

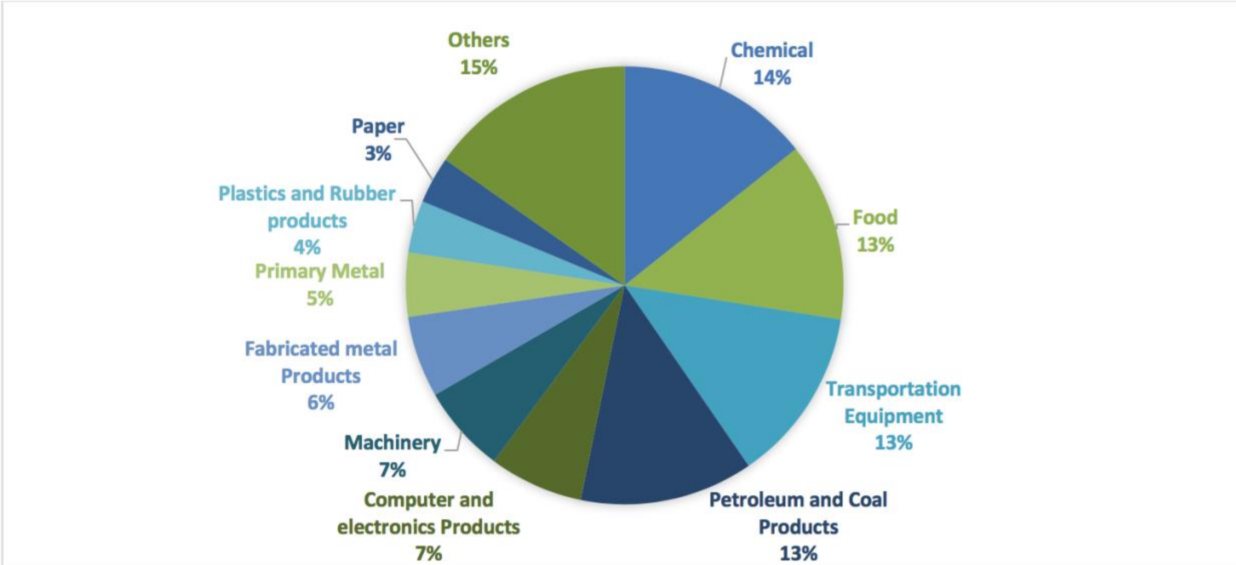


Figure 45. Industries by their Value of Shipments ***(Bureau of Economic Analysis, 2017)***

Considering that the team could not identify NAICS 423 disaggregate data, and the primary NAICS code is 334111, the latter's market shared served as the representative for the analyses.

Food Producer's Supply Chain

For a food producer, the team used Nestlé as a reference. Nestlé is Switzerland's largest company and the world's largest consumer food company, founded by Henri Nestlé in 1867. Today, it is valued at over $76 billion, and employs 253,000 people from more than 70 countries. Nestlé produces more than 15,000 different products. Nestle merged with the Anglo-Swiss Condensed Milk Company in 1905. Nestlé follows the principle of decentralization, which means each country is responsible for the efficient running of its business. Currently, the company operates in over 77 countries with 480 factories. Figure 46 and Figure 47 show simplified flow charts of the company's supply chain worldwide and in the U.S., respectively.

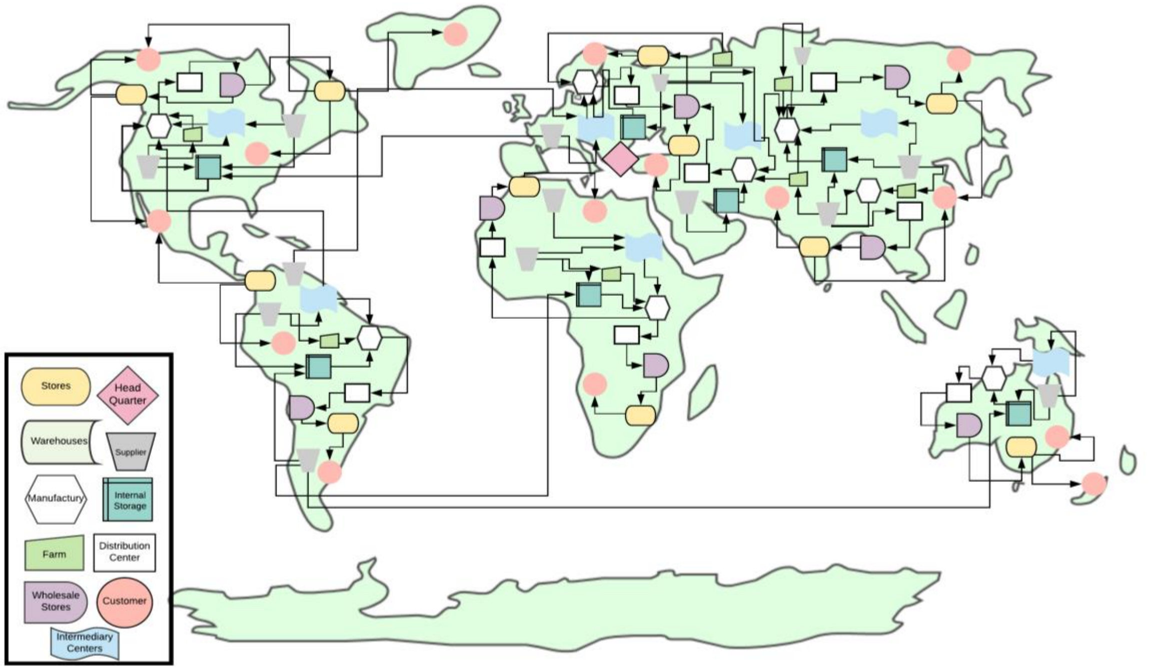


Figure 46. Nestlé World Map

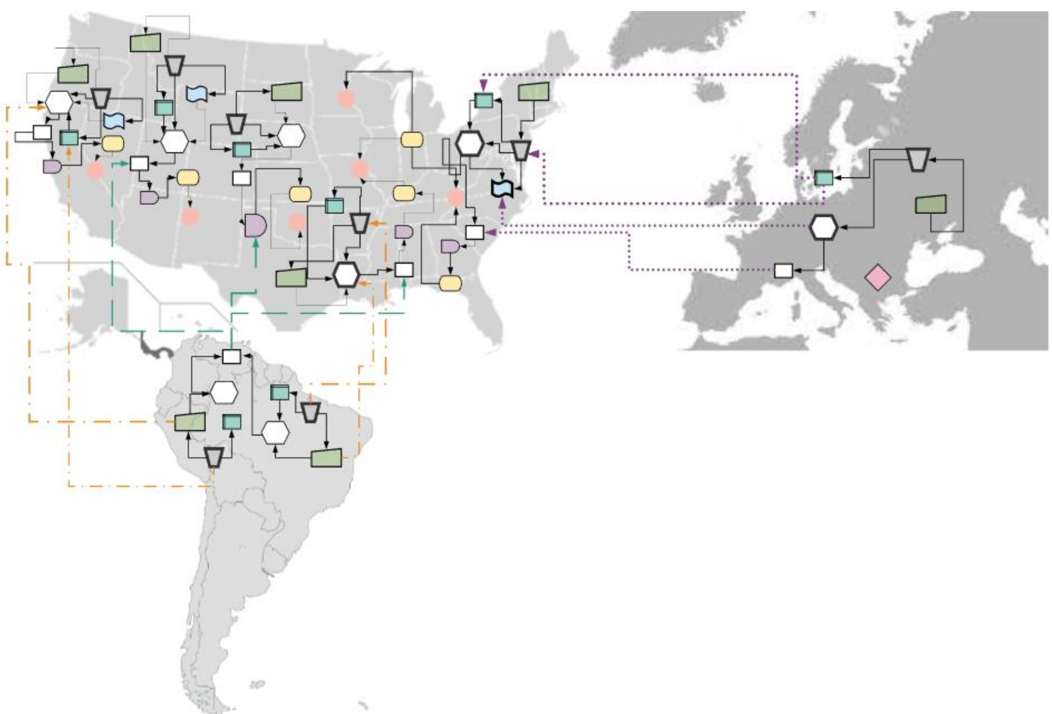


Figure 47. U.S. Map for Nestlé

Moreover, Figure 48 shows a process flow for Nestlé operations along the supply chain. Table 29 provide additional details about the company's supply chain attributes.

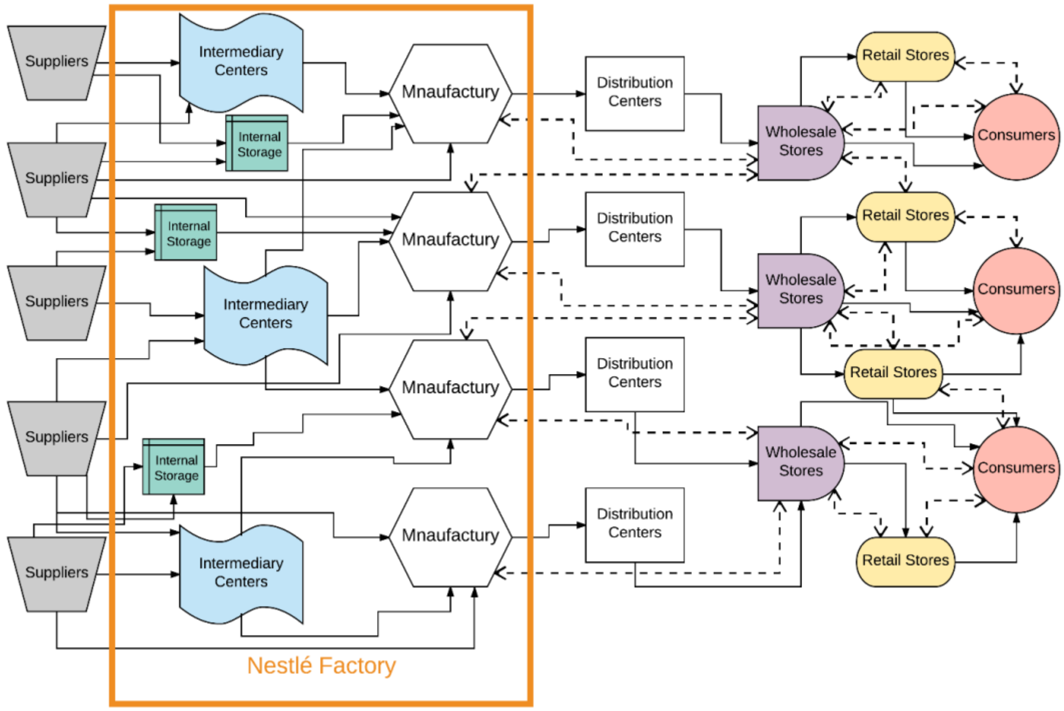


Figure 48. Nestlé Supply Chain

Table 29. Nestlé's Supply Chain Attributes

Procurement Type	Number and type of products procured	Many
	Sourcing type	Multiple (556000 Direct suppliers, and 695000 individual farmers worldwide).
	Suppliers' flexibility (Amounts to be supplied)	Varies among countries and products.
	Supplier lead time and reliability	Low (due to the feature of the products suppliers needs to be very reliable)
	Material's life cycle	By 2017: Identify or update and address the sustainability hotspots for 15 product categories.
		By 2020: Identify, update and address the sustainability hotspots for 20 product categories.
Production Type	Organization of the production process	Flow Shop
	Repetition of operations	Mass Production (447 factories, operates in 194 countries, and employs around 339,000 people.)
	Changeover characteristics	Sequence Dependent
	Bottlenecks in production	Decentralized company (country dependent
	Working time flexibility	Multiple Shifts
Distribution Type	Distribution structure	Two or three stages (highly dependent on the country)
	Pattern of delivery	could be both (mostly cyclic)
	Deployment of transportation means	Transport more than 145 000 tons from 1600 warehouses daily. The equivalent of 274 times around the world each day
	Availability of future demands	Forecasted
	Demand curve	Both seasonal and Static (Depends on the products)
	Product's life cycle	
	Number of product types	Around 15000 types of Products, selling a billion in one day
	Degree of customization	Standard
	Bill of materials (BOM)	Mixture
	Portion of service operations	Tangible Products
Typography of a supply chain	Network Structure	Mixture
	Degree of globalization	Worldwide
	Location of decoupling points	Manufacture-to-order
	Major constraints	Raw Material, Distribution
Integration and coordination	Legal position	Controversy, including a longstanding boycott, over its marketing of infant formula in poor countries.
	Balance of power	Polycentric
	Direction of coordination	Mixture
	Major constraints	All

The company's origins date to the production of condense milk, and milk formula for infants, to the large number of products produced today. In 1882, the company expand its products to the U.S. Since that time, Nestlé grew exponentially around the world selling hundred types of products. The company usually produces in the same market region using fresh ingredients[6]. Table 30 shows the different Nestlé brands in the U.S. today.

Table 30. Nestlé Brands in the U.S.

Baking	Confections	Coffee	Culinary, Chilled and Frozen Foods	Drinks	Ice Cream	Pet Care	Water
Libby's	CarlosV	Nescafe	Hot Pockets	Nesquik	Dreyers	Purina	Acqua Panna
Nestlé Toll House	Nips	Nestle Taster's Choice	Digiorno	Nestea	Haagen-Dazs	Cat Chow	Arrowhead
Nestle La Lechera	Nestle Damak	Nescafe Clasico	Stouffers	Nido	Skinny Cow	Alpo	Deer Park
Nestle Abuelita	Nestle Baby Ruth	Nescafe Dolce Gusto	Reducing Salt	Nestle Mix	Frosty Paws	Felix	Ice Mountain
Nestle Carnation	Raisinets	Nespresso	Lean Cuisine	Nestle Milo	Edys	Dog Chow	Ozarka
	Sno Caps	Nestle Coffee Mate	Cage Free Eggs	Skinny Cow	Drumstick	Pro Plan	Doland Spring
	Skinny Cow		Lean Pockets	Nestle Abuelita	Nestle Ice Cream	Chef Michae's	Resource
	Neste Oh Henry		Removing Artificial Flavors	Ovaltine	Honeybee s	Gourmet	Nestle Waters
	Sweetarts		Tombstone			Fancy Feat	Zephyrhills
	Goobers		Maggi			Beneful	
	Nerds		Jack's			Bakers	
	100 Grand		Healthy Lifestyle			One	
	Nestlé Butter Finger		Filtering The Word "Diet" Out Of Life			Friskies	
	Nestle Cruch		Buitoni				
	Nestle Candy Shop		California Pizza Kitchen				
	Laffy Taffy						

Source: (www.Nestle.com/U.S.)

[6] https://www.nestle.com/aboutus/history/nestle-company-history

Nestlé produces a large range of products therefore using one specific number for its market share may not be as indicative as it is in reality. The team studied its market share in different categories. For example, Table 31, Table 32, and Table 33 show the company's market share for a couple of product categories.

Table 31. Sales of the Leading Vendors of Chocolate Candy in the United States 2017

	Sales in million U.S. dollars
The Hershey Co.	1,855.5
Mars	1,374
Nestlé USA	277.9
Lindt & Sprüngli A.G.	285.3
Ghirardelli Chocolate Co.	215.6

Source: (https://www.statista.com/statistics/190068/leading-chocolate-candy-box-vendors-in-the-united-states-in-2011/)

Table 32. U.S. Market Share of Leading Chocolate Companies 2017

	Market share (in %)
Hershey	44.6
Mars	29.2
Lindt/Ghirardelli/R. Stover	9.2
Nestlé	4.6
All other	12.4

Source: (https://www.statista.com/statistics/238794/market-share-of-the-leading-chocolate-companies-in-the-us/)

Table 33. U.S. Confectionery Market Share in 2017

	Market share (in %)
Hershey	31.3
Mars	28.9
Mondelèz	5.1
Lindt/Ghirardelli/R. Stover	5.2
Nestlé	4.3
Private label	3.1
Ferrara	2.7
All other	19.4

Source: (https://www.statista.com/statistics/294497/us-confectionery-market-share-by-company/)

As a company, Nestlé USA Inc. is in NAICS category 311999; however, like DELL, the company covers a wide range of products in food, beverage and tobacco categories such as 311999, 3132, 312111, 311941, 311514, 3114, 311520, 311412. Table 34 shows a number of highlighted categories referencing the company's types of products.

Table 34. Nestlé NIACS Subcategories

NAICS	Description
311	**Food and beverage and tobacco products**
311111	Dog and cat food manufacturing
311119	Other animal food manufacturing
311210	Flour milling and malt manufacturing
311221	Wet corn milling
31122A	Soybean and other oilseed processing
311225	Fats and oils refining and blending
311230	Breakfast cereal manufacturing
311300	Sugar and confectionery product manufacturing
311410	Frozen food manufacturing
311420	Fruit and vegetable canning, pickling, and drying
31151A	Fluid milk and butter manufacturing
311513	Cheese manufacturing
311514	Dry, condensed, and evaporated dairy product manufacturing
311520	Ice cream and frozen dessert manufacturing
31161A	Animal (except poultry) slaughtering, rendering, and processing
311615	Poultry processing
311700	Seafood product preparation and packaging
311810	Bread and bakery product manufacturing
3118A0	Cookie, cracker, pasta, and tortilla manufacturing
311910	Snack food manufacturing
311920	Coffee and tea manufacturing
311930	Flavoring syrup and concentrate manufacturing
311940	Seasoning and dressing manufacturing
311990	All other food manufacturing
312110	Soft drink and ice manufacturing
312120	Breweries
312130	Wineries
312140	Distilleries
312200	Tobacco product manufacturing
313TT	**Textile mills and textile product mills**
313100	Fiber, yarn, and thread mills
313200	Fabric mills
313300	Textile and fabric finishing and fabric coating mills
314110	Carpet and rug mills
314120	Curtain and linen mills
314900	Other textile product mills
42	**Wholesale trade**
423000	Merchant wholesalers, durable goods
424000	Merchant wholesalers, nondurable goods
425000	Wholesale electronic markets and agents and brokers
42XXXX	Wholesale trade adjustments
423000	Merchant wholesalers, durable goods

Table 35 shows the GDP related to these NIACS codes. Using these values, the team assumes the company's market share of flows from the 18.1% of NAICS 311, and 30.7% of NAICS 313. Sales market share is not available for Nestlé; therefore, the results for Nestlé are representative to all companies such as Nestlé and not the company specifically.

Table 35. GDP by Industry (Millions of Dollars)

IO Code	Description	Year						
		2010	2011	2012	2013	2014	2015	2016
311111	Dog and cat food manufacturing	17866	17845	19388	21109	22077	23992	24084
311119	Other animal food manufacturing	26918	31951	34680	35807	34321	32362	34474
311210	Flour milling and malt manufacturing	16290	19601	19999	20791	21181	19230	19568
311221	Wet corn milling	14442	14493	12578	13411	11368	10208	9999
31122A	Soybean and other oilseed processing	27127	32950	39855	38209	41264	40164	36377
311225	Fats and oils refining and blending	12738	15259	17289	16058	14866	13015	12595
311230	Breakfast cereal manufacturing	10461	10427	10828	11000	9838	9798	9561
311300	Sugar and confectionery product manufacturing	30594	31779	32398	32458	31952	35379	35382
311410	Frozen food manufacturing	26512	27386	30044	30856	31835	32313	33387
311420	Fruit and vegetable canning, pickling, and drying	35695	36103	38912	39996	39929	41409	42917
31151A	Fluid milk and butter manufacturing	35162	38132	37177	38484	41725	38302	38578
311513	Cheese manufacturing	36675	42117	40871	43531	49892	45544	44933
311514	Dry, condensed, and evaporated dairy product manufacturing	14618	17166	19418	20100	22082	18349	18217
311520	Ice cream and frozen dessert manufacturing	7137	6935	6973	7322	7864	7613	7507
31161A	Animal (except poultry) slaughtering, rendering, and processing	123158	140858	140223	142604	155829	152069	146935
311615	Poultry processing	50879	52617	57071	61382	62664	63498	61365
311700	Seafood product preparation and packaging	10042	10480	10582	11067	12187	11776	11537
311810	Bread and bakery product manufacturing	33900	35344	35933	38103	38933	40402	41571
3118A0	Cookie, cracker, pasta, and tortilla manufacturing	24056	25339	27606	27572	28860	28545	29819
311910	Snack food manufacturing	26870	29008	31352	32415	35289	36600	37831
311920	Coffee and tea manufacturing	10347	12465	14091	12931	14553	14113	15683

IO Code	Description	Year						
		2010	2011	2012	2013	2014	2015	2016
311930	Flavoring syrup and concentrate manufacturing	9059	9739	8950	8997	10485	8386	10496
311940	Seasoning and dressing manufacturing	16599	17281	18975	19662	19303	19955	20255
311990	All other food manufacturing	20289	20744	21987	23622	24824	27244	27488
Share of Nestle in 311 Code		0.189	0.180	0.181	0.182	0.179	0.181	0.185
313TT	**Textile mills and textile product mills**							
313100	Fiber, yarn, and thread mills	6935	7594	7803	8104	8208	7955	7885
313200	Fabric mills	14719	15212	14710	15110	14973	14570	14200
313300	Textile and fabric finishing and fabric coating mills	7661	7914	7474	8148	8194	8530	8243
314110	Carpet and rug mills	7745	8870	9036	9373	9848	9539	10149
314120	Curtain and linen mills	3651	3708	3580	3549	4375	4190	4704
314900	Other textile product mills	9161	9140	9145	9665	10603	10766	12336
313100	Fiber, yarn, and thread mills	6935	7594	7803	8104	8208	7955	7885
Share of Nestle in 313 Code		0.323	0.315	0.307	0.301	0.300	0.295	0.289

**Source: (Bureau of Economic Analysis, 2017)*

Apparel/Shoes Manufacturer's Supply Chain

In this case study, the team selected Nike Inc. as an example of an apparel and shoes manufacturer for the illustrative company. Nike Inc. is a worldwide producer of athletic apparel and shoes, and is a recognized multinational corporation. In 2012, Nike had almost 44,000 employees worldwide and its revenue in 2017 was $34.4 billion. Nike has more than 20 brands including shoes, apparel and equipment around the world (https://www.kicksonfire.com/history-of-nike/). Figure 49 and Figure 50 show simplified flow charts for the worldwide and U.S. supply chains. The company has been outsourcing and getting materials from suppliers all around the world.

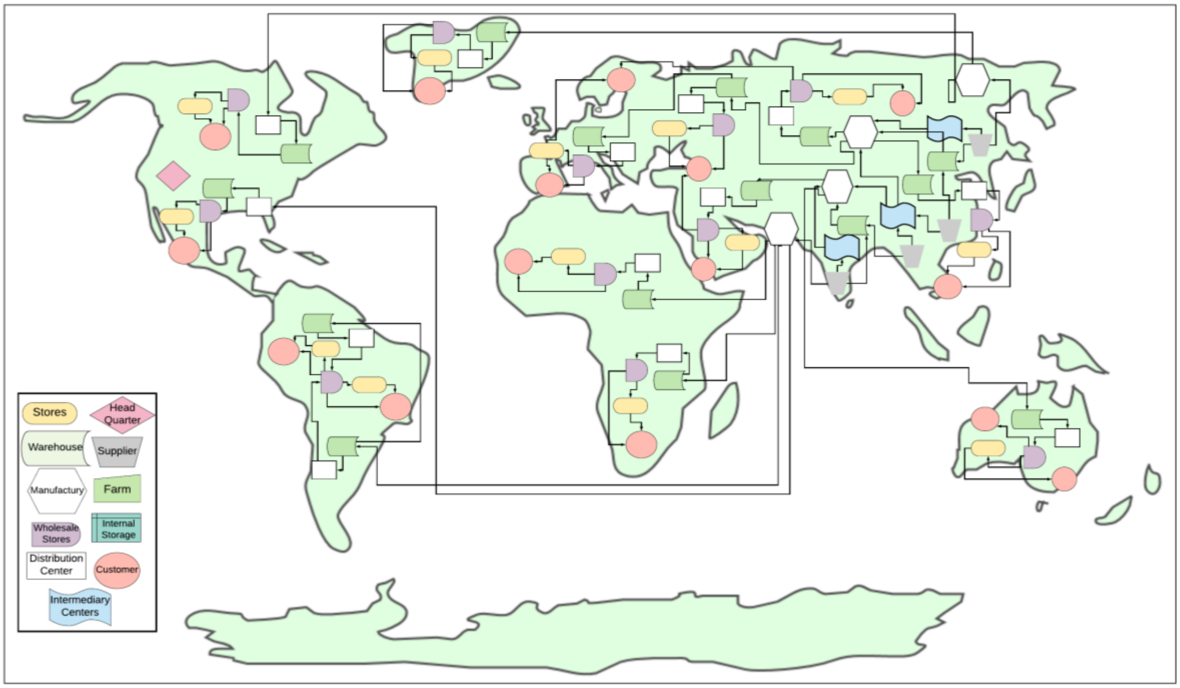


Figure 49. Nike World Map

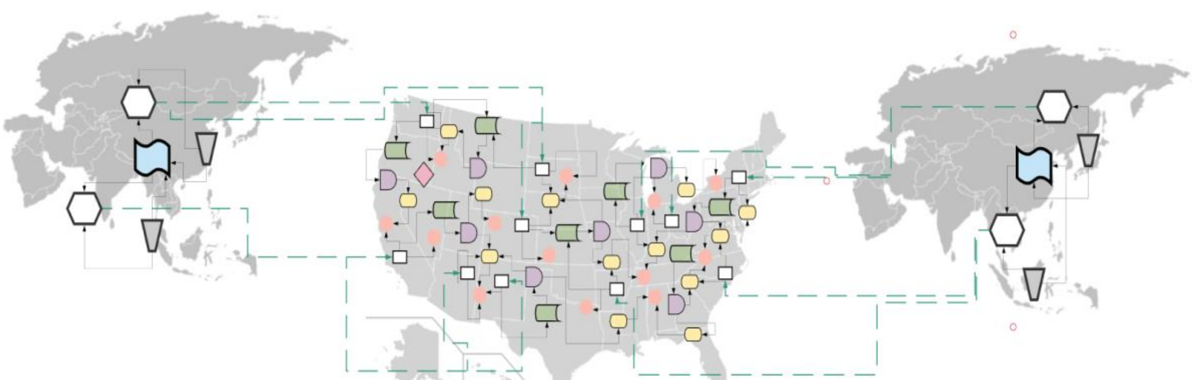


Figure 50. U.S. Map for Nike

Figure 51 and Table 36 show the company's operations along the supply chain, and details about the supply chain structures, respectively. Nike's types of products are different from the previous two case studies. The supply chain is also diverse, as it has production facilities scattered all around the world due to high demand. Suppliers are outsourced and they all agree to terms of service of Nike that mostly emphasize on Green production. After a number of media backlashes, the company has invested efforts to preserve the environment. Distribution and sales mostly happen through third parties; however, there are many Nike stores, which are under direct supervision of the company[7].

[7] https://www.kicksonfire.com/history-of-nike/)

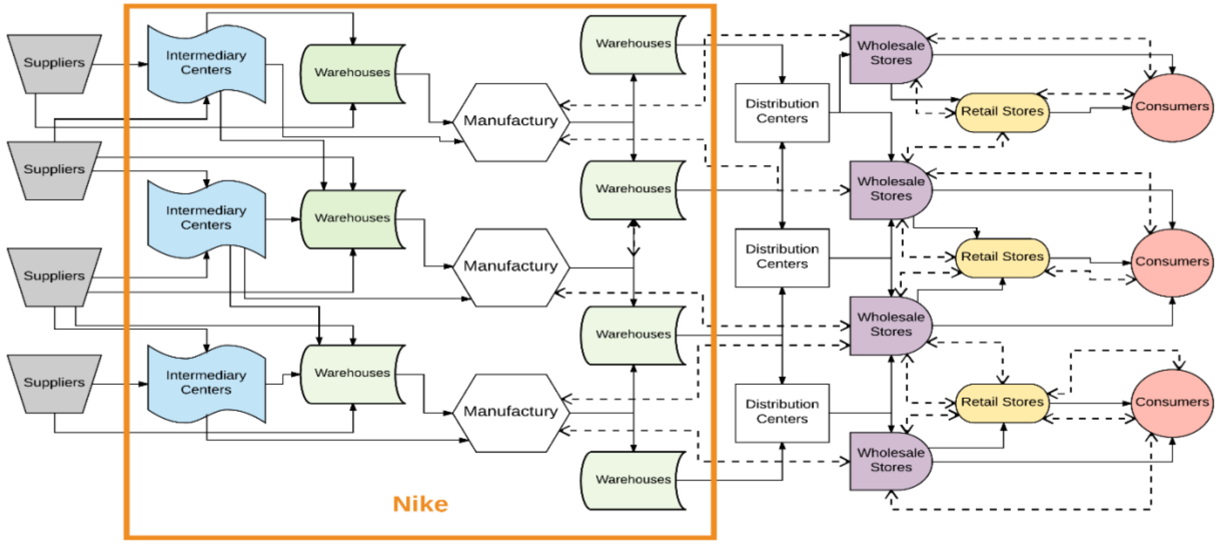


Figure 51. Nike Supply Chain

Table 36. Nike's Supply Chain Structure

Procurement Type	Number and type of products procured	120,000,000 Nike shoes each year (Annual sale of 32.46 billion$ in 2016)
	Sourcing type	Multiple (Rubber, Fabric, etc.)
	Suppliers'	Multiple (Rubber, Fabric, etc.)
	Supplier lead time and reliability	Long (Less reliable)
	Material's life cycle	Long
Production Type	Organization of the production process	Flow shop (it mostly depends due to the different factories and products)
	Repetition of operations	Mass Production
	Changeover characteristics	Sequence Dependent
	Bottlenecks in production	Raw Materials (Inventory control…)
	Working time flexibility	Multiple Shifts
Distribution Type	Distribution structure	Three stage (out-sourced)
	Pattern of delivery	Cyclic
	Deployment of transportation means	Routes: Standards
		Capacity: Limited
		Loading Requirements: Applied for Truck and air Transportation
	Availability of future demands	Forecasted
	Demand curve	Static (Due to the historical data and huge network of distributers)
	Product's life cycle	-
	Number of product types	500000 types of products
	Degree of customization	Highly specific
	Bill of materials (BOM)	Mixture
	Portion of service operations	Tangible Product
Typography of a supply chain	Network Structure	Mixture
	Degree of globalization	Worldwide
	Location of decoupling points	Engineer-to-order
	Major constraints	Inventory Control
Integration and coordination	Legal position	Inter-organizational
	Balance of power	Dominant Partner (Oregon Headquarter)
	Direction of coordination	Vertical integration
	Major constraints	All

Table 37 and Table 38 show the historic and forecasted company's market share in the footwear and apparel industry segments. The data for footwear is worldwide, whereas the apparel share data is for the U.S.

Table 37. Forecast of Nike's Global Market Share in Athletic Footwear from 2011 to 2024

	Global market share
2011	16.77
2012	18.39
2013	19.66
2014	22.49
2015	23.95
2016	25.01
2017	26.01
2018	27.51
2019	29.01
2020	30.51
2021	32.01
2022	33.01
2023	34.01
2024	35.01

Source:(https://www.statista.com/statistics/216821/forecast-for-nikes-global-market-share-in-athletic-footwear-until-2017/)

Table 38. Market Share of the Leading Brand Apparel Companies in the United States in 2016

Apparel Company	Market share (in %)
Gap	4
Wal-Mart	3.5
Nike	2.7
Hanesbrands	2.5
L Brands	2.3
VF	2.1
PVH	2.1
Under Armour	1.7
Target	1.7
Forever 21	1.6

Source: (https://www.statista.com/statistics/734460/leading-brand-apparel-companies-market-share-us/)

As a company, Nike is in the NAICS 316210 industry category; however, like the other case studies, the wide range of products come under different NAICS codes. Unlike to NAICS code 311, apparel-manufacturing code related to Nike "339" only has eleven subsections (see Table 39).

Table 39. NICS 339 Subcategories

NAICS	Description
339	**Miscellaneous manufacturing**
339112	Surgical and medical instrument manufacturing
339113	Surgical appliance and supplies manufacturing
339114	Dental equipment and supplies manufacturing
339115	Ophthalmic goods manufacturing
339116	Dental laboratories
339910	Jewelry and silverware manufacturing
339920	Sporting and athletic goods manufacturing
339930	Doll, toy, and game manufacturing
339940	Office supplies (except paper) manufacturing
339950	Sign manufacturing
339990	All other miscellaneous manufacturing

Table 40 shows the GDP shares for NAICS 339.

Table 40. GDP by Industry (Millions of Dollars)

IO Code	Description	Year						
		2010	2011	2012	2013	2014	2015	2016
339112	Surgical and medical instrument manufacturing	36321	37206	37498	40479	38429	39371	36402
339113	Surgical appliance and supplies manufacturing	38042	37475	36926	40287	37563	37810	35608
339114	Dental equipment and supplies manufacturing	4924	5200	4923	5237	4337	5015	4296
339115	Ophthalmic goods manufacturing	4742	5730	6772	7167	6887	6810	6344
339116	Dental laboratories	4885	4827	5410	5899	5694	5432	5340
339910	Jewelry and silverware manufacturing	8677	8123	7830	8185	9088	8359	8289
339920	Sporting and athletic goods manufacturing	9995	10126	10036	10281	10266	10898	10391
339930	Doll, toy, and game manufacturing	2720	2561	1700	1518	1763	1902	1699
339940	Office supplies (except paper) manufacturing	4186	4229	2674	2599	2903	3122	3034
339950	Sign manufacturing	11730	11926	11965	12758	13765	15053	13746
339990	All other miscellaneous manufacturing	28094	29491	28468	28643	29730	32797	29128
Share of Nike related code in NAICS 339		0.064	0.064	0.065	0.063	0.063	0.065	0.067

Source: (Bureau of Economic Analysis, 2017)

The table shows that the share of Sport and athletic goods manufacturing in NIACS 339 is 6.5%, which relates to Nike's products; however, 6.5% is reflecting all the sports goods companies and industries (in terms of Value) and the share of NIKE is not yet determined. Because Nike is a very large enterprise and covers varieties of products, there is a specific NAICS code for its Footwear manufacturing, which is 316210 (https://www.manta.com/c/mmn5xvn/nike-usa-inc, n.d.). However, there is no share information for this specific code. The team considered the general NAICS industry 316 (see Table 41). Table 42 shows the GDP for NAICS 339. In general, all companies like Nike have a share in terms of value of the goods of 6.5% for NAICS 339 and 2.34% for NAICS 315AL. These shares are for all the companies that are producing sportswear and goods and not NIKE itself. In order to have a better sense of NIKE's real share, the team considered its market share among other sportswear companies, which in the U.S. was 48% in 2014.

Table 41. NICS 315AL Subcategories

315AL	Apparel and leather and allied products
315000	Apparel manufacturing
316000	Leather and allied product manufacturing

Table 42. GDP by Industry (Millions of Dollars)

IO Code	Description	Year						
		2010	2011	2012	2013	2014	2015	2016
339112	Surgical and medical instrument manufacturing	36321	37206	37498	40479	38429	39371	36402
339113	Surgical appliance and supplies manufacturing	38042	37475	36926	40287	37563	37810	35608
	Share of Nike related code in NAICS 315AL	0.313	0.312	0.234	0.235	0.215	0.235	0.175

Source: (Bureau of Economic Analysis, 2017)

Company's Summary and LCA Analyses

The previous sections showed important information to help determine the market share for these companies. As discussed, for some of these, the research team could not identify the specific market share, thus the results may correspond to industry level representative companies in the electronics, footwear and apparel, and consumer goods. Table 43 summarizes the various shares, at the company, and at the industry level considering the types of sub-sectors. For example, the 48% Nike market share corresponds to the available information about sneakers sales in the U.S. Moreover, Table 43 shows the commodity types associated to the shipments of the representative companies. These values help filter the shipments from the industry level shipments provided by the CFS-PUM. The team used the data to estimate the ton-kms per mode and allocated them to the different companies.

Table 43. Summary Market Shares and Commodities Associated to the Companies

	DELL	Nestlé		Nike	
Market Share	21.30%	20%		48%	
	Industry Shares				
NAICS Code	334	311	313	339	316
% share	20.70%	18.10%	30.70%	6.50%	23.40%
	SCTG Commodities				
	35		29	1	6
	38		30	2	7
				3	8
				4	9
				5	

Source: (https://www.statista.com/)

Figure 52 shows the total inbound and outbound estimated shipments for these companies or representative businesses. The majority of the flows use for-hire trucks and parcel. Nestlé transports around 30% of the shipments using rail, while DELL uses air for 15 to 25% of the shipments.

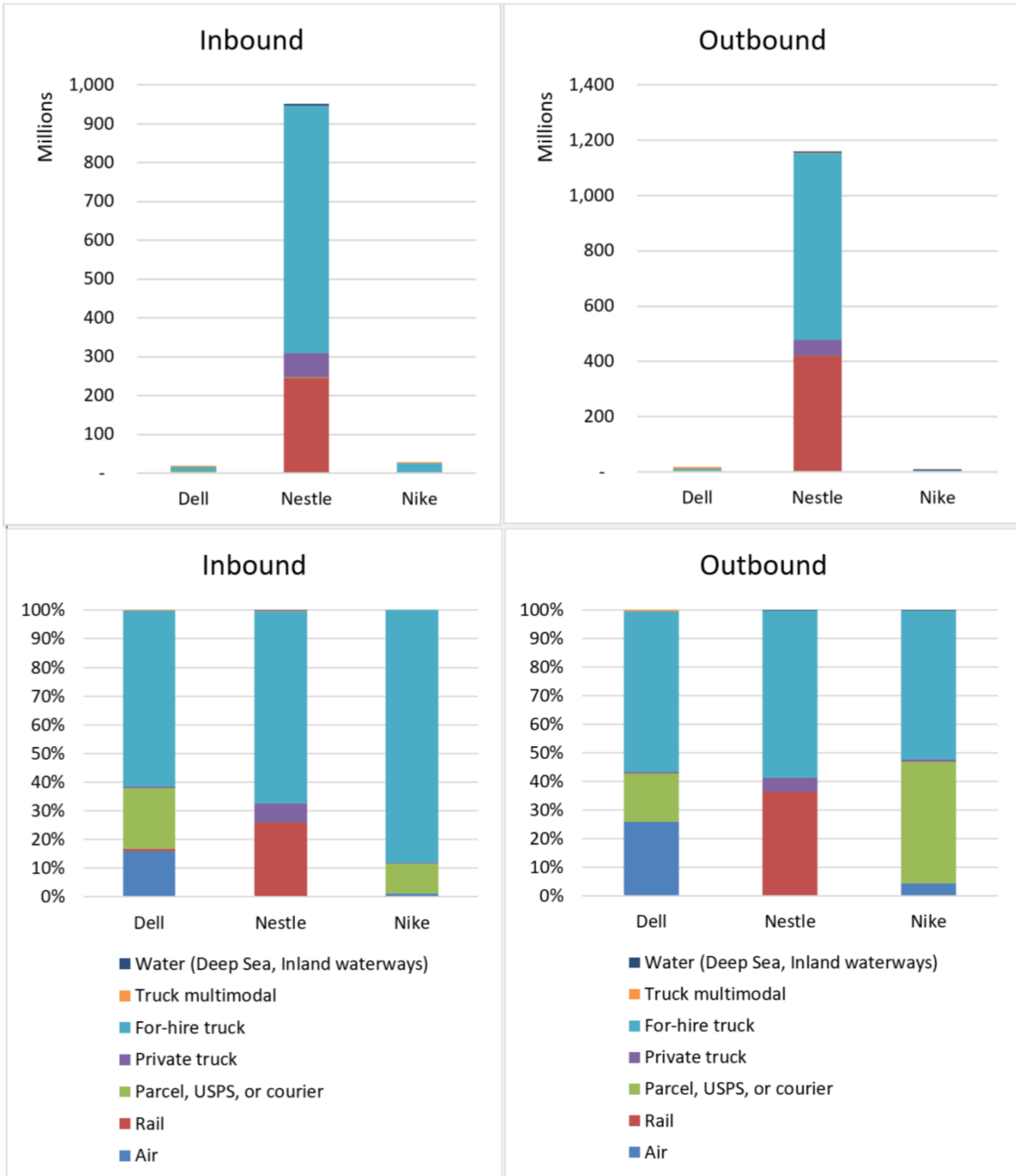


Figure 52. Inbound and Outbound Total Shipments per Mode (top), and Mode Share (bottom)

Figure 53 shows the average per ton-kms TRACI impacts for the various companies. These results are consistent with the mode shares. As expected, the higher share of rail shipments translates in reduced per unit (ton-km) for Nestlé. Moreover, the use of air shipments by DELL increases the impacts in, for instance, the global warming potential. Nike's use of mostly trucking is reflected in the overall higher impacts per unit transported. These results are for comparative purposes only for companies in these sectors and may not reflect the true impacts generated by these companies because of data and modeling limitations.

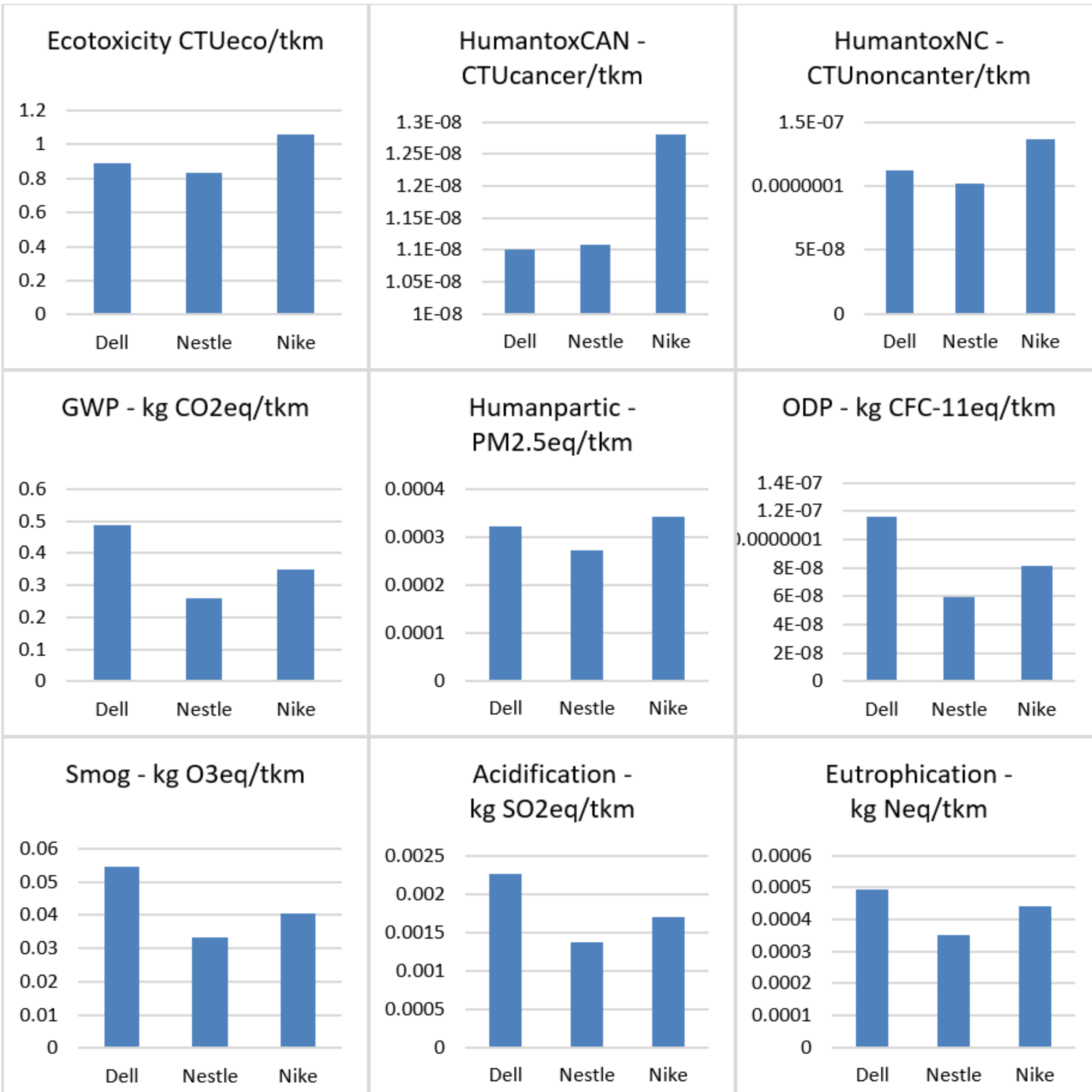


Figure 53. Average TRACI Impact per Ton-km) for each Company

IX. Conclusions

During the last few years, the freight transportation system has received increased attention from researchers, practitioners, and public agencies. Last year, the Governor's Office released the CSFAP that seeks to improve freight efficiency in the State. The CSFAP will assess freight efficiency by changes in the CO_2eq emissions per contribution to the economy from the transportation sector defined as NAICS 48 and 49 (transportation and warehousing services minus passenger transport). The research reported in this document developed a framework to conceptualize the freight system and assess the impacts (Freight System Conceptualization and Impact Assessment Framework). Specifically, the framework is a commodity-based framework that assesses the environmental impacts of freight flows. The framework can aid decision-making and provides a base description of the impacts resulting from inbound and outbound freight flows for a number of industry sectors (not only NAICS 48-49), commodity groups, and modes of transport.

The authors developed the framework using LCA as the basis. During the process, the team identified a number of existing data and modeling limitations to implement such a framework at a larger scale. In addition to the limitations discussed in the document, the team identified a shortcoming of efficiency measures focusing on specific industry sectors and stakeholders. Discussing the relationship between the different stakeholders in the freight sector, Jaller et al. (2016a) argue that in many sectors, carrier companies and other supporting facilities (NAICS 48 and 49), do not have the necessary market power to affect freight and logistics decisions. These decisions are ultimately the ones that determine the shipment sizes, distances, frequency of distribution, and mode of transport, among others. Essentially, these ones affect the efficiency of the freight transportation system. In general, carrier companies are just a conduit between the economic agents responsible for those decisions. Therefore, measuring freight efficiency on the carriers (and warehouses) operations does not necessarily translate into overall freight system improvements. Given the market forces and other system constraints, these agents may only have a limited number of options to improve their operations (movement of the cargo). These are, in many cases, only related to technological improvements (changes in drivetrain, powertrain, fuel pathway), and some logistics changes to optimize routes, and ecological driving type of strategies. However, these might only optimize parts of the freight supply chain (i.e., transportation component) and do not necessarily achieve a system optimum. Moreover, there may be unintended consequences to specific stakeholders resulting from the selection of strategies by a sub-set of the economic agents. These impacts are not fully understood. For instance, the research evidenced a lack of tools to assess the impacts of freight vehicles on the infrastructure, and adequate allocation criteria for the different segments of the freight industry and the types of infrastructure.

The analyses also show the need for additional research to understand and assess responsibility for the impacts generated by freight movements. Two different perspectives could result in different analyses for the State flows LCA estimates. For example, the results per industry show the impact of the flows generated by the establishments form these industries; however, the vehicles and carrier companies in NAICS 48 (with the exception of private trucks, which are mostly operated by the company) generate these impacts. The emerging questions is about how to allocate the impacts, should they be allocated to the generating company or the hired carrier? Moreover, the results show that only concentrating in NAICS 48-49 may not include the ~10% impacts from the flows transported by the establishments, which are not included in the NAICS 48 flows (see Table 44).

Table 44. Comparative Impacts per Mode for All California Flows

	Ecotoxicity	HumantoxCAN	HumantoxNC	GWP	Humanpartic	ODP	Smog	Acidification	Eutrophication
Air	0.3%	0.3%	0.2%	2.5%	0.6%	2.7%	2.1%	2.1%	1.3%
Rail	6.6%	15.6%	2.8%	7.3%	10.0%	6.2%	16.2%	13.8%	10.9%
Parcel, USPS, or courier	1.8%	1.6%	2.3%	2.0%	2.0%	2.1%	1.8%	1.8%	1.8%
Private truck	**10.6%**	**9.6%**	**11.1%**	**10.3%**	**10.2%**	**10.4%**	**9.3%**	**9.6%**	**10.0%**
For-hire truck	80.4%	72.7%	83.5%	77.7%	77.0%	78.5%	70.4%	72.5%	75.7%
Truck multimodal	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
Water (Deep Sea, Inland waterways)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Data availability also limits the applicability of the framework to strategies related to mode choice, and if LCIs are developed, to vehicle technology applications. For example, Table 45 compares the LCIs for the different vehicles and modes with the generic truck vehicle used in the analyses. Transporting all cargo using smaller vehicles requires a larger number of vehicles, thus increasing the overall impacts. The table also shows the impact of mode shift between truck and rail. Changing from large vehicles to rail could reduce impacts significantly, while using aircraft would negatively influence some of the categories.

Table 45. Comparative Assessment of Impacts Across Vehicle Types and Modes

		Lorry			Rail	Aircraft
TRACI Category	Unit	Small (3.5-7 tonnes)	Medium (7.5-16 tonnes)	Large (16-32 tonnes)		
Ecotoxicity	CTUeco/tkm	68	-41	-60	-86	-70
HumantoxCAN	CTUcancer/tkm	74	-42	-69	-63	-60
HumantoxNC	CTUnoncancer/tkm	48	-30	-43	-94	-81
GWP	kg CO_2 eq/tkm	59	-33	-58	-84	215
Humanpartic	PM2.5eq/tkm	55	-32	-51	-77	-20
ODP	kg CFC-11 eq/tkm	57	-32	-55	-86	232
Smog	kg O3 eq/tkm	59	-33	-54	-60	189
Accidification	kg SO2 eq/tkm	60	-34	-56	-67	181
Eutrophication	kg N eq/tkm	67	-38	-63	-75	68

Note: The values are the percentage changes (percentage increase or decrease) with respect to the base vehicle used for the analyses. This is a generic vehicle resulting from the weighted average of the impacts across vehicle sizes, and emission standards using EMFAC vehicle population mix.

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ANNEX

Annex A: LCA Databases and Tools

Life Cycle Assessment is a data driven methodology and lack of sufficient data have been a major limitation in the implementing process. Although various software and databases exist, some of them are proprietary and offer different levels of aggregation and geographic scope (Burritt et al., 2002; Hollerud et al., 2017). Some of these databases and tools provide LCA mapping, metrics and carbon footprint estimates often used in the first stages of LCA projects which are boundary and goal definition (Favara et al., 2011; Hollerud et al., 2017). Table 46 summarizes the most commonly used databases and tools.

Table 46. Summary of Databases and Tools

	Name	Description
Databases	U.S. Life Cycle Inventory (USLCI)	The National Renewable Energy Laboratory (NREL) and the Athena Institute, under the direction of the U.S. Department of Energy released the first version of the USLCI database in 2003 This database went through different stages of development by using surveys from stakeholders, their use of database, the nature of their organization and their need. Instead of spreadsheets for datasets, USLCI provides different modeling and process entries to represent data, which is more holistic in terms of the origin of the data and their modeling process. Elementary flows and unit processes are the entries in the database. The USLCI is applicable only for LCA studies inside the U.S. due to the U.S government support and sponsorship.
	CPM LCA	Developed in 1996 by the Swedish Life Cycle Assessment Center, and maintained by Chalmers University of Technology until 2006. Only provides data for LCIA and specific projects despite the LCA name. Data quality categories are sufficient, acceptable, and unsatisfying. Moreover, the data are provided with an expiration data (window of data validity), and for: Sustainable Production Information Network for the Environment (SPINE), ILCD compatible with ISO 14040/44, and formatted as an ISO/TS 14048 report. There are 745 entries in the CPM LCA Database, 612 process entries and 133 transportation entries
	EUROpean Life Cycle (ELCD)	The EUROpean Platform on LCA released the first ELCD in 2006 to provide LCA data for the EUROpean market. The data complies with entry-level requirements of the Life Cycle Data Network (LCDN) to ensure data quality, documentation level, and methodological consistency.
Modeling Tools	Ecoinvent 3.0	The ETH Domain and Swiss Federal Offices released this comprehensive methodology in 2003 (Ecoinvent 1.0). Version 3.0, released in 2013, includes a LCI and LCIA database.
	GaBi	Full service-LCA based software program (performs LCA and provides data).
	SimaPro	Similar to GaBi, developed by PRé Sustainability is both an LCA modeling tool and a database. SimaPro is a comprehensive tool, which incorporates different inputs and outputs. Outputs are mostly in forms of three categories: air emission, water emission, and finally soil emissions. SimaPro is based on ISO 14000 standards. Furthermore, it incorporates databases like Ecoinvent, USLCI, ELCD, and Agri-impression for inventory analysis and impact assessment methodologies

Source: Adapted from Hollerud et al. (2017)

Annex B: LCIA Methods

There are a number of tools specifically developed to conduct LCIA studies. This annex provides examples of LCIA methods building on the summary conducted by the Life Cycle Initiative (www.lifecycleinitiative.org) through its review (Life Cycle Initiative, 2003).

Ecological Scarcity Method (Eco points 2006)

This methodology uses eco-factor to incorporate a comparative weighting system called as ecological scarcity, or Swiss Eco scarcity or Swiss Eco points. The method applies different weighting factors to air, water, and ground emissions as well as for energy usage. The eco-factors are location sensitive and developed for the Switzerland area, considering two types of annual flows: actual annual flow which is practically current flows and the critical flows in that area (Swart et al., 2015). The method uses a reference framework to optimize flows regarding each individual product or process. There are similarities between this methodology and the ecological scarcity method in terms of classification and characterization approaches (Swart et al., 2015).

The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)

The U.S. Environmental Protection Agency developed this impact assessment methodology to indicate the environmental assessment as a midpoint evaluation for the US as a whole or per state. Developing this methodology was important in terms of its consistency with previous impact categories introduced by EPA. Human health factors regarding both cancer and non-caner categories are based on previous risk assessment conducted by EPA. (Bare, 2011). See http://epa.gov/ORD/NRMRL/std/sab/iam_traci.htm.

MEEuP

This methodology developed on behalf of the EUROpean Commission (DG Enterprise) determines which energy-using products are qualified for certain energy screening, while adopting a life cycle approach. This methodology incorporates inventory analysis as well as a specific impact assessment in order to support Eco-design of the products (Kemna et al., 2005).

EPS 2000

Conceived as an end-point impact assessment method, developed in the 1990s and updated through 2000, the EPS 2000 is a midpoint-endpoint model like LIME. The model was a progressive approach for its time to calculate all the impacts in monetary order using willingness to pay (WTP). The model considers the uncertainties regarding the environmental assessment using Monte Carlo analysis(Steen, 1999). See http://eps.esa.chalmers.se/.

IMPACT 2002+

This methodology accounts for both midpoints and endpoints. In this methodology, all types of flows categories link 14 midpoints to 4 final damage categories. This method was consistent with LCIA scopes at the time. However, there were many changes in terms of the final damages regarding the contaminants released to the food supplies and the exposure of agricultural and livestock, as well as the aquatic toxicity (Jolliet and Fantke, 2015) (Figure 54). See http://www.epfl.ch/impact.

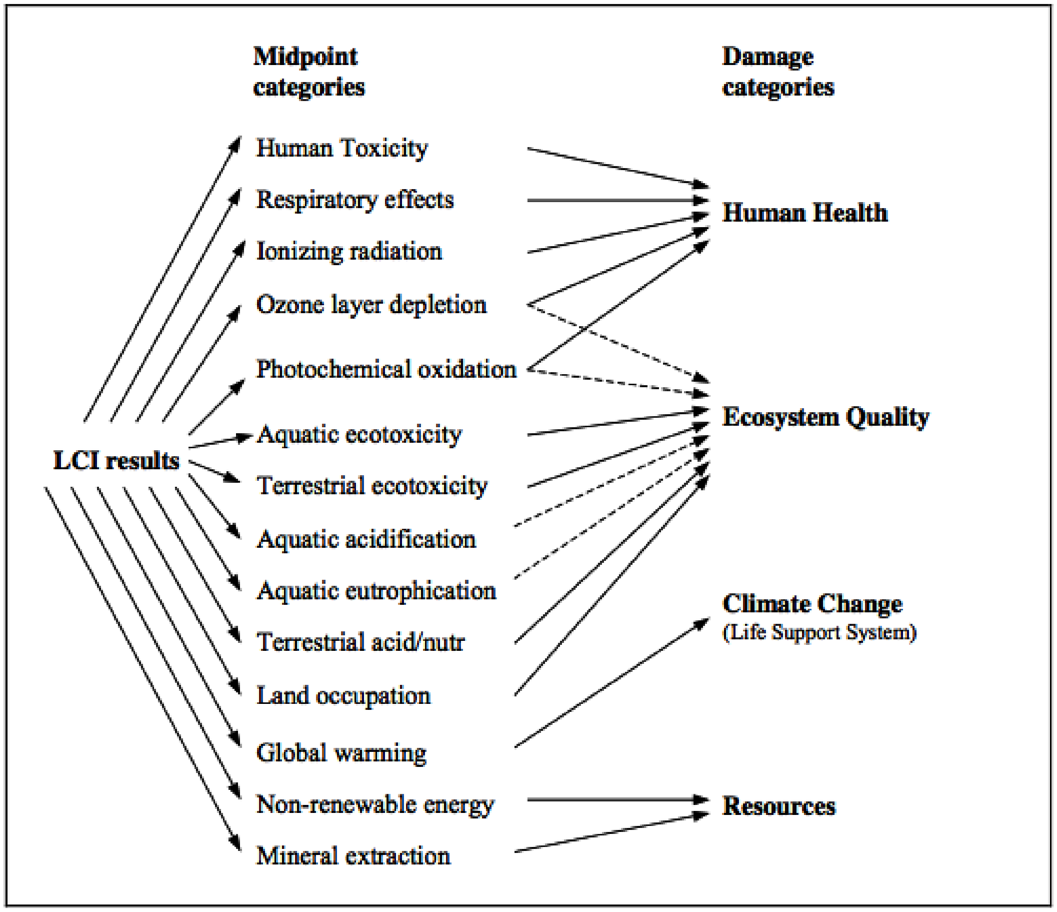

Figure 54. IMPACT 2002+ Methodology Impact Category *(Jolliet and Fantke, 2015)*

CML 2002

This method indicates a midpoint indicator to evaluate environmental impacts. The method operationalizes the ISO14040 series of Standards with regard to its normalization methods. However, the method does not fully incorporate weighting (Guinée et al., 2001) (Figure 55).

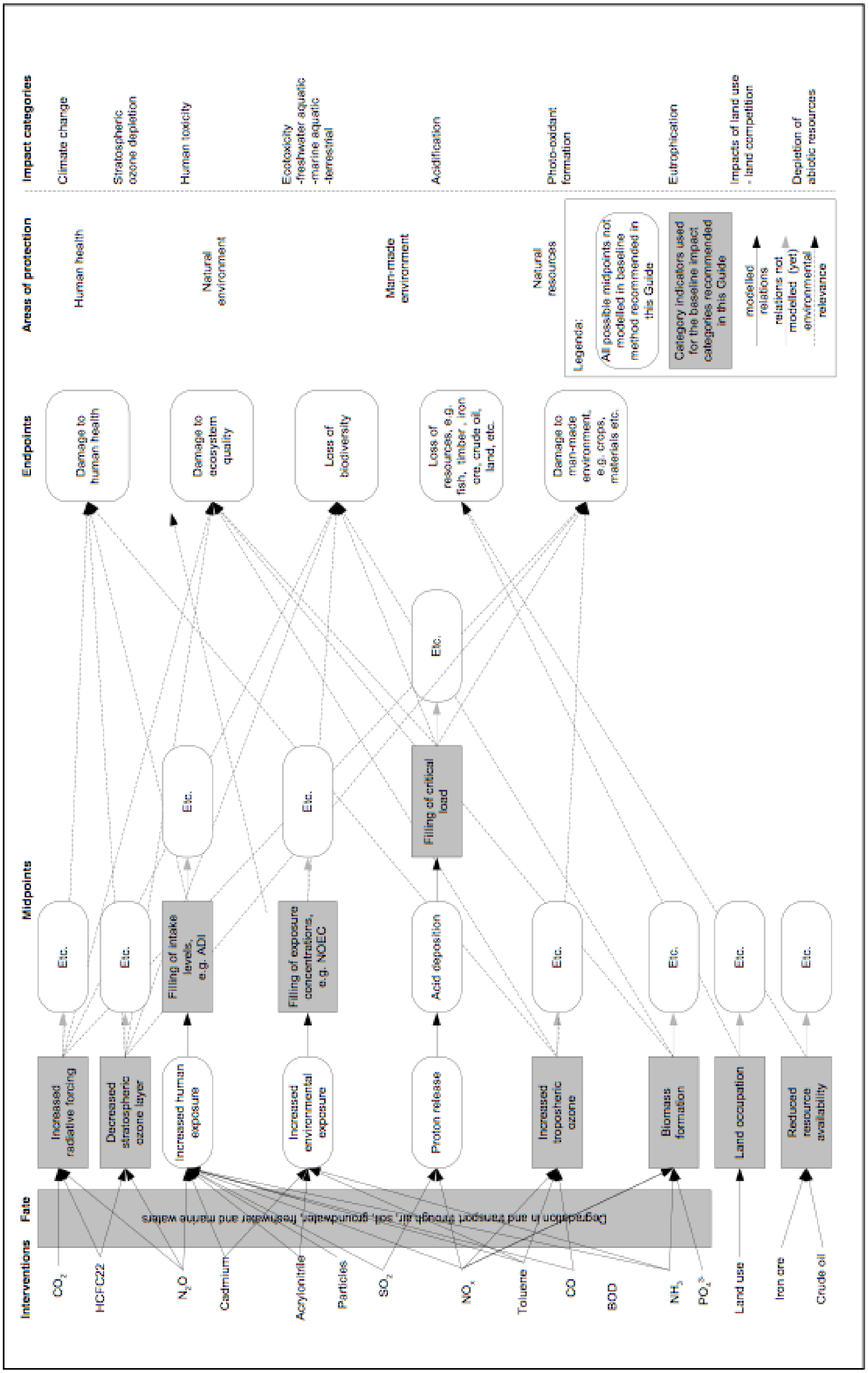

Figure 55. CML Methodology Impact Categories (de Haes et al., 1999)

Eco-indicator 99

Following the CML 2002, the Eco-indicator model was developed with a hope to simplify the interpretation and adding a weighting method to the assessment. This method had the ability to calculate the single point scores. The Eco-indicator 99 was the starting point for the development of the LIME and the Impact 2002 methods (Goedkoop and Spriensma, 2000) (Figure 56). See http://www.pre.nl/eco-indicator99/.

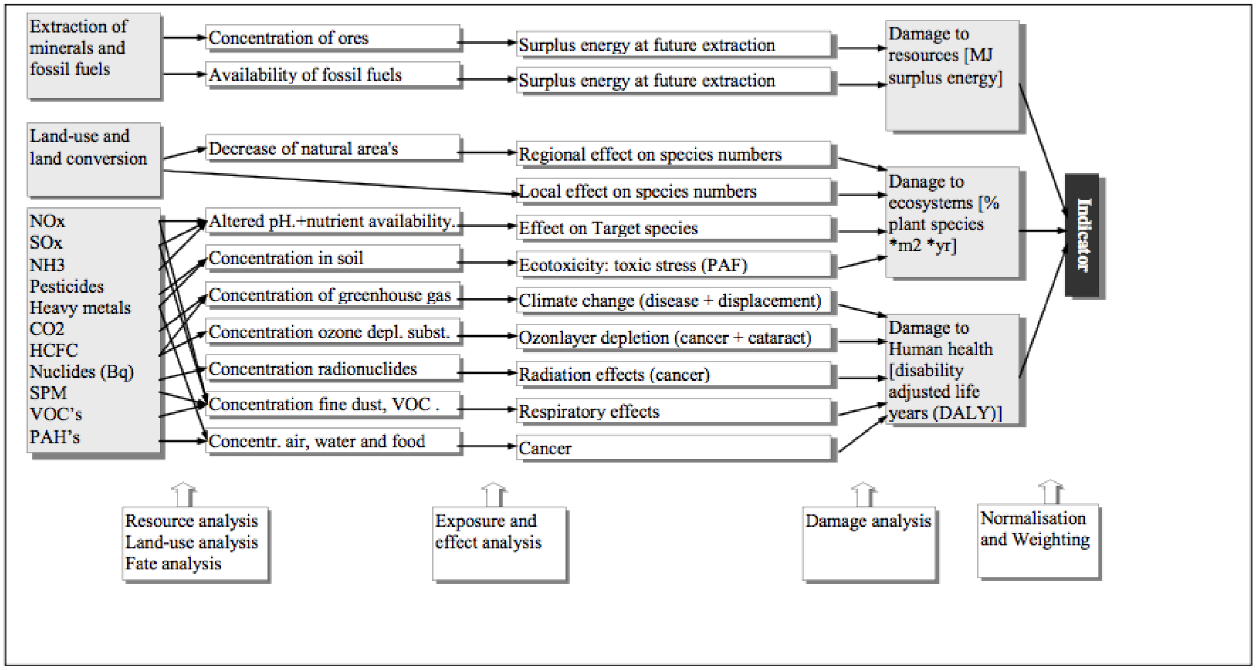

Figure 56. Eco-indicator 99 Methodology Impact Categories *(Goedkoop et al., 1998)*

LIME

The Lime method, developed and widely used in Japan, builds on various inputs from experts from around the world (Itsubo et al., 2012) (Figure 57). See http://www.jemai.or.jp/lcaforum/index.cfm.

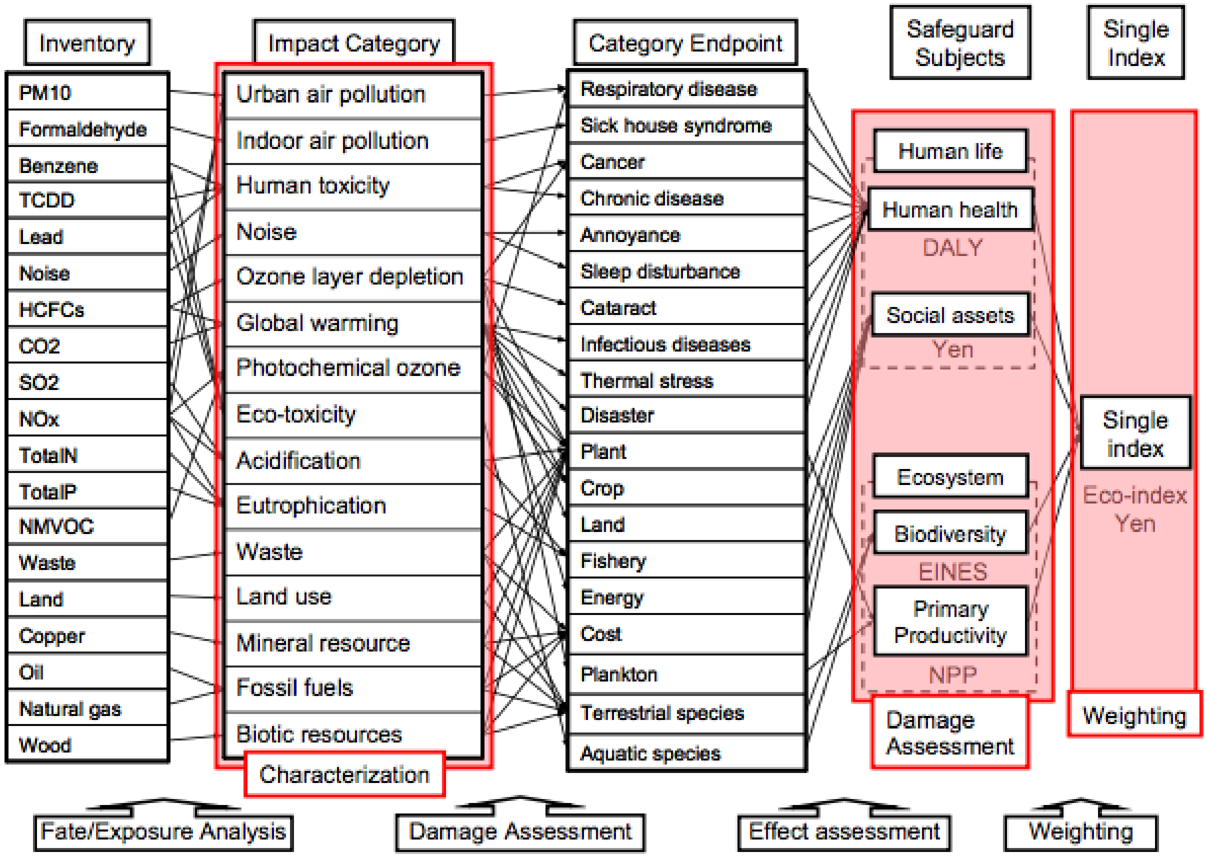

Figure 57. LIME Methodology Impact Category *(Itsubo et al., 2012)*

LUCAS

Following the development of TRACI and IMPACT 2002+, LUCAS was developed in 2005 to address the impact assessment methodology in Canada (Toffoletto et al., 2007) (Figure 58).

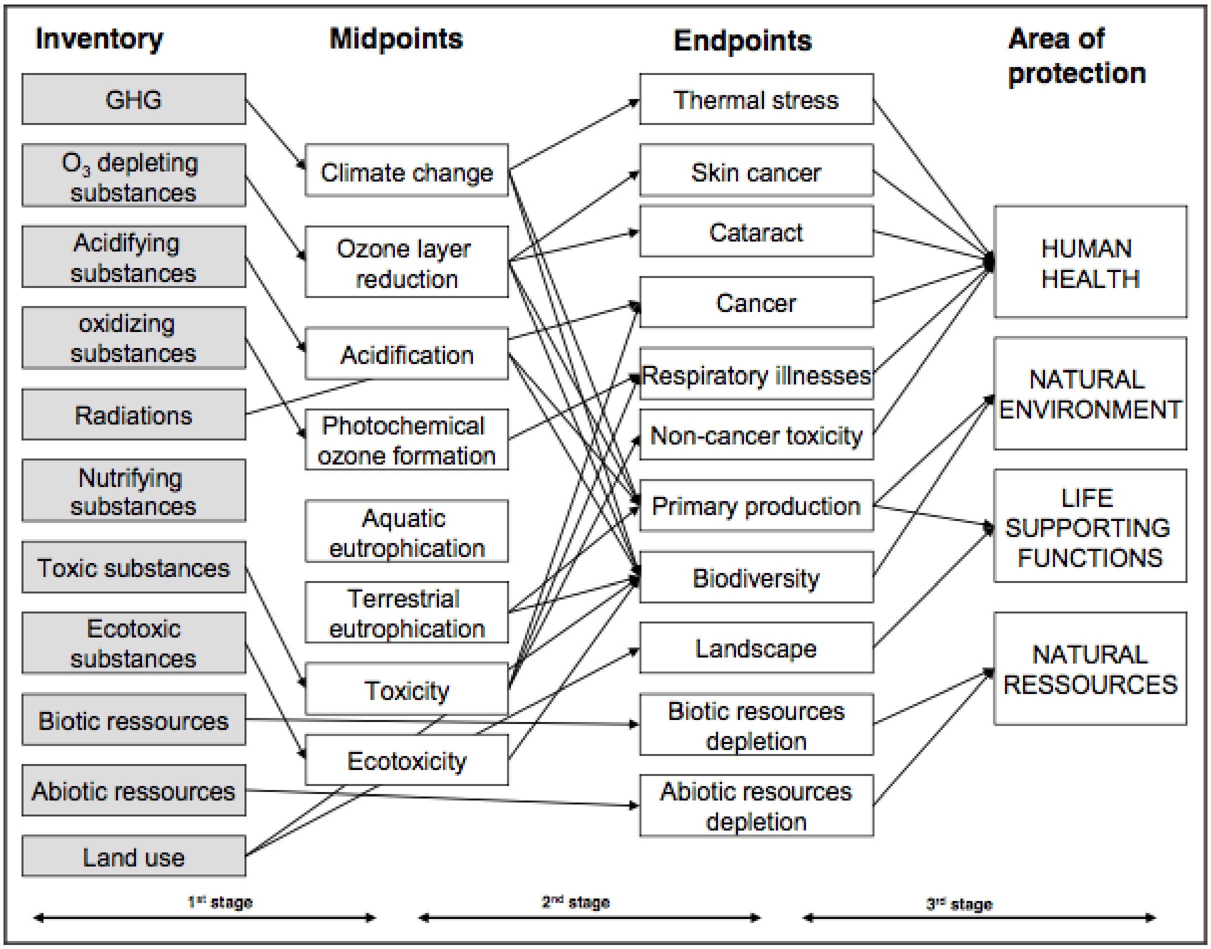

Figure 58. LUCAS Methodology Impact Category *(Toffoletto et al., 2007)*

ReCiPe

This method is a well-developed mythology encompassing both Eco-Indictor 99 and CML 2002 in terms of aggregation of both of the midpoint and endpoint assessment. The method is not published as a single document, but most impact categories have been described in peer reviewed publications (Goedkoop et al., 2009) (Figure 59).

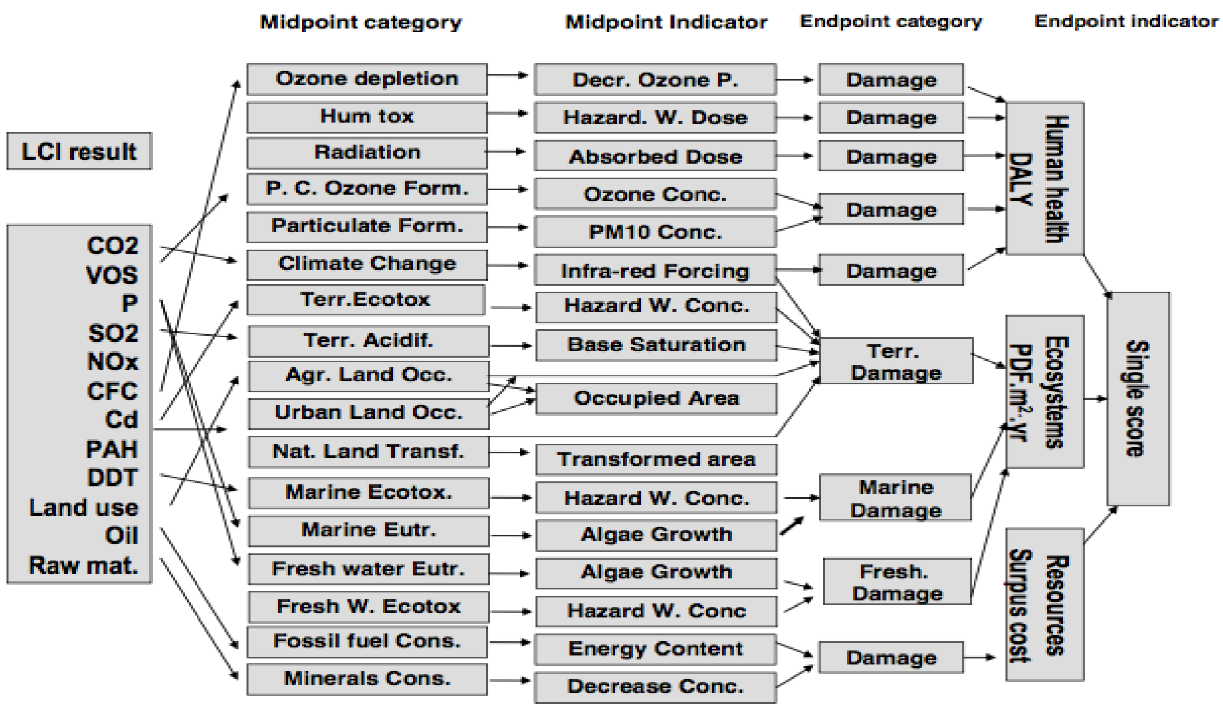

Figure 59. ReCiPe Methodology Impact Category *(Goedkoop et al., 2009)*

EDIP97 and EDIP2003

EDIP2003 model, developed following the EDIP97, incorporates midpoint environmental impact assessment and normalization factors for regional information. This method includes exposure factors to different emissions regarding human toxicity, eco toxicity, photochemical ozone formation, and acidification (Hauschild and Potting, 2005). (Figure 60). See http://ipt.dtu.dk/~mic/EDIP97 and http://ipt.dtu.dk/~mic/EDIP2003.

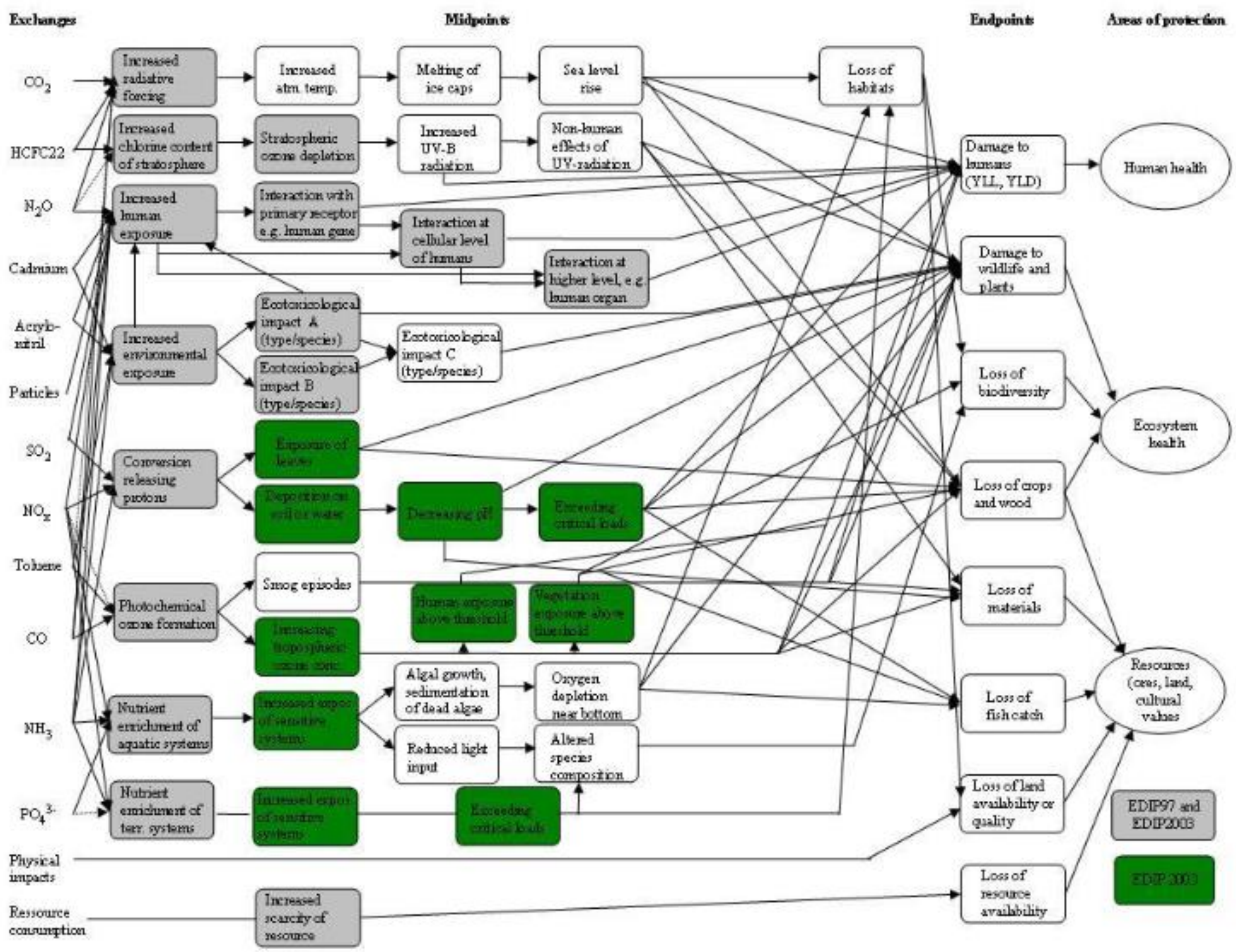

Figure 60. EDIP Methodology Impact Category *(Hauschild and Potting, 2005)*

Annex C: CAL-B/C

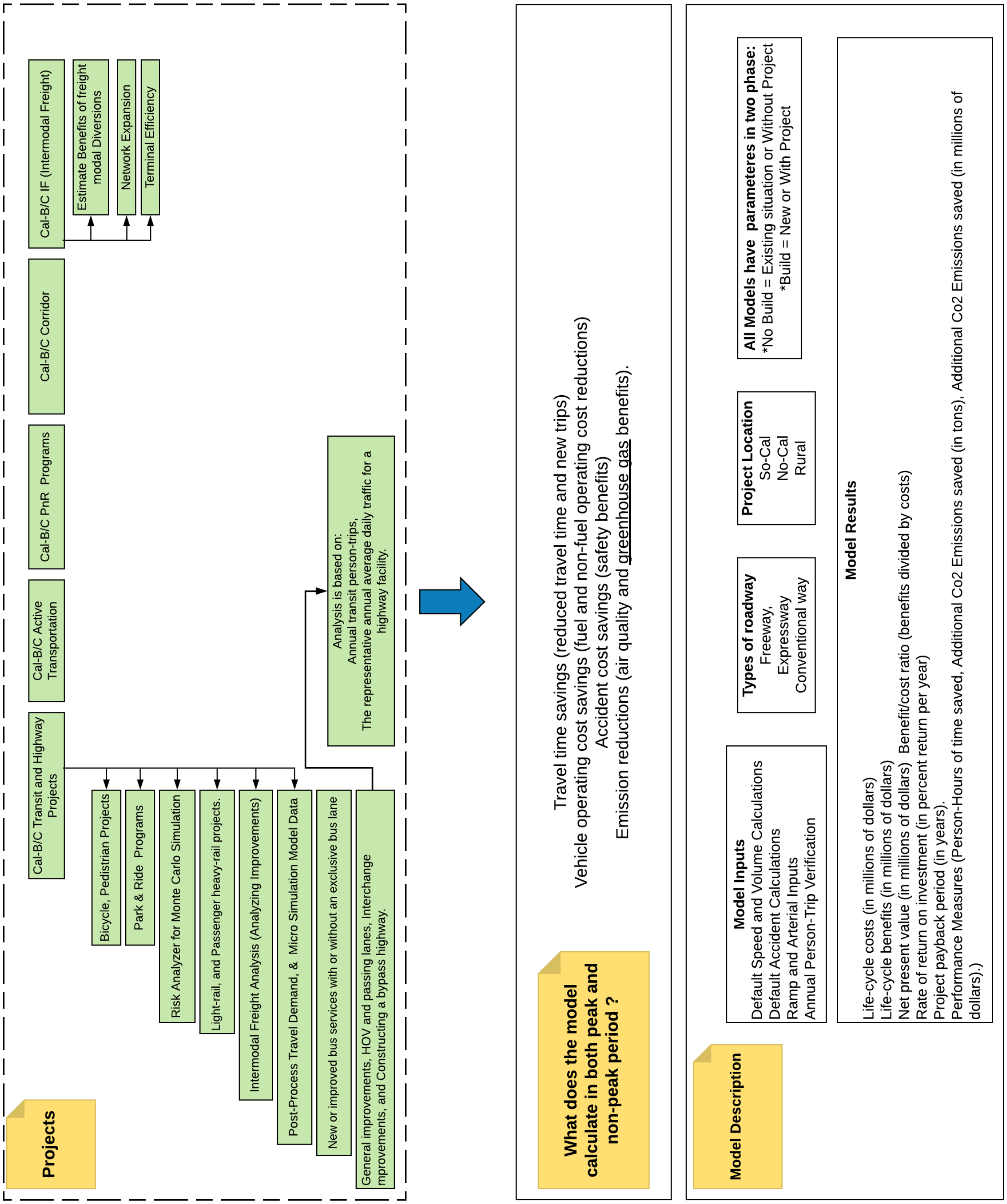

Figure 61. CAL-B/C Components

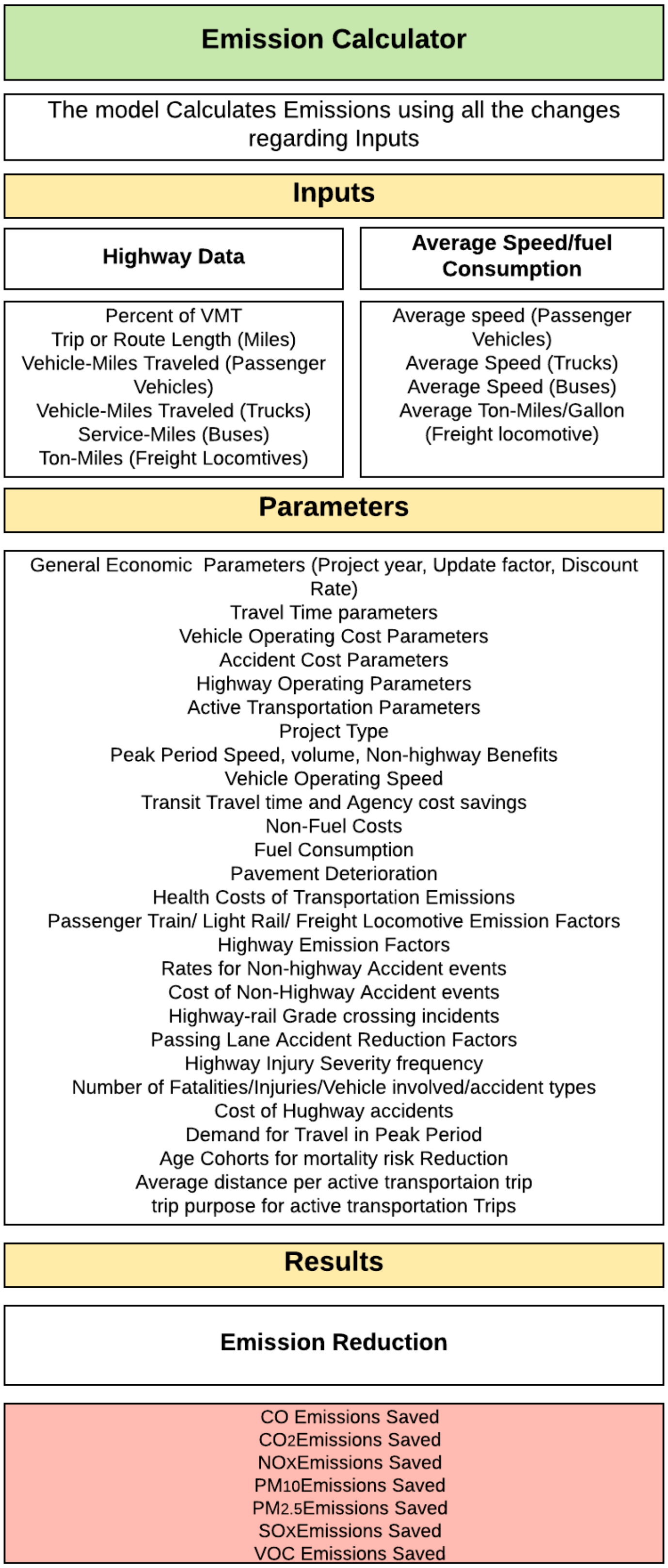

Figure 62. CAL-B/C Emissions Calculator