Goods Movement Life Cycle Assessment for Greenhouse Gas Reduction Goals

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Summary

The formation of effective policies to reduce emissions from goods movement should consider local and remote life cycle effects as well as barriers for mode shifting. Using unimodal and multimodal freight movements by truck, rail, and ocean-going vessel (OGV) associated with California, a life cycle assessment (LCA) is developed to estimate the local and remote emissions that occur from freight activity inside and associated with the state. Long-run average per tonne-kilometer results show that OGVs emit the fewest emissions, followed by rail, then trucks, and that the inclusion of life cycle processes can increase impacts by up to 32% for energy and greenhouse gas (GHG) emissions and 4,200% for conventional air pollutants. Efforts to reduce emissions through mode shifting should recognize that infrastructure and market configurations may be inimical to mode substitution. A unimodal and multimodal shipping emissions assessment is developed for intrastate and California-associated freight movements to illustrate the life cycle impacts of typical trips for certain types of goods. When targeting GHG reductions in California, it should be recognized that heavy-duty trucks are responsible for 99% of intrastate goods movement emissions. An assessment of future freight truck technology improvements is performed to estimate the effectiveness of strategies to meet 2050 GHG reduction goals. Whereas aggressive improvements in fuel economy coupled with alternative vehicles and fuels can significantly reduce GHG emissions, to meet 2050 goals will likely require zero carbon emission vehicle technology. The value of using LCA in GHG reduction policy for transportation systems is explored.

Introduction

The environmental impacts from transportation systems extend beyond the direct propulsion of vehicles, and efforts to reduce these impacts should consider the complexity of supporting systems such as infrastructure and supply chains. The life cycle assessment (LCA) of transportation services should include vehicle manufacturing/maintenance, infrastructure construction/rehabilitation/operation, and energy production, including supply chains (Chester and Horvath 2009). In the analysis of freight transportation, there have been only a handful of efforts to develop LCAs (Piecyk 2010; Kim and van Wee 2009), and the few studies that do exist (Strogen and Horvath 2013; Facanha 2006; Facanha and Horvath 2007; Meyer et al. 2011) tend to normalize results to a comparative measure of a particular weight moved over a particular distance (e.g., tonne-kilometer [km] or ton-mile [mi]) without analyzing the effects of unimodal and multimodal trips or how trips that span long distances should be addressed in environmental policy. It is important to understand trip impacts because (1) with...
interest in reducing freight emissions, it is not always possible (owing to market or infrastructure conditions) to shift goods from one mode to another and (2) many trips are multimodal. As efforts are made to reduce the environmental impacts from goods movement, life cycle thinking is needed to identify the indirect and supply-chain processes that support the freight system, as well as how complex supporting services should be assessed. Life cycle thinking can also help in our understanding of the transboundary air-quality effects of policies, as well as the technologies, fuels, and behavioral changes that lead to the greatest reductions in environmental impacts.

The development of a goods movement LCA, and the assessment of strategies that reduce emissions through technology, fuel, and behavioral changes, is particularly significant in California, where the demand for freight transportation is forecast to rise 1.8% per year and the state has greenhouse gas (GHG) reduction goals (CEC 2001). With this growth in demand, energy use and GHG emissions will increase unless alternative (or improvements in) vehicle technologies, fuels, or logistics are adopted. California is attempting to mitigate these impacts through state-wide climate and infrastructure management policies. The objective of this research is to (1) more clearly identify (using LCA) how emissions that occur as a result of goods movement in a region (in this case, California) are the result of demand, both in- and outside of the region, and (2) determine, given the existing configuration of freight infrastructure and preference for particular modes for particular goods, the life cycle emissions reductions that can realistically be achieved through technological, fuel, and behavioral change strategies.

Assembly Bill 32 (AB32), passed in 2006, calls for the development of strategies to reduce GHG emissions to 1990 levels by 2020 and 20% of 1990 levels by 2050 (State of California 2006). The California Air Resources Board (CARB) has established a specific objective of 3.5 million metric tonnes (MMT) of carbon dioxide equivalent (CO$_2$-eq) emissions reductions from the goods movement sector by 2020, with additional efforts to follow for meeting 2050 goals (State of California 2005). GHG emissions reductions from goods movement will occur, in part, as a result of the Low Carbon Fuel Standard (State of California 2007), ship electrification at ports, improved aerodynamic efficiency of heavy-duty vehicles (HDVs), and medium-duty vehicle/HDV hybridization efforts. As such, the development of a goods movement LCA for freight services associated with California is important to help the state develop an understanding of the systems (e.g., fuel production, vehicle manufacturing and maintenance, and infrastructure provision) upon which the movement of goods relies, as well as how impacts occur both in- and out-of-state.

To this end, we develop a California-specific LCA of truck, rail, and ocean-going vessel (OGV) travel into, within, and out of the state. Life cycle emissions are reported on both a unit- (tonne-km) and trip-level basis to showcase the energy and emissions intensity of typical uni- and multimodal freight services. We focus on GHG emissions, but energy consumption and conventional air pollutants (carbon monoxide [CO], nonmethane volatile organic compounds [NMVOCs], nitrogen oxides [NO$_x$], sulfur dioxide [SO$_2$], and particulate matter [PM]) are also assessed. We conclude with a discussion of the opportunities for reducing energy use and air emissions within a life cycle context. To support our discussion, we provide select emissions reduction pathways for the truck sector, the area of goods movement with the largest impacts within the geopolitical boundary of the state. These pathways include improved fuel efficiency, technology adoption, and advanced implementation of alternatively fueled vehicles (specifically, liquid natural gas [LNG]).

Methodology

LCA is a framework for evaluating the energy use, air emissions, and impacts of direct, indirect, and supply-chain processes of large systems. There have been LCAs performed of various components of freight services, but the majority of goods movement air-quality research focuses on the impacts from vehicle tailpipes, which produce significant human health impacts (English et al. 1999; Maciejczyk et al. 2004). We start by evaluating heavy-heavy duty (HHD) trucks (represented by Class 8, responsible for 55% of state-associated truck km traveled and 49% of heavy-duty truck [HDT] and rail tonne-km), medium-heavy duty (MHD) trucks (represented by Classes 6 and 7, responsible for 17% of state-associated truck km traveled and 21% of HDT and rail tonne-km), rail, container OGV, and tanker OGV movement per km of travel of 1 tonne of goods and then assess the life cycle impacts for uni- and multimodal trips (Census Bureau 2002; BTS 2007). Light-duty trucks are not included, which may be responsible for a sizable portion of goods movement in urban areas. The system boundary encompasses vehicle manufacturing and maintenance, fuel extraction, processing, and distribution, construction and operation of infrastructure, and vehicle operation (i.e., use-phase) processes. For each of the life cycle processes assessed, the associated primary material extraction, processing, transport, and use are evaluated, including upstream supply-chain effects. The analysis focuses on California-associated long-distance travel: goods movement that originates or destines in the state. State-specific freight activity profiles are developed for the per-trip assessment. For all life cycle processes, we evaluate end-use energy inputs and air emissions (GHG, CO, NMVOC, NO$_x$, SO$_2$, particles with a diameter of less than or equal to 10 microns [PM$_{10}$], and particles with a diameter of less than or equal to 2.5 microns [PM$_{2.5}$]). GHGs are characterized as CO$_2$-eq with weightings of 25 and 298 for methane and nitrous oxide corresponding to a 100-year radiative forcing potential (IPCC 2007).

Heavy- and Medium-Duty Trucks

HHD and MHD trucks are evaluated to capture two common vehicle sizes that are responsible for freight on-road movement. The HHD truck is characterized as a three- or four-axle tractor and trailer combination with a gross vehicle weight rating over 15,000 kilograms (kg) (33,000 pounds [lbs]). The MHD truck is characterized as a three-axle, single-unit truck with a gross vehicle weight rating between 8,850 and 11,800 kg (19,500 kg).
Train manufacturing and maintenance are evaluated using SimaPro. The Ecoinvent life cycle database locomotive and goods wagon processes (and all included material inputs) are used with an average U.S. energy mix given that train manufacturing occurs in several major U.S. regions (USITC 2011; SimaPro 2014).

Following the methodology developed by CARB for rail emissions inventorying for impacts from off-road diesel equipment (CARB 2006), data from Booz Allen & Hamilton Inc (1991) and CARB (2006) are used to estimate emissions from the operation of diesel locomotives. Projections for total annual emissions from freight train movement are provided along with estimates of future ton-mi of shipment. Together, these two figures are used to find a characteristic emission factor per tonne-km of freight movement by train. Trains are estimated to have an energy intensity of 270 kilojoules (kJ) per tonne-km and the production of diesel fuel is evaluated with CA-GREET (2009).

The construction and maintenance of rail infrastructure is modeled using SimaPro and includes gravel for ballast, concrete for ties, bridges, and tunnels, and steel track. Western states have moved toward concrete ties (rather than wood) over the past two decades because of improved performance on track curves and greater durability (Zeman 2010). The production of each infrastructure component is modeled with California-specific energy mixes that includes imports (40% NG, 17% coal, 28% hydro, 4% nuclear, and the remainder renewables), and there are 8,500 km of freight railway throughout the state (US DOT 2012; WECC 2011). The energy consumption and air emissions associated with the construction and maintenance of rail infrastructure are divided by state-associated tonne-km from the CFS (BTS 2007).

Ocean-Going Vessels

A characteristic tanker and container vessel are used because those ship types have comprised the two largest fractions (20% and 46%) of California port calls (CARB 2011). Similar to truck and rail, SimaPro is used to evaluate the manufacturing and maintenance of both ship types using the transoceanic tanker and transoceanic freight ship ecoinvent processes adjusted for region-specific manufacturing energy mixes. Nearly 57% of new container ship capacity in 2010 was manufactured in South Korea whereas 70% of new tanker capacity was from South Korea, Japan, and China (UNCTAD 2010). The South Korea electricity mix (33% coal, 32% oil, 31% nuclear, and the remainder renewables) is used for the manufacturing of both vessels, and lifespans are estimated at 120 and 380 billion tonne-km for the container and tanker vessels reflective of travel to and from Asia (World Shipping Council 2014; SimaPro 2014).

EMFAC (2011) is used to evaluate vehicle operation for both vessels. EMFAC includes transit, port maneuvering, and hoteling operational phases. Energy intensity values for each type of vessel are calculated based on a typical load capacity and travel speed to convert EMFAC factors from grams (g) per kilowatt-hour to g/tonne-km. Both ships are assumed to travel...
Figure 1  Freight goods movement average distances (to and from California) and commodity share by mode. The average transport distances for freight imported or exported from California are shown with the relative share (by tonne-km) of each mode to total freight movement and the share of each commodity type within the mode. The width of each arrow varies by the percent share, and the lengths vary by average distance (excluding unimodal ship). The dry and wet bulk goods category does not include petroleum. km = kilometer.

at average speeds of 31 kilometers (km) per hour at an engine loading (percentage of installed horsepower) of 80%. Based on the average ship operating conditions, a vehicle operation energy intensity of 23 and 36 kJ per tonne-km is estimated for tanker and container ships, respectively. CA-GREET (2009) is used to evaluate fuel production (crude extraction, processing, transport, and distribution) for heavy fuel oils.

Four California water ports (Long Beach, Los Angeles, Richmond, and Oakland) accounted for 8% of U.S. domestic and foreign waterborne trade in 2011 (BTS 2011). Long Beach and Los Angeles account for 77% of California port activity (by weight), handling 73 and 59 MMT respectively, in 2011, whereas Richmond and Oakland handle 22 and 17 MMT (BTS 2011). The analysis focuses on the ports of Long Beach and Los Angeles, but also includes Oakland, three ports with recent reports on their operational profiles.

Port infrastructure includes construction of facilities and operations. A GIS assessment of each port is created to estimate infrastructure material requirements, and the dominant coverage of land area is concrete surfaces. The energy consumption and air emissions from concrete production are modeled in PaLATE with region-specific energy mixes and transport distances. We rely on recent emissions inventories for operations at the ports (SCG 2012a,b). Existing emissions from port operations inventories have been developed for Los Angeles and Long Beach as part of regional clean-air action plans, and we rely on the results of these studies. The existing studies assess the activity profiles and air emissions for harbor crafts, cargo handling equipment, locomotives, and HDVs. For the port of Oakland, emissions inventories for operations were not identified, so activity profiles from the port of Los Angeles were used, but scaled based on container volumes. The port of Oakland handled 2.3 million 20-foot equivalent units (TEU; a standard container size) in 2012, compared to Los Angeles’ 8.1 million TEU (Port of Los Angeles 2014; Port of Oakland 2014). Further, dredging is included because each of the three ports excavate soil to create deeper channels during the initial construction phase of additional wharfs as well as annually for maintenance as sediment accumulates in the shipping lanes (US EPA 2009).

To normalize results per tonne-km, port-specific annual activity is calculated based on average trip distance within the emissions zone (44 km for CARB OGV fuel regulation inventory), vessel utilization (main or auxiliary diesel engines), and number of calls for each vessel type (66% container and 9% tanker) (SCG 2012a,b). Freight utilization of container and tanker vessels is calculated based on the vessel’s capacity and the average cargo (60,000 dry-weight tonnes for containers and 150,000 dry-weight tonnes for tankers) imported or exported from each port divided by the number of calls (SCG 2012a,b).

The core environmental models used to assess the modes for each of the life cycle stages are summarized in table 1. The analysis is developed for year 2010.
Table 1  Summary of core methods

| Life cycle stage          | Trucks          | Rail            | OGV             |
|---------------------------|-----------------|-----------------|-----------------|
| Vehicle operation/propulsion | EMFAC2011      | CARB (2006)     | EMFAC2011       |
| Vehicle manufacturing and maintenance | SimaPro and ecoinvent lorry processes | SimaPro and ecoinvent locomotive and goods wagon processes | SimaPro and ecoinvent transoceanic freight ship processes |
| Infrastructure            | PaLATE and freight truck routes | SimaPro and ecoinvent railway track processes | PaLATE for port asphalt and concrete; port equipment and facilities operation profiles |
| Energy production         | CA-GREET        | CA-GREET        | CA-GREET        |

Figure 2  Attributional life cycle results (per tonne-km [kilometer]). The life cycle energy use and emissions for each freight mode are shown per tonne-km. Vehicle propulsion (operation) effects are gray, vehicle manufacturing and maintenance processes blue, infrastructure red, and energy production green. OGVC are container ships and OGV tankers. HHD = heavy-heavy duty; MHD = medium-heavy duty; MJ = megajoules; CO = carbon monoxide; mg = milligrams; NOx = nitrogen oxides; g = grams; PM$_{10}$ = particles with a diameter of less than or equal to 10 microns; CO$_2$-eq = carbon dioxide equivalent; NMVOC = nonmethane volatile organic compounds; SO$_2$ = sulfur dioxide; PM$_{2.5}$ = particles with a diameter of less than or equal to 2.5 microns.

Relative Life Cycle Intensity of Freight Modes

The modal life cycle results per tonne-km are shown in figure 2 and illustrate the significance of life cycle processes in the long-run operation of trucks, rail, and OGV goods movement. Whereas vehicle operation is a dominating contributor in the life cycle of each mode, several life cycle processes can significantly increase effects. Vehicle manufacturing and energy production supply chains can add significantly to the life cycle footprint of modes, in particular, trucks. This is consistent with past findings (Chester and Horvath 2009; Facanha 2006; Facanha and Horvath 2007) of other transport systems and shows how efforts to reduce the emissions at the tailpipe of vehicles have produced valuable benefits while allowing supply-chain processes (often dominated by stationary sources)
to become larger fractions of the life cycle footprint of each mode. Infrastructure-associated emissions from construction, maintenance, and rehabilitation do not significantly appear, largely owing to the long-distance nature of the transportation systems evaluated. For all emissions except SO$_2$, trucks are the most impactful, with MHD trucks producing emissions from 2 to 74 times greater than rail or OGVs. OGVs produce the least GHG, CO, NMVOC, and NOx emissions per tonne-km because of their large capacity and long-distance trip nature. However, diesel rail produces the lowest SO$_2$ and PM emissions. Because sulfur is regulated in diesel fuels, SO$_2$ emissions associated with OGVs are significantly higher, although new regulations requiring the use of lower-sulfur marine distillates in place of heavy fuel oils within California waters and within 24 nautical miles of the state’s coast is expected to reduce emissions (CARB 2011). Though certain modes create fewer impacts per tonne-km of freight shipment, these modes cannot always be substituted for one another to reduce emissions.

The significance of vehicle operation in the life cycle of truck goods movement can vary greatly depending on the pollutant. For energy and GHG emissions of both HHD and MHD trucks, vehicle operation (fuel combustion) comprises 78% to 81% of life cycle emissions. The conventional air pollutant results show that vehicle life cycle processes may contribute significantly to emissions. In the life cycle, these emissions are the result of mining, refining, and metal and composite material production. These processes consume significant quantities of electricity and can cause emissions to be generated directly at manufacturing facilities. For SO$_2$, low-sulfur diesel and stringent emissions control policies have resulted in minimal tailpipe emissions relative to those in the life cycle. Nonoperational processes comprise 44% to 98% (for rail and trucks) of the life cycle SO$_2$ emissions and are primarily from electricity generation for upstream processes, a finding consistent with past studies (Facanha and Horvath 2007). PM$_{10}$ emissions primarily occur during mining operations for raw materials extraction and processing, whereas PM$_{2.5}$ emissions result from diesel equipment use in supply-chain processes.

The rail life cycle inventory is dominated by vehicle operation (diesel fuel combustion) for all environmental indicators, with the exception of PM. Similar to trucks, SO$_2$ emissions from electricity generation throughout the supply chain heavily contribute to life cycle results. Roughly 77% of energy consumption and GHG emissions are attributed to vehicle operation, with energy production contributing approximately 15% of life cycle energy and GHG emissions, and infrastructure processes less than 2%. Whereas the infrastructure impacts for rail are small in the life cycle, they are generally larger than infrastructure impacts associated with trucks and OGVs. This is owing to a large allocation of tonne-km across roads for trucking and the minimal infrastructure for OGVs.

Ship energy consumption and emissions are dominated by vehicle operation. CO and NMVOCs show strong contributions from vehicle manufacturing and maintenance as well as upstream energy production. CO emissions in the vehicle manufacturing and maintenance supply chain of OGVs are largely the result of truck transportation for parts and materials, as well as production of steel (EIO-LCA 2008). NMVOC supply-chain emissions from life cycle processes are resulting primarily from truck emissions, as well as waste management services (EIO-LCA 2008). The long-distance nature of OGV travel coupled with large payload weights marginalizes life cycle effects.

### Multimodal Goods Movement and the Allocation of Life Cycle Emissions to California

Trip comparisons are necessary to understand the marginal life cycle impacts of the decision to move goods. The per-tonne-km attributional results in figure 2 do not adequately illustrate the impacts of the 15% of California-associated goods movement that is multimodal (BTS 2007). The decision to use one multimodal option versus another may produce effects both within and outside of California, depending on the origin and destination of the good. As mode shifting, fuel switching, and load consolidation strategies are discussed, a life cycle understanding of multimodal trips is important for avoiding unintended trade-offs (Sathaye et al. 2010).

CARB has established an objective of a 3.5 MMT reduction of GHG emissions from the goods movement sector by 2020 (Measure T-6), with future goals of 80% GHG reduction below 1990 levels by the year 2050 (State of California 2005, 2006). An opportunity may exist to reduce GHG emissions by shifting current California freight movement from single-mode trucks to single-mode rail movement and multimodal truck and rail movement if infrastructure investments are made. However, the region where air emissions are released must be considered to distinguish between GHG emissions released within the state, as well as out-of-state emissions that result from California activity (whether that be the processing of goods in the state or the use of state infrastructure). The life cycle trip emissions are shown in figure 3 with the left graph showing only CO$_2$-eq emissions within California and the right graph showing all emissions from California-associated activity (i.e., import and export trips where the majority of emissions may occur out-of-state).

California imports and exports account for billions of tonne-km of freight movement annually. Approximately 47% of the freight that travels through California infrastructure ends up out-of-state (BTS 2007). It is not immediately clear how GHG policy goals in California specify the inclusion of these out-of-state emissions (especially in light of a current lawsuit against the state’s Low Carbon Fuel Standard that purports that the inclusion of supply-chain impacts in decision making can violate the Commerce Clause of the U.S. Constitution) or what portion of freight travel can realistically be shifted away from specific modes. We start by illustrating the GHG emissions from typical uni- and multimodal freight trips within and associated with California (figure 3) and then develop scenarios for reducing emissions through several strategies. Three single modes of transportation are considered: HHD trucks, MHD trucks, and rail. Multimodal trips were analyzed by building three multimodal categories with average trip lengths.
Figure 3 California-associated life cycle CO₂-eq emissions for freight movement (kg per average trip length). The left chart shows the emissions from intrastate (a trip that occurs entirely within the state), import, and export goods movement that occurs within California. The right chart shows emissions that occur within and outside of California from California-associated goods movement. The top quadrants are intrastate effects and the bottom import and export. The import and export portions of each chart are trips that, in some part, use California freight infrastructure, but also involve travel outside of the state. Note the different scales for the left and right charts. MHD = medium-heavy duty; HHD = heavy-heavy duty; OGVC = ocean-going container vessel; OGVT = ocean-going tanker vessel; OGV = ocean-going vessel; kg CO₂-eq = kilograms carbon dioxide equivalent.

The GHG intensity of goods movement is dependent on the type of good being moved, and three representative trip types are used to illustrate the emissions of multimodal travel. The first multimodal category is selected to evaluate different combinations of goods transportation using both rail and truck. In this scenario, it is assumed that 90% of the trip is by rail and the remaining 10% by either HHD or MHD. The second category considered is freight movement by multiple truck types, typically used by consumable and retail goods. This scenario represents freight traveling the majority of a trip (85%) in HHD trucks and the remaining distance in a smaller MHD truck. The third category considers freight transportation that begins on an ocean-going container vessel (OGVC) and completes its journey by a single mode (rail or truck) or by multiple modes (rail and truck).

To estimate in- and out-of-state travel, roadway and rail track lengths are determined for both California and typical freight trips associated with California. A distance of 360 km is used for import and export freight travel within California, the rail distance from the ports of Los Angeles or Oakland to the California border. For intrastate freight movement, an average truck shipment length of 530 km is used, the distance between the San Francisco and Los Angeles metro regions. Average rail and multimodal travel distances are calculated as 700 and 730 km, respectively (BTS 2007). Truck, rail, and multimodal truck and rail travel distances for interstate freight are calculated from the CFS as 3,300, 3,700, and 3,900 km, respectively, as shown in figure 1. The results in figure 3 show the GHG emissions from the movement of 1 tonne over the median travel distance for intra- and interstate travel.

Goods that are imported or exported by OGV have the lowest GHG emissions per trip, followed by rail travel, then truck. Freight being imported or exported by OGV tends to be either the lowest-value goods or goods that are the least time sensitive (Facanha and Horvath 2006). On land, unimodal rail travel has the lowest GHG emissions, but can satisfy only 30% of goods movement by weight; typically coal, lumber, and paper goods. The lowest emissions for land multimodal trips are rail and HHD truck, which are used for consumable goods. Load consolidation on HHD trucks, and the associated fuel economies of scale, causes the rail and HHD trip to produce 14% fewer emissions than the rail and MHD truck combination. However, more than 60% of freight currently travels by single-mode truck in California (BTS 2007).

Freight activity within California, whether goods are destined for in- or out-of-state consumption, results in GHG emissions beyond the geopolitical border that should be considered in policy goals. Vehicle manufacturing triggers, on average, 6 kg of GHG emissions to be released out-of-state for every 100 kg released during propulsion. Similarly, energy production processes release 21 kg of GHG emissions for every 100 kg released during propulsion, some of which are likely to occur out-of-state. Moreover, during an interstate trip, out-of-state emissions can be as much as 65 times more than those that occur in-state for imported or exported goods. The largest infrastructure life cycle emissions contributions amounts to 2.1%. This again highlights how long-distance freight services marginalize infrastructure impacts, either because minimal infrastructure exists combined with very long distances and large volumes of goods (as is the case with rail and OGVs) or large truck traffic volumes result in minimal allocation. California should continue to focus on reducing freight truck emissions to meet state reduction goals, but it should also acknowledge that significant benefits are likely to be experienced beyond the state's borders.
Reducing Impacts with Technology and Fuel Changes

Improved vehicle technologies and lower-carbon fuels have the potential to reduce GHG emissions during propulsion, but are likely to alter the significance of life cycle processes. Current fuels and future technologies for trucks, rail, and OGVs are shown in table 2. These factors are developed from a variety of sources, including CA-GREET and NRC (2010, 2014). They largely represent alternative technologies today, but improved fuel economies are estimated into the future. Vehicle operation and life cycle process emissions are estimated following the approaches described in the Methods section. For liquefied natural gas (LNG) trucks, though CO₂-specific emissions reductions as large as 20% have been measured, the GHG benefits are partly offset by lower-efficiency engines and the potential for methane releases resulting in an average estimated GHG reduction of 9% (NRC 2014). The fuel savings from diesel-electric hybrid trucks is estimated to be between 3% and 9% for intercity drive schedules where opportunities for recovering energy during regenerative braking are minimal (NRC 2010). An average fuel savings of 5% is assumed for diesel-electric hybrids. Emissions from electric trains are estimated using the Western Electricity Coordinating Council’s (WECC’s) 2010 electricity mix assuming the same energy intensity per tonne-km, but an improved engine efficiency over a diesel locomotive (WECC 2011).

The alternative vehicle technologies and fuels offer marginal reductions in GHG emissions and potentially large reductions in conventional air pollutants. For trucks, the most notable emission reductions from alternative fuels are for GHGs and NOₓ. Converting trains from diesel fuel to electric power enables small reductions in upstream energy consumption and life cycle GHG emissions, while also enabling up to 89% reductions in conventional air pollutants. The notable exception to these potential reductions is rail, which experiences a fivefold increase in SO₂ emissions that results from switching from low-sulfur diesel fuels to higher-sulfur electricity mixes. Converting ships from heavy fuel oil to diesel enables reductions for all impacts, with SO₂ showing the greatest improvement (96%). Changing ship propulsion from bunker fuel to LNG produces reductions as large as 97% in SO₂ and PM emissions. Large vehicle fleet and fuel mix changes are not likely to happen quickly, but California should recognize that air-quality goals are affected by GHG policies, and leveraging this interdependency could improve the opportunities for quicker turnover.

Freight operators contend that it is not advantageous to ship by multiple modes or by rail within California because the distance is too short to realize monetary benefits and shipment times are unreliable (Golob and Regan 2001). Goods movement between the San Francisco and Los Angeles regions is too short to realize the economic benefits of rail shipment (Janic 2007). Additionally, rail transfer facilities tend to be located in areas such that trucks would still be required for pickup and delivery on each end of the long haul. The additional time to transfer freight and unreliable travel times at often-crowded transfer facilities cause freight operators to defer to trucks at short distances. The consequence of such cost constraints is that goods are then shipped by more carbon-intense modes (HHD and MHD trucks). As shown in figure 4, this leads to the trucking sector having the most significant GHG emissions within the state (105 times more tailpipe emissions than unimodal rail and multimodal combined). Owing to these logistical constraints, California should focus on improving current HDT technologies and fuel sources to lower GHG emissions in accord with state-wide reduction goals.

Fuel switching during both active transport and idling has the potential to significantly reduce GHG emissions. Madanat and colleagues (2011) report that CO₂-eq emissions from 1 hour of idling while connected to California’s electricity grid are 97.5% less than 1 hour of idling on diesel fuel. Gaines and Levinson (2009) estimate that 8.5% of truck fuel consumption is from idling. Converting trucks to idle by electricity represents an immediate GHG reduction opportunity because of low equipment costs for each truck and many facilities already equipped to allow electricity access (Gaines and Levinson 2009). California freight growth forecasts are obtained from the CEC (2001) and used to estimate emissions (supported by CARB [2013] projections) from current diesel trucks and proposed alternative fuel technologies through 2050. Figure 5 shows the annual California-associated freight truck travel GHG emissions and possible savings associated with shifting to alternative fuel technology. Several alternative vehicle and fuel scenarios are developed to assess the aggressiveness of fleet turnover that is needed to meet AB32 2020 and 2050 goals. New infrastructure for alternative vehicles is not considered.

Life cycle emissions are included. It is possible for California to meet 1990 GHG emissions levels and even reach 2050 goals (80% below 1990 levels), despite a forecasted 1.8% annual increases in state-wide goods movement volumes. Note that figure 5 shows emissions associated with long-distance truck travel for California-associated emissions (i.e., truck travel to, from, and within the state) and is only a fraction of the total HDT travel in the state. The (business-as-usual) diesel truck projection (black line in figure
Table 2  Opportunities for freight shipment technological changes (per tonne-km of shipment)

| Vehicle type and propulsion fuel | End-use energy (kJ) OP/LC | CO₂-eq (g) OP/LC | CO (mg) OP/LC | NMVOC (mg) OP/LC | NOₓ (mg) OP/LC | SO₂ (mg) OP/LC | PM₁₀ (mg) OP/LC | PM₂.5 (mg) OP/LC |
|--------------------------------|--------------------------|-----------------|--------------|-----------------|---------------|--------------|----------------|----------------|
| HHD diesel truck               | 950/1,300                | 67/96           | 110/290      | 25/70           | 550/620       | 0.63/46.0     | 20/40          | 16/29          |
| HHD LNG truck                  | 580/960                  | 62/91           | 49/230       | 18/61           | 200/260       | 0/41          | 0.41/12.0      | 0.38/10.0      |
| HHD diesel-electric hybrid truck | 910/1,200                | 63/92           | 100/290      | 23/69           | 530/590       | 0.6/46.0      | 19/38          | 16/28          |
| MHD diesel truck               | 1,500/2,200              | 100/160         | 120/580      | 35/140          | 730/860       | 0.97/110.0    | 38/79          | 29/44          |
| MHD LNG truck                  | 1,200/2,100              | 130/220         | 65/530       | 36/140          | 330/470       | 0/100         | 0.89/30.0      | 0.82/11.0      |
| MHD diesel-electric hybrid truck | 1,400/2,100              | 97/160          | 110/580      | 33/140          | 690/820       | 0.92/100.0    | 36/76          | 28/42          |
| Diesel train                   | 200/260                  | 14/19           | 72/89        | 18/22           | 200/210       | 8.1/16.0      | 0.97/4.1       | 0.88/1.8       |
| Electric train                 | 89/110                   | 14/15           | 5.7/20.0     | 0.6/2.7         | 20/23         | 71/75         | 0.73/2.0       | 4.9/5.0        |
| Ocean container vessel (bunker fuel) | 33/43                   | 2.7/3.6         | 6.0/11.0     | 2.6/4.9         | 76/78         | 47/48         | 6.4/7.0        | 4.8/5.1        |
| Ocean container vessel (diesel fuel) | 22/33                   | 1.7/2.5         | 4.1/9.4      | 1.7/4.0         | 52/54         | 0.17/1.7      | 4.3/4.9        | 3.3/3.6        |
| Ocean container vessel (LNG fuel) | 26/40                   | 1.5/2.6         | 2.3/7.8      | 2.0/4.3         | 60/62         | 0.05/1.6      | 0.5/0.94       | 0.38/0.66      |
| Ocean tanker vessel (bunker fuel) | 21/26                   | 1.7/2.2         | 3.7/6.6      | 1.6/2.8         | 48/49         | 29/30         | 40.0/4.4       | 3.0/3.2        |
| Ocean tanker vessel (diesel fuel) | 22/29                   | 1.7/2.3         | 4.1/7.0      | 1.7/3.0         | 52/53         | 0.17/1.1      | 4.3/4.7        | 3.3/3.5        |
| Ocean tanker vessel (LNG fuel)  | 26/37                    | 1.5/2.3         | 2.3/5.3      | 2.0/3.2         | 60/62         | 0.05/0.95     | 0.5/0.74       | 0.38/0.54      |

Note: Energy use and emissions from vehicle operation/propulsion (OP) and the life cycle (LC; which includes OP) are shown for each vehicle and fuel technology following the aforementioned methods. End-use energy, GHG emissions, and conventional air pollutants are assessed for diesel, hybrid-diesel, and LNG trucks, diesel and electric rail, and bunker, diesel, and LNG ocean-going vessels. The base data source is CA-GREET (2009). NRC (2014) is used to assess LNG trucks and NRC (2010) for diesel-electric hybrid trucks.

unimodal truck movements generate 98% of intrastate freight GHG emissions. HHD = heavy-heavy duty; MHD = medium-heavy duty; Tg CO₂-eq = teragrams carbon dioxide equivalent.

5) assumes that all future single-mode truck freight will be transported with diesel engines, which improve fuel economy by 0.5% per year, consistent with historical improvements (TEDB 2014). Historical emissions are based on changes in historical travel and fuel economy (TEDB 2014). The projections for trucks with electric idling assume that all diesel and LNG trucks will convert to the technology by 2025 (Gaines and Levinson 2009). The projections for LNG and hybrid vehicles assume that each year, beginning in 2015, new vehicles will shift to the alternative fuel type following the schedule: 10% of the fleet by 2025, 60% by 2035, 95% by 2045, and 100% by 2050. The final two scenarios also include more aggressive fuel economy increases as noted in the legend (EIA 2013).

Assuming constant growth in the demand for truck transport, California will need to implement zero carbon emission vehicle and fuel technologies at an aggressive rate to meet AB32 2050 goals. This finding is consistent with other studies, including Sharpe (2013) and CEC (2013). With the historical 0.5% annual increasing in fuel economy, diesel emissions increase from approximately 38 teragrams (Tg) CO₂-eq today to 59 Tg CO₂-eq in 2050. Fleet turnover to hybrid technologies and LNG fuel reduce emissions by 5% and 9%, respectively, in
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Figure 5 California freight annual GHG emissions with truck technology and fuel switching projections. Freight truck emissions for California-associated freight movement are shown from 1990 to 2010 and are projected to 2050 based on current diesel technology and select fuel switching scenarios. Tg CO₂-eq = teragrams carbon dioxide equivalent; AB32 = Assembly Bill 32; GHG = greenhouse gas; LNG = liquefied natural gas.

2050. At an annual 1.27% increase in fuel economy, California can stabilize truck GHG emissions despite a projected 87% increase in tonne-km. More aggressive fuel economy and fuel switching outcomes are needed to reduce emissions to meet 2050 policy goals. A 3% annual increase in diesel fuel economy coupled with the implementation of zero emission vehicles (ZEVs) assuming a 4% annual decarbonization from the technologies results in a GHG reduction to 60% of 1990 levels by 2050. Given the projected increase in tonne-km, conventional technologies and fuels offer limited potential. A 5% annual increase in diesel fuel economy coupled with LNG turnover and a 1% annual increase in fuel economy (both with electric idling) offers short-term reductions, but long-term increases. This is the result of the limited benefit of LNG fuels being overtaken by the growth in demand for freight services. These two scenarios show that resources should be focused on improving the fuel technology that will be most heavily used in the long run, rather than improving current diesel fuel economy, given that it will ultimately be phased out for alternative fuels. To meet 2050 goals, California will need to deploy ZEV technology at a 5.5% turnover rate per year. We consider only a handful of vehicle technology and lower-carbon fuel options and it is possible that, with other strategies (including electric-propulsion trucks, optimized alternative fuel engines, allowing multiple trailers per tractor, and alternative power plants and combustion cycles), additional GHG emissions can be achieved (CEC 2013; NRC 2010).

Policy Making for Life Cycle Greenhouse Gas Reductions

GHG reduction policy formation is still in its infancy, and increasing interest in using LCA to estimate indirect and supply chain effects raises questions of how a geopolitical entity (such as a county, region, state, or country) can affect change in processes in complex systems that do not adhere to geopolitical boundaries. Such is the case with goods movement in California. California is a major producer of goods and hosts many critical infrastructure facilities involved in the processing of goods for the state, the United States, and other countries. The development of an environmental LCA of goods movement associated with California for GHG reduction policy goals reveals several layers of complexity. First, California, as with any other region, relies on a global supply chain and activities in the state (e.g., the movement of a tonne-km of goods) trigger emissions beyond its borders (e.g., the manufacturing of vehicles or production of fuels) (figure 2). Second, the freight activity system is multinational and the emissions that occur in-state are often a
small fraction of those that have occurred outside of its borders for trips associated with California (figure 3). Despite one mode having a smaller life cycle footprint than another, opportunities for short-term mode shifting to reduce air emissions may be limited. It is possible that new vehicle technologies (such as drones) and associated infrastructure emerge in the long term that offer the potential to reduce GHG emissions through mode shifting; however, in the near-term, California should focus on reducing emissions from trucks, which dominate inter- and intracity freight impacts. These complexities point toward a need for more systemic GHG reduction policies that come closer to unifying policy and activity system boundaries. Multistate or national efforts are likely to include more supply-chain processes associated with activities in a region or country, but regional or national GHG reduction policies have largely been politically infeasible to create. In the meantime, California should recognize that goods movement activity in the state is supported by activities that generate emissions beyond its borders. As such, the LCA framework can be valuable beyond comprehensive emissions assessment in the pinpointing of when and where impacts occur, thus guiding policy makers toward the creation of more systematic GHG reduction agreements.

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