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Environmental assessment of passenger transportation should include infrastructure and supply chains

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Abstract

To appropriately mitigate environmental impacts from transportation, it is necessary for decision makers to consider the life-cycle energy use and emissions. Most current decision-making relies on analysis at the tailpipe, ignoring vehicle production, infrastructure provision, and fuel production required for support. We present results of a comprehensive life-cycle energy, greenhouse gas emissions, and selected criteria air pollutant emissions inventory for automobiles, buses, trains, and airplanes in the US, including vehicles, infrastructure, fuel production, and supply chains. We find that total life-cycle energy inputs and greenhouse gas emissions contribute an additional 63% for onroad, 155% for rail, and 31% for air systems over vehicle tailpipe operation. Inventorying criteria air pollutants shows that vehicle non-operational components often dominate total emissions. Life-cycle criteria air pollutant emissions are between 1.1 and 800 times larger than vehicle operation. Ranges in passenger occupancy can easily change the relative performance of modes.

Keywords: passenger transportation, life-cycle assessment, cars, autos, buses, trains, rail, aircraft, planes, energy, fuel, emissions, greenhouse gas, criteria air pollutants

 Supplementary data are available from stacks.iop.org/ERL/4/024008

1. Background

Passenger transportation's energy requirements and emissions are receiving more and more scrutiny as concern for energy security, global warming, and human health impacts grows. Passenger transportation is responsible for 20% of US energy consumption (approximately 5% of global consumption) and combustion emissions are strongly positively correlated [1]. The potentially massive impacts of securing petroleum resources, climate change, human health, and equity issues associated with transportation emissions have accelerated discussions about transportation environmental policy.

Governmental policy has historically relied on energy and emission analysis of automobiles, buses, trains, and aircraft at their tailpipe, ignoring vehicle production and maintenance,

infrastructure provision and fuel production requirements to support these modes. Such is the case with CAFE and aircraft emission standards which target vehicle operation only [2, 3]. Recently, decision-making bodies have started to look to life-cycle assessments (LCA) for critical inputs, typically related to transportation fuels [4, 5]. In order to effectively mitigate environmental impacts from transportation modes, life-cycle environmental performance should be considered including both the direct and indirect processes and services required to operate the vehicle. This includes raw materials extraction, manufacturing, construction, operation, maintenance, and end of life of vehicles, infrastructure, and fuels. Decisions should not be made based on partial data acting as indicators for whole system performance.

To date, a comprehensive LCA of passenger transportation in the US has not been completed. Several studies and

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models analyze a single mode, particular externalities, or specific phases, but none have performed a complete LCA of multiple modes including vehicle, infrastructure, and fuel inventories for energy consumption, greenhouse gas emissions, and criteria air pollutant emissions incorporating supply chains [6–9]. The automobile has received the greatest attention while buses, rail, and air have received little focus. A review of environmental literature related to the three modal categories is shown in table S1 of the supporting information (SI) (available at stacks.iop.org/ERL/4/024008).

2. Methodology

Onroad, rail, and air travel are inventoried to determine energy consumption, greenhouse gas (GHG) emissions, and criteria air pollutant (CAP) emissions (excluding PM, lead, and ozone due to lack of data). The onroad systems include three automobiles and two urban buses (off-peak and peak). A sedan (2005 Toyota Camry), SUV (2005 Chevrolet Trailblazer), and pickup (2005 Ford F-150) are chosen to represent the range in the US automobile fleet and critical performance characteristics [10–12]. 83% of rail passenger kilometers are performed by metropolitan systems (with Amtrak serving the remaining) [1]. The generalized rail modes (heavy rail electric metro, heavy rail diesel commuter transit, and light rail transit (LRT)) are chosen to capture the gamut of physical size, fuel input, and service niche. The metro and commuter rail are modeled after the San Francisco Bay Area's (SFBA) Bay Area Rapid Transit and Caltrain while the LRT modes are modeled after San Francisco's (SF) Muni Metro and the Boston Green Line. Air modes are evaluated by small (Embraer 145), midsize (Boeing 737) and large (Boeing 747) aircraft to represent the range of impacts from aircraft sizes, passenger occupancy, and short to long haul segment performance [13]. An extended discussion of the characteristics and representativeness of the modes selected is found in the SI. US average data are used for all onroad and air mode components and particular geographic operating conditions are not captured [14, 15]. Rail operational performance is determined from specific systems [15–18].

A hybrid LCA model was employed for this analysis [19]. The use of this LCA approach is discussed in the SI and detailed extensively in [20]. The life-cycle phases included are shown in table 1. The components are evaluated from the materials extraction through the use phase including supply chains. For example, the manufacturing of an automobile includes the energy and emissions from extraction of raw materials such as iron ore for steel through the assembly of that steel in the vehicle. End-of-life phases are not included due to the complexities of evaluating waste management options and material reuse. Indirect impacts are included, i.e., the energy and emissions resulting from the support infrastructure of a process or product, such as electricity generation for automobile manufacturing.

For each component in the mode's life cycle, environmental performance is calculated and then normalized per passenger-kilometer-traveled (PKT). The energy inputs and emissions from that component may have occurred annually (such as from electricity generation for train propulsion) or

over the component's lifetime (such as train station construction) and are normalized appropriately. Detailed analyses and data used for normalization are found in [20], including mode-specific adjustments (such as the removal of freight and mail attributions from passenger air travel). Equation (1) provides the generalized formula for determining component energy or emissions.

$$E_M = \sum_c \frac{EF_{M,c} \times U_{M,c}(t)}{PKT_M(t)} \quad (1)$$

where E_M is total energy or emissions per PKT for mode M ;

M is the set of modes {sedan, train, aircraft, etc};

c is vehicle, infrastructure, or fuel life-cycle component;

EF is environmental (energy or emission) factor for component c ;

U is activity resulting in EF for component c ;

PKT is PKT performed by mode M during time t for component c .

The fundamental environmental factors used for determining a component's energy and emissions come from a variety of sources. They are detailed in SI tables S2–S4 (available at stacks.iop.org/ERL/4/024008). Further, each component's modeling details are discussed in [20] which provides the specific mathematical framework used as well as extensive documentation of data sources and other parameters (such as component lifetimes and mode vehicle and passenger kilometers traveled). Parameter uncertainty is also evaluated in the SI.

Results for modal average occupancy per-PKT performance are reported. While understanding of marginal performance is necessary for transportation planners to evaluate the additional cost of a PKT given a vested infrastructure and the assumption that many public transit trips will occur regardless, the average performance characteristics allow for the total environmental inventorying of a system over its lifetime.

3. Results and component comparisons

With 79 components evaluated across the modes, the groupings in table 1 are used to report and discuss inventory results.

3.1. Energy

The energy inputs for the different systems range from direct fossil fuel use such as gasoline, diesel, and jet fuel to indirect fossil fuel use in electricity generation. The non-operational vehicle phases use a combination of energy inputs for direct and indirect requirements. For example, the construction of an airport runway requires direct energy to transport and place the concrete and indirect energy to extract and process the raw materials. Figure 1 shows total energy inputs for each mode.

While tailpipe components account for a large portion of modal life-cycle energy consumption, auto and bus non-operational components have non-negligible results. Active operation accounts for 65–74% of onroad, 24–39% of rail, and 69–79% of air travel life-cycle energy. Inactive operation accounts for 3% of bus, 7–21% of rail, and 2–14% of air

Table 1. Analysis components (for each component, energy inputs and emissions are determined. The components are shown by generalized mode, but evaluated independently for each system).

Grouping	Automobiles and buses	Rail	Air
<i>Vehicles</i>			
Operational components			
Active operation	<ul style="list-style-type: none"> • Running • Cold start 	<ul style="list-style-type: none"> • Running 	<ul style="list-style-type: none"> • Take off • Climb out • Cruise • Approach • Landing
Inactive operation	<ul style="list-style-type: none"> • Idling 	<ul style="list-style-type: none"> • Idling • Auxiliaries (HVAC and lighting) 	<ul style="list-style-type: none"> • Auxiliary power unit operation • Startup • Taxi out • Taxi in
Non-operational components			
Manufacturing (facility construction excluded)	<ul style="list-style-type: none"> • Vehicle manufacturing • Engine manufacturing 	<ul style="list-style-type: none"> • Train manufacturing • Propulsion system manufacturing 	<ul style="list-style-type: none"> • Aircraft manufacturing • Engine manufacturing
Maintenance	<ul style="list-style-type: none"> • Vehicle maintenance • Tire replacement 	<ul style="list-style-type: none"> • Train maintenance • Train cleaning • Flooring replacement 	<ul style="list-style-type: none"> • Aircraft maintenance • Engine maintenance
Insurance	<ul style="list-style-type: none"> • Vehicle liability 	<ul style="list-style-type: none"> • Crew health and benefits • Train liability 	<ul style="list-style-type: none"> • Crew health and benefits • Aircraft liability
<i>Infrastructure</i>			
Construction	<ul style="list-style-type: none"> • Roadway construction 	<ul style="list-style-type: none"> • Station construction • Track construction 	<ul style="list-style-type: none"> • Airport construction • Runway/taxiway/tarmac construction
Operation	<ul style="list-style-type: none"> • Roadway lighting • Herbicide spraying • Roadway salting 	<ul style="list-style-type: none"> • Station lighting • Escalators • Train control • Station parking lighting • Station miscellaneous (e.g., other electrical equipment) 	<ul style="list-style-type: none"> • Runway lighting • Deicing fluid production • Ground support equipment operation
Maintenance	<ul style="list-style-type: none"> • Roadway maintenance 	<ul style="list-style-type: none"> • Station maintenance • Station cleaning 	<ul style="list-style-type: none"> • Airport maintenance
Parking	<ul style="list-style-type: none"> • Roadside, surface lot, and parking garage parking 	<ul style="list-style-type: none"> • Station parking 	<ul style="list-style-type: none"> • Airport parking
Insurance		<ul style="list-style-type: none"> • Non-crew health insurance and benefits • Infrastructure liability insurance 	<ul style="list-style-type: none"> • Non-crew health and benefits • Infrastructure liability
<i>Fuels</i>			
Production	<ul style="list-style-type: none"> • Gasoline and diesel fuel refining and distribution (includes through fuel truck delivery stopping at fuel station. Service station construction and operation is excluded) 	<ul style="list-style-type: none"> • Train electricity generation • Train diesel fuel refining and distribution (Caltrain) • Train electricity transmission and distribution losses • Infrastructure electricity production • Infrastructure electricity transmission and distribution losses 	<ul style="list-style-type: none"> • Jet fuel refining and distribution

modes. The automobile and bus non-operational components are dominated by electricity production, steel production, and truck and air transport of materials in vehicle manufacturing and maintenance [20]. The construction of the US road and highway infrastructure has large energy implications (in material extraction, material production, and construction operations), between 0.3 and 0.4 MJ/PKT for autos [21–23].

Rail modes have the smallest fraction of operational to total energy due to their low electricity requirements per

PKT relative to their large supporting infrastructures [20]. The construction and operation of rail mode infrastructure results in total energy requirements about twice that of operational.

Aircraft have the largest operational to total life-cycle energy ratios due to their large fuel requirements per PKT and relatively small infrastructure. The active and inactive operational groupings include several components (table 1) and energy consumption is dominated by the cruise phase [24, 25].

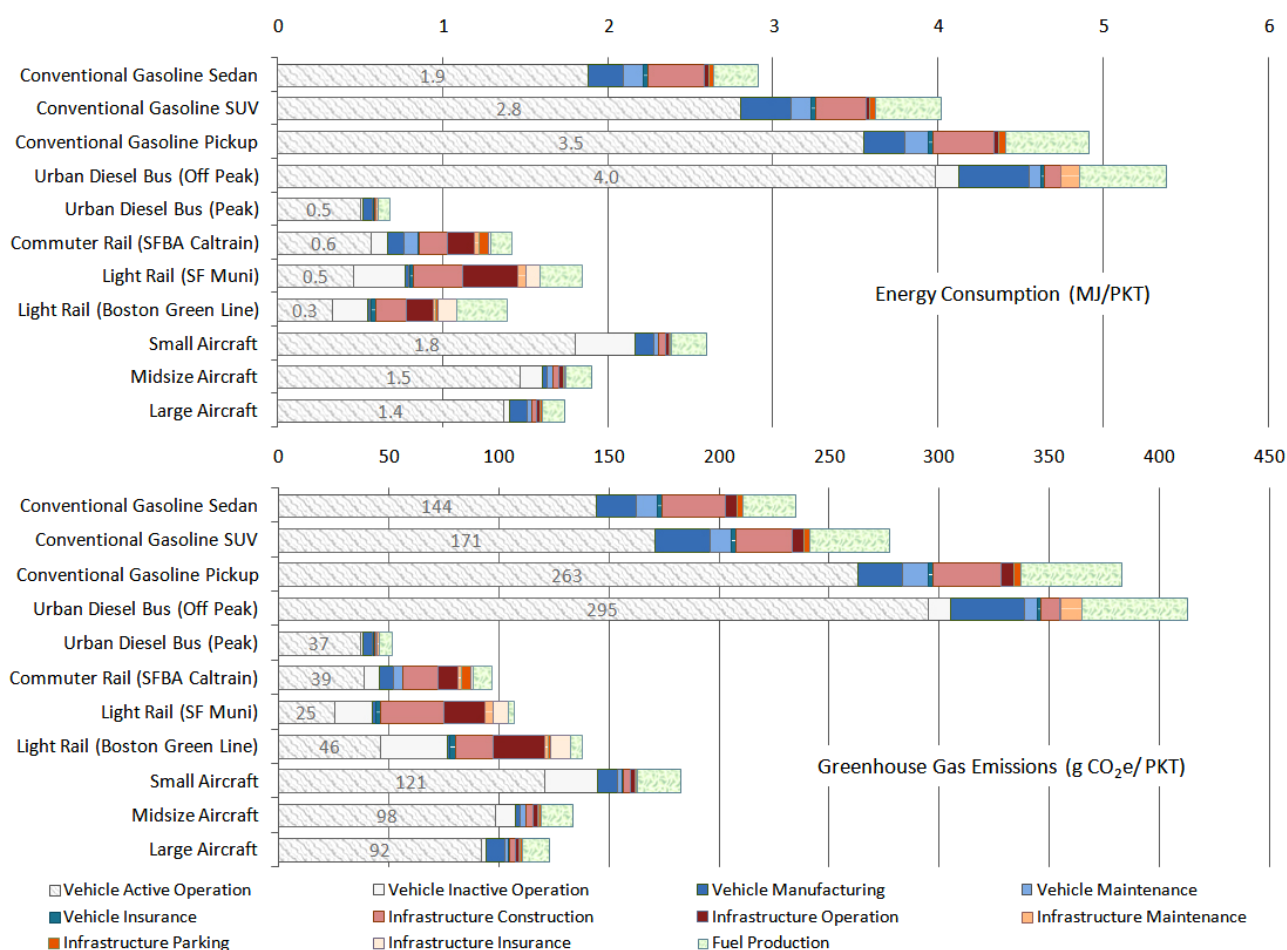


Figure 1. Energy consumption and GHG emissions per PKT (The vehicle operation components are shown with gray patterns. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel production component is shown in green. All components appear in the order they are shown in the legend.).

3.2. Greenhouse gases

The energy inputs described are heavily dominated by fossil fuels resulting in a strong positive correlation with GHG emissions. The life-cycle component contributions are roughly the same as the GHG contributions and produce 1.4–1.6 times larger life-cycle factors for onroad, 1.8–2.5 times for rail, and 1.2–1.3 times for air than the operational components. Total emissions for each mode are shown in figure 1.

While the energy input to GHG emissions correlation holds for almost all modes, there is a more pronounced effect between the California (CA) and Massachusetts (MA) LRT systems. The San Francisco Bay Area's electricity is 49% fossil fuel-based and Massachusetts's is 82% [26, 27]. The result is that the Massachusetts LRT, which is the lowest operational energy user and roughly equivalent in life-cycle energy use to the other rail modes, is the largest GHG emitter.

3.3. Criteria air pollutants

Figure 2 shows SO₂, NO_x, and CO emissions for each life-cycle component. The inclusion of non-operational components can lead to an order of magnitude larger emission factor for total emissions relative to operational emissions.

3.3.1. SO₂ contributors. Electricity generation SO₂ emissions dominate life-cycle component contributions for all modes. While electric rail modes have large contributions from vehicle operation components, this is not the case for autos, buses and commuter rail due to the removal of sulfur from gasoline and diesel fuels. Low sulfur levels in fuels result in low SO₂ emissions from fuel combustion compared to the relatively large SO₂ emissions from electricity generation in other components. Total automobile SO₂ emissions are 19–26 times larger than operational emissions and are due to vehicle manufacturing and maintenance, roadway construction and operation (particularly lighting), parking construction, and gasoline production. The electricity requirements in vehicle manufacturing, vehicle maintenance, roadway lighting, road material production, and fuel production (as well as off-gasing) result in significant SO₂ contributions [20, 21, 26, 28]. Bus emissions are dominated by vehicle manufacturing, roadway maintenance [21], and fuel production. Vehicle manufacturing, infrastructure construction, infrastructure operation, parking, insurance, and fuel production produce emission factors for rail modes that are 2–800 times (assuming Tier 2 standards) larger than operational components. The majority of vehicle manufacturing emissions result from direct electricity

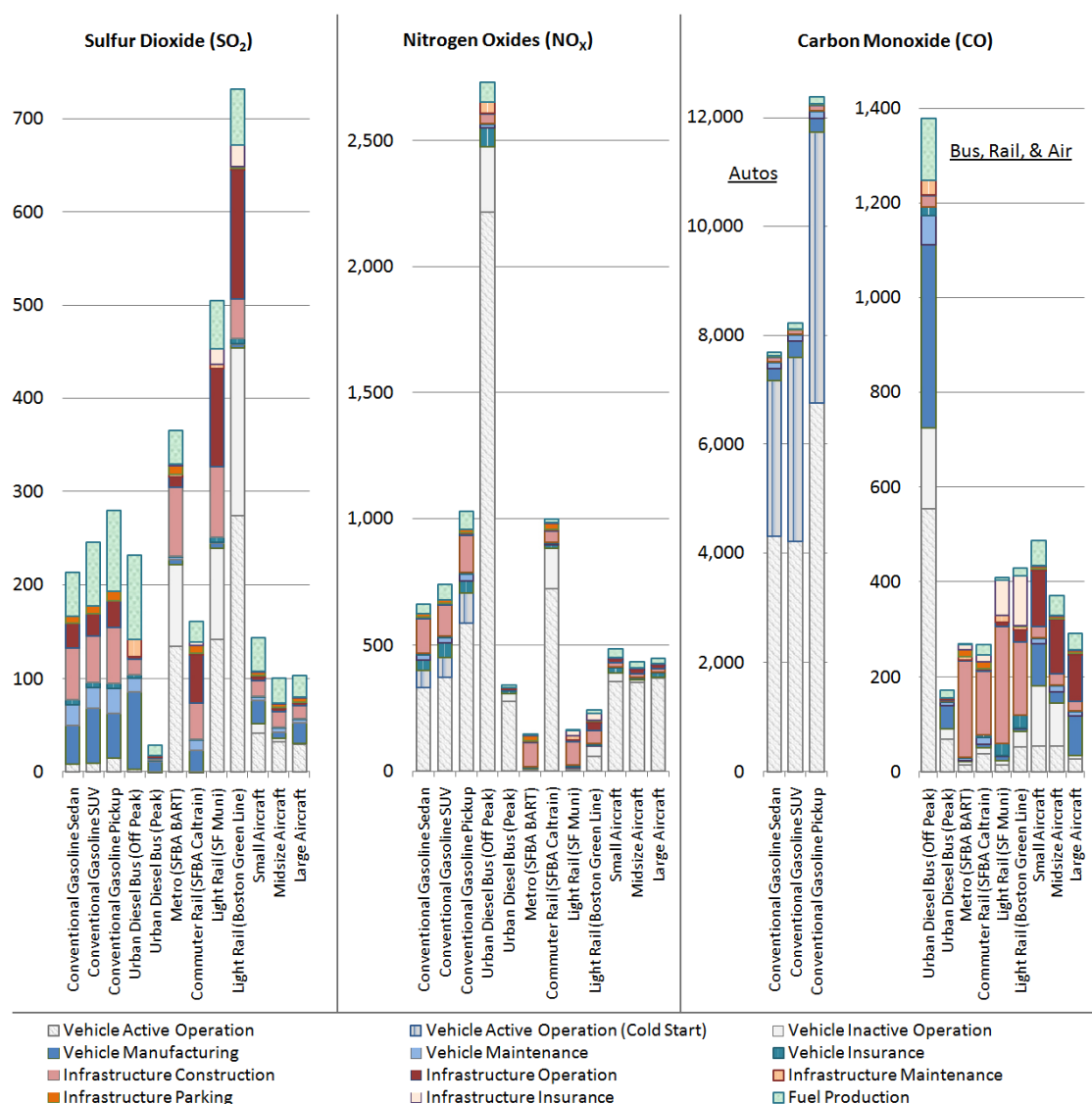


Figure 2. Criteria air pollutant emissions in mg per PKT (The vehicle operation components are shown with gray patterns. Other vehicle components are shown in shades of blue. Infrastructure components are shown in shades of red and orange. The fuel production component is shown in green. All components appear in the order they are shown in the legend.).

requirements in assembling the parts as well as the energy requirements to produce steel and aluminum for trains. Total aircraft SO_2 emissions are composed of 64–71% non-operational emissions, and are attributed mostly to the direct electricity requirements in aircraft manufacturing and indirect electricity requirements in the extraction and refinement of copper and aluminum [20].

3.3.2. NO_x contributors. Life-cycle NO_x emissions are often dominated by tailpipe components, however, autos and electric rail modes show non-negligible contributions from other components. Non-operational NO_x emissions are due to several common components from the supply chains of all the modes: direct electricity use, indirect electricity use for material production and processes, and truck and rail transportation. With onroad modes, electricity requirements for vehicle manufacturing and maintenance as well as truck and rail material transport are large contributors [20]. The

transport of materials for asphalt surfaces is the primary culprit in roadway and parking construction [21]. Fuel refinery electricity and diesel equipment use in oil extraction add to the component's contribution to total emissions [20]. For rail, the dependence on concrete in infrastructure (resulting in large electricity requirements for cement manufacturing and diesel equipment use in placement) impacts the contribution from construction and maintenance increasing total NO_x emissions by 2.4–12 times for the electric modes and 1.1 times for commuter rail. Aircraft manufacturing, infrastructure operation, and fuel production produce emissions from aircraft that are 1.2 times larger than operational emissions. The direct electricity requirements and truck and rail transport are the key components in aircraft manufacturing.

3.3.3. CO contributors. While automobile CO emissions are dominated by the vehicle operation phase, this is not the case for bus, rail, and air modes. Automobile CO emissions

are approximately 110 and 40 times larger per PKT than rail and aircraft, respectively, due to a roughly equivalent per vehicle-kilometers-traveled (VKT) emission factor but vastly different occupancy rates. The largest non-operational component is vehicle manufacturing which accounts for about 3% and 28% of total automobile and bus emissions due mainly to truck transport of materials and parts. The production of cement for concrete in stations and truck transport of supplies for insurance operations are the underlying non-operational causes for rail CO emissions. Large concrete requirements result in large CO emissions during cement production for station construction and maintenance [20]. Rail infrastructure emissions (140–260 mg/PKT) are 42–76% of life-cycle emissions (270–430 mg/PKT). Truck transport in aircraft manufacturing, airport ground support equipment (GSE) operation, and jet fuel production produce life-cycle emissions that are 2.6–8.5 times larger than operation (30–180 mg/PKT) [24, 25]. The use of diesel trucks to move parts and materials needed for aircraft manufacturing contributes strongly to the component (20–90 mg/PKT) [20]. The emissions from airport operation are dominated by GSE operations. Particularly, the use of gasoline baggage tractors contributes to roughly half of all GSE emissions [25, 29].

4. Sensitivity to passenger occupancy

While the per-VKT performance of any mode can potentially be improved through technological advancements, the per-PKT performance, which captures the energy and emissions intensity of moving passengers, is the result of occupancy rates. An evaluation of these occupancy rates with realistic low and high ridership illustrates both the potential environmental performance of the mode as well as the passenger conditions when modes are equivalent.

Figure 3 highlights these ranges showing average occupancy life-cycle performance and the ranges of performance from low and high ridership (low ridership captures the largest energy consumption and emissions per PKT, at the worst performing times, while high ridership captures the mode's best performance). Auto low occupancy is specified as one passenger and the high as the number of seats. Bus low occupancy is specified as five passengers and the high as 60 passengers (including standing passengers). Rail low occupancy is specified as 25% of the number of seats and the high as 110% of seats (to capture standing passengers). Aircraft low occupancy is 50% and the high is 100% of the number of seats. The occupancy ranges are detailed in SI table S5 (available at stacks.iop.org/ERL/4/024008). Discussion of the environmental performance of transit modes often focuses on the ranking of vehicles assuming average occupancy. This approach does not acknowledge that there are many conditions under which modes can perform equally. For example, an SUV (which is one of the worst energy performers) with 2 passengers (giving 3.5 MJ/PKT) is equivalent to a bus with 8 passengers. Similarly, CA HRT with 120 passengers (27% occupancy giving 1.8 MJ/PKT) is equivalent to a midsize aircraft with 105 passengers (75% occupancy). Similarly, commuter rail (with one of the highest average per-PKT

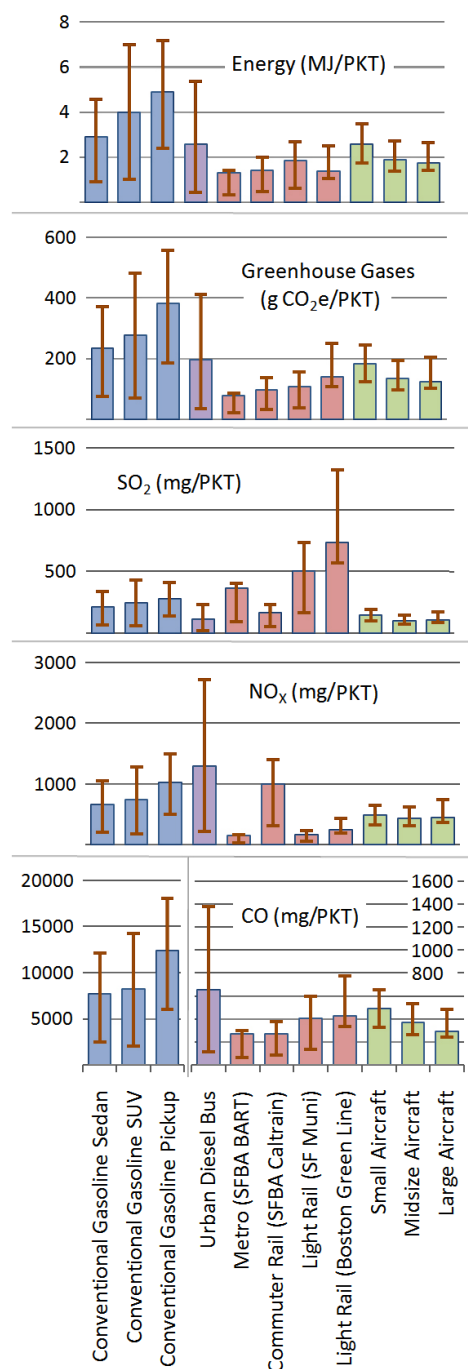


Figure 3. Occupancy sensitivity (Average occupancy and life-cycle performance is shown as the blue (autos), purple (bus), red (trains), and green (aircraft) bars. The maroon-colored line captures the range in per-PKT energy consumption and emissions at low and high occupancy).

NO_x emission rates) at 34% occupancy (147 passengers) is equivalent to a bus with 13 passengers or a sedan with one passenger. Focusing on occupancy improvements does not acknowledge the sensitivity of performance to technological changes. For example, holding occupancy at the average, electric rail modes would have to decrease SO₂ per-PKT emissions between 24 and 85% to compete with onroad modes, an effort that would have to focus on electricity fuel inputs and scrubbers at power plants.

5. Appropriate emission reduction targets

The dominant contributions to energy consumption and GHG emissions for onroad and air modes are from operational components. This suggests that technological advancements to improve fuel economy and switches to lower fossil carbon fuels are the most effective for improving environmental performance. Rail's energy consumption and GHG emissions are more strongly influenced by non-operational components than onroad and air. While energy efficiency improvements are still warranted coupled with lower fossil carbon fuels in electricity generation, reductions in station construction energy use and infrastructure operation could have notable effects. Particularly, the reduction in concrete use or switching to lower energy input and GHG-intensity materials would improve infrastructure construction performance while reduced electricity consumption and cleaner fuels for electricity generation would improve infrastructure operation. Utilizing higher percentages of electricity from hydro and other renewable sources for rail operations could result in significant GHG reductions over fossil-based inputs such as coal.

The life-cycle non-operational components are sometimes responsible for the majority of CAP emissions so reduction goals should consider non-operational processes. SO₂ emissions for all modes are heavily influenced by direct or indirect electricity use. Similarly, significant NO_x emission reductions can be achieved through cleaner electricity generation but also the reduction of diesel equipment emissions in transport and material extraction operations. The reductions could be achieved by decreased or cleaner electricity consumption, using equipment with cleaner fuel inputs, or through the implementation of improved emissions controls. While automobile CO emissions are mainly from active operation (with a large portion attributed to the cold start phase), rail emission reductions are best achieved by reducing the use of concrete in stations. A switch away from diesel or gasoline equipment or stronger emission controls can have strong implications for aircraft total CO emissions in truck transport and GSE operations.

This study focuses on conventional gasoline automobiles and it is important to consider the effects of biofuels and other non-conventional energy inputs on life-cycle results. LCAs of biofuels are starting to be developed and will provide the environmental assessments necessary for adjusting primarily the 'fuel production' component of this LCA. Inputs such as electricity for plugin hybrid electric vehicles could also significantly change several components in this study. Batteries in vehicle manufacturing, differing operational characteristics, and electricity production (especially wind and solar) are just some of the components that would affect the results presented here. This study creates a framework for comprehensive environmental inventorying of several modes and future assessment of non-conventional fuels and vehicles can follow this methodology in creating technology-specific results.

Future work should also focus on environmental effects not quantified herein, such as the use of water [30], generation of waste water, and toxic emissions [31]. Detailed assessments

of the end-of-life fate of vehicles [32], motor oil [33] and infrastructure [34] should also be factored into decisions.

Through the use of life-cycle environmental assessments, energy and emission reduction decision-making can benefit from the identified interdependencies among processes, services, and products. The use of comprehensive strategies that acknowledge these connections are likely to have a greater impact than strategies that target individual components.

Acknowledgments

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