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Greenhouse gas and air quality effects of auto first-last mile use with transit

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ABSTRACT

With potential for automobiles to cause increased greenhouse gas emissions and air pollution relative to other modes, there is concern that using automobiles to access or egress public transportation may significantly increase the environmental impacts from door-to-door transit trips. Yet little rigorous work has been developed that quantitatively assesses the effects of transit access or egress by automobiles. This research evaluates the life-cycle impacts of first-and-last mile trips on multimodal transit. An environmental life-cycle assessment of transit and automobile travel in the greater Los Angeles region is developed to evaluate the impacts of multimodal transit trips by utilizing existing transportation life-cycle assessment methods. First-last mile automobile trips with transit may increase multimodal trip emissions significantly, mitigating potential impact reductions from transit usage. In some cases, multimodal transit trips with first-last mile automobile use may have higher emissions than competing automobile trips. In the near-term, first-last mile automobile trips in some Los Angeles transit services may account for up to 66% of multimodal greenhouse gas emissions, and as much as 75% of multimodal air quality impacts. Fossil fuel energy generation and combustion, low vehicle occupancies, and longer trip distances contribute most to increased multimodal impacts. Supply chain analysis indicates that life-cycle air quality impacts may occur largely locally (in Los Angeles) or largely remotely depending on the propulsion method and location of upstream life-cycle processes. Reducing 10% of transit system greenhouse emissions requires a shift of 23–50% of automobile first-last mile trips to a neutral emissions mode.

1. Introduction

With heightened awareness of the impacts of greenhouse gas (GHG) emissions and criteria air pollutants (CAP), focus on understanding and mitigating human and environmental impacts from transportation has become a major priority for many planning and government agencies. In 2014, the transportation sector accounted for over a quarter of all GHG emissions in the United States (EPA, 2016). In the last two decades, extensive research and literature has evaluated the human and environmental impacts of various transportation modes. This has led to increased regulations for air quality (CARB, 2000), improvements to automobile fuel economies (Jaffe et al., 2005), and frequent use of life-cycle assessment (LCA) to evaluate the direct and indirect effects of transportation systems (McKenzie and Durango-Cohen, 2012; Nordelöf et al., 2014). Public transit has been shown to reduce human and environmental impacts and is increasingly utilized to meet policy goals of

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reduced GHG and CAP emissions (Matute and Chester, 2015). Public transportation can reduce GHG and CAP emissions per passenger mile in comparison to private automobile travel (Chester and Horvath, 2009), especially when considering the low occupancy of auto travel (Santos et al., 2011) and the use of alternative fuels transit vehicles (Neff and Dickens, 2016). Most studies, however, focus on comparative assessments of modes, not accounting for access and egress in door-to-door travel. In Los Angeles (LA), approximately 25% of rail trips begin with an automobile trip (LA Metro, 2016a). There remain significant gaps in our understanding of how first-last mile transit access and egress contribute to human and environmental impacts. With high potential for automobiles to contribute to multimodal transit trip emissions, this research aims to evaluate the life-cycle impacts of first-last mile trips in multimodal transit using LA as a case study.

Environmental LCA has become a powerful tool to aid in the understanding of direct, indirect, and supply chain impacts in many systems including electric supply technologies (Turconi et al., 2013; Weisser, 2007), agriculture processes (Meisterling et al., 2009), and transportation systems (Chester and Horvath, 2009; Facanha and Horvath, 2007). LCA has also been used to aid in transportation policy and decision making (Chester and Cano, 2016; Eisenstein et al., 2013; Plevin et al., 2014). With the National Ambient Air Quality Standards, agencies such as the California Air Resource Board (CARB) regulating air quality, and metropolitan planning organizations developing policies to reduce GHG emissions through transportation planning, there continues to be great value in using LCA to evaluate transportation related life-cycle impacts.

Some literature has investigated multimodal environmental impacts in transit systems, however, there is a lack of analyses that comprehensively assess first-last mile automobile travel in transit systems with both regional travel characteristics and life-cycle modeling. Chester and Cano (2016) utilize environmental LCA to evaluate time-based impacts of the LA Expo light rail transit (LRT) line with comparison to a LA automobile. In this study, first-last mile auto use with the Expo LRT line was found to have similar or more GHG and CAP emissions per trip compared to a typical auto trip. However, there remains room for improvement because competing and first-last mile auto trips were assumed to occur with average LA travel characteristics. Additionally, the study focuses on only one transit line, so it is unclear if this travel profile is representative. In another study, Mathez et al. (2013) evaluates GHG emissions in Montreal, Canada across multiple modes of transportation by conducting and analyzing a comprehensive regional travel survey. However, this analysis omits LCA and instead utilizes average GHG emission factors for auto and transit modes, with GHG emission factors for regional transit modes provided by the regional transit authorities. These emissions factors only account for the operation phase, therefore LCA would provide a more comprehensive evaluation of impacts. For example, the Montreal Metro is assumed to emit no GHG emissions per passenger mile citing that the system is fully powered by hydro-electric power. Although hydro-electric power has very low GHG emissions, they are non-zero (Varun et al., 2009). Despite limitations, both studies similarly conclude that auto first-last mile trips with transit can produce comparable emissions to a competing auto trip.

Due to a lack of comprehensive studies on first-last mile human and environmental impacts in multimodal transit, it is unclear if targeting these trips could promote emission reductions and continue to aid in policy decision making. A case study of transit and automobile travel in the LA metropolitan region is used to evaluate the impacts of multimodal transit trips to address this question. Through urban planning and sustainable transportation development, public and urban transportation may be positioned to reduce human and environmental impacts. This requires comprehensive LCA with inclusion of first-last mile travel in transportation systems to establish the underlying characteristics that govern human and environmental impacts in multimodal transit.

2. Methodology

An environmental LCA framework is developed by expanding on previously related work to evaluate the impacts of multimodal transit trips. LCA is applied to ten transit services in the LA metropolitan region consisting of four light rail lines, one heavy rail line, three bus services, one bus rapid transit service, and one commuter rail service. In addition, regional automobile impacts are developed to evaluate the characteristics of competing automobile trips and automobile trips accessing or egressing transit. The LCA is designed to account for near-term and long-term life-cycle impacts to provide estimates of how technological improvements, ridership changes, and changes in energy mixes will affect environmental performance in the coming years as well as several decades out. The LCA includes vehicle manufacturing, vehicle maintenance, vehicle operations (e.g., fuel combustion or propulsion effects), infrastructure (construction, maintenance, and operation), and energy production following the methodology developed by Chester and Horvath (2009). Trip characteristics in the LA region are compiled using travel survey data from the California Household Travel Survey (CHTS) and combined with environmental impacts characterized through LCA to estimate multimodal trip impacts.

2.1. Energy and environmental indicators and stressors

The LCA focuses on attributional impacts allocated to each transit service by evaluating near-term and long-term footprints per passenger-mile traveled (PMT). The life-cycle inventory includes end use energy and emissions of GHGs, carbon monoxide (CO), nitric oxide and nitrogen dioxide (NO_X), fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), and volatile organic compounds (VOC). GHG emissions are reported as carbon dioxide equivalence (CO_2e) using radiative forcing multipliers of 25 for CH_4 and 298 for N_2O over a 100 year horizon. CO, NO_X, PM, and SO_2 are evaluated because they are regulated through National Ambient Air Quality Standards and NO_X and VOC are ozone precursors (EPA, 2006). To evaluate the air quality impact potential, impact characterization factors from the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts were used to transform the CAP emissions inventory into smog and respiratory stressors (Bare, 2011). A stressor indicates the potential upper limit of impacts that could occur, not the actual impacts. SO_2, PM, and NO_X emissions were normalized into respiratory stressors ($PM_{2.5}e$), and CO, VOC, and NO_X emissions were normalized into photochemical smog stressors (O_3e) to assess midpoint impact potentials.

2.2. Characteristics of Los Angeles transportation systems

All major transit services in the Los Angeles County Metropolitan Transit Authority (LA Metro) and a representative Metrolink service are evaluated to identify the characteristics that contribute to transit life-cycle impacts in the greater LA metropolitan region. LA Metro runs four LRT lines and two heavy rail transit (HRT) lines, all powered by electric propulsion. Due to the similarities and shared properties between the two HRT lines, the impacts are evaluated as a single line. Four LA Metro bus services are evaluated; Local Bus service, Rapid Bus service, Express Bus service, and the Orange Bus Rapid Transit (BRT) service. Together, they account for nearly three quarters of all LA Metro annual boardings (LA Metro, 2016b). All LA Metro buses run on compressed natural gas (CNG). The Local Bus service operates over 100 routes in the LA metropolitan region providing traditional local and shuttle bus services. The Rapid Bus service operates in mixed traffic with fewer stops and traffic signal priorities. The Express Bus service operates longer routes with partial limited stop and nonstop segments. The Orange BRT service operates on an 18 mile dedicated right-of-way busway operating in the San Fernando Valley. Metrolink is a commuter rail transit (CRT) service operating seven lines throughout Southern California operated by the Southern California Regional Rail Authority (SCRRA). Each of Metrolink's seven lines operate under similar conditions, with a shared vehicle fleet and mandated infrastructure design and maintenance for the whole system. As such, impacts for the Metrolink CRT service are modeled based on average operations and standardized train and track construction.

2.3. Life-cycle modeling of the Los Angeles transportation systems

The LCA builds on previous related research and significant efforts are made to obtain up-to-date line-specific data. The approach uses processes and methods previously outlined for assessing impacts in passenger transportation (Chester and Horvath, 2009), some of which includes previous analysis of the Expo LRT line (Chester and Cano, 2016), and the Gold LRT and Orange BRT services (Chester et al., 2013). The following discussion focuses on the new and updated data collection and general methods used to assess the most significant life-cycle processes.

2.3.1. Vehicle manufacture and maintenance

Vehicle manufacturing and maintenance are modeled by weighted vehicle characteristics for the rolling stock of each transit line or service. Weighted vehicle characteristics (e.g., length, weight, capacity, etc.) are estimated for each service based on reports of rolling stock from the transit authorities (LA Metro, 2016b, 2016c; SCRRA, 2012) and the National Transit Database (NTD). Manufacturing impacts of these weighted vehicle characteristics are assessed in SimaPro (PRé Consultants, 2014) with regional energy mixes for the locations where assembly occurred and final delivery of vehicles to LA. Near-term rail manufacturing and maintenance impacts are modeled after Siemens, Nippon Sharyo, Kinkisharyo, and AnsaldoBreda light rail vehicles (LRV) and heavy rail vehicles. Near-term Metrolink impacts are modeled after various passenger and cab cars manufactured by Bombardier and General Motors. Long-term light rail manufacturing impacts are modeled after Kinki Sharyo P3010 light rail vehicles assuming LA Metro exercises their full contract with Kinki Sharyo to obtain 235 LRVs (LA Metro, 2012). The long-term Metrolink impacts are modeled after the new EPA tier 4 emission compliant locomotives (SCRRA, 2016a). Manufacturing and maintenance impacts for the Metro bus fleet are modeled after 60 foot articulated CNG buses (for the Orange BRT) and an amalgamation of other CNG bus models ranging from 31 feet to 60 feet (all other lines) manufactured by North American Bus Industries and New Flyer Industries. Manufacturing locations for transit vehicles are assumed to be the primary company manufacturing plants in the US unless otherwise stated. Battery life-cycle impacts for buses (including replacements) are included in these models. Earlier model Kinko Sharyo LRVs were manufactured in Japan and two models of AnsaldoBreda vehicles were manufactured in Italy before being shipped to the US and assembled in Los Angeles (Chester and Cano, 2016; Upton, 2011). New LRVs procured for LA Metro were manufactured and assembled in California (Nelson, 2014).

2.3.2. Infrastructure construction and maintenance impacts

Life-cycle impacts from construction and maintenance are modeled for rail track, transit stations, parking infrastructure, roadways, and other ancillary infrastructure. The assessment is based on engineering design documents (LA Metro, 2016c; SCRRA, 2016b) to evaluate at-grade, aerial, and underground track and station construction as well as parking infrastructure construction. This approach follows previous research (Chester and Cano, 2016) in which use of concrete and asphalt have been identified to have significant impacts on the life-cycle of transit systems. As such, a region-specific material production analysis is developed in SimaPro with additional assessment of station and parking construction and maintenance in the City Road Network (CiRN) LCA model (Fraser and Chester, 2015). To allocate impacts of road construction and maintenance to LA Metro bus use, roadway damages caused by LA Metro buses are also estimated. The total damage from Metro buses is determined by estimating the equivalent single axle loading (ESAL) per VMT as a fraction of the total ESAL per VMT on all bus routes. All routes are assumed to take place on major or minor arterial roads with the total route miles determined from LA Metro route data. Total yearly VMT data was obtained from the 2014 Highway Statistics Series data set (USDOT, 2014). Road construction and maintenance impacts are estimated with CiRN-LCA based on typical LA arterial segments.

2.3.3. Operational and propulsion effects

The LA Metro rail service operational impacts are attributed to electricity use (vehicle propulsion and station operation), which varies by rail line. LA Metro stations consume electricity due to various processes including lighting, escalator use, ticket kiosks, and station cleaning. Electricity consumption data were obtained from LA Metro in the form of meter readings by station and utility provider (LA Metro, 2014a). Energy mixes of the three utility providers are estimated to determine operational impacts in the LA Metro rail system. The Los Angeles Department of Water and Power (LADWP) provides most of the electricity in the LA Metro rail system, entirely supplying the Red HRT line and also supplying significant amounts to the Expo and Gold LRT lines. Southern California Edison (SCE) provides most of the electricity used by the Blue and Green LRT lines, and Pasadena Water and Power (PWP) supplies only small amounts to the Gold LRT line. Although California has largely abandoned coal-fired energy generation methods (CEC, 2015), LADWP and PWP still supply a significant amount of out-of-state coal-fired energy to meet consumption demands in the region (LADWP, 2015; PWP, 2015). As a result, coal-fired generation makes up over a third of the electricity supplied to the Red, Gold, and Expo lines. The Green and Blue LRT lines' electricity use is comprised of less than a fifth of coal generation, instead utilizing more natural gas (Ellis et al., 2014). Fig. 1 shows detailed electricity use for each of the LA Metro rail lines.

Due to a lack of robust modeling of CNG bus drive cycle emissions, LA Metro bus operational impacts are estimated by aggregating CNG emissions tested under various drive cycles. LA Metro schedule data are summarized to estimate the scope of observable bus stops per mile for each bus service (LA Metro, 2016d). Characteristics of urban bus drive cycles are then compared to the observable route stops per mile for the Local, Rapid, and Express Bus services to determine appropriate drive cycles. Matching similar drive cycles to each bus service's route characteristics allows for estimated tailpipe emissions during Metro bus operation. Three drive cycles that most closely matched the range of observed LA Metro bus driving characteristics (speed and stop frequency) are chosen: the Central Business District drive cycle, the Manhattan drive cycle, and the Orange County drive cycle. Drive cycle tailpipe emissions were then inventoried and estimated for the Local, Rapid and Express Bus services from test results of similar CNG buses from three separate sources (Ayala et al., 2002; Bradley, 2013; Posada, 2009). Due to uncertainties about future emissions, it is assumed that long-term bus use will achieve fuel economies and emissions consistent with the best available current technology, and air pollutants will meet 75–85% reductions as outlined by the CARB 2020 certification standards (CARB, 2000). Orange BRT operational impacts are based on emissions testing by CARB of similar bus engines (Thiruvengadam et al., 2011) following a similar procedure outlined in Chester et al. (2013). Fuel consumption of the entire LA Metro CNG bus fleet from the NTD is compared to estimated fuel economies to verify results. CNG fuel consumption from 2014 was estimated to be 4% lower than the actual fuel consumption reported in the NTD in 2014 (NTD, 2015a). This indicates that estimated impacts of LA Metro buses are reasonably accurate. Because fuel consumption estimates rely on yearly vehicle miles traveled (VMT), underestimation likely occurs because VMT (via odometers readings) does not account for idling. Additionally, it is possible that under or unreported non-revenue services also contribute to this underestimation.

Metrolink operational impacts are modeled after representative operating schedules in the Metrolink system. Representative operational impacts are modeled after routes that match the Metrolink service average distribution of stations per mile and system average train speeds. Using EMD F59PH locomotive emissions recorded at multiple steady-state operation levels found in Fritz (1994), locomotive exhaust emissions are then estimated over the representative routes. Diesel fuel consumption from 2014 was estimated to be 7% lower than the actual fuel consumption reported in the NTD (2015a). This indicates that the estimated impacts of Metrolink locomotives are also reasonably accurate. Similar to the trend in LA Metro bus services, under estimation likely occurs due to unaccounted idling or non-revenue services.

2.3.4. Los Angeles automobile Life-cycle assessment

An automobile trip in LA that would substitute, access, or egress transit is assessed. Internal combustion engine vehicle and battery manufacturing, vehicle operation, and vehicle maintenance of a LA sedan using California reformulated gasoline is modeled in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (GREET, 2015). Near-term use is assessed at 25 mile per gallon (MPG) fuel economy and long-term use is assessed at 55 MPG fuel economy to be consistent with Corporate Average Fuel Economy standards by year 2025 (EPA, 2012). It should be acknowledged that the potential relaxing of long-term standards could result in fuel economies lingering at near-term levels. Long-term automobile manufacture and operation are modeled as lighter weight with improvements in manufacturing to help meet fuel economy standards. Impacts of LA roadway infrastructure construction and maintenance of a typical arterial segment are allocated by ESAL per VMT (following the same method outlined previously for buses).

2.4. Multimodal trip development

Trip characteristics are developed to compare multimodal trip impacts in the LA metropolitan region. Travel survey data were obtained from the CHTS with supplementary transit statistics from LA Metro. The CHTS data set is filtered to include

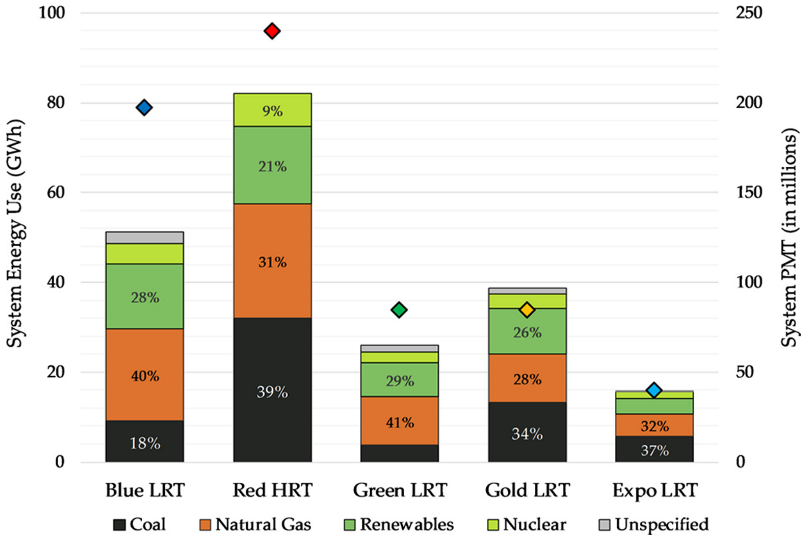

Fig. 1. Electricity use in the LA Metro rail system. LA Metro rail system electricity consumption in 2014 is shown by line and generation methods. A secondary axis (right) with corresponding diamond indicators of 2014 PMT by line is shown for comparison. Energy mix compositions are based on reports from LADWP, PWP, and SCE (Ellis et al., 2014; LADWP, 2015; PWP, 2015). Note that coal-firing occurs largely outside California.

samples only in the greater LA metropolitan region where 82% of trips were by automobile (Caltrans, 2013). All transit trips (public and private) account for less than 4% of the samples. Most transit trips are accessed or egressed through walking, with a small fraction of first-last mile auto trips. Metrolink CRT has the highest fraction first-last mile auto trips at 33% in the CHTS, and 28% according to a separate origin-destination study (Redhill Group, 2015). First-last mile statistics are displayed in Table 1. Metro rail users reported accessing their rail trip with auto nearly one quarter of the time, and Metro bus users reported accessing their bus trip with auto roughly one tenth of the time.

To determine auto trip characteristics, an origin-destination analysis is conducted. A competing auto trip is defined as a single automobile trip that replaces a multimodal transit trip from origin to destination. To determine the characteristics of competing auto trips, transit trip origin-destination pairings are cross-referenced with auto trips of the same origins and destinations in the CHTS. Based on the size and spatial distribution of the samples, the origin-destination analysis is conducted at a zip code level. This allowed evaluation of transit and auto trip characteristics between or within over 900 sub-regions in the greater LA metropolitan region. Because transit routes are fixed but serve dynamic user origin-destination demand, competing auto trips often benefit from more direct routes between the same origins and destinations. This leads to shorter average competing auto trips than multimodal transit trips for the same origin-destination pairings in most cases. Due to the small sample size of first-last mile auto trips in the Metro Local and Rapid Bus services, first-last mile trip trends were merged together for these two services. Additionally, because the Expo LRT system opened in mid-2012 while the CHTS was already underway, only four auto-rail trips were observed, and were not assumed to be representative. Therefore, Expo LRT characteristics assumes average LA Metro auto-rail trip characteristics. Table 2 summarizes the trip characteristics by line. With comprehensive multimodal trip characteristics, life-cycle trip impacts are developed by joining trip characteristics with per mile LCA results.

3. Results

Per mile end use energy, GHG emissions, respiratory impact potential, and smog impact potential are first shown for each transit line followed by discussion of major contributing processes. Once the underlying trends for each transit system are established, multimodal trip and competing auto trip impacts are introduced and discussed.

3.1. Life-cycle impacts per passenger mile

Fig. 2 shows the near and long-term life-cycle end use energy, GHG emissions, respiratory impact potential, and smog impact potential per PMT for all modes assessed. For transit modes, vehicle operation (propulsion electricity or fuel combustion) is the largest contributor to GHG emissions and total end use energy per PMT followed by infrastructure operation (primarily station electricity use). For LA Metro rail, near-term GHG emissions are largely impacted by the carbon-intensity of electricity generation. The Gold and Expo LRT lines are supplied with high fractions of coal-fired electricity, and have lower average ridership than the other rail lines. Higher average ridership (Red HRT, Blue LRT, and Metrolink CRT), and less carbon-intense electricity generation (Blue and Green LRT) are the main factors that contribute to lower GHG emissions per PMT.

Table 1
First-last mile modal split in Los Angeles. First-last mile mode selection data are shown from two different surveys, the CHTS and LA Metro on-board surveys (LA Metro, 2016a). LA Metro on-board survey results are shown from the year 2012 to compare with the CHTS data, which was conducted in the same year.

Transit Mode	Walk	Auto	Other
CHTS			
Blue LRT	91%	7%	2%
Red HRT	90%	5%	5%
Green LRT	76%	21%	3%
Gold LRT	78%	19%	3%
Local/rapid bus	99%	1%	0%
Express bus	100%	0%	0%
Orange BRT	95%	2%	3%
Metrolink CRT	65%	33%	2%
LA Metro			
Bus	84%	10%	6%
Rail	64%	27%	9%

Table 2
Multimodal transit and competing auto trip characteristics by transit line. Average trip distance and average trip occupancy for each transit line are shown for transit trips, first-last mile auto trips, and competing auto trips based on CHTS (Caltrans, 2013), LA Metro, and SCRRA statistics. Note that due to small sample sizes, the Expo line was excluded, and first-last mile auto trip statistics for Local and Rapid Bus were merged together.

Transit mode	Transit trip		First-last mile auto trip		Competing auto trip	
	Distance (miles)	Occupancy (passengers)	Distance (miles)	Occupancy (passengers)	Distance (miles)	Occupancy (passengers)
Blue LRT	17.2	77.5	2.3	1.3	17.2	2.2
Red HRT	8.8	139	6.3	2.2	13.3	2.4
Green LRT	15.5	46.1	5.0	1.2	18.4	1.4
Gold LRT	9.4	34.9	4.8	1.8	15.4	1.5
Local Bus	8.9	22.6	8.7	2.6	9.2	1.9
Rapid Bus	10.1	28.5	2.1	2.6	9.2	1.9
Express Bus	24.7	17.3	5.3	1.7	30	2.0
Orange BRT	10.2	43.0	3.8	1.3	13.8	2.0
Metrolink CRT	38.1	247	8.7	1.8	45.2	2.1

Near-term GHG emissions for Metrolink CRT are dominated by diesel fuel combustion during vehicle operation followed by energy production (fuel extraction and production). All rail modes are found to have lower near-term GHG emissions and end use energy per PMT than average auto travel (at the LA average of 2.0 passengers per auto trip). Long-term LA Metro rail GHG emissions are projected to drop significantly due to reductions of imported coal-fired energy and increased use of renewable energy. Electricity use and oxidation of organic materials emitted during the production of concrete and steel are the main contributors to GHG emissions in infrastructure construction and maintenance. Producing large amounts of concrete and steel requires high heating (energy) in turn increasing emissions from energy generation (Flower and Sanjayan, 2007).

Respiratory impact potential in LA transit life-cycles occur mostly during the operation phase, and are typically lower per PMT than auto travel, with two exceptions (Gold and Expo LRT). In the Metro rail services, respiratory impacts arise mainly from fossil fuel energy production and generation. Respiratory impacts can also arise as byproducts from the production of sedimentary materials (concrete and asphalt). This has the most profound impact on auto respiratory impact potential due to the vast amount of road and parking infrastructure that is largely built for and worn down by extensive auto travel. With a high volume of passengers per mile and very low Metro bus travel as a fraction of the total travel in the LA road system, infrastructure construction and maintenance for buses has much lower respiratory impact potential per PMT. Long-term SO_2, PM, and NO_X emission will significantly drop as cleaner electricity generation become more prevalent.

Potential for photochemical smog creation in LA transit life-cycles occur mainly from the production, generation, and combustion of fossil fuels. Metrolink CRT has significantly higher potential for smog creation than all other rail and bus services, due to high amounts of nitrogen oxides released during diesel fuel combustion. In this case, it is worsened by the older and less efficient Metrolink locomotives, which in 2013, had a mean manufacture year of 1995, and a median manufacture year of 1993 (NTD, 2015b). However, assuming that current policies hold, future Metrolink locomotives will achieve large reductions in long-term smog impacts due to reductions of PM and NOx emissions (by up to 85%) as new locomotive tech-

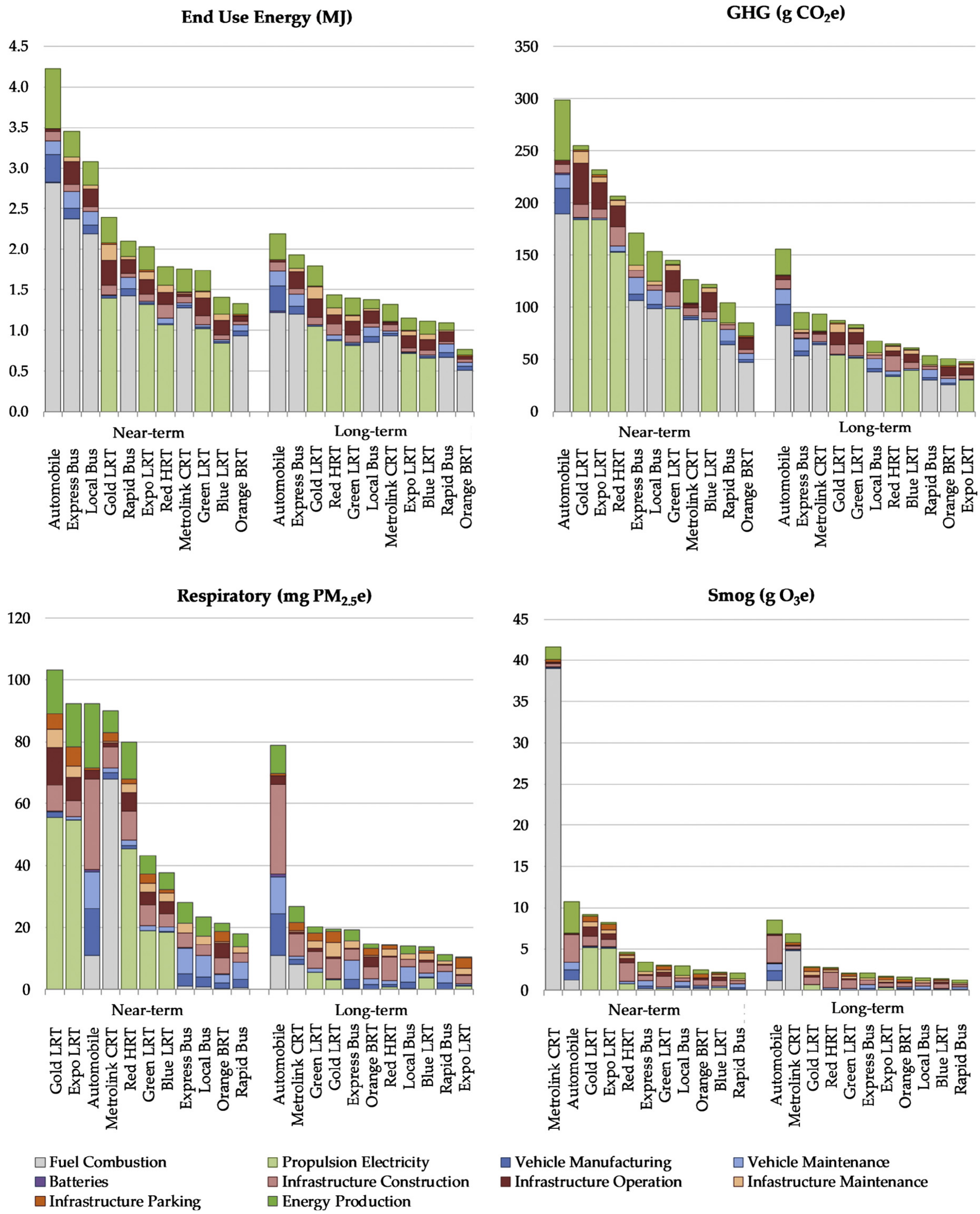

Fig. 2. Life-cycle impacts per passenger mile. Vehicle operation (fuel combustion in gray and electricity generated for rail propulsion in light green) are shown with life-cycle processes for global warming potential, end use energy, respiratory impact potential, and photochemical smog impact potential. Occupancies of each mode are based on average unlinked trip occupancies in the region from the transit authorities and the CHTS (for auto). Note that because of this, average LA auto occupancy for this figure is approximately 2 passengers per mile traveled. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

nologies with EPA Tier 4 compliance are being integrated in the fleet over the next few years (SCRRA, 2016a). The Gold and Expo LRT lines to have similar potential to auto per PMT to create photochemical smog. This is largely due to the fact that NOx emissions contribute the highest to potential for smog creation, and large amounts of nitrogen are oxidized during coal-firing energy generation (Smoot and Smith, 2013). The Green and Blue LRT lines are provided with most of their electricity from SCE which provides more natural gas in place of coal-firing, reducing their attributed smog (and respiratory) impact potential. Also, smog impact potential in LA Metro buses is very small due to low NOx and VOC emissions during CNG vehicle operation. This indicates that potential for smog creation locally from LA Metro transit modes is much lower than auto travel per PMT. Long-term emissions for Metrolink CRT and the Expo and Gold LRT services will be much lower due to cleaner methods of electricity generation and combustion.

When considering the location of electricity generation provided by utilities in addition to many upstream life-cycle processes, most air quality impacts are created outside the LA metropolitan region. Later discussion will explore the local and remote air quality impacts of LA transportation modes.

3.2. Multimodal trip Life-cycle impacts

First-last mile auto travel with transit can significantly increase near-term multimodal trip impacts, and in some cases, a multimodal trip may have greater trip impacts than a competing auto trip. Two main factors contribute to increased multimodal trip emissions. Firstly, multimodal trip lengths are increased to reach the same destinations due to fixed and indirect transit routes. Secondly, first-last mile auto occupancy is often lower than the average competing auto trip occupancy. Single occupancy vehicle (SOV) first-last mile auto trips can significantly increase (and sometimes more than double) the multimodal trip impacts. These first-last mile auto trip characteristics can lead to mitigation of impact reduction benefits from transit. The following results focus on GHG emissions. For multimodal respiratory and smog impacts, see the Supporting Information.

Near-term multimodal GHG emissions are lower than competing auto trip emissions in eight of ten systems, but first-last mile auto trips significantly increase multimodal trip emissions, mitigating potential GHG reduction savings. Near-term multimodal transit and competing auto GHG emissions per passenger trip are shown in Fig. 3. In two services (Local Bus and Red HRT), average multimodal GHG emissions per passenger trip are greater with auto access or egress when compared to competing auto trips. First-last mile auto occupancy was lowest for trips connecting to the Green LRT and Blue LRT lines (1.2 and 1.3 passengers per auto first-last mile trip respectively). Total multimodal trips in the Blue and Green LRT lines averaged over 17 miles in total trip distance. Therefore, despite low first-last mile auto occupancies, multimodal trips in the Green and Blue LRT lines still have lower impacts per trip compared to competing auto trips due to a majority of the trips occurring on a transit segment. As mentioned before, multimodal trips with auto and transit averaged longer distances than non-auto transit trips. Auto first-last mile trips in the Local Bus and Red HRT services increased trip GHG emissions such that multimodal trip emissions surpassed the competing auto trip emissions. For Local Bus service, multimodal trip distances were much longer than competing auto trips and far less direct than other multimodal transit trips. Additionally, auto first-last mile use with Local Bus service is rare (around 1% first-last mile use by auto in CHTS). Therefore, these trips are less comparable to typical auto use with transit likely due to the lack of dedicated parking infrastructure for the Local Bus service. Red HRT multimodal trip GHG emissions are larger than a competing auto trip largely due to high occupancies in competing regional auto trips as well as more carbon-intense electricity consumption in the Red HRT line (mainly coal-fired generation imported by LADWP). SOV auto travel can have a significant impact on competing and first-last mile auto trips. In six of ten services, competing SOV auto trips typically more than double impacts per trip compared to multimodal trips with average first-last mile auto occupancies. However, when first-last mile trips are made alone, four services have higher total multimodal transit trip impacts compared to an average occupancy competing auto trip. This indicates that auto occupancy is a significant factor when determining per passenger impacts in the region, and in all cases SOV trips should be avoided.

Overall, long-term trip GHG emissions decrease due to vehicle improvements, less carbon-intense energy sources, and higher vehicle occupancies, and all but one system (Local Bus) has lower multimodal GHG impacts per passenger trip than a competing auto trip. Long-term multimodal transit and competing auto GHG emissions per passenger trip are shown in Fig. 4. Reductions in carbon-intense energy generation and production methods cause a significant decrease in Metro rail lines' impacts due to high electricity use for infrastructure and vehicle operation (propulsion). The Local Bus system is shown to still have higher GHG impacts per passenger trip with first-last mile auto use due to high auto access and egress distances. However, auto use with Local, Express, and Rapid Bus service is rare (0–2% in CHTS), and often not representative of typical first-last mile trips. Therefore, Local, Express, and Rapid Bus use with auto first-last mile trips are not discussed further.

Replacing first-last mile auto trips with bus trips can significantly reduce multimodal life-cycle impacts especially when trips contain SOV auto segments (compare "+Auto to "+Bus" in Figs. 3 and 4). However, when replacing first-last mile auto trips with rail trips, there are less pronounced reductions in life-cycle impacts. This is largely due to much larger bus system coverage than rail system coverage. In most cases, it is infeasible to replace first-last mile auto trips with rails trips because rail coverage is limited to high volume travel corridors. Overall, trips that use exclusively transit have reduced life-cycle impacts compared to competing auto trips (especially SOV auto trips).

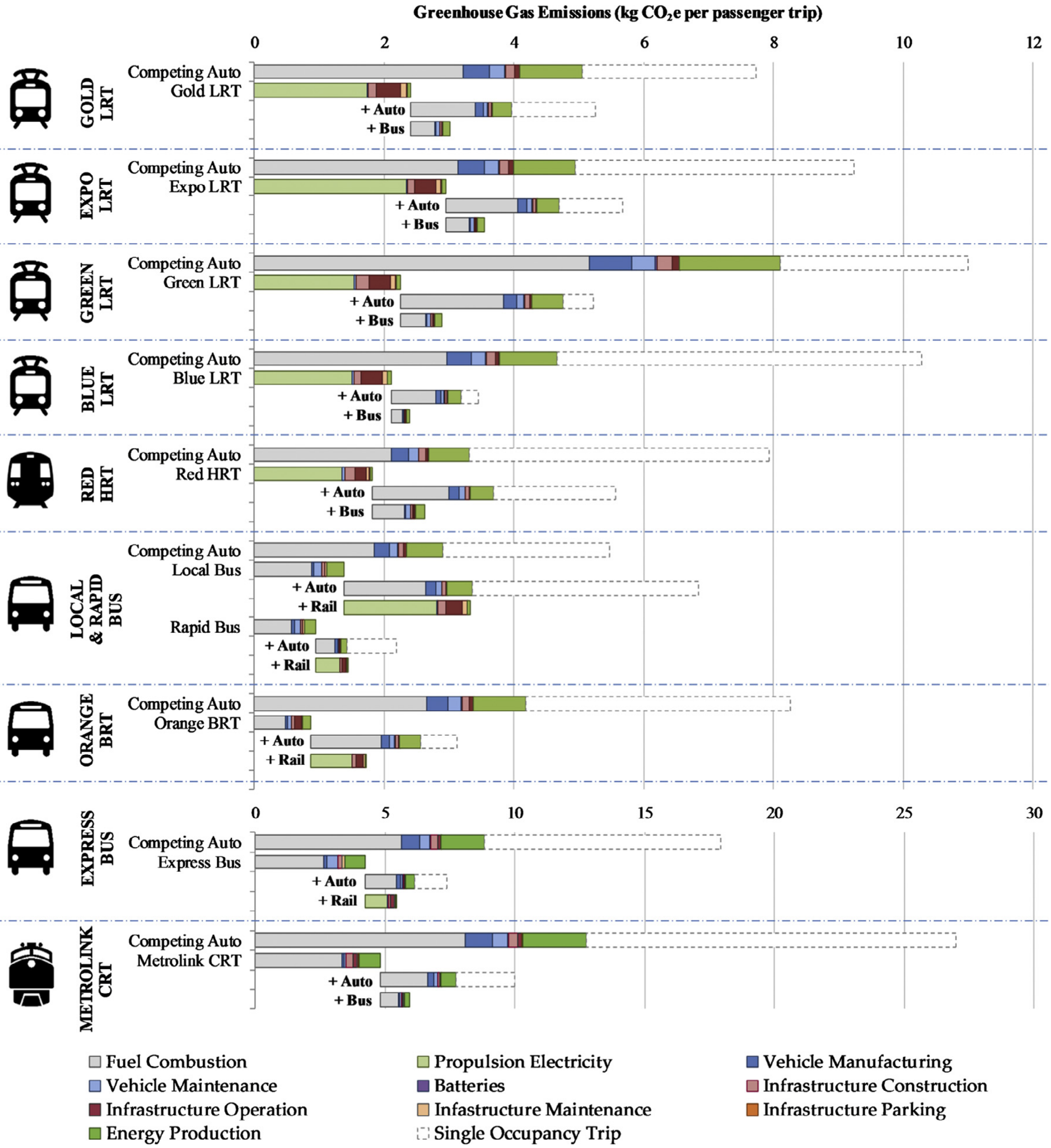

Fig. 3. Near-term multimodal and competing auto GHG emissions per passenger trip for major LA transit services. Near-term multimodal trip impacts are shown compared to competing auto trip impacts. For each mode, region specific average trip distance and occupancies were used. Single occupancy auto trip impacts are shown extending in dashed outlines. The addition of first-last mile auto and transit (+Auto, +Bus, +Rail) trips are shown for each transit service. Note that due to longer trip distances, Express Bus and Metrolink are shown on a separate scale. For complete transit and auto trip characteristics (trip distance and vehicle occupancy), refer to Table 2.

4. Discussion

First-last mile auto use accounts for a significant portion of multimodal trip impacts. In the near-term, first-last mile auto use can account for up to to 66% (Orange BRT) of multimodal transit trip GHG emissions, and up to 63% (Red HRT and Orange BRT) of long-term multimodal transit trip GHG emissions. Multimodal trips may also have higher GHG emissions than a competing auto trip (Red HRT) and higher respiratory impact potential (see Supporting Information) than a competing auto trip (Expo LRT and Metrolink CRT). Multimodal trips with a SOV first-last mile portions on the Expo LRT, Gold LRT, and Red HRT lines average higher GHG emissions per trip than average occupancy competing auto trips. Although multimodal transit

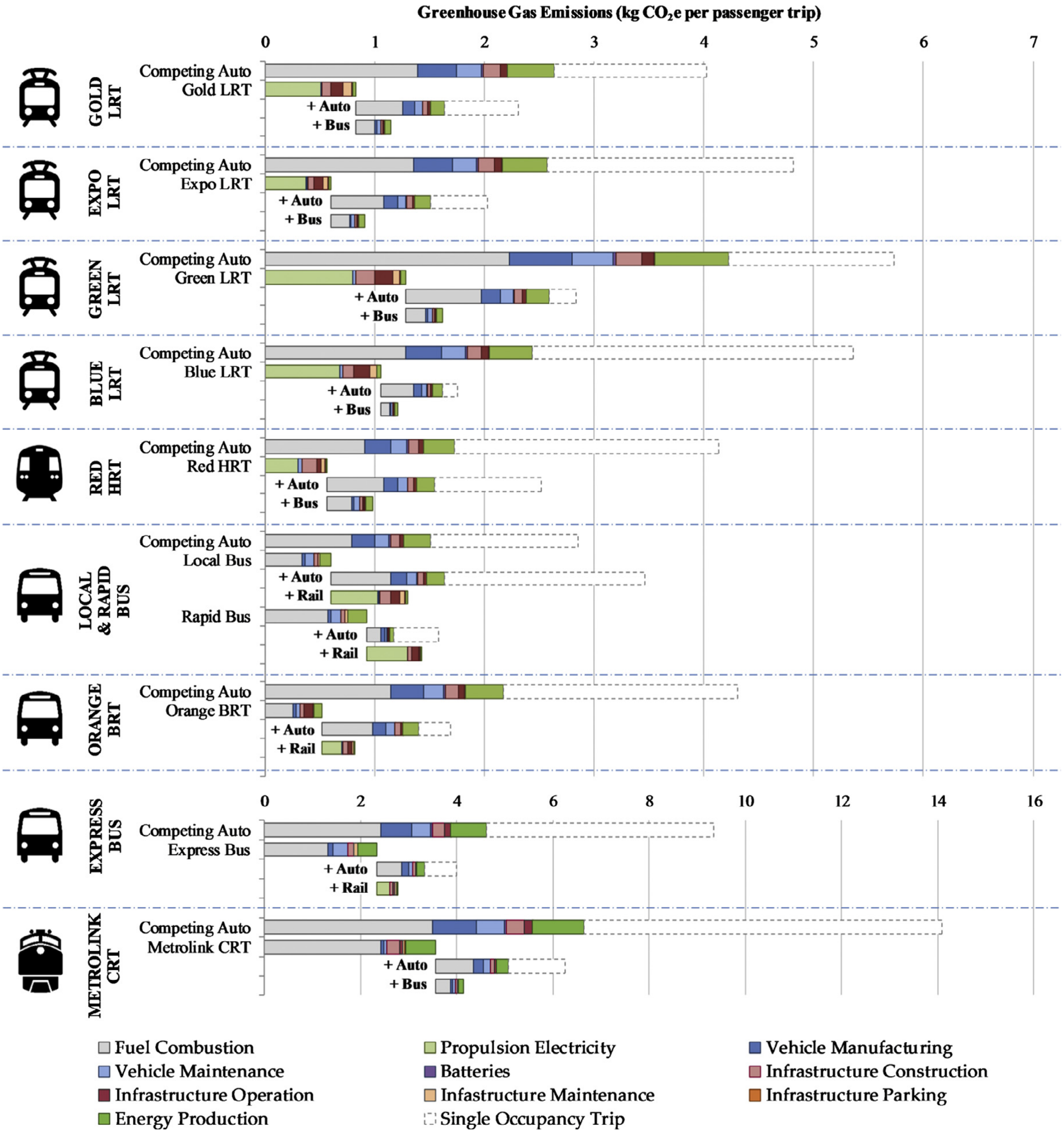

Fig. 4. Long-term multimodal and competing auto GHG emissions per passenger trip for major LA transit services. Long-term multimodal trip impacts are shown compared to competing auto trip impacts. For each mode, current region specific average trip distance and occupancies were used. Single occupancy auto trip impacts are shown extending in dashed outlines. The addition of first-last mile auto and transit (+Auto, +Bus, +Rail) trips are shown for each transit service. Note that due to longer trip distances, Express Bus and Metrolink are shown on a separate scale. For complete transit and auto trip characteristics (trip distance and vehicle occupancy), refer to Table 2.

trips with first-last mile auto use have smaller trip impacts than a competing auto trip in most services, it is clear that first-last mile auto use contributes to a significant portion of impacts in multimodal transit.

4.1. Local versus remote Life-cycle impacts

Spatial supply chain analysis of LA transportation systems indicates that life-cycle air quality impacts may occur largely locally or largely remotely depending on the propulsion method and location of upstream life-cycle processes. Local impacts are defined as occurring within the LA metropolitan region and remote impacts are defined as occurring elsewhere. The locations of material extraction, processing, and transportation were tracked using SimaPro, and electricity consumption impacts were estimated through a geospatial analysis of local and imported electricity generation. Final impacts were aggregated into GHG and air quality impacts per PMT for Metro rail, Metro bus, Metrolink CRT, and auto travel. Fig. 5 displays the local and remote impact potentials by transportation mode. Metro rail and bus impacts are significantly lower than competing auto travel per PMT. When not considering the location of supply chain processes, impacts per PMT in the Gold and Expo LRT lines are similar or greater than auto impacts. However, local impacts from the Gold and Expo LRT lines were only 6–21% of total life-cycle impacts. The combination of electric train propulsion, infrastructure operation, and maintenance activities consume large amounts of electricity with significant imports from outside of LA. Coal-fired electricity generation contributes to a major fraction of near-term impacts in the Gold and Expo LRT lines, but is generated almost entirely outside the state of California with the majority of regional electricity being generated by natural gas (CEC, 2015). Additionally, many manufacturing processes do not occur in LA, such as the production of steel (and other alloys). Although asphalt and concrete are typically produced within the greater LA region, upstream processes such as industrial machinery manufacturing and resource extraction occur remotely. Therefore, due to high imports of electricity generated remotely and high imports of remotely extracted and produced materials, life-cycle impacts in LA transit systems do not significantly contribute to local degradation of air quality (with the exception of Metrolink). Metrolink impact potentials are significantly higher and mainly local compared to other modes due to high PM and NOx emissions from combustion of diesel fuel during locomotive operation. As mentioned earlier, the future use of new Metrolink locomotives will reduce PM and NOx emissions by up to 85%. This will significantly reduce the respiratory and smog impact potential from Metrolink train operations in the long-term, putting local air quality on par with other transit modes. With future cleaner electricity generation and improved locomotive technologies, LA transit will contribute to far lower local human and environmental impacts than auto travel per passenger mile.

4.2. Marginal impacts

It is important to consider marginal impacts when assessing mode shifts. Within the context of LCA, marginal impacts are typically associated with the operation and propulsion phase (Chester and Horvath, 2012). For transit modes, the marginal increase in emissions is negligible due transit service already occurring. The non-operational impacts (infrastructure construction, vehicle manufacturing, etc.) have occurred in the past, and the influence on operational impacts such as energy and fuel use are insignificant due to the weight of a single passenger being less than 1% of total typical operating transit vehicle weight. However, if a new auto trip is created in place of transit, biking, or walking, the marginal emissions are equivalent to the tailpipe emissions of that auto trip. In the case of carpooling, the marginal impacts are likely also negligible if an auto trip was not created (although additional passenger weight may slightly decrease fuel efficiency). Therefore, creation of auto trips in place of transit, biking, or walking, increase GHG and CAP emissions and directly relate to trip distance and auto fuel efficiency. Furthermore, total life-cycle impacts can be considerably reduced by replacing auto first-last mile trips with bus (+Auto vs. +Bus, Figs. 3 and 4), which further highlights the significance of first-last mile auto impacts. Near-term planning to reduce transit system impacts should focus on reducing or replacing auto first-last mile trips (especially SOV trips) because the majority of impacts occurring on the margin are attributed to the creation of first-last mile auto trips.

4.3. Scenarios for first-last mile impact reductions

Ultimately, shifting away from auto travel will be most effective in reducing long-term GHG and air quality impacts by replacing high impact auto trips with lower or neutral impact modes. Neutral impact modes are defined as non-motorized modes such as biking and walking, or modes that have no marginal increase in impacts. Life-cycle impacts of electric vehicles are non-zero, however, when considering the number of remote processes in electric rail and conventional gasoline automobile travel, it is likely that electric vehicle first-last mile local impacts are small. As such, electric vehicles may be an alternative to neutral impact modes, or be effective at replacing first-last mile trips through use in shared mobility services (Uber, Lyft, etc).

Expansion of the Metro rail service and continued transit-oriented urban growth will soon position nearly 80% of LA County residents within three or less miles of transit stations, and one half of transit users who access or egress by auto live close enough to bike or walk (LA Metro, 2014b). As such, there is significant potential to replace first-last mile auto trips to reduce GHG emissions and improve air quality. Fig. 6 shows the reductions achievable by switching from auto first-last mile trips to a neutral impact mode. Reducing multimodal GHG emissions by 10% would require shifting 23–50% of auto first-last mile trips to a neutral impact mode depending on the service (alternatively reducing an average of 500–4500 trips per day). Although long-term elimination of auto access and egress is ideal for reducing impacts, a substantial portion of transit users still rely on an automobile to access transit. With SOV trips common in some transit systems, near-term scenarios for reductions should also target carpooling for trips not realistically replaced by walking, biking, or transit. Following, specific strategies to reduce and replace first-last mile auto impacts are discussed, such as promoting and incentivizing carpooling, adjusting parking availability and pricing, and increasing transit accessibility.

Emphasis on carpooling and the substitution of SOV trips with neutral impact trips are necessary to reduce multimodal trip impacts for transit users who do not have access to feasible alternatives. LA rail systems are strong candidates for increased carpooling due to high regional auto occupancy, high congestion, and high parking demand. The Green and Blue LRT systems have mostly free parking, and consequently also the lowest auto first-last mile occupancies. Implementation of

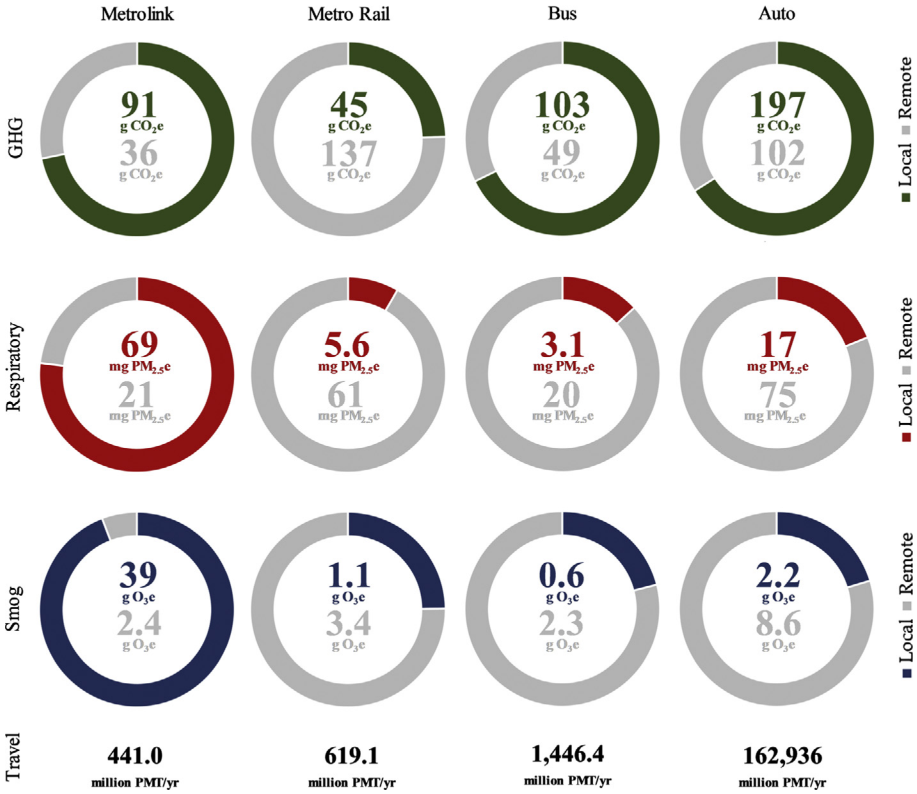

Fig. 5. Local versus remote impact potentials per PMT. Local (inside LA metropolitan region) impact potential per PMT is shown as colored portions of doughnuts: GHG impacts in grams CO_2e (green), respiratory impacts in milligrams $PM_{2.5}e$ (red), and smog impacts in grams O_3e (blue). Gray portions represent remote (outside LA metropolitan region) impact potential. Note that global warming potential does not depend on the location of impacts, and local GHG impacts are shown only to indicate the contribution of local (LA) processes to global warming potential of the transportation system. Also note that high local smog and respiratory impact potential per PMT in the Metrolink system will be greatly reduced with the implementation of EPA Tier 4 compliant locomotives in the near future. PMT per year estimates are made from the most recent figures available. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

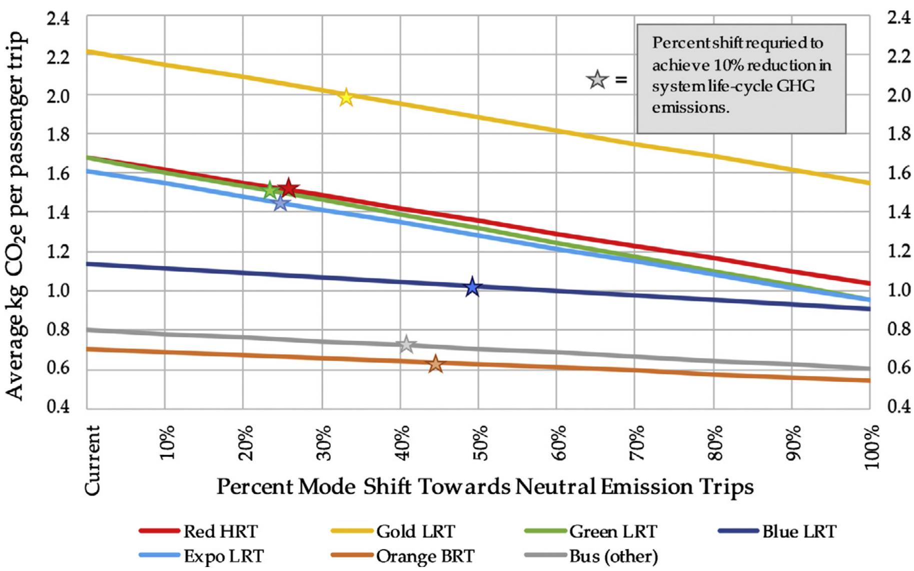

Fig. 6. Reductions in GHG emissions per passenger trip by percent mode shift away from first-last mile auto trips and towards neutral emission trips. Starred locations indicate the point at which 10% of the life-cycle GHG emissions can been reduced by shifting from auto to a neutral emissions mode. Estimates shown are for near-term travel. For every service in this figure to reach the 10% reductions shown, a total of approximately 12,000 auto trips per day would need to be avoided or replaced with neutral emission trips.

demand-driven dynamic pricing may be a viable solution to further reduce first-last mile impacts. Incentives for carpooling are necessary to push transit riders away from SOV trips. LA Metro is already testing demand-driven dynamic pricing at nine stations. This pilot program will include reduced costs for carpooling and is aimed at managing the availability of parking spots (LA Metro, 2016e). The Green LRT line is a highly desirable line to increase carpooling due to frequent SOV access and egress trips and high parking availability. If demand-driven dynamic pricing and carpool incentives are effective at increasing first-last mile auto occupancies at current locations, they should be explored at other parking locations. With correlation between parking availability and parking price to auto first-last mile distance and occupancy, high parking availability may unintentionally contribute to first-last mile trip impacts. Parking demand is very high for accessing transit in the LA region, with some parking lots operated by LA Metro filling up as early as 7 am (LA Metro, 2016e). To avoid increasing first-last mile impacts, promoting increased carpooling incentives for transit users should be a high priority. This will promote increased occupancy of necessary auto trips and offer further incentive to those with adequate, but underutilized, alternatives.

To replace auto first-last mile trips with neutral impact trips, biking accessibility in the LA Metro system should be improved. LA Metro's First-Last Mile Strategic Plan outlines an approach to develop active transportation improvements (paths) to encourage non-auto intermodal connectivity (LA Metro, 2014b). With average biking speeds of 10 mph (Thompson et al., 1997), and bikers willing to ride up to 15 min to access or egress stations (LA Metro, 2014b), it is assumed that biking can replace first-last mile trips around 2.5 miles. Approximately 60% of auto first-last mile trips are 3 miles or less in the Blue and Green LRT lines, while approximately 40% are less than 3 miles in the Red HRT, Gold LRT, and Expo LRT lines (Caltrans, 2013). The Red HRT line has the lowest amount of auto trips below 2.5 miles (26%), and the Blue LRT line had the most auto trips below 2.5 miles (60%). This indicates the potential for many first-last mile trips to be replaced with biking, especially within the Green and Blue LRT lines. High biking accessibility should be implemented within a 2–3 mile range of all stations with high parking demand and availability. Additionally, bike storage at or near all stations would need to be bolstered if a significant shift from auto to bike is desired. LA Metro rail stations currently average 174 parking spaces per station, but only 19 biking spaces per station[1]. Due to short first-last mile auto trips in the Blue LRT line, increasing biking access and mobility surrounding Blue LRT line stations would be ideal to evaluate the feasibility of dramatic auto-to-bike first-last mile mode shifts. Auto first-last mile trips in the Blue LRT line are often short (<3 miles) and low occupancy (average 1.3 passengers). The Blue LRT line currently only has 82 bike rack spaces and 42 bike lockers but over 2000 parking spaces (not including nearby independent parking) across the lines' 22 stations. Based on first-last mile trip data, as much as 12,000 first-last mile auto trips to or from the Blue LRT line occur per day. Replacing a significant portion of these trips with biking would require extensively increased biking accommodations and nearby bike path infrastructure. Replacing 50% of auto first-last mile trips (about 5700 per day) with neutral impact trips in the Blue LRT line would reduce 560 tons CO_2e per year, or an average of 114 g CO_2e per passenger trip.

4.4. Limitations

This study did not consider the impacts from traffic congestion. As congestion has notable influence on on-road travel in Los Angeles, it is acknowledged that time of day and traffic levels may alter the impacts of competing trips (Reyna et al., 2015). Although a reasonable estimate for auto impacts could be made by altering trip MPG, more comprehensive drive cycle modeling would be necessary, especially for transit buses, to accurately estimate impacts from congestion. Initially, this analysis included auto congestion effects by calibration based on Reyna et al. (2015), but were ultimately excluded due to lack of comparable estimates for transit buses. Initial estimates indicated auto GHG emission could vary by as much as 9% due to congestion. Initial estimates also indicated that the total trip impacts would likely have a small influence on peak-hour bus trips when attributing impacts on a per PMT basis. This is due to the fact that although peak-hour service may include reduced fuel efficiency due to road conditions, there is also significant increase in bus ridership.

Another limitation is a lack in understanding of how shared mobility services (such as Uber and Lyft) influence first-last mile trends. Transit access and egress can be limited by gaps in service, lack of auto ownership, and parking constraints. Therefore, first-last mile shared mobility options can be a solution for many travelers in the LA region. The main source for travel data was the 2010–2013 CHTS, which did not include indicators for these types of services. The CHTS was designed before these services become commonplace; Uber did not debut in LA until March 2012 (Kalanick, 2012). In the near future, these data are likely to become more available, and therefore will be important when assessing the impacts of first-last mile trips.

5. Conclusion

LCA of multimodal transit is necessary for quantifying the impacts of first-last mile trips and evaluating the effectiveness of strategies to reduce human and environmental impacts. First-last mile auto use with transit has significant potential to increase impacts per trip, and in some cases may result in door-to-door trip impacts that are larger than a competing auto trip. When evaluating multimodal air quality trip impacts, it is important to acknowledge the local versus remote impacts,

[1] Includes free and paid Metro parking, but not independent parking. Bike spaces includes bike rack or bike locker spaces (LA Metro, 2016d).

especially in systems that use electric propulsion. Methods to reduce first-last mile transit trip impacts depend on the characteristics of the transit systems and may include promoting first-last mile carpooling, adjusting station parking pricing and availability, and increased emphasis on non-auto access or egress in areas with low first-last mile trip distances. Ultimately, transportation policy and planning should be conscious of significant potential for human and environmental impacts from long-term auto access and egress of transit.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.trd.2017.04.030.

References

Ayala, A., Kado, N.Y., Okamoto, R.A., Holmén, B.A., Kuzmicky, P.A., Kobayashi, R., Stiglitz, K.E., 2002. Diesel and CNG Heavy-duty Transit Bus Emissions over Multiple Driving Schedules: Regulated Pollutants and Project Overview, pp. 1–13. http://dx.doi.org/10.4271/2002-01-1722.
Bare, J., 2011. TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technol. Environ. Policy 13, 687–696. http://dx.doi.org/10.1007/s10098-010-0338-9.
Bradley, M.J., 2013. Comparison of Modern CNG, Diesel and Diesel Hybrid-Electric Transit Buses: Efficiency & Environmental Performance.
Caltrans, 2013. California Household Travel Survey. National Renewable Energy Laboratory.
CARB, 2000. Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-Fueled Engines and Vehicles. California Air Resource Board.
CEC, 2015. California Electricity Data, Facts, & Statistics. California Energy Commission.
Chester, M.V., Cano, A., 2016. Time-based life-cycle assessment for environmental policymaking: greenhouse gas reduction goals and public transit. Transp. Res. Part D Transp. Environ. 43, 49–58. http://dx.doi.org/10.1016/j.trd.2015.12.003.
Chester, M.V., Horvath, A., 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. Environ. Res. Lett. 4, 24008. http://dx.doi.org/10.1088/1748-9326/4/2/024008.
Chester, M., Horvath, A., 2012. High-speed rail with emerging automobiles and aircraft can reduce environmental impacts in California's future. Environ. Res. Lett. 7, 34012. http://dx.doi.org/10.1088/1748-9326/7/3/034012.
Chester, M., Pincetl, S., Elizabeth, Z., Eisenstein, W., Matute, J., 2013. Infrastructure and automobile shifts: positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. Environ. Res. Lett. 8, 15041. http://dx.doi.org/10.1088/1748-9326/8/1/015041.
Eisenstein, W., Chester, M., Pincetl, S., 2013. Policy options for incorporating life-cycle environmental assessment into transportation planning. Transp. Res. Rec. J. Transp. Res. Board 2397, 30–37. http://dx.doi.org/10.3141/2397-04.
Ellis, T.P., Garcia, T., Vargas, J., Hodgins, P., Hammond, C., Leigh, F., Frierson, T., 2014. Corporate Responsibility Report. Southern California Edison.
EPA, 2006. Air quality criteria for ozone and related photochemical oxidants. EPA/600/R-05/004aF-cF.
EPA, 2012. EPA and NHTSA Set Standards to Reduce Greenhouse Gases and Improve Fuel Economy for Model Years 2017–2025 Cars and Light Trucks. EPA-420-F-12-051.
EPA, 2016. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–1998. EPA 430-R-16-002.
Facanha, C., Horvath, A., 2007. Evaluation of life-cycle air emission factors of freight transportation. Environ. Sci. Technol. 41, 7138–7144. http://dx.doi.org/10.1021/es070989q.
Flower, D.J.M., Sanjayan, J.G., 2007. Green house gas emissions due to concrete manufacture. Int. J. Life Cycle Assess. 12, 282–288. http://dx.doi.org/10.1065/lca2007.05.327.
Fraser, A., Chester, M.V., 2015. Environmental and economic consequences of permanent roadway infrastructure commitment: city road network lifecycle assessment and Los Angeles county. J. Infrastruct. Syst. 22, 4015018. http://dx.doi.org/10.1061/(ASCE)IS.1943-555X.0000271.
Fritz, S.G., 1994. Exhaust emissions from two intercity passenger locomotives. J. Eng. Gas Turbines Power 116, 774–783. http://dx.doi.org/10.1115/1.2906885.
GREET, 2015. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Vehicle and Fuel Cycle Model.
Jaffe, A.B., Newell, R.G., Stavins, R.N., 2005. A tale of two market failures: technology and environmental policy. Ecol. Econ. 54, 164–174. http://dx.doi.org/10.1016/j.ecolecon.2004.12.027.
Kalanick, T., 2012. Uber LA Officially Launched. https://newsroom.uber.com/us-california/uber-la-officially-launched/.
LA Metro, 2012. Light Rail Vehicle Procurement. http://media.metro.net/board/Items/2010/06_june/20100616OPItem37.pdf.
LA Metro, 2014a. 2014 Metro Energy and Resource Report. http://media.metro.net/projects_studies/sustainability/images/report_ecsd_2014-0624.pdf.
LA Metro, 2014b. First Last Mile Strategic Plan. http://media.metro.net/docs/First_Last_Mile_Strategic_Plan.pdf.
LA Metro, 2016a. Metro Research. Los Angeles County Metropolitan Transportation Authority, Los Angeles, CA https://www.metro.net/news/research/.
LA Metro, 2016b. Scheduled Service Operating Cost Factors Report No. 4–24. http://libraryarchives.metro.net/DPGTL/4_24_Reports/.
LA Metro, 2016c. Transportation Research Library & Archive. http://libraryarchives.metro.net.
LA Metro, 2016d. Maps and Timetables. https://www.metro.net/riding/maps/.
LA Metro, 2016e. Paid Parking Pilot Program. https://d1akjheu06qp1r.cloudfront.net/board/Items/2016/02_february/20160210wesitem3.pdf.
LADWP, 2015. Integrated Resource Plan. http://docketpublic.energy.ca.gov/PublicDocuments/15-RETI-02/TN210745_20160315T155739_LADWP_2015_Integrated_Resource_Plan.pdf.
Mathez, A., Manaugh, K., Chakour, V., El-Geneidy, A., Hatzopoulou, M., 2013. How can we alter our carbon footprint? Estimating GHG emissions based on travel survey information. Transportation (Amst). 40, 131–149. http://dx.doi.org/10.1007/s11116-012-9415-8.
Matute, J.M., Chester, M.V., 2015. Cost-effectiveness of reductions in greenhouse gas emissions from high-speed rail and urban transportation projects in California. Transp. Res. Part D Transp. Environ. 40, 104–113. http://dx.doi.org/10.1016/j.trd.2015.08.008.
McKenzie, E.C., Durango-Cohen, P.L., 2012. Environmental life-cycle assessment of transit buses with alternative fuel technology. Transp. Res. Part D Transp. Environ. 17, 39–47. http://dx.doi.org/10.1016/j.trd.2011.09.008.
Meisterling, K., Samaras, C., Schweizer, V., 2009. Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. J. Clean. Prod. 17, 222–230. http://dx.doi.org/10.1016/j.jclepro.2008.04.009.
Neff, J., Dickens, M., 2016. Table 27: Alternative Fuel Powered Vehicles by Mode. 2016 Public Transportation Fact Book Appendix A: Historical Tables.
Nelson, L.J., 2014. Japanese firm plans to build light-rail cars in L.A. area after all, Los Angeles Times. http://thesource.metro.net/2011/12/19/how-do-they-do-that-ship-rail-cars-to-l-a/.

Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M., Van Mierlo, J., 2014. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int. J. Life Cycle Assess. 19, 1866–1890. http://dx.doi.org/10.1007/s11367-014-0788-0.
NTD, 2015a. 2014 Annual Energy Consumption. Federal Transit Administration, https://www.transit.dot.gov/ntd/data-product/2015-annual-database-energy-consumption.
NTD, 2015b. 2014 Annual Revenue Vehicle Inventory. Federal Transit Administration, https://www.transit.dot.gov/ntd/data-product/2015-annual-database-revenue-vehicle-inventory.
Plevin, R.J., Delucchi, M.A., Creutzig, F., 2014. Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. J. Ind. Ecol. 18, 73–83. http://dx.doi.org/10.1111/jiec.12074.
Posada, F., 2009. CNG Bus Emissions Roadmap: from Euro III to Euro VI, The International Council on Clean Transportation. http://www.theicct.org/sites/default/files/publications/CNGbuses_dec09.pdf.
PRé Consultants, 2014. SimaPro 8.0.3.
PWP, 2015. Integrated Resource Plan. Pasadena Water and Power, Pasadena, CA.
Redhill Group, 2015. Metrolink 2015 Origin-Destination Study. http://www.metrolinktrains.com/pdfs/Facts&Numbers/Surveys/2015_Origin-Destination_Study.pdf.
Reyna, J.L., Chester, M.V., Ahn, S., Fraser, A.M., 2015. Improving the accuracy of vehicle emissions profiles for urban transportation greenhouse gas and air pollution inventories. Environ. Sci. Technol. 49, 369–376. http://dx.doi.org/10.1021/es5023575.
Santos, A., McGuekin, N., Nakamoto, H.Y., Gray, G., Liss, S., 2011. Table 16. Average Vehicle Occupancy for Selected Trip Purpose 1977, 1983, 1990, and 1995 NPTS, and 2001 and 2009 NHTS (Person Miles per Vehicle Mile). Summary of Travel Trends: 2009 National Household Travel Survey.
SCRRA, 2012. Metrolink Fleet Plan 2012–2017. Southern California Regional Rail Authority.
SCRRA, 2016a. First Metrolink Tier 4 locomotive completed, Metrolink News. http://www.metrolinktrains.com/news/news_item/news_id/1051.html.
SCRRA, 2016b. Engineering and Construction. http://www.metrolinktrains.com/agency/page/title/engineering_construction.
Smoot, L.D., Smith, P.J., 2013. Coal Combustion and Gasification. Springer Science & Business Media.
Thiruvengadam, A., Carder, D., Besch, M.C., Shade, B., Thompson, G., Clark, N., Collins, J., 2011. Testing of Volatile and Nonvolatile Emissions from Advanced Technology Natural Gas Vehicles.
Thompson, D.C., Rebolledo, V., Thompson, R.S., Kaufman, A., Rivara, F.P., 1997. Bike speed measurements in a recreational population: validity of self reported speed. Inj. Prev. 3, 43–45. http://dx.doi.org/10.1136/ip.3.1.43.
Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. Renew. Sustain. Energy Rev. 28, 555–565. http://dx.doi.org/10.1016/j.rser.2013.08.013.
Upton, K., 2011. How do They do That? Ship Rail Cars to L.A. The Source http://thesource.metro.net/2011/12/19/how-do-they-do-that-ship-rail-cars-to-l-a/.
USDOT, 2014. Highway Statistics Series. U.S. Department of Transportation.
Varun, Bhat, I.K., Prakash, R., 2009. LCA of renewable energy for electricity generation systems—a review. Renew. Sustain. Energy Rev. 13, 1067–1073. http://dx.doi.org/10.1016/j.rser.2008.08.004.
Weisser, D., 2007. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 32, 1543–1559. http://dx.doi.org/10.1016/j.energy.2007.01.008.