First-last mile environmental life-cycle assessment of multimodal transit in Los Angeles

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Christopher G. Hoehne
Doctoral Student
Civil, Environmental and Sustainable Engineering
Arizona State University
Tel: 636-293-1487; Email: chris.hoehne@asu.edu

Mikhail V. Chester, Ph.D.
Associate Professor
Civil, Environmental and Sustainable Engineering
Arizona State University
Tel: 480-965-9779; Email: mchester@asu.edu

660 S College Avenue
P.O. Box 873005
Tempe, AZ 85287-3005

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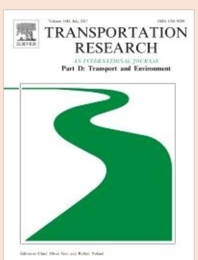

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ABSTRACT

With potential for automobiles to cause air pollution and greenhouse gas emissions relative to other modes, there is concern that automobiles accessing or egressing public transportation may significantly increase human and 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. A case study of transit and automobile travel in the greater Los Angeles region is developed. First and last mile automobile trips were found to increase multimodal transit trip emissions, mitigating potential impact reductions from transit usage. In some cases, a multimodal transit trips with automobile access or egress may be higher than a competing automobile trip. In the near-term, automobile access or egress in some Los Angeles transit systems may account for up to 66% of multimodal greenhouse gas trip 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 trip impacts. Spatial supply chain analysis indicates that life-cycle air quality impacts may occur largely locally (in Los Angeles) or largely remotely (elsewhere) depending on the propulsion method and location of upstream life-cycle processes. Reducing 10% of transit system greenhouse emissions requires a shift of 23% to 50% of automobile access or egress trips to a zero emissions mode.

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The case study development outlined in Task 2 is discussed within section *2: Methodology* under subsection *2.4: Multimodal Trip Development*. The results of this task can be found within section *3: Results* under subsection *3.2: Multimodal Trip Life-cycle Impacts*.

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The scenario development outlined in Task 3 is discussed qualitatively and quantitatively within section *4: Discussion* under subsection *4.2: Scenarios for First-last Mile Impact Reductions*.

1 INTRODUCTION

With heightened awareness of the impacts of criteria air pollutants (CAP) and greenhouse gas (GHG) emissions, focus on understanding and mitigating human and environmental impacts from transportation has become a major priority for many urban 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 assess the direct and indirect effect transportation systems (Chester and Horvath, 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 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 single occupancy vehicle (SOV) travel (USDOT, 2009). 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 remains 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 comprehensively 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 understanding the direct, indirect, and supply chain impacts in many economic sectors including electric supply technologies (Turconi et al., 2013; Weisser, 2007), agriculture processes (Meisterling et al., 2009), transportation systems (Chester and Horvath, 2009; Facanha and Horvath, 2007) and many other systems. 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 aiming 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 attempted to address multimodal transit trip environmental impacts that include auto trip first-last mile characteristics, however, there is a lack of analyses that include both regional first-last mile trip 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) system with comparison to a LA automobile. In this study, first-last mile auto use with the Expo LRT system 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) evaluate 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 emissions 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 life-cycle assessment 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 10 transit systems 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 characteristics of competing automobile trips and automobile trips accessing or egressing transit. The LCA is designed to account for near-term life-cycle impacts as well as 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 (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 transit impacts.

2.1 Energy and Environmental Indicators and Stressors

The LCA focuses on attributional impacts allocated to each transit system by evaluating near-term and long-term footprints per passenger-mile traveled (PMT). The life-cycle inventory includes end use energy, GHG emissions, carbon monoxide (CO), nitric oxide and nitrogen dioxide (NO_X), fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}), sulfur dioxides (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 air quality impact potential, impact characterization factors from the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 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 potential.

2.2 Characteristics of Los Angeles Transportation Systems

Ten transit system in the LA metropolitan region are evaluated to identify the characteristics that contribute to various transit life-cycle impacts. The Los County Metropolitan Transit Authority (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; a Local bus, a Rapid bus, an Express bus, and the Orange bus rapid transit (BRT) line. Together, they account for nearly three quarters of all LA Metro boardings a year (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) system 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 system 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 in this study builds on previous related research and significant efforts are made to obtain up-to-date system-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 systems (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 weighting vehicle characteristics for each transit system. Weighted vehicle characteristics (e.g., length, weight, capacity, etc.) are estimated for each system based on reports of vehicle operations from the transit authorities (LA Metro, 2016b, 2016c; SCRRA, 2012). 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 delivery of vehicles to LA. Long-term manufacturing impacts are modeled after Kinki Sharyo P3010 LRVs assuming LA Metro exercises their full contract with Kinki Sharyo to obtain 235 total LRVs (LA Metro, 2012). The Orange BRT system operates 60 foot articulated buses while all other bus lines use an amalgamation of over 2,000 CNG buses ranging from 31 feet to 60 feet (LA Metro, 2016b; USDOT, 2014a). The Metrolink fleet consists of Electro-Motive Diesel locomotives, and various types of passenger and cab cars (SCRRA, 2012; USDOT, 2014a). The long-term fleet was modeled after the newly ordered locomotives that will cut NOx and PM emissions by up to 85% (SCRRA, 2016a).

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 LA Metro 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 impact in the life-cycle of transit systems. As such, a region-specific material production analysis is developed with SimaPro (PRé Consultants, 2014) 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 included. The total damage from Metro buses is determined by estimating the equivalent single axel 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, 2014b). 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 system operational impacts are attributed to electricity use (vehicle propulsion and station operation), which varies by rail system. LA Metro stations consume electricity due to various processes including lighting, escalator use, ticket kiosks, and station cleaning. Electricity consumption data was obtained from LA Metro in the form of meter readings by station and utility provider (LA Metro, 2014). 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 system and also supplying significant amounts to the Expo and Gold LRT systems. Southern California Edison (SCE) provides most of the electricity used by the Blue and Green LRT systems, and Pasadena Water and Power (PWP) supplies only small amounts to the Gold LRT system. 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, 2014; PWP, 2015). As a result, coal-fired generation makes up over a third of the electricity supplied to the Red, Gold, and Expo systems. The Green and Blue LRT systems' electricity use comprises less than a fifth coal generation, instead utilizing more natural gas (Ellis et al., 2014). Figure 1 shows detailed electricity use for each of the LA Metro rail systems.

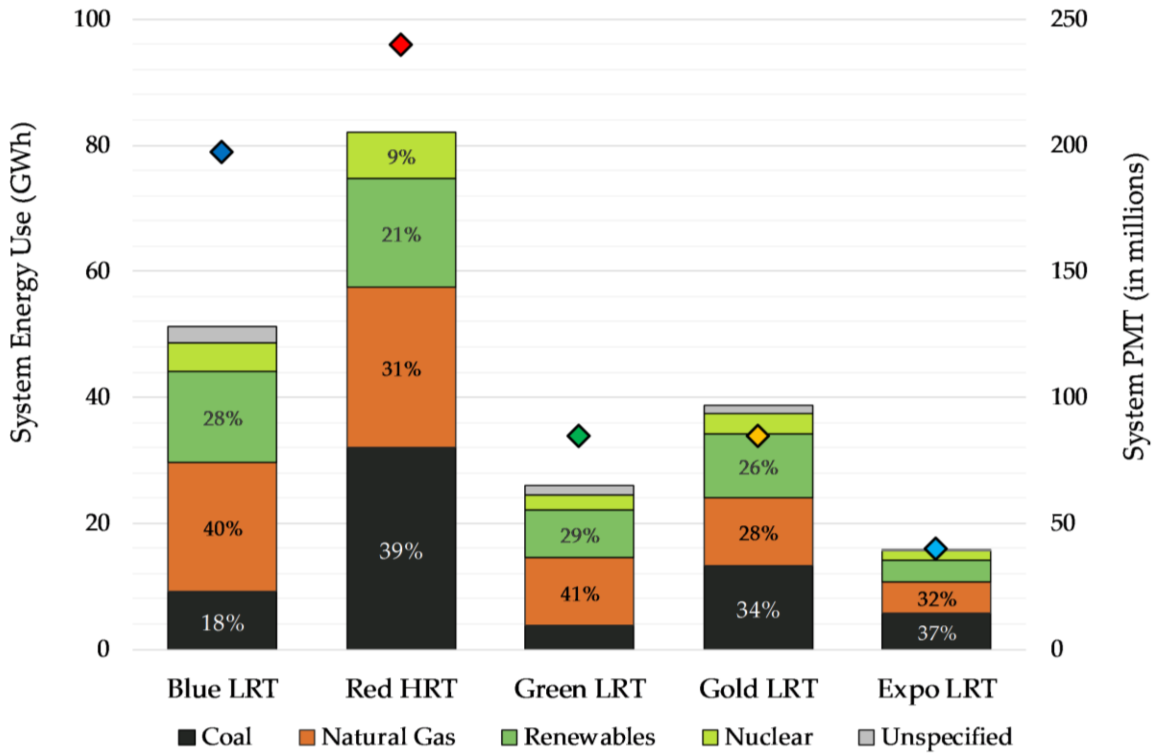

FIGURE 1 Electricity Use in LA Metro Rail System.
LA Metro rail system electricity consumption in 2014 is shown comprised by generation methods. A secondary axis with corresponding indicators of 2014 transit system PMT is shown for comparison. Energy mix compositions are based on reports from the LADWP,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

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 the appropriate drive cycle. 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 (CBD), the Manhattan drive cycle (MAN), and the Orange County drive cycle (OCC). Drive cycles tailpipe emissions were then inventoried and estimated for the Local, Rapid and Express bus services from test results of CNG buses of similar buses from three separate sources (Ayala et al., 2002; MJ Bradley, 2013; Posada, 2009). Due to uncertainties about future emissions, it is assumed that buses 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 the CARB of similar bus engines (Thiruvengadam et al., 2011) flowing a similar procedure outlined in Chester et al. (2013). Fuel consumption of the entire CNG bus fleet from the National Transit Database (NTD) is compared to estimated fuel economies to verify results. CNG fuel consumption in 2014 was estimated to be 4% lower than the actual fuel consumption reported in the NTD in 2014 (USDOT, 2014a). This indicates that estimated impacts of LA Metro buses are reasonably accurate. Because fuel consumption estimates rely on yearly vehicle miles traveled (VMT), under estimation likely occurs because VMT (via odometers readings) does not account for idling.

Metrolink operational impacts are modeled after representative operating schedules in the Metrolink system. Representative operational impacts are modeled after routes that match the Metrolink system 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 in 2014 was estimated to be 7% lower than the actual fuel consumption reported in the NTD in 2014 (USDOT, 2014a). This indicates that estimated impacts of Metrolink locomotives are reasonably accurate. Similar to the trend in LA Metro bus system, under estimation likely occurs because VMT does not account for idling.

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 manufacturing, operation, and 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 MPG fuel economy and long-term use is assessed at 55 MPG fuel economy to be consistent with Corporate Average Fuel Economy (CAFE) standards by year 2025 (EPA, 2012). Long-term automobile manufacture and operation is 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 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 accessed or egressed by automobile. 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. Although this skew in the CHTS data set lowers the number of observed samples of paired auto-transit trips, it is not expected that the trip characteristics would alter significantly with increased sample size. Auto trip occupancies are also recorded and analyzed. In the LA region, the CHTS average auto occupancy for all purposes (including carpools) was 2 passengers per auto trip. According to the 2009 National Household Travel Survey (NHTS), this is slightly above the reported all-purpose national average auto occupancy of 1.7 passengers per trip

(USDOT, 2009). The Expo LRT system opened in mid-2012 while the CHTS was already underway. As result, only a couple (n=4) of auto-rail trips were observed, and were not assumed to be representative. Therefore, auto-rail trip characteristics for the Expo LRT assumed average characteristics.

TABLE 1 First-last Mile Modes in LA Transit System
First-last mile mode selection data are shown from two different surveys, the CHTS (Caltrans, 2013) 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 System (CHTS)	Percent Walk	Percent Auto	Percent Other
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%
Transit System (Metro)	**Percent Walk**	**Percent Auto**	**Percent Other**
Bus	84%	10%	6%
Rail	64%	27%	9%

To determine competing auto trip characteristics, an origin-destination analysis is conducted. A competing auto trip is defined as a single automobile trip that replaces a single or 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 utilize more direct routes between identical origins and destinations. This leads to shorter competing auto trips than multimodal transit trips for the same origin-destination pairings. Due to small sample size of first-last mile auto trips in the Metro Local and Rapid bus systems, first-last mile trip trends were merged together for these two systems. With comprehensive multimodal trip characteristics, multimodal life-cycle trip impacts are estimated by synergizing trip characteristics with per mile LCA results.

3 RESULTS

Per mile GHG emissions, end use energy, respiratory impact potential, and smog impact potential are first shown for each transit system 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. Further results covering more scenarios and induvial CAP emissions by mode can be found in Hoehne (2016).

3.1 Life-cycle Impacts per Passenger Mile

Figure 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 transportation 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 systems are supplied with high fractions of coal-fired electricity, and have lower average ridership than the other rail systems. 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. Near-term GHG emissions for Metrolink CRT is 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 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 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).

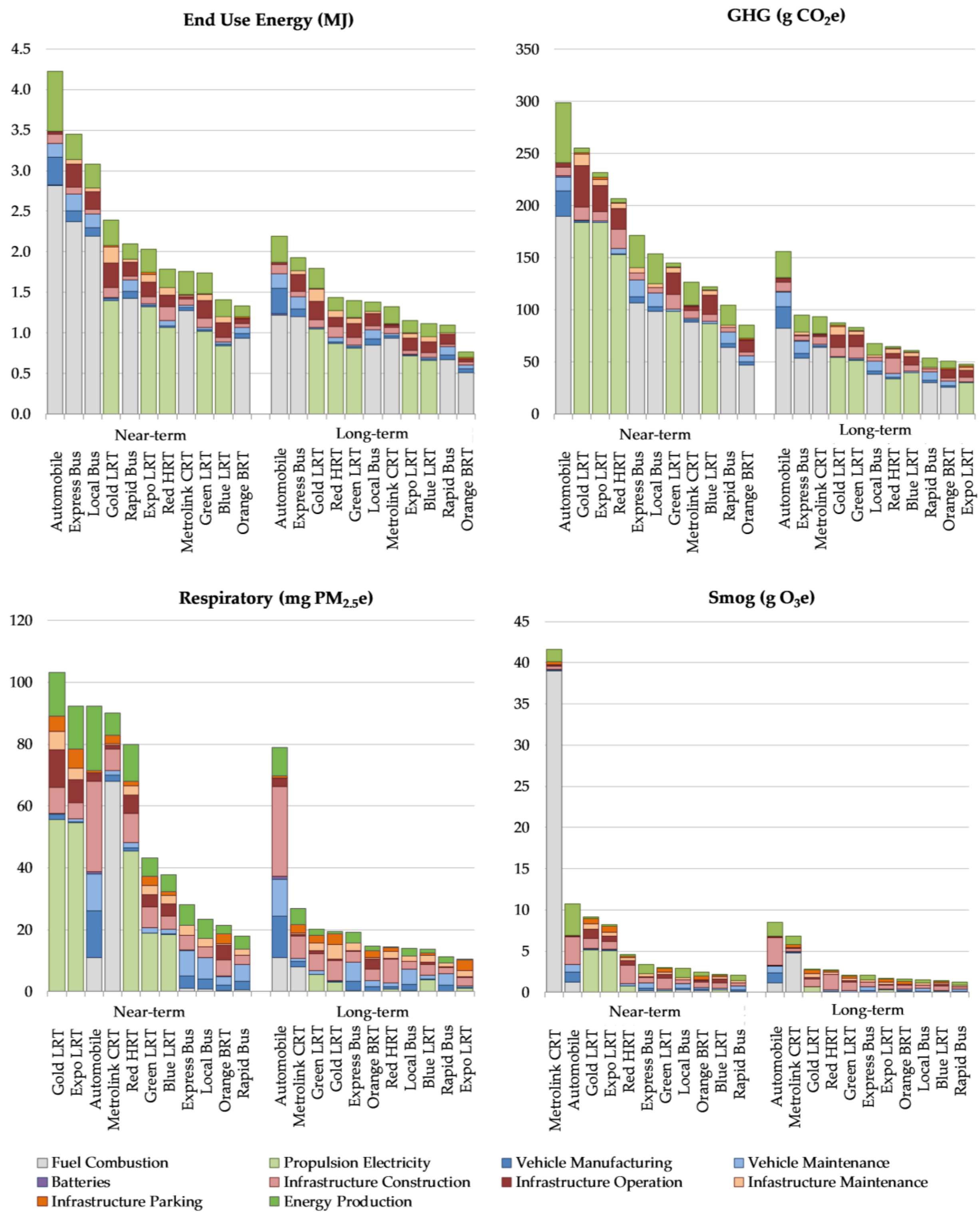

FIGURE 2 Life-cycle impacts per passenger mile.
Vehicle operation (fuel combustion in gray and electricity generated for rail propulsion in light green) are shown with life-cycle processes for global warming potential, end use energy, respiratory impact potential, and photochemical smog impact potential.

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 system, 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 infrastructure that is largely built for and worn down by extensive auto travel. With a higher 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. The future use of new Metrolink locomotives that are slated to be compliant with the latest EPA Tier 4 emissions standards and may cut PM, and NO_X emissions by up to 85% (SCRRA, 2016a). This will significantly reduce the respiratory and smog impact potential from Metrolink locomotive operation. It should be noted that these Metrolink trains will begin operating as early as 2017 (SCRRA, 2016a), meaning smog impact potential in the Metrolink system may begin rapidly declining in the next few years as the switch to the new locomotives is made.

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 modes, due to high amounts of NOx released during locomotive diesel fuel combustion. The Gold and Expo LRT systems to have similar potential to auto per PMT to create photochemical smog. This is largely due to the fact that NOx emissions contribute to the highest 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 systems are provided with most of their electricity from SCE which provides more natural gas in place of coal-firing, reducing their smog (and respiratory) impact potential. Also, smog impact potential in LA Metro buses is very small due to low NOx and VOC emissions during 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 systems will be much lower due to cleaner methods of electricity generation and combustion. Metrolink CRT smog impact potential mainly arises from locomotive diesel fuel combustion, but as mentioned previously, future Metrolink locomotives will have great reductions in long-term impacts.

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. Many factors can 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. Last, 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 Figure 3. In two systems (Local bus and Red HRT), average multimodal GHG emissions per passenger trip are greater with auto access or egress when compared to competing auto trip. First-last mile auto occupancy was lowest for trips connecting to the Green LRT and Blue LRT (1.2 and 1.3 passengers per auto first-last mile trip respectively). Total multimodal trips in the Blue and Green LRT systems averaged over 17 miles in total trip distance. Therefore, despite low first-last mile auto occupancies, multimodal trips in the Green and Blue LRT systems still had 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 systems increased trip GHG emissions such that multimodal trip emissions surpassed the competing auto trip emissions. In the Local bus system, multimodal trip distances were much longer than competing auto trips and far less direct than other multimodal transit trips. Therefore, transit user behavior motivating these trips are less comparable to typical park-and-ride transit riders likely due to the lack of dedicated parking infrastructure in the Local bus system. 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 system (mainly coal-fired generation imported by LADWP). SOV auto travel can have a significant impact on competing and first-last mile auto trips. Competing SOV auto trips often have much higher impacts per trip than multimodal trips with average first-last mile auto occupancies. However, when first-last mile trips are made alone, total trip impacts are usually higher for a multimodal transit trip 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 SOV trips should be avoided.

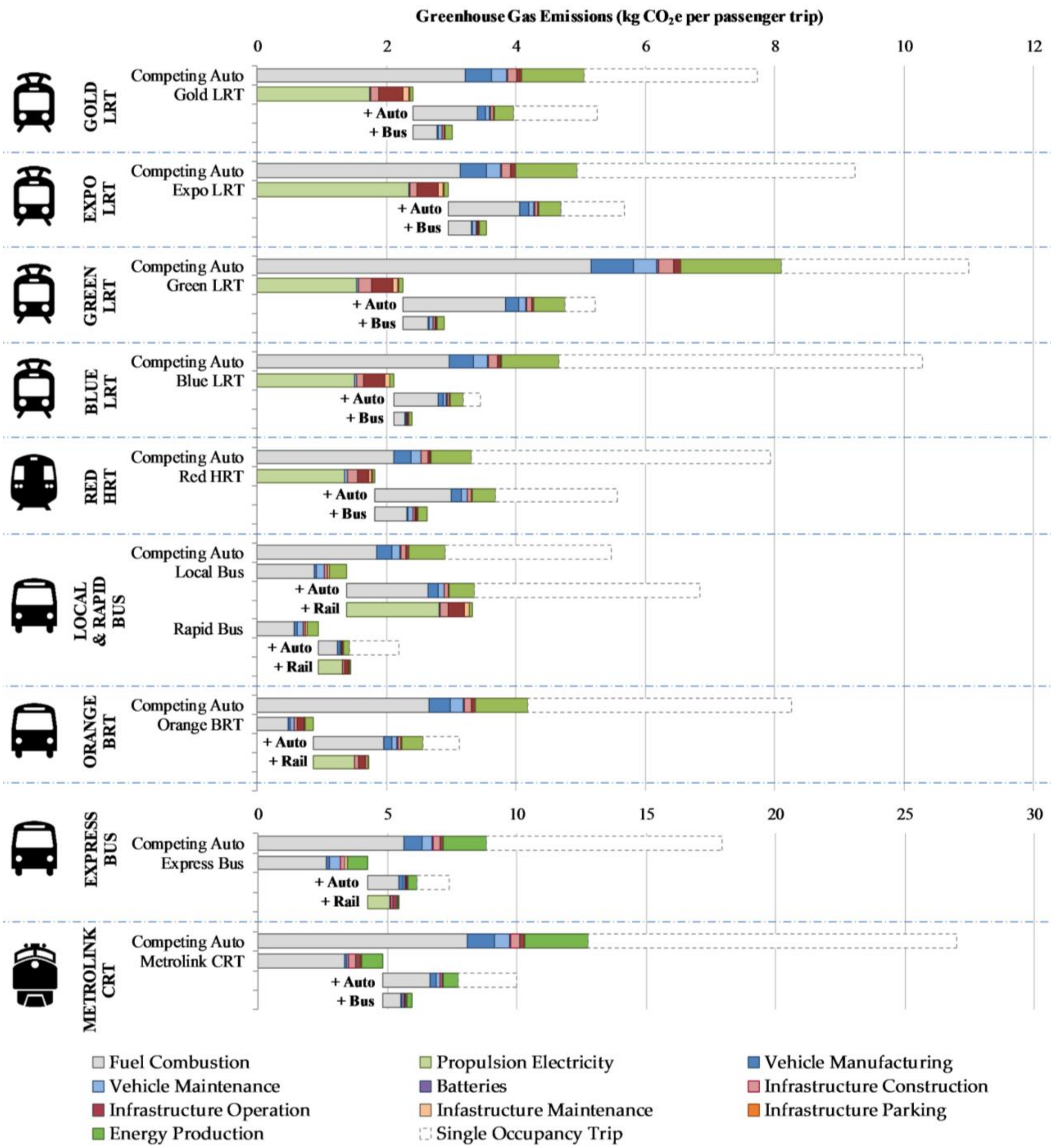

FIGURE 3 Near-term multimodal and competing auto GHG emissions per passenger trip in the LA transit system.
Near-term multimodal trip impacts are shown compared to competing auto trip impacts. For each mode, region specific average trip distance and occupancies were used. Single occupancy auto trip impacts are shown extending in white. Note that due to longer trip distances, Express Bus and Metrolink are shown on a separate scale.

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 Figure 4. Reductions in carbon-intense energy generation and production methods cause a significant decrease in the Metro rail systems 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. Long term reductions in both bus and auto impacts per PMT will occur due to improved vehicle efficiencies so the gap in emissions per PMT or per passenger trips does not significantly change. However, trip characteristics such as auto occupancies and transit and auto trip distances is assumed to not significantly change. It is possible with improvements network mobility or changes in user behavior that multimodal Local bus trips may become more direct with reduced impacts per trip.

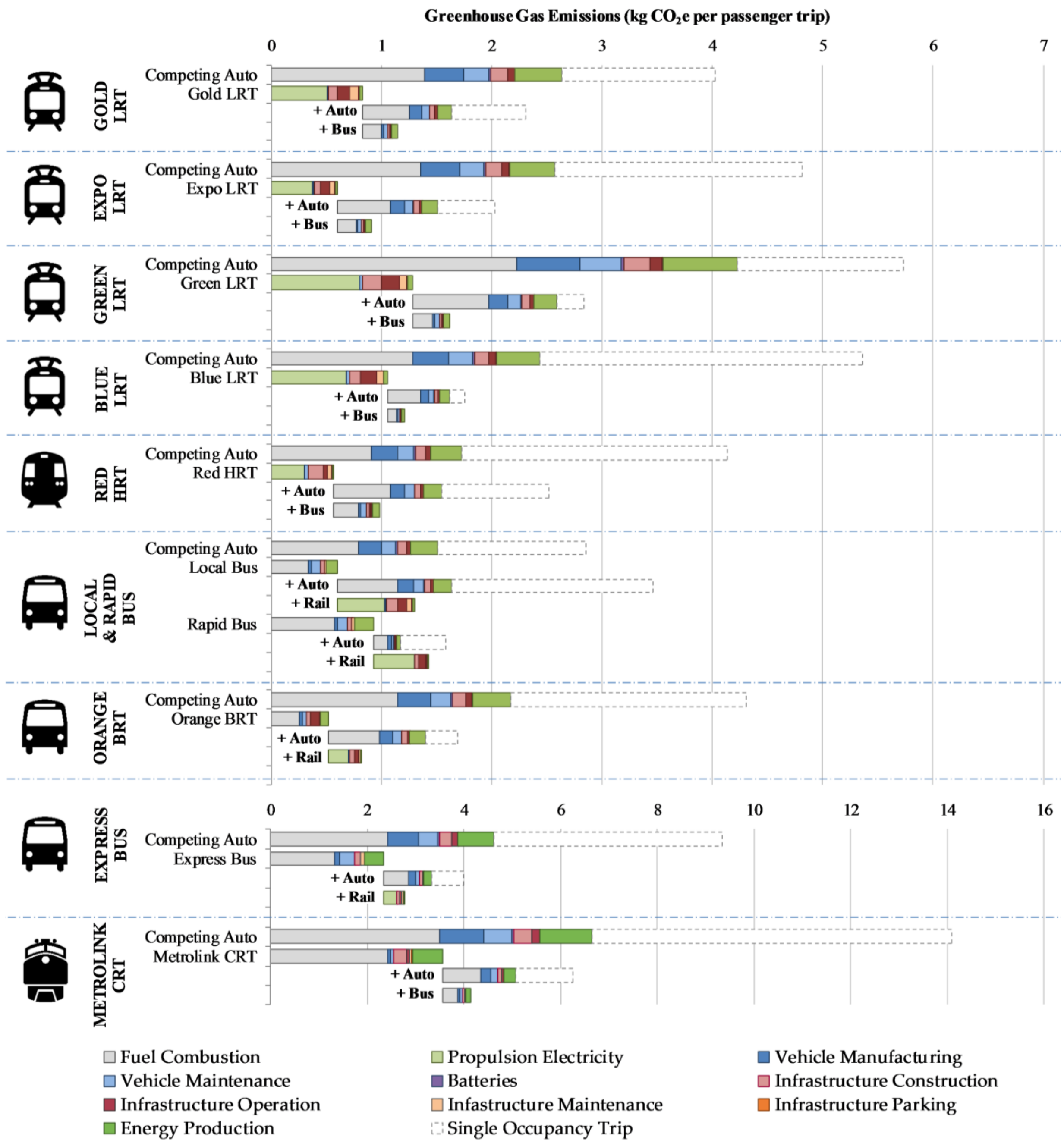

FIGURE 4 Long-term multimodal and competing auto GHG emissions per passenger trip in the LA transit system.

Long-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 dotted outlines. Note that due to longer trip distances, Express Bus and Metrolink are shown on a separate scale.

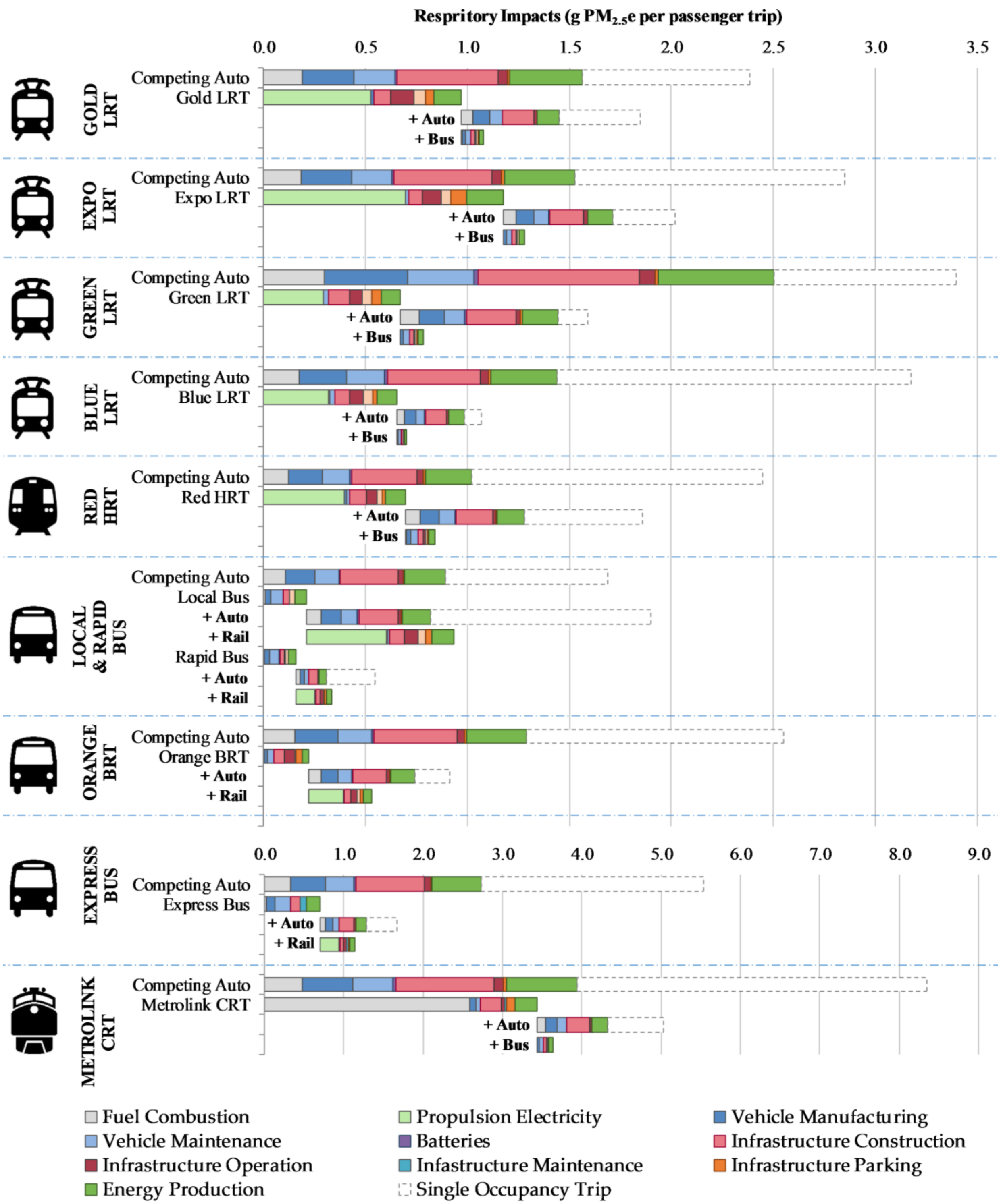

FIGURE 5 Near-term multimodal and competing auto respiratory impacts per passenger trip in the LA transit system.

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 white. Note that due to longer trip distances, Express Bus and Metrolink are shown on a separate scale.

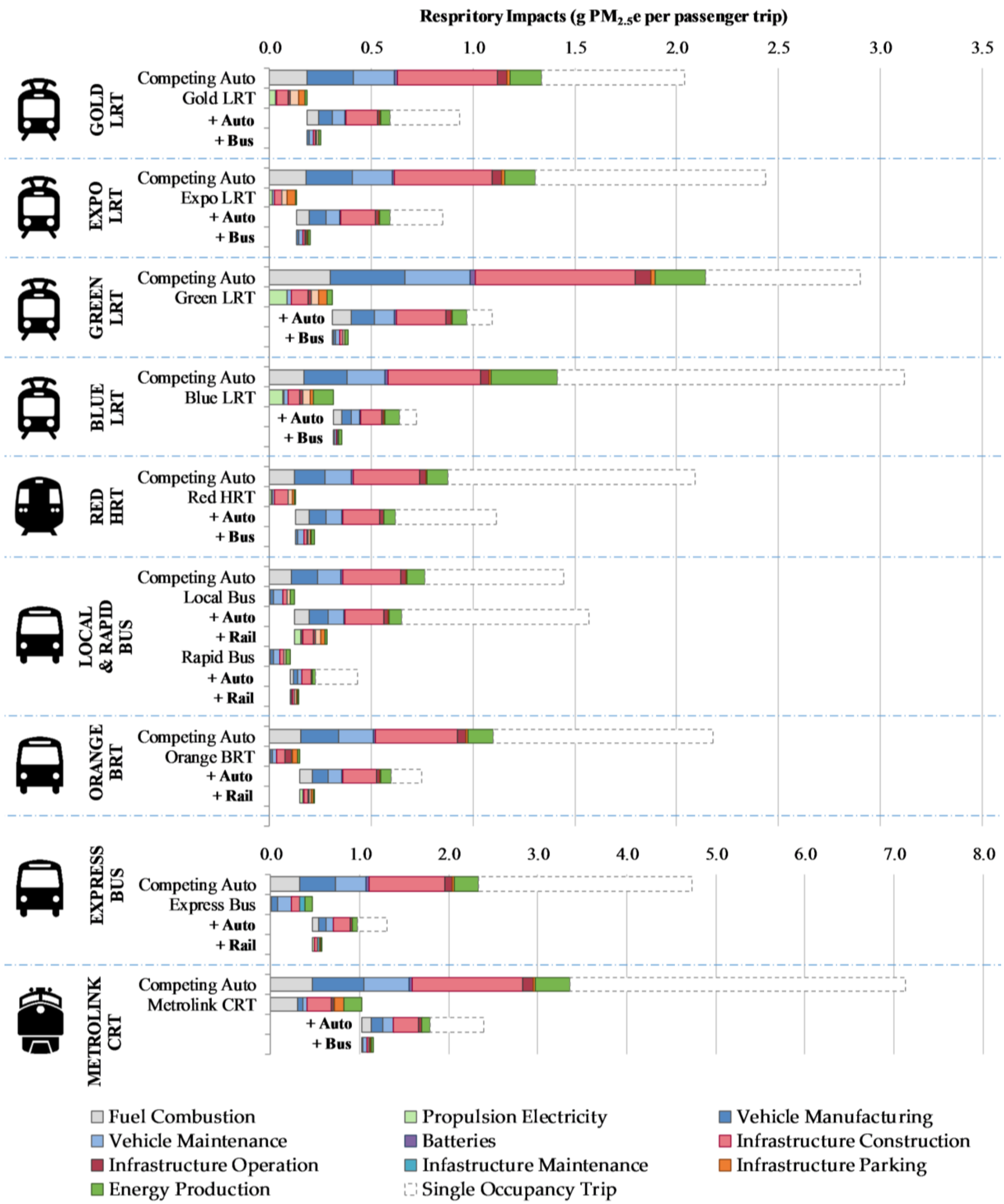

FIGURE 6 Long-term multimodal and competing auto respiratory impacts per passenger trip in the LA transit system.
Long-term multimodal trip impacts are shown compared to competing auto trip impacts. For each mode, region specific average trip distance and occupancies were used. Single occupancy auto trip impacts are shown extending in white. Note that due to longer trip distances, Express Bus and Metrolink are shown on a separate scale.

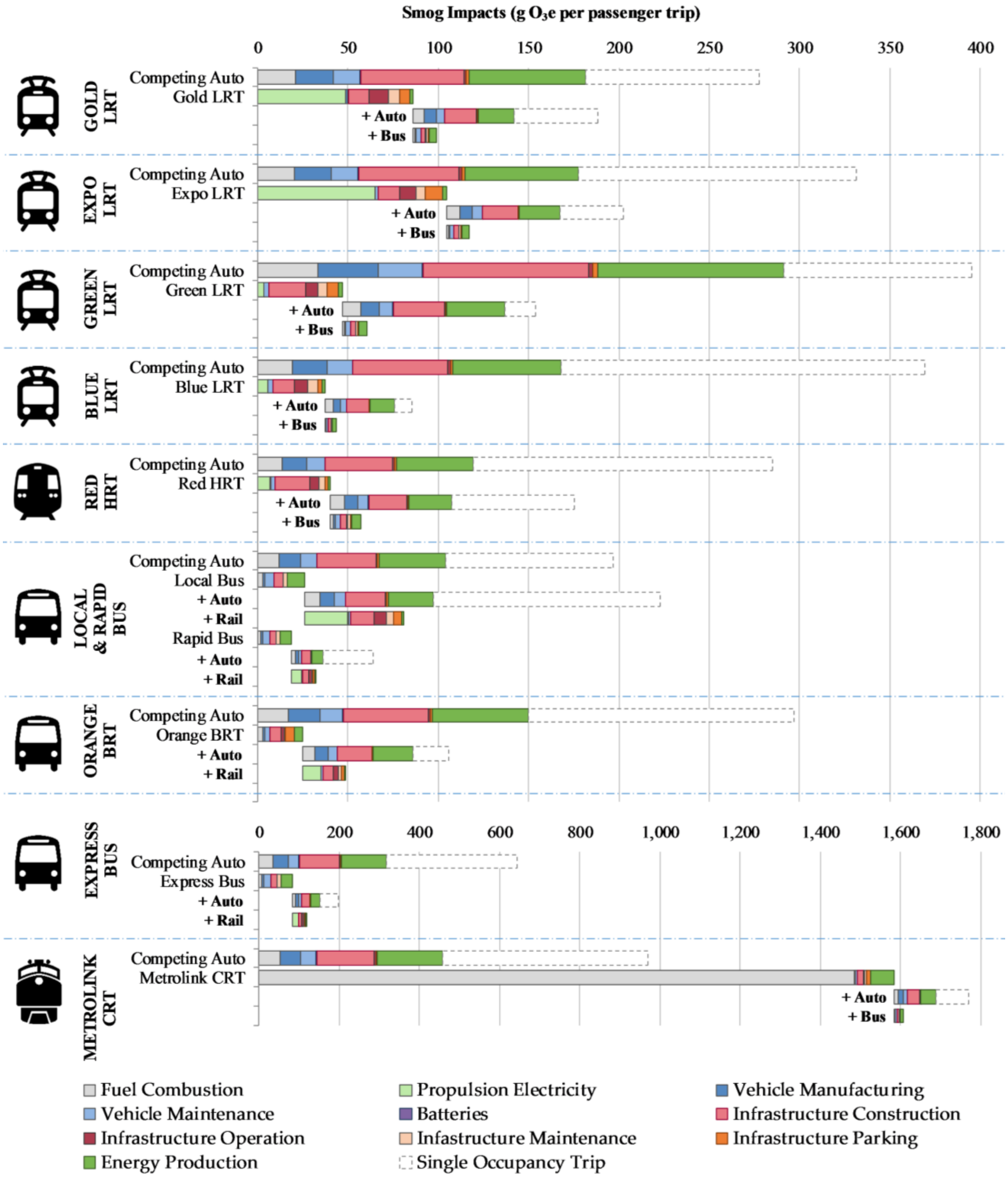

FIGURE 7 Near-term multimodal and competing auto smog impacts per passenger trip in the LA transit system.

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 white. Note that due to longer trip distances, Express Bus and Metrolink are shown on a separate scale.

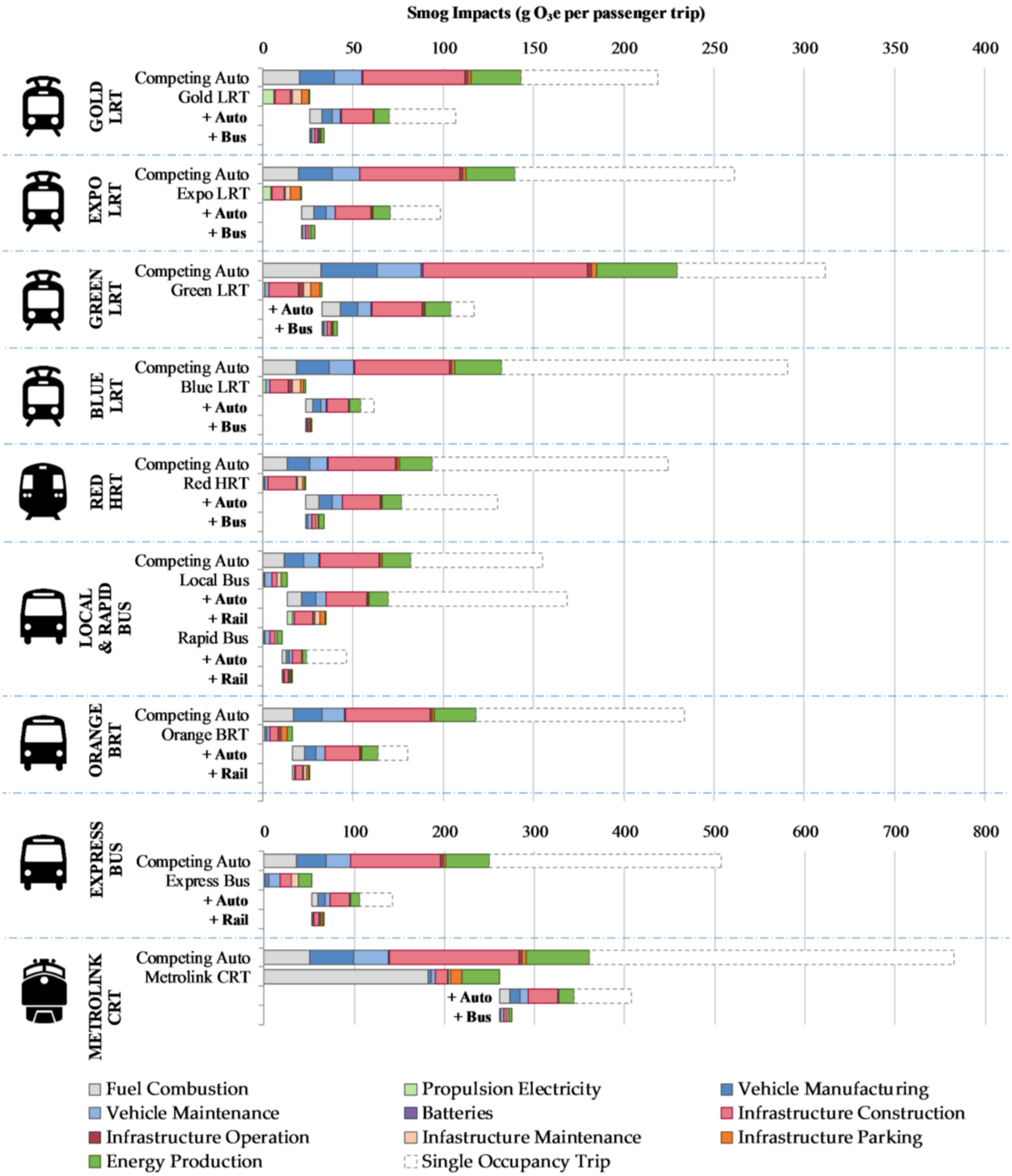

FIGURE 8 Long-term multimodal and competing auto smog impacts per passenger trip in the LA transit system.
Long-term multimodal trip impacts are shown compared to competing auto trip impacts. For each mode, region specific average trip distance and occupancies were used. Single occupancy auto trip impacts are shown extending in white. Note that due to longer trip distances, Express Bus and Metrolink are shown on a separate scale.

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 31% (Express bus) to 66% (Orange BRT) of multimodal transit trip GHG emissions, and 21% (Rapid bus) to 63% (Red HRT, Local bus, 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 Local bus) 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 portion on the Expo LRT, Gold LRT, Red HRT, and Local bus systems average higher GHG emissions per trip than average occupancy competing auto trips. Although multimodal transit trips with auto access or egress have smaller trip impacts than a competing auto trip in most systems, 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 fraction of local and remote environmental impacts were determined by regional supply chain analysis of life-cycle processes. 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, and auto travel. Figure 9 displays the local and remote impact potentials by transportation system. 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 systems are similar or greater than auto impacts. However, local impacts from the Gold and Expo LRT systems were only 6% to 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 systems, 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 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 be compliant with the latest EPA Tier 4 emissions standards and will reduce PM and NOx emissions by up to 85% (SCRRA, 2016a). 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.

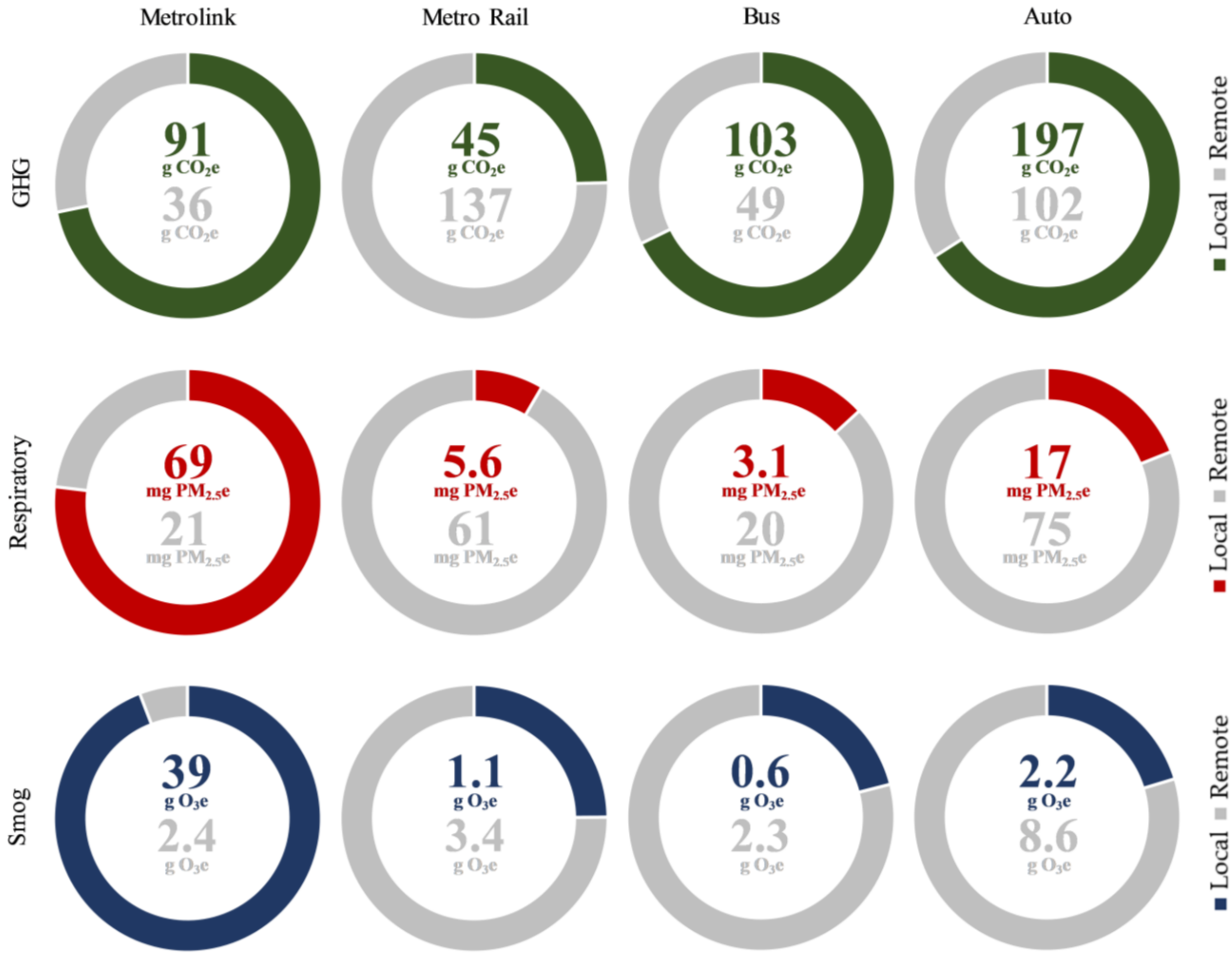

FIGURE 9 Local versus remote impact potentials per PMT.
Local (inside LA metropolitan region) impact potential per PMT is shown as colored portions of doughnuts: GHG in grams CO_2e (green), respiratory in milligrams $PM_{2.5}$e (red), and smog in grams O_3e (blue). Gray portions represent remote (outside 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.

4.2 Scenarios for First-last Mile Impact Reductions

Ultimately, a mode shift 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 zero impact modes. Zero 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 very small. As such, electric vehicles may be an alternative to zero impact modes, or be effective at replacing first-last mile trips through use in ridesharing.

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, 2015). As such, there is significant potential to replace first-last mile auto trips to reduce GHG emissions and improve air quality. Figure 10 shows the reductions achievable by switching from auto first-last mile trips to a zero impact mode. Shifting 23-50% of auto access or egress trips to a zero impact mode would reduce multimodal GHG emissions by 10%. 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, short term scenarios for reductions should also target carpooling or ridesharing 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.

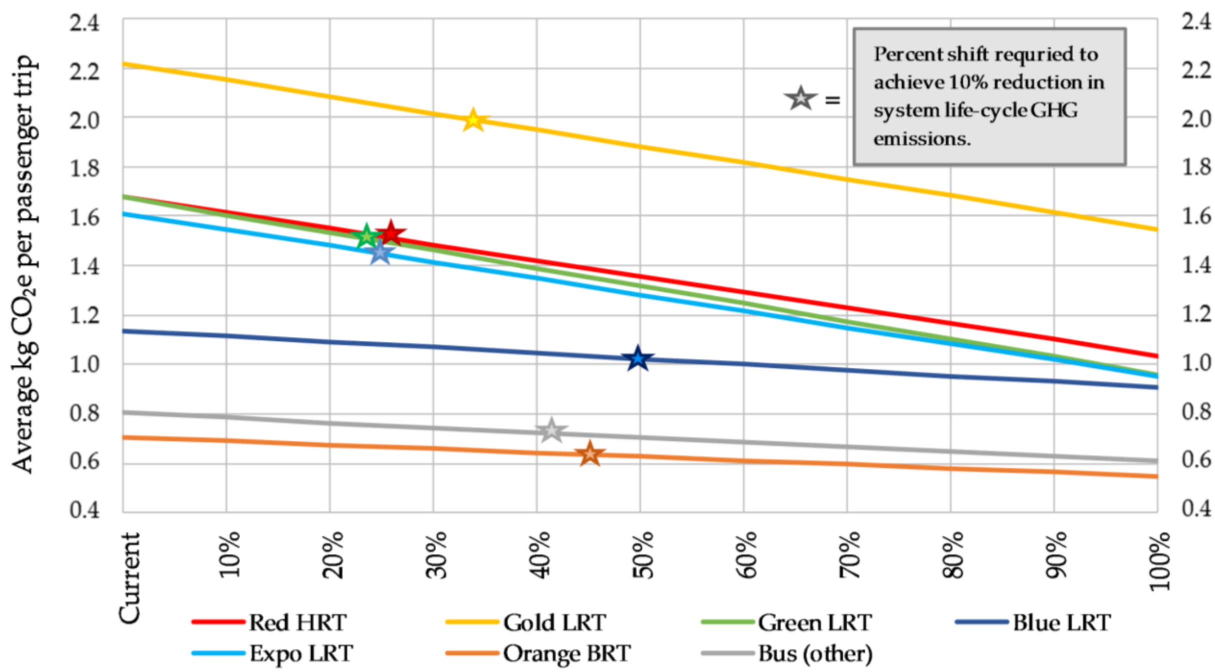

FIGURE 10 Reductions in GHG emissions per passenger trip by percent mode shift away from first-last mile auto trips and towards zero emission trips.
Average GHG emissions per transit trip include auto access and egress trends. Starred locations indicate the point at which 10% of the life-cycle GHG emissions can been reduced by shifting from auto to a zero emissions mode. Estimates shown are for near term travel.

Emphasis on carpooling and the substitution of SOV trips with zero impact trips is 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 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 system is a highly desirable system 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. However, accessing transit via auto should not be dissuaded if it causes a shift to auto over transit. 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 7am (LA Metro, 2016e). To avoid increasing first-last mile impacts, promoting increased carpooling for transit users who do not have access to feasible non-auto alternatives should be a high priority.

To replace auto first-last mile trips with zero impact trips, biking accessibility in the LA Metro system needs to 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, 2015). With average biking speeds of 10 mph (Thompson et al., 1997), and bikers willing to ride up to 15 minutes to access or egress stations (LA Metro, 2015), 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 systems, while approximately 40% are less than 3 miles in the Red HRT, Gold LRT, and Expo LRT systems (Caltrans, 2013). The Red HRT system has the lowest amount of auto trips below 2.5 miles (26%), and the Blue LRT system 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 systems. High biking accessibility should be implemented within a 2 to 3 mile range of stations all 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 system, increasing biking access and mobility surrounding Blue LRT system 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 system are often short (< 3 miles) and low occupancy (average 1.3 passengers). The Blue LRT system currently only has 82 bike rack spaces and 42 bike lockers but over 2000 parking spaces (not including nearby independent parking) across the systems' 22 stations. Based on first-last mile trip data, as much as 17,000 first-last mile auto trips to or from the Blue LRT system 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 5,700 per day) with zero impact trips in the Blue LRT system would reduce 560 tons CO_2e per year, or an average of 114 g CO_2e per passenger trip.

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

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, especially in systems that use electric propulsion. Methods to reduce first-last mile transit trips 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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