First-Last Mile Life Cycle Assessment of Los Angeles Transit

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved July 2016 by the
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ARIZONA STATE UNIVERSITY

August 2016

ABSTRACT

With high potential for automobiles to cause air pollution and greenhouse gas emissions, there is concern that automobiles accessing or egressing public transportation may cause emissions similar to regular automobile use. Due to limited literature and research that evaluates and discusses environmental impacts from first and last mile portions of transit trips, there is a lack of understanding on this topic. This research aims to comprehensively evaluate 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 evaluated by using a comprehensive life cycle assessment combined with regional household travel survey data to evaluate first-last mile trip impacts in multimodal transit focusing on automobile trips accessing or egressing transit. First and last mile automobile trips were found to increase total multimodal transit trip emissions by 2 to 12 times (most extreme cases were carbon monoxide and volatile organic compounds). High amounts of coal-fired energy generation can cause electric propelled rail trips with automobile access or egress to have similar or more emissions (commonly greenhouse gases, sulfur dioxide, and mono-nitrogen oxides) than competing automobile trips, however, most criteria air pollutants occur remotely. Methods to reduce first-last mile 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 walking and biking paths in areas with low access-egress trip distances.

ACKNOWLEDGMENTS

This research was supported by the Federal Highways Administration with cooperation from the Southern California Association of Governments and the Los Angeles County Metropolitan Transportation Authority.

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1 INTRODUCTION

With growing concern in recent years regarding increased criteria air pollutants (CAP) and greenhouse gas (GHG) emissions, focus on understanding and mitigating 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 environmental impacts of various transportation activities. This has led to increased regulations in air quality (CARB 2000), improvements to automobile fuel efficiencies (Jaffe et al. 2005), and frequent use of life cycle assessment (LCA) to promote sustainable methods in transportation systems (Chester & Horvath 2012). Additionally, public transit has proven to be a sustainable method for reducing environmental impacts and may be increasingly utilized to meet policy goals of reduced GHG and CAP impacts (Nahlik & Chester 2014; Matute & Chester 2015). Public transit can reduce GHG and CAP impacts per passenger mile in comparison to private automobile travel (Davis & Hale 2007; Chester & Horvath 2009), especially when considering single occupancy vehicle (SOV) travel (FHWA 2009) and regional driving and vehicle characteristics (Reyna et al. 2015). Despite this, transit use is frequently accessed or egressed with automobiles. As much as 33% of transit trips in Los Angeles (LA) begin with an automobile trip (Caltrans 2013). There is limited literature and research that evaluates and discusses environmental impacts from first-last mile transit access and egress. 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 on multimodal transit.

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 (Weisser 2007; Turconi et al. 2013), agriculture processes (Meisterling et al. 2009), transportation systems (Chester & Horvath 2009; Facanha & Horvath 2007) and many other areas. LCA has also been used to aid in transportation policy and decision making (Eisenstein et al. 2013; Plevin et al. 2014; Chester & Cano 2016). With the National Ambient Air Quality Standards, agencies such as the California Air Resource Board (CARB) regulating air quality, and metropolitan planning organization 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 accurate regional first-last mile trip characteristics and comprehensive life cycle modeling. Chester & Cano (2016) utilize a comprehensive environmental LCA to evaluate the time-based impacts of the LA Expo light rail transit line (LRT) 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 on the accuracy of first-last mile trip characteristics such as investigating characteristics of linked auto trips to transit rather than average trip characteristics. Additionally, the study focuses on only one transit line, so it is unclear if this trend is typical. In another study, Mathez et al. (2013) evaluates GHG emissions in Montreal, Canada across multiple modes of transportation (including various transit modes) 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 a LCA would provide a more comprehensive evaluation of environmental impacts. For example, in the study, the Montreal Metro is assumed to emit no GHGs per passenger mile citing that the line 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 similar conclude that auto access or egress trips with transit potentially emit similar emissions to a competing auto trip.

Due to a lack of complete understanding of first-last mile environmental impacts from 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 greater LA region is used to evaluate the impacts of multimodal transit trips to address this question. With public and urban transportation being positioned to reduce emissions through urban planning and sustainable transit development, identifying comprehensive near and long term first-last mile life cycle impacts across multiple transit systems will help establish a better understanding of the underlying characteristics that govern environmental impacts in multimodal transit.

2 METHODOLOGY

An environmental LCA framework is developed by expanding on previously related work to more comprehensively evaluate the impacts of multimodal transit trips with focus on auto trips accessing or egressing transit. LCA is applied to 10 transit lines in the greater LA region consisting of four light rail (Metro Blue, Metro Green, Metro Gold, and Metro Expo), one heavy rail (Metro Red), three bus services (Metro Local, Metro Rapid, and Metro Express), one bus rapid transit service (Metro Orange), and one commuter rail service (Metrolink). Consistent with recent studies of LA transit, both near term and long term life cycle effects are estimated. In addition, regional automobile impacts were developed to evaluate characteristics of competing automobile trips and automobile trips accessing or egressing transit. The LCA is designed to account for average, peak, and off-peak near term life cycle impacts as well as long term life cycle impacts to aide in understanding the full scope in which transit and automobiles can be positioned to meet air quality and environmental standards. 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 & Horvath 2009) which are detailed in a system scope shown in **Table 1**.

Table 1 - Life Cycle Scope. All life cycle process evaluated are shown and grouped by mode and category.

Life Cycle Grouping	Automobiles/Buses	Rail
Vehicle		
Manufacturing	▪ Vehicle Manufacturing ▪ Battery Manufacturing ▪ Transport to Point of Sale	▪ Train ▪ Transport to Point of Sale
Operation	▪ Propulsion ▪ Idling	▪ Propulsion ▪ Idling
Maintenance	▪ Typical Maintenance ▪ Tire Replacement ▪ Battery Replacement	▪ Typical Train Maintenance ▪ Train Cleaning ▪ Flooring Replacement
Infrastructure		
Construction	▪ Roadway	▪ Track ▪ Station
Operation	▪ Roadway Lighting ▪ Herbicide Use	▪ Track, Station, and Parking Lighting ▪ Herbicide Use ▪ Train Control ▪ Miscellaneous (Escalators, Equipment)
Maintenance	▪ Roadway Maintenance	▪ Track and Station Maintenance
Parking	▪ Curbside Parking	▪ Dedicated Parking
Energy Production		
Extraction, Processing, & Distribution	▪ Gasoline/Diesel/Natural Gas Extraction, Processing, & Distribution	▪ Raw Fuel Extraction and Processing, Electricity Generation, Transmission & Distribution

With environmental impacts characterized with LCA for each LA transit and automobile travel, trip characteristics in the LA region are compiled using data from the

California Household Travel Survey (CHTS) and Los Angeles County Metropolitan Transportation Authority (LA Metro) to estimate first-last mile GHG and CAP impacts associated with multimodal transit trips. A multimodal transit trip is defined as any trip utilizing multiple modes of travel (excluding walking and other non-motorized modes) with at least one portion using transit. Trip statistics were aggregated and filtered in CHTS to assess multimodal travel characteristics in the greater LA metropolitan region. Specifically, auto first-last mile trip distances and occupancies were assessed across average, peak, and off-peak time-of-day for near term impacts and across average time-of-day for long term impacts. This provides a comprehensive assessment of first-last mile GHG and CAP impacts in multimodal trips in the Southern California region to help identify scenarios that can be beneficial for reducing environmental impacts through transportation policy and planning.

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 GHG emissions and CAP emissions including 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 chemicals (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, NOx, PM, and SO_2 are evaluated because they are regulated through National Ambient Air Quality Standards (EPA 1990) and NOx and VOC are ozone precursors (USDA 2012).

2.2 Life Cycle Characteristics of Los Angeles Transportation Systems

The LCA methods in this study follow those reported in previous similar research, however, significant efforts are made to obtain up-to-date system-specific data from the LA systems. The approach uses processes and methods previously outlined for assessing impacts in passenger transportation (Chester & Horvath 2009), some of which includes previous analysis of the Expo LRT line (Chester & Cano 2016), and the Gold LRT and Orange BRT Lines (Chester et al. 2013). The following discussion focuses on the new and updated data collection and methods used to assess the most significant life cycle processes.

2.2.1 Los Angeles Metro Rail Life Cycle Assessment

LA Metro runs four LRT lines. The Blue LRT line runs 22 miles north-south between downtown LA and Long Beach, the Green LRT line runs 20 miles at full grade separation between Norwalk and Redondo Beach with partial service along Interstate 105, the Gold LRT line runs 31 miles between Pasadena and East LA with service through downtown LA, and the Expo LRT line runs 15.2 miles between Santa Monica and downtown LA. LA Metro runs two heavy rail transit (HRT) lines, the 17.4 mile Red HRT line and the 6.5 mile Purple HRT line. Due to the similarities and shared properties between the two lines (including shared stations and ridership data), the Purple line impacts are merged into the Red line.

To allocate the usage of the rail fleet vehicles by line, weighted train characteristics (e.g., length, weight, capacity, etc.) are estimated for each line during average, peak, and off-peak periods based on reports of train operations from the LA Metro Transportation Research and Library Archives (LA Metro 2016e; LA Metro 2016d; LA Metro 2015b; LA Metro 2014a). The rolling stock of LA Metro includes Breda A650 heavy rail vehicles (Red and Purple HRT lines) and a number of different light rail vehicles (LRVs) shared between the light rail lines. The light rail fleet consists of AnsaldoBreda P2550 LRVs (Gold LRT line), Nippon Sharyo P850 and P2020 LRVs (Blue and Expo LRT lines), and Siemens P2000 LRVs (Blue, Expo, and Green LRT lines) and new Kinki Sharyo P3010 LRVs (Gold and Expo LRT lines). Manufacturing impacts of these weighted vehicle characteristics are assessed in SimaPro (PRé 2014) with regional energy mixes and delivery of vehicles to LA. Long term manufacturing impacts are modeled mainly after Kinki Sharyo P3010 LRVs assuming LA Metro exercises their full contract with Kinki Sharyo to obtain 235 total LRVs (LA Metro 2012).

The infrastructure assessment is based on engineering design documents from the LA Metropolitan Transportation Research and Library Archives (LA Metro 2016e) with supplemental Google Earth satellite imagery when necessary to evaluate at-grade, aerial, and underground track and station construction as well as LA Metro parking infrastructure construction. This approach follows previous similar research (Chester & Cano 2016) in which use of concrete and asphalt has 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 2014) with additional assessment of station and parking construction and maintenance in the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) (Horvath 2003).

Energy consumption data for each rail line was provided by LA Metro in the form of meter readings by station, line, and utility provider. In 2014, LA Metro purchased 139 GWh from the Los Angeles Department of Water and Power (LADWP), 65 GWh from Southern California Edison (SCE), and 9.5 GWh from Pasadena Water and Power (PWP) (LA Metro 2014b). **Figure 1** shows the energy use by rail line and utility provider and **Figure 2** shows the near term estimated energy portfolios of these utilities.

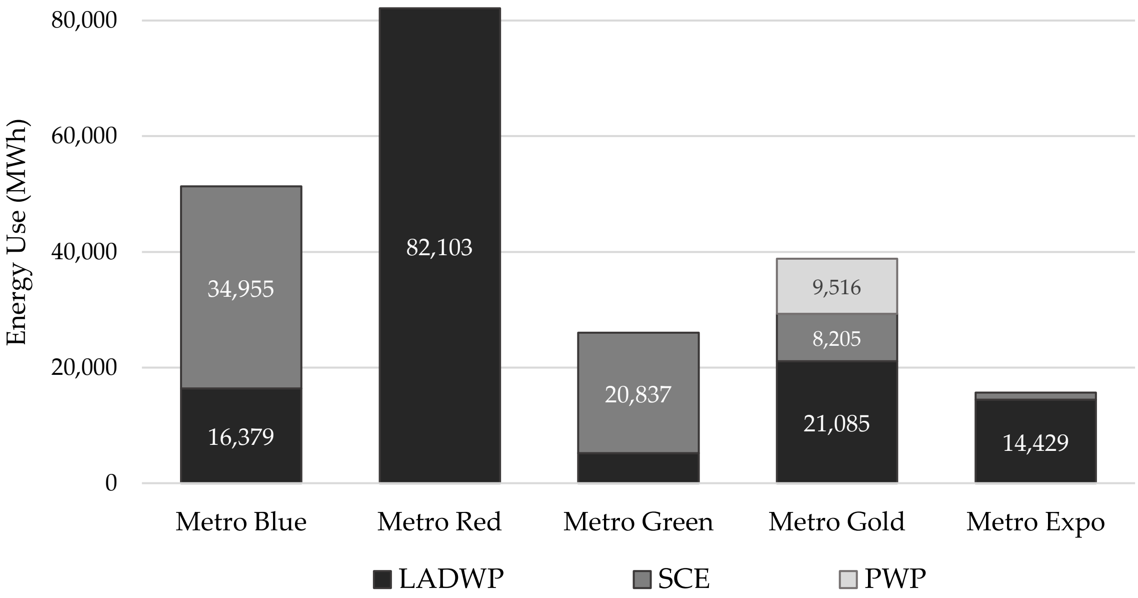

Figure 1 - LA Metro Energy Use by Rail System and Utility Provider. Total energy supplied by utility provider to each LA Metro rail system for the calendar year of 2014. Abbreviations: Los Angeles Department of Water and Power (LADWP); Pasadena Water and Power (PWP); Southern California Edison (SCE).

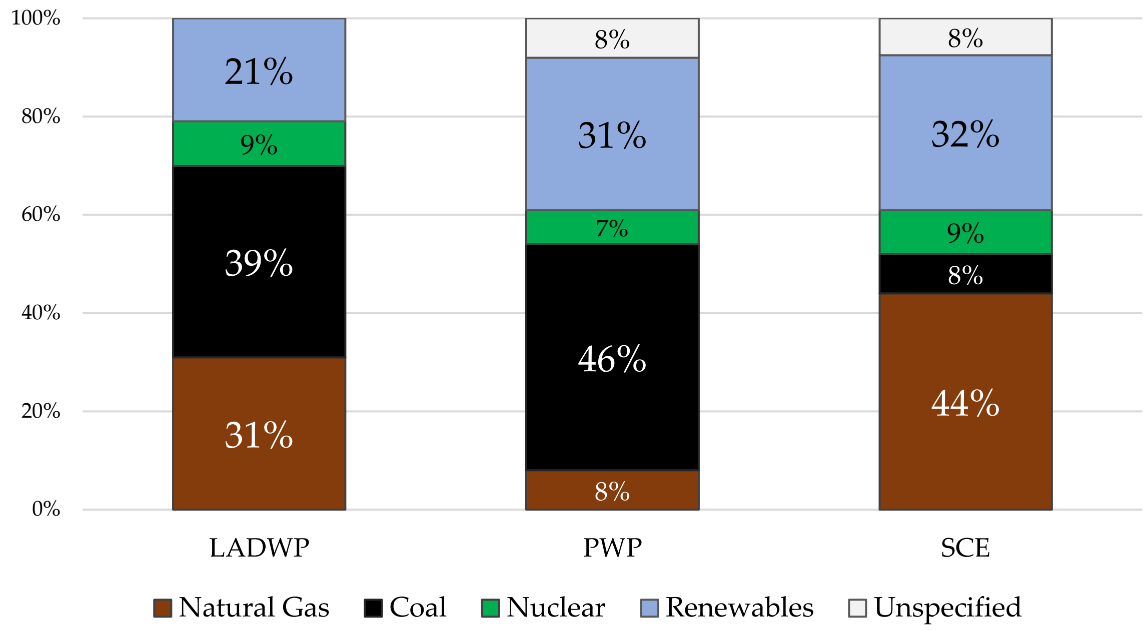

Figure 2 - LA Metro Utility Provider's Near Term Energy Portfolios. The approximate energy supply mix for the three utility providers in the LA Metro system (LADWP 2014; PWP 2015; Ellis et al. 2014). Note that the energy mix reflects energy supplied by the each utility, not the generation mix. Abbreviations: Los Angeles Department of Water and Power (LADWP); Pasadena Water and Power (PWP); Southern California Edison (SCE).

2.2.2 Los Angeles Metro Bus Life Cycle Assessment

LA Metro runs four bus services, Local Bus, Rapid Bus, Express Bus, and Metroliner. Together they account for nearly three quarters of all LA Metro boardings (LA Metro 2016d). All LA Metro buses run on compressed natural gas (CNG). The Local bus service operates over 100 routes in the greater LA metropolitan region providing traditional local bus, limited stop, and shuttle bus services. The Rapid bus service operates in mixed traffic with fewer stops than Metro Local service. Metro Rapid operates with some bus rapid transit characteristics such as traffic signal priorities and quicker low-floor boarding. The Express bus service operates on select longer routes with limited stops and nonstop portions. Metroliner operates two bus lines, the Metro Orange bus rapid transit (BRT) line and the Metro Silver line. The Orange BRT line utilizes an 18 mile dedicated right-of-way busway operating in the San Fernando Valley. The Silver line is a limited-stop bus service with some features of bus rapid transit, however, due to its similarities in operational characteristics to the Express line, analysis of the Metroliner system focused only on the Orange BRT line.

Following the same approached outlined for assessing the usage of the rail fleet by rail line, average weighted bus characteristics are estimated for each bus service based on reports of bus operations by line from the LA Metro Transportation Research and Library Archives. The Orange BRT line operates 60 foot articulated North American Bus Industry vehicles, while all other lines use an amalgamation of over 2,400 CNG buses ranging from 31 feet to 60 feet (articulated), most which are manufactured by North American Bus Industries (NABI) (USDOT 2014b; LA Metro 2016d). Manufacturing impacts of weighted vehicle characteristics for each bus service is assessed in SimaPro (PRé 2014) with regional energy mixes and delivery of vehicles to LA.

Local, Rapid, and Express bus service vehicle operation impacts are estimated by aggregating CNG emissions testing results under various drive cycles. Due to a lack of literature with robust modeling of CNG bus drive cycles and tailpipe emissions, assumptions were necessary to estimate peak and off-peak tailpipe emissions for current LA Metro bus operations. LA Metro schedule data is summarized to estimate the scope of observable bus stops per mile for each bus service (LA Metro 2016a). 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. It is assumed that extra stops occur due under normal operation due to congestion and stops at intersections (or other road interferences). Matching similar drive cycles to each bus service's route characteristics allows for estimated tailpipe emissions for peak and off-peak bus operation. Average bus tailpipe emissions are then calculated by weighting peak and off-peak tailpipe emissions by hours of peak and off-peak travel on each bus service route. **Table 2** shows the bus services, estimated minimum and maximum stops per mile, and chosen peak and off-peak drive cycles. Three drive cycle are considered; the Central Business District drive cycle (CBD), the Manhattan drive cycle (MAN), and the Orange County drive cycle (OCC). These were selected based on the range of stops observed and the available CNG testing results in the literature under matching drive cycles. With matched drive cycles to each service for peak and off-peak operation, tailpipe emissions for Local, Rapid and Express Bus services is estimated from test results of CNG buses from three separate sources that included similar buses to the LA Metro fleet operating under the chosen drive cycles (Posada 2009; Ayala et al. 2002; MJ Bradley 2013). Due to uncertainties about future emissions, it is assumed that buses will achieve fuel economies and emissions consistent with best available current technology today and air pollutants will meet 75–85% reductions as outlined by the CARB 2020 certification standards (CARB 2000). Orange BRT line vehicle operational impacts are based on emissions testing by the CARB of similar bus engines (CARB 2000; Thiruvengadam et al. 2011) flowing the same 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 (USDOT 2014b). With estimated fuel consumption per mile for all buses determined through this analysis, consumption of CNG fuel in 2014 was estimated to be 4% lower than actual reported fuel consumption by the NTD in 2014

(USDOT 2014b). This indicates that estimated impacts LA Metro buses are reasonably accurate. Under estimation is likely due to fuel consumption estimates relying on yearly vehicle miles traveled (VMT) which does not account for idling.

Table 2 - Selected LA Bus Service Drive Cycles. Other stops per mile are assumed to be stops due to congestion and at intersections. Abbreviations: Central Business District drive cycle (CBD), Manhattan drive cycle (MAN), Orange County drive cycle (OCC). Minimum and maximum stops per mile for bus services are estimated via LA Metro schedule data.

Bus Service	Period	Stops Per Mile	Chosen Drive Cycle	Drive Cycle Stops Per Mile	Assumed Other Stops Per Mile
Local	Min / Off-peak	2.6	CBD	7	4.4
	Max / Peak	5.3	MAN	10	4.7
Express	Min / Off-peak	1.3	OCC	5	3.7
	Max / Peak	2.9	CBD	7	4.1
Rapid	Min / Off-peak	1.3	OCC	5	3.7
	Max / Peak	1.8	CBD	7	5.2

Construction and maintenance impacts are estimated with PaLATE on typical minor and major LA arterials segments. To allocate the fraction of impacts to LA Metro bus use, roadway damages caused by LA Metro buses are estimated. 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 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 2014a).

2.2.3 Metrolink Life Cycle Assessment

Metrolink is a 388 mile commuter rail transit (CRT) system operating seven lines throughout Southern California operated by the Southern California Regional Rail

Authority (SCRRA). Each of Metrolinks 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 typical operations and standard train and track construction. Vehicle inventory, operations, and fuel consumption data was obtained via the NTD (USDOT 2014b).

The Metrolink fleet consists of Electro-Motive Diesel (EDM) F59PH and F59PHI locomotives, Bombardier Bi-level passenger and cab cars, and Hyundai Rotem Bi-level passenger and cab cars (SCRRA 2012; USDOT 2014b). Average weighted fleet characteristics were estimated using NTD data (USDOT 2014b) with manufacturing and delivery of vehicles modeled in SimaPro using similar trains (PRé 2014). The long term fleet was modeled after the newly ordered EDM F125.

Operational effects were modeled from selected representative timetable schedules during peak and off-peak periods. Specifically, routes from the Inland-Orange County line are chosen as being most representative of typical Metrolink CRT train operations due to the lines distribution of stations per mile and the average train speed equivalent to the system average station distribution and system average train speed. Using EMD F59PH locomotive emissions recorded at multiple steady-state operation levels found in Fritz (1994), peak, off-peak, and average locomotive exhaust emissions are estimated through building custom locomotive drive cycles from representative train timetables. With average fuel consumption per mile from estimated drive cycles, estimated fuel consumption in 2014 was found to be approximately 7% lower than actual diesel fuel consumption of Metrolink locomotives in 2014 (USDOT 2014b). This indicates that the estimated operational impacts of Metrolink trains are reasonably accurate. Underestimation is likely due to fuel consumption estimates relying on yearly VMT which does not account for idling. Long term operational effects were modeled assuming the use of new Metrolink EDM F125 locomotives which will be compliant with the latest Environmental Protection Agency Tier 4 emissions standards and will cut particulate matter and nitrogen oxide emissions by up to 85% (SCRRA 2016c).

The entire Metrolink CRT system's engineering and construction of track and stations is detailed in comprehensive design manuals and uniform standards. The infrastructure assessment utilized these design documents (SCRRA 2016b) to develop a material and construction equipment assessment to evaluate track and station construction as well as parking infrastructure construction following previously outlined methods.

2.2.4 Los Angeles Automobile Life Cycle Assessment

An automobile trip in LA that would substitute, access, or egress transit is assessed. Standard 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) produced by Argonne National Laboratory (GREET 2015a; GREET 2015b). Near term use assumes 25 mile per gallon (MPG) fuel economy and long term use is assessed at 35 MPG or 55 MPG fuel economies. Long term 55 MPG automobile use is modeled to be lighter weight with improvements in manufacturing to help meet Corporate Average Fuel Economy (CAFE) 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 in bus impacts) and modeled with PaLATE. This process is similar to that outlined by in Chester and Cano (2016). An adjustment factor for peak and off-peak travel was used to adjust GHG vehicle operation effects for LA based on findings from Reyna et al. (2015), but CAP emissions were not adjusted for peak and off-peak travel.

2.2.5 Multimodal Trip Development

With LCA impacts per mile for all transit modes and auto modes developed, multimodal trip characteristics are developed to compare multimodal transit emissions in the LA metropolitan region. Quantitative travel survey data were obtained from the CHTS with supplementary transit statistics from LA Metro. The CHTS is conducted approximately every 10 years in California by the California Department of Transportation (Caltrans) to assess characteristics and travel behaviors in the state of California. For this analysis, the main focus was on multimodal trips including auto and transit. Peak hour travel is defined as 7am to 9am and 3pm to 6pm for all equivalent Metro bus and rail trips and before 8:30am and 3:30pm to 7pm for equivalent Metrolink CRT. In addition, with the purpose of this analysis assessing GHG and CAP impacts, biking, wheelchair and other non-motorized modes (i.e. skateboard, longboard) were grouped together with walking under the assumption that these modes create zero or no significant increase in impacts per mile. To examine first-last mile impacts, trips with at least one of the transit modes evaluated in the life cycle assessment are targeted. Although there were over 42,000 households that participated in the CHTS (Caltrans 2013), only a fraction of samples occurred in the LA metropolitan area, with few using transit, and a very small subset using multimodal transit with first-last mile auto trips.

The CHTS data set provides detailed trip characteristics that allow in depth examination of unimodal and multimodal trip trends occurring in the LA metropolitan region. The CHTS data set is filtered to include samples only in the Southern California Association of Governments (SCAG) region minus Imperial County (i.e. Los Angeles, Orange, Riverside, San Bernardino, and Ventura Counties). There were over 125,000 observed trips recorded in these counties (Caltrans 2013). 82% of trips were recorded being by automobile (either as driver or passenger). All transit modes (public and private) account for less than 4% of the samples. **Table 3** gives a detailed overview of the general CHTS statistics for the SCAG region. Most transit trips are accessed or egressed through walking, with a small fraction accessed or egressed through automobile 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 by Redhill Group (2015). The Metro Green and Gold LRT lines have approximately 20% of access or egress by auto, and the higher density Red HRT and Blue LRT lines have 5% and 7% first-last mile auto trips respectively (**Table 4**). Metro bus services have very low access and egress by auto, all 3% or lower. According to recent LA Metro on-board surveys, the CHTS results are likely under-representing the current frequency of auto access or egress to Metro transit. 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 (**Table 5**). Although this skew in the CHTS data set lowers the number of overserved samples of paired auto-transit trips, it is not expected that the trip characteristics would alter significantly. Auto trips occupancies are also recorded and analyzed. In the SCAG region, the CHTS average auto occupancy for all purposes (including carpools) was 2 passengers per auto trip (Caltrans 2013). According to the 2009 National Household Travel Survey (NHTS), this is slightly above the reported all-purpose national auto occupancy average of 1.7 passengers per trip (FHWA 2009). Auto first-last mile distances and occupancies also varied. Auto first-last distances to and from LA transit systems averaged around 4 miles, and auto occupancy for these trips was less than the SCAG region average at around 1.7 passengers per auto (**Table 6**). Finally, the Expo LRT line opened in mid-2012 while the CHTS was already underway. Some trips on the Expo LRT line are reported in the study, however they are far fewer than the other rail lines, and auto-rail trips are only observed twice. Therefore, auto-rail trip characteristics for the Expo LRT are assumed to be the average of the other four rail lines.

Table 3 - Mode Distribution in Los Angeles Metropolitan Region. Modal split estimated via the CHTS. Mode description: Non-motorized includes walking, biking, wheelchair, and other non-motorized modes. Auto includes drivers, passengers, or carpooling in auto, vans, or trucks. Metro Bus includes Local, Rapid, Express, and Metroliner. Rail includes light, heavy and commuter rail but excludes all other rail or trolley modes.

Mode	Number of Observations	Percent of Total	Average Distance (miles)	Percent Travel During Peak
Non-Motorized	17,188	13.7%	1.0	51%
Auto	102,497	81.6%	9.2	49%
Metro Bus	3,184	2.5%	4.9	54%
Rail	785	0.6%	14.1	55%
Other	2,026	1.6%	-	-

Table 4 - First-last Mile Modes by Transit System in LA Region. Percent represents the fraction of survey respondents in the CHTS that accessed or egressed to transit.

Transit System	Percent Walk	Percent Auto	Percent Other
Blue LRT	91%	7%	2%
Red / Purple 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%
Metroliner	95%	2%	3%
Metrolink CRT	65%	33%	2%

Table 5 - Access Mode on LA Metro Bus and Rail. Surveys were conducted on-board of transit modes directly by LA Metro (LA Metro 2016b).

Mode	Access Mode	Walk	Dropped off	Drove	Bike	Other
Bus	2015	83%	8%	2%	5%	3%
	2014	86%	6%	2%	3%	4%
	2013	82%	8%	3%	4%	3%
	2012	84%	8%	2%	3%	3%
	4 year average	84%	8%	2%	4%	3%
Rail	2015	68%	11%	12%	7%	3%
	2014	65%	9%	15%	5%	6%
	2013	64%	10%	17%	6%	3%
	2012	66%	12%	15%	4%	3%
	4 year average	66%	11%	15%	6%	4%

Table 6 - LA Transit System First-last Mile Trip Characteristics. Results are from 2013 CHTS. Average auto first-last mile trip distance is the average distance of an auto trip when the following linked was a transit trip. Average linked transit trip distance is the distance of the transit trip linked with an auto access or egress trip. Average auto occupancy is the average occupancy of the automobile for the access or egress trip.

Transit System	Average Auto Access Trip Distance (miles)	Average Auto Egress Trip Distance (miles)	Average Linked Transit Trip Distance (miles)	Average Auto Occupancy (passengers)
Blue LRT	2.35	2.16	17.2	1.25
Red / Purple HRT	5.89	6.60	8.76	2.00
Green LRT	5.36	4.48	15.5	1.19
Gold LRT	5.62	3.43	9.42	1.83
Local / Rapid Bus	2.33	1.91	8.92	2.62
Metroliner	2.54	4.76	10.2	1.33
Metrolink CRT	8.08	9.24	38.1	1.78
Average (All)	4.59	4.65	15.4	1.71
Average (LA Metro)	4.01	3.89	11.7	1.70

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 single or multimodal transit trip from origin to destination. To determine the characteristics of competing auto trips, trip origin-destinations pairings are cross-referenced with auto trips of the same origins and destinations. Based on the size of samples and average trip distances, the origin-destination analysis is conducted at the 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. **Figure 3** shows the boundaries of zip codes in the SCAG region used for this sub-regional analysis. 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 typically leads to shorter competing auto trips than multimodal transit trips for the same origin-destination pairings. **Table 7** displays the average competing auto trip distance and occupancy compared to their multimodal trip counterparts. Multimodal trip characteristics are also evaluated at peak and off-peak hours. 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. Additionally, auto trips competing with unimodal bus trips are assumed to have the same trip distance due to most of these trips occurring within their sub region as well as both being on-road. With comprehensive multimodal trip characteristics, multimodal first-last mile trip life cycle impacts are estimated by synergizing trip characteristics with per mile LCA results.

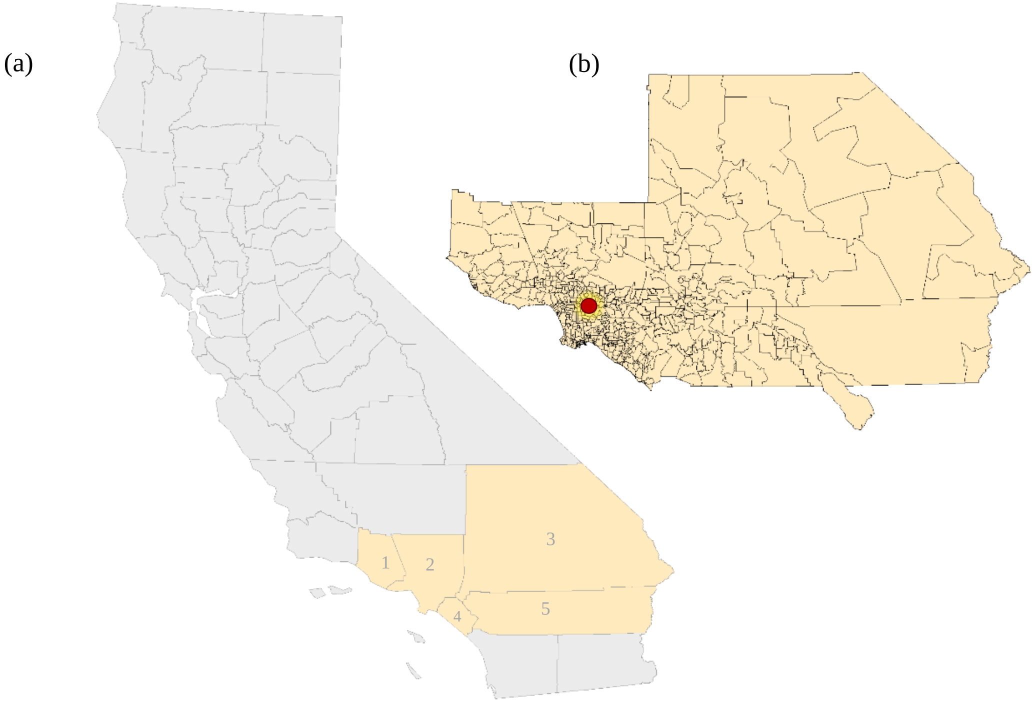

Figure 3 – Case Study Analysis Region in Southern California. The five counties in the state of California included in the analysis (a) and sub-regions bound by zip codes used to for origin-destination trends (b). Ventura (1), Los Angeles County (2), San Bernardino County (3), Orange County (4), and Riverside County (5) make up five of the six counties in the SCAG region (Imperial County was excluded). Downtown LA (which the location of the major rail hub Los Angeles Union Station) is marked by the red dot to signify the nucleus of transit activity in the region.

Table 7 - LA Transit System Auto-transit Trip and Competing Auto Trip. Average auto first-last mile trip distance is the average distance of an auto trip when the following linked was a transit trip. Average linked transit trip distance is the distance of the transit trip linked with an auto first-last mile trip. Auto + transit distance is the combined distance for a linked auto-transit trip. Competing auto trip distance is the average distance of auto trips for the same origin-destination pairings of the auto + transit trip.

Transit System	Average Auto First-Last Mile Trip Distance	Average Linked Transit Trip Distance	Auto + Transit Trip Distance	Competing Auto Trip Distance
Blue LRT	2.25	17.2	19.5	17.2
Red / Purple HRT	6.28	8.76	15.0	13.3
Green LRT	4.98	15.5	20.5	18.4
Gold LRT	4.76	9.42	14.2	12.9
Local / Rapid Bus	2.10	8.92	11.0	9.15
Metroliner	3.77	10.2	14.0	13.8
Metrolink CRT	8.66	38.1	46.7	45.2
Average	4.69	15.4	20.1	18.6
Metro Average	4.02	11.7	15.7	14.1

3 RESULTS

Per mile GHG and CAP emissions are first introduced for each transit system and the causes of unique impacts in each case are discussed. Next, results of CHTS data combined with per mile life cycle impacts are shown for unimodal transit trips and their competing auto trips to establish base trends. Finally, multimodal impacts and their competing auto trips are displayed. It should be noted that long term impacts are based mainly on projected future energy and ridership changes. The Gold LRT line is planned to become an extension of the Blue LRT line in the near future. Long term impacts for the Gold LRT line may therefore become consolidated into the Blue LRT line. However, this analysis does not consolidate the long term impacts of the Gold and Blue LRT lines. Also, unless otherwise noted, LA sedan impacts per mile are based on average occupancy of auto trips in the analysis region (2 passengers per auto trip).

3.1 Rail Life Cycle Impacts per Passenger Mile

LA rail system near term versus long term GHG emissions are summarized in **Figure 4a**, and near term peak versus off-peak emissions are summarized in **Figure 4b**. GHG impacts per PMT for LA rail systems range between 95 and 288 grams CO_2e per PMT in the near term, and between 48 and 94 grams CO_2e per PMT in the long term. Near term rail GHGs are 15% greater to 73% lower per PMT than near term average occupancy LA sedan GHGs and 43% to 86% lower than a near term single occupancy LA sedan GHGs. Long term rail GHGs are 30% to 78% lower than long term average occupancy LA sedan GHGs and 65% to 89% lower than long term single occupancy LA sedan GHGs. Vehicle propulsion is the largest contributor of GHGs per mile followed by infrastructure operation (i.e. station electricity use). These processes GHGs can be traced to energy generation at power plants and transmission loses and dominate near term LA Metro rail impacts, accounting for 90% of GHGs per passenger mile in some systems. Near term GHG emissions for Metrolink CRT is dominated by diesel fuel combustion during vehicle operation followed by energy production (diesel fuel production). Long term LA Metro rail GHG emissions are projected to drop significantly due to projected reductions of coal-firing and increases in renewable energy production by regional utility providers. The Gold (+35 g CO_2e/PMT) and Expo LRT (+2 g CO_2e/PMT) emit slightly higher GHGs per PMT than an average occupancy LA sedan during off-peak times. The main contributing factors to this are lower fuel consumption due to less congestion during off-peak auto travel and low off-peak train occupancies on the Gold and Expo LRT. Infrastructure construction can also be recognized as a small but noticeable contributor. GHG emissions are most commonly emitted during the production of cement and concrete, in which large amounts are necessary in large scale transit infrastructure. Producing large amounts of concrete requires high heating for calcination which requires large amounts of energy, in turn producing GHG emissions from energy generation (Flower & Sanjayan 2007).

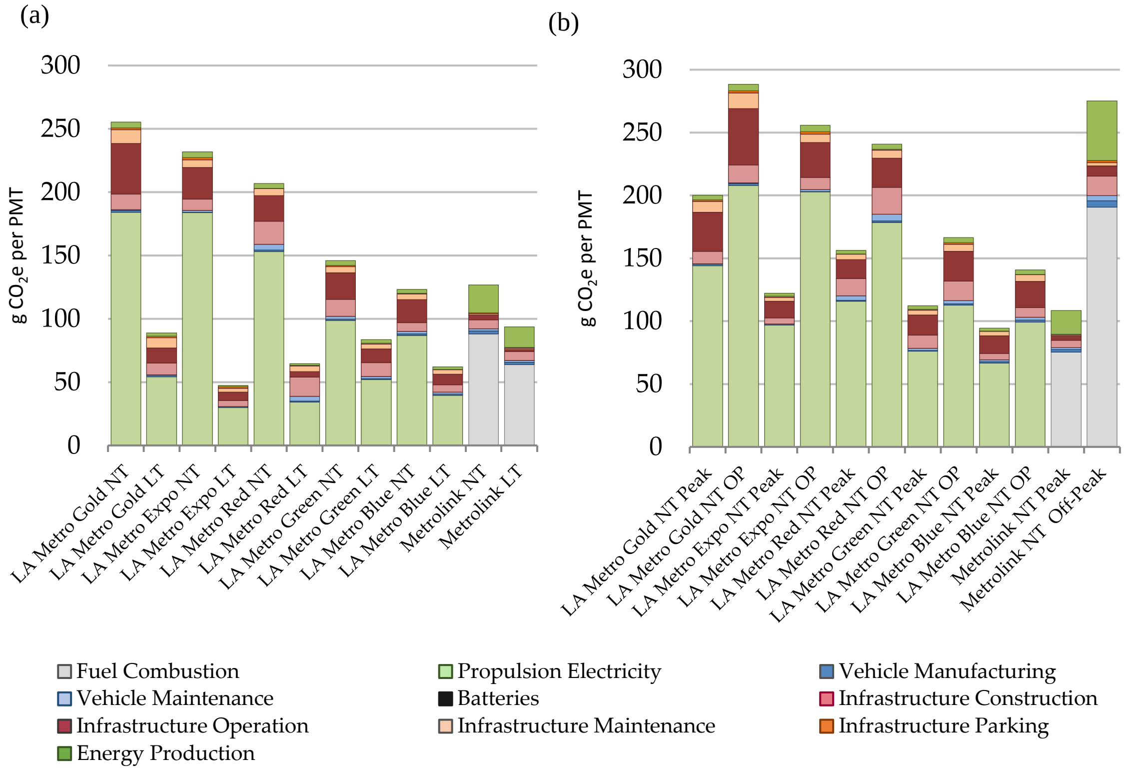

Figure 4 – Rail GHG Emissions per PMT. GHG emissions in milligrams CO_2e per PMT for rail near versus long term (a) and rail near term peak versus off-peak (b).

LA rail system near term versus long term CO emissions are summarized in **Figure 5a**, and near term peak versus off-peak CO emissions are summarized in **Figure 5b**. CO impacts for LA rail systems range between 89 and 515 mg CO per PMT in the near term, and between 83 and 200 mg CO per PMT in the long term. Near term rail CO emissions are 75% to 96% lower per PMT than near term average occupancy LA sedan CO emissions and 87% to 98% lower than a near term single occupancy LA sedan CO emissions. Long term rail CO emissions are 89% to 96% lower than long term average occupancy LA sedan CO emissions and 95% to 98% lower than long term single occupancy LA sedan CO emission. Long term CO emissions are not projected to significantly decrease due to the infrastructure characteristics not greatly fluctuating. In these rail systems, CO emissions are mainly caused in the infrastructure construction and maintenance primarily due to the production concrete and steel. CO is a byproduct in the production of steel due to oxidation of excess carbon during smelting. The Red HRT line has the highest CO impacts from infrastructure construction and maintained due to high the volumes of concrete and steel used to build the subway system. Metrolink CO emissions are highest per PMT in the near term due to infrastructure and maintenance in addition CO emissions from diesel fuel combustion during train operation.

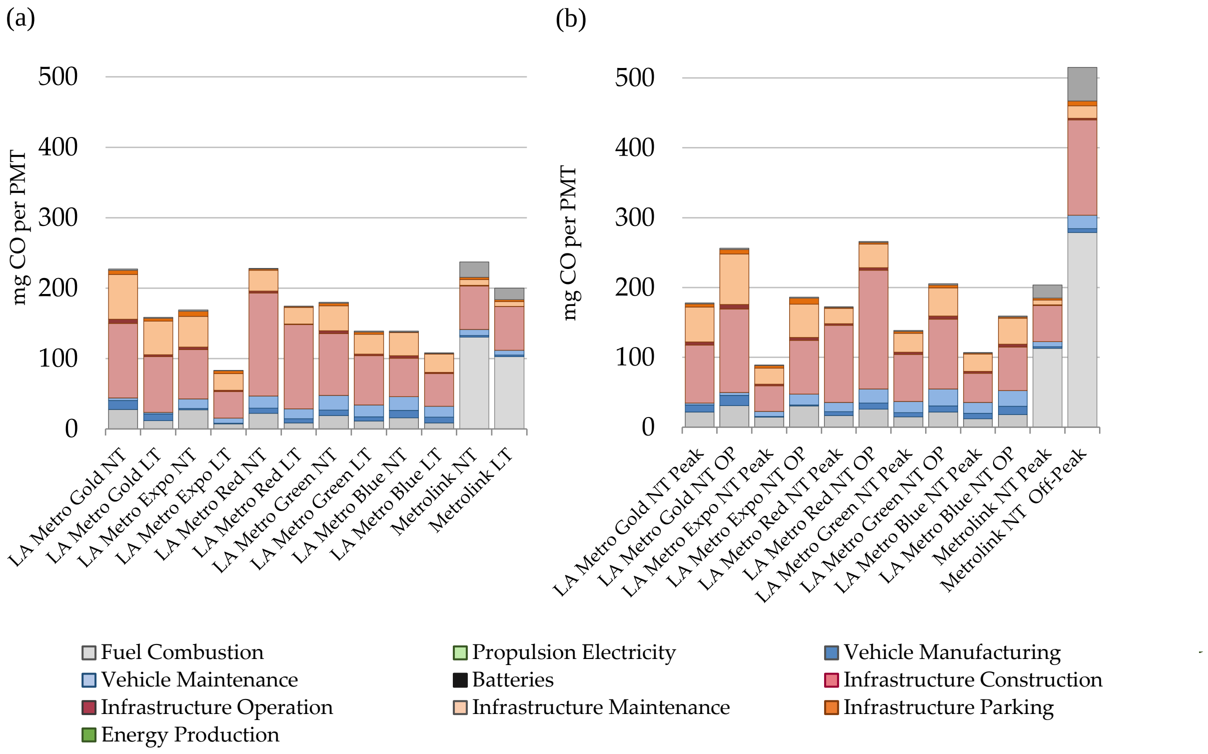

Figure 5 – Rail CO Emissions per PMT. CO emissions in milligrams per PMT for rail near versus long term (a) and rail near term peak versus off-peak (b).

LA rail system near term versus long term NO_X emissions are summarized in **Figure 6a**, and near term peak versus off-peak NO_X emissions are summarized in **Figure 6b**. NO_X impacts for LA rail systems range between 63 and 3,613 mg NO_X per PMT in the near term, and between 51 and 263 mg NO_X per PMT in the long term. Near term rail NO_X emissions are 900% greater (Metrolink) to 83% lower per PMT than near term average occupancy LA sedan NO_X emissions and 400% greater (Metrolink) to 91% lower than near term single occupancy LA sedan NO_X emissions. Long term rail NO_X emissions are 413% greater (Metrolink) to 84% lower than long term average occupancy LA sedan NO_X emissions and 156% greater (Metrolink) to 92% lower than long term single occupancy LA sedan NO_X emission. For the Gold and Expo LRT lines, over half of near term NO_X emissions are from energy production and generation, while the Red HRT, Blue LRT, and Green LRT lines have small near term NO_X emissions from energy generation. The Gold and Expo LRT lines energy sources (LADWP and PWP) currently contain high amounts of coal-fired energy production which causes higher NO_X emissions due to the high content of nitrogen in coal (Smoot & Smith 2013). The Green and Blue LRT lines are provided with most of their energy from SCE which utilizes more natural gas in place of coal-firing. The Gold and Expo LRT lines emit similar NO_X emissions per PMT as an average occupancy LA sedan, while the Red, Blue and Green lines are much lower per PMT. Metrolink CRT has significantly higher NO_X emissions than all other rail and bus modes, and between four and 20 times as much as other rail modes per PMT due to high amounts released during locomotive diesel fuel combustion. Long term emissions for Metrolink CRT and the Expo and Gold LRT lines will be much lower due to cleaner methods of energy generation and combustion. The future use of new Metrolink locomotives will be compliant with the latest Environmental Protection Agency Tier 4 emissions standards and will cut particulate matter and nitrogen oxide emissions by up to 85% (SCRRA 2016c).

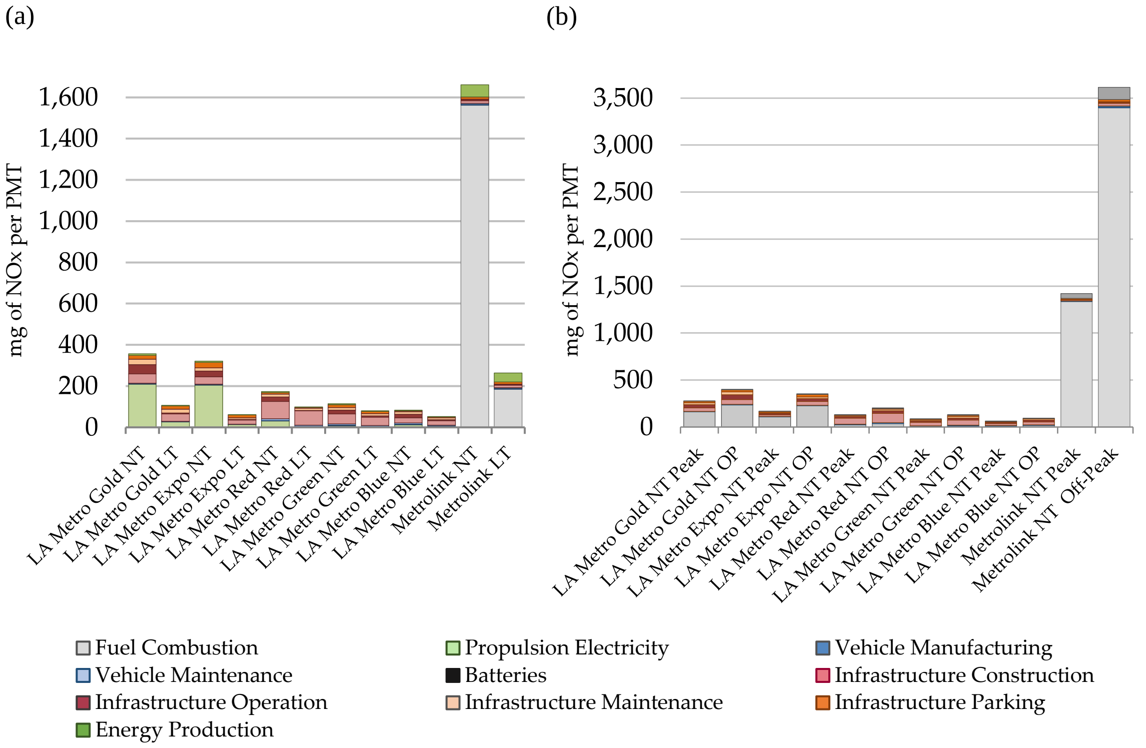

Figure 6 – Rail NO$_X$ Emissions per PMT. NO$_X$ emissions in milligrams for rail near versus long term (a) and rail near term peak versus off-peak (b).

LA rail system near term versus long term SO_2 emissions are summarized in **Figure 7a**, and near term peak versus off-peak SO_2 emissions are summarized in **Figure 7b**. SO_2 impacts for LA rail systems range between 65 and 813 mg SO_2 per PMT in the near term, and between 29 and 98 mg SO_2 per PMT in the long term. Near term rail SO_2 emissions are 293% greater to 69% lower per PMT than near term average occupancy LA sedan SO_2 emissions and 96% greater to 84% lower than near term single occupancy LA sedan SO_2 emissions. Long term rail SO_2 emissions are 33% to 84% lower than long term average occupancy LA sedan SO_2 emissions and 67% to 92% lower than long term single occupancy LA sedan SO_2 emissions. Near term SO_2 emissions very high for the Gold LRT, Expo LRT, and Red HRT due to high coal firing from the current energy sources (mainly from LADWP) during which sulfur in coal is oxidized (Smoot & Smith 2013). Due to LA utility providers projected shift away from coal firing with large increases in renewable energy and natural gas, long term SO_2 emissions will drop drastically.

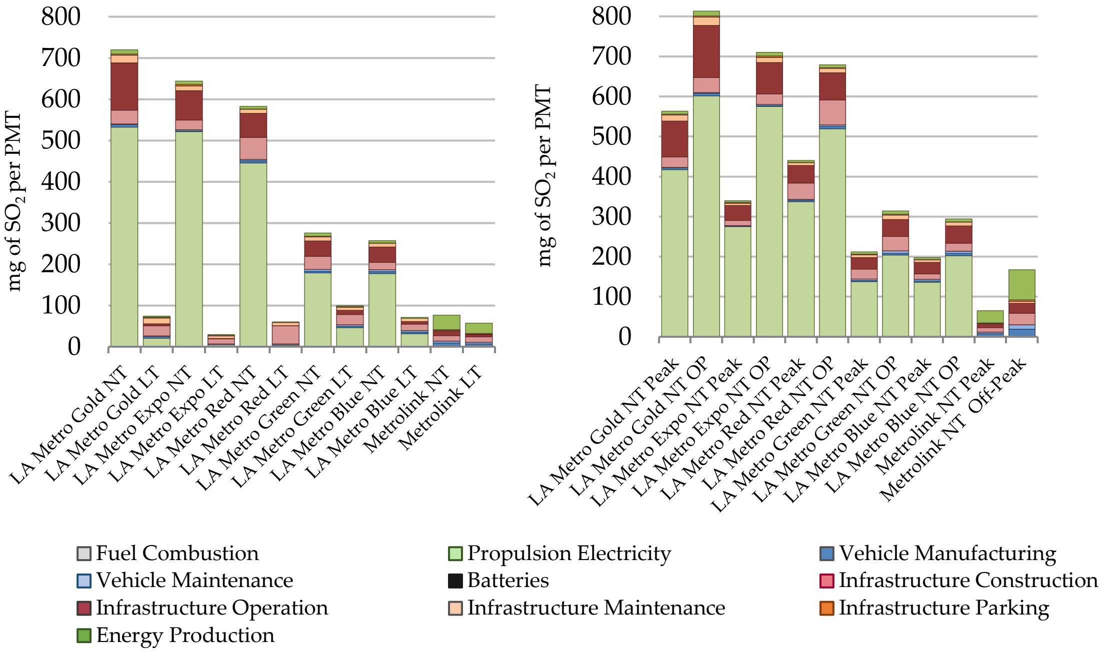

Figure 7 – Rail SO_2 Emissions per PMT. SO_2 emissions in milligrams for rail near versus long term (a) and rail near term peak versus off-peak (b).

LA rail system near term versus long term VOC emissions are summarized in **Figure 8a**, and near term peak versus off-peak VOC emissions are summarized in **Figure 8b**. VOC impacts for LA rail systems range between 26 and 238 mg VOC per PMT in the near term, and between 26 and 90 mg VOC per PMT in the long term. Near term rail VOC emissions are 46% to 94% lower per PMT than near term average occupancy LA sedan VOC emissions and 73% to 97% lower than near term single occupancy LA sedan

VOC emissions. Long term rail VOC emissions are 78% to 94% lower than long term average occupancy LA sedan VOC emissions and 89% to 97% lower than long term single occupancy LA sedan VOC emissions. Concrete production and asphalt paving (infrastructure construction, parking, and maintenance) contribute most to VOC emissions per PMT for LA Metro rail. Volatile organic diluents contribute to the large majority of VOC emissions in asphalt, while organics released in cement production are the major VOC contributor in concrete (Chester et al. 2010). Rail VOC emissions are highest per PMT in the Metrolink CRT system due to additional VOC emissions from locomotive diesel fuel combustion.

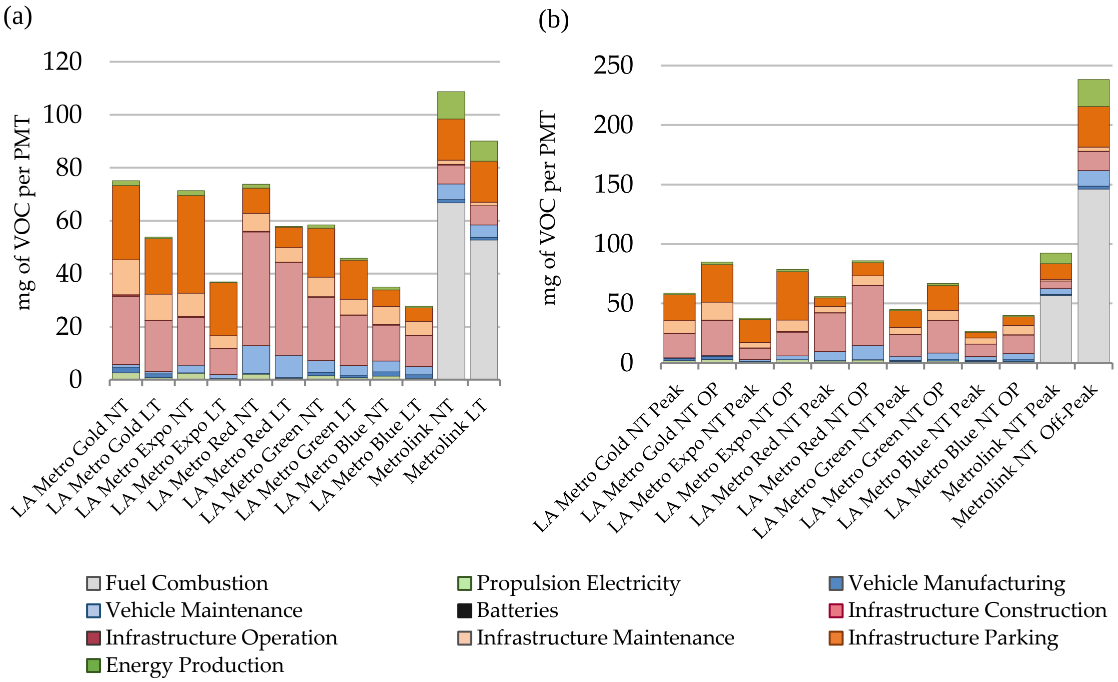

Figure 8 – Rail VOC Emissions per PMT. VOC emissions in milligrams for rail near versus long term (a) and rail near term peak versus off-peak (b).

LA rail system near term versus long term PM emissions are summarized in **Figure 9a** (coarse) and **Figure 9c** (fine), and near term peak versus off-peak PM emissions are summarized in **Figure 9b** (course) and **Figure 9d** (fine). Near term coarse PM impacts for LA rail systems range between 23 and 148 mg PM_{10} per PMT, and near term fine PM impacts range between 12 and 126 mg $PM_{2.5}$ per PMT. Long term coarse PM impacts for LA rail systems range between 13 and 25 mg PM_{10} per PMT, and long term fine PM impacts range between 5 and 16 mg $PM_{2.5}$ per PMT. Near term rail PM emissions are 191% greater to 81% lower per PMT than near term average occupancy LA sedan PM emissions and 44% greater to 91% lower than a near term single occupancy LA sedan PM emissions. Long term rail PM emissions are 24% greater to 90% lower than long term average occupancy LA sedan PM emissions and 38% to 95% lower than long term single occupancy LA sedan PM emission. The majority of particulate matter emissions are a result of energy production and generation in the LA Metro system. Long term particulate matter emission will significantly drop with cleaner energy generation and productions methods becoming more prevalent. Metrolink CRT particulate matter emissions mainly result from locomotive diesel fuel combustion, but as mentioned previously, future Metrolink locomotives will have great reductions in particulate matter (up to 85%) to be compliant with EPA emissions standards. With these reductions, long term rail particulate matter emissions will all be under 30 mg PM_{10} and 20 $PM_{2.5}$ per PMT.

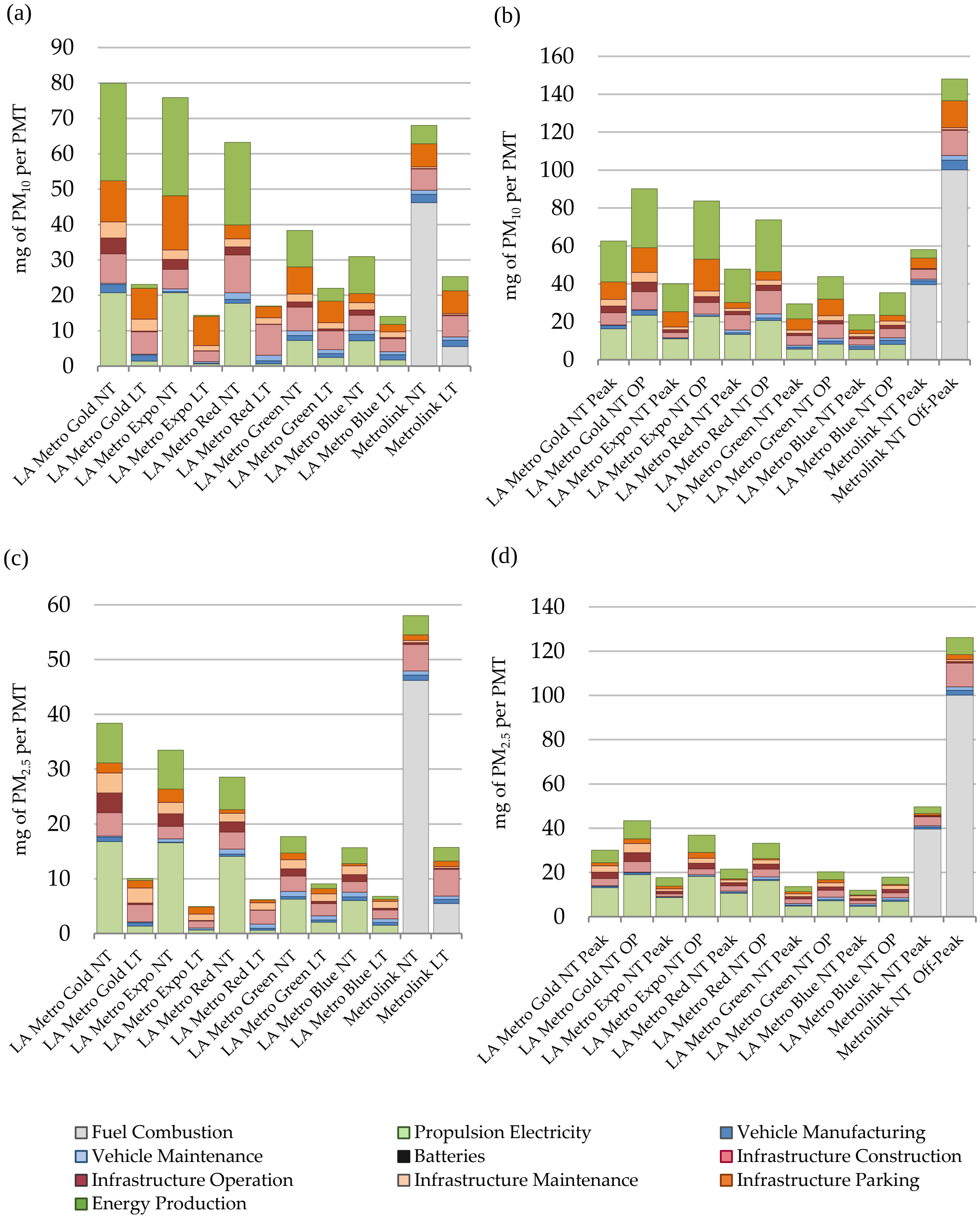

Figure 9 - Rail Particulate Matter Emissions per PMT. PM_{10} for rail near versus long term (a), PM_{10} for rail near term peak versus off-peak (b), $PM_{2.5}$ for rail near versus long term (c), and $PM_{2.5}$ for rail near term peak versus off-peak (d).

Near term peak versus off-peak rail GHG and CAP impacts are dictated by changes in operations largely defined by train occupancy causing nearly similar or identical ratios of peak to off-peak impacts for all impact categories. All Gold LRT line impacts increase by 44% from peak to off-peak, all Expo LRT line impacts increase by 109% from peak to off-peak, all Red HRT line impacts increase by 54% from peak to off-peak, all Green LRT line impacts increase by 48% from peak to off-peak, and all Blue LRT line impacts increase by 49% from peak to off-peak. GHG and CAP impacts for Metrolink CRT are found to increase between 154% and 158% from peak to off-peak service. Metrolink peak to off-peak impacts are effected by occupancy and small changes in train drive cycles. Although Metrolink CRT impacts increase greatly during off-peak service, nearly 88% of passenger ride during peak hours (before 8:30am or between 3:30pm and 7pm) based on 2016 time-day ridership (SCRRA 2016a). The other 12% of ridership occurs during the midday and night where service less frequent on most lines. Therefore, off-peak impacts make up a small fraction of the total Metrolink system impacts. However, off-peak impacts are more influential to total system impacts in the LA Metro system. Based on 2015 time-of-day boarding trends, around half or more (50% to 53%) of all rail boardings occurred during peak hours, but less than half (37% to 39%) of passengers were on-board during peak hours (**Table 8**). This indicates more consistent ridership during off-peak times and a higher fraction of trips starting or ending during off-peak times in the LA Metro system.

Table 8 – LA Metro Peak Hour Ridership. Fractions were calculated from LA Metro hourly boarding reports for rail lines in fiscal year 2015. Percent of daily boardings during peak is determined by the fraction of boarding that occur during peak hours (7am-9am and 3pm-6pm), and percent of daily riders on board during peak is determined by hourly average car occupancy data.

Metro rail line	Percent of daily boardings during peak	Percent of daily riders on board during peak
Blue LRT	50%	38%
Red HRT	51%	41%
Green LRT	53%	38%
Gold LRT	52%	37%
Expo LRT	51%	49%

3.2 On-road Life Cycle Trip Impacts per Passenger Mile

On-road near term versus long term GHG emissions are summarized in **Figure 10a**, and near term peak versus off-peak emissions are summarized in **Figure 10b**. GHG impacts per PMT for LA buses range between 78 and 193 grams CO_2e per PMT in the near term, and between 51 and 95 grams CO_2e per PMT in the long term. GHG impacts per PMT for an average occupancy LA sedan are between 254 and 344 grams CO_2e per PMT in the near term, and between 92 and 125 grams CO_2e per PMT in the long term. GHG impacts per PMT for a single occupancy LA sedan are between 507 and 688 grams CO_2e per PMT in the near term, and between 183 and 251 grams CO_2e per PMT in the long term. Near term Metro bus GHGs are 41% to 77% lower per PMT than near term average occupancy LA sedan GHGs and 62% to 89% lower than near term single occupancy LA sedan GHGs. Long term Metro bus GHGs are 39% to 76% lower than long term average occupancy LA sedan GHGs and 70% to 88% lower than long term single occupancy LA sedan GHGs. Local Bus service has the highest GHG emissions per PMT (154 g CO_2e per PMT), mainly due to lower average occupancy per vehicle than other Metro Bus services (23 PMT per VMT). The Orange Line BRT has the lowest GHG emissions per

PMT of Metro Bus services (85 g CO_2e per PMT), with Metro Rapid bus service close behind (105 g CO_2e per PMT). GHG emissions are lower for these services due to more express service (less frequent stops) due to dedicated route infrastructure (Orange BRT), traffic signal priority (Orange and Rapid service), and higher average occupancy (43 PMT per VMT on Orange line fully using 60 foot articulated buses; 29 PMT per VMT on Rapid Line using a mixed fleet). Although Metro Express features express service over long distances, its average occupancy is the lowest of the Metro Bus services (17 PMT per VMT).

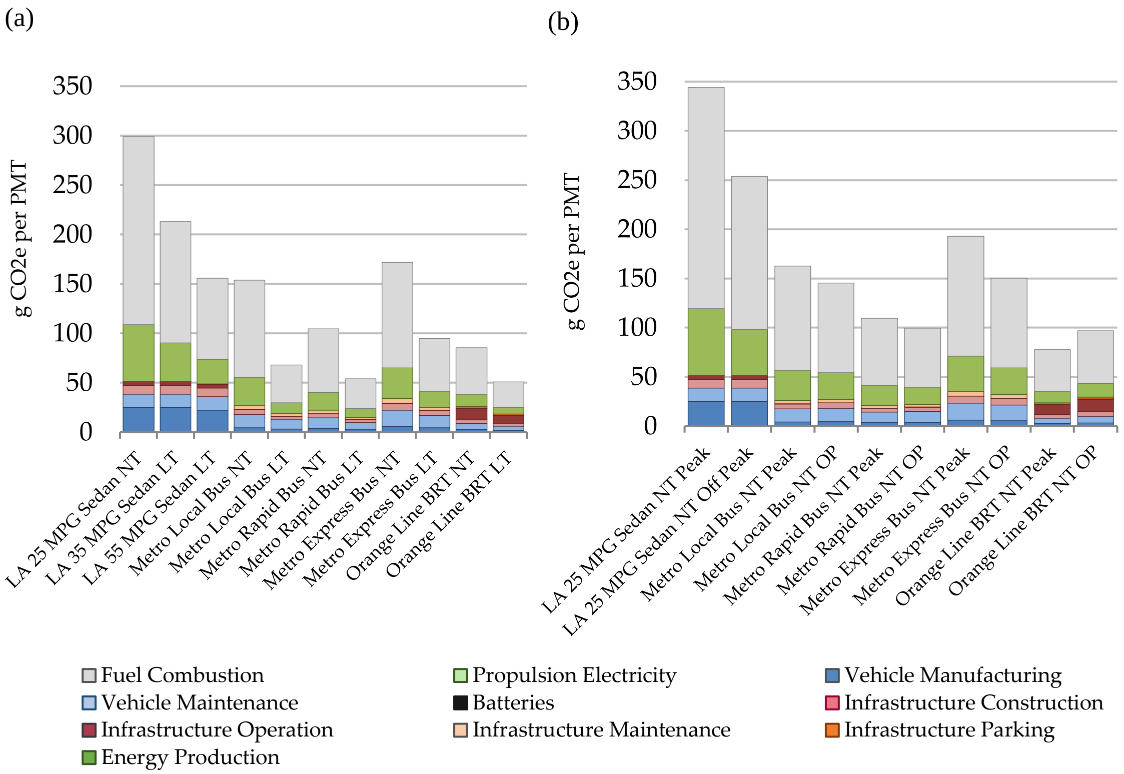

Figure 10 – On-road GHG Emissions per PMT. GHG emissions in milligrams CO_2e per PMT for on-road near versus long term (a) and on-road near term peak versus off-peak (b). Note that LA Sedan impacts are for average (2.0 passengers per car) occupancy, not single occupancy use.

LA bus system near term versus long term CO emissions are summarized in **Figure 11a**, and near term peak versus off-peak CO emissions are summarized in **Figure 11b**. CO impacts for LA bus systems range between 633 and 1,095 mg CO per PMT in the near term, and between 273 and 642 mg CO per PMT in the long term. Near term bus CO emissions are 46% to 76% lower per PMT than near term average occupancy LA sedan CO emissions and 73% to 85% lower than a near term single occupancy LA sedan CO emissions. Long term bus CO emissions are 66% to 86% lower than long term average occupancy LA sedan CO emissions and 83% to 93% lower than long term single occupancy LA sedan CO emission. Although LA bus system CO emissions are significantly higher than rail per PMT, they still produce much lower CO emissions than auto travel. Fuel combustion of CNG causes the majority of CO emissions during vehicle operation near term, and long term emissions are projected to decrease due to improved performance and occupancy of buses.

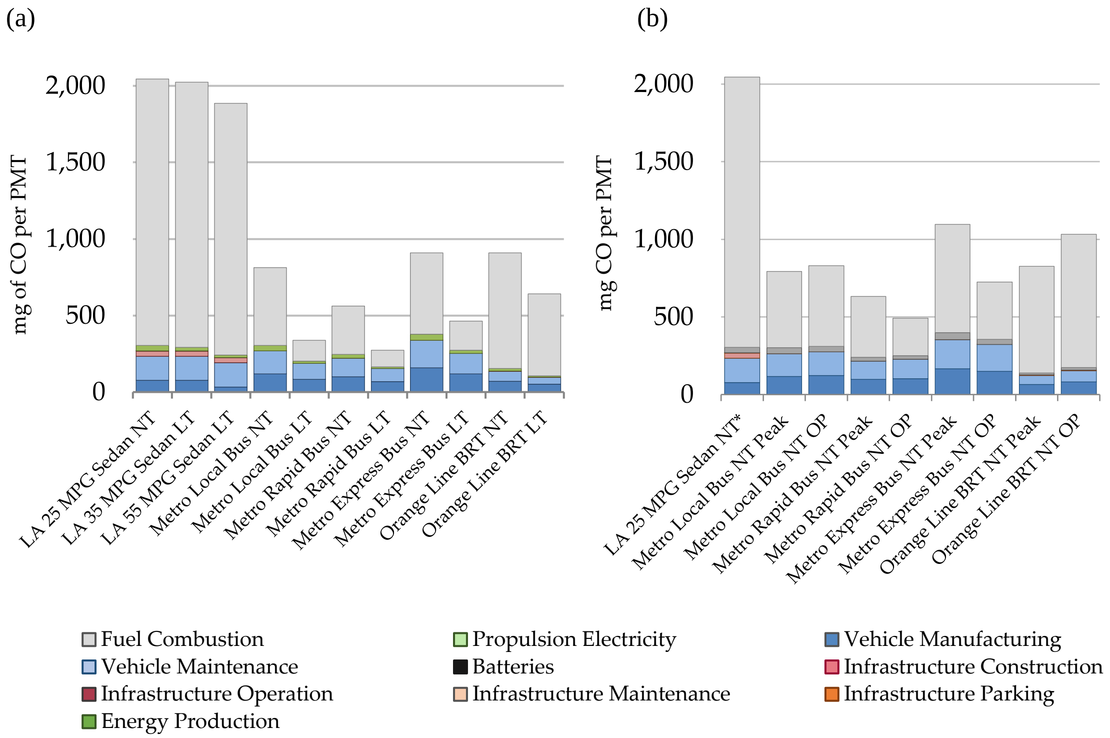

Figure 11 – On-road CO Emissions per PMT. CO emissions in milligrams for on-road near term versus long term (a) and on-road near term peak versus off-peak (b). Note that LA Sedan impacts are for average (2.0 passengers per car) occupancy, not single occupancy use. *Peak versus off-peak emissions were not assessed.

LA bus system near term versus long term NO$_X$ emissions are summarized in **Figure 12a**, and near term peak versus off-peak NO$_X$ emissions are summarized in **Figure 12b**. NO$_X$ impacts for LA bus systems range between 123 and 216 mg NO$_X$ per PMT in the near term, and between 70 and 123 mg NO$_X$ per PMT in the long term. Near term bus NO$_X$ emissions are 40% to 66% lower per PMT than near term average occupancy LA sedan NO$_X$ emissions and 70% to 83% lower than near term single occupancy LA sedan NO$_X$ emissions. Long term bus NO$_X$ emissions are 56% to 78% lower than long term average occupancy LA sedan NO$_X$ emissions and 78% to 89% lower than long term single occupancy LA sedan NO$_X$ emission. NO$_X$ emissions are created in many LA bus life cycle processes, but the primary contributor is energy production and generation that occurs in many processes (CNG production, maintenance energy, material productions energy, etc.). Major fluctuations of NO_X emissions in LA bus systems are therefore most linked to ridership fluctuations.

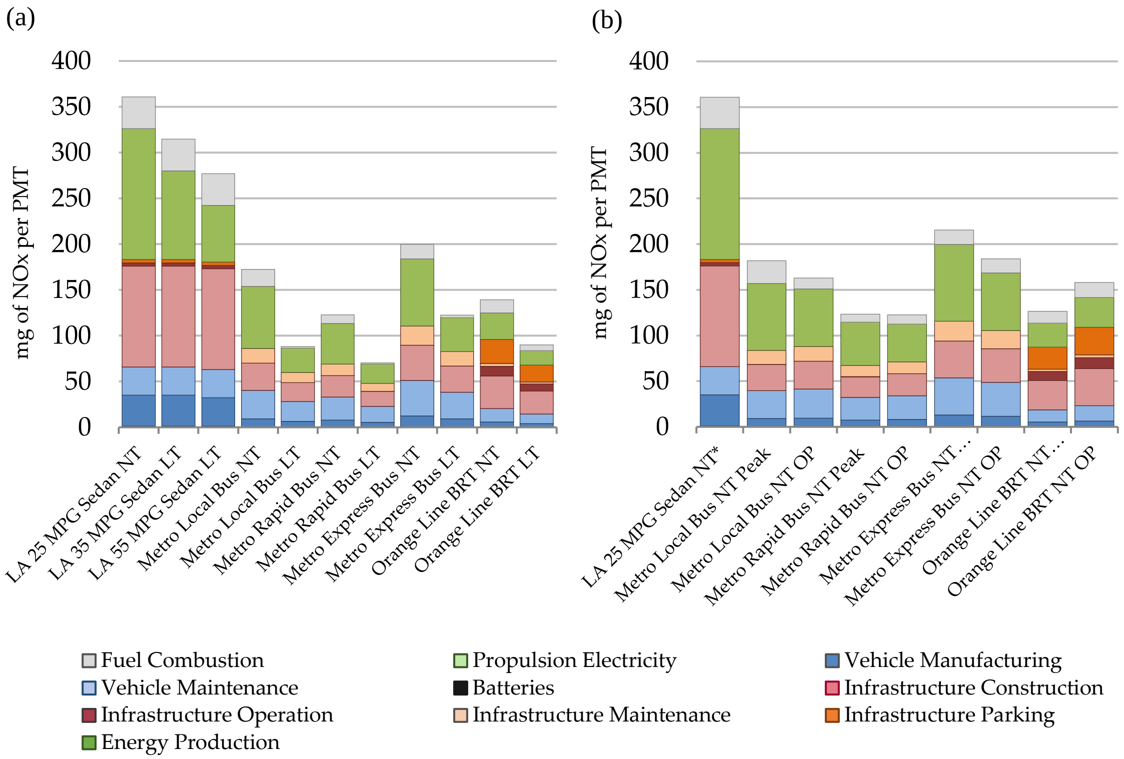

Figure 12 – On-road NO_X Emissions per PMT. NO_X emissions in milligrams for on-road near term versus long term (a) and on-road near term peak versus off-peak (b). Note that LA Sedan impacts are for average (2.0 passengers per car) occupancy, not single occupancy use. *Peak versus off-peak emissions were not assessed.

LA bus system near term versus long term SO_2 emissions are summarized in **Figure 13a**, and near term peak versus off-peak SO_2 emissions are summarized in **Figure 13b**. SO_2 impacts for LA bus systems range between 65 and 113 mg SO_2 per PMT in the near term, and between 42 and 73 mg SO_2 per PMT in the long term. Near term bus SO_2 emissions are 53% to 68% lower per PMT than near term average occupancy LA sedan

SO_2 emissions and 73% to 84% lower than near term single occupancy LA sedan SO_2 emissions. Long term bus SO_2 emissions are 50% to 77% lower than long term average occupancy LA sedan SO_2 emissions and 75% to 88% lower than long term single occupancy LA sedan SO_2 emission. SO_2 impacts are highest for Express bus service due to more VMT per year, therefore causing more frequent maintenance. Most SO_2 emissions are produced during tire production and other energy generation for maintenance operations. Energy necessary for station operation also increases Orange BRT line SO_2 emissions by a moderate amount.

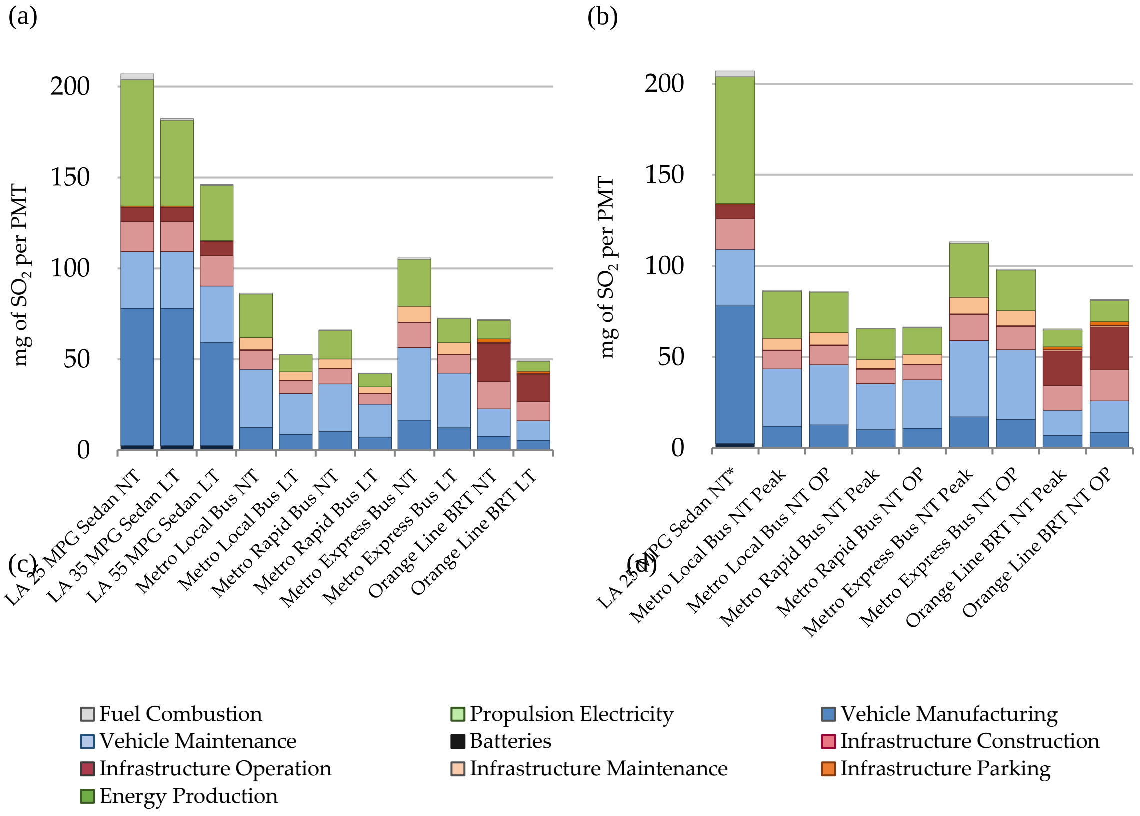

Figure 13 – On-road SO_2 Emissions per PMT. SO_2 emissions in milligrams for on-road near term versus long term (a) and on-road near term peak versus off-peak (b). Note that LA Sedan impacts are for average (2.0 passengers per car) occupancy, not single occupancy use. *Peak versus off-peak emissions were not assessed.

LA bus system near term versus long term VOC emissions are summarized in **Figure 14a**, and near term peak versus off-peak VOC emissions are summarized in **Figure 14b**. VOC impacts for LA bus systems range between 85 and 147 mg VOC per PMT in the near term, and between 58 and 100 mg VOC per PMT in the long term. Near term bus VOC emissions are 66% to 81% lower per PMT than near term average occupancy LA sedan VOC emissions and 83% to 90% lower than near term single occupancy LA sedan VOC emissions. Long term bus VOC emissions are 76% to 87% lower than long term average occupancy LA sedan VOC emissions and 88% to 93% lower than long term single occupancy LA sedan VOC emissions. VOC emissions are produced in many phases of LA bus life cycles, most commonly from infrastructure and parking construction as well as vehicle and infrastructure maintenance. Major fluctuations of VOC emissions in the LA bus system is also mainly linked to ridership fluctuations due to the number of consistent areas that to contribute VOC emissions.

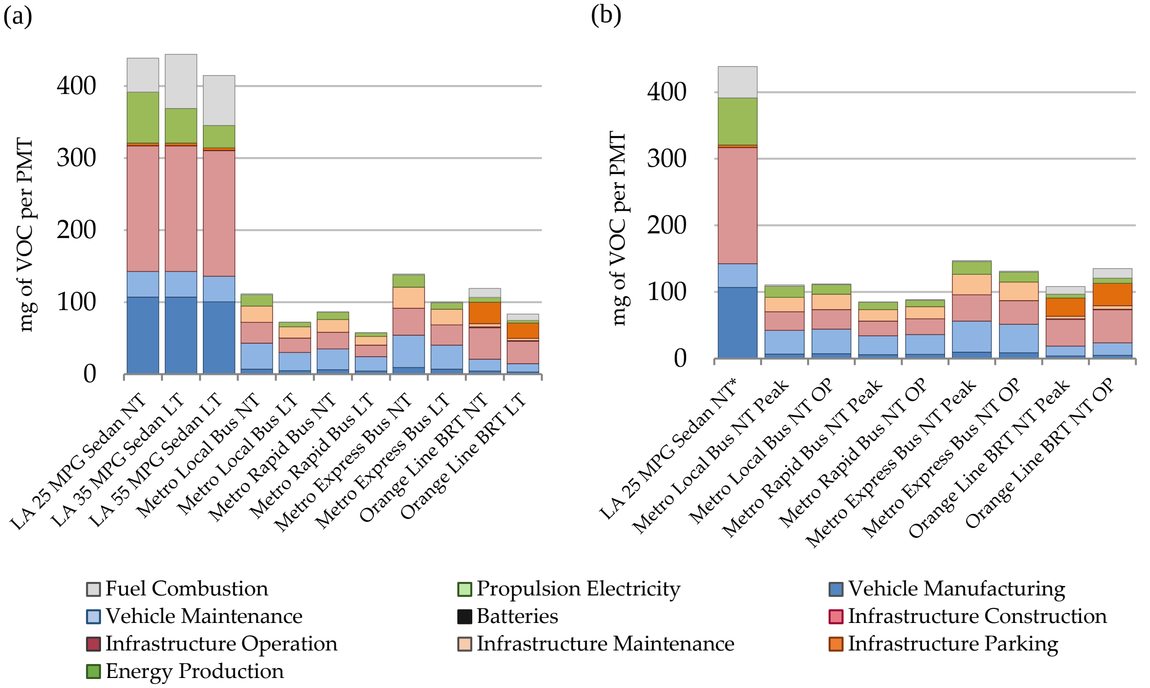

Figure 14 – On-road VOC Emissions per PMT. VOC emissions in milligrams for on-road near term versus long term (a) and on-road near term peak versus off-peak (b). Note that LA Sedan impacts are for average (2.0 passengers per car) occupancy, not single occupancy use. *Peak versus off-peak emissions were not assessed.

LA bus system near term versus long term PM emissions are summarized in **Figure 15a** (coarse) and **Figure 15c** (fine), and near term peak versus off-peak PM emissions are summarized in **Figure 15b** (course) and **Figure 15d** (fine). Near term coarse PM impacts for LA bus systems range between 41 and 70 mg PM_{10} per PMT, and near term fine PM impacts range between 14 and 24 mg $PM_{2.5}$ per PMT. Long term coarse PM impacts for LA bus systems range between 26 and 45 mg PM_{10} per PMT, and long term fine PM impacts range between 9 and 15 mg $PM_{2.5}$ per PMT. Near term bus PM emissions are 44% to 67% lower per PMT than near term average occupancy LA sedan PM emissions and 71% to 83% lower than a near term single occupancy LA sedan PM emissions. Long term bus PM emissions are 64% to 79% lower than long term average occupancy LA sedan PM emissions and 82% to 90% lower than long term single occupancy LA sedan PM emissions. Coarse PM is associated with many processes throughout the life cycle of LA buses, but similar to VOC and NO_X, these emissions are byproducts of common processes necessary for operation and therefore PM_{10} emissions are linked mostly to ridership levels. Fine PM emissions occur in a number of life cycle process as well, but vehicle manufacture and maintenance accounts for over half of all fine $PM_{2.5}$ emissions for all bus systems. Infrastructure operation and parking causes moderate PM emissions in the Orange BRT system due to the large stations serving the busway and inclusion of dedicated parking in the system. Other LA Metro bus systems do not have significant infrastructure in stations and no dedicated parking.

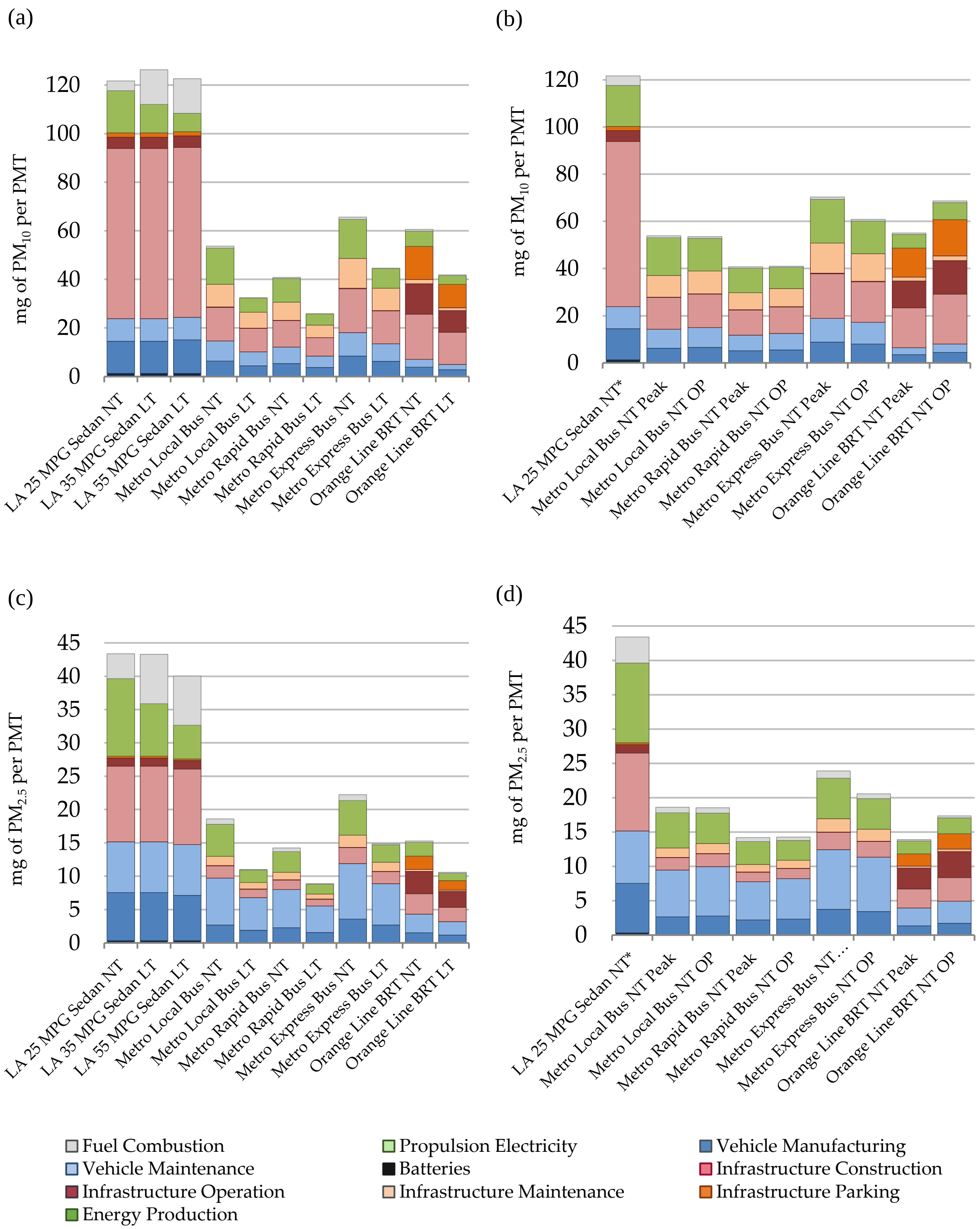

Figure 15 – On-road Particulate Matter Emissions per PMT. PM_{10} for on-road near versus long term (a), PM_{10} for on-road near term peak versus off-peak (b), $PM_{2.5}$ for on-road near versus long term (c), and $PM_{2.5}$ for on-road near term peak versus off-peak (d). Note that LA Sedan impacts are for average (2.0 passengers per car) occupancy, not single occupancy use. *Peak versus off-peak emissions were not assessed.

3.3 Unimodal Trip Impacts

With per mile impacts established, unimodal LA transit trip impacts are shown compared versus their respective regional competing auto trips in **Figure 16** (GHG emissions) and appendix **Figure 25** through **Figure 30** (CAP emissions). In these figures, average trip impacts are shown with error bars repressing change in emissions per trip due to peak and off-peak travel variations. Peak and off-peak fluctuations are primarily a function of vehicle occupancies, travel distance and road congestion. In some instances, the combination of these characteristics are not seen to cause major variations in peak to off-peak impacts, while in other instances it can cause highly variable emission during peak or off-peak hours (see Metrolink). In most cases, transit lines are observed to have less GHGs or criteria pollutant emissions per trip than their competing auto trips with all auto trips being equal or shorter distances.

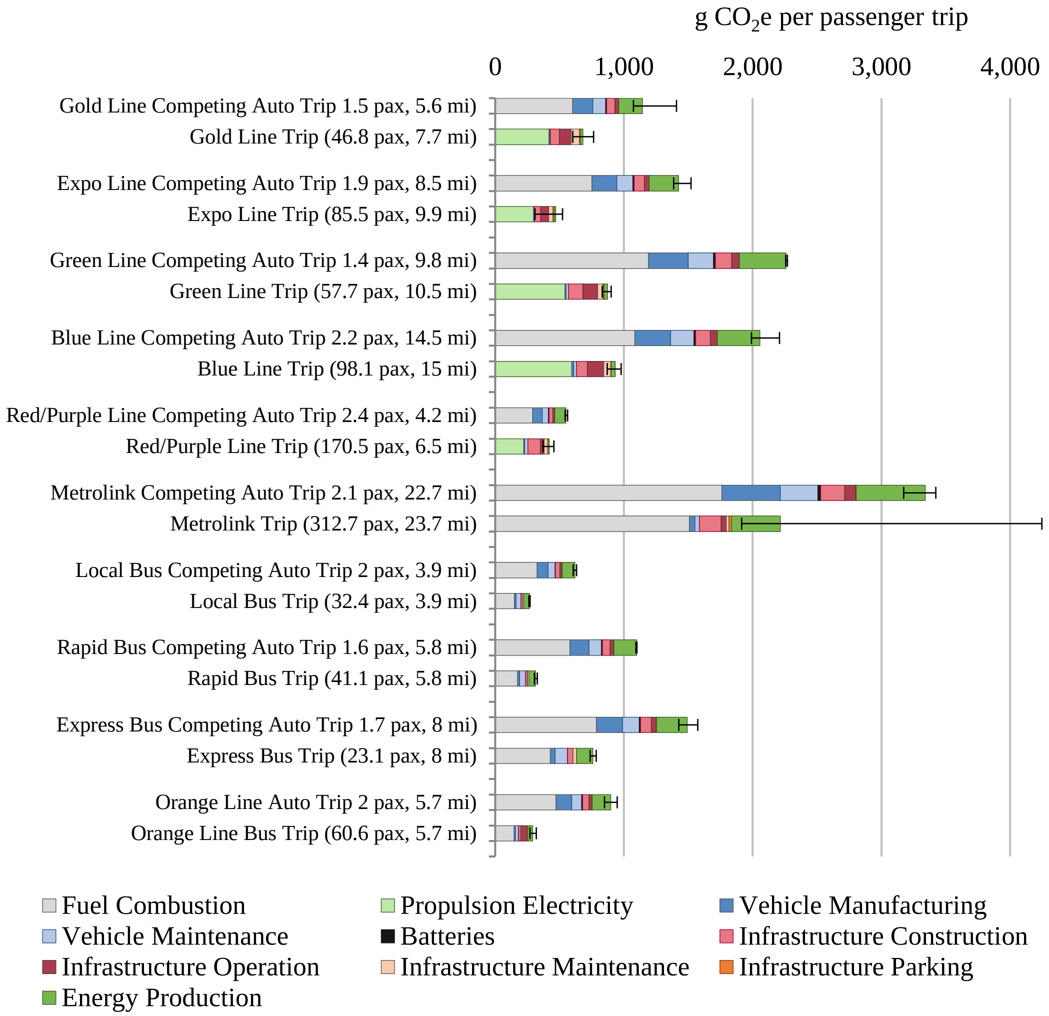

Figure 16 – Average Near Term GHG Passenger Trip Emissions of LA Unimodal Transit vs. Competing Auto Passenger Trips. Positive and negative fluctuations due to peak and off-peak travel is represented via error bars. Auto occupancy (in passengers, i.e. "pax") and trip distance are for average time-of-day.

Nearly all transit systems are observed to have less unimodal GHG trip emissions than their competing auto trips. The lone exception occurs in the Red HRT line and its competing auto trip where GHG trip emission increase by an average of 27%. Although Red HRT line unimodal trip GHG emissions are the lowest of all rail transit, the competing auto trip in this region has the highest occupancy of any competing auto trip (including a higher than the regional average) auto occupancy at 2.4 PMT per VMT. This is because the Red HRT line travels mostly through some of the most frequent and dense travel areas in the region (downtown LA and Hollywood). The Gold and Expo LRT lines have similar unimodal GHG emissions compared to their competing auto trips, and the Gold line may have more GHG emission during off-peak travel than a competing Gold line auto trip. Low recent ridership, short trip distance, and more carbon-intense energy use in the Gold LRT system causes trip emissions to be not significantly lower than competing regional auto trips. The Expo LRT line has slightly higher ridership but also more carbon-intense energy generation with higher auto occupancy for competing trips. However, this trend will be short lived as new expansions in both systems are projected to stimulate substantial growth in ridership long term. The Blue LRT, Green LRT and Metrolink CRT trips emit much less GHGs than their competing auto trips. However, off-peak travel on Metrolink may be similar or worse than its competing auto trip. It should also be noted that Blue LRT line trips and their competing auto trips are similar in length, however actually competing trips may be longer in this case due to less direct auto routes in this region. Over the same distance traveled, bus emissions are far lower, with the Rapid Bus and Orange BRT systems reducing trip emissions by around 70% compared to auto trips.

When comparing competing auto trips to unimodal transit trips in LA, many trips have fewer CAP emissions, however the Gold LRT, Expo LRT, Red HRT, and Metrolink CRT have many instances were criteria pollutants per trip are similar or higher than a competing auto trip. For the Gold, Expo, and Red systems, these higher pollutants are most usually associated with their energy generation source and the completive auto trip characteristics. All three of these Metro lines have higher amounts of coal-fired generation in the energy sources (from LADWP and PWP, shown in **Figure 1** and **Figure 2**) than the Green and Blue LRT lines. All transit systems are observed to have less unimodal CO trip emissions than their competing auto trips ranging from 94% reductions (Green LRT line) to 56% reductions (Orange BRT line). Rail trips are most significantly lower in CO emissions than their competing auto trips. Blue and Green LRT line NO_X emissions are significantly lower than their competing auto trips (77% and 74% respectively) due to far fewer emissions during energy generation used in train propulsion. However, Gold LRT, Expo, LRT and Red HRT lines have similar NO_X emissions per trip when compared to their respective competing auto trips. All bus systems have significantly lower NO_X emissions versus their competing auto trips as well (53% to 72% decrease). Metrolink CRT has alarmingly higher NO_X emissions than all other modes, worsening further during off-peak times. Due to improvements in the Metrolink fleet in the near future, these emission will drop significantly to meet up-to-date air quality standards. Due to high SO_2 emissions from energy generation in for all LA Metro rail lines, per trip SO_2 emissions are significantly higher than competing auto trip emissions for the Gold LRT, Expo LRT and Red HRT lines (237% to 418% increase), but significantly lower for Metrolink CRT and all bus systems (59% to 74% decrease). VOC emissions are significantly lower per trip for transit compared to competing auto trips (73% to 91% decrease). The Gold LRT, Expo, LRT and Red HRT lines again have similar trip emissions to competing auto trip for fine and coarse particulate matter, and Metrolink has high PM emissions potential, especially during off-peak operation. All other rail and bus lines have significantly lower PM emissions than their competing auto trips (50% to 77% decrease).

3.4 Multimodal Trip Impacts

Accessing or egressing transit with an auto trip was found to increase near term multimodal trip GHG and CAP emissions by as much as 12 times (most extreme for CO and VOC) and rarely increased trip emissions by less than 50%. In some cases, first-last mile auto trips may cause total trip emissions greater than competing auto trips. Emissions were observed to be greater than competing auto trips most commonly for NO_X and SO_2 emissions, off-peak time periods, and for the Gold LRT, Expo LRT, Red HRT, and Local Bus transit systems. Additionally, multimodal trip length is longer to reach the same destinations due to fixed and often indirect routes in transit. For all transit systems, transit trip distance increased when travelers accessed or egressed with auto. Also, first-last mile occupancy was most often found to be lower than competing auto trips or average regional trip occupancies. With longer multimodal trips, competing auto trip distances became more similar in total trip distance. This occurs mainly due to routes taken to access-egress points from origin or destinations being less direct than a unimodal auto trip of the same purpose. These characteristics lead to mitigation of GHG and CAP impact reduction benefits with first-last mile auto trips. Near term GHG emission in multimodal transit trips with linked auto first-last mile trips are shown in **Figure 17** (average trip emissions), **Figure 18** (peak trip emissions), and **Figure 19** (off-peak emissions). Near term criteria pollutant emissions for average, peak, and off-peak periods are shown in the appendix (**Figure 31** through **Figure 48**).

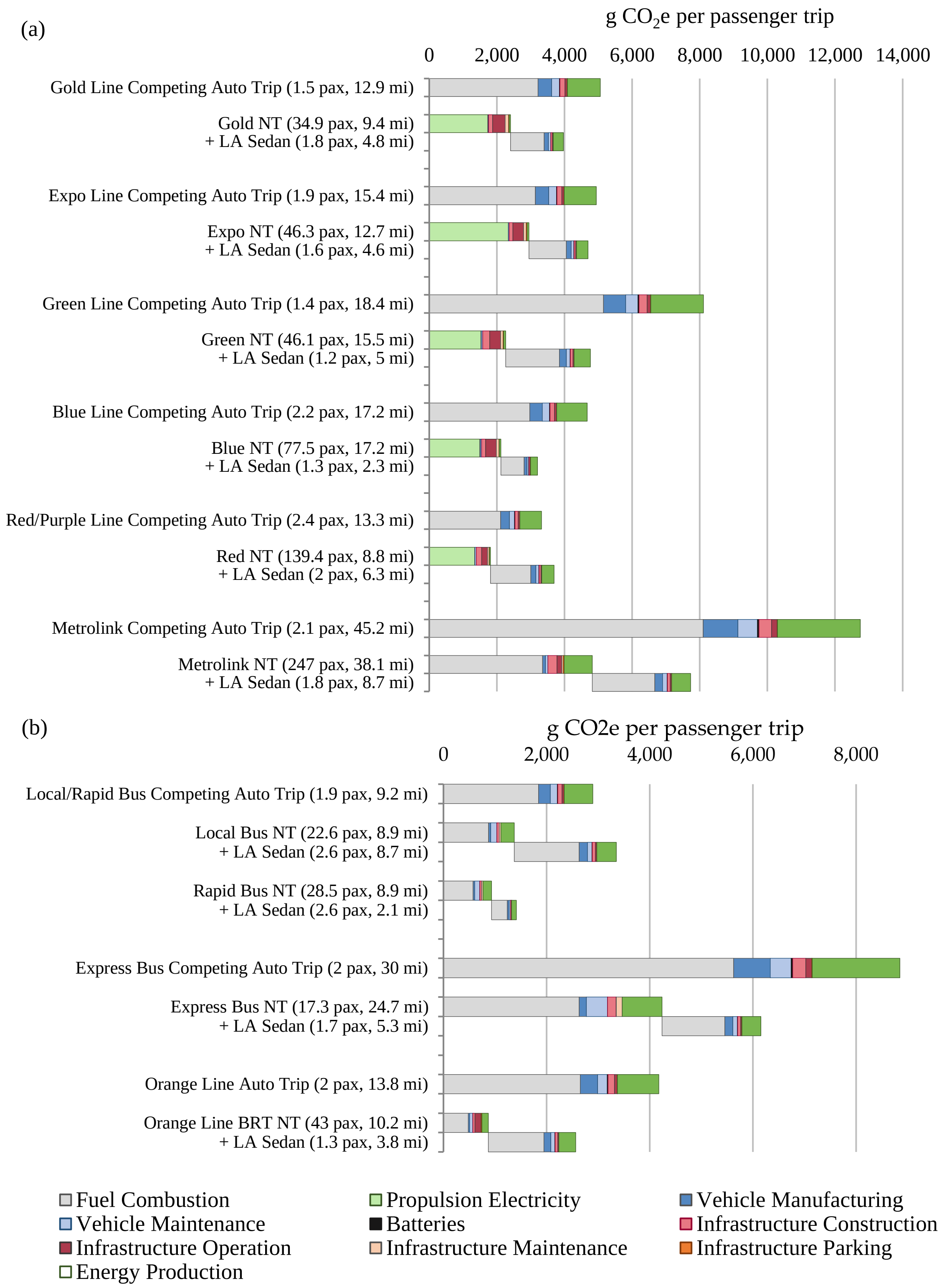

Figure 17 - Average Near Term GHG Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent average auto first-last mile trip characteristics to the linked transit system. Auto occupancy (in passengers, i.e. "pax") and trip distance are for average time-of-day.

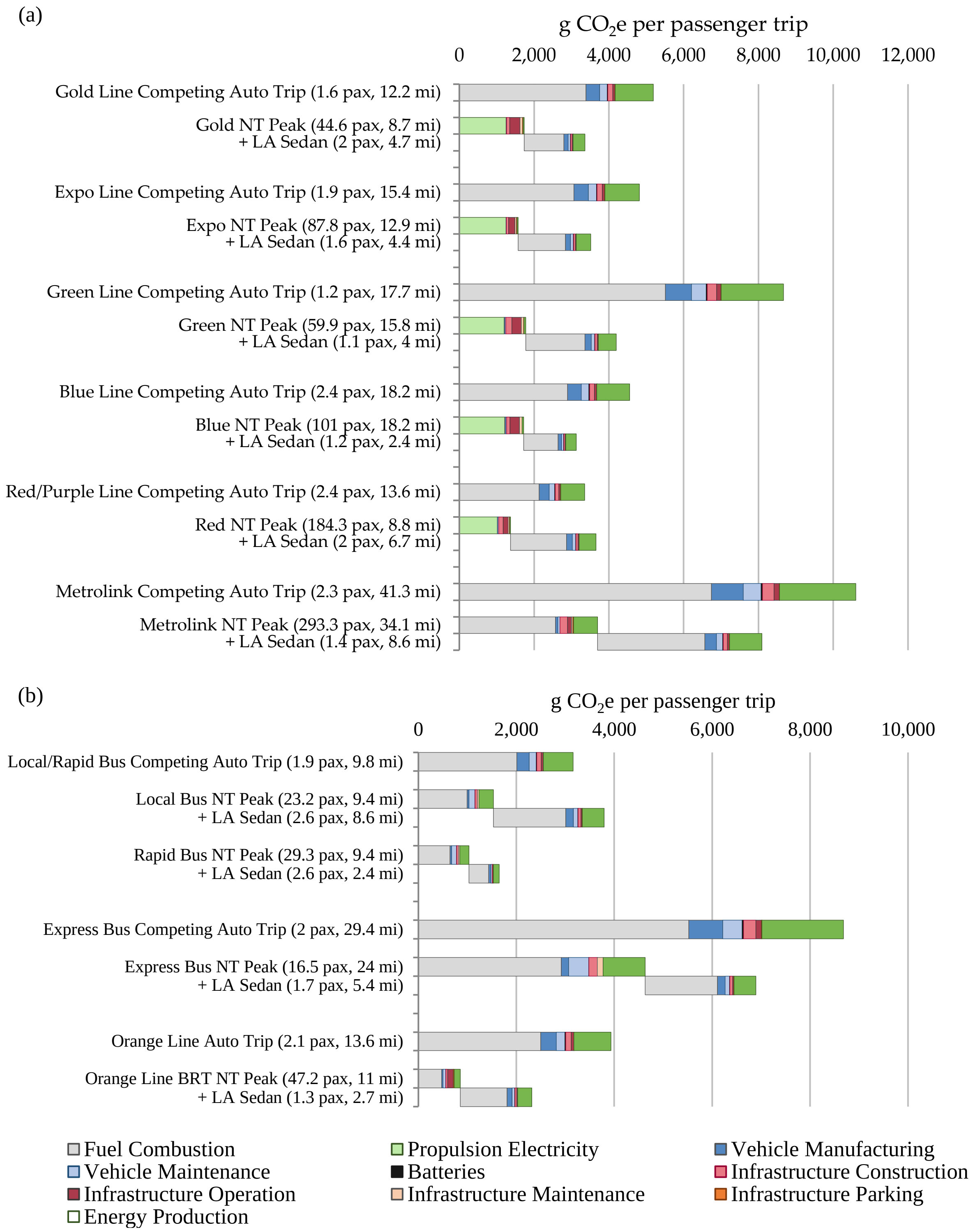

Figure 18 - Peak Near Term GHG Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent peak auto first-last mile trip characteristics to the linked transit system. Auto occupancy (in passengers, i.e. "pax") and trip distance are for peak time-of-day.

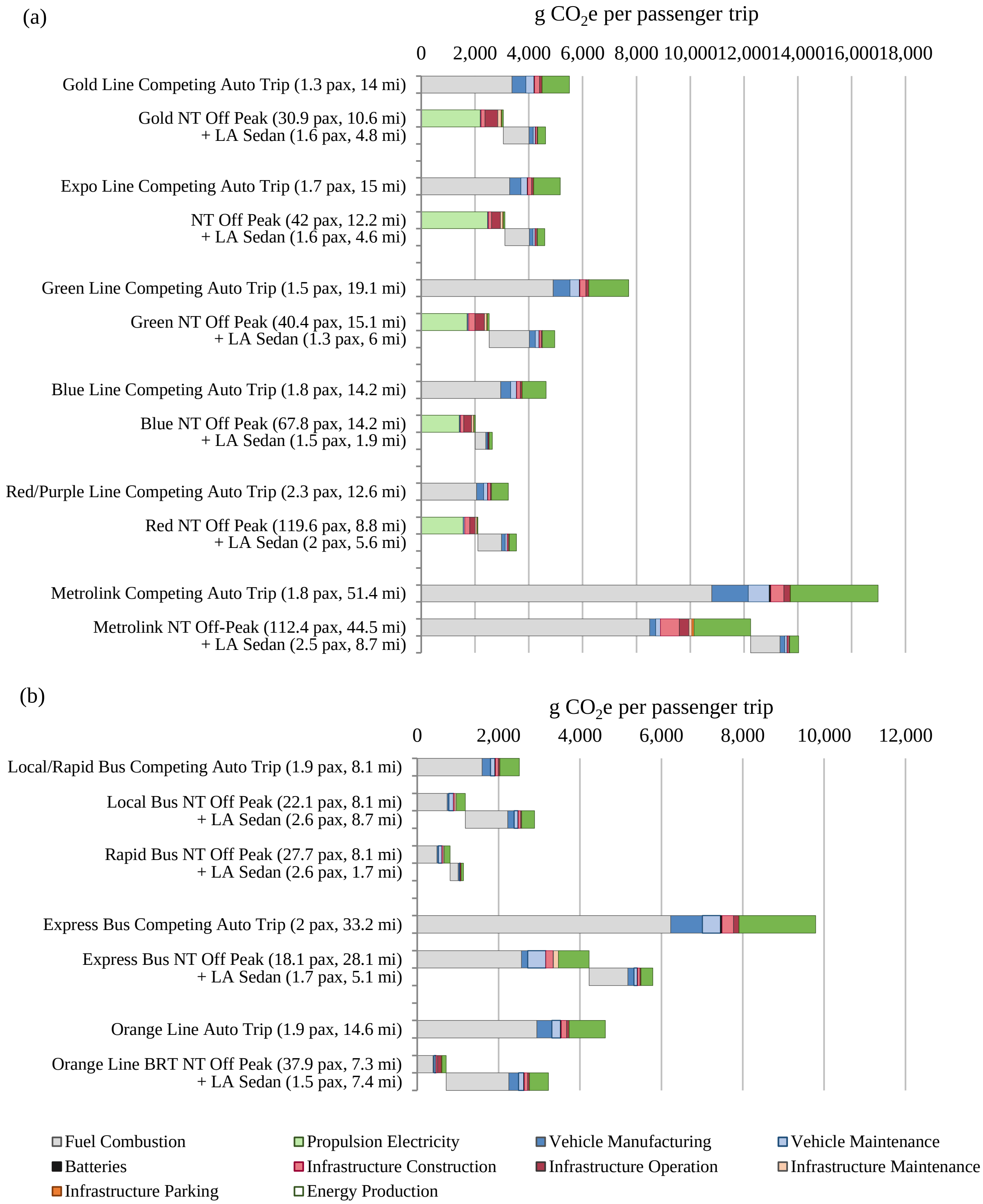

Figure 19 - Off-peak Near Term GHG Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent off-peak auto first-last mile trip characteristics to the linked transit system. Auto occupancy (in passengers, i.e. "pax") and trip distance are for off-peak time-of-day.

Multimodal GHG emissions are lower or similar to competing auto trip emissions in most cases but first-last mile auto trips can significantly increase multimodal trip emissions, mitigating potential GHG reduction savings. As Gold LRT, Expo LRT, and Red HRT trips were already found to have similar impacts to unimodal auto trips in many cases, auto first-last mile trips in these lines did not significantly increase or reduce trip GHGs. In most cases, total trip GHG emissions are similar to a competing auto GHG emissions (+/- 20%). Auto ingress or egress to the Green LRT line caused significant increase in trip emissions, in most cases doubling the trip emissions while only increasing the total distance by roughly 50%. Despite the increase, trip GHG emissions were still lower than competing Green line auto trips. Auto ingress or egress occupancy was also lowest for auto trips connecting to the Green line. The Blue LRT line was found to have the shortest linked ingress and egress auto trips, and low ingress or egress occupancy. The Blue line transit portion of the trip increased to over 17 miles while auto ingress or egress was most often under 3 miles with an average of 1.3 passengers. This caused moderate increase in overall trip emissions, but was among the lowest increases. Auto first-last mile trips in the Local Bus system were found to increase trip GHG emissions such that it surpassed the competing auto trip. However, due to lack of dedicated parking infrastructure for Local bus routes, but this was uncommon. Auto first-last mile trips in the Orange BRT system often tripled or quadrupled total trip emissions substantially mitigating the environmental benefits per trip.

In multimodal transit, first-last mile auto trips significantly increase CAP emissions with auto first-last mile trips, but remain similar or lower in total emissions than competing auto trips in the majority of cases. The exception occurs in Metro rail trips were SO_2 emissions can be around twice that of competing auto trips. However, this is due to energy (coal) generation used for rail propulsion, not emissions from auto first-last mile trips. Auto travel has significantly higher CO emissions per mile, so even short first-last mile trips by auto can double trip CO emissions. Increases of CO per trip when accessing or egressing with auto increased by up to 12 times. Although the increases in CO emissions were very large, most multimodal transit trips with auto still have less trip CO emissions than competing auto trips. Multimodal transit trips significantly increase NO_X emissions per trip. Most multimodal transit trips have either significant increases or significant total NO_X emissions per trip. Only the Green and Blue LRT lines have less than half as much trip NO_X emissions than their competing auto trips. Energy generation and production dominates most multimodal transit trip SO_2 emissions. Local, Rapid, and Express, bus trips are the notable exceptions, due to these systems not utilizing much electricity throughout their life cycles along with lower SO_2 emissions from CNG production per mile compared to gasoline and diesel fuel. All rail lines have significantly large SO_2 trip emissions. As a result, auto trip access or egress does not greatly increase the total SO_2 trip emissions for these lines. SO_2 emissions increase most from auto ingress or egress on the Orange BRT line and Local bus system, more than doubling the total trip SO_2 emissions. Similar to the trend with multimodal transit trip CO emissions, multimodal transit trip VOC emissions greatly increase with even small auto access or egress, increasing trip emissions by 2 to 8 times. In the majority of cases however, the multimodal transit trip VOC emission are still significantly lower than their competing auto trips.

Due to increased ridership and cleaner energy sources, the gap between multimodal trip and competing auto trip long term impacts is observed to increase. Increased auto fuel economies and vehicle light-weighting do not overcompensate for the reductions in transit impacts per PMT. Therefore, auto access and egress trips will increase long term multimodal trip emissions further unless there are significant changes in auto and transit travel behavior (long term trip characteristics assume current travel trends). Comparing **Figure 20** (long term GHG multimodal emissions) to **Figure 17** (average short term GHG multimodal emissions) exemplifies this trend. Most CAP emissions follow the same trend, with the major exception occurring for SO_2. Cleaner energy generation and production methods cause a significant decrease in SO_2 trip emissions for transit systems with high electricity use (Metro Rail). This causes multimodal SO_2 emissions to be much lower long term, making them similar or less than competing auto trip SO_2 emissions (**Figure 21**). The Red HRT line only has moderate reduction in GHGs, and is the only line that may have greater long term trip emissions with auto access or egress. This is due to short transit trips, high occupancy competing auto trips, and only moderate increases in ridership. For all bus systems, only the Local bus trips with auto access or egress are likely to have higher trip emissions than competing auto trips. However, because Local bus use is rarely accompanied with first-last mile auto trips, this is not a major concern.

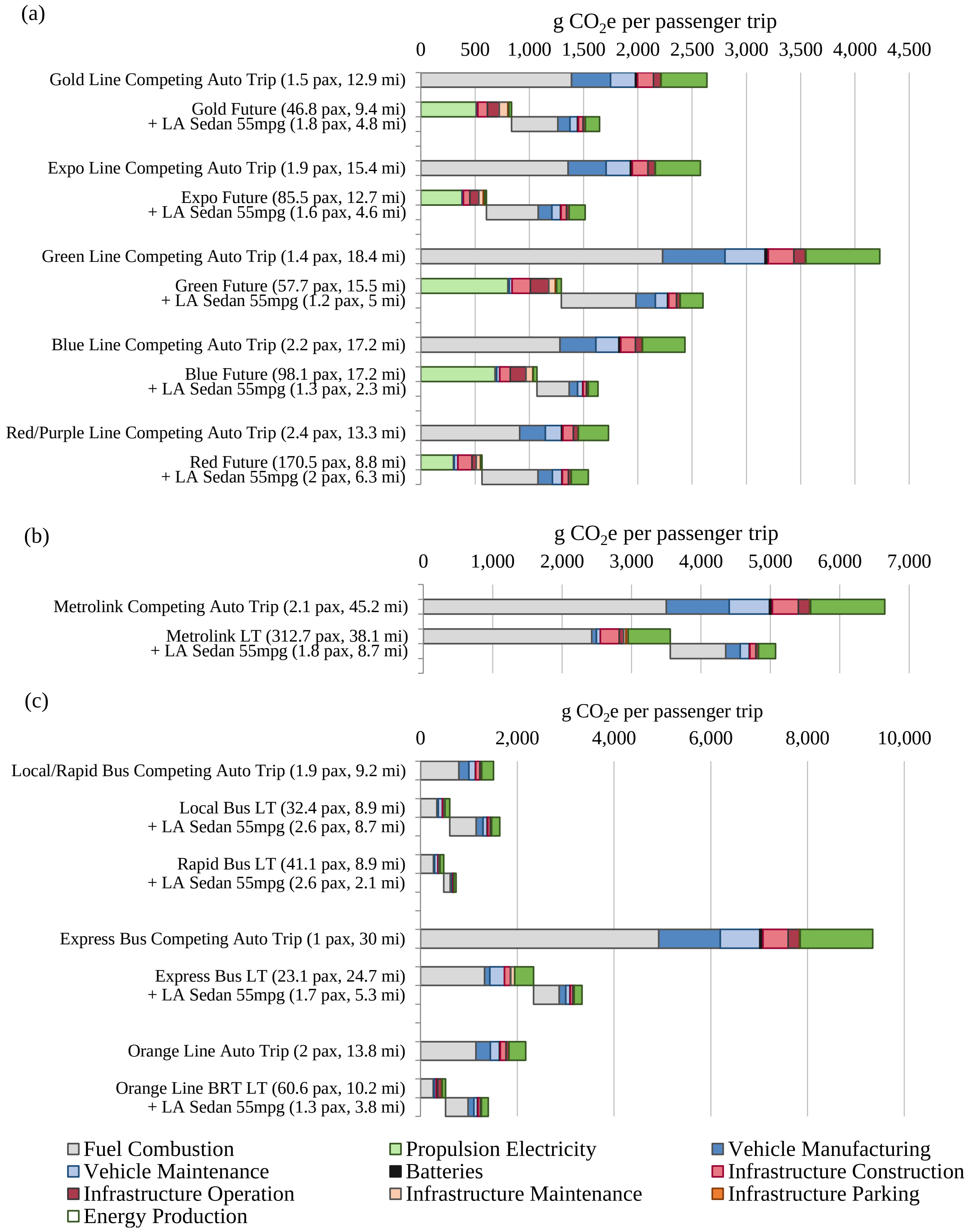

Figure 20 – Long Term GHG Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a), Metrolink (b), and Bus (c) Systems. Linked auto trips represent average auto first-last mile trip characteristics to the linked transit system. Auto occupancy (in passengers, i.e. "pax") and trip distance are for average time-of-day.

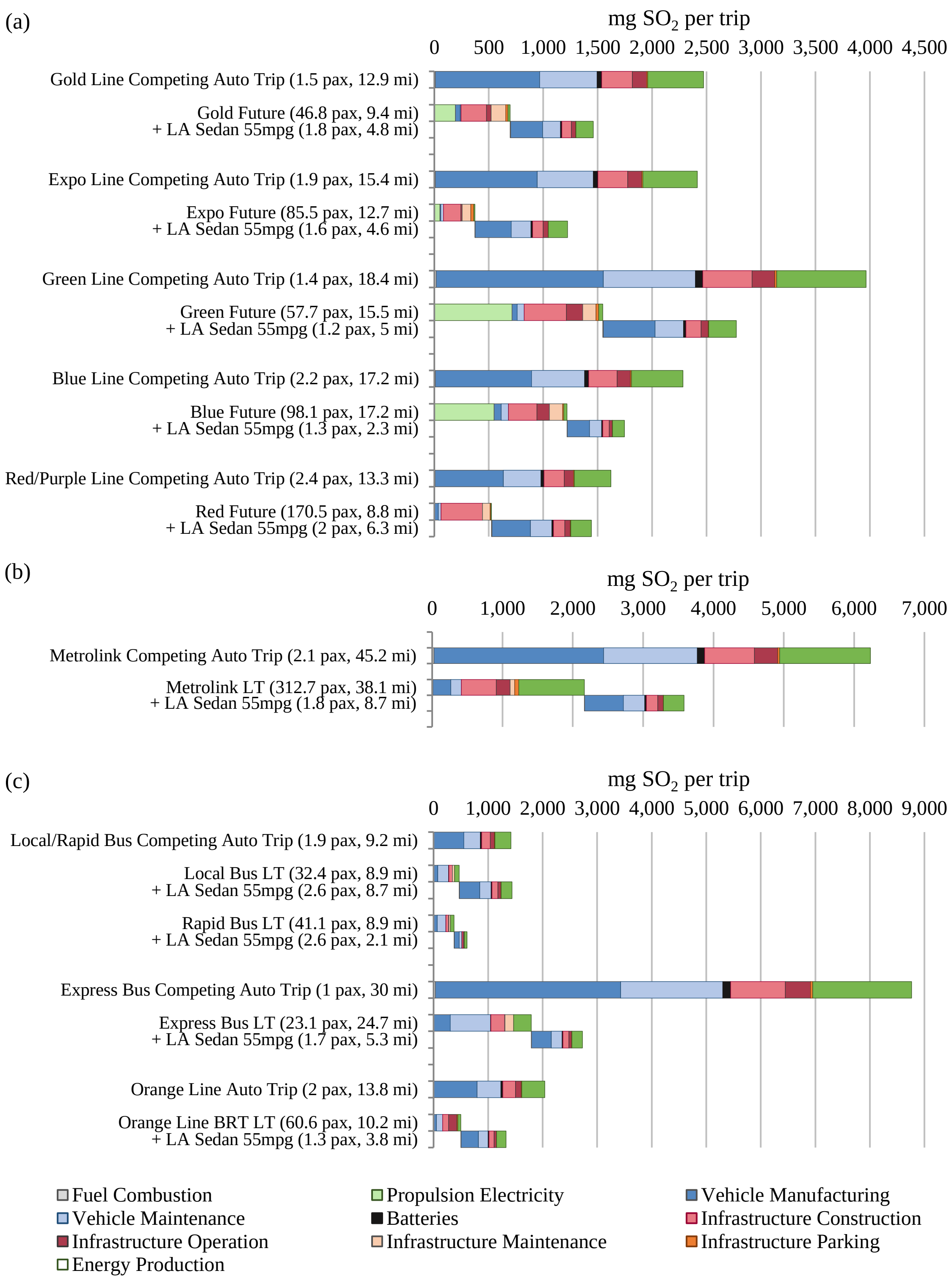

Figure 21 – Long Term SO_2 Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a), Metrolink (b), and Bus (c) Systems. Linked auto trips represent average auto first-last mile trip characteristics to the linked transit system. Auto occupancy (in passengers, i.e. "pax") and trip distance are for average time-of-day.

3.5 Local Versus Remote Impact Characterization

When considering air quality in the LA region, the location where pollutants are created is essential for determining the most important concerns for urban transit policy and planning decisions. Although coal-fired energy generation contributes to significant near term impacts in the Metro rail system, it occurs almost entirely outside the state of California with the majority of regional energy being generated by natural gas (CEC 2015). With California's aggressive goals to reduce GHG and CAP emissions, long term impacts from transit systems will be significantly affected by the decarbonization of the electrical grid. To evaluate the long term impact potential on local air quality, 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 impacts equivalencies ($PM_{10}e$), and CO, VOC, and NO_X emissions were normalized into photochemical smog impacts equivalencies (O_3e) to assess midpoint impact potential. System impacts were tagged as either occurring in the LA metropolitan region (local) or remote (elsewhere). The long term local versus remote potential for creation of photochemical smog (**Figure 22**) and respiratory impacts (**Figure 23**) is shown for the LA rail and bus systems. The LA Metro rail system will contribute fewer local impacts due to CAP emissions being dominated by remote energy production and generation. Metrolink CRT (heavy NO_X and PM emissions reductions from new locomotives), will still have high potential for local long term creation of respiratory impacts. With tailpipe emissions from the combustion of gasoline fuel having high potential for increasing photochemical smog and respiratory impacts (Elsom 2014), auto access and egress to transit may account for a significant portion of transit system impact potential in the long term. 48% of long term local rail system respiratory impact potential originates from first-last mile auto travel and parking infrastructure construction and maintenance. Over a quarter of all long term transit system air quality impact potential arises from first-last mile auto travel and parking infrastructure impacts. Additionally, long term Metro rail and bus impact potential from during operation is very small compared to auto first-last mile respiratory and smog impact potential and Metrolink respiratory impact potential. With over 80% of total LA transit PMT occurring in the Metro system, CNG bus and electric rail are sustainable long term transit propulsion methods with low local impact potential relative to the service level provided.

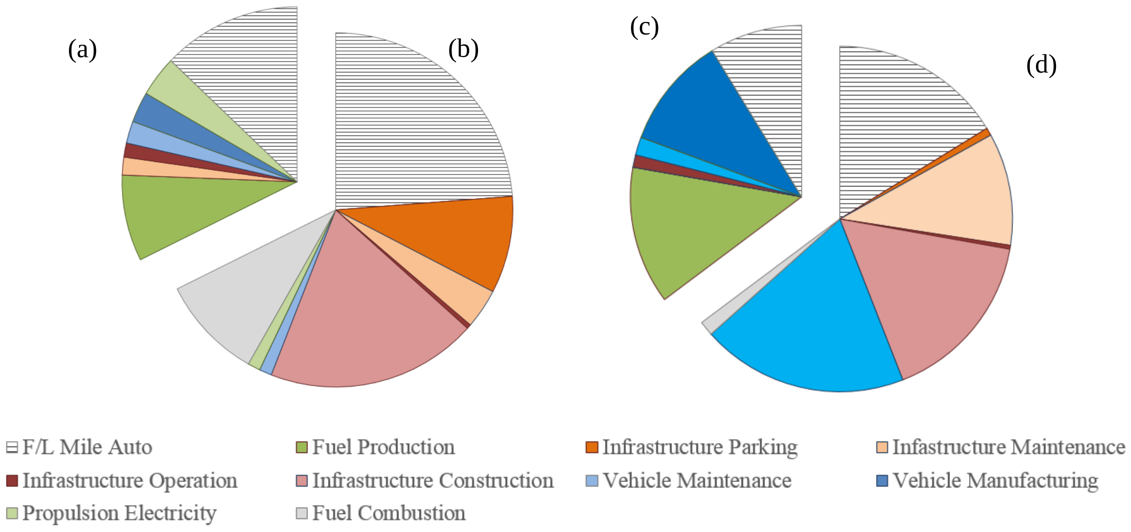

Figure 22 – Long Term Remote vs. Local Photochemical Smog Impact Potential for LA Rail and Bus Systems by Life Cycle Processes and First-last Mile Auto Travel. LA rail system photochemical smog impact potential in remote locations (a) versus local locations (b), and LA bus system photochemical smog impact potential in remote locations (c) versus local locations (d). First-last mile auto impact potential assumes approximately 12 miles of first-last mile PMT for every 100 miles of rail PMT and 8 miles of first-last mile PMT for every 100 miles of bus PMT.

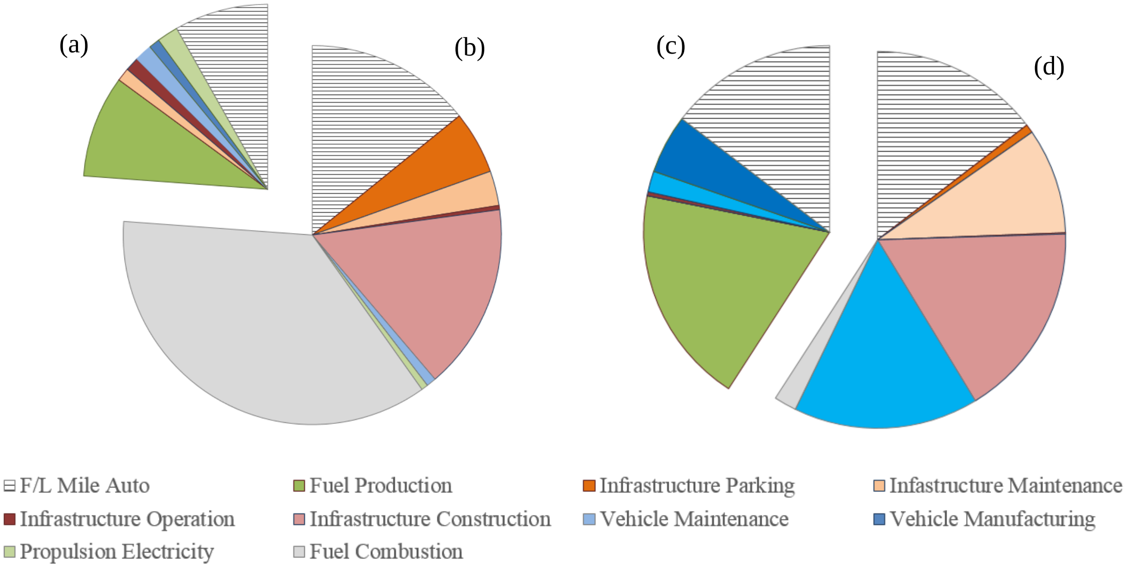

Figure 23 – Long Term Remote vs. Local Respiratory Impact Potential for LA Rail and Bus Systems by Life Cycle Processes and First-last Mile Travel. LA rail system respiratory impact potential in remote locations (a) versus local locations (b), and LA bus system respiratory impact potential in remote locations (c) versus local locations (d). First-last mile auto impact potential assumes approximately 12 miles of first-last mile PMT for every 100 miles of rail PMT and 8 miles of first-last mile PMT for every 100 miles of bus PMT.

4 DISCUSSION

Transit trips with first-last mile auto access or egress will have increased GHG and CAP trip emissions, and increases are most significant for CO and VOC pollutants. In the Metro rail system, 57%-72% of CO and VOC emissions originate locally via first-last mile auto tailpipe emissions. With recent LA Metro estimates of transit auto access, approximately 22% of GHG emissions (around 107 kilotonnes CO_2e per year) originate from first-last mile auto use. Although life cycle emissions increase with first-last mile auto travel, unimodal and multimodal transit trips in the LA region will contribute less total impacts than competing auto trips in the majority of scenarios. The major exceptions occur in the Metro rail system for multimodal SO_2 trip and GHG and NO_X emissions in the Metro Red HRT, Gold LRT, Expo LRT, and Local bus systems. However, Metro rail system CAP emissions largely occur outside of the LA metropolitan region due to high amounts of remote energy generation used in vehicle propulsion, and system operation. This indicates that the near term transit system GHG and CAP emissions can be significantly reduced by avoiding first-last mile auto access and egress to transit.

Due to decreases in long term transit system impacts from improved vehicle technologies, increased ridership, and decarbonization of the energy grid, first-last mile auto trips will significantly contribute to total transit system air quality impact potential. In the long term, nearly half of local rail system respiratory impact potential and over a quarter of all transit system air quality impact potential arises from first-last mile auto travel and parking infrastructure impacts. This indicates that a shift away from auto access and egress of transit will be beneficial in maintaining sustainable long term regional transportation. Long term local respiratory impacts in the LA rail system are dominated by Metrolink diesel locomotive emissions even with improved technologies. Although Metrolink long term system impacts are not disproportionate to the total PMT served, long term shift towards electric propulsion CRT vehicles would greatly reduce local respiratory impact potential with decarbonization of the electric grid.

4.1 Scenarios for First-last Mile Impact Reductions

Desirability to utilize transit in LA without automobiles indicates significant potential to reduce first-last mile transit impacts. Based on multimodal transit trends, decreasing first-last mile impacts would require reducing the frequency or increasing the occupancy of first-last mile auto trips, or by replacing unimodal auto trips with multimodal transit trips.

To achieve these impact reductions, strategies could be implemented that promote and incentivize carpooling, adjust parking availability and pricing, or increase non-auto transit accessibility.

Although this analysis does not quantify the marginal impacts of shifting travel behavior (i.e. using transit over auto), increasing transit ridership will decrease marginal auto trip emissions when considering the transit systems are already operating. With high parking demand, and strong correlation indicating that parking availability increases the average auto first-last mile distance to transit (**Figure 24**), it is clear that first-last mile auto trips helps many riders reach access points in the LA Metro transit system. This indicates that increasing parking access will increase first-last mile trip impacts, however, accessing transit via auto should not be dissuaded if the side-effect results in any partial or 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 2016c). To avoid increasing first-last mile and parking infrastructure related impacts, promoting increased carpooling or increasing non-auto access strategies to transit stations should be the highest priority.

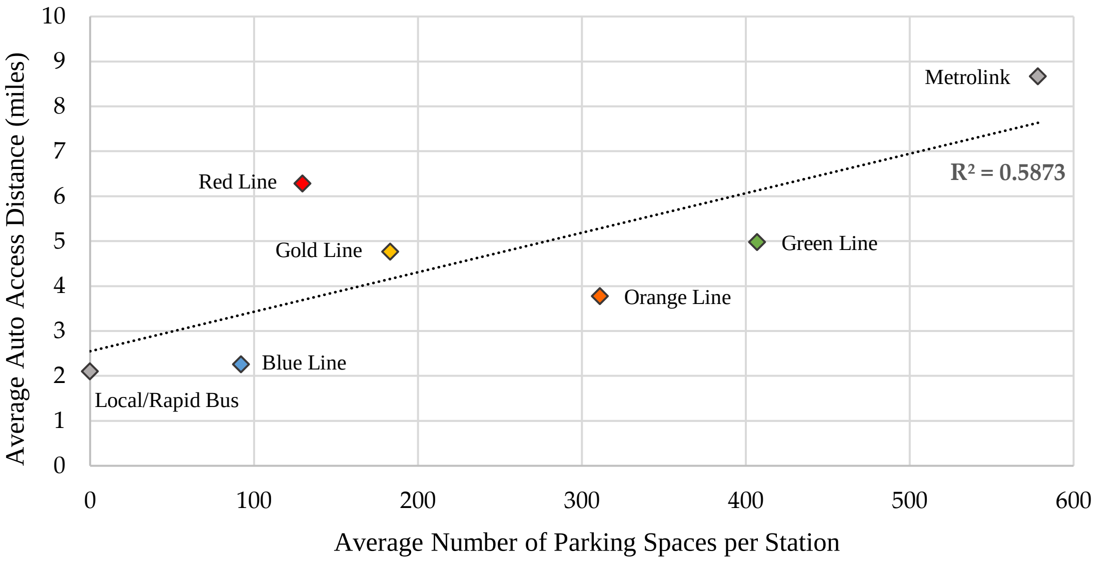

Figure 24 - Parking Availability vs. First-last Mile Auto Distance. Average number of parking spaces per station represent LA Metro dedicated parking only, independent parking near stations is not included.

To continue to reduce GHG and CAP impacts in the LA region, an emphasis on carpooling and eliminating SOV trips to transit would be ideal because it removes marginal local auto trips emissions while maintaining or increases transit ridership. The Red HRT, Expo LRT, and Gold LRT lines may be strong candidates for increased carpooling due to high regional auto occupancy, high congestion and high parking demand. LA Metro will be implementing a parking pricing pilot plan that targets nine high demand station parking lots at the Red, Expo, and Gold lines to evaluate the potential for adjusting parking pricing. This pilot plan will include reduced costs for carpooling and is aimed at managing the availability of parking spots (LA Metro 2016c). If offering competitive pricing and incentives for carpooling is effective at increasing first-last mile auto occupancy, similar methods should be explored at other parking locations. However, if increased parking pricing leads to underutilization of the parking infrastructure, this may increase auto only trips that were previously first-last mile auto trips with tranist. Due to the Red, Expo and Gold lines having the highest potential for similar competing auto impacts, increasing total first-last mile trips to these lines is less desirable if the average first-last auto occupancy does not increase. Additionally, the Green LRT line may be a strong candidate for carpooling due to it very low auto access and egress occupancy and large parking availability. The Green line has among some of the most parking availability in the region (5000+ parking spaces), with no charge to park. Due to lower demand and free parking, SOV trips are frequent with auto occupancy at 1.3 passengers per auto trip when accessing transit during off-peak periods and 1.1 passengers per trip auto trip when accessing transit during peak periods. These characteristics indicate high potential for decreasing first-last mile impacts by increasing auto occupancies, potentially by charging for parking with pricing incentives promoting carpooling. However, applying parking pricing to previously free parking areas may have adverse effects on transit ridership. To further investigate and understand transit user's behavior behind first-last auto use, it would be beneficial to also implement a pilot pricing plan at select Green LRT station parking lots.

LA Metro has developed a first-last mile strategic plan to promote intermodal connection in the Metro system and increase non-motorized accessibility to Metro transit (LA Metro 2015a). One key element to this plan is to develop a series of active transportation improvements along pathways between Metro stations. Many transit lines in the network are accessed by trips that are four or more miles, which likely is the upper limit for non-motorized access (such a biking). Application of a pathways approach should focus on scenarios where auto access trips are shortest. The most likely line to benefit from a pathways approach would be the Blue LRT line. The Blue line is observed to have among the lowest frequency of auto access and egress as well as the lowest average trip distances when accessing or egressing with an auto trip. With these auto trips being short and less frequent, these trips may be most susceptible to being replaced with biking or walking on pathways to Blue line access points. Additionally, the Blue line averages under four bike rack spaces and under two bike lockers per station with one bike station at the Long Beach station. Increasing bike accommodations may further develop biking over walking to the Blue line.

4.2 Limitations

The CHTS may not entirely represent multimodal trip characteristics in the LA region due to variance in reporting, small sample size, and non-current trends. The main limiting factor was the sample size of multimodal transit trips. The sample size for first-last mile trips was small, but does indicate clear trends. However, complex multimodal (i.e. auto → bus → rail) trips were seldom observed. This made it difficult to compare multimodal trip trends with more than one transit portion without making assumptions concerning the travel characteristics. Additionally, there were some user reporting errors in the CHTS. Some survey respondents entered erroneous trip distances, or reported the incorrect mode. For example, a sample reported a HRT trip of greater than the distance of the Red or Purple HRT line systems in LA, however the trip was actually identified to be a CRT trip due to location. Samples of these nature were eliminated in the analysis, however, in some cases it is difficult to be certain all samples are 100% accurate. Last, the CHTS took place from 2012 to 2013 and may not represent the current trends in region over the last few years.

When considering peak and off-peak impacts, per-mile and per-trip emissions are subject to varying degrees of sensitivity from transit vehicle occupancies. In some cases, occupancy can be much lower or much higher than the average occupancies. **Table 9** displays the high and low percentile occupancies and an occupancy sensitivity factor. This factor reflects the magnitude of increased impacts per PMT that occur from a low to high occupancy trip. The most notable gaps in high and low occupancy occur in the Metrolink CRT and Blue line LRT at occupancy increases of 11.3 and 6.5 times respectively. Higher occupancy sensitivity factors indicate high variations in ridership by time-of-day. This indicates that marginal impacts may fluctuate heavily in some extreme scenarios.

Table 9 – Impact Sensitivity to High and Low Transit Occupancy. Impact occupancy sensitivity factor expresses the magnitude increase in impacts from low (10th percentile) to high (90th percentile occupancy).

Transit System	10th Percentile Occupancy	Average Occupancy	90th Percentile Occupancy	Occupancy Sensitivity Factor
Blue LRT	15	78	116	6.51
Red HRT	67	139	194	1.89
Green LRT	15	46	63	3.30
Gold LRT	11	35	49	3.28
Expo LRT	14	56	77	4.47
Metrolink CRT	43	247	528	11.31
Local Bus	8	23	38	3.73
Rapid Bus	15	29	43	1.91
Express Bus	8	17	40	4.16
Orange BRT	16	43	67	3.27

5 CONCLUSION

Comprehensive life cycle evaluation of multimodal transit is useful in identifying trends of first-last mile trip impacts and scenarios that may be useful in further decreasing long term environmental footprints of transit. Auto access or egress to transit has significant potential to increase GHG and CAP emissions per trip, and in some cases may not significantly reduce trip emissions when compared to a competing auto trip. When evaluating multimodal air quality trip impacts, it is important to acknowledge the local versus remote impacts especially in transit systems requiring 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 in areas with low first-last mile trip distances or frequencies. Ultimately, transportation policy and planning should be conscious of significant potential for environmental impacts from long term auto access and egress of transit.

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APPENDIX A

SUPPLEMENTAL FIGURES OF CRITERIA AIR POLLUANT TRIP EMISSIONS

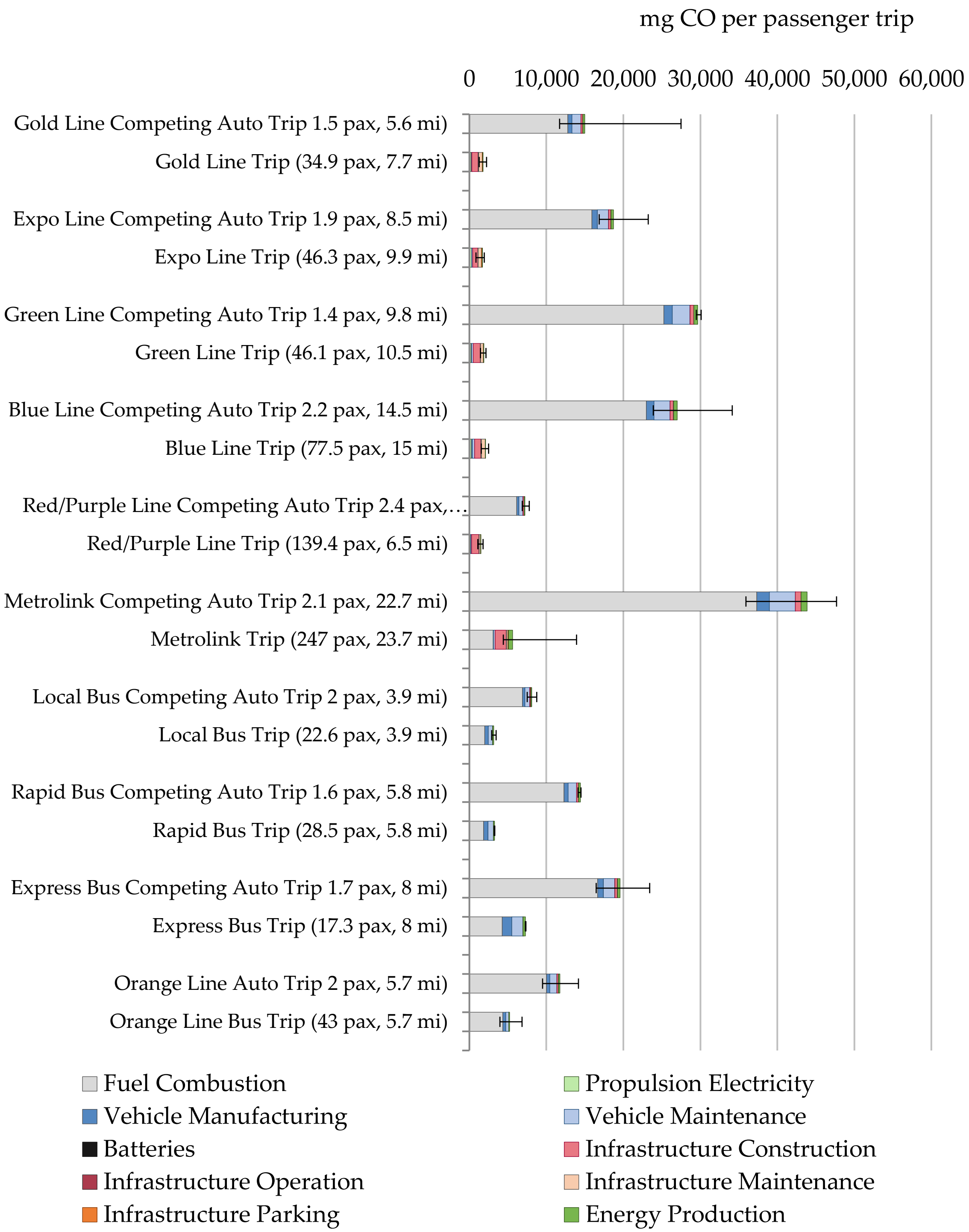

Figure 25 - CO Emissions per Passenger Trip of LA Unimodal Transit vs. Competing Auto Trips. Positive and negative fluctuations due to peak and off-peak travel is represented via error bars.

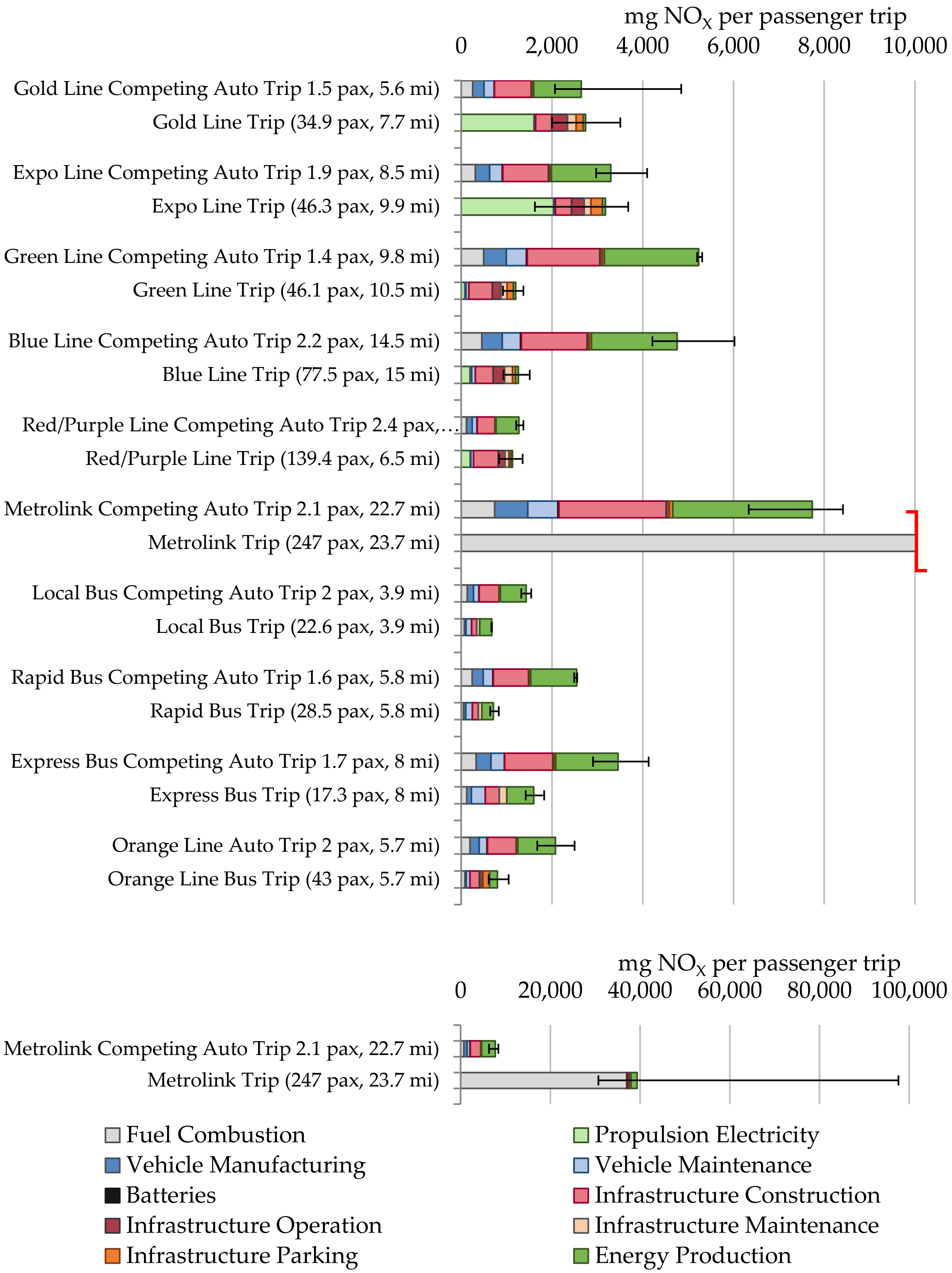

Figure 26 - NO_X Emissions per Passenger Trip of LA Unimodal Transit vs. Competing Auto Trips. Positive and negative fluctuations due to peak and off-peak travel is represented via error bars. Due to extreme emissions in the Metrolink case, the figure was amended so show these results separately.

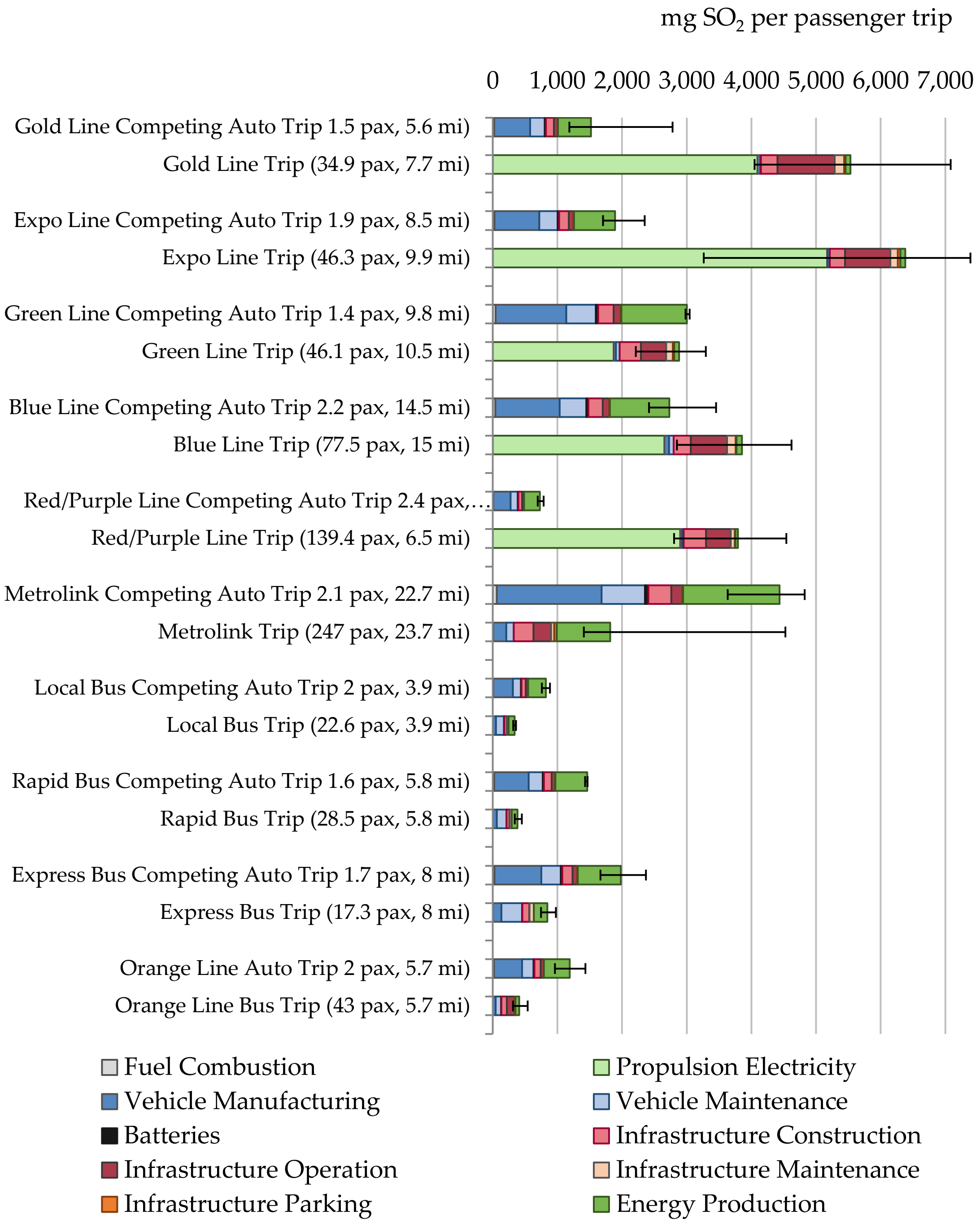

Figure 27 - SO_2 Emissions per Passenger Trip of LA Unimodal Transit vs. Competing Auto Trips. Positive and negative fluctuations due to peak and off-peak travel is represented via error bars.

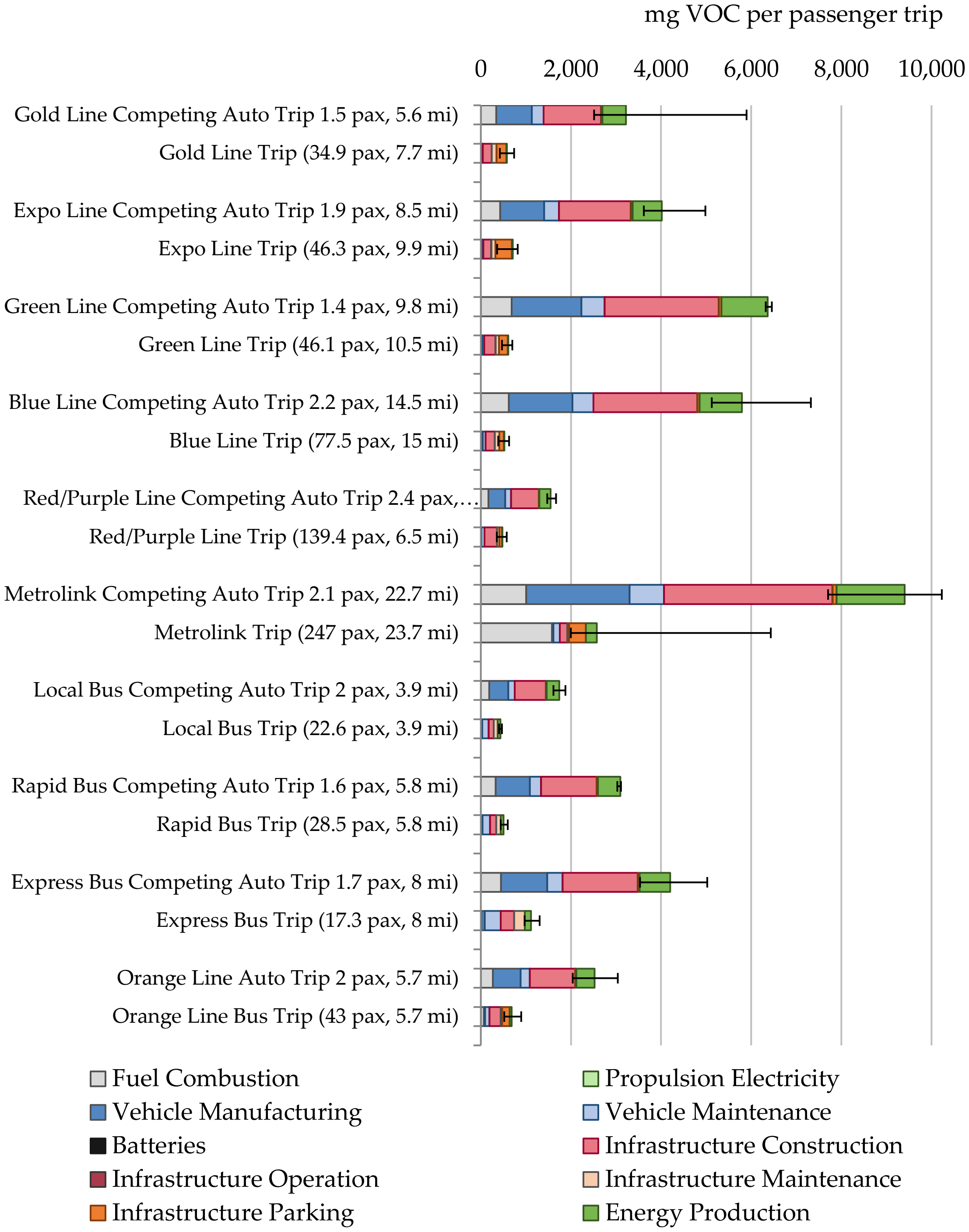

Figure 28 – VOC Emissions per Passenger Trip of LA Unimodal Transit vs. Competing Auto Trips. Positive and negative fluctuations due to peak and off-peak travel is represented via error bars.

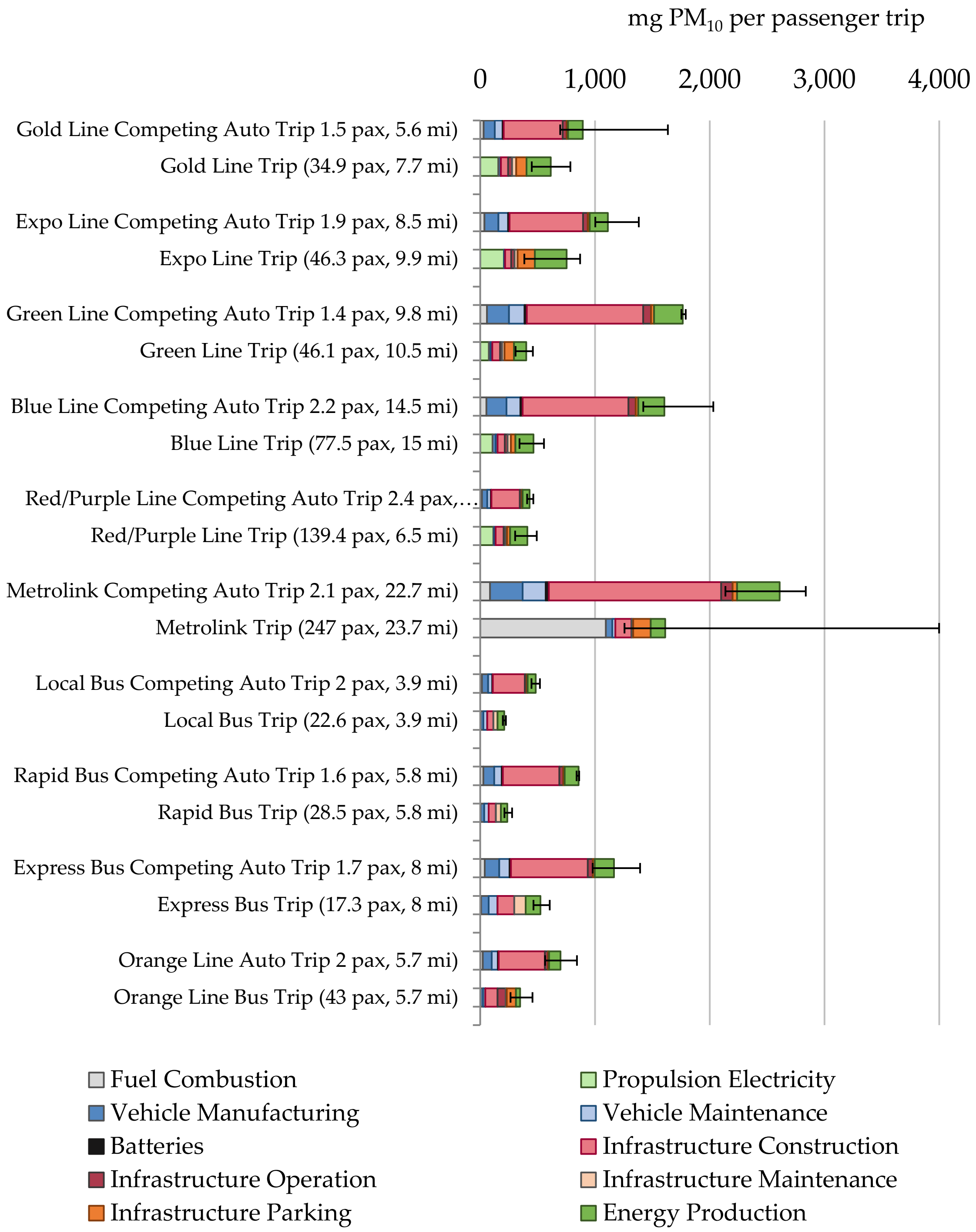

Figure 29 - PM_{10} Emissions per Passenger Trip of LA Unimodal Transit vs. Competing Auto Trips. Positive and negative fluctuations due to peak and off-peak travel is represented via error bars.

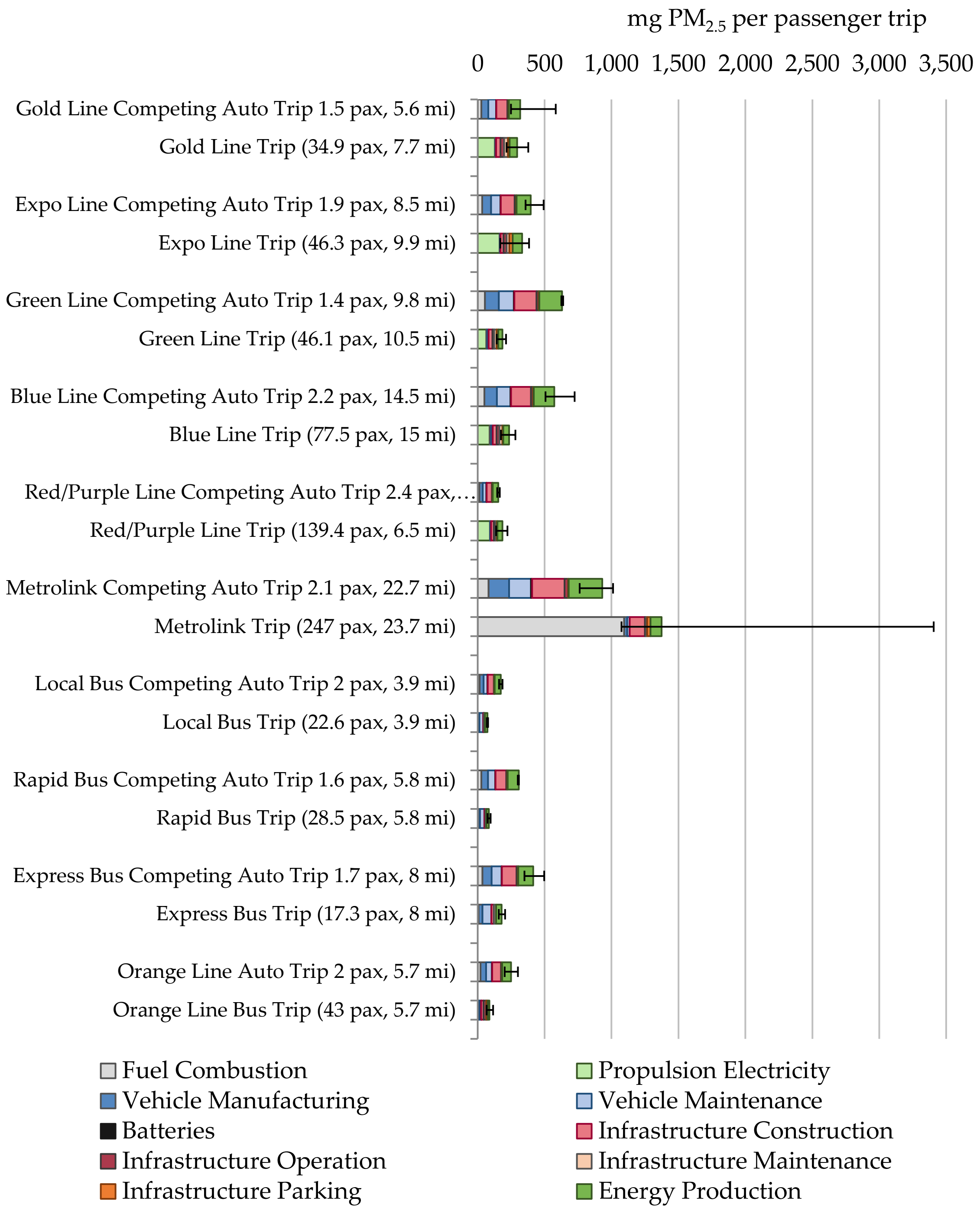

Figure 30 - $PM_{2.5}$ Emissions per Passenger Trip of LA Unimodal Transit vs. Competing Auto Trips. Positive and negative fluctuations due to peak and off-peak travel is represented via error bars.

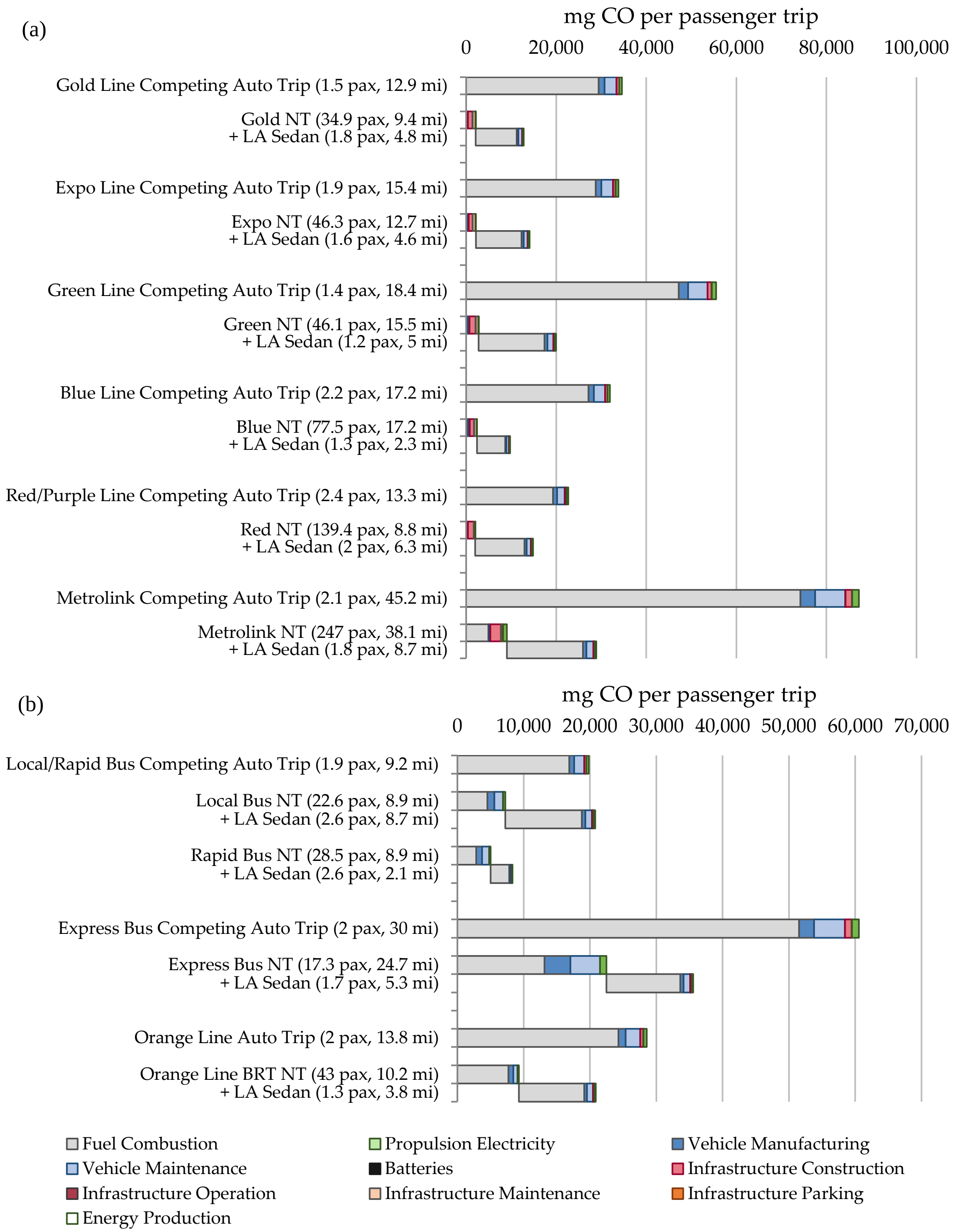

Figure 31- Average Near Term CO Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent average auto first-last mile trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

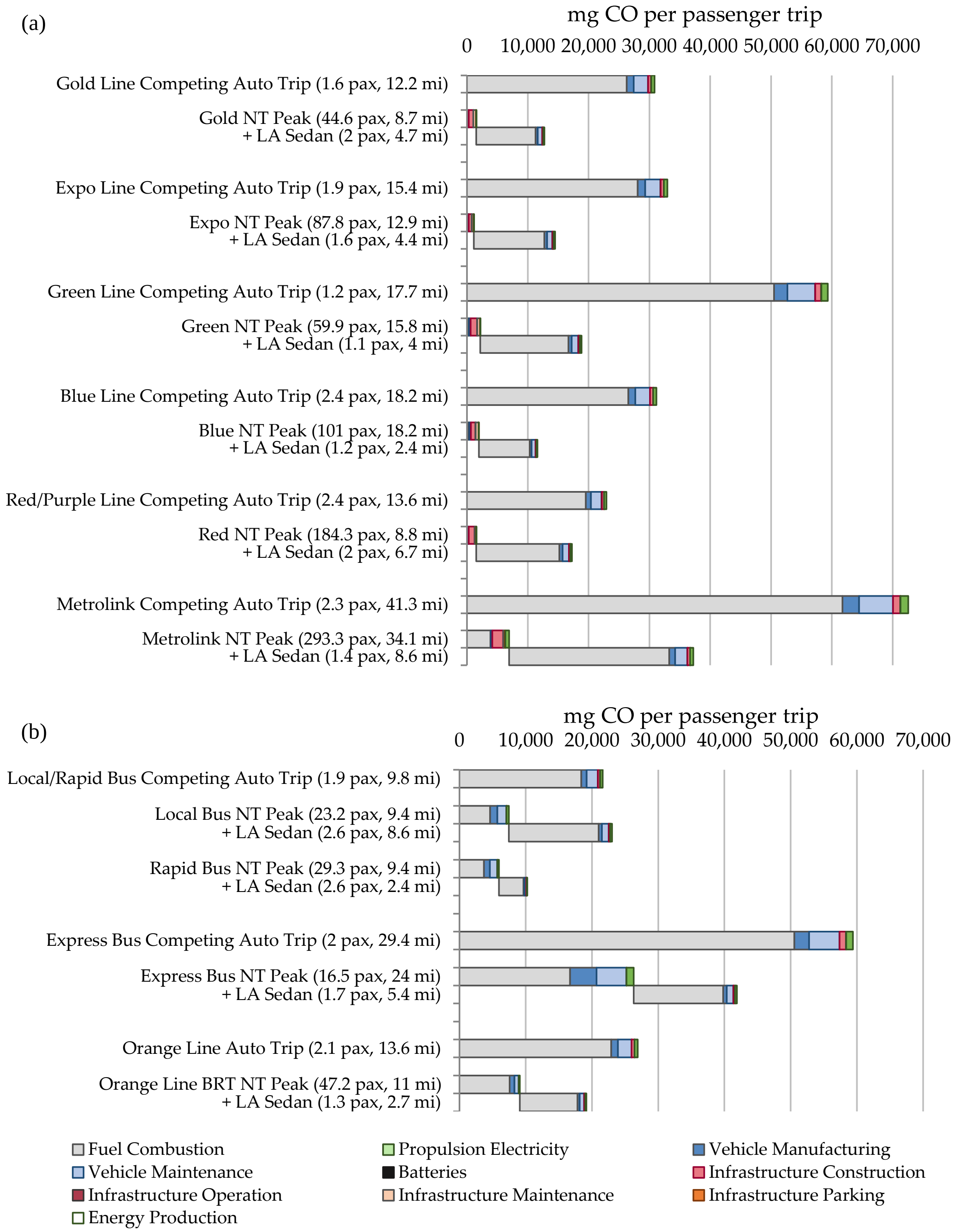

Figure 32 - Peak Near Term CO Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent peak auto first-last mile trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

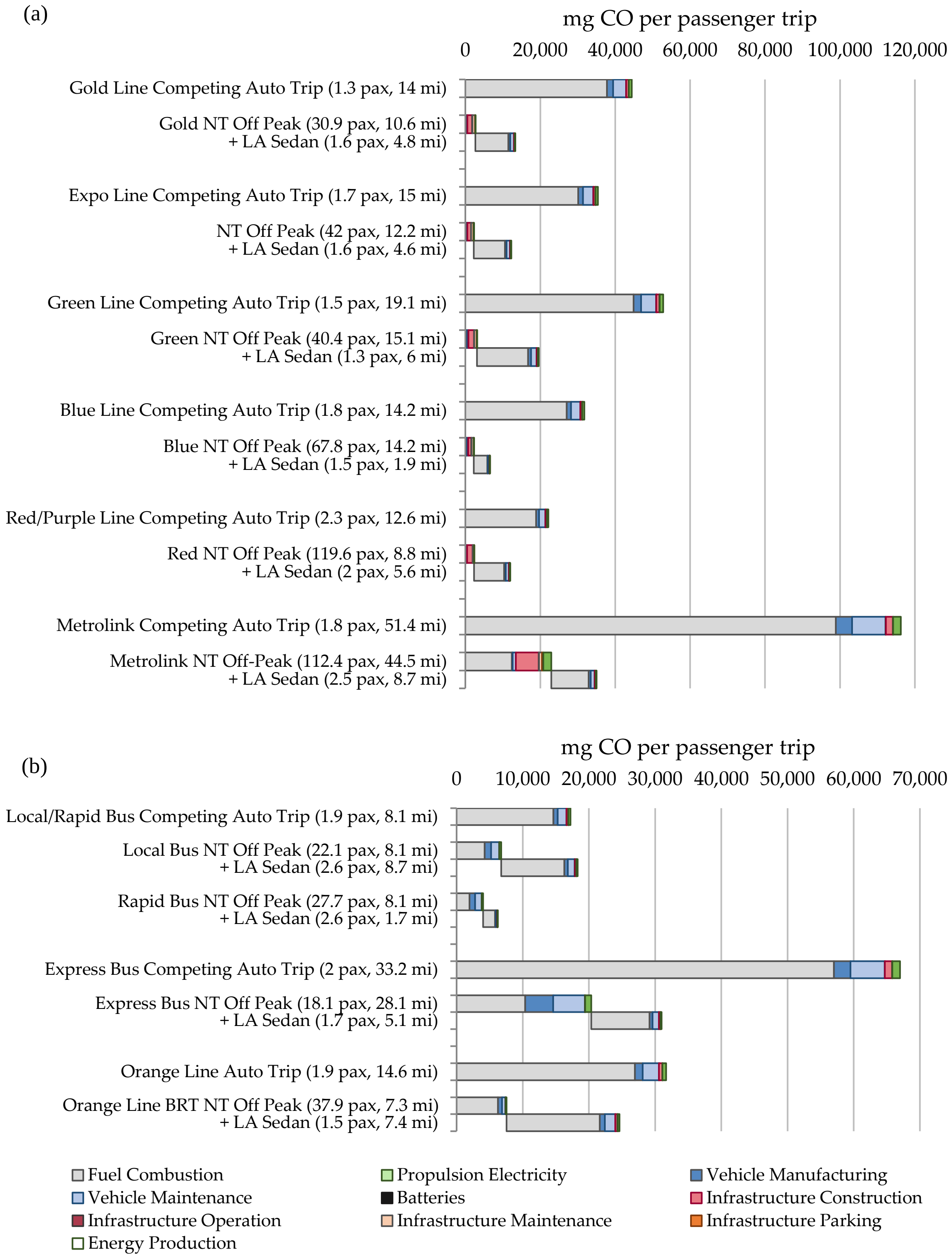

Figure 33 - Off-peak Near Term CO Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent off-peak auto first-last mile trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

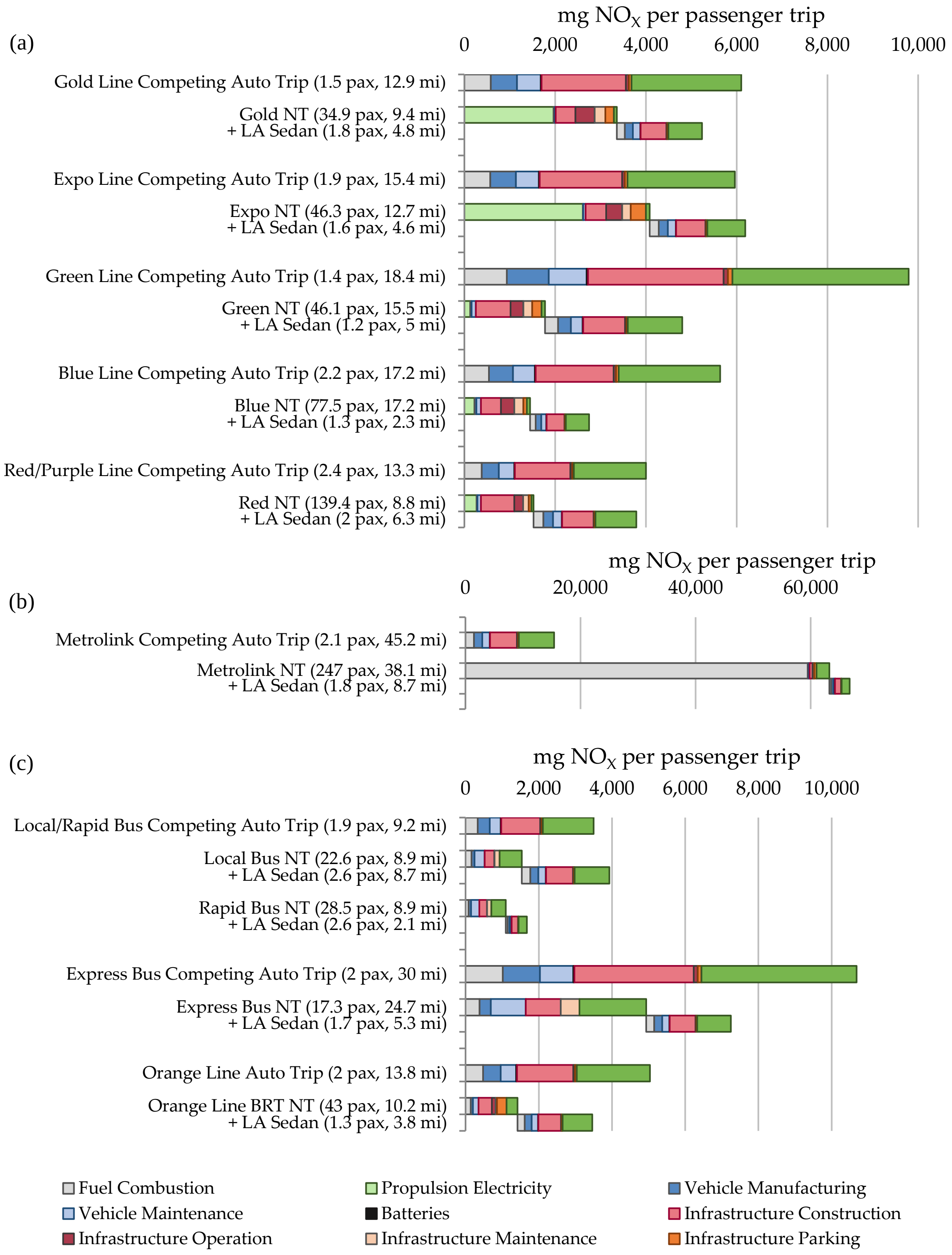

Figure 34 - Average Near Term NO_X Emissions per Passenger Trip with First-last Mile Auto Trips in Metro Rail (a), Metrolink (b), and Bus (c) Systems. Linked auto trips represent average auto first-last mile trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

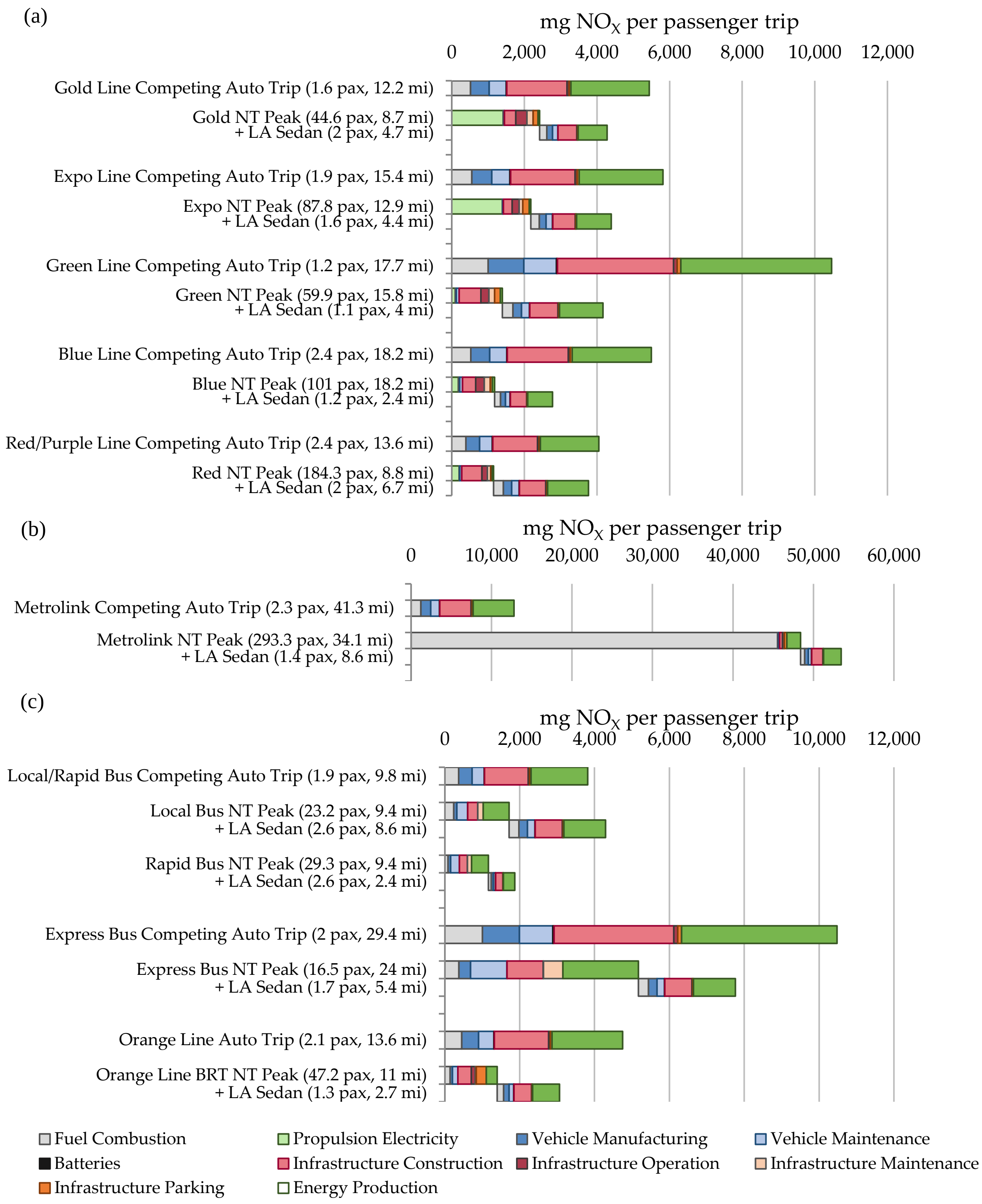

Figure 35 - Peak Near Term NO$_X$ Emissions per Passenger Trip with First-last Mile Auto Trips in Metro Rail (a), Metrolink (b), and Bus (c) Systems. Linked auto trips represent peak auto first-last mile trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

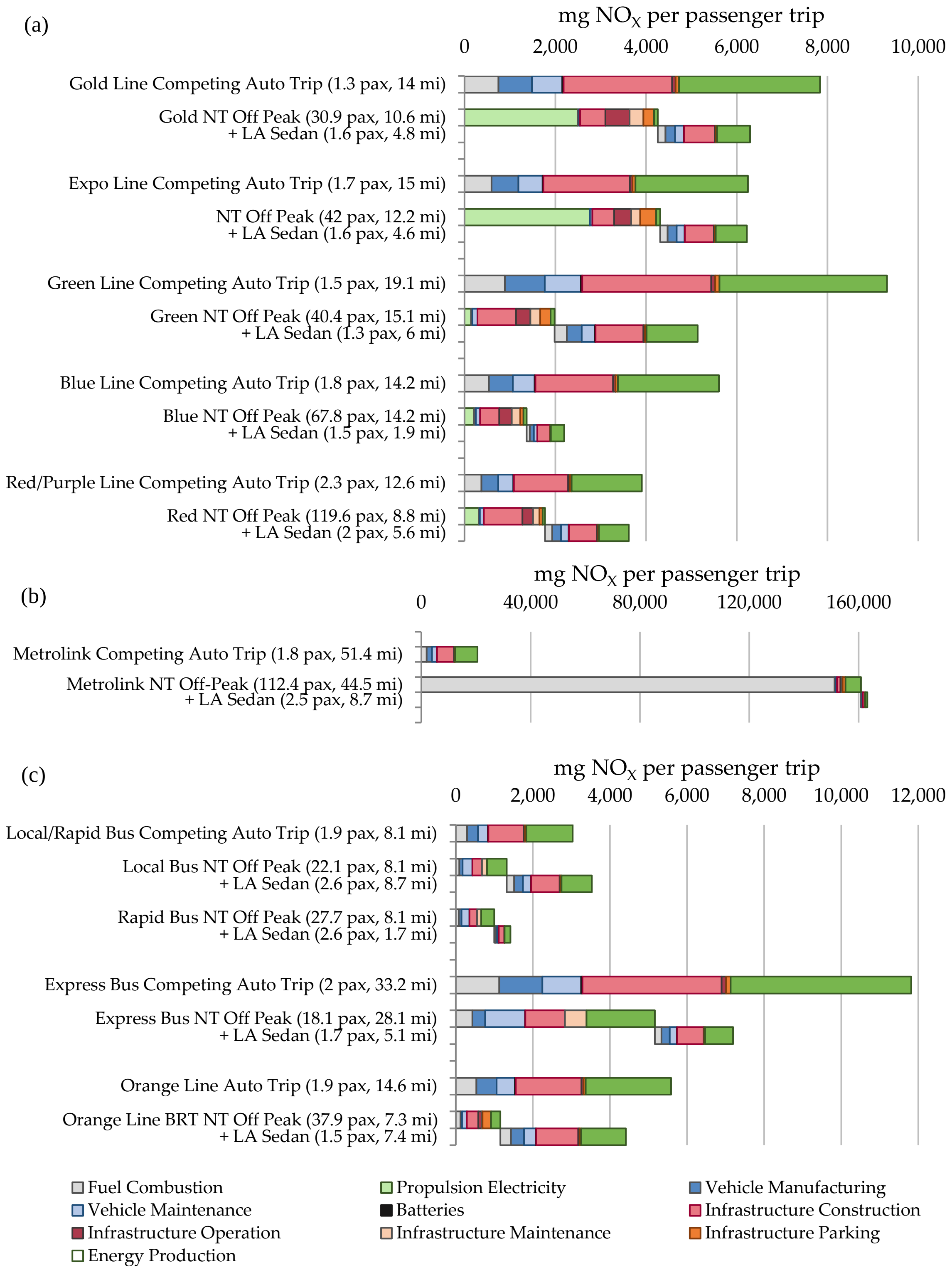

Figure 36 - Off-peak Near Term NO_X Emissions per Passenger Trip with First-last Mile Auto Trips in Metro Rail (a), Metrolink (b), and Bus (c) Systems. Linked auto trips represent off-peak auto first-last mile trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

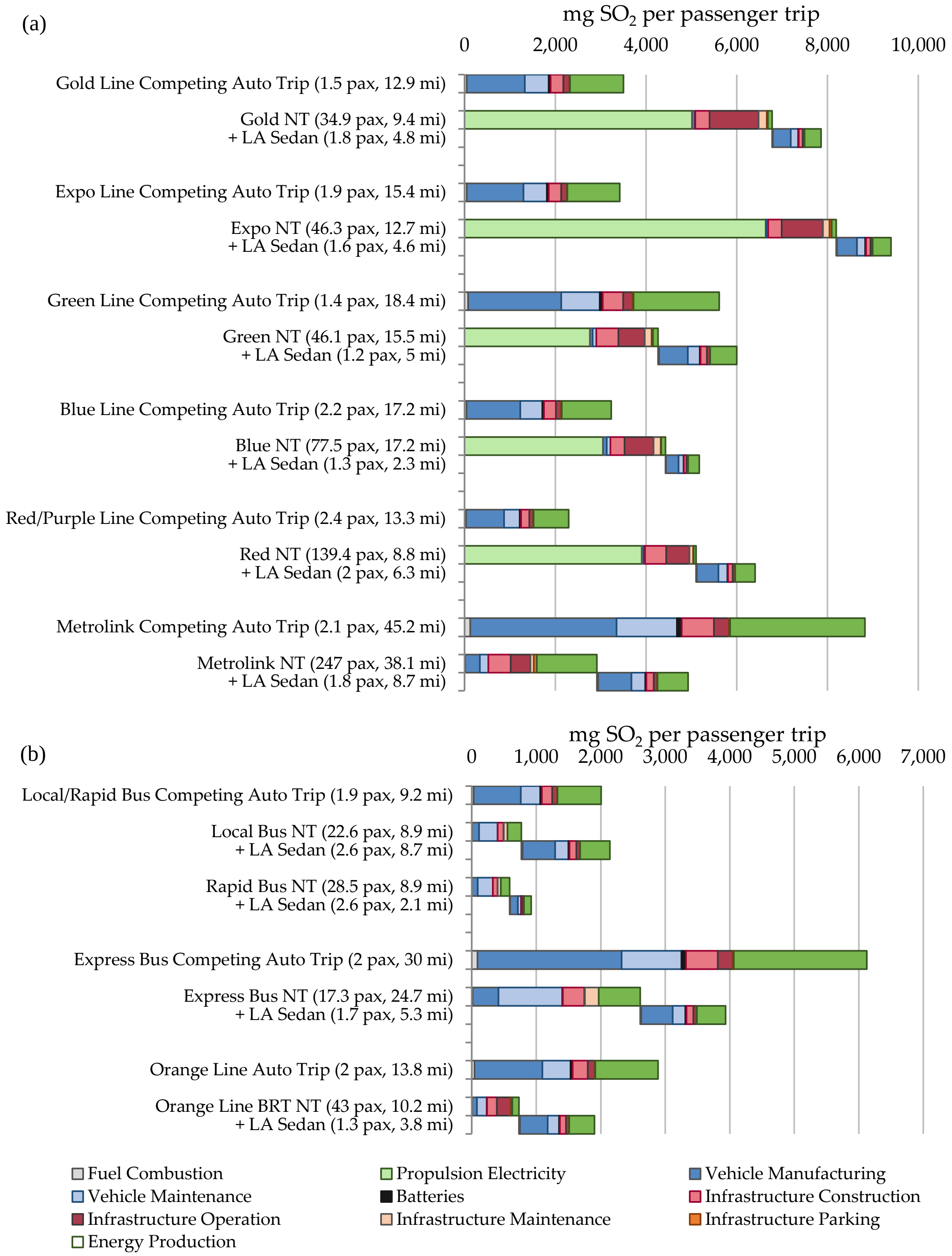

Figure 37 - Average Near Term SO_2 Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent average auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

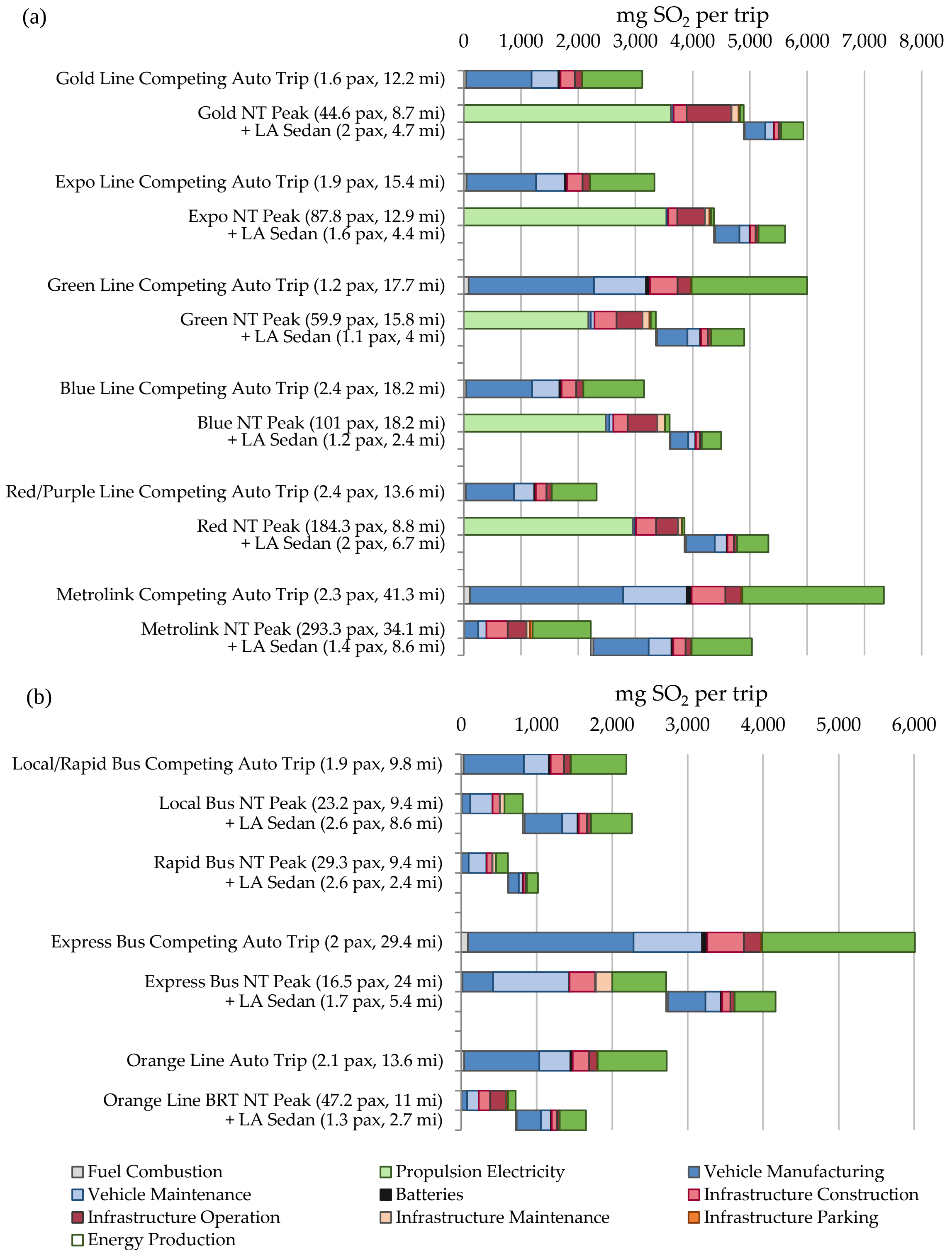

Figure 38 - Peak Near Term SO_2 Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) systems. Linked auto trips represent peak auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

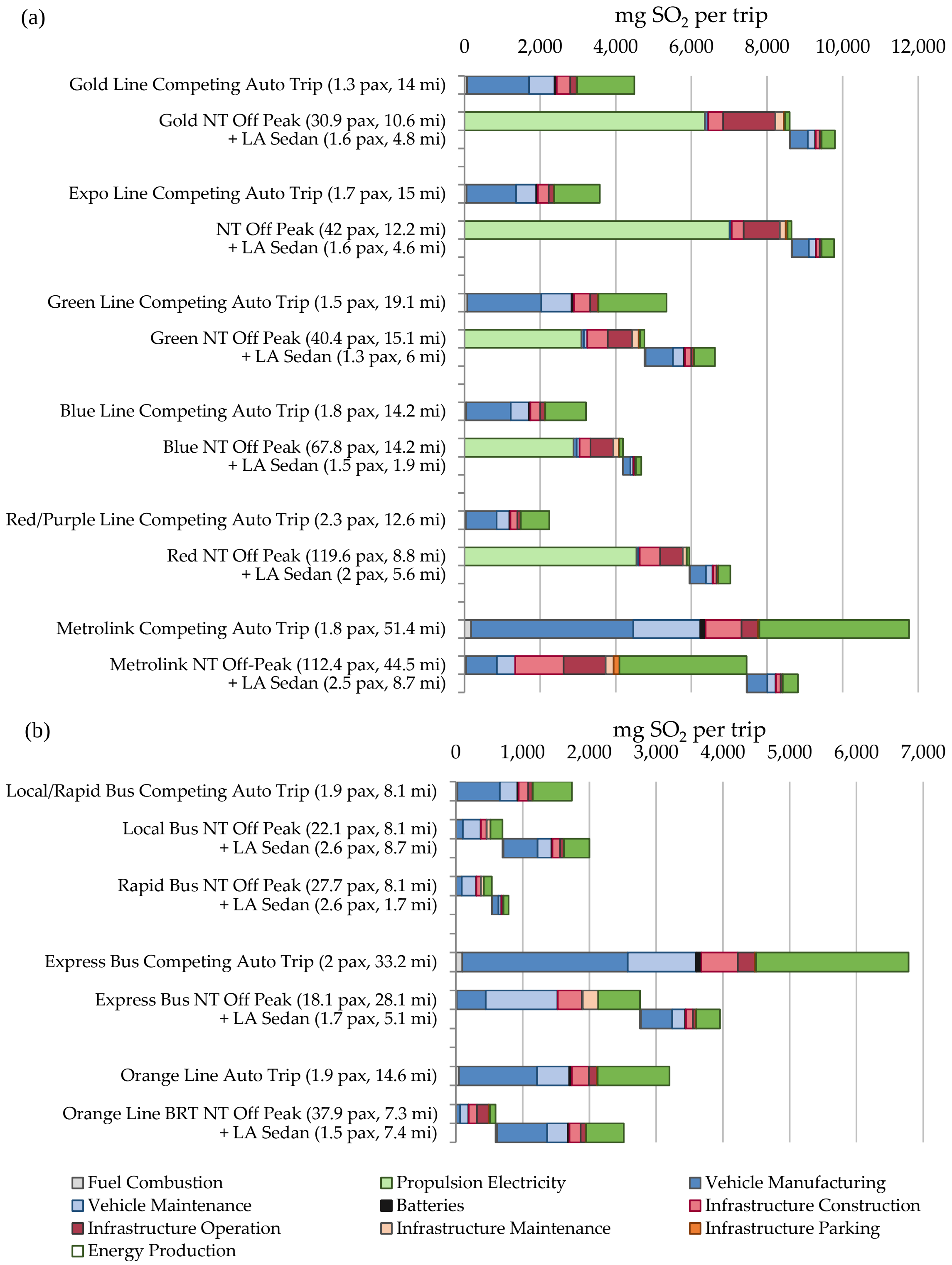

Figure 39 - Off-peak Near Term SO$_2$ Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent off-peak auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

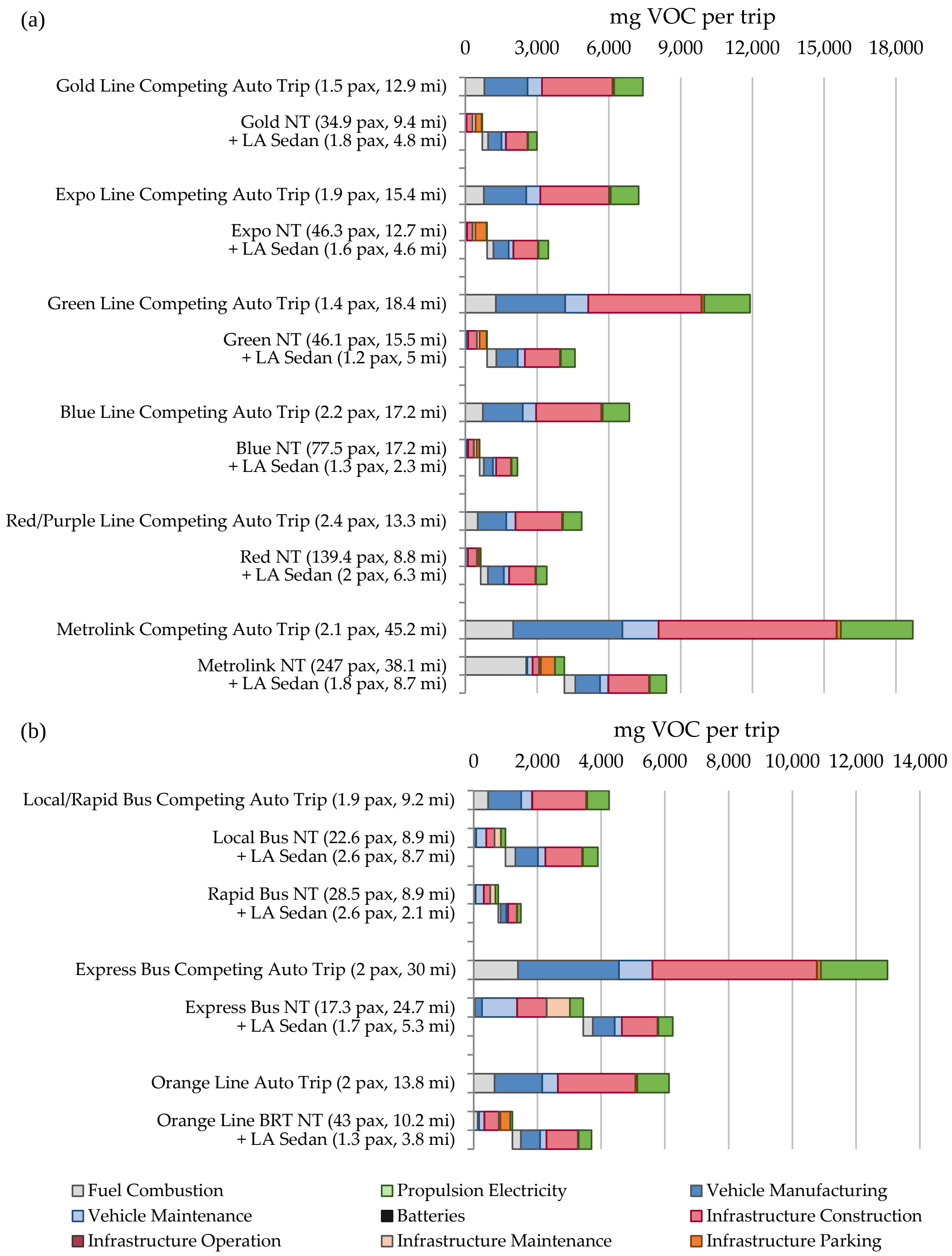

Figure 40 - Average Near Term VOC Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent average auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

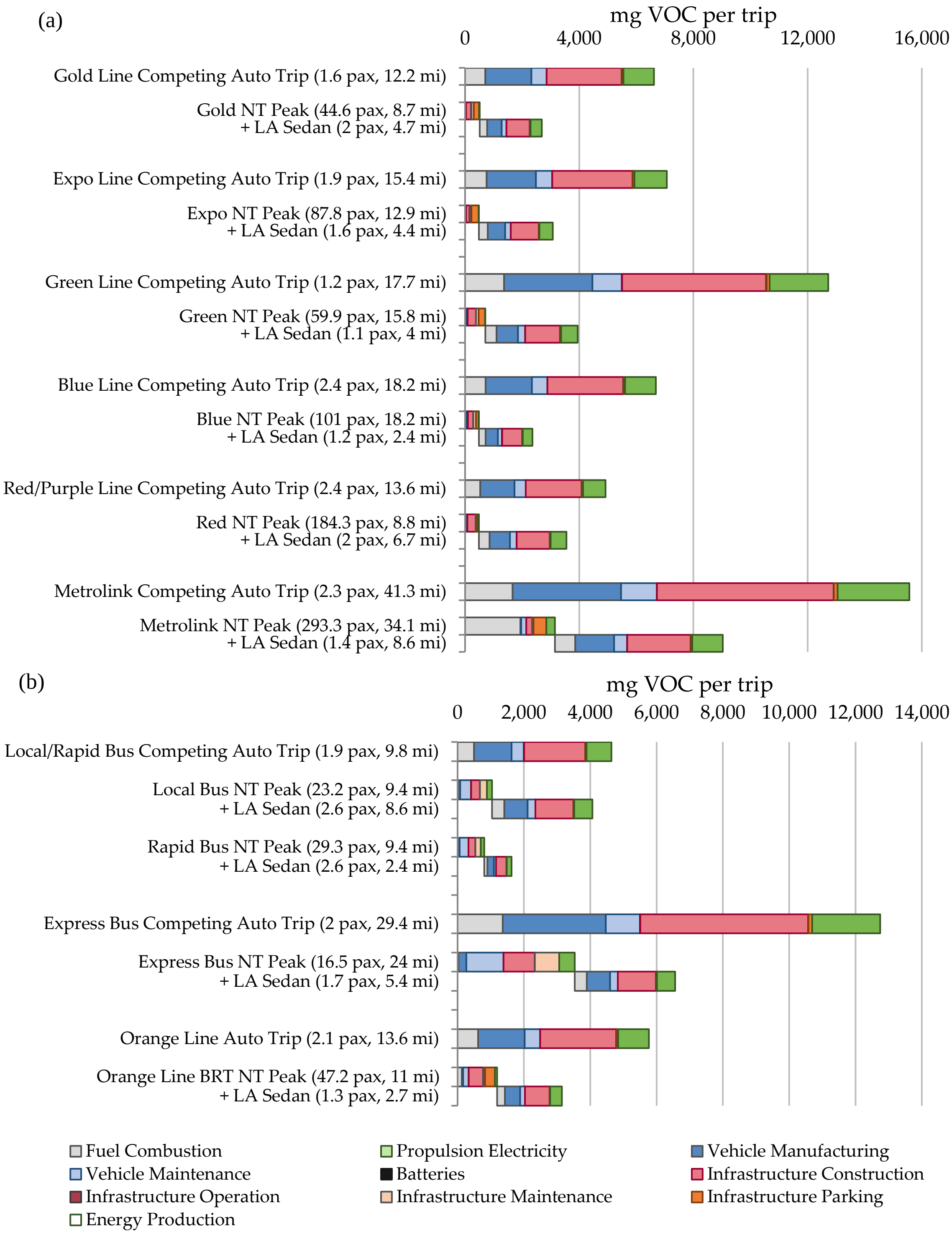

Figure 41 – Peak Near Term VOC Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent peak auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

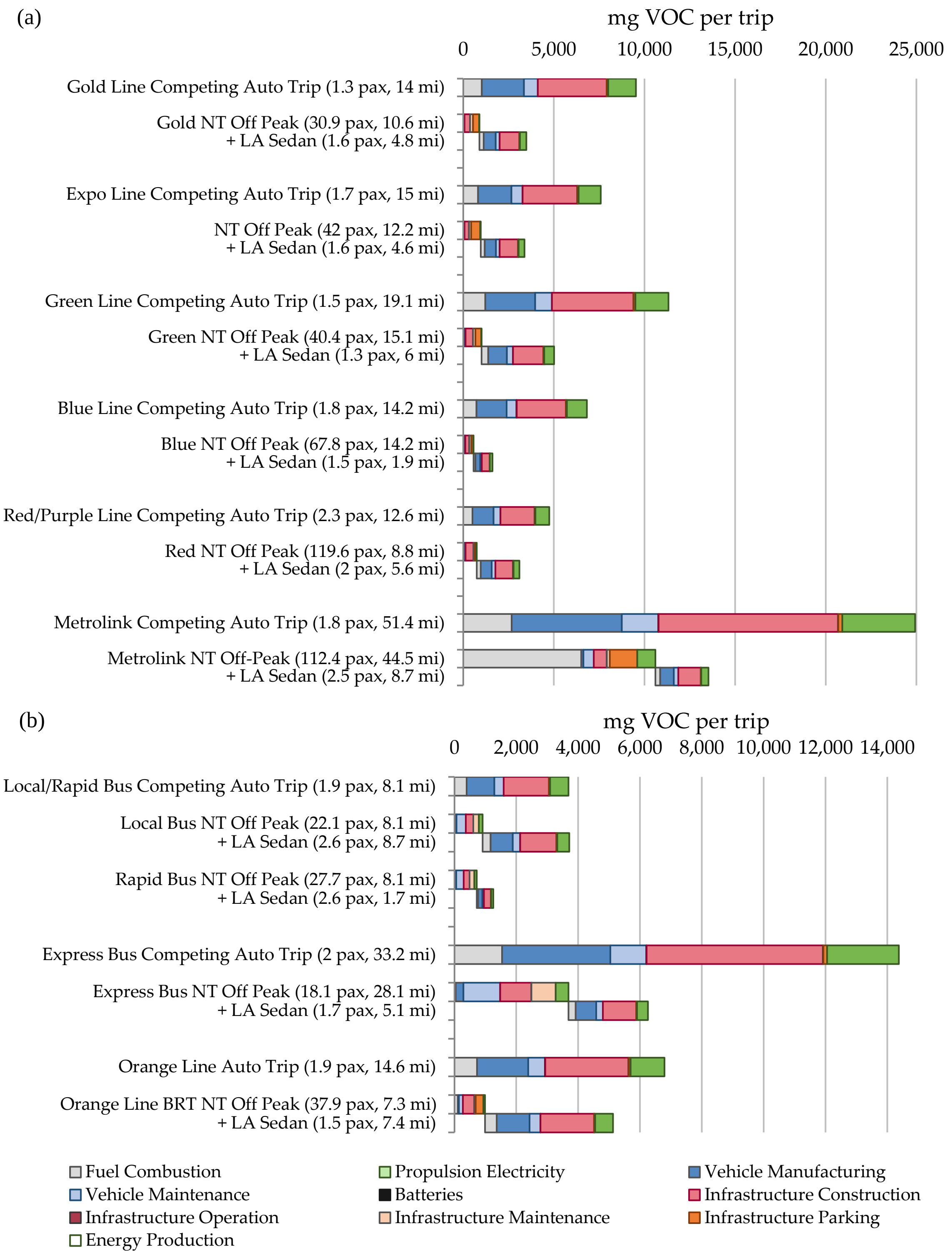

Figure 42 - Off-peak Near Term VOC Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent off-peak auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

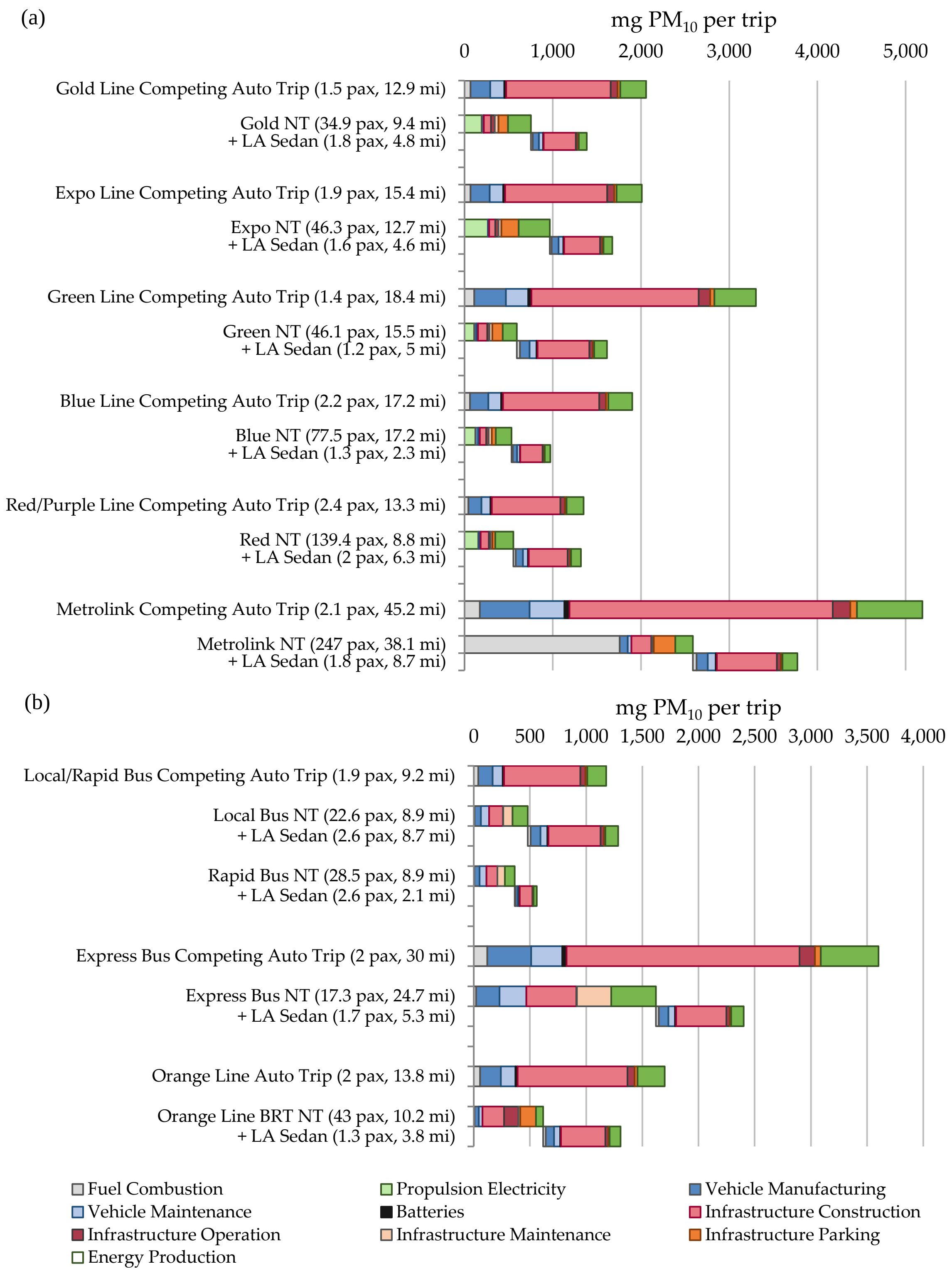

Figure 43 – Average Near Term PM_{10} Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent average auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

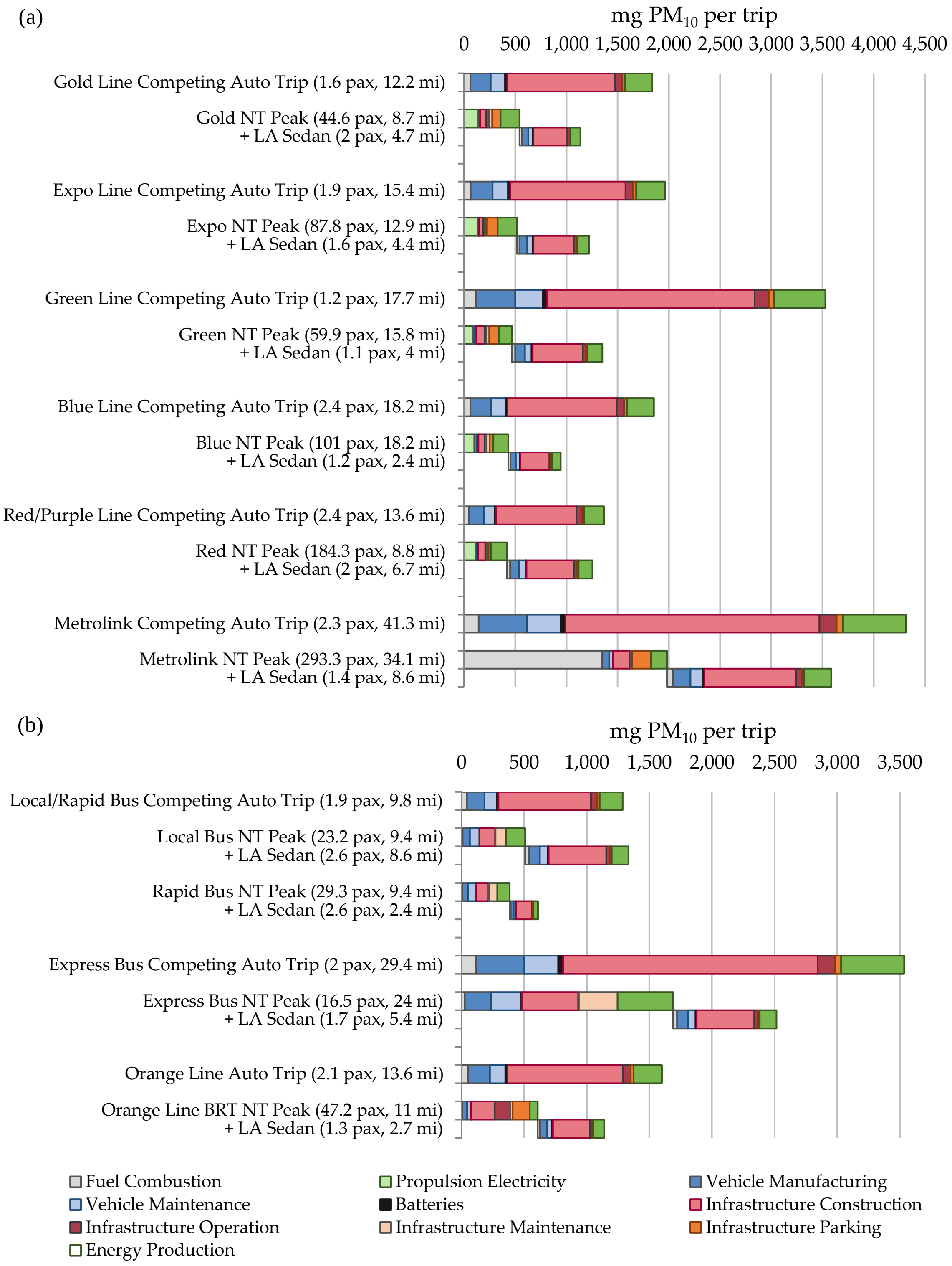

Figure 44 – Peak Near Term PM_{10} Emissions per Passenger with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent peak auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

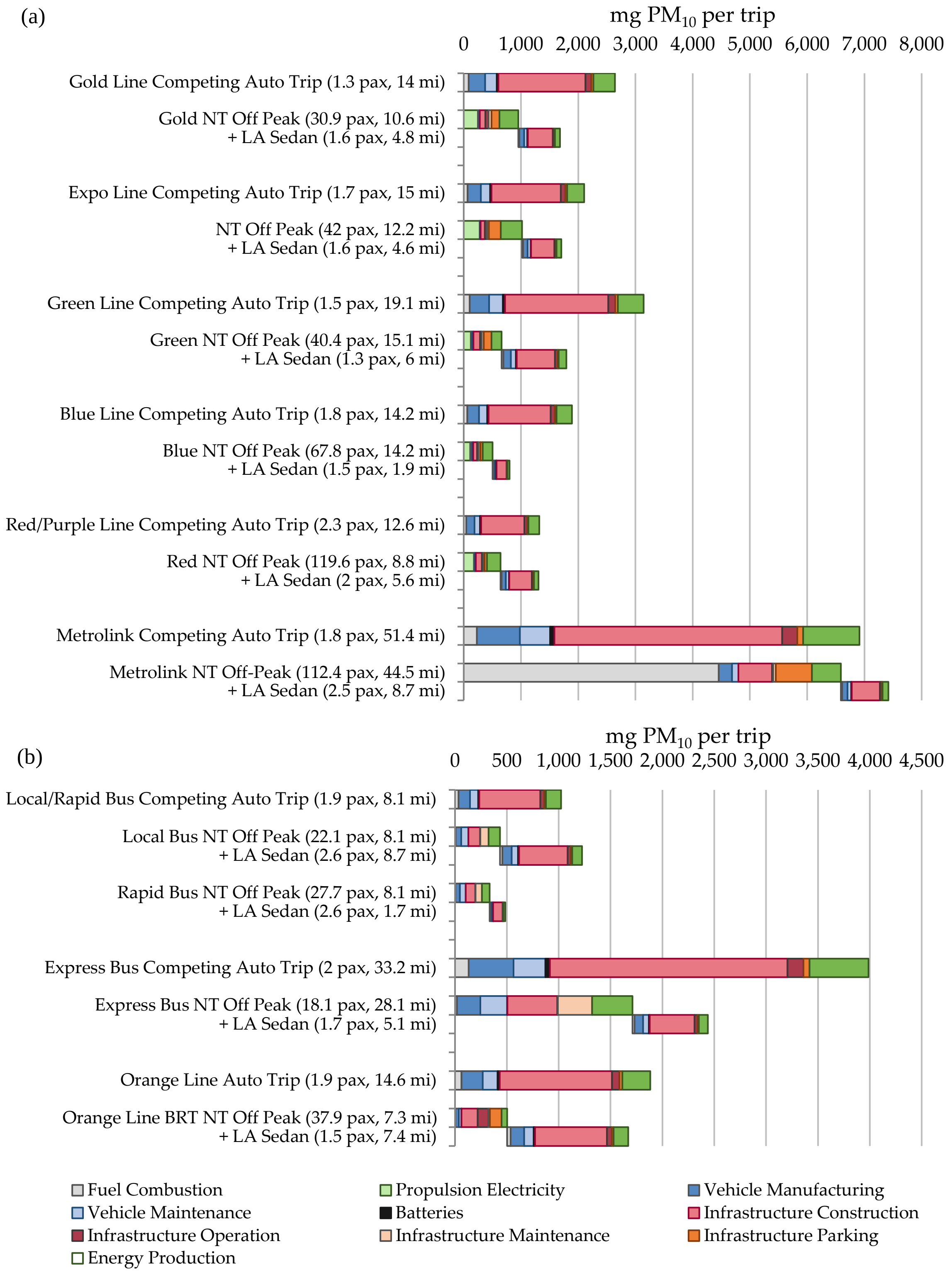

Figure 45 - Off-peak Near Term PM_{10} Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent off-peak auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

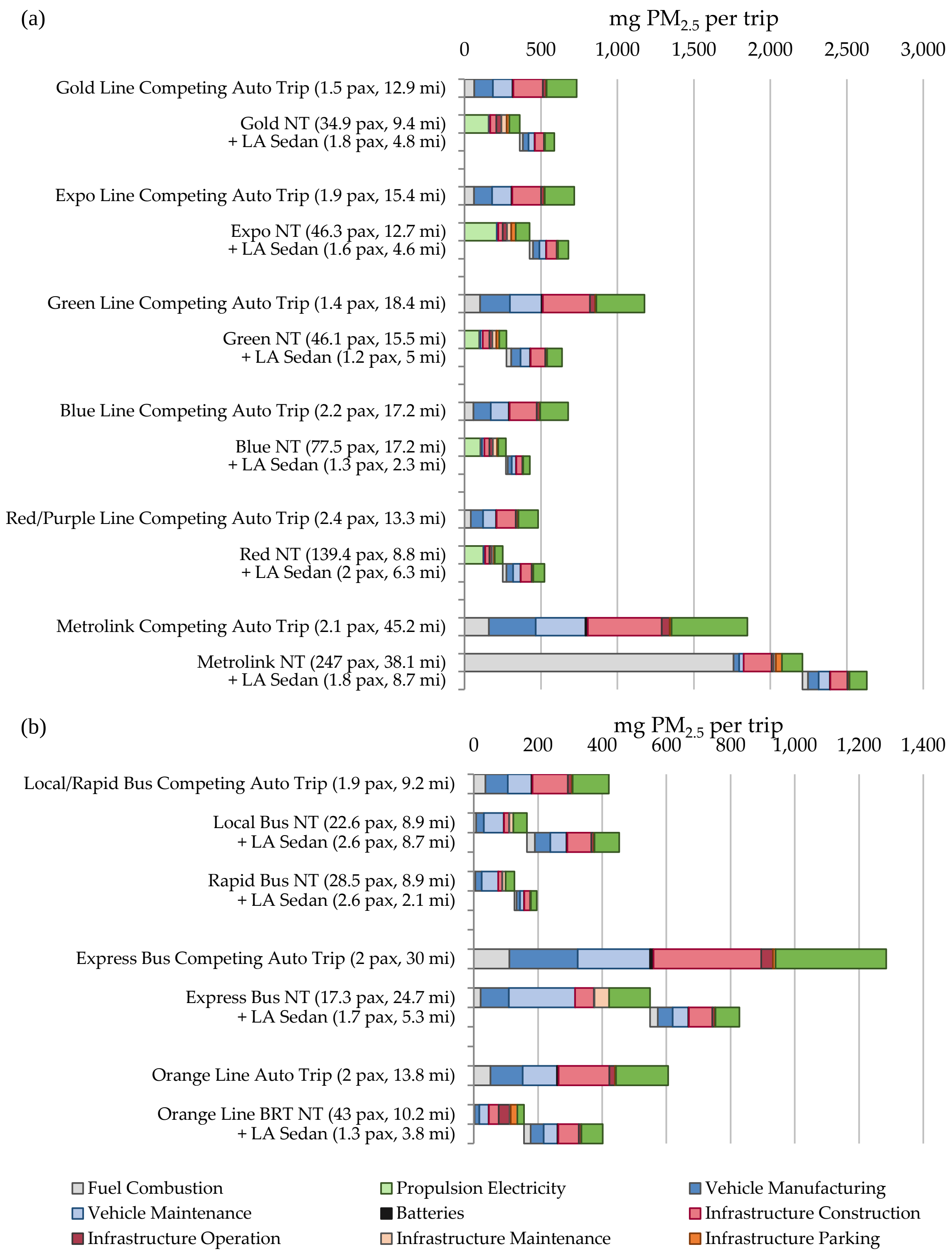

Figure 46 - Average Near Term $PM_{2.5}$ Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent off-peak auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

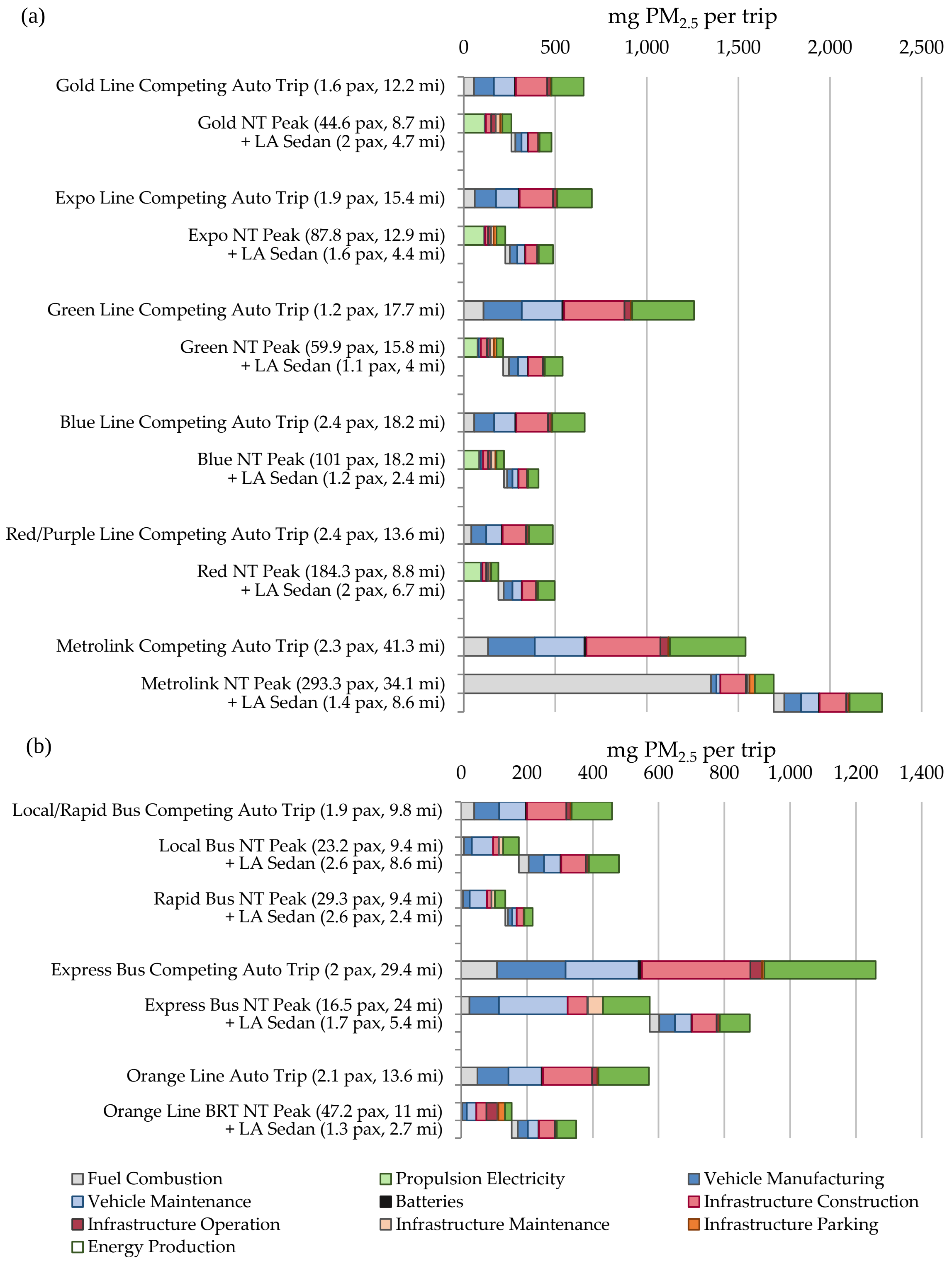

Figure 47 – Peak Near Term $PM_{2.5}$ Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent peak auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.

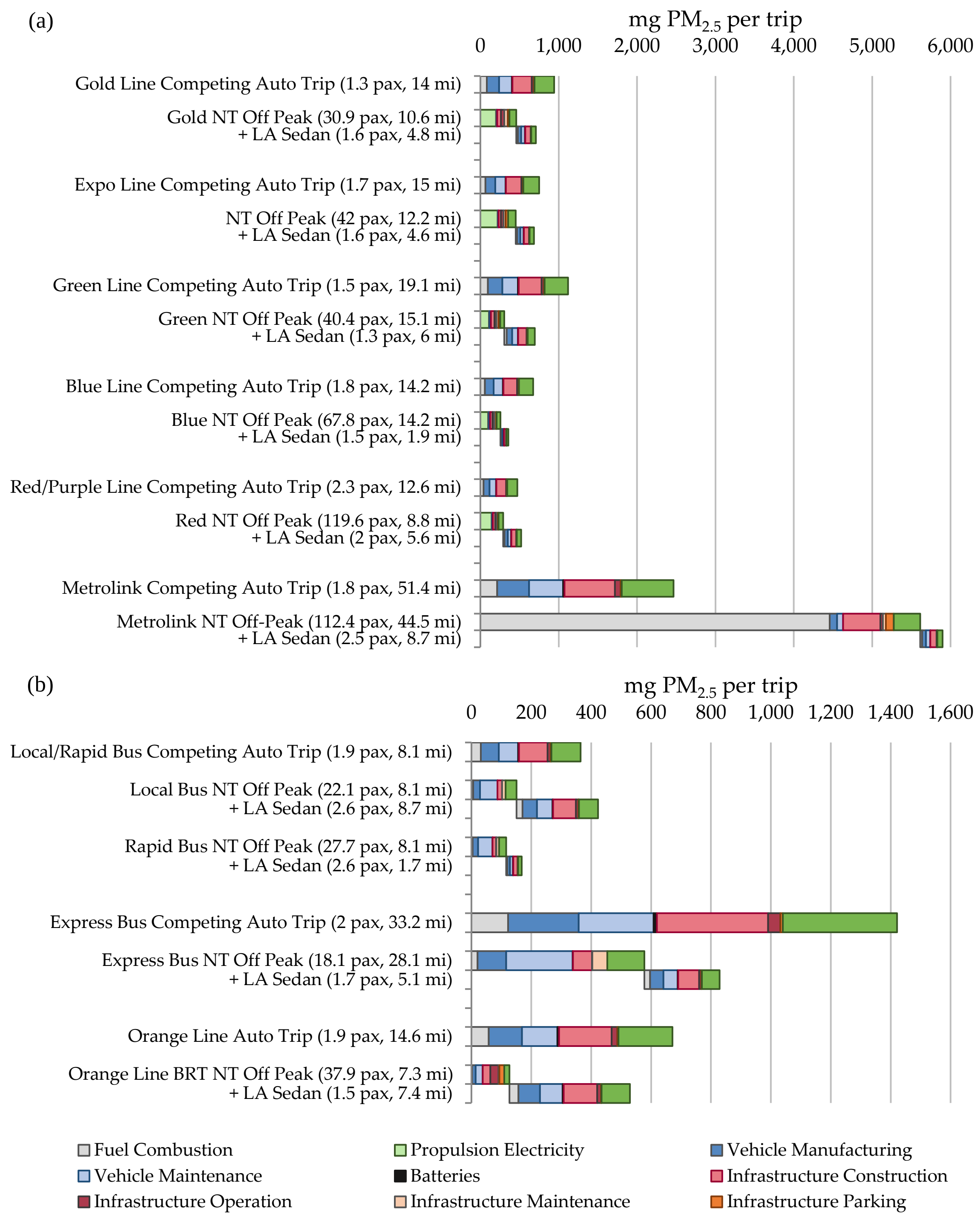

Figure 48 - Off-peak Average Near Term PM$_{2.5}$ Emissions per Passenger Trip with First-last Mile Auto Trips in Rail (a) and Bus (b) Systems. Linked auto trips represent off-peak auto access or egress trip characteristics to the linked transit system. Passengers (pax) are average per train or on-road vehicle.