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METHODOLOGY for the Environmental Life-cycle Assessment of Los Angeles Metro's Orange Bus Rapid Transit and Gold Light Rail Transit Lines

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WORKING PAPER

Working Paper Objective and Disclaimer: **www.sustainable-transportation.com**
This working paper is intended to provide the preliminary methodology used to assess the life-cycle energy consumption and air emission effects of Los Angele Metro's Orange bus rapid transit and Gold light rail transit lines for upcoming reports and peer-reviewed journal publication. The methodology is subject to future updates during the peer-review process as we incorporate feedback. Before using the information in this working paper, the reader is strongly advised to visit the research project website (🗗) for notification of the release of our final results, and for a listing of related publications.

METHODOLOGY for the Environmental Life-cycle Assessment of Los Angeles Metro's Orange Bus Rapid Transit and Gold Light Rail Transit Lines

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1 Acronyms

BRT	Bus Rapid Transit
BTU	British Thermal unit
CARFG	California Reformulated Gasoline
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalence
EIOLCA	Economic Input-Output Life Cycle Assessment
GHG	Greenhouse Gas
LADWP	Los Angeles Department of Water and Power
LCA	Life Cycle Assessment
LRT	Light Rail Transit
MJ	Megajoule
NMHC	Non-Methane Hydrocarbons
NOx	Nitrogen Oxides
PM	Particulate Matter
PMT	Passenger Mile Traveled
PWP	Pasadena Water and Power
SCE	Southern California Edison
SO_2	Sulfur Dioxide
SOx	Sulfur Oxides
THC	Total Hydrocarbons
VMT	Vehicle Mile Traveled
VOC	Volatile Organic Compounds
WECC	Western Electricity Coordinating Council

2 Document Background

The goal of this working paper is to provide the methodological background for several upcoming reports and peer-reviewed journal publications. This manuscript only provides background methodology and does not show or interpret any of the results that are being generated and interpreted by the research team. The methodology is consistent with the transportation LCA approach developed by Chester and Horvath (2009). The discussion in this working paper provides the detailed background data and steps used by the research team for their assessment of Los Angeles Metro transit lines and a competing automobile trip.

3 Methodology

Orange and Gold line travel are compared to a competing automobile trip. In phase one, a life cycle inventory of energy consumption and air emissions is developed for the Orange line, Gold line, and a 35 mile per gallon sedan. While current average automobile fuel economy in these transit corridors is likely lower, the use of this improved economy is meant to consider how a typical automobile is expected to perform in the future, especially given the long lifetimes of transit systems. In phase one, per PMT life cycle inventories are presented to illustrate the effects of including indirect and supply chain processes not typically included in vehicle energy or environmental footprints. The inventory will be the cornerstone of our phase two corridor assessment to be completed in future work.

3.1 System Boundary Selection

System boundary selection is a critical first step in LCA to establish a consistent scope for comparing the three modes. LCAs that do not establish a consistent system boundary are likely to compare uncommon components across systems of interest leading to results that cannot be contrasted. Recent transportation LCAs have established system boundaries that include vehicle, infrastructure, and energy components [Chester et al. AE 2010, Chester and Horvath 2009]. These studies have shown that for many air emissions, the majority of emissions often occur from life cycle components and not vehicle operation. Furthermore, these studies establish the need to include upstream supply chains. For example, aggregate use for concrete and asphalt, requires mining raw materials, processing to final form, and distribution, and these processes can dominate certain emissions [Chester and Horvath 2009]. A system boundary consistent with that used in these aforementioned studies is applied including upstream supply chain requirements. For this report, the terminology of life cycle *grouping* and life cycle *components* is used. A grouping refers to the aggregation of several components. For example, the Gold Line infrastructure construction grouping includes extraction and processing of raw materials into final products (e.g., steel and concrete), excavation and construction activities for different track segment types (e.g., aerial and at-grade), station construction, and so on. There are roughly 150 components evaluated for each mode and the groupings (used in the discussion of the analysis methodology and reporting of results) are designed to relay critical information in the most usable form to readers. This analysis builds on existing research and in-depth discussion of fundamental approaches used to determine process effects is available in other literature (and cited where appropriate). Table 3 shows the system boundary of analysis with life cycle groupings and generalized life cycle components for each of the modes.

Table 1 – Life Cycle Assessment System Boundary

Life Cycle Grouping	Sedan	Orange Line	Gold Line
Vehicle			
Manufacturing	▪ Sedan ▪ Transport to Point of Sale	▪ Bus ▪ Transport to Point of Sale	▪ Train ▪ Transport to Point of Sale
Operation	▪ Propulsion ▪ Idling	▪ Propulsion ▪ Idling	▪ Propulsion ▪ Idling
Maintenance	▪ Typical Sedan Maintenance ▪ Tire Replacement ▪ Battery Replacement	▪ Typical Bus Maintenance ▪ Tire Replacement ▪ Battery Replacement	▪ Typical Train Maintenance ▪ Train Cleaning ▪ Flooring Replacement
Insurance	▪ Sedan Liability	▪ Bus Liability ▪ Operator Fringe Benefits	▪ Train Liability ▪ Operator Fringe Benefits
Infrastructure			
Construction	▪ Roadway Construction	▪ Roadway Construction ▪ Station Construction	▪ Track Construction ▪ Station Construction
Operation	▪ Roadway Lighting ▪ Herbicide Use	▪ Road and Station Lighting ▪ Herbicide Use ▪ Control and Signaling	▪ Track, Station, and Parking Lighting ▪ Herbicide Use ▪ Train Control ▪ Miscellaneous (Escalators, Equipment)
Maintenance	Roadway maintenance is the result of heavy duty vehicles and thus not charged to small cars.	▪ Road and Station Maintenance	▪ Track and Station Maintenance
Parking	▪ Curbside Parking	▪ Dedicated Parking	▪ Dedicated Parking
Insurance	▪ Road Workers Fringe Benefits	▪ Non-vehicle Workers Fringe Benefits ▪ Infrastructure Liability	▪ Non-vehicle Workers Fringe Benefits ▪ Infrastructure Liability
Energy Production			
Extraction, Processing, & Distribution	▪ Gasoline Extraction, Processing, & Distribution	▪ Natural Gas Extraction, Processing, Distribution, & Compression	▪ Raw Fuel Extraction and Processing, Electricity Generation, Transmission & Distribution

3.2 Energy and Environmental Indicators

We evaluate energy inputs and air emission outputs including greenhouse gases and conventional air emissions. Reporting energy use is challenging because of the many forms that may be valuable to the research question asked. Energy use can be reported as primary, end-use, fossil, non-fossil, renewable, non-renewable, electrical, non-electrical, and so on. We report energy use as end-use, a useful metric for transportation decision makers who have some control over the energy consumption of their system. Greenhouse gases (GHGs) include CO_2, CH_4, and N_2O normalized to CO_2-equivalence (CO_2e) using IPCC

100 year radiative forcing factors of 25 for CH_4 and 298 for N_2O. Conventional air pollutants is a term used to describe the primary air emissions of particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOCs), carbon monoxide (CO), and lead. These conventional air pollutants are either directly or indirectly (through atmospheric chemistry where secondary pollutants such as ozone are formed) responsible for significant human health and environmental impacts. PM is disaggregated to 2.5 micron diameter or less ($PM_{2.5}$), and greater than 2.5 microns to 10 microns (PM_{10}), to capture their differing human health impacts. Conventional air pollutants are evaluated (with the exception of lead due to lack of data) for all life cycle components. Including a broad suite of environmental indicators is necessary for understanding the comprehensive impacts of transportation systems. By evaluating multiple indicators, it is sometimes the case that a decision that decreases one emission may increase another.

3.3 Development of Modal Life Cycle Inventories

The approach for generating the life cycle inventories of the three modes is based on existing work by the authors. Detailed methodological discussions are available in existing literature [Chester and Horvath 2009, Chester 2008] and the following discussion identifies the critical factors and approaches for evaluating the three Los Angeles modes and their geographic-specific processes. For each mode, vehicle, infrastructure, and energy production groupings are discussed with the fundamental assumptions for critical parameters.

3.3.1 Los Angeles Sedan

3.3.1.1 Vehicle

The LA sedan is a 3,200lb automobile similar to a Toyota Camry. The conventional gasoline vehicle is specified with a baseline fuel economy of 35 miles per gallon, consistent with 2020 Corporate Average Fuel Economy standards. There are several challenges when evaluating a single fuel economy in the life cycle inventory. First, while the Orange line started operation in 2005 and the Gold line 2003, evaluating the sedan with a typical fuel economy in these years is not useful comparison against transit systems that will last decades. Next, it is likely that some vehicles will have lower fuel economies and some higher (e.g., hybrids). Lower fuel economies would include older vehicles, vehicles that were not required or chose not to meet 2020 standards, and even congestion effects. Congestion effects for Los Angeles automobiles are important when vehicles are operating in stop-and-go traffic. While the cumulative distribution may produce some average speed, in reality the vehicle may have spent time above or below this speed. Below 40 miles per hour, the lower the speed, the more fuel is consumed and emissions produced per VMT [Chester et al. AE 2010, Ross 1994]. If congestion worsens in Los Angeles then average vehicle speeds will decrease. As fuel economies improve, it is difficult to say without additional study the extent to which congestion-affected fuel economy will change. To illustrate life cycle effects, the 35 mile per gallon baseline is used as an expected reasonable middle ground. We acknowledge that average future fuel economies may affected by a breadth of factors, including congestion, and our corridor analysis future work will explore the surrounding range.

Vehicle and battery manufacturing energy use and air emissions are determined with GREET2 (2007). The sedan is estimated to travel 160,000 miles in its lifetime and manufacturing is assumed to occur in an average U.S. electricity mix to capture the possibility of vehicle import to Los Angeles from a generic U.S. manufacturing location. It is assumed that two battery replacements will occur during the vehicle's lifetime and current lead-acid battery technology is evaluated. Replacement battery manufacturing is assigned to the vehicle maintenance life cycle grouping. Furthermore, transport from the manufacturing plant to point of sale/use is included assuming a distance of 2,000 miles by a Class 8b heavy duty truck.

Operational emissions include gasoline fuel combustion, brake wear, tire wear, and evaporative VOC losses. The LA sedan is evaluated with CA Reformulated Gasoline (CARFG). Automobile PM emissions from brake and tire wear have been shown to produce non-negligible health impacts and are included. Furthermore, the volatilizing of liquid gasoline to gaseous form where it escapes from vehicles as VOCs is also included. CA-GREET1 (2009), a model adapted from GREET1 (2010) to more accurately capture California conditions, is used to evaluate operational emissions.

Vehicle maintenance includes general maintenance (parts replacement, general servicing), tire replacement, and battery replacement (previously discussed). The American Automobile Association reports that in 2010, maintenance costs were ¢4.29 per VMT and tire costs ¢1.11 per VMT [AAA 2011]. Evaluating these costs within EIOLCA (2011)'s *Automotive Repair and Maintenance* and *Tire Manufacturing* sectors produces maintenance impacts from general maintenance services and parts production, and the production of tires. Following Chester and Horvath (2009), automotive repair shop emissions are included, based on the California Air Resources Board's 1997 Consumer and Commercial Products Survey (see Chester (2008) for additional discussion).

The provision of vehicle liability insurance including energy for administrative facilities and waste generation produces significant emissions in the vehicle life cycle [Chester and Horvath 2009]. AAA (2011) reports that in 2010 insurance costs for a medium size sedan were $948 per year. Evaluating this cost within EIOLCA (2011)'s *Insurance Carriers* sector allows for the determination of energy use and emissions from the physical insurance infrastructure.

3.3.1.2 Infrastructure

An automobile trip that is substituted for an Orange or Gold Line trip reduces onroad infrastructure dependence. Onroad infrastructure includes roadway construction and maintenance, roadway operation, parking, and associated roadway worker requirements. While all of these groupings are considered, there is a necessary distinction between average and marginal effects. The removal of a single automobile trip does not result in transportation engineers reducing road capacity and therefore reconstruction, maintenance, or new construction requirements. The reduction in capacity will occur according to a step-wise function where a certain number of auto trips shifted to the Orange and Gold lines would result in a future roadway capacity disinvestment commitment by Los Angeles. Distinguishing life cycle effects between average and marginal is important for deciding which components actually occur because of a decision in order to determine the true environmental footprint of the decision to build and operate the public transit lines. When establishing baselines however, average effects are necessary. We choose to first establish the comprehensive life cycle footprint of all modes and in our corridor assessment, evaluate consequential effects by considering only marginal life cycle effects.

Roadway construction and maintenance for the 21 mile trip are evaluated with PaLATE (2004) and coupled with VOC and $PM_{2.5}$ emissions [Chester et al. ERL 2010a, Chester 2008]. The automobile trip would likely include local, collector, and arterial roadways. A typical Los Angeles collector is evaluated with asphaltic cement with a width of 32 feet and depths of 6 inches for the wearing layers and 12 inches for the subbase. This width includes only the traveled way and excludes multi-purpose area for parking (parking effects are evaluated independently). The road is assumed to have a lifetime of 10 years for the wearing layers and 50 years for the subbase. While routine roadway maintenance is determined, its energy use and emissions are not allocated to the automobile. Damage to roadways occurs based on a fourth-power relationship to axle loads [Huang 2004]. This means that roadway damage is the result of large vehicles, particularly freight trucks. Roadway capacity on the other hand is dictated by automobile demand and therefore construction effects should be attributed to the sedan.

Herbicide use and lighting are evaluated for roadway operation. Herbicide use is assumed to be negligible given a general lack of roadside greenery. Lighting is evaluated based on data from nationwide roadway lighting estimates [Chester 2008]. Nationwide estimates include urban and rural roads and applying these factors to Los Angeles is expected to produce a conservative estimate since the collector we consider is fully lit.

Parking spaces are generally grouped as curbside (onstreet), surface (offstreet), parkade (or multi-story garage), or home driveway or garage. Following Chester et al. ERL (2010a), an energy and emissions inventory is determined for each parking space type. The multi-use nature of asphalt surfaces produces challenges for evaluating parking effects in regions or along roadway segments. By first establishing the per-space inventories, several scenarios can be considered in later analyses. This includes evaluating parking spaces along the 21 mile trip as well as the marginal effects of a single trip shifted from automobiles to the Orange or Gold lines.

3.3.1.3 Energy Production

The lifetime use of CARFG by the sedan is evaluated from raw material extraction through delivery to the point of sale. Crude oil extraction, transport, refining, and additives are evaluated with CA-GREET1 (2009) assuming a 9.4% mix of oil sands. With refineries located near major population centers in California, a delivery distance of 30 miles is used to capture fuel tanker transport from the refineries to refueling stations [CA-GREET1 2009].

3.3.2 Los Angeles Metro's Orange Line

3.3.2.1 Vehicle

The Orange line uses 60 foot articulated buses manufactured by North American Bus Industries (NABI). The buses have Compressed Natural Gas (CNG) engines and can seat 57 passengers [Callaghan and Vincent 2007]. There are approximately 200 "Metro Liner" buses in the fleet, with each weighing 48,000 lbs unloaded and can operate up to 60,000 lbs at full passenger loads [LA Metro Personal Communications 2011 Note A]. For vehicle manufacturing energy use and emissions, the Ecoinvent (2010) *Bus Manufacturing* process is used. Ecoinvent (2010) provides estimates for a 18 Mg Volvo 8500 bus manufactured in the European electricity mix. To determine the manufacturing effects of the Orange line buses, energy and emissions are scaled with weight and the Western Electricity Coordinating Council (WECC) mix is applied. LA Metro uses conventional lead-acid batteries weighing 51 lbs with an expected lifetime of 13 months in Orange line buses [LA Metro Personal Communications 2011 Note D]. Bus manufacturing occurs in Hungary and Anniston, Alabama. NABI relies on Hungarian manufacturing for certain components and ships these components for final assembly to Anniston. After final assembly, buses were driven to Los Angeles, a distance of 2,100 miles. 54% of the bus, by weight are shipped by ocean going vessel from Hungary to Alabama, a distance of 5,000 miles [LA Metro Personal Communications 2011 Note A]. LA Metro expects buses to last 15 years and would not consider replacing them before 12 years [LA Metro Personal Communications 2011 Note C].

Existing literature is used to estimate the operational fuel use and emissions of Orange line buses. Several CNG buses have been deployed in the past decade around the U.S. including New York City and Washington DC. Touted as a cleaner fuel than diesel, a body of literature has emerged to quantify the tradeoffs of each and conditions in which CNG outperforms diesel. Synthesizing the CNG bus literature [NREL 2006, NREL 2005, ICCT 2009, Nylund 2004, Ayala et al. SAE 2003, Ayala DEER 2003, Ayala et al. 2002, Clark et al. 1999, Kado et al. 2005, Lanni et al. 2003], a range and characteristics of energy use and emissions are determined (see Table 4).

Table 2 – Synthesis of Diesel and CNG Energy Use and Emissions from Literature

	Energy VMT/DGE	CO_2 g/VMT	CH_4 g/VMT	CO g/VMT	NOx g/VMT	NMHC g/VMT	THC g/VMT	PM mg/VMT	SO_2 mg/VMT
Diesel									
Min (Best)	3.7	2,586		0.10	18	0.002	0.01	10	9.7
Median	3.2	2,990		0.16	26	0.01	0.08	47	13
Mean	3.3	2,892		0.84	28	0.02	0.08	97	17
Max (Worst)	2.8	3,369		7.2	52	0.07	0.21	631	28
CNG									
Min (Best)	3.5	1,952	6.0	0.1	8.2	0.1	6.3	0.02	8.5
Median	2.7	2,535	8.3	11	19	1.2	18	24	18
Mean	2.4	2,832	9.6	18	23	1.8	26	33	18.7
Max (Worst)	1.3	5,254	17	69	73	5.4	78	102	36

DGE = Diesel Gallon Equivalent.

With a broad range of vehicles and operating conditions, a median (representative) value is chosen and used for Orange line emissions. The implications of such a broad range of fuel consumption and emissions are discussed throughout this report.

Brake and tire wear are included from EPA Mobile6 (2003). Brake wear produces 13 mg PM_{10} and 3.7 mg $PM_{2.5}$ per VMT. Tire wear produces 12 mg PM_{10} and 5.4 mg $PM_{2.5}$ per VMT.

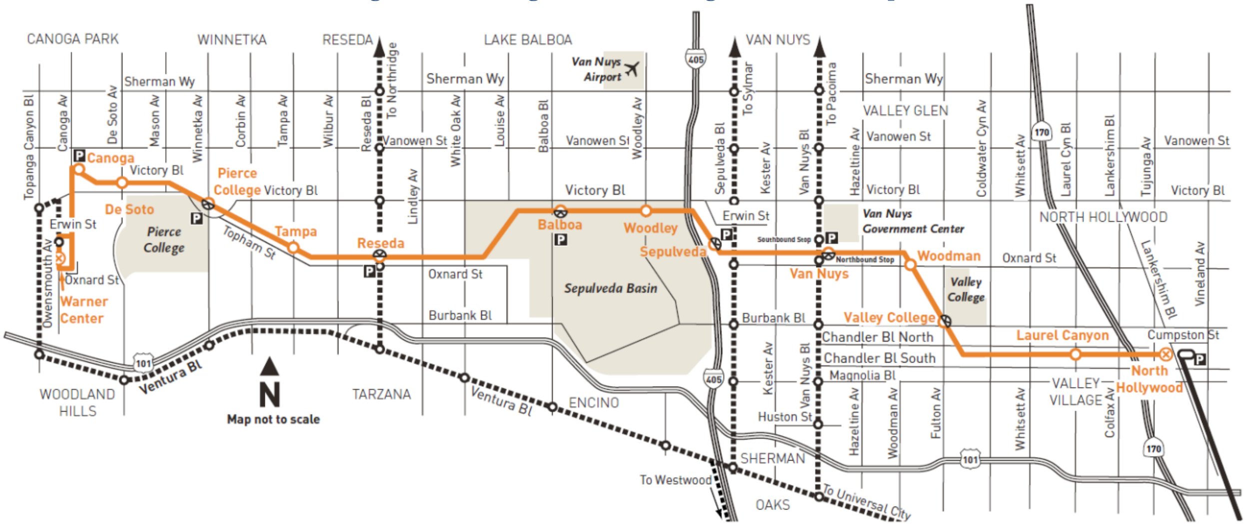
Maintenance incudes general servicing, tire replacement, battery replacement, and vehicle repair facility processes. Evaluating CNG buses in the Washington Metropolitan Area Transit Authority's fleet, NREL (2006) reports maintenance costs between ¢52 and ¢58 per VMT, including tire replacement. Tire-specific replacement costs are evaluated independently from NREL (2006) and are determined from the NTD (2009), based on Metro's total bus fleet, at ¢79 per VMT. These costs are evaluated with within EIOLCA (2011)'s *Automotive Repair and Maintenance* and *Tire Manufacturing* sectors to determine energy use and emissions from these maintenance activities. Following Chester and Horvath (2009), vehicle repair shop CO_2 and VOC emissions are determined from statewide inventories reported by the California Air Resources Board's 1997 Consumer and Commercial Products Survey (see Chester 2008 for additional discussion) allocated by vehicle VMT.

The provision of fringe benefits for bus operators and liability insurance requires energy and produces emissions in the insurance infrastructure. Combining fringe benefit and casualty and liability cost data reported for Metro buses in NTD (2009) with employee counts produces per bus annual costs. For a single bus in one year, operator fringe benefits amount to $39,000 and casualty and liability insurance costs $4,300. These costs are evaluated with the *Insurance Carriers* sector of EIOLCA (2011).

3.3.2.2 Infrastructure

The Orange line infrastructure is 14.2 miles of two-way road, landscaping, and a bike path in North Hollywood. The BRT system is primarily East-West connecting North Hollywood (and the Red line metro) with the Woodland Hills neighborhood. The line commenced service in 2005 and was constructed on existing Southern Pacific Railroad right-of-way.

Figure 1 – Los Angeles Metro Orange Line Route Map



Source: LA Metro Orange (2011).

There are 14 stations in the Orange line system. Stations are fairly minimal with a raised concrete platform from the roadway, approximately 15 feet in width and 200 feet in length, with awnings for weather protection (see Figure 2).

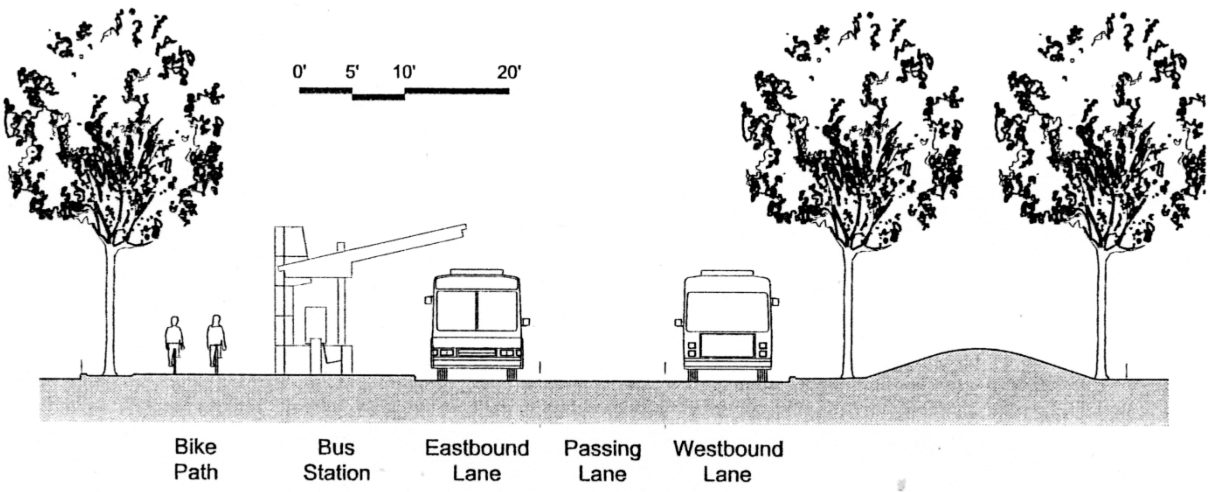
Figure 2 – Typical Orange Line Station and View of Roadway

Photo by Mikhail Chester on April 6, 2011, Van Nuys station.

Roadway construction and maintenance are evaluated by asphalt and concrete segments. For the entire 14.2 miles, a subbase with dimensions of 24 feet width and 12 inch depth is applied. The last mile (Canoga Station to the Warner Center Transit Hub) of the bus system uses city streets. Because roadway construction is dictated by automobile throughput, this segment is not allocated to the Orange line. The traveled-way and turnoffs at each station are concrete, each approximately 550 feet in length. As a result, of the 13.2 dedicated miles, 11.7 miles are asphalt and 1.5 miles are concrete. These wearing layers are evaluated with a 20 feet width and 6 inch depth. The subbase and wearing layers are evaluated with the PaLATE (2004). The subbase is specified with a 100 year lifetime, asphalt segments 20 years, and concrete 15 years. The subbase is constructed with recycled materials [LA Metro Personal Communications 2011 Note F] and the PaLATE (2004) material production life cycle component is assumed to be zero so only materials transport and subbase installation equipment are accounted for. Future work will evaluate the material recycling requirements for avoided virgin material use. Opening for service in 2005, the initial construction of the Orange line used traditional asphalt for the respective segments. Due to greater than expected wear, Metro resurfaced these segments in shortly after initial operation using Superpave asphalt. Superpave is an asphalt program for the improved selection of component materials, asphalt mixture design, analysis, and pavement performance prediction, to control stiffness at high temperatures and reduce fatigue cracking at intermediate temperatures ultimately improving wear and increasing the surface lifetime [FHA 1995]. The initial paving is included in the infrastructure construction life cycle component. The Orange line also includes dedicated bike paths and greenery on one or both sides of the traveled way. The Class 1 bike paths are often separated from the road by roughly 20 to 60 feet of landscaping. Bike path construction energy and environmental effects are not allocated to the Orange line. The paths and greenery provide visual, aesthetic, community enhancement, and natural barriers, all of which are not primarily aimed at the functionality of the Orange line. Also, the benefits of these qualities are realized primarily by bicyclists, pedestrians, and the surrounding homes. It is acknowledged that the bike paths would not exist without the Orange line. Furthermore, they likely provide additional energy and environmental benefits from motorized trips shifting to biking and walking. However, these additional benefits are not captured in this analysis.

Orange line stations are evaluated as bus turnoffs from the traveled-way, and platforms. Bus turnoffs are approximately 200 feet long and 10 feet wide with concrete wearing layers. Their depth is specified as 6 inches, consistent with the traveled-way, and a subbase of 12 inch depth is used. It is estimated that each station has two turnoffs, a total of 28 inches the system. For each station, elevated from the roadway are rider platforms, also 200 feet long and 10 feet wide, primarily concrete material. These platforms are modeled with a 12 inch depth.

Figure 3 – Orange Line Section at Topham Street



Source: LA Metro Orange (2000).

The Orange line operates roughly 22 hours per day requiring nighttime lighting of the roadway [LA Metro Orange 2011]. In 2010, 1.2 GWh of electricity was consumed for infrastructure operation including roadway, station, and parking lot lighting [LA Metro Personal Communications 2011 Note B]. This electricity was purchased from LADWP and is evaluated in the current LADWP mix for baseline infrastructure operations emissions [LADWP 2010]. Water for landscaping around the traveled-way is evaluated but ultimately excluded from the system boundary because greenscape effects are allocated to bicycling, walking, and the homes around the line. LA Metro planted xeriscape vegetation resulting in minimal water and landscaping requirements [City of Los Angeles 2011]. Assuming that landscaping requires 6 inches of water per year, based on data reported by McPherson (1990) for arid urban environments, water effects (determined from Stokes and Horvath 2009) would be negligible in the life cycle of the Orange line.

There are 4,709 park and ride surface lot spaces at Orange line stations [LA Metro Orange 2011]. Using the approach from Chester et al. ERL (2010a) and the PaLATE (2004) model, surface lot construction and maintenance energy use and emissions are determined. A 20 year lifetime is assumed for the parking infrastructure.

3.3.2.3 Energy Production

CNG use by the Orange line includes extraction, processing, transport, and compression. Orange line natural gas consumption is evaluated with CA-GREET1 (2009) which evaluates all major components involved with natural gas production and use. To evaluate Orange line specific consumption, recovery, processing, and long-distance transmission are first evaluated as the fuel feedstock. Short distance delivery to Metro refueling stations is captured as well as compression of natural gas using electricity. While Metro has traditionally used natural gas-fueled compressors to produce CNG, they are in the process of switching to electrical compressors. Compression energy of 8.2 kWh per mmBTU is applied for this final step [CA-GREET1 2009].

3.3.3 Los Angeles Metro's Gold Line

3.3.3.1 Vehicle

The Gold line operates AnsaldoBreda P2550 and Siemens P2000, the latter of which are being transitioned to other lines. The AnasaldoBreda trains are used for the analysis of vehicle life cycle components and are not expected to produce significantly different results than an analysis of the Siemens trains. The Italian-made AnsaldoBreda P2550 Gold line trains are six-axle articulated light rail vehicles with steel structures and dimensions of 8.7 feet width by 90 feet length [AnsaldoBreda 2011]. Trains weigh 54 Mg and can seat 76 passengers [AnsaldoBreda 2011]. Manufactured in Italy, shipment at 10,000 miles by ocean going vessel was evaluated [GREET1 2010]. Train manufacturing energy use and emissions were evaluated with SimaPro (2006)'s light rail train processes in an Italian electricity mix. A 30 year lifetime is assumed for trains.

LA Metro does not collect propulsion energy consumption information so electricity consumption of 10 kWh per VMT reported for aggregated LA Metro LRTs is used [NTD 2009]. In addition to the Gold line, LA Metro operates the Blue and Green LRT lines. The Blue line currently uses Nippon Sharyo trains and the Green line Siemens P2000. The aggregate electricity consumption factor is assumed to be a reasonable approximation for the Gold line because of the similarity in train size and models. Furthermore, the electricity consumption factor is similar to those reported for other AnsaldoBreda trains [Chester and Horvath 2009]. Additionally, when system-wide annual Gold line propulsion electricity is calculated, the energy consumed corresponds with the total electricity (vehicle propulsion plus infrastructure operation) reported by LA Metro (this is discussed in the *Infrastructure* section). The propulsion energy consumption and corresponding power plant emissions are assessed in the *Energy Production* life cycle component. This accounting is different from previous electric train LCAs [Chester and Horvath ERL (2010b), Chester and Horvath (2009), Chester (2008)].

Vehicle maintenance requirements include servicing of trains, cleaning, and replacement of flooring. General servicing maintenance (replacement of glass, fabric, aluminum, copper, steel, paint, and plastics in standard wear and tear) is evaluated with SimaPro (2006) in a City of Pasadena Water and Power 2008 electricity mix [PWP 2009]. Daily cleaning of trains including electricity use and cleaning supplies is considered. The replacement of composite flooring for the 660 ft^2 of train passenger area is included at a lifetime of 20 years.

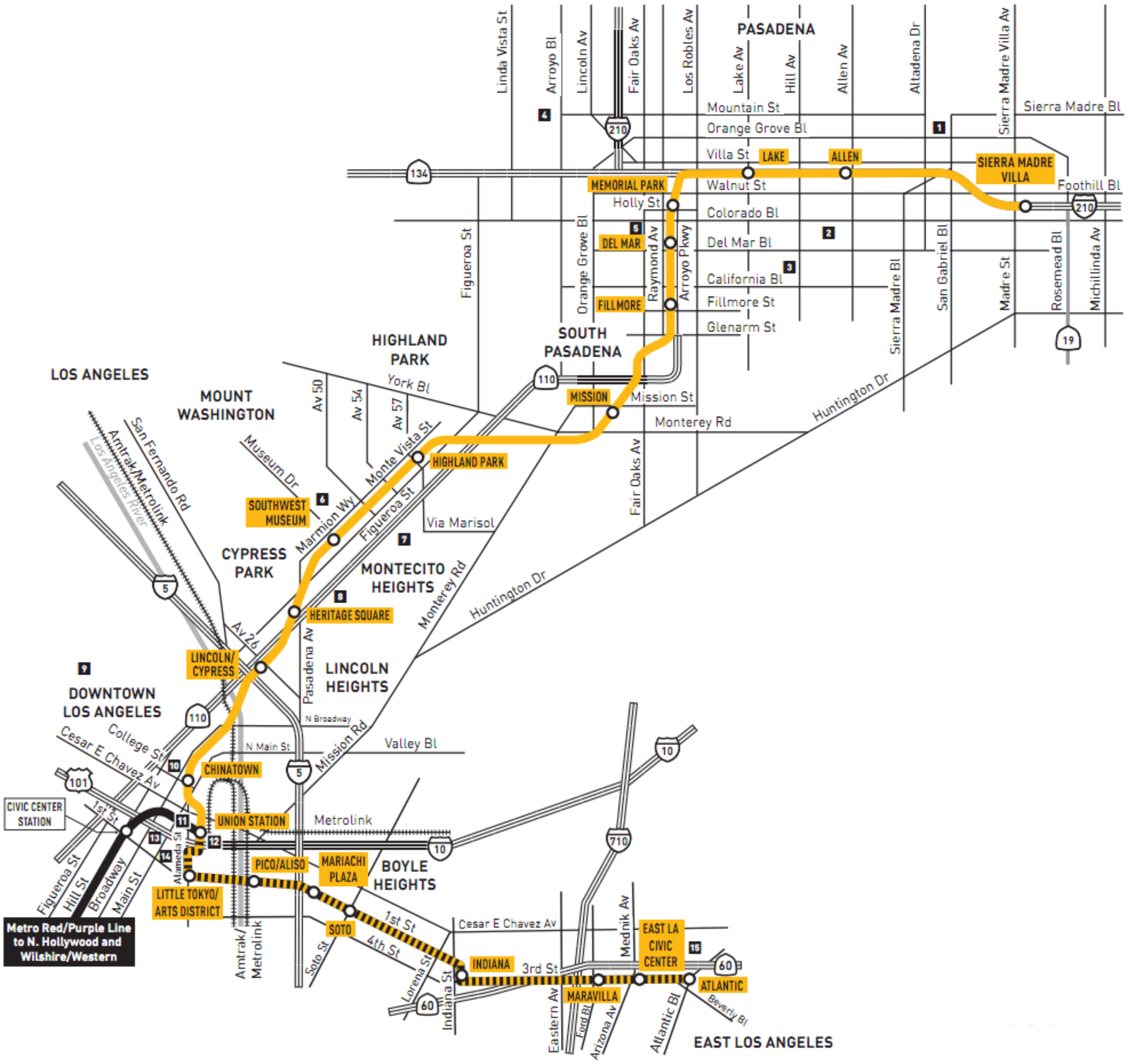
Operator fringe benefits and liability are evaluated for vehicle insurance. Combining fringe benefit and casualty and liability cost data reported for Metro light rail trains in NTD (2009) with employee counts produces per vehicle annual costs. For a single train in one year, operator fringe benefits amount to $4,239 and casualty and liability insurance costs $13,576. These costs are evaluated with the *Insurance Carriers* sector of EIOLCA (2011).

3.3.3.2 Infrastructure

The Gold line infrastructure consists of 19.7 miles of two-way track and 21 stations. The line starts in East Los Angeles, travels through Union Station in downtown Los Angeles, and ends in Pasadena (see Figure 4). The current infrastructure is phase one of several potential extensions. Ultimately, Pasadena would be connected with Ontario airport, a distance of roughly 30 miles. The current infrastructure is assessed and we do not estimate the effects of potential future extensions.

The infrastructure assessment is fundamentally an engineering analysis that estimates material use and processes involved with each life cycle component. Given the unique design attributes and large-scale nature requiring many design and construction actors of rail transit infrastructure construction, it is generally the case that detailed total construction inputs are consolidated. The approach for estimating energy inputs and emission outputs from construction materials and processes is reported in extensive detail by Chester and Horvath (2009) and Chester (2008). Additional refinement is reported by Chester and Horvath ERL (2010b). While the methodology, material data, and process data in this study are consistent with those developed in the aforementioned study, the infrastructure design, operational requirements, and maintenance requirements are unique. In this section, the critical infrastructure station and track parameters are identified.

Figure 4 – Los Angeles Metro Gold Line Route Map



Source: LA Metro Gold (2011).

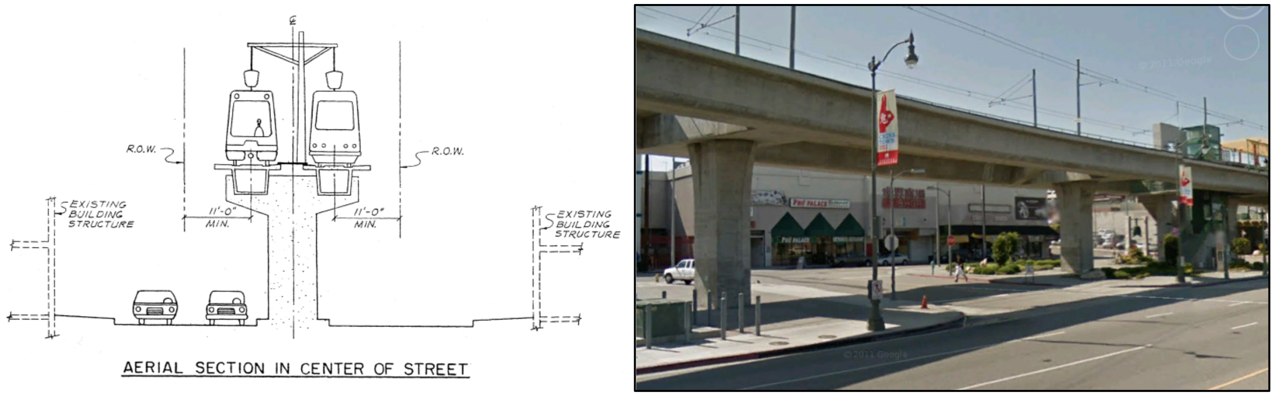
Of the 21 current stations, one is aerial (Chinatown), one is below grade (Memorial Park), and the remainder are at-grade. Satellite imagery was used to evaluate the dimensions of stations [Google Earth 2011]. In general, station platforms are roughly 300 feet in length and 10 to 27 feet wide. The aerial station platform is 300 feet in length and 25 feet wide. The platform slab is evaluated with a 3 feet depth. The columns and elevated track are not allocated to stations but to the aerial track segments. For the below grade station, platforms, floor caps, footings, structural columns, and walls are included. A roof cap is not considered since this station has a transit oriented development apartment structure above. The Memorial park station is evaluated with a 330 feet length, 50 feet width, and 30 feet height, with all primary structure elements evaluated as reinforced concrete. At-grade stations are treated as simple platforms with an average length of 330 feet and width of 15 feet [Google Earth 2011]. The platforms are evaluated a structural steel-reinforced concrete with a depth of 3 feet (see Figure 5). An additional 3 feet subbase is also implemented. The inclusion of ancillary infrastructure like buildings, other structures (e.g., walkways, coverings), and fixtures are not included due to lack of data and would only increase the inventory effects. The tracks themselves through stations are not attributed to the station but to the track infrastructure life cycle components. Excavation activities are attributed to the track. There are 2,334 dedicated parking spaces across the Gold line stations [LA Metro Gold 2011]. All spaces are treated as surface lots and evaluated with PaLATE (2004). This is likely a conservative estimate as parkade or garage spaces have greater effects than surface lots.

Figure 5 – Typical Gold Line Platform Station

Photos by Mikhail Chester on April 6, 2011.

Track segment materials and processes are evaluated by engineering segment type: aerial, elevated on fill, open cut, and at-grade. For each segment type, aggregate, concrete, and steel are considered in detail as primary materials, including their associated life cycle effects and placement processes. Soil work construction activities are also included for excavation and amendments. The use of wiring and electrical equipment for power delivery, train control, and signaling is also included. For all materials, raw material extraction through production and delivery are modeled. Using Google Earth (2011) it is estimated that there is 1 mile of elevated structure, 1 mile of elevated on fill, 2 miles of open cut, and the remainder of track segments at-grade.

Figure 6 – Gold Line Aerial Track Segment

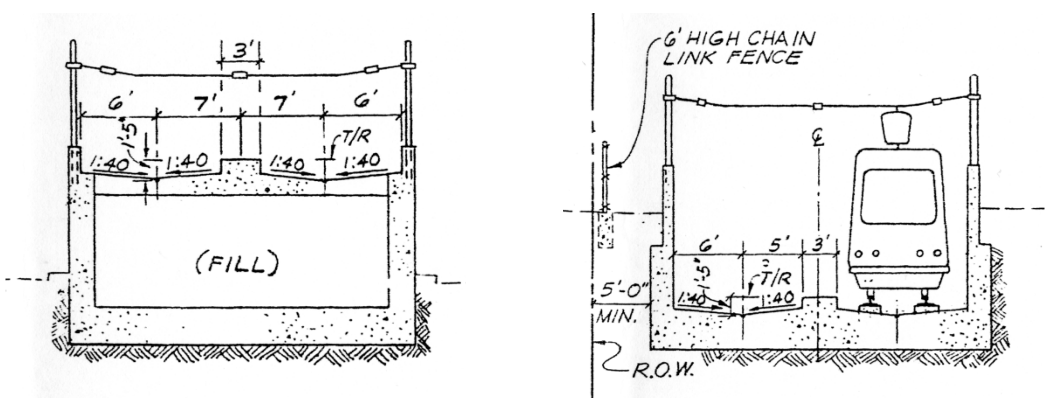


Source: LACTC (1988) and Google Earth (2011).

An engineering design takeoff is performed for each segment type. For aerial segments, both supports and platforms are evaluated. Supports are placed every 100 feet and are designed at a minimum height of 11 feet, and cross sectional area of 15 square feet [LACTC 1988, Google Earth 2011]. Support footings and piers are included. The two-way tracks are supported at the pier and have a cross sectional area of 50 square feet each. Figure 6 shows an aerial segment near the Chinatown station.

The assessment of elevated on fill and open cut segments include earthwork activities in addition to the aforementioned factors. Retained filled segments are designed with a cross sectional area of 390 square feet. For open cut segments, and excavation volume cross sectional area of 300 square feet is used. Structural concrete volumes are determined from engineering drawings [LACTC 1988]. Retaining walls and concrete bases are included (see the designs in Figure 7 and Figure 9).

Figure 7 – Retained Fill and Open Cut Gold Line Segments



Source: LACTC (1998).

At-grade segments are generally ballasted track but some segments are integrated with local roadways serving as the median (see Figure 8 and Figure 9). For ballasted segments, width of 26 feet and depth of 20 inches is used. For concrete segments serving as roadway medians (see Figure 8), a subbase of ballast is used followed by a concrete covering with a cross-sectional area of 26 square feet. Concrete ties are evaluated where applicable and assumed to be every 24 inches on center.

Figure 8 – At-Grade in Roadway Median Gold Line Track Segment

Photo by Mikhail Chester on April 6, 2011.

Power structure and substations are determined from existing light rail literature (see the discussion in Chester 2008). These components are evaluated based on their initial costs with the EIOLCA (2011) *Other Communication and Energy Wiring Manufacturing* and *Electric Power and Specialty Transformer Manufacturing* sectors.

Figure 9 – At-Grade in Freeway Median Gold Line Track Segment

Photo by Mikhail Chester on April 6, 2011.

LA Metro tracks electricity consumption at meters generally located at stations or maintenance yards. Gold line electricity is purchased from LADWP, PWP, and SCE and is not disaggregated to propulsion and non-propulsion uses. In 2010, 27 GWh of electricity were consumed including 5 GWh at Union Station which serves both the Gold and Red lines [LA Metro Personal Communications 2011 Note B]. LA Metro gathers monthly station, traction power, signals, crossings, and maintenance yard electricity data from meters. Assuming that one-half of Union Station's electricity consumption can be attributed to the Gold line results in 20 GWh of electricity purchased from LADWP, 3.2 GWh from PWP, and 1.2 GWh from SCE. Stations are responsible for 15 GWh of the 27 total GWh electricity consumed.

Station and track maintenance are evaluated including routine replacement of materials and associated reconstruction activities. For stations, it is assumed that roughly 5% of concrete, steel, and power/electrical components are replaced each year. Station cleaning is also included. Track maintenance is evaluated with SimaPro (2006)'s light rail train track maintenance processes. Track maintenance includes energy use and emissions for maintaining and replacing materials as well as the effects of herbicide and lubricant use.

Non-operator fringe benefits are evaluated for infrastructure employee insurance. Combining fringe benefit cost data reported for Metro light rail trains in NTD (2009) with employee counts produces per vehicle annual costs. For a single train in one year, non-operator fringe benefits amount to $46,918. This cost is much larger than the operator per-vehicle cost because it captures the many employees needed in the system for the handful of train operators. This cost is evaluated with the *Insurance Carriers* sector of EIOLCA (2011).

3.3.3.3 Electricity Production

The PWP electricity mix is used to evaluate Gold line emissions. In 2008, the PWP mix was 14% natural gas, 62% coal, 5% nuclear, 4% hydro, and 15% other renewables [PWP 2009]. Using GREET1 (2010) electricity upstream and at-plant generation emission factors, life cycle electricity emissions are determined. An 8.4% transmission and distribution loss is assumed. As noted earlier, vehicle operation electricity consumption and emissions at electricity generation facilities are assessed in the energy production life cycle component.

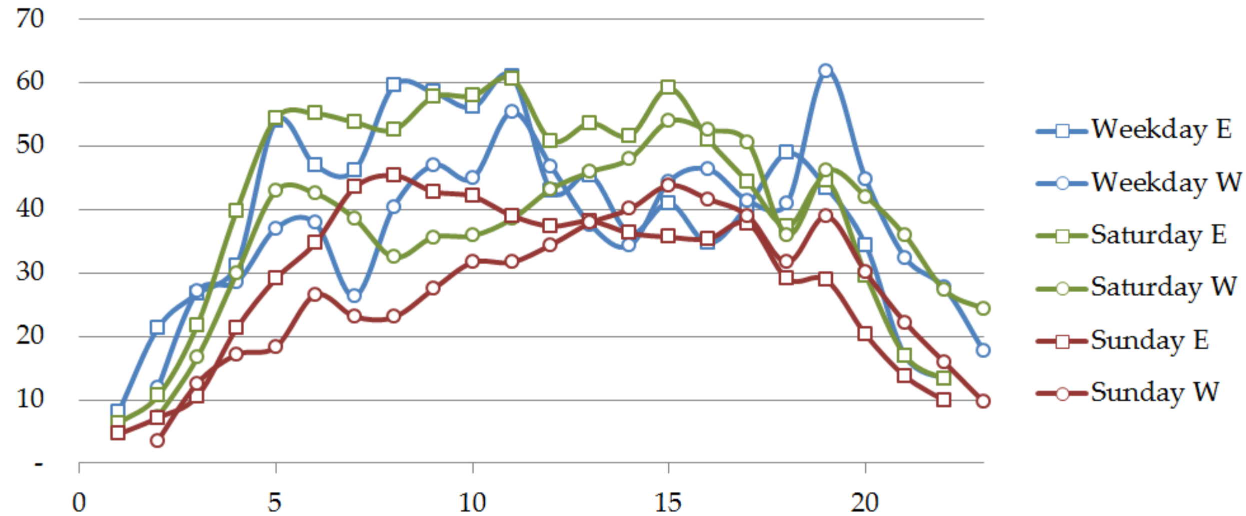
3.3.4 Functional Unit and Occupancy Variation

Results are normalized to per VMT and PMT for leveled comparison of modes. These life cycle inventories will serve as the basis of our phase two analysis, the development of a consequential assessment of the travel corridors the transit systems serve. The life cycle inventory results for phase one are presented in average and marginal attributional forms, and will serve as the basis of phase two's consequential assessment. Attributional inventories evaluate the full system (in this case the vehicle, infrastructure, and energy production life cycle components) and allocate energy and emissions to the sedan, Orange line, and Gold line per VMT and PMT. The goal of this approach is to identify and understand the comprehensive footprint of a transportation system to evaluate the critical life cycle processes that should be targeted for energy and emissions reductions. When decision analysis is included in life cycle scoping then consequential assessment must be used. Consequential assessment evaluates what has changed from the status quo and is better suited for informing policy. While understanding the comprehensive footprint with attributional assessment is important, questions related to effects of decisions and policy on the integrated transportation system must be answered with consequential assessment. The phase one attributional results presented here are designed to inform transportation decision makers of the life cycle components that should be targeted for energy and emissions improvements. These results are presented in both average and marginal forms. Average results show all life cycle components and assume that a decision to use a transportation mode results in long-term effects including the need to construct, operate, and maintain all aspects of the system. The marginal results assume that the fixed cost components are in-place and the decision to use a transportation mode generates additional effects that do not require the expansion of infrastructure or the manufacturing of a new vehicle. The average and marginal results are useful for particular questions and the goal of presenting both is to provide the appropriate information for a broad range of decision interests. In phase two future work, consequential results will be generated to determine the energy and emissions effects to Los Angeles from the decision to construct and operate the Orange and Gold lines. The goal of the phase one results is to present the current system, in 2010. Data collection was focused on this year but it is sometimes the case that the most recent reporting was for an existing year (e.g., the latest LADWP electricity mix reporting was for 2009). In phase two, we plan to evaluate future forecasts of car travel, the Orange line, and the Gold line.

Several functional units can be used depending on the question that is being informed and we start with *per VMT*. Using the methodology described, life cycle component energy consumption and emissions are first evaluated with inconsistent temporal resolution. For example, bus manufacturing energy consumption is determined for a vehicle with a 15 year lifetime, bus operation CNG consumption is determined per VMT, and Orange line infrastructure electricity consumption is determined for 2010. The Sedan lifetime VMT is used to normalize vehicle life cycle components. Los Angeles roadway infrastructure components are normalized to a per VMT functional unit based on urban roadway classification VMTs reported by FHA (2008). Using LA Metro's *Scheduled Service Operating Cost Factors Reports* [LA Metro 4-24 2010], all life cycle components are first normalized to a per VMT common functional unit for aggregation. LA Metro 4-24 (2010) reports weekday, Saturday, and Sunday VMT for the Orange and Gold lines as well as the number of vehicles in operation.

A primary goal of passenger transportation modes is to provide mobility for people and the *per PMT* functional unit is the most appropriate for evaluating this. Normalizing public transit life cycle inventories per VMT produces results that are often an order-of-magnitude larger than automobiles. The per VMT functional unit is useful for evaluating corridor or regional emission profiles but does not provide a ground for comparing the energy and environmental effectiveness of moving individual passengers. Results in Chapter 4 are ultimately normalized to a *per PMT* functional unit to provide a fundamental comparative unit for readers. For the baseline results, the sedan is evaluated with an occupancy of 1.58 passengers [SCAG 2003]. Like any public transit mode, occupancy rates can vary significantly depending on the position on the line and time of day. The Orange line, with 57 seats, is operating with 38 passengers on average. Figure 10 shows how this occupancy changes between time of day and weekdays or weekends.

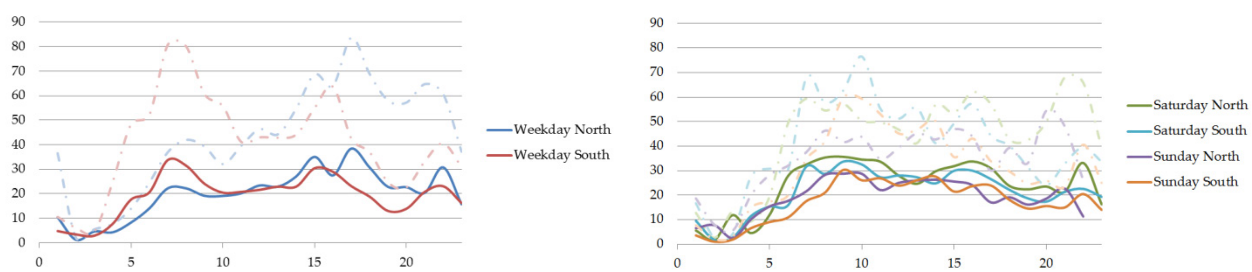
Figure 10 – Orange Line Bus Occupancy by Hour of Day



Source: LA Metro Orange Ridership (2011).

Similarly, Figure 11 shows the variations in Gold line occupancy. The median ridership for Gold line trains is 43 passengers [LA Metro Gold Ridership 2011].

Figure 11 – Gold Line Train Occupancy by Hour of Day



Source: LA Metro Gold Ridership (2011). Solid lines are averages. Dotted lines are maximum observed.

While reporting averages is useful, it masks the variations in ridership that may inform more intelligent policies or decisions, and it implies that modes are universally better or worse than others. Average occupancies are used to report baseline inventory results and the relative contribution of life cycle components. Ultimately, however, life cycle results are reported across low to high occupancies to illustrate the ridership conditions under which modes are energy and environmentally competitive.

4 Forthcoming Results and Future Work

This methodology will be used to develop an attributional and consequential LCA of Los Angeles Metro systems with the goal of informing climate change goals and urban sustainability transitional strategies. The research team is preparing several reports and manuscripts that show and discuss the results and readers should contact the author or visit his research project website (www.sustainable-transportation.com) for further information.

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