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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 Executive Summary

Public transit systems are often accepted as energy and environmental improvements to automobile travel, however, few life cycle assessments exist to understand the effects of implementation of transit policy decisions. To better inform decision-makers, this project evaluates the decision to construct and operate public transportation systems and the expected energy and environmental benefits over continued automobile use. The public transit systems are selected based on screening criteria. Initial screening included advanced implementation (5 to 10 years so change in ridership could be observed), similar geographic regions to ensure consistency of analysis parameters, common transit agencies or authorities to ensure a consistent management culture, and modes reflecting large infrastructure investments to provide an opportunity for robust life cycle assessment of large impact components. An in-depth screening process including consideration of data availability, project age, energy consumption, infrastructure information, access and egress information, and socio-demographic characteristics was used as the second filter. The results of this selection process led to Los Angeles Metro's Orange and Gold lines.

In this study, the life cycle assessment framework is used to evaluate energy inputs and emissions of greenhouse gases, particulate matter (10 and 2.5 microns), sulfur dioxide, nitrogen oxides, volatile organic compounds, and carbon monoxide. For the Orange line, Gold line, and competing automobile trip, an analysis system boundary that includes vehicle, infrastructure, and energy production components is specified. Life cycle energy use and emissions inventories are developed for each mode considering direct (vehicle operation), ancillary (non-vehicle operation including vehicle maintenance, infrastructure construction, infrastructure operation, etc.), and supply chain processes and services. In addition to greenhouse gas emissions, the inventories are linked to their potential for respiratory impacts and smog formation, and the time it takes to payback in the lifetime of each transit system.

Results show that for energy use and greenhouse gas emissions, the inclusion of life cycle components increases the footprint between 42% and 91% from vehicle propulsion exclusively. Conventional air emissions show much more dramatic increases highlighting the effectiveness of "tailpipe" environmental policy. Within the life cycle, vehicle operation is often small compared to other components. Particulate matter emissions increase between 270% and 5400%. Sulfur dioxide emissions increase by several orders of magnitude for the on road modes due to electricity use throughout the life cycle. NOx emissions increase between 31% and 760% due to supply chain truck and rail transport. VOC emissions increase due to infrastructure material production and placement by 420% and 1500%. CO emissions increase by between 20% and 320%. The dominating contributions from life cycle components show that the decision to build an infrastructure and operate a transportation mode in Los Angeles has impacts far outside of the city and region. Life cycle results are initially compared at each system's average occupancy and a breakeven analysis is performed to compare the range at which modes are energy and environmentally competitive.

The results show that including a broad suite of energy and environmental indicators produces potential tradeoffs that are critical to decision makers. While the Orange and Gold line require less energy and produce fewer greenhouse gas emissions per passenger mile traveled than the automobile, this ordering is not necessarily the case for the conventional air emissions. It is possible that a policy that focuses on one pollutant may increase another, highlighting the need for a broad set of indicators and life cycle thinking when making transportation infrastructure decisions.

3   CHAPTER 1:

Project Background

The Los Angeles Metro Orange and Gold lines are recently implemented public transit systems that have the opportunity to reduce energy consumption and emissions impacts from passenger transportation in the megaregion. The assessment of the Orange and Gold lines provides information about the potential successes of implementing cleaner transportation options in one of the most heavily utilized automobile cities in the United States. Comparing these lines to automobile use should not be based strictly on vehicle operation effects. While passenger movement is the underlying goal of these systems, vehicle travel cannot happen without many other processes and services. Vehicles must be manufactured and maintained, an infrastructure constructed and operated, and energy produced and delivered.

Life cycle assessment is the preeminent framework for evaluating energy and environmental effects of complex systems. Previous LCAs have been developed for passenger transportation modes and have shown that the bulk of some effects are often not associated with vehicle operation [Chester and Horvath 2009, Chester and Horvath ERL 2010b]. The inclusion of vehicle, infrastructure, and energy production life cycle components captures a more comprehensive footprint for modes and identifies ancillary and supply chain processes that are often ignored. To evaluate the Orange line, Gold line, and competing automobile trip, the LCA framework is used to determine energy inputs and emission outputs of vehicle, infrastructure, and energy production components. Results are normalized per passenger mile traveled (PMT) to capture the energy and environmental effectiveness of providing passenger mobility.

This project is administered in two phases. In phase one, the life cycle inventories for the Orange line, Gold line, and competing automobile trip are developed to determine the comprehensive footprints of each mode. In phase two, the inventories are used in a consequential LCA framing to evaluate the environmental outcomes of the decision to build and operation the Orange and Gold lines. In phase two, the net energy and environmental impacts to Los Angeles are determined by evaluating the life cycle effects of adding transit, operating transit, and potential reduced automobile use.

4   CHAPTER 2:

Site Selection

To provide decision-makers with the information necessary to weigh public investments in transportation systems, we developed a set of criteria for site selection that would provide the most consistent and reliable data among all the systems. Data also had to be accessible that would inform the LCA analysis. The first task was to develop a list of transportation systems across the state and to then develop screening criteria and assure there was sufficient data available to conduct a robust LCA comparative analysis.

All transportation system modes were assumed to be compared to traditional automobile travel with explicit assumptions about type of car, ridership numbers and distance of travel appropriate for the region selected.

4.1   Screening Criteria

The following initial screening process was developed:

- Advanced implementation – 5 to 10 years so change in ridership could be observed.
- Two projects in the same geographic region to ensure consistency of variables such as climate and socio-demographics.
- Multiple modes operated by the same transit agency/authority to ensure consistent management culture and that would capture choice decisions between modes by the same agency.
- Modes reflecting large infrastructure investments such that the LCA analysis would compare and contrast important public investments.

4.1.1   Initial Screening Process

Using the initial screening criteria enumerated above, researchers eliminated the College Ave corridor in Berkeley and Oakland, the Redding "Sundial" Pedestrian Bridge, the Riverside RTA Commuter Link, the Altamont Commuter Express - Train Stockton to San Jose and the San Joaquin Regional Rail Commission (among other regional systems). These did not provide a sufficiently consistent management framework so they could be compared without risking comparing very different local transportation agencies, nor did they reflect the management of 2 different types of systems by one agency.

4.1.2   In-Depth Screening process

In-depth screening criteria consisted of creating two tiers of information focusing on a. data availability and b. information availability about detailed system characteristics.

Primary criteria focused on the existence of robust and relevant data. This included

- Sufficient information so the potential for a mode-shift analysis to be undertaken (a feasibility criterion), especially from auto to mass transit.

- Sufficient information to conduct a valid LCA, including

  o Vehicle Miles Traveled (VMT)

  o Operation/maintenance inputs

  o Ridership survey data

  o Congestion analysis around the project area/region

  o Pre and post-project mode shift information about changes.

    ▪ Systems needed to be in place at least 5 years to theoretically notice a difference in travel behavior, but no more than 10 years so that other changes would not influence the fundamental mode shift travel behavior (such as land use change).

    ▪ Magnitude of infrastructure investment (costs and engineering studies)

    ▪ Energy type and switch, including "clean" energy.

Secondary criteria were developed as well. These included:

- Project specific data availability about infrastructure inputs

- Statistics about travel to and from the infrastructure projects

- Growth and planning projections: population, land use development and density changes as well as targeted growth policies

- Regional population characteristics

- Community population characteristics around the system(s)

- Contrasting population characteristics

- Supportive policy environment for alternative transportation mode development.

4.1.3   Choice Selection

Applying the screening criteria to multiple transportation systems across MPOs in California, researchers determined to develop the life cycle analysis of two transportation modes in Southern California, built and managed by the Los Angeles Metropolitan Transit Authority, a county-wide transportation agency overseen by a Board of Directors representing member cities and the county. The two systems chosen for comparison are the Orange Line Bus Rapid Transit corridor, and the Gold Line light rail system.

Table 1 – Site Selection Initial Screening

	LA Metro Gold Line	LA Metro Orange Line	LA/Long Beach Blue Line	LA Metro Silver Line	LA Metro Red Line Extension	San Francisco Muni Metro "T Third Street" Line	Sacramento Blue Line Extension	San Diego Green Line Extension
Ability to analyze two projects in same geographic region	Y	Y	Y	Y	Y	Y	Y	Y
Ability to analyze two projects run by same transit agency/authority	Y	Y	Y	Y	Y	Y	Y	Y
Ability to study two different modal types run same transit agency/authority	Y	Y	Y	Y	Y	Y	Y	Y
Multiple modes (e.g. bus, rail, walking, biking, driving) are available along the route	Y	Y	Y	Y	Y	Y	Y	Y
Large Infrastructure Changes	Y	Y	Y	Y	Y	Y	Y	Y

Los Angeles Metro is one of the largest transit agencies in the nation, serving a county population of nearly 10 million people. It has been at the forefront of trying to meet transportation needs over a very large geographical region with limited resources. Every investment is based on highly vetted choices and alternatives, and backed with extensive studies and analysis. At the same time the agency has also experimented with different modes in different parts of the region. Choosing to study two LA Metro transportation systems provided researchers with the ability to conduct robust LCAs. Such an analysis should provide transportation policy makers across the state with information that will support their investment strategies, regarding energy consumption, air emissions, and ridership.

Table 2 – Site Selection In Depth Screening

	LA Metro Gold Line	LA Metro Orange Line	LA/Long Beach Blue Line	LA Metro Silver Line	LA Metro Red Line Extension	San Francisco Muni Metro "T Third Street" Line	Sacramento Blue Line Extension	San Diego Green Line Extension
PRIMARY CRITERIA								
Mode Shift								
Large Mode Shift Potential (cars to alternative)	Y	Y	Y	Y	Y	Y	Y	Y
Data Availability (EIRs/feasibility studies/survey data available to provide the following)								
VMT	Y-EIR, Scag	Y-EIR, Scag	Y-EIR, Scag		Y-EIR, Scag	Y-MTA	Y-RT	Y-MTS/Caltrans
Pre-project mode split	Not in EIR	Y-EIR	Y-EIR		Y-EIR			
Post-project mode split	Not in EIR	Not in EIR	Not in EIR		Not in EIR			
Congestion around project area and region	Intersections only in EIR	Y-EIR	Y-EIR		Y-EIR	Y	Y	Y
Ridership Survey Data	Y-EIR, Metro	Y-EIR, Metro	Y-EIR, Metro		Y-EIR, Metro	Y-MTA	Y-RT	Y-MTS/Caltrans
Operation/maintenance inputs	Y-Metro	Y-Metro	Y-Metro		Y-Metro	Y-MTA	Y-RT	Y-MTS/Caltrans
Infrastructure								
Advanced Implementation (5-10 years)						N	Y	Y
Large Infrastructure Changes	Y-EIR	Y-EIR	Y-EIR		Y-EIR	Y	Y	Y
Magnitude of Infrastructure Investment	Y-EIR	Y-EIR	Y-EIR		Y-EIR	Y	Y	Y
Energy type/switch/clean energy switch	Y-EIR	Y-EIR	Y-EIR		Y-EIR			
SECONDARY CRITERIA								
Data Availability								
Infrastructure Inputs								
Statistics on travel to and from the project	Y-EIR	Y-EIR	Y-EIR		Y-EIR	Y-EIR	Y-EIR	Y-EIR
Geography								
Area of anticipated population growth	Y-EIR	Y-EIR	Y-EIR		Y-EIR	N-already urban	Y	Y
Area of targeted growth/development/density	Y-EIR	Y-EIR	Y-EIR		Y-EIR	Y	Y	Y
Demographics								
Regional population size	Y-EIR	Y-EIR	Y-EIR		Y-EIR	Y	Y	Y
Sociodemographics of surrounding community	N	Y-EIR	Y-EIR		Y-EIR			
Relationship								
Key overlap in characteristics								
Same type of project, different geo-demography								
Policy Environment								
Complimentary transportation policies exist in the region								
Considered BMP by CARB/CEC or other								

5   CHAPTER 3:

Phase 1 – Energy and Environmental Assessment 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 competing sedan trip. 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 is the foundation for the phase two consequential assessment.

5.1   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 leading to results that cannot be contrasted. Recent transportation LCAs have established system boundaries that include vehicle, infrastructure, and energy components [Chester and Horvath 2012, Chester et al. AE 2010, Chester and Horvath 2009]. These studies have shown that for many air emissions, the majority of pollutants 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 cited literature 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 in later sections). Table 3 shows the system boundary of analysis with life cycle groupings and generalized life cycle components for each of the modes.

Table 3 – 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

5.2 Energy and Environmental Indicators

Energy inputs and air emission outputs including greenhouse gases and conventional air emissions are evaluated. Reporting energy use is challenging because of the many forms that may be valuable to the research questions 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 inputs 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 and are regulated by the 1970 Clean Air Act and Amendments. 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 and transportation planners that have life cycle results in hand can develop strategies for avoiding these tradeoffs.

5.3   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.

5.3.1   Los Angeles Sedan

5.3.1.1   Vehicle

The base LA sedan is a 3,300lb automobile similar to a Toyota Camry. The conventional gasoline vehicle is specified with a fuel economy of 35 miles per gallon, consistent with 2020 Corporate Average Fuel Economy standards. There are several challenges when identifying a representative fuel economy for a competing automobile trip. 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 a 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.

A 35 mile per gallon sedan is used as a reasonable forecast for near term travel. Given the likely decades or century lifetimes of the transit systems, this fuel economy is reasonable for Los Angeles auto travel in the coming decades. Given the extended lifetimes of the transit systems, a long term future automobile that achieves 55 miles per gallon is also considered [Chester and Horvath 2012]. To meet 55 mile per gallon standards, lower vehicle weights will likely be needed. A 2,000lb automobile is modeled for this future vehicle reducing manufacturing effects.

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 when it escapes from fuel tanks in the form of 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.

5.3.1.2   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. While average effects are reported for Phase 1, marginal effects are determined in Phase 2.

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.

5.3.1.3 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].

5.3.2 Los Angeles Metro's Orange Line

5.3.2.1 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 manufacturing location-specific electricity mixes are 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 4 – 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 for Orange line emissions. The implications of such a broad range of fuel consumption and emissions are discussed throughout this report. Furthermore, a Best Available Technology (BAT) Orange line bus is also modeled using the min (best) energy consumption and emission factors. The BAT bus is shown to capture a potential future vehicle that LA Metro uses that has a state-of-the-art configuration for reducing emissions.

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).

5.3.2.2 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.
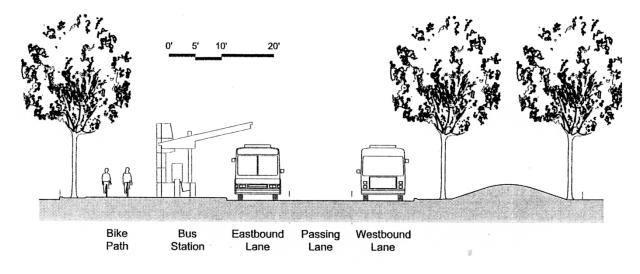
Figure 3 – Orange Line Section at Topham Street

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 2011]. 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.

5.3.2.3   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].

5.3.3   Los Angeles Metro's Gold Line

5.3.3.1   Vehicle

The Gold line operates AnsaldoBreda P2550 and Siemens P2000, the latter of which are being transitioned to other lines. The AnsaldoBreda 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 metric tonnes 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 and reported separate from the *Vehicle Operation* 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 ft² 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).

5.3.3.2 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 (2012). 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.
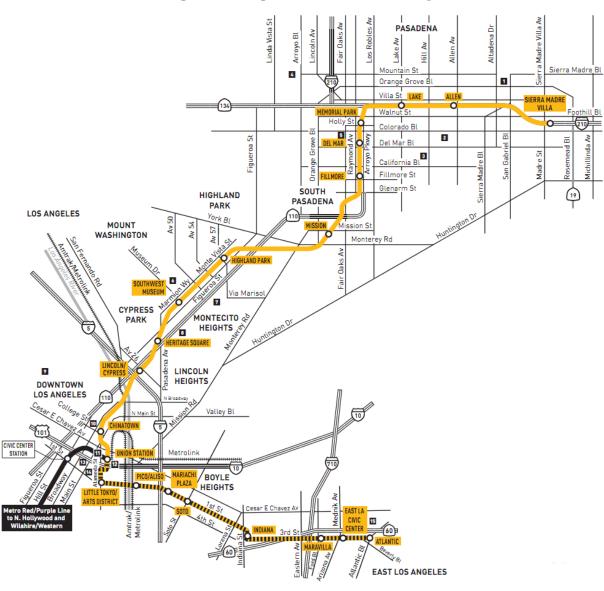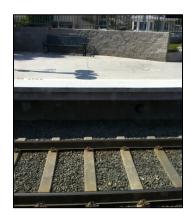
Figure 4 – Los Angeles Metro Gold Line Route Map

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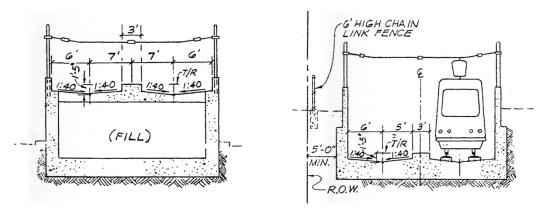
Source: LACTC (1988) and Google Earth (2011).

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).

5.3.3.3   Electricity Production

The LADWP electricity mix, which accounts for 82% of total electricity used by LA Metro for the Gold line, is used to evaluate propulsion and infrastructure operation emissions. Current and potential future LADWP electricity mixes [LADWP 2011] are used to assess vehicle propulsion and infrastructure operation emissions. The future mix is LADWP's preferred energy portfolio for meeting Renewable Portfolio Standards (RPS) in 2030 [LADWP 2011]. The RPS mix is used to model a Gold line train that may operate with clean electricity in the coming decades. The mixes are shown in Table 5.

Table 5 – LADWP Electricity Mixes for 2009 and Future RPS

	Natural Gas	Coal	Nuclear	Hydro	Renewables
2009	31%	39%	9%	7%	14%
2030 RPS	50%	-	9%	4%	37%

The total for each row may not sum to 100% due to rounding. Renewables include wind, photovoltaic, geothermal, biogas, and others.

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.

5.3.4   Functional Unit

Results are normalized per VMT and PMT for leveled comparison of modes. These life cycle inventories will serve as the basis of our Phase 2 analysis, the development of a consequential assessment of the travel corridors the transit systems serve. The life cycle inventory results for Phase 1 are presented in average and marginal attributional forms, and will serve as the basis of Phase 2'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 for the transit operator or planner to improve the systems, questions related to effects of decisions and policy on the integrated transportation system must be answered with consequential assessment. The Phase 1 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. Attributional (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. In Phase 2, consequential results are developed to determine the energy and emissions effects to Los Angeles from the decision to construct and operate the Orange and Gold lines (i.e., marginal effects).

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 functional unit 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].
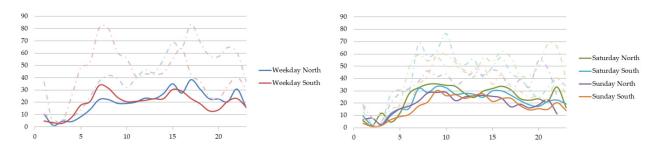
Figure 11 – Gold Line Train Occupancy by Hour of Day

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. It is acknowledged that occupancy variations will change the per PMT results.
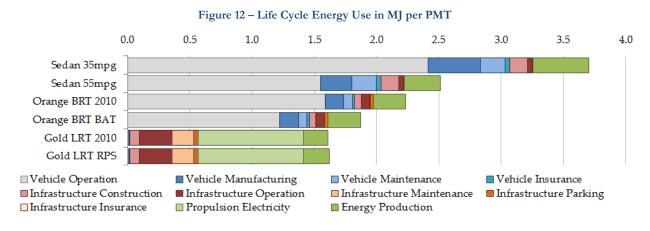
6 CHAPTER 4:

Phase 1 – Modal Results and Interpretation

With the life cycle assessment methodology and functional unit considerations described in Chapter 3, energy use and emissions results per PMT are determined. For each environmental indicator, results are reported and a short discussion is provided of the critical contributing factors in direct and ancillary life cycle processes. The results compare two automobiles, two Orange line buses, and two Gold line trains to capture the uncertainty in future environmental performance of each system. For each mode, the first vehicle is modeled to assess the performance in the short term (35 mile per gallon sedan, Orange line bus with average emission profiles, and a Gold line train with the current LADWP electricity mix). The second vehicle is modeled to assess the potential improvements in energy consumption and emissions in the long run. This includes a 55 mile per gallon sedan, Organ line bus with best available technology to reduce emissions, and a Gold line train in an LADWP electricity mix that has met RPS goals.

6.1 Energy Use and GHG Emissions

End-use energy is dominated by vehicle operation but life cycle components can increase inventories significantly. For the sedan and Orange line, Vehicle Manufacturing, Vehicle Maintenance, and Energy Production components are significant contributors to life cycle energy use and GHG emissions (see Figure 12 and Figure 13).

Figure 12 – Life Cycle Energy Use in MJ per PMT

Component production (including raw material extraction through component assembly) contributes roughly 55% of energy use and GHG emissions to vehicle manufacturing. Battery manufacturing and final assembly each contribute roughly 15% with the remainder of effects attributed to fluid production [GREET2 2007].

Vehicle maintenance effects are the result of general servicing (including parts production and transport, 55% of total) and tire replacement (due to associated energy production and carbon black manufacturing, 37% of total). Battery production and replacement accounts for roughly 9% of total effects. CARFG and CNG production requires upstream raw fuel extraction, processing, and transport activities that contribute an additional 16-19% energy use and 25% GHG emissions on top of combustion [GREET1 2010]. CARFG relies on a limited market with unique processing requirements and is evaluated with 9.4% oil sands sources resulting in larger effects than average US gasoline.
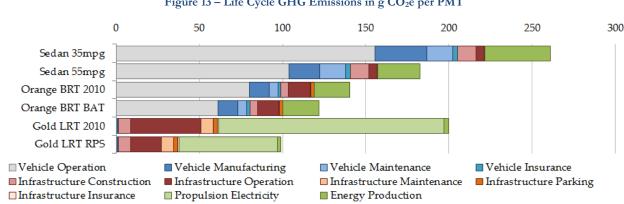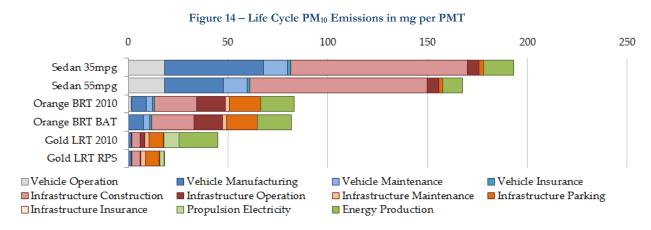
Figure 13 – Life Cycle GHG Emissions in g CO$_2$e per PMT
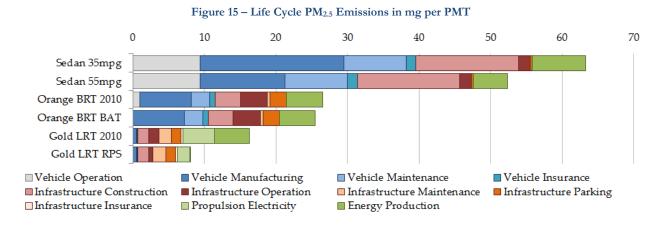
The Gold line shows significant contributions from infrastructure operation which is the result of electricity generation for stations, signaling, controls, lighting, and miscellaneous components. The electricity use is dominated by LADWP consumption which in 2009 relied on 39% of primary energy from coal and 31% from natural gas [LADWP 2011].

6.2   Conventional Air Emissions
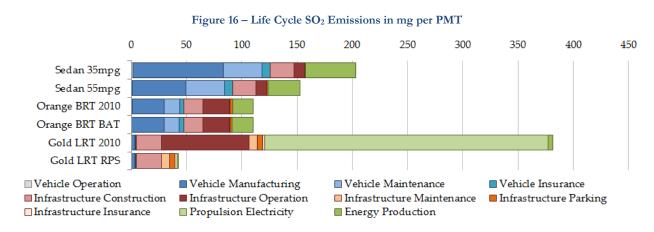
The conventional air emissions results reveal the importance of including a broad suite of environmental effects in sustainability assessment beyond GHG emissions, as well as the importance of including life cycle components. When comparing the conventional air emissions results, the Orange and Gold lines are often lower emitting per PMT. Per VMT the transit vehicles will generally emit more pollutants than automobiles, however, given their large passenger loads the per PMT results typically favor transit.

Figure 14 – Life Cycle PM$_{10}$ Emissions in mg per PMT
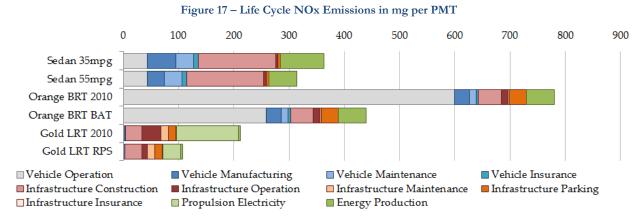
PM$_{10}$ emissions are generally the result of mechanical processes but can also be affected by combustion. During material extraction, mining tends to contribute a large share of PM$_{10}$ emissions. This is the case for vehicle manufacturing as well as infrastructure construction. For vehicle manufacturing, steel, iron, and aluminum production are the major PM$_{10}$ contributors. For infrastructure construction, aggregate mining for asphalt is a major contributor. PM emissions for the Gold line are significantly diminished as LADWP transitions from the current mix to the RPS. This is due to the significant reductions in coal and natural gas use.

Figure 15 – Life Cycle PM$_{2.5}$ Emissions in mg per PMT
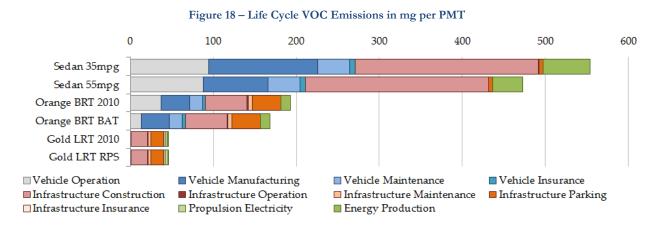
PM$_{2.5}$ emissions are often the result of combustion processes. For vehicle manufacturing, steel and aluminum production dominate, the result of furnace operations. Diesel truck fuel combustion in the supply chain of life cycle components is also a common contributor. For vehicle operation, brake and tire wear contribute roughly equivalent per VMT emissions to fuel combustion for the sedan. The Orange line CNG bus produces much lower PM$_{2.5}$ emissions per VMT than typical diesel urban buses.

Figure 16 – Life Cycle SO₂ Emissions in mg per PMT

Electricity generation dominates SO₂ emissions throughout the life cycle components. Gold line 2010 vehicle operation relies on the LADWP electricity mix that includes 39% coal resulting in significantly higher SO₂ emissions than the sedan and Orange lines. The transition to an RPS mix eliminates this SO₂ effect for the Gold line. Comparatively, the sedan and Orange lines produce little SO₂ emissions at the tailpipe because of removal of sulfur from gasoline (since it is a poison to the catalytic converter) and the low sulfur content in CNG fuel.

Figure 17 – Life Cycle NOx Emissions in mg per PMT

Outside of Orange line vehicle operation NOx emissions, life cycle effects are generally the results of diesel equipment use including truck and rail transportation and electricity generation throughout the supply chain. The Orange line vehicle operation NOx emissions are 28 grams per VMT which is equivalent to a diesel engine and matches results from existing studies [Chester and Horvath 2009]. As shown in Table 4, existing literature reports a range of 8.2 to 73 grams per VMT [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]. Future engine studies for the Orange line could identify where in this range the buses are located. Because vehicle operation dominates life cycle results for the Orange line, this research would be invaluable. The Orange BAT bus reports an 8.2 grams of NOx per VMT significantly reducing the mode's footprint.

Figure 18 – Life Cycle VOC Emissions in mg per PMT

Vehicle operation, vehicle manufacturing, and infrastructure construction dominate VOC emissions. GREET2 (2007) determines that for a CARFG sedan, vehicle manufacturing VOC emissions are larger than vehicle operation. This is the result of engine oil, power steering fluid, brake fluid, transmission fluid, powertrain coolant, and windshield fluid. For the Orange line, bus manufacturing VOC emissions occur primarily in direct manufacturing processes but also in ancillary truck transport activities. VOC emissions from asphalt and concrete use across the three modes are generally associated with volatilization of organic diluents in asphalt placement, and the release of organics in cement production [Chester and Horvath 2009].

Figure 19 – Life Cycle CO Emissions in mg per PMT

For the sedan and Orange lines, the majority of life cycle CO emissions are associated with vehicle operation, but for the Gold line infrastructure construction has significant impacts. CO emissions in Gold line infrastructure construction are the result of heavy concrete use and its associated truck transportation requirements.

6.3   Occupancy Sensitivity

Passenger transportation modes should be evaluated at their occupancy ranges to understand where environmental breakeven points occur and the conditions under which certain decisions promote utilization that achieves long run environmental gains. The per PMT life cycle results in Figure 12 through Figure 19

evaluate the modes at their averages to emphasize the significance of life cycle components. However, the relative results of a sedan with a single passenger to an Orange line bus with 20 passengers to a Gold line train with 90 passengers produces very different outcomes than the average. Since the Orange and Gold lines are likely to shift trips away from the automobile, the full occupancy range of the sedan can be used to question at what occupancy loads for the transit modes are modes environmentally better or worse.

The occupancy sensitivity breakeven analysis focuses on near term vehicle technologies (i.e., the 35 mile per gallon sedan, current Orange line buses, and Gold line trains in the current LADWP electricity mix) to identify the short term adoption goals that should be targeted by transit agencies. It is acknowledged that similar breakeven analyses could be developed for future vehicles.

Figure 20 shows breakeven energy consumption and GHG emissions. For the Orange and Gold lines, the x-axes are the percentage of seats filled. This percentage exceeds 100% to capture standing only passengers. The blue shows the sedan's per PMT energy consumption or GHG emissions range from one to five passengers. For example, for energy consumption, a sedan with one passenger consumes 5.9 MJ per PMT in the life cycle and with five passengers 1.2 MJ per PMT. In the figure the breakeven Orange and Gold occupancies are reported.

Figure 20 – Breakeven Energy Consumption and GHG Emissions

X-axes are the percentage of Orange or Gold line seats occupied.

The breakeven energy consumption and GHG emissions in Figure 20 show that between roughly 13 and 72 passengers the Orange line is in the competitive range of a one to five passenger sedan. At over 72 passengers, the Orange line will consume less energy and produce fewer GHG emissions per PMT than the sedan in the long run. While average occupancy for the Orange and Gold lines are 38 and 43 passengers, Figure 10 and Figure 11 show the occupancy distribution and identify when these modes are competitive.

Figure 21 – Breakeven PM Emissions

Life Cycle PM$_{10}$ Emissions mg per PMT

Life Cycle PM$_{2.5}$ Emissions mg per PMT

The Orange and Gold lines are PM10 equivalent to a 5 passenger Sedan with 51 and 32 passengers. The Orange and Gold lines are PM10 equivalent to a single passenger Sedan with 10 and 6 passengers.

The Orange and Gold lines are PM2.5 equivalent to a 5 passenger Sedan with 50 and 35 passengers. The Orange and Gold lines are PM2.5 equivalent to a single passenger Sedan with 10 and 7 passengers.
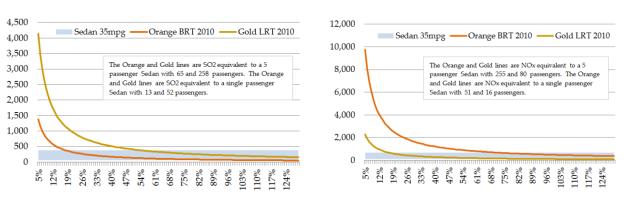
X-axes are the percentage of Orange or Gold line seats occupied.

Breakeven characteristics are shown for each of the conventional air emissions in Figure 21 through Figure 23.

Figure 22 – Breakeven SO$_2$ and NOx Emissions

Life Cycle SO$_2$ Emissions mg per PMT

Life Cycle NOx Emissions mg per PMT

The Orange and Gold lines are SO2 equivalent to a 5 passenger Sedan with 65 and 258 passengers. The Orange and Gold lines are SO2 equivalent to a single passenger Sedan with 13 and 52 passengers.

The Orange and Gold lines are NOx equivalent to a 5 passenger Sedan with 255 and 80 passengers. The Orange and Gold lines are NOx equivalent to a single passenger Sedan with 51 and 16 passengers.

X-axes are the percentage of Orange or Gold line seats occupied.

When comparing the energy use and emissions per PMT it is imperative that attributional and consequential characteristics are included. While the breakeven figures may show that at a certain time of day a bus emits more per PMT than a car, the decision maker must recognize that a vested transit system is in place that will run regardless of the passenger's decision to use one mode over another. In this case, the appropriate analysis would not compare the difference in per PMT emissions between the modes but the avoided VMT emissions that did not need to occur by a passenger choosing the public transit mode. This consequential analysis is shown in Phase 2.

Figure 23 – Breakeven VOC and CO Emissions

Life Cycle VOC Emissions mg per PMT

The Orange and Gold lines are VOC equivalent to a 5 passenger Sedan with 41 and 11 passengers. The Orange and Gold lines are VOC equivalent to a single passenger Sedan with 8 and 2 passengers.

Life Cycle CO Emissions mg per PMT

The Orange and Gold lines are CO equivalent to a 5 passenger Sedan with 27 and 7 passengers. The Orange and Gold lines are CO equivalent to a single passenger Sedan with 5 and 1 passengers.

X-axes are the percentage of Orange or Gold line seats occupied.

6.4 Ridership Targets and Environmental Payback

The occupancy sensitivity is valuable for understanding the long run ridership levels that are needed to breakeven with automobiles, however, it is also important to evaluate the speed at which environmental paybacks occur as a result of mode switching from automobiles to the new public transit modes. Figure 24 shows the payback speed for both the Orange and Gold lines which is dependent on the number of passengers that have shifted from automobiles. The x-axis is a measure of the number of passengers on the Orange and Gold line that would have previously taken automobiles for their trip. The Orange and Gold lines in Figure 24 show 2010 operation to facilitate a discussion of adoption strategies for new transit systems. Again, it is acknowledged that the Orange BAT and Gold RPS modes will produce very different profiles.
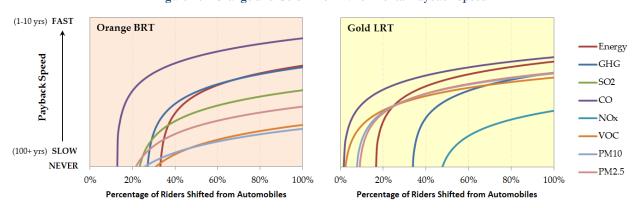
Figure 24 – Orange and Gold Line Environmental Payback Speed

The payback speed sensitivity shows two critical factors for transportation planners. First, minimum shifts from automobiles must be achieved to have environmental paybacks. Second, the payback speed for each environmental indicator is different.

The intersection of the environmental indicator curves with the x-axis show breakeven points, or the minimum percentage of transit trip takers that must have been shifted from automobiles in order to achieve an environmental payback. For the Orange line, the purple CO curve shows that at around 15% of riders having shifted from autos, the new transit mode will achieve a CO reduction (the question is how quickly). For every indicator, the greater the percentage of riders shifted from automobiles, the faster the payback. Energy consumption (maroon) requires the greatest shift in order to achieve some payback, of around 35%. The 15% to 35% range is a valuable metric for transit planners. The metric says that at 15% of riders shifted you will start to achieve environmental paybacks and at 35% the new mode will achieve environmental benefits across all pollutants. For the Orange line, the NOx curve is not present because even at 100% of riders having shifted from automobiles, NOx emissions will be increased by the transit modes because it has a larger per PMT footprint than autos (Figure 17). For the Gold line the range starts close to 0% for CO and VOCs and has a maximum of 48% for NOx.

The payback speed curves for the environmental indicators are different and show that each mode will take a different amount of time to payback for each indicator in the life cycle of the system. For example, the Gold line starts achieving a $PM_{2.5}$ payback at around 10% and NOx at around 48%. At 50% of riders shifted from automobiles, $PM_{2.5}$ will payback in several decades while NOx may take over a century. For all environmental indicators, the payback speed is monotonically increasing with the percentage of riders shifted from automobiles meaning. Transit planners can internalize these measures by identifying energy consumption and air emission payback goals and establishing policies that incentivize the corresponding shifts that are needed to meet the payback speeds.

7   CHAPTER 5: Phase 2 – Regional Environmental Effects

By structuring the LCA around the question of "What are the net effects of the decision to build and operate the orange or gold lines in Los Angeles?", a different analytical system boundary must be used to evaluate only life-cycle components that have changed. In Figure 13 the attributional life cycle footprint for a sedan includes infrastructure construction. However, the decision to build and operate the Orange and Gold lines did not likely reduce roadway construction in Los Angeles. To determine when environmental paybacks occur, it is necessary to evaluate the upfront effects from constructing the transit systems, the effects of operating the transit systems, and the avoided effects of passengers switching from automobiles.

The operation/propulsion and avoided automobile effects are based on historical trends and ridership surveys. The Orange and Gold lines each currently perform roughly 1.5 million VMT annually system wide [LA Metro 4-24 2010]. Given historical trends and increasing demand it is estimated that this will increase to 2.5 million VMT after two decades. For all vehicles, it is assumed that the environmental efficiency gains (55 mile per gallon sedan, Orange BAT, and Gold RPS) are achieved over two to three decades. Payback is most sensitive to the number of avoided automobile trips which is consistent with findings for future mode long-distance travel in California [Chester and Horvath 2012]. Travel surveys indicate that 25% of Orange line travelers were previously driving and 67% of Gold line travelers [Flynn et al. 2011, LA Metro Gold 2004]. Few travel surveys exist for mode shift behavior creating a large degree of uncertainty around these sensitive input parameters. While the following discussion uses the percentages to illustrate the payback concept, future work should explore the sensitivity of payback to this input.

7.1   GHG Payback

The GHG payback is shown in Figure 25. The x-axis is decades with construction occurring in decade one and transit operation commencing in decade two.
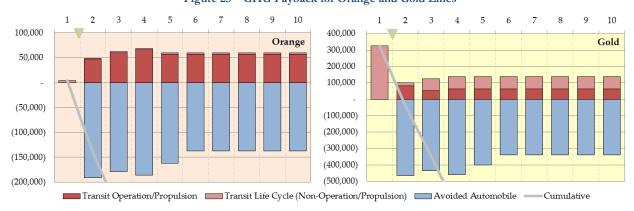

Figure 25 – GHG Payback for Orange and Gold Lines

Both the Orange and Gold lines produce paybacks on GHG emissions during the first operational decade due to the large avoided automobile emissions that dwarf initial construction emissions. Avoided automobile emissions decrease over time because it is assumed that vehicles transition towards 55 miles per gallon in decade six. The Orange line initial construction effects are minimal due to the lower GHG material footprint compared to the Gold line's use of concrete. While uncertainty exists around automobile mode shifts, preliminary indications are that both systems will produce GHG savings for Los Angeles in the near term.

7.2 Connecting Emissions with Impact Potentials

CAP emissions are joined with human and environmental impact characterization factors from the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI, v2.03) to assess the potential for human health and environmental impacts [Bare et al. 2002]. Impact characterization factors are used to show the maximum potential effects of pollutant releases. Human health respiratory impact and tropospheric ozone (smog)formation potentials are determined. The impact potentials are the maximum effects that can occur and actual effects may be lower.

The potential for respiratory impacts will be reduced by the Orange and Gold lines (Figure 26) in the near term. The Orange line will produce significant respiratory impact potential savings immediately after operation begins and the Gold line will produce savings after roughly 30 years of operation due to the large initial construction $PM_{2.5}$ emissions impacts that it must overcome.
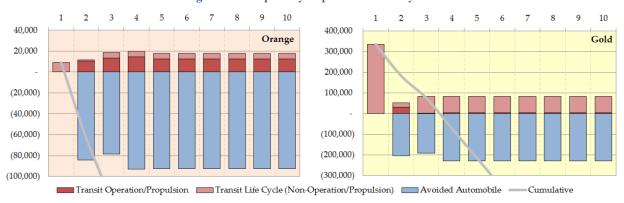
Figure 26 – Respiratory Impact Potential Payback

The large NOx footprint of Orange line buses will increase the potential for smog formation while the Gold line will decrease the potential in the long term. The larger per PMT NOx footprint for the Orange line compared to autos means that passengers switching to the new transit system will increase their NOx footprint and potential for smog formation. The Gold line must payback the initial construction NOx and VOC emissions, largely the result of cement production. The initial construction effects highlight the importance of utilizing low impact materials. Future transit systems should attempt to use recycled materials, supplementary cementitious materials for concrete, and advanced emission control technologies at cement

kilns to reduce initial construction impacts [Chester and Horvath 2012]. Again, it is stressed that impact *potentials* are calculated and actual outcomes are likely to be lower.

Figure 27 – Smog Formation Potential Impact

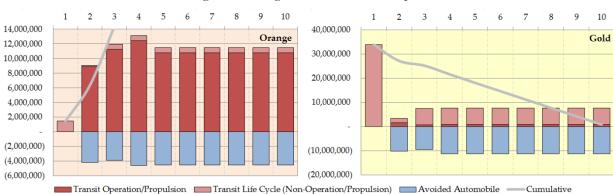
Transit Operation/Propulsion — Transit Life Cycle (Non-Operation/Propulsion) — Avoided Automobile — Cumulative

8   CHAPTER 6:

Policy Implications of LCA and LA Transportation Alternatives

The results described in Chapter 4 have a number of basic policy implications. Because LCA involves a comprehensive inventory of energy use and emissions over the entire production cycle and operational lifespan of a given transportation system, it considers impacts that are diffuse in time and space. This means that policymaking to consider life cycle impacts will not follow a one-size-fits-all approach, but instead will vary depending on which emission(s) and which transportation systems are being discussed.

In this analysis, we have considered energy use, GHGs, and conventional air emissions for cars, bus rapid transit, and light rail transit in the Los Angeles basin. Three basic observations relevant to policymaking can therefore be made about these travel modes and emissions types:

1. For any given greenhouse gas, all emissions everywhere are functionally the same. Because the atmosphere is a global commons and climatic changes take decades to manifest, a molecule of carbon dioxide emitted in Los Angeles today as a vehicle is being operated has essentially the same impact as one emitted in Alabama or Italy two years ago when the vehicle was being manufactured. Moreover, the eventual impacts to Los Angeles are the same for a given level of global CO2 pollution, no matter where the CO2 was emitted. (The same is largely true for other GHGs, although some are shorter-lived in the atmosphere than CO2 and therefore the timing of emissions could matter more.) This means that policymakers in Los Angeles (or California) concerned about global warming theoretically have just as much incentive to reduce supply-chain-related GHG emissions as they do local vehicle-operations-related emissions.

2. For conventional air emissions, spatial and temporal differences matter greatly. These pollutants are not globally equivalent, but instead have impacts that are concentrated either near the site of emission, or in downwind locations dictated by prevailing regional weather patterns. Moreover, they disperse relatively rapidly, meaning that it may be possible to avoid acute impacts on human health or ecological systems by distributing emissions through time. Emissions that result from vehicle operation will have impacts on air quality within the local air basin, whereas those that result from vehicle manufacture (for example) will not. For local planners and air quality regulators charged with meeting attainment standards within the Los Angeles basin, there may be relatively little incentive under the current regulatory regime to incorporate consideration of supply-chain-related emissions of these pollutants.

3. With respect to life cycle energy use, it is important to remember that climate and environmental impacts of concern do not arise from energy use per se. Instead, they are by-products of the various forms of energy in use throughout the economy, including gasoline, diesel fuel, natural gas, biofuels,

and the electricity generated from coal, nuclear, solar, wind and other sources. The degree to which energy use is undesirable is really a matter of what the fuel or generating mix in question consists of, and what its by-products are. Policy should therefore focus on that issue, at least with respect to environmental impacts.

8.1 Policy Implications of Life Cycle GHG Emissions

As shown in Figure 13, the travel modes have different life cycle GHG profiles. These results have a number of broad implications for transportation and land use policy.

GHG emissions associated with vehicle operation and propulsion are the majority of all six life cycles. The retrospective assessment shows that the largest potential source of GHG emissions reductions from the existing transportation system will be achieved by targeting vehicle operation and propulsion, either by reducing usage (i.e. less travel), improving fuel efficiency of vehicles, or reducing the carbon intensity of the energy inputs. That is indeed where policy is currently focused, as the emission-reducing effects of improved Corporate Average Fuel Economy standards for cars, and the electricity Renewable Portfolio Standard for the propulsion electricity of the light rail, are clearly evident in Figure 13. It is worth noting that none of the improvements analyzed in Figure 13 even approaches an 80% reduction of GHG emissions, the official goal of the State of California and the international scientific consensus.

The large additional increment of life cycle GHG emissions associated with the manufacture and maintenance of cars (approximately one-third as big as operational emissions for both 35mpg and 55mpg sedans) suggests that policy should also focus on ways to reduce the absolute number of cars in use (and hence avoiding their manufacture), not only the number of miles that they are driven. From a policy perspective, this implies smart land use planning to create communities where it is convenient and desirable for households to own fewer cars. Enabling zero-car or one-car households to thrive on a large scale will require a qualitative transformation in regional land use patterns, not small tweaks to prevailing patterns of widely dispersed single-family homes.

Though both transit systems outperform cars, BRT also significantly outperforms LRT under current conditions, where it is about 30% lower in life cycle GHG emissions. BRT systems generally also have significantly lower initial capital costs and much greater operational flexibility than LRT projects, which rely upon expensive fixed rails that cannot easily be retrofitted, re-routed or connected to existing local streets. For these reasons, it may be easier for local or regional transportation agencies to implement and manage BRT projects autonomously through self-help revenues rather than through diminishing, restrictive, and competitive state and federal funds. For regions and localities seeking to meet GHG emissions targets under AB 32 and SB 375, these are significant advantages.

Despite BRT's present-day advantages over light rail in GHG emissions per PMT, Figure 13 also shows that LRT may have greater potential to deeply reduce life cycle emissions as the state seeks to achieve its long-range goal of 80% GHG reductions by 2050. This is because propulsion electricity and infrastructure operations dominate the life cycle GHG emissions of LRT, and theoretically both could be provided by almost-GHG-free electricity, such as that generated from nuclear, solar or wind. Cars and BRT could also be converted to almost-GHG-free electricity for operations, but vehicle manufacturing components are a much larger slice of their overall life cycle GHGs than for LRT (where they are almost negligible). Manufacturing processes are likely to be more difficult to fully decarbonize than vehicle operations, since they often rely on intense applications of energy (e.g. steel smelting) that may not be efficiently or effectively supplied by electricity.

The policy levers for decarbonizing vehicle operations for BRT and LRT are quite different. Because BRT is more likely to be locally implemented and controlled, it may be easier for a motivated local government to decarbonize more rapidly through their BRT system design and fueling decisions, but there may be less direct leverage for state or federal regulation (apart from heavy-vehicle fuel efficiency standards). Decarbonization of LRT systems, on the other hand, will depend on decisions made by utilities, state energy regulators and legislators about the electricity generating mix that are beyond the control of local governments. California's Renewable Portfolio Standard, for example, will reduce the life cycle GHG emissions of electricity-dependent LRT systems, but will have minimal effects on BRT life cycle emissions.

The environmental payback speed analysis in Figure 24 also suggests certain policy priorities for state, regional, and local governments. For GHGs, the Gold Line will begin payback at mode shifts of about 35%, whereas the Orange Line will require mode shifts of at least 25%. However, in both cases, GHG payback accelerates rapidly until mode shift reaches about 60%, at which point the curves begin to flatten out. That suggests that ensuring that 60% or transit riders have switched from automobiles is an important GHG-related target for transportation and land use policy under SB 375 and other regulatory efforts, at least under current technologies and planning conditions. As Figure 25 and the discussion preceding it show, mode shifts to the Gold Line appear to have exceeded that threshold already, but those to the Orange Line have not. Despite this, the Orange Line BRT will pay back GHGs more quickly than the Gold Line because of lower initial GHG "costs" to build the system. By the end of the second decade of operation, each system will have achieved approximately the same GHG payback, though the Gold Line will do so on a steeper payback trajectory, and therefore will likely achieve greater GHG payback in subsequent decades.

8.2   Policy Implications of Life Cycle Conventional Air Emissions

Figure 14 through Figure 19 show the life cycle emissions for various criteria pollutants from the three transportation systems. These results have a number of broad implications for transportation and land use policy.

With respect to particulates (Figure 14 and Figure 15), vehicle operation effects are dwarfed by supply-chain effects, including mining and metals production. Since these emissions generally don't occur in the air basin where the vehicles are operated, there is a spatial mismatch for policymaking. Clean Air Act enforcement largely focuses on reducing emissions within local air basins, not the out-of-basin consequences of local decisions. Environmental impact assessment for the transportation systems could certainly take these out-of-basin emissions into account, but it is unclear whether it currently would be practical to require mitigation of these impacts. Greater standardization and acceptance of LCA techniques in environmental impact assessment might allow this. It is worth noting that within the vehicle operation emissions slice, the transit systems do significantly outperform cars, so local air quality policy can focus on shifting people into transit for air basins that are out of attainment for particulates.

As noted, SO_2 emissions (Figure 16) are predominantly a by-product of coal-fired electricity generation. The Gold Line LRT therefore shows a huge reduction in life cycle emissions associated with the implementation of the Renewable Portfolio Standard. From a policy point of view, this dovetails well with GHG emissions reduction objectives, since minimizing coal combustion is imperative to meeting global climate goals. As with particulates, these electricity-related emissions are generally not within the same air basin as the vehicle operations.

NOx emissions (Figure 17) are predominantly from diesel and natural gas combustion, and for this reason are the one area in which the BRT greatly underperforms the other modes, even with future best available technology. Furthermore, these emissions do occur in the same air basin as the transportation systems operate. In local air basins that are out-of-attainment for NOx, local air quality regulations could be a barrier to BRT implementation, and mitigation actions for NOx emissions might be required in order to gain regulatory permission to construct the systems.

Emissions of VOC (Figure 18) are largely an out-of-basin impact, and hence are subject to the same spatial mismatch as particulates and SO2. For local air basins that are out-of-attainment for VOC, however, LRT performs very well in terms of vehicle operations (as well as full life cycle) emissions.

NOx and VOC emissions react to produce ozone, a secondary pollutant, and Los Angeles is currently the worst-ranked city in the US [American Lung Association 2011]. The Orange and Gold lines have the potential to reduce ambient ozone concentrations in Los Angeles. However, efforts must first be made to reduce NOx emissions from the Orange line. NOx emissions from Orange line buses are based on a

literature review of CNG buses in Washington DC and New York City and summarized in Table 4. It is possible that Orange line buses operate not at the average NOx emissions reported in the literature but anywhere in the range. At the minimum, the NOx vehicle propulsion emissions would be roughly one-third those reported in Figure 17 making the transit mode roughly competitive with the sedan. Gold line NOx emissions are significantly lower than the sedan and occur at power generation facilities which may be located further away from dense population centers. However, both the Orange and Gold lines produce fewer VOC emissions than the sedan (see Figure 18). Provided that LA Metro reduces Orange line bus emissions (either by using cleaner vehicles which may already be occurring, or by installing advanced emission control devices), both transit modes have the potential to improve ozone levels in Los Angeles. In our phase two work the total changes in NOx and VOC emissions will be determined from the implementation of the Orange and Gold lines.

CO emissions (Figure 19) are almost exclusively an in-basin impact. LRT performs very well on a life cycle basis because there is minimal localized combustion of gasoline, diesel, or natural gas.

As Figure 24 shows, paybacks for most of these criteria pollutants (with the exception of NOx) begin at mode shifts below 20% for the Gold Line LRT, and in the range between 15 and 35% for the Orange Line BRT. As noted above, this suggests that transit planners can be assured that, as long as they achieve 35% mode shift, payback will eventually occur for all pollutants other than NOx. However, the potential speed of payback varies significantly for the Orange Line BRT, whereas the payback curves for the Gold Line are tightly clustered in a range of 3-4 decades for payback. Figure 26 underscores this, as payback for maximum potential respiratory impact is about three decades for the Gold Line LRT, but almost immediate for the Orange Line BRT.

The payback on maximum potential smog formation is very slow (about 95 years) for the Gold Line, and never occurs for the Orange Line, primarily because of the large life-cycle NOx emissions for the latter. These results must be interpreted with care, however. These are theoretical maxima for potential smog formation (and respiratory illness), not projections of how much would actually be produced by these transit systems. Moreover, LCA data are typically not geographically specified leaving the practitioner with an inability to distinguish between in-basin and out-of-basin effects, a crucial distinction when considering smog formation, which requires interaction between NOx and VOCs as well as other geographic and atmospheric conditions. In addition, mitigation actions may also be able to reduce in-basin emissions of NOx from the transit lines

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