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Infrastructure and automobile shifts: positioning transit to reduce life-cycle environmental impacts for urban sustainability goals

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Abstract
Public transportation systems are often part of strategies to reduce urban environmental impacts from passenger transportation, yet comprehensive energy and environmental life-cycle measures, including upfront infrastructure effects and indirect and supply chain processes, are rarely considered. Using the new bus rapid transit and light rail lines in Los Angeles, near-term and long-term life-cycle impact assessments are developed, including consideration of reduced automobile travel. Energy consumption and emissions of greenhouse gases and criteria pollutants are assessed, as well the potential for smog and respiratory impacts. Results show that life-cycle infrastructure, vehicle, and energy production components significantly increase the footprint of each mode (by 48–100% for energy and greenhouse gases, and up to 6200% for environmental impacts), and emerging technologies and renewable electricity standards will significantly reduce impacts. Life-cycle results are identified as either local (in Los Angeles) or remote, and show how the decision to build and operate a transit system in a city produces environmental impacts far outside of geopolitical boundaries. Ensuring shifts of between 20–30% of transit riders from automobiles will result in passenger transportation greenhouse gas reductions for the city, and the larger the shift, the quicker the payback, which should be considered for time-specific environmental goals.

Keywords: transportation, greenhouse gas emissions, life cycle assessment, urban

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1. Background

It is widely accepted that the combustion from passenger vehicle tailpipes is a leading cause of environmental pollution and emerging life-cycle approaches present an opportunity to better understand how transit investments reduce transportation impacts. In California, automobile travel is responsible for 38% of statewide greenhouse gas (GHG) emissions and other pollutants have been linked to significant health impacts [1, 2]. California's Assembly Bill 32 calls for the reduction of statewide GHG emissions to 1990 levels by 2020. To achieve this, a suite of strategies will be deployed, including Senate Bill 375 which requires regional transportation plans to achieve GHG emissions targets from the transportation system and may induce cities to deploy new public transit systems.

Passenger vehicles, however, do not exist in isolation as they require a large and complex system to support a vehicle's operation. To understand the environmental impacts from transportation systems, and more importantly how to cost-effectively minimize these impacts, it is necessary to include vehicle, infrastructure, and energy production life-cycle components, in addition to operation [3]. A life-cycle approach is particularly important for new mass transit systems that produce large upfront impacts during the deployment of new infrastructure systems for long-run benefits in the reduction of automobile travel [4]. However, little is known about the life-cycle environmental benefits and costs of deploying public transit systems to meet urban energy and environmental goals. Using the city of Los Angeles as a case study, a life-cycle assessment (LCA) of the Orange bus rapid transit (BRT) and Gold light rail transit (LRT) lines is developed. These transit lines, both deployed in the past decade, provide an opportunity to better understand how new transit systems will help cities reduce transportation impacts.

2. Methodology

An environmental LCA is developed for the Orange BRT, Gold LRT, and competing automobile trips. The LCA includes vehicle (e.g., manufacturing and maintenance), infrastructure (e.g., construction and operation), and energy production components, in addition to vehicle propulsion effects [3]. To inform a broad array of transportation policy and decision makers, two different LCA framings are used: attributional and consequential. The attributional framing evaluates the long-run average footprint of each system allocating impacts to a passenger-mile-traveled (PMT). It includes, for example, the construction impacts of the existing road system for an automobile trip. However, given the importance of understanding how public transit investments contribute to urban sustainability goals, a consequential analysis of the decision to build each system is also produced, culminating in a cumulative impact savings at some future time. The consequential analysis answers how the BRT and LRT systems may contribute to Los Angeles (LA) meeting its Senate Bill 375 GHG and air quality goals. The results from the attributional and consequential approaches should be considered independently.

2.1. Life-cycle characteristics of Los Angeles transportation systems

The LCA methods used follow those reported in existing research by the authors, however, significant efforts were made to obtain system-specific data from LA Metro [5] and model life-cycle impacts with regionalized energy mixes and processes. Extensive details are provided in Chester *et al* [6] and the following discussion focuses on the data collection and methods used to assess the dominating life-cycle processes. For each mode, near-term (at maturity, in the 2020–2030 time period) and long-term (2030–2050) vehicles are modeled.

2.1.1. Orange line BRT. The Orange BRT is an 18 mile dedicated right-of-way running east–west through the San Fernando Valley. The line opened in 2005 and now services 25 500 riders per day, exceeding initial forecasts [7]. The line is viewed as a tremendous success; service has been increased to meet the latent demand, its construction has induced 140 000 new annual bike trips on the buffering green belt, and has roused development [8–10]. The initial line consists of a two-lane asphalt roadway connecting 18 stations, sometimes buffered by landscaping. In 2012 a 4 mile extension from Canoga Park to Chatsworth was opened. Orange BRT buses are 60 foot compressed natural gas (CNG) articulated North American Bus Industry vehicles with the structure, chassis, and suspension (54% of weight) manufactured in Hungary and final assembly occurring in Alabama [5]. Vehicle manufacturing is assessed with Ecoinvent's bus manufacturing processes using current and projected European mixes [11–13]. The buses use conventional lead-acid batteries with an expected lifetime of 13 months [5]. The energy and emissions effects from ocean going vessel transport (Hungary to Alabama) and driving the buses from Alabama to LA are included [14]. LA Metro expects buses to last 15 years [5]. Engineering design documents are used to determine busway characteristics. The western-most segment of the line uses local roadways and the 17 mile dedicated busway consists of roughly 13 miles of asphalt and 4 miles of concrete surface layers. Recycled materials were used for the subbase. Asphalt wearing layers, concrete wearing layers, and the subbase are modeled with PaLATE [15] and are assumed to have 20, 15, and 100 year lifetimes. Stations are also included and are designed as a raised concrete platform [16]. The construction and maintenance of the 4700 parking spaces are also assessed with PaLATE. The Orange BRT line uses 1.2 GWh of electricity [5] purchased from LA Department of Water and Power (LADWP) for infrastructure operation including roadway, station, and parking lot lighting, and is evaluated with GREET [14]. Routine maintenance of vehicles and infrastructure are modeled with SimaPro [13].

Orange BRT vehicle operation effects are based on emissions testing by the California Air Resources Board (CARB) of similar bus engines [17, 18]. CARB results for urban duty drive cycles are used and assume that buses will use three way catalysts in the near-term. The emission profiles are validated against other testing reports for similar vehicles and engines [19–28]. In the long-term, it is assumed that Orange BRT buses will achieve fuel economies consistent with best available technology buses today (effectively a 23% improvement from today's buses) and that the CARB 2020 certification standards are met which require 75–85% reductions in air pollutants [17]. The extraction, processing, transport, and distribution of CNG for the buses are evaluated with GREET [14] including upstream effects.

2.1.2. Gold line LRT. The Gold line is an expanding rail system that extends from downtown LA to east LA and Pasadena, with plans to triple the line length in the coming decades. The system began operation in 2003 and currently consists of 19.7 mile of at-grade, retained fill, open cut, and aerial sections. LA Metro uses 54 tonne AnsaldoBreda P2550 2-car 76-seat trains manufactured in Italy and shipped by ocean going vessel to LA. Train manufacturing was assessed with SimaPro [13] with current and future European electricity mixes [12] and transport with GREET [14]. The infrastructure assessment is based on engineering design documents [29] which are used to develop a material and construction equipment assessment following the methods used by Chester and Horvath (2009) [4]. The unique construction activities associated with track sections are assessed and detailed characteristics are reported in Chester *et al* (2012) [6]. There are currently 21 stations of which 19 are at-grade. Satellite imagery is used to determine the area of station platforms which are designed as steel-reinforced concrete slabs on a subbase. The Gold line has 2300 parking spaces across 9 stations, and these are assessed with PaLATE [15]. Electricity consumption data were provided to the research team by LA Metro and are from meters at stations and maintenance yards [5]. In 2010, 20 GWh were purchased from LADWP, 3.2 GWh from Pasadena Water and Power, and 1.2 GWh from Southern California Edison, and propulsion electricity use accounts for roughly one-half of the total [30]. Given the dominating share of LADWP electricity consumed, the utility is used to assess the air emissions of electricity production [14]. Currently, 39% of LADWP electricity is produced from coal and there are plans to phase this fuel out by 2030 as the utility transitions their portfolio towards renewable targets [31]. The 2030 LADWP mix will use more natural gas and renewables and would decrease electricity generation GHG emissions by 50% and SO_x by 60% [14]. Vehicle and infrastructure maintenance and insurance impacts are also modeled [6].

Gold line trains consume approximately 10 kWh of electricity per vehicle mile traveled (VMT) [30] and current and future electricity mixes are assessed to determine near-term and long-term vehicle footprints. The 2030 LADWP mix is used for long-term train operation where the generation of propulsion electricity produces fewer GHG and CAP emissions. Primary fuel extraction, processing, and transport to the generation facility (i.e., energy production) effects are modeled with GREET [14].

2.1.3. Orange BRT and Gold LRT indirect automobile effects. The Orange BRT and Gold LRT lines produce indirect automobile effects through new station access and egress by auto travel. Additionally, the Orange BRT's new biking and walking infrastructure avoids auto trips. The cumulative effect is included in the LCA. 7% of transit riders drive alone to the station and 3% from the stations [9]. These trips are between 1.7 and 2.5 miles [32]. LA Metro [8] estimates that the Orange BRT's biking and walking shift reduces auto annual VMT between 71 000 and 540 000. The indirect auto effects of transit implementation are included in the life-cycle footprint of the Orange BRT and Gold LRT lines, averaged over all PMT.

2.1.4. Competing automobile trip. While LA has an extensive and well-utilized public transportation network, the large sprawling region is dominated by automobile travel at 85% of trips (or 97% of PMT), biking and walking at 13%, and transit at 2% [32]. New transit lines have experienced success in reducing automobile travelers, with (in 2009) 25% of Orange BRT passengers having previously made the trip by auto and 67% of Gold line travelers [9, 33]. Consequently, the assessment of the Orange BRT and Gold LRT lines should consider the life-cycle effects of competing automobile trips to assess the traveler's environmental footprint had transit not existed. The avoided automobile effects are also necessary for evaluating the net change of air pollutants in the region as a result of new transit options.

An automobile trip that substitutes an Orange BRT or Gold LRT line trip is assessed. The transit lines are expected to operate indefinitely so representative automobiles are selected to assess near- (35 mile gallon^{-1}, 3000 lb) and long-term (54 mile gallon^{-1}, 1800 lb) car travel [14]. The long-term automobile is modeled with a lighter weight to assess technology changes that may be implemented to meet aggressive fuel economy standards. Both automobiles are estimated to have a 160 000 mile lifetime. A transport distance of 2000 mile from the manufacturing plant to LA is included by class 8b truck. Infrastructure construction is based on a typical LA arterial segment allocated by annual VMT facilitated [34], and modeled with PaLATE [15]. Vehicle insurance and infrastructure construction and maintenance are also included [6].

The near and long-term automobiles are modeled with 35 and 54 mile gallon^{-1} standards in GREET [14] to assess emerging fuel economy standards in the long life expectancy of the new transit systems. Petroleum extraction, processing, and transport effects assuming California Reformulated Gasoline and 16% oil sands are modeled.

2.1.5. Ridership and mode shifts. Orange BRT and Gold LRT ridership have been steadily increasing since the lines opened and forecasts for future ridership are developed to assess long-term effects. From its first year of operation to 2009, the Orange BRT has increased yearly boardings from 6.1 to 8.4 million, and the Gold line from 4.8 to 7.6 million [7]. This corresponds to 49 and 55 million PMT in 2009 for the respective systems, an increase of 30% (in 5 years) and

36% (in 7 years). Future ridership estimates are developed using 2035 station access forecasts developed by LA Metro. A polynomial interpolation is used to assess adoption between now and 2035 when an estimated 100 and 130 million annual PMT are delivered by the respective systems [5]. In 2009 the Orange BRT average occupancy was 37 with 57 seats and the Gold line 43 with 72 seats per car [7]. The average occupancy of automobile travel in LA is 1.7 passengers for all trips, 1.4 for households that also use transit, and 1.1 for work trips [32]. Auto trip purpose characteristics are joined with transit onboard survey results and future forecasts to determine avoided automobile travel. Currently, 25% of Orange BRT and 67% of Gold LRT previous trip takers would have made the trip by automobile [9, 33]. Given that fuel prices are expected to increase and the transit lines are expanding to auto dominated regions, may be interconnected with other transit lines [35], and are anticipated to experience further development [10], auto shift forecasts are developed to 2050. Using future trip and station access forecasts from LA Metro, the current auto shift growth rates are extrapolated resulting in a median long-term shift of 52% for the Orange BRT and 80% for the Gold LRT. Furthermore, to assess avoided automobile travel distance from transit shifts, a clustering approach was used to determine that across household income, workers, and vehicles, one PMT shifted to the Orange BRT or Gold LRT lines avoids one PMT of automobile travel [32, 36].

2.2. Energy and environmental indicators and stressors

An energy and environmental life-cycle inventory is developed and then joined with photochemical smog formation and human health respiratory impact stressors. The inventory includes end-use energy and emissions of greenhouse gases (GHGs), NO_x, SO_x, CO, PM_{10}, $PM_{2.5}$, and VOCs. GHGs are reported as CO_2-equivalence (CO_{2e}) for a 100 year horizon using radiative forcing multipliers of 25 for CH_4 and 298 for N_2O. Los Angeles has struggled to meet National Ambient Air Quality Standards for PM and ozone so inventory results are joined with impact characterization factors from the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI, v2) to assess respiratory and smog stressors [37]. A stressor is the upper limit of impacts that *could* occur and not the actual impact that will occur. The deployment of these new transit systems may help LA reduce GHG emissions to meet environmental goals. However, by assessing a broad suite of environmental indicators, unintended tradeoffs (i.e., reducing one impact but increasing another) can be identified early and mitigation strategies developed.

3. Modal passenger mile comparisons

The Orange BRT and Gold LRT lines will reduce life-cycle per PMT energy use, GHG emissions, and the potential for smog formation at the anticipated near-term and long-term ridership levels. However, given the $PM_{2.5}$ intensity of coal-fired electricity generation powering the Gold LRT, there is a potential for increasing out-of-basin respiratory impacts in the near-term, highlighting the unintended tradeoffs that may occur with disconnected GHG and air quality policies. The Gold LRT respiratory impact potential is the result of coal electricity generation in LADWP's mix and associated mining activities. The coal-fired Navajo Generating Station (NGS) in Arizona and the Intermountain Power Plant (IPP) in Utah are owned, at least in part, by LADWP and the utility is planning to divest in the plants by 2025 [31]. The NGS and IPP are two of the largest coal-fired power plants in the Western US and have been targeted for emissions reductions, primarily to improve visibility at nearby parks including the Grand Canyon [38, 39]. However, secondary particle formation from NO_x and SO_x, in addition to $PM_{2.5}$, have been shown to be a respiratory concern despite the each facility's remote location [39–41]. LADWP is aggressively pursuing divestiture in its 21% share of NGS and 100% share of IPP which will lead to significant long-term benefits for the Gold LRT [31].

Figure 1 shows that significant environmental benefits can be achieved by automobiles, Orange BRT, and Gold LRT in the long-term as a result of established energy and environmental policies as well as vehicle technology changes, and that public transit technology and energy changes will produce more environmental benefits per trip than automobiles. In the near-term, both the Orange BRT and Gold LRT lines can be expected to achieve lower energy and GHG impacts per PMT than emerging 35 mile gallon^{-1} automobiles. While propulsion effects (vehicle operation and propulsion electricity) constitute a majority share of life-cycle effects for energy and GHGs, vehicle manufacturing, energy production, and in the case of the Gold line, electricity for infrastructure operation (train control, lighting, stations, etc) contribute significantly. Due to high NO_x and $PM_{2.5}$ emissions in coal-fired electricity generation, Gold LRT in the near-term creates large potential smog and respiratory impacts, however, the replacement of this coal electricity with natural gas by 2015–2025 will result in significant reductions in the long-term [31]. For non-GHG air emissions, indirect and supply chain processes (in this case vehicle manufacturing and infrastructure construction) typically dominate the life-cycle footprint of modes showing how vast supply chains that traverse geopolitical boundaries result in remote impacts far from where the decision to build and operate a transportation mode occurs. Diesel equipment use, material processing, and electricity generation for the production and distribution of materials throughout the supply chain generate heavy NO_x and $PM_{2.5}$ emissions that when allocated to LA travel can dominate the life-cycle smog and respiratory effects.

In the long-term, automobile fuel economy gains, reduced emission buses, and RPS electricity will have the greatest impacts on passenger transportation energy use and GHG emissions in LA. Larger renewable shares feeding Orange BRT bus manufacturing drives a 46% reduction in life-cycle respiratory impacts. For the Gold LRT, RPS electricity will reduce both propulsion and infrastructure operation smog effects by 93%. Automobile indirect effects show non-negligible contributions to life-cycle impacts when

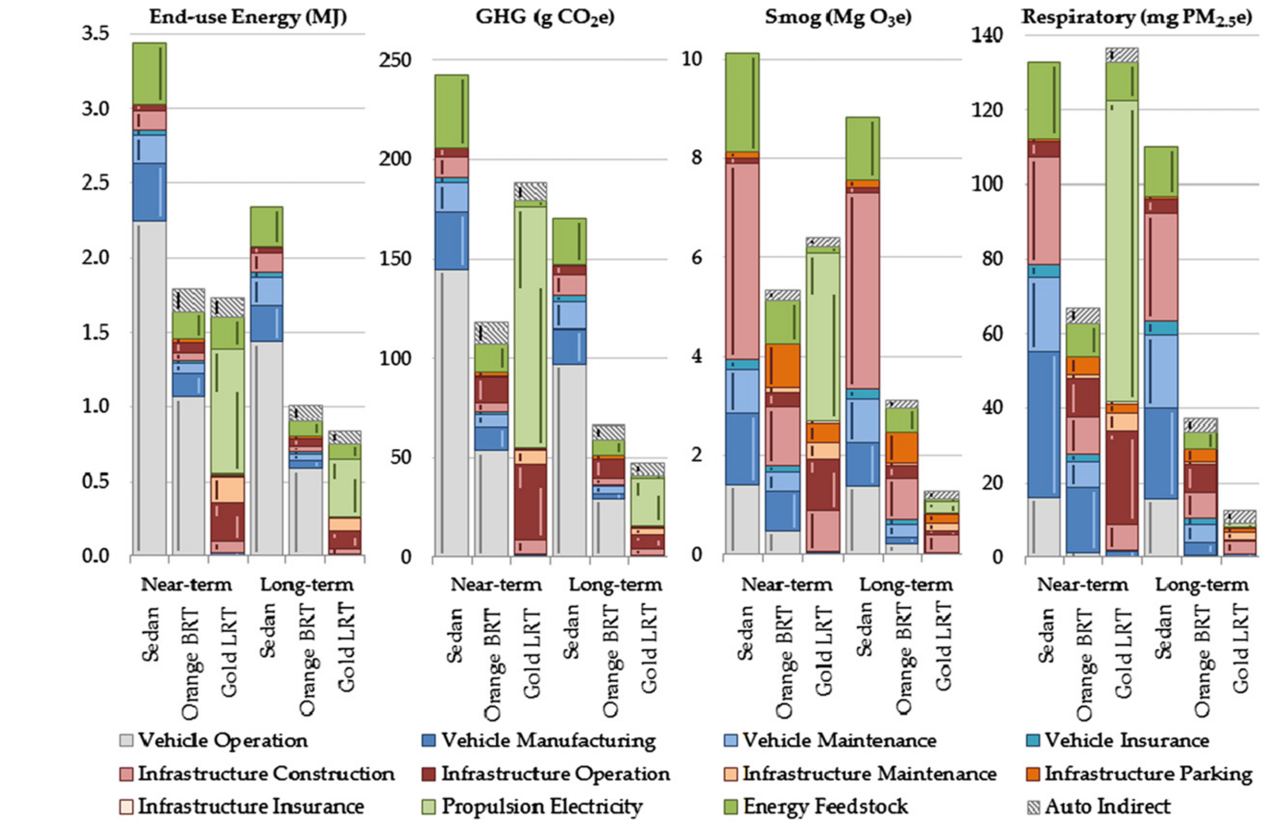

Figure 1. Life-cycle per PMT results for average occupancy vehicles. For each impact both near-term and long-term results are shown for each mode. Vehicle tailpipe effects are gray, vehicle are blue, infrastructure are red, and energy production are green. Local impacts are shown with a line on the left of the life-cycle result and remote on the right if the dominating share of effects occurs inside or outside of LA county.

allocated across all trip takers. The impacts of station access and egress by motorized travel are explored in later sections.

LCA transcends geopolitical boundaries in its assessment of indirect and supply chain processes, and urban sustainability policy makers should recognize that local vehicle travel triggers energy use and emissions outside of cities. This is clear for coal-fired electricity generation in Arizona but can become complex when moving up the supply chain for vehicle and infrastructure components. Vehicle operation and propulsion electricity effects are a large portion of energy consumption and GHG emissions and will occur locally while energy production (i.e., primary fuel extraction and processing) and vehicle manufacturing occur remotely. For the sedan, roughly 72–77% of life-cycle energy consumption and GHG emissions occurs locally meaning that for every 75 MJ of energy consumed or grams of CO_{2e} emitted in LA, an additional 25 are triggered outside of the city. For the Orange BRT, local energy use and GHG emissions constitute 74–82% and for the Gold LRT, only 53–62% due to electricity generation both outside of the county and the state. These percentages change significantly for smog and respiratory stressors due to the larger contributions of non-propulsion effects in the life-cycle.

For the sedan, remote electricity generation for vehicle manufacturing and energy production emissions mean that only 52–73% of potential impacts may occur locally. Similarly, remote vehicle manufacturing and CNG production emissions for the Orange BRT result in roughly 55–76% of respiratory impact stressors occurring locally. Due to out-of-state coal electricity generation, in the near-term the Gold LRT line has the lowest fraction of life-cycle smog and respiratory effects occurring locally, at 54% and 31%. Urban energy and environmental goals should recognize that cities rely on complex and dynamic energy and material supply chain networks and that it may be possible through contracts or supplier selection to reduce remote impacts. This will only occur if policymakers adopt an environmental assessment framework that acknowledges that cities are not isolated systems and trigger resource use and emissions that exist beyond their geopolitical boundaries [42].

The per PMT assessment is valuable for understanding how regions should allocate their total emissions or impacts to each mode's travel and identify which life-cycle processes should be targeted for the greatest environmental gains, however, a consequential assessment is needed for assessing how new modes will contribute to a city reaching their environmental goals, by comparing against a regional baseline.

4. Public transit for energy and environmental goals

To assess the effects of the decision to deploy a public transit system and how such a system contributes to a city reaching an environmental goal, a consequential LCA framework

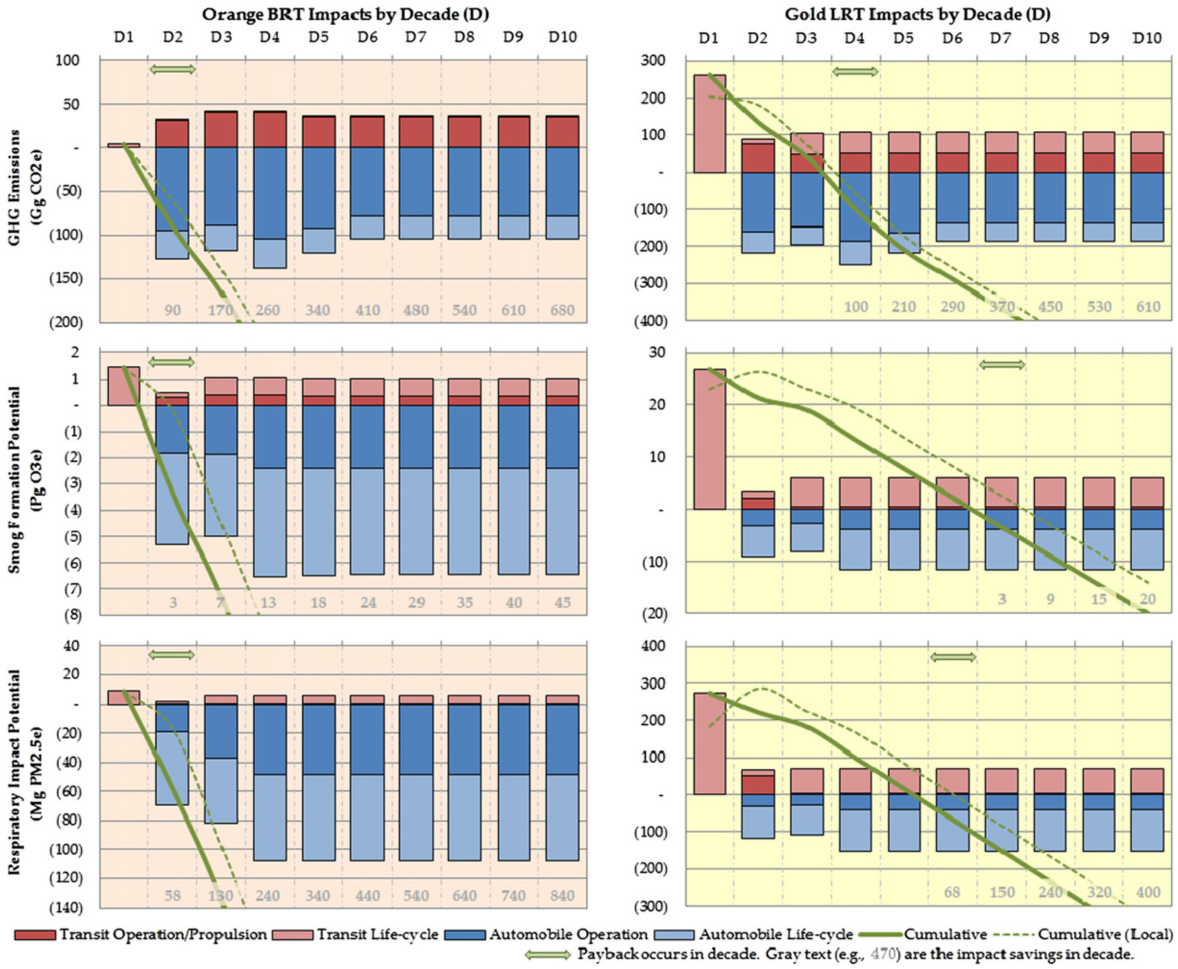

Figure 2. Environmental impact schedules and resulting paybacks. Decadal (D) life-cycle results (bars) are shown for the new transit system (red) and avoided automobile (blue) effects. Cumulative (i.e., net effects) life-cycle and local green lines are shown and when they cross the abscissae have resulted in a net reduction of impacts as a result of the transit system. When payback occurs, the net benefits are shown at the bottom of the decade.

must be used. The decision to deploy the Orange and Gold lines resulted in the operation of new vehicles that require infrastructure and trigger life-cycle processes that consume energy and generate emissions. While induced demand is created, reduced automobile travel has also occurred [9, 33], which should reduce future energy consumption and emissions from personal vehicles. A consequential LCA is used to assess the increased impacts from new transit modes and avoided impacts of reduced automobile travel. Future adoption forecasts [5] are used with mode shift survey results to develop the decadal benefit–cost impact assessment and payback estimates shown in figure 2.

For both transit lines, construction impacts (light red life-cycle bar) begin the series in the first decade. Starting in the second decade the transit systems begin operation, offsetting automobile travel, and over the coming decades reach ridership maturity. For both modes and all impacts, the benefits from reduced automobile travel outweigh the environmental costs of the new transit systems. The avoided impacts are 1.5–3 times larger for GHG emissions than the added transit emissions, 1.3–5.5 times for smog, and 1.4–15 times for respiratory impacts. There are significantly fewer impacts produced from the initial construction of the dedicated Orange BRT right-of-way than from the Gold LRT tracks due to a variety of process, material, and supply chain life-cycle effects. The heavy use of concrete for Gold line tracks results in significant CO_2, VOC, and $PM_{2.5}$ releases during cement and concrete production due to calcination of limestone and emissions of organics elements and fine particles during kiln firing. The result is that the Orange line payback for GHGs and respiratory effects is almost immediate and the Gold line paybacks occur 30–60 years after operation begins. The results highlight the sensitivity of payback to auto trips shifted to transit. Transportation planners can position new transit to help cities meet environmental goals by developing strategies that ensure certain levels of automobile shifting are achieved to accelerate paybacks. Figure 3 shows the payback speed for energy consumption and air emissions as a response to the percentage of transit trip takers that have shifted from automobiles.

Figure 3 shows that with greater shifts to transit from automobiles paybacks occur more quickly. This response will hold true for any public transit system where the per PMT effects of automobiles are larger than the public transit mode.

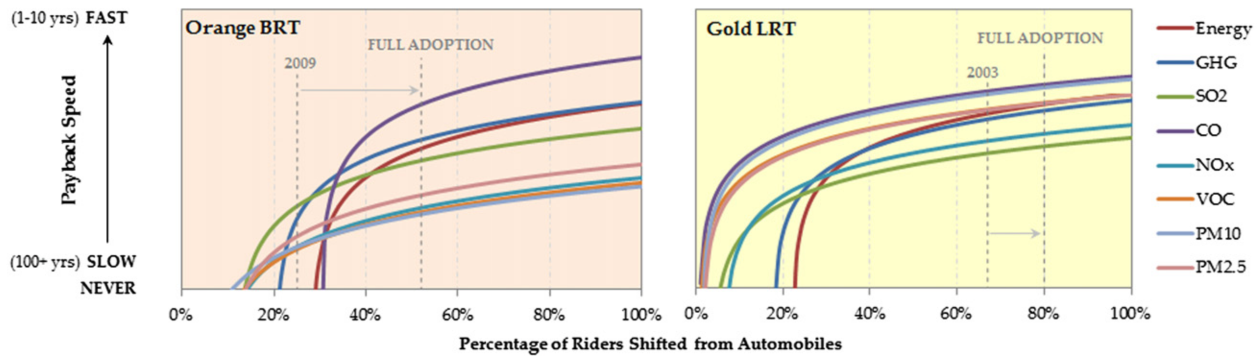

Figure 3. Transit energy and environmental payback speed with automobile shifts. The different payback speed curves are shown as a function of the percentage of transit riders having shifted from automobiles. For each mode, current and forecasted full adoption levels are shown as dashed vertical gray lines. At the abscissa, payback does not occur.

The life-cycle energy and emissions curves have different intercepts and trajectories showing that paybacks will occur at different rates, and will not be the same for any environmental indicator. A transit system that achieves 50% of riders having shifted from automobiles will experience a different payback date for VOCs than it will for GHGs. The Orange line's 2009 25% shift is currently below the 30% needed to produce energy and CO reductions, however, given the anticipated full adoption shift of 52% the system will over 50 years produce a net reduction of 320 Gg CO_{2e} (see figure 2). The information in figure 3, while specific to the LA transit systems, can provide valuable goals for cities. For any mode, there is a minimum window of percentage of transit riders shifted from automobiles where pollutants will be reduced. For example, the abscissa for the Orange BRT reveals that at between roughly 10% and 30% pollutant reductions will be achieved (how quickly is a separate question). At 30%, the Orange BRT system is guaranteed to have payback across all pollutants. This maximum in the window can be used by cities that are discussing the implementation of new transit systems to help meet environmental goals. Planning efforts should be coordinated such that the systems achieve these minimum mode shifts.

5. Door-to-door life-cycle effects

Transportation environmental policies should consider the multi-modal door-to-door impacts of trips, and LCA can provide valuable insight for both the operational and non-operational effects of a traveler's choice. A life-cycle understanding of door-to-door trips is particularly important for transit travelers whose access or egress to stations occurs by automobile where questions arise of the benefits of these trips, particularly when infrastructure (specifically station parking) is included. A door-to-door GHG LCA is developed for a unimodal automobile trip compared against each transit line. For each transit line, access/egress is shown with local bus service as well as by automobile. Typical trip distances are used (as described in previous sections) and processing of LA Metro and travel survey data provides information on feeder bus and automobile typical trip characteristics [7, 8, 32, 33]. The typical Orange BRT trip is 6 mile with feeder bus and auto trips adding on average 1.8 and 4.2 mile respectively. A competing unimodal auto trip is 10.2 mile assuming distance shifts identified in the previously described mode shift clustering analysis [7, 32]. The typical Gold LRT trip is 7.5 mile with feeder bus and auto trips of 3.3 and 5 mile and is compared against a 12.5 mile competing auto trip [7, 32, 33]. Current and future Orange BRT, Gold LRT, and feeder bus offpeak, average, and peak occupancies are determined from LA Metro data and forecasts [5, 7]. Auto feeder travel is shown as both average and single occupancy travel. The impacts of the 4700 and 2300 parking spaces (shown as bright orange in figure 1) are now shifted to the automobile feeder trips. The results are shown in figure 4 in both the near-term and long-term for GHG emissions for offpeak, average, and peak travel.

The Orange BRT and Gold LRT door-to-door trips with typical access/egress by other local buses or automobiles are likely to have a lower life-cycle footprint than a competing unimodal automobile trip. The only exceptions are offpeak (low occupancy) transit travel with single occupancy automobile feeder access/egress compared against average (1.7 passenger) unimodal auto trips. Transit travel (even with single occupancy automobile feeder access/egress) consistently produces lower impacts than a competing single occupancy automobile trip. On average, transit+local bus trips have 77% lower GHG trip footprints than a competing automobile trip and transit+auto 52% lower. Recent onboard travel surveys report that 49% of Orange BRT passengers arrive to or leave from stations by local transit and 14% by automobile, and for the Gold line 41% link bus and other rail trips (data on access/egress by automobile were not identified) [9, 33]. Strategies that shift travelers from automobiles to public transit-only service produces the greatest environmental benefits and parking infrastructure management is central to changing behavior [43]. Figure 4 shows that parking construction and maintenance (orange bar) impacts for transit+auto trips can be as large as the transit infrastructure construction and maintenance (pink bars) per trip. These infrastructure enable the emergent travel behavior and the provision of low cost or free parking at LA Metro stations helps to encourage the auto access/egress impacts [43]. Environmental benefit–cost analyses should

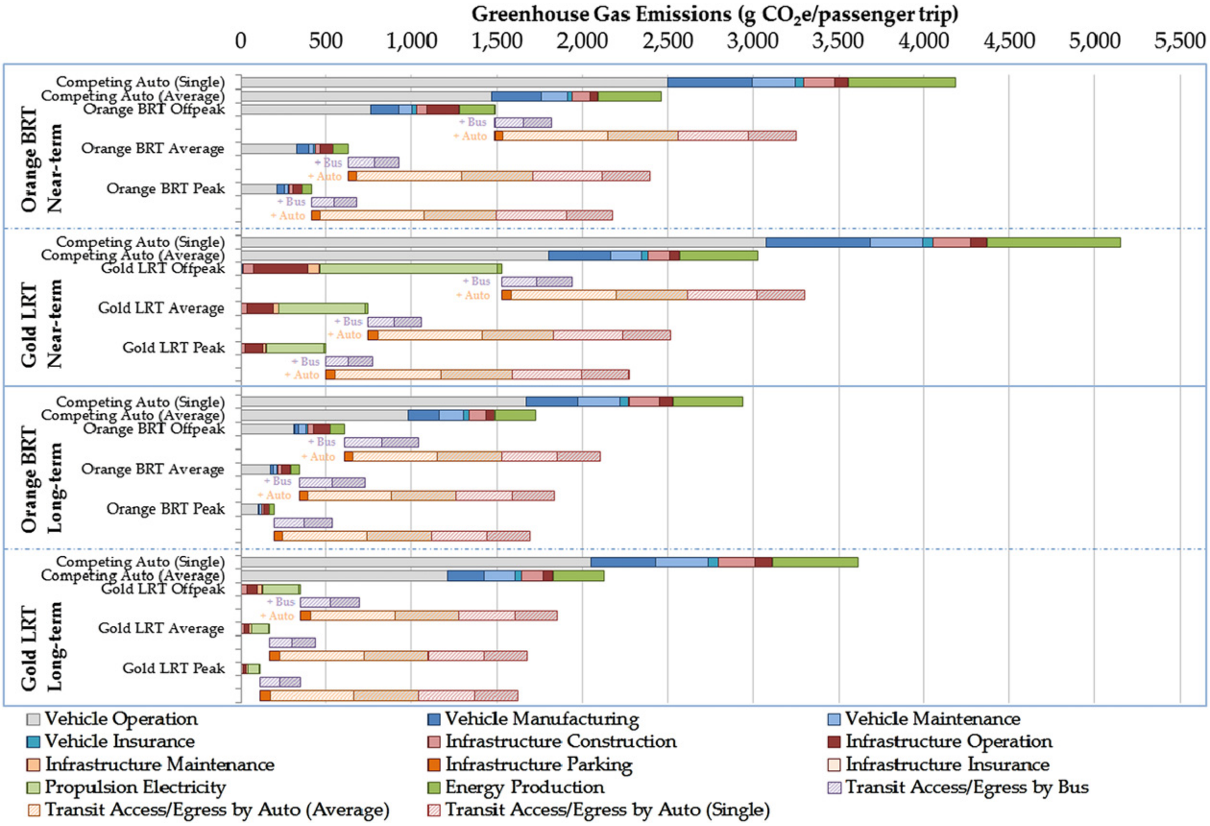

Figure 4. Life-cycle door-to-door ghg comparison. For the transit modes, feeder bus and automobile impacts should be assessed cumulatively. For example, an Orange BRT or Gold LRT trip that starts or ends with a bus trip is equal to the transit life-cycle bar plus the bus purple striped bars. Feeder bus and auto travel results are shown with both operational (striped bar with white background) and life-cycle (striped bar with gray background) portions. For auto access/egress to transit, the effects of average occupancy (1.7) passengers per car is shown as orange stripes and if the automobile was single occupancy then the red striped bar would be added on. Bike and walk impacts are not considered.

consider the life-cycle tradeoffs of land use for station parking versus transit-oriented development (TOD) and the co-benefits that could be achieved by TODs in reducing both auto access/egress impacts and household energy use [44].

6. Integrating transportation LCA in urban environmental policymaking

Public transit systems are typically positioned as transportation environmental impact reducers and as policy and decision makers begin to incorporate life-cycle thinking into planning, new strategies must be developed for integrating LCA. The results show that both local and remote life-cycle environmental impacts will be reduced by implementing BRT and LRT for all impacts in the long-term. The results also show that the decision to implement a new transit system in a city has significant local and remote energy and environmental impacts beyond vehicle operation. These life-cycle impacts are the result of indirect and supply chain processes that are often ignored by policy and decision makers, as well as environmental mitigation strategies.

Challenges exist for implementing life-cycle results in governmental processes [45]. Because life-cycle emissions are distributed across numerous air basins throughout the United States and the world, there exists a spatial mismatch for policymaking. Both transportation planning and emissions control policy structures in the United States are fragmented across jurisdictions and across different components of the life-cycle. The transportation system is created through a series of federal, state, regional and local programs and authorities acting in an independent, yet interdependent, manner. Designing a policy structure to reduce life-cycle emissions is therefore a complex task, and a variety of policy options may be viable. While there is no simple policy fix, mitigation strategies that effectively incorporate LCA into transportation planning should involve all of the following:

(i) changing analytical and decision criteria for project selection;
(ii) improving the capability to compare different transportation modes to one another in planning and project financing processes;
(iii) improving the capability to conduct analysis of complex environmental impacts into transportation planning *before* project selection occurs (i.e. not only in post-decisional environmental impact assessments);
(iv) improving analytical integration across different spatial and temporal scales; and,

(v) creating purchasing strategies that emphasize the use of products and materials with higher recycled content and establish relationships with suppliers that have instituted efficiency measures.

Given these needs, the metropolitan region is likely the most useful geographic scale for transportation LCA integration and LCA can be used as a valuable guiding framework for novel mitigation strategies. Metropolitan Planning Organizations (MPOs) already offer the greatest planning integration across modes and already possess relatively advanced analytical and planning capabilities for the development of Regional Transportation Plans. Pigovian tax or cap-and-trade structures for carbon or other emissions can use life-cycle results to capture indirect and supply chain impacts and if cast at a large geographic scale can reduce urban and hinterland impacts by transcending the notion that activities in cities are contained within a geopolitical boundary.

Data.

Results data are available at www.transportationlca.org.

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