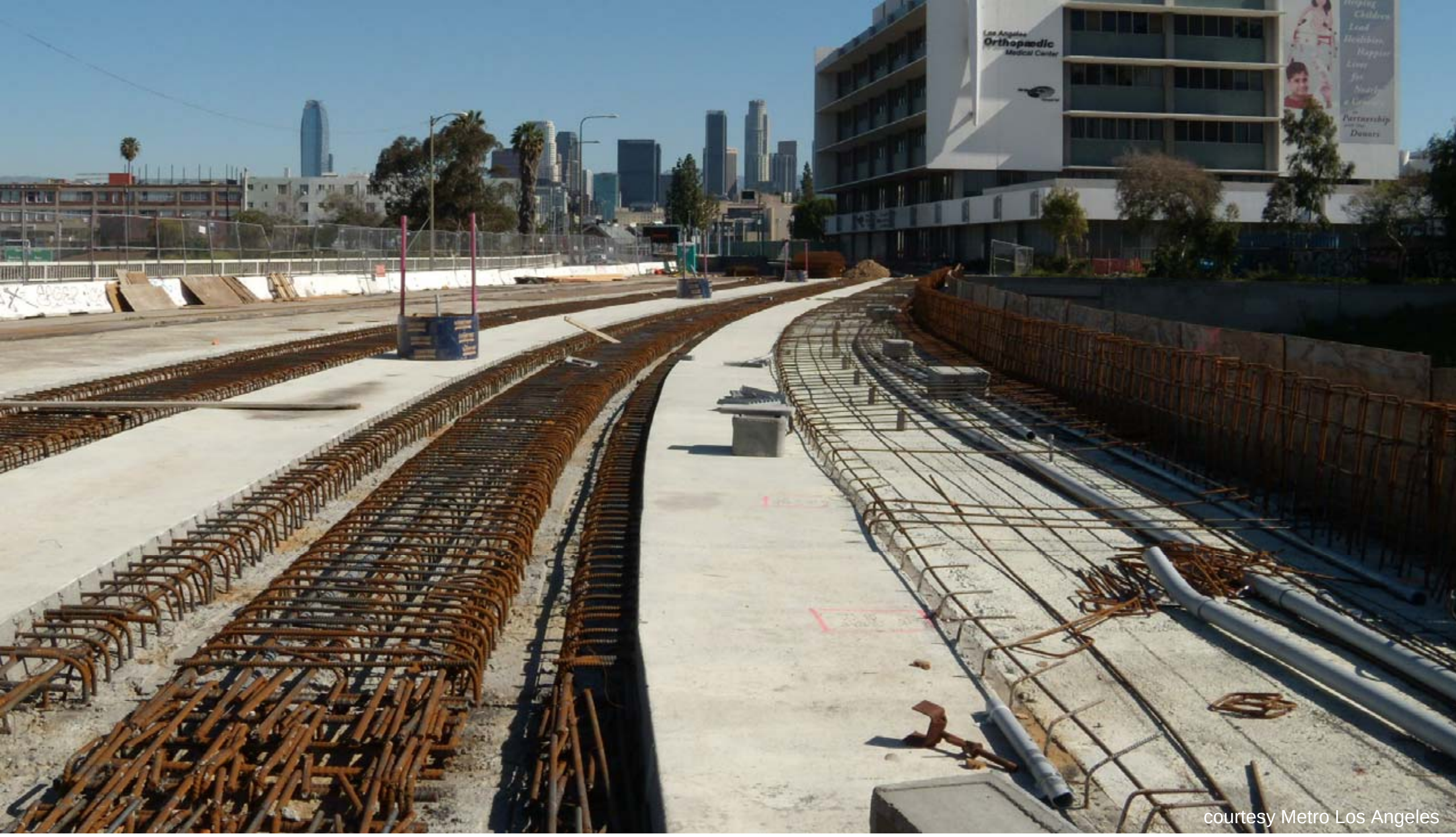
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Life-Cycle Assessment for Transportation Decision-making

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Introduction

Those charged with making decisions regarding transportation systems have, in recent years, become more interested in the indirect impacts of these systems. This interest is in part a response to advancements in vehicle technology and evolving policy goals.

The State of California seeks to reduce emissions and conserve energy resources in all sectors of its economy and has adopted several policies that address transportation energy use and emissions. All of these policies, such as The Sustainable Communities Planning Act,[1] consider vehicle tailpipe emissions. One policy, California's Low

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Carbon Fuel Standard[2], also considers the effects of greenhouse gas emissions from the production and distribution of transportation fuels, even when these emissions are out of state.

The recent availability of mass-market electric vehicles also has decision-makers contemplating the indirect effects of transportation systems. Although the tailpipe emissions from an internal combustion engine vehicle are more obvious than the indirect power plant emissions generated to propel an electric vehicle, both sets of emissions affect climate change.

Life-Cycle Assessment (LCA) provides decision-makers with information needed to evaluate the direct and indirect impacts of transportation systems. This report will guide the reader through the process of identifying sources, inventorying impacts, and interpreting results specific to LCA of energy and emissions indicators for transportation projects. The authors highlight the impacts that dominate overall results and discuss how to incorporate LCA into existing transportation planning, construction, and operation processes.

Life-Cycle Assessment: A Primer

LCA is a framework for evaluating products, processes, services, activities, and the complex systems in which they reside, from cradle-to-grave. LCA has been developed for roughly 40 years and has been formalized by the International Organization for Standardization in their 14040 series. The framework is robust in that any quantifiable flow can be evaluated including labor, costs, materials, and water, in addition to energy use and pollutant discharges.

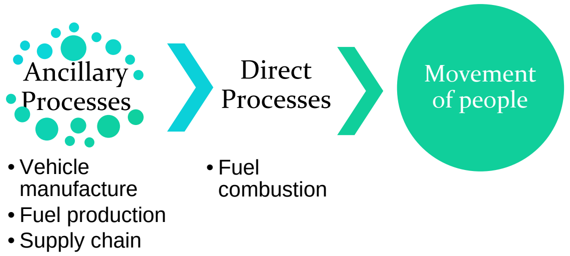
In this document, we focus on using LCA to quantify the cradle-to-grave energy use and air emissions of transportation systems. As transportation agencies and cities become increasingly aware of the complexity of transportation systems, LCA has made its way to the forefront of discussions and life-cycle thinking has begun to permeate into the planning, construction, operation, and maintenance processes.

Identify processes and boundaries

An LCA begins with the identification of direct, ancillary (or indirect), and supply chain processes that are relevant to the transportation system. Because the goal of a transportation system is to move people and goods, the direct effects are the energy use and emissions associated with movement of the vehicle. For example, to move a car, gasoline is consumed and work is produced through the release of energy by breaking apart the gasoline hydrocarbon molecules. The combustion process produces air emissions in the form of carbon dioxide, carbon monoxide, sulfur oxides, nitrogen oxides, particulate matter, to name a few. The fuel use and emissions produced are called direct emissions in transportation LCA because they are associated with the direct goal of the system, to facilitate the movement of people and goods.

Ancillary processes are those that must exist in order for the direct process to exist. For transportation systems, these are generally classified as vehicle, infrastructure, and energy production services. For example, in order for a vehicle to move, the vehicle must first be produced. Infrastructure must be constructed, operated, and maintained. And an energy production system must exist to produce gasoline, diesel, natural gas, electricity, or other fuels (e.g., biofuels). Some fraction of these ancillary processes exists to support the vehicle's

Ancillary processes are required for direct processes to occur



movement. Furthermore, these ancillary processes rely on a supply chain to provide materials, sub-processes, services, and other activities, possibly far from where the vehicle operates.

LCAs of transportation systems have shown that ancillary and supply chain processes can at times dominate the life-cycle environmental footprint. This reveals that a decision to operate a transit vehicle in a region may have far-reaching effects beyond that region. These LCAs also reveal that a transportation agency may achieve the greatest environmental benefits at the lowest costs by targeting ancillary and supply chain life-cycle processes.

Framing the Life-Cycle Assessment

Conducting an LCA begins with defining the goal of the study. This goal can lead to a retrospective or prospective LCA approach. Until recently, retrospective LCAs have dominated the field but as practitioners look more and more towards using LCA to inform policies and decisions, prospective thinking has taken on a more important role.

Retrospective LCA takes a viewpoint that an established transportation system will have a footprint that consists of direct, ancillary, and supply chain processes that can in some way be allocated. For example, a retrospective LCA of a light rail trip would include the direct effects (moving the train), ancillary effects (e.g., evaluating the total greenhouse gas emissions from constructing the infrastructure and dividing it by the total number of trips), and supply chain effects (e.g., evaluating the greenhouse gas emissions from mining materials for train manufacturing and dividing it by the total number of trips served in the train's lifetime). Retrospective LCA is invaluable for understanding how a transit agency, for example, can reduce the impacts of their system as it has been constructed.

Prospective LCA takes a fundamentally different approach by asking how direct and ancillary processes in a transportation system will change when a policy or decision has been implemented. For example, the decision to implement a bus rapid transit (BRT) line in a city by taking over a lane in an arterial does not produce greenhouse gas emissions from the construction of a new roadway. The city's greenhouse gas emissions do not increase because of this BRT line. In this case, a retrospective LCA would attempt to allocate the infrastructure construction greenhouse gas emissions before the BRT line to automobiles and after the BRT line's implementation to the bus.

However, in a scenario where LCA is being used to inform environmental policy, prospective LCA is needed to evaluate the net effects in a region of the decision to implement the transportation system, and would thus only include the net change that has resulted from the decision.

Retrospective LCAs are valuable for informing questions such as '*Where can a transit agency most cost-effectively reduce their energy and environmental footprint?*' Prospective LCAs are necessary to answer questions like '*What is the effect of implementing a new transit line in a city?*'

Both approaches are useful and can help inform environmental impact reductions, but depending on the goal of the LCA it is necessary for the practitioner to identify the single approach that is most useful for the decision they are trying to inform. The selection of an approach in the definition of the assessment's goal will ultimately inform the system boundary that is selected for the analysis.

Why use Life-Cycle Assessment for transportation decision-making?

LCA expands on existing environmental impact assessment methods which only consider emissions from construction and operations. A more complete picture of all impacts associated with a prospective or past project is more informative for decision-makers concerned with greenhouse gas emissions and energy use.

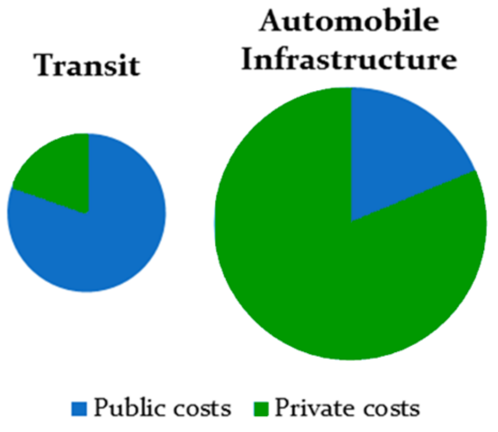
Better understand full impacts with LCA

While the public sector pays to build and maintain automobile infrastructure, individual automobile ownership, operation, and maintenance costs are borne by households and private firms. In contrast, costs to build and operate transit are borne by the public sector, with customers contributing roughly a quarter of operating costs through fares.

The illustration below shows a scenario where a transportation agency considers a transit project versus an equivalent automobile project. For the transit project, the transportation agency must pay to construct, operate, and maintain the facility. For the automobile project, the transportation agency pays to construct the infrastructure, but the private sector picks up the tab for much of the vehicle operations and maintenance costs.

Though the automobile project is more costly overall, it is cheaper to the transportation agency.

Public and private costs to meet transportation need



In the above illustration, a transportation agency may decide it preferable to pursue automobile infrastructure if it only considers its own costs.

This may cause the agency to pursue more automobile infrastructure projects than it if it had considered the effect that all monetary costs would have on both the private and public sectors of the regional economy.

In the past, transportation agencies have only considered on-site emissions and energy use from facility construction and operations. Most transportation agencies have not considered emissions that result from the manufacture of passenger and transit vehicles, cement, steel, and refining of fuels. These upstream emissions can be significant, and are becoming increasingly important as governments enact policies to mitigate climate change, as greenhouse gas emissions have similar effects on climate change regardless of their location of emission.

Compare across modes with LCA

The proportion of total energy use and emissions that occur in the operation phase can be different across modes. For example, an electric-powered light rail vehicle emits no tailpipe emissions from operations, but the electricity it uses creates emissions upstream. This in in contrast with a natural gas powered bus that emits from both its tailpipe and upstream. LCA is necessary to compare emissions and energy use among alternatives from different modes. This is especially true when comparing energy use and emissions impacts between private automobiles and public transit.

Using Life-Cycle Assessment in Transit Capital Planning

Existing transportation LCAs can serve as guidance for future LCA practitioners. To-date, transportation LCAs have focused primarily on the vehicle and energy production cycles. Vehicle cycles include manufacturing and maintenance of cars, buses, and trains. With increasing interest in biofuels, a separate body of literature has examined energy production for transportation frame raw fuel extraction (crude oil or primary inputs for electricity generation) or feedstock (corn production for biofuels) production through delivery of that energy in its final usable form (e.g., gasoline, diesel, ethanol, or electricity).

Many transportation LCAs combine aspects of the vehicle and energy production cycles to produce their final results and reveal several dominating consistent characteristics across transportation systems. Another body of research has focused on also including infrastructure impacts in transportation LCA. These studies reveal several critical parameters that dominate the life-cycle footprint of transportation systems.

In this section, we discuss how a transportation policy and decision maker can incorporate LCA thinking by focusing our discussion on these critical parameters.

Establishing the study goal: retrospective and prospective LCA

The first step in LCA is the defining of the goal of the study and practitioners must consider whether they are interested in understanding a system as it has been built (retrospective) or how a new system will contribute to energy and environmental impacts going forward (prospective). If the practitioner's goal is to reduce the environmental footprint of an existing system the retrospective LCA is the appropriate framing. However, if the practitioner's goal is to determine the environmental changes that result from changes to the current system or implementation of a new system then prospective LCA is appropriate.

Retrospective LCA seeks to allocate direct, ancillary, and supply chain effects to the transportation system of study, no matter how small or remote they may be. Prospective LCA evaluates only the changes that result from a policy or decision and should ignore ancillary and supply chain processes that do not change from the business-as-usual option. For example, the question '*What is the greenhouse gas footprint of automobile travel versus bus travel in a city?'* would be answered with retrospective LCA framing which would establish a system of study that includes as many ancillary and supply chain processes that can be allocated to each mode. However, by asking '*How does a new BRT line on an existing arterial help a city meet its greenhouse gas reduction goals?'* should be answered with prospective LCA and components that do not change (for example, the construction of the roadway) from one system to the next would not be considered. Establishing a retrospective or prospective viewpoint is a critical step for an LCA practitioner to establish a useful system boundary of analysis so that they can answer their question.

Set the system boundary

Once the study goal has been established, a system boundary should be selected to determine which life-cycle components will and will not be included in the assessment. LCA theory says that the selection of the system boundary should be based on elementary flows meaning that the practitioner should select a boundary that begins with life-cycle components that extract raw materials from the earth (cradle) and with components that deposit waste back to the earth (grave). This captures exchanges from the ecosphere (natural environment) to the technosphere (man-made systems and the built environment) and back to the ecosphere.

In practice, the LCA practitioner can truncate the system boundary as long as the life-cycle components removed do not change the ranking of one choice over another. Previous transportation LCA research has shown that practitioners should include mining operations (e.g., materials for infrastructure) and primary energy (i.e., fossil fuel) extraction in the system boundary because of their sometimes dominating contributions to the environmental inventory.

Life-Cycle assessment can account for supply chain processes involved in transportation service delivery

Consider appropriate indicators

LCA practitioners should consider including a broad suite of environmental indicators to understand resource and environmental tradeoffs of their systems. The LCA framework is adaptable in that it allows any quantifiable flow to be evaluated. This could include energy, environmental effects (e.g., greenhouse gas emissions, criteria pollutant emissions), costs, labor requirements, and so on. It can sometimes be the case that an LCA practitioner that considers a single or small subset of indicators (e.g., only greenhouse gas emissions) will miss unintended tradeoffs. That is, the practitioner can use LCA to reduce greenhouse gas emissions, but in doing so may unintentionally increase some other impact that is not being analyzed.

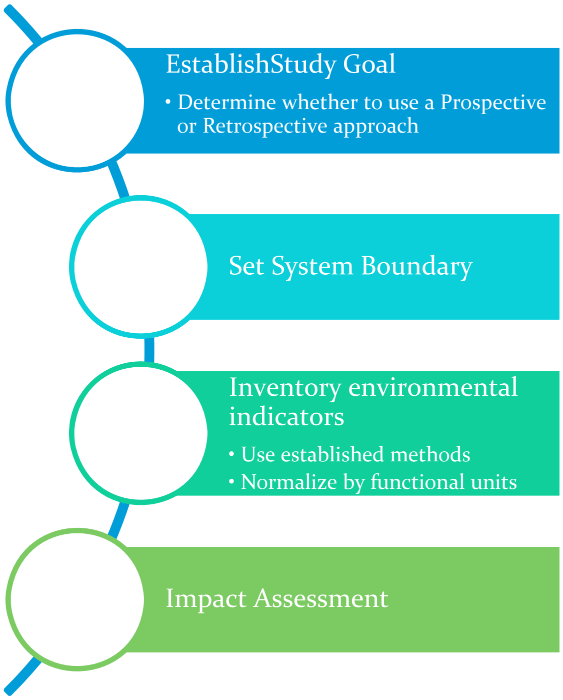
For example, an LCA of electric cars should track both greenhouse gas and human health effects because it is possible that the new technology will reduce greenhouse gas emissions by switching to lower carbon energy in propulsion but may increase health impacts to populations living near battery manufacturing facilities[3]. LCAs of passenger transportation systems typically include energy inputs and emissions of greenhouse gases and conventional air pollutants. The practitioner should consider the different forms of energy (i.e., primary vs. secondary, electrical vs. non-electrical, fossil vs. non-fossil, and renewable vs. non-renewable) and should attempt to characterize where possible.

Conventional air pollutants are the emissions or precursors that contribute to the EPA Clean Air Act Criteria Air Pollutants, those that cause direct human and environmental impacts. Conventional air pollutants are sulfur oxides, nitrogen oxides, particulate matter, carbon monoxide, volatile organic compounds, and lead emissions.

Select a functional unit

With the selection of the system boundary and environmental indicators of interest, the LCA practitioner must select a functional unit to ultimately normalize the differing units and scales of the analysis components to a consistent measure. For passenger transportation LCA, results are often normalized per vehicle mile traveled (VMT) or passenger mile traveled (PMT) but could also be expressed in any relevant measure that transportation agencies typically consider (for example, per unit cost, passenger time of travel, etc.). If the goal of the study is to inform regional emissions inventories from vehicle movement, then a per VMT functional unit is sufficient. If the LCA practitioner wants to evaluate system ridership characteristics, then a per PMT functional unit is necessary. It is important that for changes to existing or emerging systems, the practitioner considers results. For example, if a ridership uncertainty in the per PMT normalized forecast shows the potential low and high ends of a new bus line's ridership then the LCA practitioner can incorporate this information and evaluate the bus system per PMT at low to high occupancy.

Incorporating LCA into Practice



Calculate each processes contribution to indicators

Having established the system boundary, the practitioner can develop a life-cycle inventory of the indicators of interest by evaluating the processes, activities, services, products, and their supply chain, ultimately allocating the effects of each to the functional unit. A passenger transportation LCA will include an inventory that shows the energy consumption and air emissions (assuming these are the environmental indicators chosen) for vehicle, infrastructure, and energy production components each normalized per VMT or PMT.

Existing LCAs of passenger transportation have revealed that while hundreds of life-cycle components can be evaluated, only a handful tend to dominate results. Developing a rigorous LCA requires a continuous commitment to gathering data and interpreting results in several iterations. Many transit agencies and decision makers may not have the capacity to invest in extensive LCAs but may desire to understand what the hotspots are in their transportation systems.

In an effort to assist LCA beginners, the hotspots identified from existing research are discussed and should provide a window for those interested in understanding which processes may dominate in a complex system.

Manufacturing

Automobile, bus, or train manufacturing tends to be dominated by electricity generation for final assembly and parts manufacturing, material use, and transportation in the supply chain. Vehicle manufacturing improvements that incorporate clean electricity will achieve the greatest greenhouse gas reductions in this life-cycle component. This should be followed by strategies that reduce the greenhouse gas intensity of materials, by say incorporating greater recycled content or by using low CO_2 strategies. For conventional air pollutants, electricity generation and supply chain truck transport dominate. Again, strategies that call for clean electricity use both in final assembly as well as upstream parts manufacturing are likely to significantly reduce the environmental footprint of vehicle manufacturing. Furthermore, strategies that incorporate parts suppliers that use cleaner freight vehicles are also likely to reduce the conventional air pollutant emissions.

Construction

Infrastructure construction continuously appears as a major transportation life-cycle component across public and private modes. In particular, production and placement of asphalt and concrete produce significant greenhouse gas and conventional air pollutant effects. Hot-mix asphalt plants dominate greenhouse gas and conventional air pollutant emissions, however, the placement of that asphalt should also be a focus of LCA practitioners as it is likely to occur near populations. Cement kilns are the major source of air emissions in the concrete life-cycle. The kilns require significant energy and produce significant CO_2 and conventional air pollutant emissions. Kilns are the target of many environmental regulations and efforts to improve their energy efficiency or emission control devices will provide significant benefits in the life-cycle. Furthermore, transportation agencies can incorporate low-CO_2 concrete[4] into their infrastructure and should explore if these material options exist and if they cost more than traditional concrete.

Operation

For public transit systems, electricity for infrastructure operation is a common high-impact component in transportation LCAs. The component tends to show significant effects for rail and bus rapid transit infrastructure. For rail system, electricity required for train control, station HVAC and lighting, and signaling can be significant. For bus rapid transit systems, electricity for signaling can be significant. Strategies that reduce electricity use for these components, or rely on renewable electricity are likely to have benefits in the system's life-cycle footprint.

Energy production

Energy use for transportation systems is delivered through a complex system with components that also consume energy and generate emissions when performing their task. Energy production is a significant life-cycle component and captures the dynamic that it takes energy to produce and deliver energy. This is true for liquid fuels (e.g., gasoline or diesel), natural gas, electricity, or any other distributed energy form. Energy is consumed extracting the primary fuel, refining it, and transporting it. And along the way emissions are also produced from this energy consumption.

When possible, the LCA practitioner should make efforts to geographically and temporally track indicators. Inevitably, transportation agencies and decision makers performing LCA will identify effects that occur both inside and outside of their region. This introduces the interesting dynamic of reducing a transportation system's footprint by targeting processes indirectly related to the movement of the vehicle. Furthermore, effects may occur at different time periods in the system. While the emissions from combusting diesel fuel on a transit bus occur relatively continuously, the emissions from constructing the roadway that the bus uses occur in a short period of time well before the bus begins operations. Understanding this temporal dimension is critical for connecting emission inventories to the health and environmental impacts they may cause.

Assess impacts

The final stage of LCA is impact assessment, or the connection between energy use and emissions and the human health and environmental impacts they produce. For transportation LCA practitioners there are several impact categories that are of general concern: material depletion (including primary energy consumption), climate change, human health, and ecosystem quality. Material depletion impacts quantify the use of finite resources, whether that be materials used extensively in the system or the primary energy forms to which the system relies (for example, diesel fuel for a bus).

With the implementation of policies and an underlying societal concern for climate change, greenhouse gas emissions have become a major focus of many transportation agencies. Transportation agencies have also historically made significant strides to reduce conventional air pollutants, or those that cause human health and ecosystem damages. As resource constraints and environmental concerns grow, agencies will need to use impact assessment to move from inferences about quantities of energy consumed and emissions produced to an understanding of outcomes. Impact assessment will also help illuminate the paths towards reducing multiple impact categories at once.

Recommended system boundary for assessment of LCA environmental indicators

Grouping	Automobile (Gasoline)	Bus Rapid Transit	Light Rail Vehicle
Vehicle			
Manufacturing	▪ Automobile ▪ 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 Automobile Maintenance ▪ Tire Replacement ▪ Battery Replacement	▪ Typical Bus Maintenance ▪ Tire Replacement ▪ Battery Replacement	▪ Typical Train Maintenance ▪ Train Cleaning ▪ Flooring Replacement
Insurance	▪ Automobile 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	▪ Primary fuel extraction, Processing, & Distribution	▪ Primary fuel extraction, Processing, & Distribution	▪ Raw Fuel Extraction and Processing, Electricity Generation, Transmission & Distribution

Source: (Adapted from Chester and Horvath 2009)

Downstream effects of new transportation systems

In a prospective LCA, a practitioner might use ridership forecasts to estimate impacts per PMT. While there is some uncertainty in ridership forecasts, LCA practitioners can assess impacts versus a range of PMT forecasts. An increase in transit ridership is a primary effect of a new transit facility.

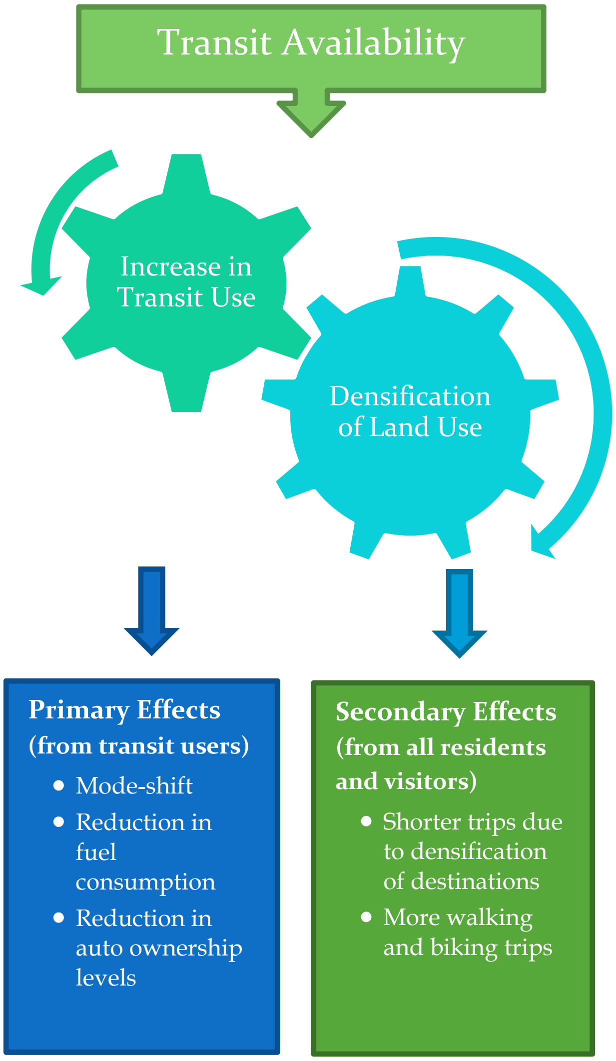
The availability of transit service also leads to secondary effects on land use patterns and travel behavior, which are more difficult to forecast. These secondary effects can lead to reductions in energy use and emissions beyond the primary effects of mode-shift.

One secondary effect of transit availability can be to reduce automobile ownership rates among households. When a household reduces the number of vehicles it has available because of transit, fewer vehicles are manufactured.

Another secondary effect is that residences near transit are often more compact, in that they have less space per occupant, and are more likely to be attached to other housing units in a single building. Both of these factors contribute to reduced energy needs for heating, cooling, and lighting. Additionally, larger, more efficient equipment can be used for attached housing and large, multitenant commercial buildings.[5]

Another secondary effect is that transit enables denser land use patterns, which lead to less driving among all residents, even those who never use transit. Researchers used modeling techniques to infer the influence of public transportation on land use patterns[6]. The group found that transit enables more compact land use, which can make trips shorter, reducing total travel and increasing the viability of biking and walking for some trips. They estimated the cumulative national total of these indirect effects to be a 30.1 million metric ton reduction in CO_2 emissions. This is over four times greater than

Primary and secondary effects of transit availability



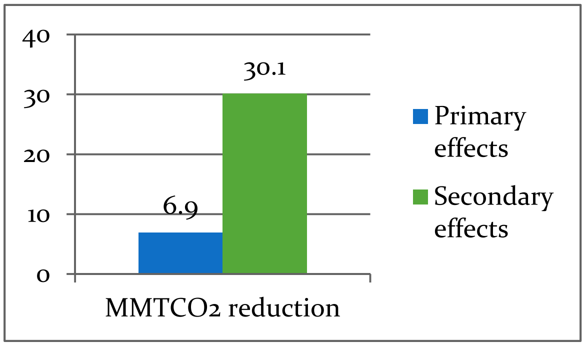
Primary Effects (from transit users)

- Mode-shift
- Reduction in fuel consumption
- Reduction in auto ownership levels

Secondary Effects (from all residents and visitors)

- Shorter trips due to densification of destinations
- More walking and biking trips

Annual National Effect of Transit on Total CO_2 Emissions Reductions from Transit

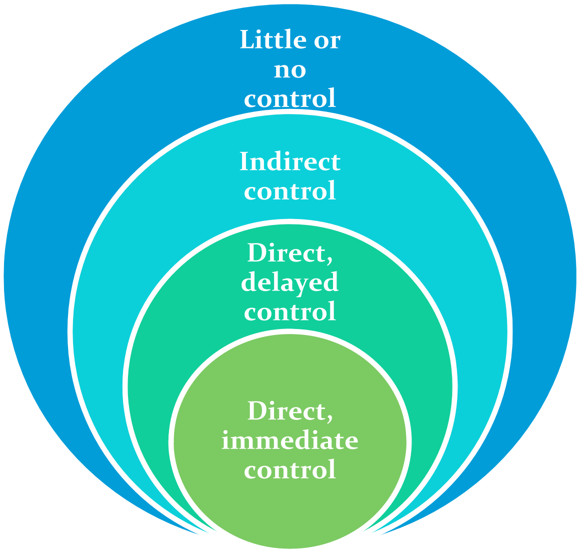


Source: (Bailey, Mokhtarian, Little, 2008) the 6.9 million metric ton reduction in CO_2 emissions found in an earlier study from mode-shift and congestion reduction resulting from transit availability[7]. Although the ratio of secondary effects to primary effects will differ based on local conditions, planners can consider whether the secondary effects generated in response to a new transit route or fixed guideway facility will be high or low.

Secondary effects will be higher in locations that are dense or have few barriers to densification, have complete pedestrian networks, desirable destinations to capture some trips within station areas, and complementary policies that can lead to a reduction in automobiles per household, like car share. The density required to support a transit line will vary based on the line's cost, capacity, and proportion of potential users in the area surrounding each station.

Secondary effects will be lower in areas that have barriers to densification, weak pedestrian connections to the transit station, and lack plans to capture local trips within the station area through a targeted mix of land use types.

Varied control over life-cycle components



Implementation Guidance

Efforts to implement policies based on LCA results can face several challenges. The first is that the control an agency has varies over different sources of life-cycle energy use and emissions. The second is that existing policies may complicate or efforts to make decisions based on LCA. The third is that not all emissions will affect an agency equally, and LCA that places equal weight on emissions regardless of location may not reflect local policy goals. A fourth challenge is that collecting quality data can be administratively burdensome, and an agency will likely face trade-offs with data quality. A final challenge is that there is no single point of the process to create a new transportation facility where its full life-cycle effects can be analyzed.

Control over life-cycle components

The level of control an agency has over a specific source of emissions or energy use will dictate the effort and timeline needed to affect those emissions. An agency which seeks to reduce the life-cycle energy and emissions impact of its capital projects and operations should first focus on factors over which it has the most control, or over which it can influence in the near term.

The control an agency has over a source of life-cycle energy use or emissions depends on its service delivery model.

Vehicle procurement

A transit agency which directly operates service has the greatest controls of its operations, and can typically implement strategies to reduce operational emissions and energy use more easily than agencies which purchase transportation.

For an agency that purchases transportation services, control will depend on whether or not the agency owns the vehicles. Agencies that maintain autonomy in vehicle purchase and replacement decisions can incorporate an assessment of the vehicle's construction, delivery, and operation phases into their selection process. An agency which outsources service provision to an owner-operator will likely have less immediate control factors which influence energy use and emissions. However, when entering into a new contract, an agency can specify terms and conditions that will affect energy use and emissions.

Vehicles versus infrastructure

Some decisions affecting transit energy use and emissions are made once a decade or less frequently. Vehicle purchase decisions are made regularly, but their consequences remain with the length of the contract and the life of the vehicles purchased. Agencies make decisions regarding infrastructure and heavy maintenance less frequently.

Transit agencies exercise indirect control over supplied goods and service. An agency's ability to affect change depends on the terms and length of their purchasing and service contracts. While an agency can address life-cycle emissions from short term contracts in the current planning period, integrating LCA into the sourcing process is one way to ensure that future long-term contracts for vehicles, equipment, and services consider upstream and downstream energy and emissions. Then, LCA will be considered along with other performance criteria when decision makers evaluate long-term contracts for vehicles and services.

Policy considerations

Even when an agency has direct control, the range of actions it can take can be limited by regulations and contractual obligations. Transit agencies are accustomed to a bevy of regulations and agreements which shape infrastructure planning and construction, vehicle purchases, service planning, and operations.

A legislative provision known as Buy America restricts Federal Transit Administration capital funding to vehicles that have 60% of value sourced from domestic sources. In California, the Air Resources Board Fleet Rule for Transit Agencies restricts tailpipe emissions and vehicle technologies. Thus, only a few manufacturers make transit vehicles intended for sale in the California market.

The California Environmental Quality Act (CEQA) review process may also drive increases in energy and emissions. The cause is not inherent to CEQA, but has become codified in many city & county planning review processes.

Grade separation is a significant driver of fixed guideway construction expenses, energy, and emissions. Grade separation may be preferable for a variety of reasons: to reduce aesthetic impacts, or minimize right-of-way acquisition. Grade separation can also be a mitigation measure for cases where operation of a new transit line will cause significant traffic impacts under CEQA. Local governments determine the methods used to measure traffic impacts and define their significance thresholds in their general planning process. Where significant traffic impacts will arise from the operation of new transit line, the agency must either implement the grade separation or issue a statement of overriding considerations.

Location of emissions

Because LCA tallies impacts from the manufacturing and construction phases in addition to operations, the analysis considers emissions both inside and outside of the region.

This analysis is useful for greenhouse gas emissions, where the location of the emission is irrelevant to the long-term impact the gasses will have on climate change.

However, criteria pollution emissions have a more immediate, localized impact and are regulated by the Clean Air Act. A region that is challenged to meet air quality standards will likely place higher importance on criteria emissions within the air basin than outside of it, as these local emissions will impact the region's ability to conform with regulations. Regions easily able to meet air quality standards may deem local criteria pollutant emissions more important than extra-regional emissions because the region will not bear the air quality and health impacts. While out-of-basin criteria pollutant emissions may be less significant to decision-makers, calculating these impacts is still important as it allows insight into the potential environmental effects of shifting production locally.

Data considerations

Many impact assessments are plagued by issues with data availability and quality. Imprecise data should not serve as a barrier to conducting LCA, but its use does require critical thinking about how possible errors will impact the assessment. In general the data needs to be good enough so that high-level decisions made based on the analysis wouldn't change if more precise data were available.

Data precision often comes at the expense of lengthy and potentially costly analysis, and an agency may choose to forgo this additional analysis when first incorporating LCA into its planning process.

However, by analyzing current data gaps, the agency can develop procedures to collect precise data that will facilitate future analyses. In future requests for proposals, the agency can incorporate manufacturing process disclosure requirements or consider requiring that suppliers perform a supply-chain LCA assess embodied energy and emissions in their vehicle creation and delivery process.

Incorporating LCA into existing processes

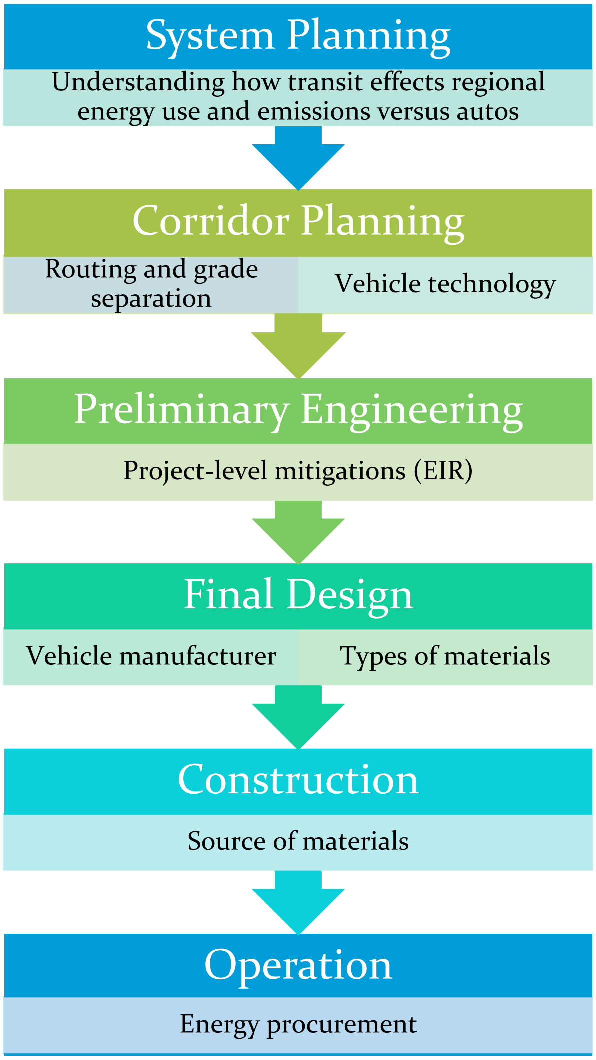
The recommended practice is to incorporate components of LCA at each phase of existing processes. This allows planners and decision-makers to use the best information available when comparing between project alternative to reduce a project's life-cycle energy use and emissions. While project decisions in all phases will affect life-cycle energy use and emissions, decisions made during corridor planning phase will have the most significant impacts.

Throughout each phase, an agency should assess among project alternatives, rather than across projects. Each transportation project is different and insufficient data exists to make normative comparisons between substantially different projects[8].

The result of **system planning** is often the Long Range Transportation Plan, which guides long-term capital investment. In the plan, an agency prioritizes future transit corridors by anticipated future revenue for capital expenditures. Information about future transit lines available at this stage is often short on specifics that would be required to generate a useful LCA for decision-makers. An agency may make decisions at this stage for a broad understanding of how an increase in transit service ability can affect life-cycle emissions and energy use versus an alternative of continued or increased auto use.

A transit agency will engage in **corridor planning** when it wishes to move forward with a project identified in the Long Range Transportation Plan. During this phase, the agency will consider specific right-of-ways and vehicle technology within a corridor. Each combination of right-of-way and vehicle technology can be analyzed, along with transportation system management and no-build alternatives, in a federally-mandated Alternatives Analysis report. Because of the breadth of scope, but also specificity of analysis, the Alternatives Analysis phase is highly appropriate for LCA. At this stage of the transit project development process sufficient information is usually available to analyze substantially differing alternatives with an acceptable degree of precision, and the results of that analysis can still have an impact on decision-making. After an agency completes the Alternatives Analysis and selects a Locally Preferred Alternative it can make fine-tuned adjustments that will affect project energy use and emissions, but it has already decided the factors which will have the greatest impact on life-cycle emissions and energy use: route, grade separation, and vehicle technology.

Incorporating LCA into existing processes



In preparation of cost estimates for the Alternatives Analysis, an agency will generate approximate information about miles of bridged, above-grade, at-grade, trenched, cut-and-cover, or deep bore tunnel needed for the route. Alternatives with substantial variations in the amount of required grade separation will have significantly different life-cycle energy use and emissions impacts.

Additionally, the agency can analyze the anticipated energy use and emissions from different vehicle technologies. These figures should be normalized by vehicle miles traveled and vehicle capacity in order to make valid comparisons for vehicles of different sizes. While the analysis will be more precise after the agency has selected a manufacturer, during this phase it can make decisions based on efficiency variations inherent to a vehicle technology.

In **preliminary engineering**, planners and engineers consider macro and meso-scale issues that will impact the project and the surrounding areas. During this phase, a project team might discover the need to fortify or replace an existing bridge to accommodate transit vehicles. It might also fine tune the estimates of grade separated track that might be needed for the project.

During preliminary engineering, planners examine the environmental impacts of both the construction and operation phases of the transit line. Planners will look at the potential criteria pollutant emissions from construction equipment and vehicles, and propose that vehicles used on the project meet current or future state and federal emissions guidelines. Such a proposal would reduce life-cycle emissions in the construction phase. These and other impacts and mitigation measures are presented to decision-makers in an Environmental Impact Report or Environmental Impact Statement.

Issues identified during the **final design** phase will have a small but significant impact on project life-cycle energy use and emissions. In this stage, the agency may make a determination on vehicle procurement. Even if the energy use needed to forge steel and construct a vehicle is similar across manufacturers, local energy mix and emissions controls will dictate the resulting criteria and greenhouse gas emissions. Emissions and energy use required to transport a vehicle between the initial construction location, final assembly location, and the project site will differ among manufacturers.

During the final design phase, project planners will also decide material types. Low energy asphalt mixes or low-carbon cement are design options that can reduce project energy use and emissions.

During the **construction** phase a build contractor will procure steel, asphalt, concrete, and other materials. Variations in the source of these materials, notably steel, will lead to different life-cycle energy and emissions outcomes.

When a new transit line moves to the **operation** phase, an agency can implement a low energy and emissions operating plan that includes measure to procure electricity for traction power with an emissions factor that is lower than the U.S. EPA eGrid average or utility-specific emissions factor for the area[9]. For natural gas buses, the agency can source natural gas with high biogenic content (e.g. landfill gas or byproducts of wastewater treatment) or take precautions to reduce fugitive methane emissions from tanks and during fueling. For diesel vehicles, agencies can procure diesel fuel with high biogenic content (biodiesel).

Conclusions and Recommendations

Rather than performing a full LCA of current and future infrastructure and operations, many agencies will implement LCA incrementally through their planning processes and when considering contracts. This incremental approach can be effective as agencies consider LCA impacts as they are faced with decisions, for example when considering a contract to purchase new vehicles or considering the routing and vehicle technology of a new fixed guideway system. Additionally, the contracting process is appropriate for addressing impacts as hot-spots tend to correlate with high non-labor and capital expenditures.

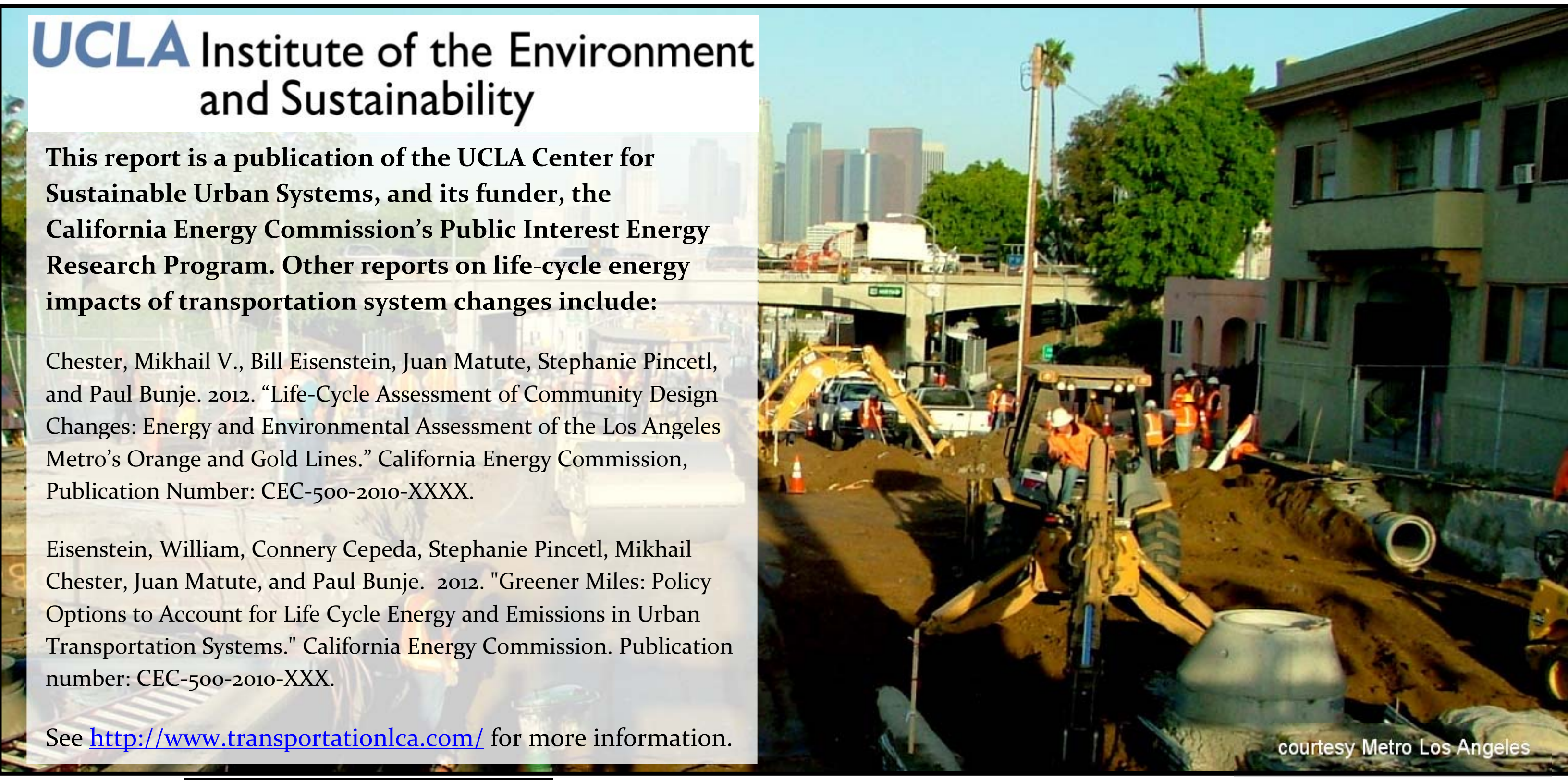
A transit agency can take immediate or near-term steps to address life-cycle emissions by using clean electricity for infrastructure operation. For liquid and natural gas fuels, an agency can look at fuel production cycle emissions and consider biofuels with low energy production requirements or a low anthropogenic content[10]. An agency can also take direct measures to increase the efficiency of its vehicles and operations.

California is already pursuing policies that will reduce the baseline greenhouse gas emissions associated with vehicle propulsion over time. The State's Renewable Portfolio Standard will lead to the continued reduction of emissions per megawatt hour used in vehicle operation, facility operations, and maintenance. The Low Carbon Fuel Standard will increase the proportion of renewable, biogenic carbon in the state's transportation fuels. Further study is required to determine of the net effects of these and other policies means a relatively cleaner future for electric traction or internal combustion engine vehicles.

In evaluating system performance, agencies should be aware that increases in the vehicle occupancy can reduce per-PMT indicators. Thus, an agency can reduce the normalized life-cycle impacts of its infrastructure and operations by increasing its service effectiveness. A combination of an increase in service effectiveness and a reduction in energy use or emissions will accelerate an agency's progress as measured through performance indicators.

A transit agency that seeks to exceed these statewide baselines must actively strive to reduce cradle-to-grave energy use and emissions associated with its activities. The State can assist these agencies by leveraging economies of scale in LCA that would benefit several agencies. For example, the California Air Resources Board or other state agency could perform a regular assessment of life-cycle emissions from transit vehicles available for purchase in California. A local air quality management district might perform an assessment of life-cycle emissions for concrete and asphalt distributed locally. Local agencies could then incorporate this information into their decision-making without devoting local resources to the analysis. This would make the process of incorporating LCA into California's transportation decision-making more efficient.

Ultimately the success of LCA in driving transportation decision-making will depend on how deeply the practice is integrated within an agency. While an agency can take incremental steps to introduce LCA on an ad-hoc basis, a transportation agency which seeks to lead the field in reducing the life-cycle impacts of its construction projects and operations will need to systematically introduce LCA into all aspects of its planning and operations.


courtesy Metro Los Angeles

UCLA Institute of the Environment and Sustainability

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Chester, Mikhail V., Bill Eisenstein, Juan Matute, Stephanie Pincetl, and Paul Bunje. 2012. "Life-Cycle Assessment of Community Design Changes: Energy and Environmental Assessment of the Los Angeles Metro's Orange and Gold Lines." California Energy Commission, Publication Number: CEC-500-2010-XXXX.

Eisenstein, William, Connery Cepeda, Stephanie Pincetl, Mikhail Chester, Juan Matute, and Paul Bunje. 2012. "Greener Miles: Policy Options to Account for Life Cycle Energy and Emissions in Urban Transportation Systems." California Energy Commission. Publication number: CEC-500-2010-XXX.

See http://www.transportationlca.com/ for more information.

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[1] SB 375, 2008, Senator Darrell Steinberg

[2] Executive Order S-01-07

[3] For an example, see Michalek, Jeremy, Mikhail Chester, Paulina Jaramillo, Constantine Samaras, Ching-Shin Norman Shiau, and Lester B. Lave. 2011 "Valuation of plug-in Vehicle life-cycle air emissions and oil displacement benefits." Proceedings of the National Academy of Sciences.

[4] i.e., through the use of supplementary cementitious materials such as ground granulated blast furnace slag or fly ash

[5] Ewing, Reid, Keith Bartholomew, Steve Winkelman, Jerry Walters, and Don Chen. 2008. *Growing Cooler: The Evidence of Urban Development and Climate Change*. 2008.

[6] Bailey, Linda, Patricia L. Mokhtarian, and Andrew Little. 2008. "The Broader Connection between Public Transportation, Energy Conservation and Greenhouse Gas Reduction." ICF International.

[7] ICF. 2007. "Public Transportation and Petroleum Savings in the U.S.: Reducing Dependence on Oil." American Public Transportation Association.

[8] For more information, see The "Greener Miles" report by William Eisenstein (see above call-out box)

[9] See http://cfpub.epa.gov/egridweb/ for more information

[10] When combusted, the renewable, or biogenic, portion of biofuels produces emissions that do not add new carbon dioxide to the atmosphere. The anthropogenic portion of biofuels represents mass derived from fossil-fuel, or from energy used to process the biofuels.