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Life-cycle assessment of high-speed rail: the case of California

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Abstract
The state of California is expected to have significant population growth in the next half-century resulting in additional passenger transportation demand. Planning for a high-speed rail system connecting San Diego, Los Angeles, San Francisco, and Sacramento as well as many population centers between is now underway. The considerable investment in California high-speed rail has been debated for some time and now includes the energy and environmental tradeoffs. The per-trip energy consumption, greenhouse gas emissions, and other emissions are often compared against the alternatives (automobiles, heavy rail, and aircraft), but typically only considering vehicle operation. An environmental life-cycle assessment of the four modes was created to compare both direct effects of vehicle operation and indirect effects from vehicle, infrastructure, and fuel components. Energy consumption, greenhouse gas emissions, and SO_2, CO, NO_X, VOC, and PM_{10} emissions were evaluated. The energy and emission intensities of each mode were normalized per passenger kilometer traveled by using high and low occupancies to illustrate the range in modal environmental performance at potential ridership levels. While high-speed rail has the potential to be the lowest energy consumer and greenhouse gas emitter, appropriate planning and continued investment would be needed to ensure sustained high occupancy. The time to environmental payback is discussed highlighting the ridership conditions where high-speed rail will or will not produce fewer environmental burdens than existing modes. Furthermore, environmental tradeoffs may occur. High-speed rail may lower energy consumption and greenhouse gas emissions per trip but can create more SO_2 emissions (given the current electricity mix) leading to environmental acidification and human health issues. The significance of life-cycle inventorying is discussed as well as the potential of increasing occupancy on mass transit modes.

Keywords: passenger transportation, life-cycle assessment, California, high-speed rail, trains, cars, autos, aircraft, planes, energy, fuel, emissions, greenhouse gas, criteria air pollutants

S Supplementary data are available from stacks.iop.org/ERL/5/014003/mmedia

1. Introduction

The implementation of a high-speed rail (HSR) service in the United States is of significant interest to transportation planners to reduce the burden of automobile and air travel in congested corridors. Several HSR systems have been proposed throughout the United States. California stands as one the few states that has invested significant funding and garnered substantial public interest which may propel the California HSR (CAHSR) conceptualized system into the design phase. HSR investment is a complex decision that includes technical, social, economic, and environmental tradeoff considerations. It is contended that the economic investment in CAHSR could provide a higher level of passenger service (reduced door-to-door trip times and lower cost trips) than equivalent investment in auto, air, and even heavy rail transit (HRT) in

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the California corridor (San Diego to Los Angeles to San Francisco to Sacramento) (CAHSRA 2005). However, the outcome of such a new system in an untested market is uncertain (Levinson *et al* 1997). From total construction costs to ridership levels, the success of the proposed CAHSR system is affected by many factors. One such factor is the reduction of environmental burdens over existing modes. With increased concern for fossil energy use and climate change, CAHSR is often touted as less energy intense and greenhouse gas (GHG) emitting than autos, HRT, and aircraft. This assumes that CAHSR trains are of a particular design, operate at some level of service, and achieve a particular passenger utilization. This improved performance does not consider the life-cycle components beyond the electricity needed to move vehicles, and their corresponding emissions at power plants. Vehicle manufacturing and maintenance energy and emissions are important, as are those resulting from infrastructure and electricity production life-cycle components. The environmental tradeoffs of the CAHSR system should be evaluated from a life-cycle perspective against other modes so that total environmental accounting and its associated costs are transparent in policy and decision-making.

Life-cycle environmental inventorying should capture the energy inputs and emission outputs for vehicle, infrastructure, and fuel production components, including the associated supply chains. For each grouping, construction/production, use/operation, maintenance, and end-of-life components can be evaluated. Previous transportation life-cycle assessments (LCA) highlight the importance of including vehicle, infrastructure, fuel, and supply chain components in modal energy and emission performance (Chester and Horvath 2009, Facanha and Horvath 2007, Maclean and Lave 1998, Lave 1977). These studies show that it is not uncommon for life-cycle components to increase total energy consumption and emissions significantly from just vehicle operation, sometimes accounting for the large majority of emissions (e.g., Chester and Horvath (2009) shows that the bulk of SO_2 emissions in an automobile's life-cycle are from fossil-based electricity generation in vehicle manufacturing, infrastructure construction and operation, and petroleum refining, with only a small portion from the vehicle's tailpipe).

No published life-cycle inventory (LCI) of HSR exists. Several environmental assessments have been performed, and focus on European and Japanese systems. The existing environmental assessments of HSR focused on the direct electricity use and corresponding power plant emissions from train active operation energy requirements. These studies often detail environmental tradeoffs between HSR and other modes or operating conditions to illustrate potential energy and emission reductions (Givoni 2007, Andersson and Lukaszewicz 2006, Janic 2003, van Wee *et al* 2003, Lynch 1990). Other studies have quantified the total costs of HSR against automobile or air travel investments by including emission externalities (de Rus and Nombela 2007, de Rus and Inglada 1997, Levinson *et al* 1997). HSR's contribution to sustainable transportation goals has also been discussed (Azar *et al* 2003, Smith 2003) A comprehensive cost assessment was found to be critical in evaluating the effectiveness of new rail systems (Webber 1976).

This paper highlights many of the critical considerations for transportation planners and other decision-makers in determining the benefits and costs of HSR investment over other modes. However, the addition of a life-cycle framework to the environmental valuation of HSR is critical in determining the total impacts of these systems.

2. Methodology for inventorying energy and emissions

CAHSR is compared to automobiles, HRT, and aircraft travel. Currently in the California corridor, automobiles account for roughly 90% of trips and 75% of passenger kilometers traveled (PKT), HRT 1% and 1%, and air 9% and 24% (CASYS 2007). While other modes exist in the corridor (e.g., bus and vanpool), we have chosen these three vehicles because they currently dominate travel in the corridor and are expected to be the direct CAHSR competitors.

The CAHSR inventory is determined by estimating energy consumption and resulting emissions from vehicle, infrastructure, and electricity production components. The methodology follows Chester and Horvath (2009), which details the LCI of automobiles, buses, commuter rail, and aircraft. Additionally, Chester (2008) provides much of the detail behind the inventorying of these modes as well as for CAHSR. The life-cycle components are aggregated into vehicle, infrastructure, and fuel groupings for reporting and discussion. Component details are found in table 1. For each component, energy inputs and emissions of greenhouse gases (GHG, reported in CO_2 equivalence, CO_2e), SO_2, CO, NO_X, VOC, and PM_{10} are inventoried. Automobile and aircraft LCI correspond to those in Chester and Horvath (2009) (and automobile fuel economy has been adjusted to reflect highway driving).

The groupings incorporate the critical life-cycle components associated with the CAHSR system. Vehicle active operation captures propulsion electricity while inactive operation captures idling and HVAC requirements. The CAHSR Authority's (the organization lobbying for CAHSR) vehicle electricity consumption estimate of 170 kWh per vehicle kilometer traveled (VKT) is based on the German ICE HSR, a similar train to the expected vehicle design (CAHSRA 2005). SimaPro (2006) is used with the Ecoinvent 1.3 database to produce an LCA for HSR manufacturing of the projected 86 trains in the system, using the Western Electricity Coordinating Council (WECC) electricity mix, and are based on actual German ICE manufacturing data (Deru and Torcellini 2007, CAHSRA 2005, Frischknecht *et al* 2005). While the CAHSR system will operate in a state with a relatively moderate fossil fuel production mix, the import of coal-based electricity changes the emissions profile of the mode (Marriott and Matthews 2005). Mandates for CAHSR to purchase cleaner electricity have not been established so the WECC mix has been used to capture electricity imports to California and provides a more reasonable estimate of the electricity consumption profile with additional use of out-of-state carbon-intense fuels. Standard upkeep, cleaning, and flooring replacement are included in the vehicle maintenance grouping (EIO-LCA 2008, SimaPro 2006). The indirect effect

Table 1. Life-cycle components included in modal inventories.

Component	Automobiles	Rail	Aircraft
Vehicle components grouping			
Active operation	Running Cold start	Running (propulsion)	Take off Climb out Cruise Approach Landing
Inactive operation	Idling	Idling Auxiliaries (heating, ventilation, air conditioning, and lighting)	Auxiliary power unit operation Startup Taxi out Taxi in
Manufacturing (facility construction excluded)	Vehicle manufacturing Engine manufacturing	Train manufacturing	Aircraft manufacturing Engine manufacturing
Maintenance	Vehicle maintenance Tire replacement	Train maintenance Train cleaning Flooring replacement	Aircraft maintenance Engine maintenance
Insurance	Vehicle liability	Crew health and benefits Train liability	Crew health and benefits Aircraft liability
Infrastructure components grouping			
Construction	Roadway construction	Station construction Track construction	Airport construction Runway/taxiway/tarmac construction
Operation	Roadway lighting Herbicide spraying Roadway salting	Station lighting Escalators Train control Station parking lighting Station miscellaneous (e.g., other electrical equipment)	Runway lighting Deicing fluid production Ground support equipment operation
Maintenance	Roadway maintenance	Station maintenance Station reconstruction Station cleaning Track maintenance	Airport maintenance
Parking construction and maintenance	Roadside, surface lot, and parking garage parking	Station parking	Airport parking
Insurance	Infrastructure benefits and liability (e.g., automechanics and construction workers)	Non-crew health insurance and benefits Infrastructure liability insurance	Non-crew health and benefits Infrastructure liability
Fuel components grouping			
Gasoline, diesel, jet A, and electricity production	Gasoline and diesel fuel refining and distribution (includes through fuel truck delivery stopping at fuel station. Service station construction and operation is excluded)	CAHSR operational electricity generation upstream requirements HRT diesel fuel extraction, transport, refining and distribution CAHSR electricity transmission and distribution losses CAHSR and HRT infrastructure electricity generation upstream requirements CAHSR and HRT infrastructure electricity transmission and distribution losses	Jet fuel refining and distribution

of energy use and emissions from insurance services can be significant for transportation modes so vehicle health benefits and liability are bundled (Chester and Horvath 2009). The production and placement of concrete and steel in construction is evaluated for the 25 stations (EIO-LCA 2008, Guggemos and Horvath 2005). Because station designs do not yet exist, stations are evaluated as platforms, and buildings are not included (Chester 2008). The station construction assessment is conservative considering the large transit terminals currently under discussion for major cities. Station operation includes lighting, escalators, and train control systems (FTA 2007, Fels 1978). Station maintenance consists of routine work (assumed to be 5% annually of initial construction requirements) and cleaning which takes place every other day (Paulsen 2003). Assuming 25 000 system-wide spaces (1000 per station), parking lot construction and maintenance energy requirements and emissions are included (PaLATE 2004, Santero and Horvath 2009). Construction of the 1100 km of two-way track and the power delivery system includes aggregate, concrete, steel, wood, and power structure material and component requirements and placement (CAHSRA 2005, Guggemos and Horvath 2005). Using preliminary design estimates, track construction is evaluated by specific segment types: at-grade (including elevated on fill and open cut), underground, and aerial (PB 1999). For each of these track types, material production, material transport, site work, and installation are included (EIO-LCA 2008, SimaPro 2006, EPA 2004). SimaPro (2006) is used to determine HSR track maintenance requirements. Similarly to vehicles, the liability insurance for infrastructure components is included. For electricity production, WECC factors are used throughout all electricity production components and include extraction, processing, and transport of primary fuels as well as electricity conversion efficiencies and transmission and distribution (T&D) losses (Deru and Torcellini 2007). Additional details of the critical parameters in the CAHSR LCI are found in the supplementary data (available at stacks.iop.org/ERL/5/014003/mmedia) as well as Chester (2008).

The HRT LCI calculates the energy and emissions of the California Amtrak network, a long-distance diesel locomotive system. The methodology used to evaluate HRT is similar to that used to evaluate Caltrain in Chester and Horvath (2009), however, the two systems provide different travel purposes (long-distance versus commuter trips) resulting in different environmental performance. The fundamental parameters used to evaluate the HRT LCI are detailed in the supplementary data (available at stacks.iop.org/ERL/5/014003/mmedia). For aircraft, high altitude CO_2 emissions adjustment factors are not implemented. A life-cycle impact assessment should include these adjustments (such as global warming potential calculations of GHG emissions), but the scope of this LCI stops short of quantification of environmental or human health impacts.

3. Ridership estimates and occupancy uncertainty

The assessment of energy and emissions across life-cycle components requires normalization of results to common functional units. The normalization of results per VKT is based on CAHSRA (2005) forecasting of 35 million annual VKT by 2020. Trains will have between 650 and 1200 seats depending on ridership forecasts and train configuration (CAHSRA 2005). This range in ridership presents significant differences in the potential energy and environmental performance of the system. One goal of the HSR system is to serve PKT that are less of a burden on the environment than other transportation modes. However, the range in potential ridership highlights the utilization possibilities of the proposed system. To evaluate the life-cycle environmental performance of the CAHSR system, both the low and high occupancies should be considered with their corresponding PKT. This should be compared against low and high occupancy automobiles, HRT, and aircraft. To capture the potential occupancy ranges, realistic riderships are applied. For HSR, the low is set as 120 passengers (10% occupancy of the longest trains, a proxy for a mostly empty train) and the high as 1200 passengers (maximum seats on the longest trains) (CAHSRA 2005). The CAHSR Authority has completed an energy assessment using an average occupancy of 761 passengers (63% utilization) when the system is fully constructed and is operationally mature (CAHSRA 2005). The adoption period where passengers switch from autos, HRT, and air to CAHSR will be determined by many factors, including cost and time competitiveness. While the utilization and ultimate ridership success of CAHSR is difficult to predict, it is likely that a low utilization (and poor energy and emissions performance) adoption period will be needed for the system to reach full ridership potential. It is also unclear if the large trainsets (16 cars with 75 seats each) will be pursued in the final design or if smaller trains (with seating for around 600 passengers, similar to current HSR systems, and requiring less electricity per VKT) will be considered (CAHSRA 2005).

Automobile, HRT, and aircraft low, high, and average occupancies are also assessed. For autos, the low is set as 1 passenger and high at 5 passengers, with an average of 2.2, based on travel statistics between Northern and Southern California (MTC 2000). HRT is specified as 35 passengers (10% occupancy) for the low and 350 for the high (100% utilization). Currently, the main Amtrak lines which operate in this corridor have between 100 and 150 passengers on average, which is around 35% utilization (Caltrans 2007). Between California airports, the average aircraft has 120 seats, average occupancy is 81 passengers, and a low of 24 passengers is used (20% occupancy) in our calculations (USDOT 2007). While the specified low occupancies may not be the technical minimum of a mode (1 passenger), they are meant to represent realistic under-utilized travel. These occupancy ranges coupled with per-VKT energy and emissions factors (supplementary data figure S1 available at stacks.iop.org/ERL/5/014003/mmedia, Chester and Horvath 2009, Chester 2008) result in a range in the per-PKT energy and emission factors for each mode.

4. Inventory results

Figure 1 shows the life-cycle energy and emissions performance of each mode at both low and high occupancy. At high occupancy, the per-PKT energy and emissions are at their lowest because the environmental performance is distributed over a large number of passengers. In figure 1, the grayscale components (vehicle active and inactive operation) are the direct end-use energy (and resulting emissions) requirements that are often used as the entire environmental performance of the mode. The colored sections of the bars are the other life-cycle components (blue bars are vehicle-related, red/orange are infrastructure, and green are energy production). The life-cycle energy and emissions inventory for CAHSR shows similar significant life-cycle components to the other modes:

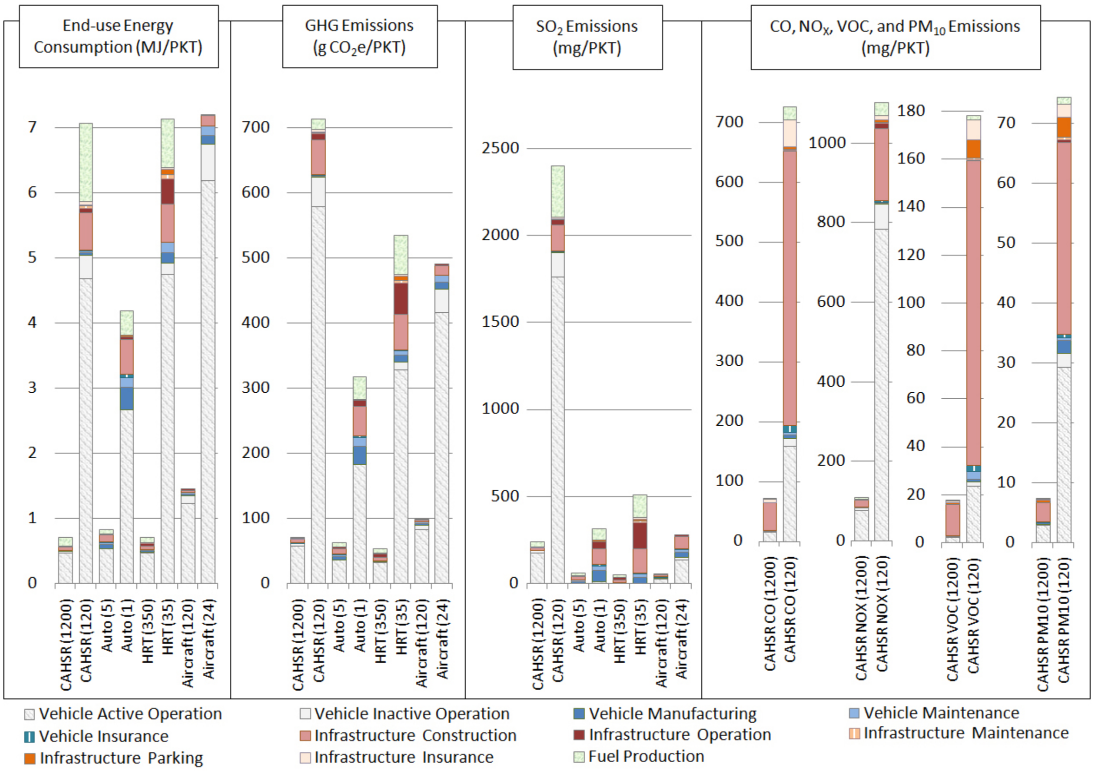

Figure 1. Energy and emissions life-cycle results per PKT. (For each mode the per-PKT performance at both low and high occupancy is shown. The best energy and emissions performance per PKT is achieved at high occupancy. The per-VKT results are found in supplementary data figure SI (available at stacks.iop.org/ERL/5/014003/mmedia).)

vehicle manufacturing, vehicle maintenance, infrastructure construction, infrastructure maintenance, and fuel production.

The energy and GHG performance of CAHSR is dominated by active operation but shows significant contributions from infrastructure construction and fuel (electricity) production. The primary contribution to the infrastructure construction component is from concrete and steel material production. Construction of retaining walls and aerial track segments are the two largest concrete requirements in the inventory (PB 1999). The production of concrete is energy intensive and releases CO_2 in cement production from both fossil fuel use for kilns in clinker production and the calcination of limestone. The extraction, processing, and transport of primary energy inputs as well as an 8.4% T&D loss result in indirect energy and GHG effects as a result of direct electricity use (Deru and Torcellini 2007).

The contribution of life-cycle component SO_2, CO, NO_X, VOC, and PM_{10} emissions against operational emissions can show dominating results. The CAHSR system shows much larger SO_2 emissions than the other modes because the primary fuel input is electricity. For automobiles and HRT which use low-sulfur fuels, life-cycle components dominate total performance. This is often due to electricity requirements throughout the supply chain, particularly in material production for infrastructure construction and assembly processes in vehicle manufacturing. The CO, NO_X, VOC, and PM_{10} emissions for CAHSR are shown to highlight the importance of life-cycle considerations and the dominating contributions from infrastructure construction. The infrastructure construction component for these emissions is typically larger than emissions from vehicle operation (due to material production, processing, and diesel truck and equipment use). Chester and Horvath (2009) details the counterpart emissions for automobiles, heavy rail, and air travel.

The per-PKT LCI factors can be evaluated as average or marginal energy and emissions depending on the life-cycle components included. The energy and emissions factors for existing modes evaluate the current infrastructure and do not include expansion to meet growth forecasts. By including all life-cycle components, average assessments are made because they include all vehicle, infrastructure, and fuel requirements to provide some expected level of service. In comparing the new CAHSR infrastructure with existing modes, it is necessary to evaluate marginal effects because the alternative to the new rail infrastructure is an expansion of automobile, aircraft, and HRT services. The marginal LCI factors can be determined by considering the fixed and variable components, primarily the infrastructure grouping. For the existing modes, the vested infrastructure may have the capacity to facilitate additional PKT without expansion and this should be taken into account when apportioning the component in assessing marginal effects.

5. Tradeoffs and payback

The investment in a new HSR infrastructure can offer transportation energy consumption and GHG emission

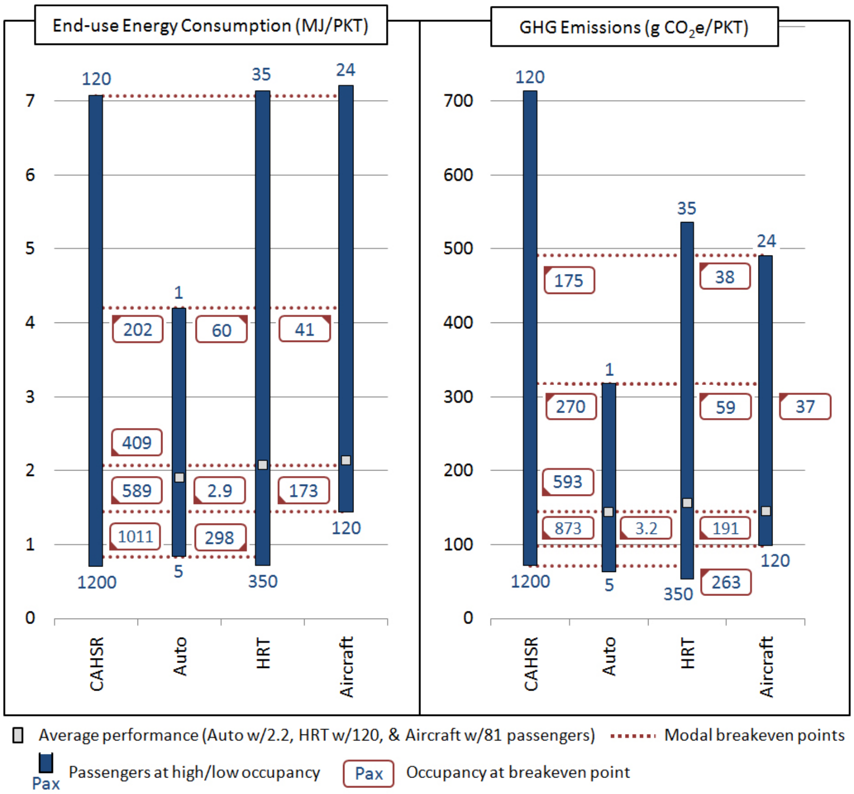

Figure 2. End-use energy consumption and GHG emission passenger equivalencies.

reductions over the *status quo*. However, these benefits should not be taken as a given since they are contingent on many factors, one of the most critical being utilization. While the environmental performance of a mode at average occupancy can be a useful metric for some comparisons, it is critical to look at the off-peak and peak ridership to assess the range in performance. While at the average one mode may outperform another, there may be particular times when this is not the case. By evaluating the energy consumption and GHG emissions of the four modes from low to high occupancy, breakeven points can be established that show at what level of utilization the modes compete.

Figure 2 shows the range in energy consumption and GHG emissions per PKT as vertical bars. The horizontal dotted lines are critical breakeven points where one mode is better or worse than another (and the balloons identify the occupancy of the mode at that breakeven point). The vertical distance between breakeven points is the range in which modes are energy or GHG competitive. For example, a car with 5 passengers is energy-equivalent to CAHSR with 1011 passengers and HRT with 298 passengers. The ranges and breakeven points highlight several concepts that should be considered when evaluating investment in one mode over another. The use of average environmental factors can hide the full potential of a mode. And while one mode may outperform the other at their average occupancies, there are many ridership levels where this may not be the case. From an environmental decision making perspective, this consideration is important when uncertainty is expressed in forecasted ridership levels. While a mode may not be as environmentally friendly as another mode at average occupancy, figure 2 shows the potential for improvement. Some modes have significantly higher occupancy levels than other modes, and filling empty seats for a trip that will happen regardless can improve the environmental performance of the mode at potentially lower cost and resource investment than alternatives.

The energy and GHG payback for the CAHSR investment varies significantly depending on utilization of all competing modes in the corridor. A time until return on investment (ROI) can be determined for construction of the CAHSR system, which we estimate at 9.7 million Mg CO_2e, roughly 2% of California's 490 million Mg CO_2e emitted in 2004 (CEC 2006). The ranges in potential occupancy levels for each mode can produce scenarios where CAHSR will or will not outperform the other modes. Assuming that autos currently capture 75% of PKT, HRT 1%, and air 24%, the time until ROI is determined (CASYS 2007). Including all non-operational life-cycle components, the energy and GHG emissions ROI ranges from 8 and 6 years to never as shown in table 2. At mid-level occupancy for all modes the ROI is achieved at 28 years for energy and 71 years for GHG emissions. The GHG ROI can be reduced with the purchase of less carbon-intense electricity.

These modal splits do not take into account the adoption period for CAHSR, which would increase the time until ROI. They also do not account for the use of less carbon-intense electricity purchases. An ROI for SO_2 emissions is not achieved for CAHSR in any of the scenarios. This illustrates the tradeoff of switching to a potentially lower energy-consuming and GHG-emitting mode reducing climate

Table 2. Return on investment modal utilization assumptions and results. (Note: Loading denotes the percentage of seats filled.)

	Automobiles, HRT, and air at low occupancy, CAHSR at high occupancy	Automobiles, HRT, and air at high occupancy, CAHSR at low occupancy	Automobiles, HRT, and air at mid-level occupancy, CAHSR at mid-level occupancy
CAHSR loading	75%	25%	50%
Automobile passengers	2	2.5	2.25
HRT loading	25%	75%	40%
Air loading	50%	90%	85%
CAHSR energy ROI	8 years	Never	28 years
CAHSR GHG ROI	6 years	Never	71 years

change impacts while increasing environmental acidification burdens.

6. Discussion

The decision to construct a HSR system in the California corridor will have direct and indirect energy and emissions impacts that should be evaluated through LCA. Environmental valuation often pits the propulsion (vehicle operation) energy intensity of CAHSR against the other modes. This LCI highlights the indirect consequences of each modal alternative in the corridor and presents several environmental considerations. While energy and GHG emissions are important, so are the impacts of the release of other emissions. Although CAHSR may have lower GHG emissions under particular occupancy conditions, because it is powered by electricity, higher SO_2 emissions will result in switches from existing modes leading to environmental acidification issues as well as direct human health impacts. Furthermore, the LCI creates the ability to more comprehensively target reductions. For example, the large concrete requirements needed in rail infrastructure produces significant GHG emissions. Decision-makers who invest in CAHSR can reduce the mode's total GHG emissions by using lower-CO_2 concrete mix designs (Gartner 2004) or by reducing system concrete use when designing tracks.

Occupancy ranges are highlighted instead of average ridership to stress the broad range in environmental performance of the modes. The use of average energy consumption or emissions can be misleading because it hides the sometimes significant variation in ridership, particularly for mass transit modes. Results are presented showing low to high occupancy levels to illustrate the importance of evaluating modes across this range in developing more well-formed policy that does not treat modes as universally better or worse than others. Decisions should not be made on average performance but instead on the potential to increase passengers during off-peak or low ridership times. This is an important consideration for any public transit mode but particularly for CAHSR given the potential massive new investment and the ability to construct the system with transit-oriented development in mind. The accessibility and frequency of service are two important factors affecting potential CAHSR ridership. The implications of transit hubbing and community development around CAHSR stations are crucial for increasing utilization. It is important to acknowledge that trips are often not uni-modal, as the beginning and end of travel may occur on different modes than the line-haul mode. This has energy and environmental implications when considering trip travel instead of per-PKT travel on a particular mode. Additionally, the use of large trains (1200 passengers) over small trains (e.g., 650 passengers) may affect frequency resulting in different mode choices by passengers. Demand analyses can consider the energy and environmental per-PKT tradeoffs of large trains with reduced frequency and small trains with increased frequency to inform decision-makers in reaching environmental goals. It could also consider the effects of the different configurations on system-wide modal shares and resulting energy demand and emissions for California. The CAHSR system offers the potential to provide lower energy and emissions transportation, but should be assessed within the life-cycle framework and with the myriad of factors that affect ridership.

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