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Life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system

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ABSTRACT

This study estimates of the life cycle greenhouse gas inventory for construction of high-speed rail infrastructure from San Francisco to Anaheim indicates it will result in 2.4 million metric tons of CO_2 with material production comprising 80% of emissions and transportation of construction materials, 16%. While tunneling and aerial structures account for only 15% of the route's length, they are responsible for 60% of emissions. Based on estimates of avoided emissions from operation of the system of just over one million metric tons of CO_2 per year, construction emissions would be recuperated in about two years and their global warming effect in about six after services begin. This range of recuperation times is relatively short given the long-life of the constructed infrastructure. Avoided emissions estimates are dependent on ridership and if low ridership lead to a 75% decrease in offset emissions, recuperation times may increase to more than 20 years.

1. Introduction

In 2008 the California public voted to support nearly 10 billion dollars in bonds for all stages of planning and construction of a high-speed rail (HSR) system for California. At the time of its completion, construction of the HSR system is expected to cost 45 billion dollars, making it the largest infrastructure project in the state in 50 years.

This enormous public investment in HSR comes at the same time that California begins implementing greenhouse gas (GHG) reduction strategies to meet regulatory commitments for climate change mitigation. Both the California High-Speed Rail Authority (CHSRA) and the California Air Resources Board (CARB) (2008) estimate that the proposed HSR system will reduce GHG emissions by offsetting auto and air travel. CARB estimates the HSR system may reduce annual emissions by 1.15 million metric tons of CO_2-equivalent (Mt CO_2e). CHSRA is even more optimistic – proposing an estimated reduction of 3.08 Mt CO_2e per year by 2030 (California High-Speed Rail Authority, 2008). However, not only do these emissions reduction estimates hinge on assumptions about ridership and the performance of the other passenger modes, neither considers the upfront emissions that would result from construction of HSR infrastructure.

This study estimates construction-related GHG emissions of the HSR trackbed and its supporting infrastructure through a process-based life cycle assessment (LCA). Construction of trackbed, electrification infrastructure, cut-and-fill operations, aerial structures, and tunnels are all characterized. This analysis is the first to ever characterize life cycle emissions from tunnel construction for any type of infrastructure, and may serve as a source of information and data for future LCAs. The result of the LCA allows for comparison of emissions from investment in HSR infrastructure to changes in passenger transportation emissions due to HSR operation.

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Few studies have examined the potential impact of the HSR infrastructure development in the US. Chester and Horvath (2010) published the only study of the California HSR system that examines HSR construction and operation from a life cycle perspective. Their LCA characterized vehicle operation, vehicle non-operation, electricity production components, and infrastructure components, including construction, maintenance, and operation using a hybrid LCA approach. The hybrid LCA approach combines economic input–output methods and process-based methods. The construction components of their analysis include material and construction processes for aerial, cut-and-fill, and at-grade infrastructure segments and terrain-specific assessment for earthwork activities. Their study did not model tunneling processes or materials.

Chester and Horvath provide estimates of life cycle GHG emissions for the California HSR system on a per passenger-kilometer traveled (PKT) basis, and report a range from well under 100 g CO_2e/PKT to over 700 g CO_2e/PKT depending on ridership levels. Chester and Horvath's finding that ridership levels were critical in determining the extent to which the California HSR system would reduce – or potentially even increase – GHG emissions compared to air and auto travel modes highlights the uncertainty of HSR use-phase emissions reductions.

2. Goal and scope

The goal of this study is to provide a preliminary estimate of the life cycle GHG emissions resulting from construction of the basic infrastructure for the proposed California HSR system.

The geographic scope of the study includes HSR infrastructure between the downtown San Francisco and Anaheim stations; the segment CHSRA has proposed to build for its first phase. The planned route is characterized by mostly flat terrain in the central valley, mountainous or hilly terrain between the central valley and metropolitan regions of the Bay Area and greater Los Angeles, and urban infrastructure within those metropolitan areas. The terrain encountered by the route determines the type of infrastructure required during construction. Trackbeds and electrification infrastructure are required over the entire length of the HSR system (725 km). Depending on terrain, construction of the following infrastructure types are required; cut-and-fill sections (138 km), aerial structures (61 km), tunnels (49 km), embankments (26 km), and trenches (11 km).

The study's system boundary includes life cycle GHG emissions from material production, material transport to construction sites, and construction equipment operation. As shown in Fig. 1, the system boundary excludes transportation of equipment and construction waste to and from construction sites, largely because of uncertainty as to where equipment will be sourced from at the time of construction and uncertainty regarding the final site of disposal for scrap or construction waste. Other exclusions from the system boundary include production and operation of temporary structures at construction sites, the manufacture of equipment, and the construction of trenches and embankments in the HSR route infrastructure. The driver for these exclusions is lack of data. Their exclusion is not expected to have a significant effect on the outcome of the study.

3. Methods

To evaluate the construction-related emissions, the emission inventory model combines data from construction material LCAs, diesel and electricity LCAs, and emissions factors for construction equipment and heavy duty trucks. CO_2, CH_4 and N_2O

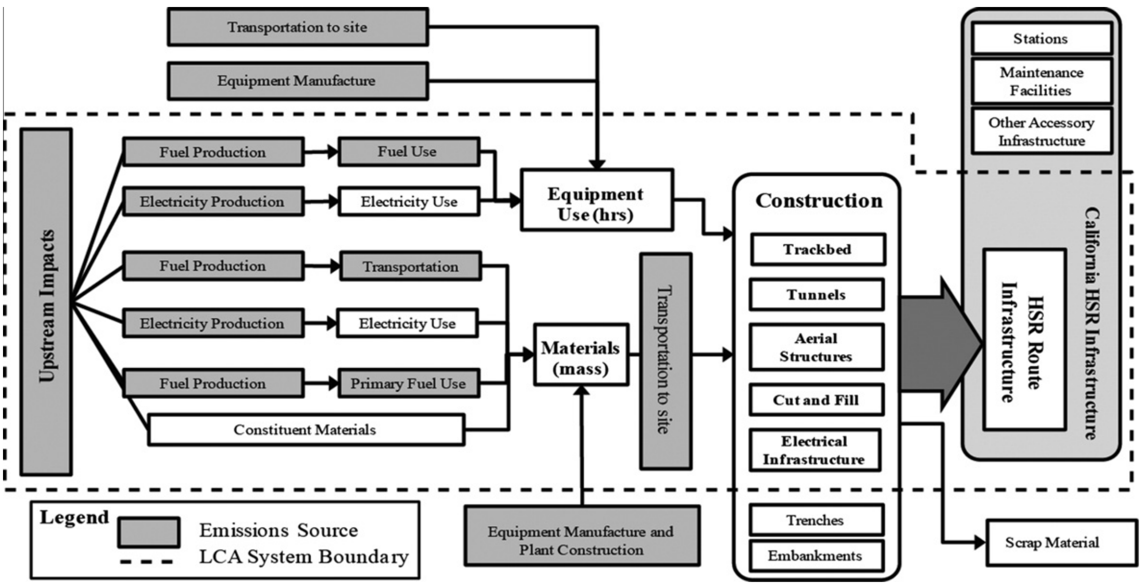

Fig. 1. Flow diagram and system boundary for the HSR construction emissions model.

emissions are tracked in this study. These emissions are reported in CO_2-equivalents (CO_2e) using the Intergovernmental Panel on Climate Change's (IPCC's) (2007) estimates for 100-year global warming potentials.

3.1. Emissions inventory model

There are two main categories of emissions for HSR construction; material production and delivery, and construction equipment operation. Of the nearly 15 million metric tons (Mt) of materials required for route construction: 45% is aggregate not used in concrete; 34% is ready-mix concrete; 14% is precast concrete; 4% is steel; and 3% is cement not used in concrete mixes.

Life cycle emissions for materials include: raw material acquisition, refining or processing of raw materials, manufacture, and transport of materials to the construction site. Process-based life cycle inventory datasets are used to define material production emissions and fuel cycle emissions for transport; Table 1 lists the sources.

Transport distances for construction materials are from the US Commodity Flow Survey, which provides national average shipment distances for commodity groupings (US Bureau of Transportation Statistics, 2004). Composite materials, such as concrete, were broken down into their component materials for these calculations. Rubber and copper wire are excluded from transportation calculations due to a lack of data and because they constitute a relatively small proportion of material mass. Diesel-powered trucks were assumed as the only mode of travel, with an emissions-intensity of 0.21 kg CO_2e per tonne-km. Since truck transport is the least efficient freight mode for construction materials, this is a worst-case scenario for transport-related GHG emissions.

Combustion emissions and fuel use for construction equipment are modeled using the OFFROAD model (California Air Resources Board, 2006). OFFROAD emission factors used in this study are based on forecasted emissions for the fleet of construction equipment operating in the year 2015. Detailed accounting of the equipment type, horsepower, and hours of use for all construction equipment are available in Chang (2009). Fuel use from the OFFROAD model is coupled with diesel production emissions to account for fuel cycle GHG emissions.

3.2. Trackbed and electrification infrastructure

The HSR system requires trackbed and electrification over its length. LCA calculations for trackbed construction draw on the life-cycle inventory analysis in Kiani et al. (2008) for the Rheda 2000 HSR system, which has been implemented in Europe and Asia. Kiani et al.'s study includes material and equipment use for the construction of one kilometer of double track. The three main equipment types modeled by Kiani et al. include an in situ slab former, rail laying machine, and concrete train that pours and forms the concrete base of the trackbed.

By combining Kiani et al.'s equipment data for the rail laying machine, concrete train, and in situ slab former, with fuel cycle emissions for construction equipment, the estimated emissions for track bed construction are 1785 kg CO_2e per km of single track.

Modeling of the electrification infrastructure only considers emissions from material production and delivery. The electrification infrastructure for HSR requires catenary poles and overhead contact wires. This study assumes steel catenary poles are used, and overhead contact wires consist of parallel lines of copper alloy wires. Federici et al.'s (2008) study provides the quantity of steel and copper alloy required for electrification per km of HSR track. These quantities are linked to life cycle emissions data for steel and copper alloy described in Table 1.

3.3. Cut-and-fill processes

The HSR system is constrained to a maximum vertical gradient of only 3.5% to maintain desired travel speeds. While tunnels and aerial structures are required where the terrain is most challenging, the gradient constraint is met by cut-and-fill

Table 1
Life cycle GHG emissions for producing HSR construction materials.

Material	Use[a]	Dataset notes and source
Portland cement	Tr	Marceau et al. (2007)
Precast concrete	A	50 MPa, Mix 1; Marceau et al. (2007)
Ready mix concrete	Tr, Tu, A	20 MPa, Mix 3; Marceau et al. (2007)
Aggregate	Tr	IDEMAT (2001)
Rail	Tr	Section steel; World Steel Institute (2005)
Reinforcement bars	Tr, Tu, A	Rebar/wire steel; World Steel Institute (2005)
Rail fasteners	Tr	Hot rolled coil; World Steel Institute (2005)
Rail pads	Tr	Natural rubber; Franklin Associates (1998)
Steel poles	E	Average of section, rebar, and coil; World Steel Institute (2005)
Contact wire	E	CuMg alloy; IDEMAT (2001)
Truck transport	Tr, Tu, A, E	Franklin Associates (1998)
Diesel production	Tr, Tu, A	PE International (2006)

[a] Tr: track, Tu: tunnel, A: aerial, E: electrical.

processes over 138 km of the HSR route. Cut-and-fill requires excavation of soil from one section of the route, followed by placement of the soil in another. Where local movements of soil cannot meet the demand, import or export of non-local soil is required.

Calculation of the volume of soil moved during cut-and-fill requires coupling route coordinates with a digital elevation model, followed by estimation of required cut-and-fill volumes. In this study the estimated cut-and-fill volumes were assessed with the Haversine formula using a horizon of 5.1 km in the southbound direction. This method yielded estimates of 49.1 million m^3 for cut soil, and fill requirements of 50.7 million m^3.

The aim of cut-and-fill calculations is to use as much locally excavated soil as possible for fill, thus reducing need for soil import or export. However, as evidenced by the balance of cut-and-fill volumes, 1.6 million m^3 of imported soil was required to meet the estimated fill volume. In the emissions model locally excavated soil travels, on average, 1 km, while imported soil travels 10 km.

Stripple (2001) provides hourly fuel consumption for cut-and-fill activities on the basis of per volume soil moved per km. This fuel consumption rate is coupled with fuel cycle emissions for diesel production and combustion in California equipment.

3.4. Tunnels

HSR tunnel construction is modeled based on the construction process of the first major transportation tunnel project in 50 years in California, the Devil's Slide Tunnel (DST) on Route 1 in Pacifica. Because the DST is a roadway tunnel, tunnel design requirements for size and shape are similar to the proposed HSR tunnels. A material inventory list from the preliminary construction bid for the DST project provided an estimate for material use per km of tunnel construction (California Department of Transportation, 2006). All construction material inventory items directly used in constructing the tunnel are considered. However, materials that would be used to construct the in-tunnel road are excluded, because trackbed will be laid instead of pavement. Cement, steel, and aggregate make up the bulk of material used in the construction of the tunnel. These materials are used to line and support the walls of the tunnel as excavation progresses.

Shift diaries from the DST project provided data for both northbound and southbound tunneling directions. These shift diaries cover a 24-h period for March 31, 2009; a date selected by a California Department of Transportation (Caltrans) representative when asked to provide a date most representative of a day with average construction progress.[1] An average progress rate of 9 m per 24-h day was also provided by the Caltrans representative. Equipment types and hours of use are listed in the shift diaries. Typical horsepower ratings for each of the equipment models listed in the diaries were matched with the appropriate emissions factors from the OFFROAD model to estimate GHG emissions from the equipment used on the tunneling site (Chang, 2009).

While ventilation is a critical process during tunnel excavation, Caltrans and its contractors could not provide an estimate of the site's electricity consumption, so the electricity consumed by the ventilation process during tunnel construction is not included in this study. Electricity consumed by temporary structures at construction and tunneling sites is also excluded due to lack of data.

3.5. Aerial structures

Aerial structures are modeled based on the specifications of a recent HSR project in Taiwan (Kuhendran, 2005).[2] Because of its recent construction, and because it was designed and built in a seismically active region, the Taiwan HSR system can reasonably be adapted to model the California HSR design. The Taiwan HSR data provides the quantity of concrete and steel used per length of aerial structure, but does not estimate equipment-related emissions, or distinguish between precast and cast-in-place concrete sections. Because precast concrete life-cycle CO_2 emissions are nearly twice that of ready-mix concrete, differentiation between cast-in-place and precast sections is important. This study assumes the superstructure is precast and the substructure is cast-in-place.

When pre-cast spans are used, on-site construction activities will mostly involve ground improvement, concrete pouring for the substructure, and the lifting and installation of precast segments. However, there is no data available on the equipment required for these construction processes. On the premise that aerial structure construction is likely to require less equipment activity than the continuous excavation activities required in tunneling, aerial structure equipment activity is modeled as 50% of tunneling equipment activity on a per-km basis. Because this assumption is uncertain, a range between 0% and 100% of tunneling equipment is tested in a sensitivity analysis.

4. Discussion

The contributions of material production, material transport and equipment for each infrastructure type are seen in Table 2. Production of construction materials contributes to more than 80% of emissions, transport of materials to the site approximately 16% of CO_2e emissions and construction equipment operations only 5%. Construction of tunnels and aerial

[1] Nagid, B., Personal Communication. Caltrans Representative for Devil's Slide Tunnel Project. Pacifica, CA.

[2] From CH2M Hill's Nobari Farid via personal communication with Caltran's Vong Toan, 2009.

Table 2
Summary results of CO_2e emissions by infrastructure type and process.

	Material production	Material transport	Equipment	Total
Track bed (t)	733,110	133,517	2588	869,215
Tunnel (t)	483,077	110,085	44,635	637,797
Aerial[a] (t)	653,079	110,833	27,969	791,881
Electrification (t)	62,806	6804	–	69,610
Cut fill (t)	–	–	42,580	42,580
Total (Mt)	1.9	0.4	0.1	2.4

[a] Aerial construction equipment emissions are 50% of tunneling equipment emissions on a per-km basis.

structure structures contributes nearly 60% of emissions, despite that these infrastructure types are only 15% of the infrastructure length. Sensitivity analysis shows that when aerial construction equipment emissions are varied from 0% to 100% of tunneling equipment emissions, GHG emissions change by only ±1.2%.

Cut-and-fill activities contribute less than 2% of HSR route emissions and are dominated by equipment use, in large part because of the transport of excavated soil. Sensitivity analysis of the average cut-and-fill transport distance for excavated soil assumed to be 1 km in the baseline model, shows that doubling the average distance of local cut-and-fill transport increases cut-and-fill equipment emissions by less than 1%.

To put construction emissions in context, we compare the time required to avoid the equivalent mass of emissions based on avoided emissions during HSR system operation. This calculation assumes that the HSR system will reduce vehicle kilometers travelled by other modes (namely roads and airplanes) that are more GHG intensive on a PKT basis, leading to 1.15 Mt CO_2e avoided per annum as estimated by CARB. The calculations reflect only the direct reduction in vehicle emissions, not the reduction in maintenance or averted expansion of infrastructure other modes would experience if they were used less. Based on these assumptions, a simple recuperation calculation (2.4 Mt CO_2e/1.15 Mt CO_2e) results in slightly more than two years after HSR operation begins. This simple calculation, however, may distort the time needed to offset the climate change effect of emissions from construction. Recent studies suggest that the climate change effect of emissions that occur at the outset of a system's life cycle are underestimated in traditional carbon accounting and LCA methods (Kendall et al., 2009). To address this shortcoming, we can assess a recuperation time based on global warming effect, rather than the mass of GHG emissions as estimated by CO_2e.

For this recuperation time approach, global warming effect is modeled using cumulative radiative forcing (CRF). The IPCC uses CRF to calculate their widely applied global warming potentials and is an indicator of a GHG's capacity to trap radiation over time. The recovery time calculated using CRF identifies the time when the global warming effect of the initial construction emissions are offset by the global warming effect of avoided use-phase emissions.

Construction is expected to take seven years. The construction emissions calculated in this study (2.4 Mt CO_2e) are averaged over the seven-year time horizon, so yearly emissions are modeled to be constant from groundbreaking to completion. Fig. 2 shows construction emissions, avoided emissions (1.15 Mt CO_2e per year), and the net global warming effect over time.

Seven years after groundbreaking, the CRF profile begins to decrease because of emissions offsets from avoided auto and air travel emissions. The recuperation time occurs when net-CRF is zero, and is achieved in a approximately six years after operation begins, or 13 years after groundbreaking. While six years is a nearly threefold increase over simple CO_2e recuperation time estimates, it is short compared to the 60–100 year design life of the HSR infrastructure. Estimates of avoided emissions during operation are uncertain. Recuperation times assuming lower estimates for avoided emissions non-linearly

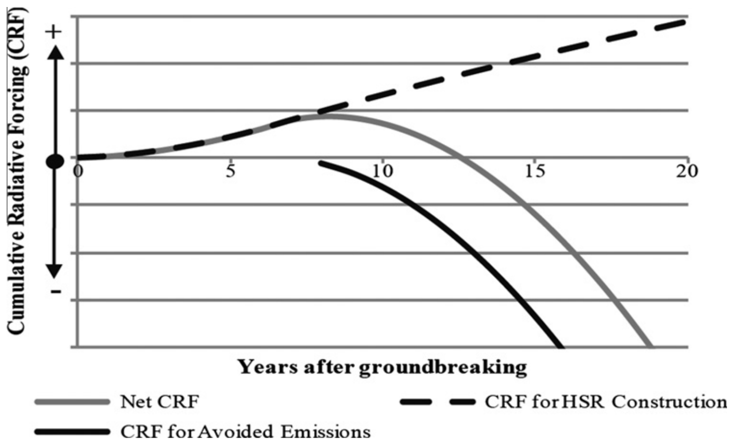

Fig. 2. Global warming effect of construction emissions, avoided emissions and net emissions from California HSR.

increase using the CRF approach. If avoided emissions halve to 0.575 Mt CO_2e per year, recuperation time increases by only 3.3 years. However, if avoided emissions decrease to one quarter of CARB's estimate, recuperation time increases by nearly 20 years. Because of the nonlinearity of CRF calculations, if avoided emissions are drammatically lower than current CARB estimates, recuperation time may not occur for many decades.

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