Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Lifecycle Environmental Impact of High-Speed Rail System in the I-45 Corridor

Project No. 18PPPVU01

Lead University: Prairie View A&M University

Final Report

August 2019

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16. Abstract

The Houston-Dallas (I-45) corridor is the busiest route among 18 traffic corridors in Texas. The expected population growth and the surge in passenger mobility could result in a significant impact on the regional environment. This study uses a life cycle framework to estimate the net change in environmental impact with the development of a high speed rail system (HSR) along the I-45 corridor. The study follows ISO 14040 principles and standards of life cycle assessment and uses SimaPro 8.5® software and the Ecoinvent 3.3 inventory database. Infrastructure construction, vehicle manufacturing, system operation, and end of life phases are included in the life cycle assessment. The energy and emissions of the system are evaluated per vehicle/passenger-kilometers traveled and compared with the existing transportation modes. The vehicle component accounts for 14.50 kgCO_2eq/VKT, of which fossil-fuel usage during operation is the primary contributor with 98% of the greenhouse gas (GHG) emissions. For the infrastructure component, 56.76% of GHG emissions result from the material extraction and processing phase (23.75kgCO_2eq/VKT). Life cycle CO_2 emissions of this system are 40% lower than comparable systems in Europe, Asia, and North America. The minimum ridership levels required to offset the environmental impact from conventional modes of transport are around 12% and 27% for GHG emissions and NOx emissions respectively. For the stakeholders, policymakers, and community leaders, this study recommends the construction of HSR system between Dallas-Houston, since it does not only save time, reduces traffic jam, and improve passengers' mobility, but it also saves energy, which benefits the regional environment.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AADT	Annual Average Daily Traffic
Bq	Becquerel
C-14	Radioactive Isotope
CAP	Criteria Air Pollutants
C_2H_4	Ethene
C_2H_3Cl	Vinyl chloride
CO	Carbon Monoxide
$CO_{2\ eq}$	Carbon Dioxide Equivalent
DFWA	Dallas-Fort Worth-Arlington
DFW	Dallas-Forth Worth
DOT	Departments of Transportation
E	Vehicle emissions per Person Kilometers Traveled
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
FHWA	Federal Highway Administration
GHG	Greenhouse Gases
HSLB	Houston Sugar Land Baytown
HSR	High Speed Rail
I-45	Interstate 45
IPCC	International Panel of Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Impact
LCIA	Life Cycle Impact Assessment
MJ	Megajoule
m^2org	Square meter organic
MOW	Maintenance-of-Way
MWh	Megawatt-hour

NEPA	National Environmental Policy Act
NETL	National Energy Technology Laboratory
NO_x	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
PKT	Passenger Kilometers Travelled
PM	Particulate Matter
P	Person (Seat)
PO_4	Phosphate Ion
Q	Total lifetime emission of a given pollutant
$Q_{V/INFRA}$	Vehicle and infrastructure lifetime emission of a given pollutant
R	Vehicle utilization rate
RI	Respiratory Inorganics
SO_2	Sulfur dioxide SUV Sport Utility Vehicles
TEG	Triethylene Glycol
TCEQ	Texas Commission on Environmental Quality
TMF	Transient Maintenance Facility
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
VOC	Volatile Organic Compounds

EXECUTIVE SUMMARY

Increased urbanization rates inflict stresses on transportation infrastructure, and Texas has three of the ten largest metro areas in the U.S. (Houston, San Antonio and Dallas) with an estimated population growth of 70% by 2050 (*1*). With the increase in population, the total mobility in passenger kilometers traveled (PKT) is projected to be four times greater than the national average. Therefore, it is pertinent to consider the development of a high speed rail (HSR) system to accommodate the travel demand and mitigate the environmental impact of the transportation sector in this region. One of the most successful strategies often used in Japan, Europe, and China is the migration of road traffic to the railway system which is generally more environmentally beneficial. Studies comparing the environmental impact of car and HSR transportation show considerable benefits toward reducing the energy used and pollutants. In an effort to develop sustainable transportation modes, legislators initiated significant steps toward the implementation of an HSR system using Shinkansen N700 series trains.

However, the construction phase requires a significant amount of energy and material, consequently resulting in an increase in the environmental impact. A cumulative assessment of the overall environmental impact from the proposed HSR system requires a life cycle assessment (LCA) study that accounts for all emissions generated over its lifetime, including phases such as raw material extraction and processing, manufacturing and construction, operation and maintenance, and end of life. LCA is one of the most effective methods that estimate the environmental impact and evaluate mitigation methods and technologies. The environmental impact of infrastructure construction may not contribute to sustainable mobility. Studies comparing road, air, and railway systems conducted in Europe, Asia, and the U.S. indicate rail transportation as one of the most sustainable modes that have significantly lower releases of criteria air pollutants (CAPs) and greenhouse gases (GHGs). It is of vital importance that quantitative environmental analysis with a life-cycle perspective that includes all phases (raw material extraction, manufacturing, transportation, construction, operation and maintenance, and end-of-life) be conducted for the HSR system in Texas. The current project conducts an environmental LCA as per the framework and procedures of ISO 14040 and ISO 14041. Data collections for the input and output were consistent with similar studies in the U.S., Europe, and Asia. The HSR system analysis was divided into two main sub-systems (Vehicle and infrastructure), in which, each subsystem accounts for various phase life cycle processes. In addition, the system boundary also accounts for phase study of facilities and auxiliary equipment used during the operation and maintenance of the HSR system. The inventory base case begins with Ecoinvent v3 process for transportation services, adjusted to reflect the actual conditions of the Dallas-Houston HSR system.

The estimated energy and emissions are evaluated per passenger-kilometers traveled (PKT) and compared with the existing transportation modes. Vehicle component accounts for 0.19 kgCO2eqPKT, of which fossil-fuel usage during operation is the primary contributor with 97% of the greenhouse gas (GHG) emissions. For the infrastructure component, 94% of GHG emissions are contributed by the construction phase (0.21 kgCO2eq/PKT). The minimum ridership levels required to offset the environmental impact from conventional modes of transport, such as personal cars, bus and aircraft, are around 12% and 27% for GHG emissions and NOx emissions respectively.

To the stakeholders, policymakers, community leaders, and Texas Central, this study recommends the implementation of a continuous education program to increase public awareness on the environmental benefits of HSR, at the same time they maximize the use of renewable energy for HSR system operation. It is expected that, the increase in awareness, will reduce the population of passengers traveling by car, maximize the percentage of train occupancy, improve mobility and air quality. In addition, this study also found that, the use of renewable energy can significantly reduce the total environmental impact generated by construction of the HSR system.

1. INTRODUCTION

Interstate 45 (I-45) (Figure 1) connects the fourth and fifth largest metropolitan areas of the U.S., Houston and Dallas, respectively, and has an annual average daily traffic (AADT) volume as high as 314,000 in 2016 *(2)*. The I-45 corridor connects the Gulf Coast, a major port area, to domestic markets in Texas, and it is of crucial importance to the economy of the State of Texas. The combined GDP of the two metropolitan areas of Dallas-Fort Worth-Arlington (DFWA) and Houston-Sugar Land-Baytown (HSLB), is estimated to be close to $ 1 trillion in 2016 *(3)*. A recent report from the Texas Department of Transportation (TxDOT) estimated that half of total truck freight in Texas traverses through the 11 counties comprising the I-45 freight corridor *(4)*. The 276-mile I-45 highway also gained strategic significance in terms of public safety, with the national disasters associated with Hurricane Rita (2005), Ike (2008), and Harvey (2017) *(5)*. Considering the economic and public safety significance of the I-45 corridor, Texas A&M Transportation Institute (TTI) studied the potential for the development of Intercity Passenger Transit System in 18 corridors of Texas and ranked the Houston to Dallas corridor as the highest priority route in the state of Texas *(6)*. The construction of an alternative mass transit HSR system in this route would alleviate stress on I-45 and improve the efficiency of commodity transport by truck.

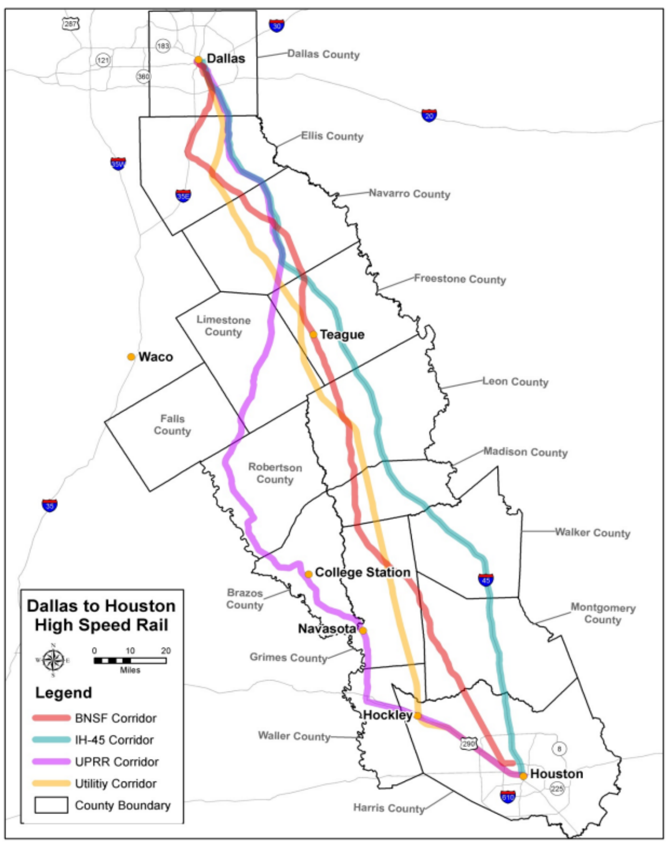


Figure 1. Dallas-Houston HSR utility corridor *(1, 2)*.

The city councils of Dallas and Houston have recently taken legislative steps toward the construction of a 386.24-kilometers HSR system to connect Dallas and Houston; the system will have a top speed of 200 mph *(7)*. The estimated traveling was calculated using a highway centerline geographic data from TxDOT and measured from city center to city center. The geographic limits are the delineated counties, which represents the project limit of disturbance for construction, material storage, and disposal.

The utility corridor with high-voltage electric transmission lines between the DFW and HSLB regions is shown in Figure 1 *(8)*. Although the rationale for a mass transit system on this route is unquestionable, there is an *imperative to examine the life cycle environmental impacts of this proposed HSR system* and compare it with the environmental impact associated with existing modes of transportation. HSR systems, typically powered by electricity, have significant environmental benefits during the operation stage in comparison to conventional transportation by road/air fueled by petroleum products. During the operation stage, HSR systems have a minimal release of regulated (criteria air pollutants) CAPs and greenhouse gases GHGs *(9-13)*. This could immensely benefit air quality in the nonattainment areas of Houston and Dallas. However, consideration of the total life cycle of an HSR system includes stages such as raw material extraction, infrastructure development, vehicle manufacturing, and electricity generation for powering the high-speed trains *(14)*. A holistic study exploring the potential environmental impact and the role of the HSR system in improving the durability of existing I-45 highway is key to understanding the net socio-economic benefit due to the HSR system. In this context, this project conducted an environmental LCA of the 240-mile corridor between Houston and Dallas to estimate the potential improvements across four end-point impact categories of Human Health, Ecosystem Quality, Climate Change, and Resources.

2. OBJECTIVES

The overall goal of this study is to provide an estimate of the environmental impact resulting from the total life cycle of the Houston-Dallas HSR system. The following are the major objectives to realize the overall goal:

1. Develop the framework for methodological environmental LCA of current/proposed HSR corridors in the south-central U.S.
2. Estimate the net change in GHG emissions and global warming potential ($CO_{2, eq}$) due to the Houston-Dallas HSR system from a lifecycle perspective.
3. Evaluate the effect of the HSR system in improving the regional air quality of Texas with emphasis on the Houston-Galveston-Brazoria area.
4. Compare the improvements in sustainability resulting from the HSR system under varying degrees of traffic migration/passenger adoption from existing transportation modes.
5. Analyze the effect of source electricity mix scenarios on the environmental impacts from the operation phase of the proposed HSR system.
6. Provide guidance to stakeholders, policymakers, and community leaders on the potential environmental benefits/costs of HSR mode of transportation in the U.S.

3. LITERATURE REVIEW

Considering the complexity of life cycle data acquisition, the research team conducted an extensive peer-reviewed investigation of existing publications, technical reports, documents, and databases to gather the necessary information to build a LCA process that reflects the conditions of the HSR systems in the U.S. The literature review data sources considered journals from different reputed publications: Transportation Research Records, Federal Highway Administration (FHWA) records, projects of departments of transportation (DOTs), U.S government agencies such as Environmental Protection, National Renewable Energy Laboratory (NREL), National Energy Technology Laboratory (NETL) and Argonne National Laboratory, environmental/energy assessment studies for life cycle processes of HSR systems, and Shinkansen train-based HSR systems. The data was used to ascertain the extent and quality of information available for the LCA study. Additionally, the current and historic AADT data for various highway segments between Dallas and Houston was obtained from TxDOT to estimate the peak usage and trends of traffic statistics for the I-45 corridor. The comprehensive database of literature along with the Ecoinvent 3.3 databases enabled the development of vehicle and infrastructure processes of I-45 HSR LCA system.

According to the 2014 International Panel of Climate Change (IPCC) report, the transportation sector contributed 14% of the global GHG emissions *(13)*. The U.S Environmental Protection Agency's (EPA) report on *U.S. Greenhouse Gas Emissions and Sinks* shows that transportation leads the total U.S GHG emissions, with 28% share (*14*). Transportation accounts for 10% of gross domestic product, 70% of all petroleum use, and 27% of GHG emissions, and 58% of the total transportation emissions are from light-duty vehicles *(15)*. The Texas Commission of Environmental Quality (TCEQ) report shows that mobile sources contributed 67% of nitrogen oxide (NOx) emissions, and 23% of volatile organic (VOC) emissions in the Greater Houston Area *(16)*. This is directly linked to an increase in population and the use of medium and heavy-duty vehicles in this region. Texas has the highest energy-related carbon dioxide emissions by state *(17)*. The increase in criteria pollutants, particularly nitrogen oxide (NOx), carbon monoxide (CO), and particulate matter (PM), originate from regional population growth and increased fossil fuel used by the transportation sector.

Increased urbanization rates inflict stresses on transportation infrastructure and Texas has three of the ten largest metro areas in U.S. (Houston, San Antonio, and Dallas), with an estimated population growth of 70% by 2050 (*1*). With the increase in population, the total mobility in PKT is projected to be four times greater than the national average (*18*). Therefore, it is pertinent to consider the development of an HSR system to accommodate the travel demand and mitigate the environmental impact of the transportation sector in this region. One of the most successful strategies often used in Japan, Europe, and China is the migration of road traffic to the railway system which is generally more environmentally beneficial (*19*). Studies comparing the environmental impact of vehicle and high-speed rail transportation show considerable benefits toward reducing the energy used and pollutants. In the effort to develop sustainable transportation modes, legislators initiated significant steps toward the implementation of an HSR system using Shinkansen N700 series trains. However, the construction phase requires a significant amount of energy, material and consequently results in an increase in environmental impact (*19*). A cumulative assessment of the overall environmental impact from the proposed HSR system requires an LCA study that accounts for all emissions generated over its lifetime, including phases such as raw material extraction and processing, manufacturing and construction, operation and maintenance and end of life. LCA is one of the most effective methods that estimate the environmental impact and evaluate the mitigation methods and technologies (*20*).

Table 1 summarizes the main reference studies used. In addition to the ones listed below, other studies were also considered for literature review. However, it was observed that researchers compared HSR with other transportation modes using non-LCA approaches.

Table 1. List of reference studies using SimaPro software.

Reference	Objective	Methodology	Approach	Normalized Unit	Summary of Findings
(10)	Evaluate the environmental impacts of China's HSR system between Beijing and Shanghai.	Impact 2002+ IPCC and other default methods.	End-point and mid-point	PKT	Operation stage is the major contributor due to the use of coal during the electricity generation process.
(21)	Assess the LCA ecological screening of the German high-speed passenger train system	Single score-Cumulative Energy Demand (CO_2).	Energy and CO_2		Energy consumption dominate the total impact.
(14, 22)	Identifies the critical environmental characteristics of several major urban transport networks and the influence that these parameters have on overall performance	Mid-point and single score.	Energy, GHG and CAP emissions	Passenger and Vehicle Miles Traveled	Increase in train occupancy reduces the environmental impact at all stages.
(19)	Total life cycle environmental impact of the planned high-speed rail line Lisbon-Porto	Mid-point and single score.	CO_2, PM_{10} and SO_2 emissions	Km and PKT	Train operation process contributes the most to total environmental emissions.

4. METHODOLOGY

The methodology of this LCA are strictly from the framework and procedures of the ISO standards and SimaPro®. Modeling life cycle using the SimaPro® software helps estimate emissions based on the application of ISO 14040 standard and the Ecoivent3 methodology. ISO 14040-44 provides guidelines to conduct a cradle to grave evaluation of a product or process.

The international environmental management defines the ISO Standards for LCA. It frames the LCA principles through the definition of goal and scope, life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, and the life cycle interpretation phase; the reporting and critical review of the LCA iterative processes and phases are described Figure 2 below. In addition, the standard also provides established cutoff criteria guidelines that eliminate minor impacts and help set up boundaries for the total system inventory.

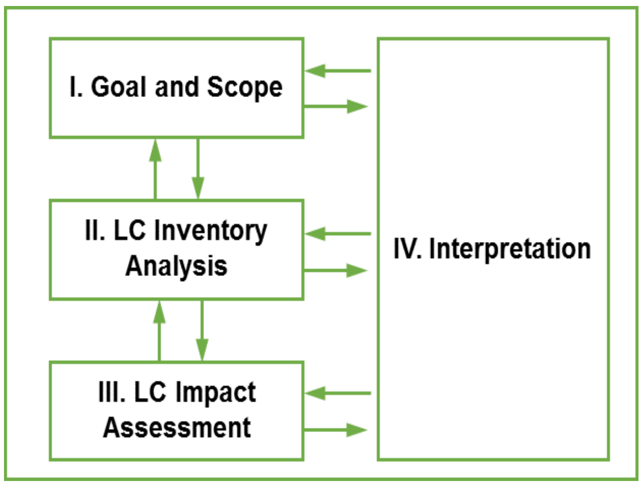


Figure 2. Four phases of LCA.

There are a number of LCA software database and methods, some of which have a similar data set. However, selecting the adequate tool/method requires a systematic evaluation of data credibility, and processes that account for the conditions and the specificity of a particular study area and objectives.

Some of the most used methods include:

- Cumulative Energy Demand: Non-renewable and renewable impact category.
- Greenhouse gas protocol: GHG emissions.
- IPPC 2013: Global warming potential.
- USEtox: Human and eco-toxicological impact.
- Ecological footprint: Nuclear energy use, CO_2 emissions, Land occupation.
- CML-IA: Mid-point approach .
- Impact 2002+: Combination of mi-point/end-point approach.
- ReCipe: Combination mid-point/damage yet oriented to end-point approach.
- EPS 2000: Damage oriented approach.
- Environmental product Declaration: Essentially for a good.
- EI99: Damage oriented approach.

The *Evaluation of Life-Cycle Assessment Tools* (*23*) report provides a list of common LCA software tools used in U.S. and Europe. Out of thirty-seven software, SimaPro is one of the most popular for LCA analyses in the world. One study found that over a period of 4 years, there was 71 more published article using SimaPro than all the other software combined (*24*). The increase in the number of users reflects the software's ability to help users minimize the complexity between industrial and ecological systems providing science-based methods that identify and analyze environmental results. In addition, the software comes with extensive inventory database (Ecoinvent 3.3) and a diverse impact assessment method that specifically select the data region and the environmental output for each study. Over the years, SimaPro has expanded its assessment boundaries by incorporating new methods and conducts a frequent update on the database to account for conditions in Europe, U.S., and other parts of the globe. Method selection depends the study objectives. This study's goal is to evaluate the cause of the increase/decrease in emissions with the implementation of a Dallas-Houston HSR system. SimaPro methods allow users to perform a cause and effect evaluation of a process/product. Out of many existing methods, Impact 2002+ was selected to account for all emissions, at different scenarios. This methodology provides viability process that associates the input data with mid-point (cause) and endpoint (effect). Table 2 describes the framework of Impact 2002+ linking LCI results via the mid-point categories to damage categories. However, considering that the scope of this study is centered on substances/pollutants that ultimately result in damage to human health, ecosystem quality, climate change and resources, all results were presented as mid-point (cause).

Data collections for the input and output and the potential environmental impact of the HSR system throughout its life cycle were consistent with similar studies in the U.S., Europe, and Asia. In addition, the life cycle inventory (LCI) databases (Ecoinvent v3) was consulted for each material used. Life Cycle Assessment is one of the most used tools/techniques used to assess the overall environmental impact of a product/process from its cradle to grave. It is distinguished from an environmental impact assessment (EIA) which analyzes and documents potential environmental effects from the construction and operation of a proposed project. EIA, as required by the National Environmental Policy Act (NEPA), is site-specific and evaluates potential impacts on the local environment from a point-source orientation, considering temporal and spatial situations and existing background environmental quality *(13, 14)*. Whereas, the key feature of LCA studies is the inclusion of focus on the product supply chain level and the global environmental implications including degradation of resources *(13)*.

Table 2. Schematic of the IMPACT 2002+ framework.

Mid-point Category	Damage Category
Human toxicity (carcinogens + non-carcinogens)	Human health
Respiratory (inorganics)	
Ionizing radiations	
Ozone layer depletion	
Respiratory organics	
Aquatic ecotoxicity	Ecosystem quality
Terrestrial ecotoxicity	
Acidification/nutrification	
Aquatic acidification	
Aquatic eutrophication	
Land occupation	
Global warming	Climate change
Non-renewable energy	Resources
Mineral extraction	

Source: Owen compilation with reference to impact 2002+ guideline (24)

4.1. Definition of Goals and Scope

Under the ISO-standardized LCA, the goal and scope phase establishes the details of the product system being studied which centers on three essential features: the reason for the study, intended use, and audience. The framework of this study was essential for the development of an environmental assessment impact of a future HSR System across the mid-point impact of human health, climate change, ecosystem quality and resources damage category. Therefore, the environmental scope of this project incorporates the evaluation of selected criteria air pollutants (nitrous, particulate matter, sulfur dioxide and ozone) greenhouse gases (carbon dioxide and methane) and the energy consumption associated with the HSR system and conventional road/air transportation modes. The study includes all the mid-point categories and the pollutants associated with them; yet special attention was given to those with a high percentage. According to AECOM's report the first operation phase will take place in 2024, with the prior four years allocated to construction. The geographic area includes the surrounding counties along the I-45 corridor as shown in Figure 1.

4.1.1. System Boundaries and Function Unit

In LCA studies, the delimitation of system boundaries and function unit are key to interpret the impact assessment results. Figure 3 below depicts the system boundary for both vehicle and infrastructure including the analyses of alternative transportation mode (air and road). The HSR system analysis was divided into three main sub-systems (Vehicle, infrastructure, and a combination of both), in which, each subsystem accounts for various phase life cycle processes including raw material extraction and processing, vehicle manufacturing, material distribution, construction, operation & maintenance and end-life. This project selected a function unit of Passenger Kilometer Traveled (PKT) that normalize the energy consumption and allow comparison across transportation modes. In addition, the system boundary also accounts for phase study of facilities and auxiliary equipment used during the operation and maintenance of the HSR system. The complete framework addresses the requirement of Objective 1 proposed for the LCA study of HSR system in Dallas-Houston area.

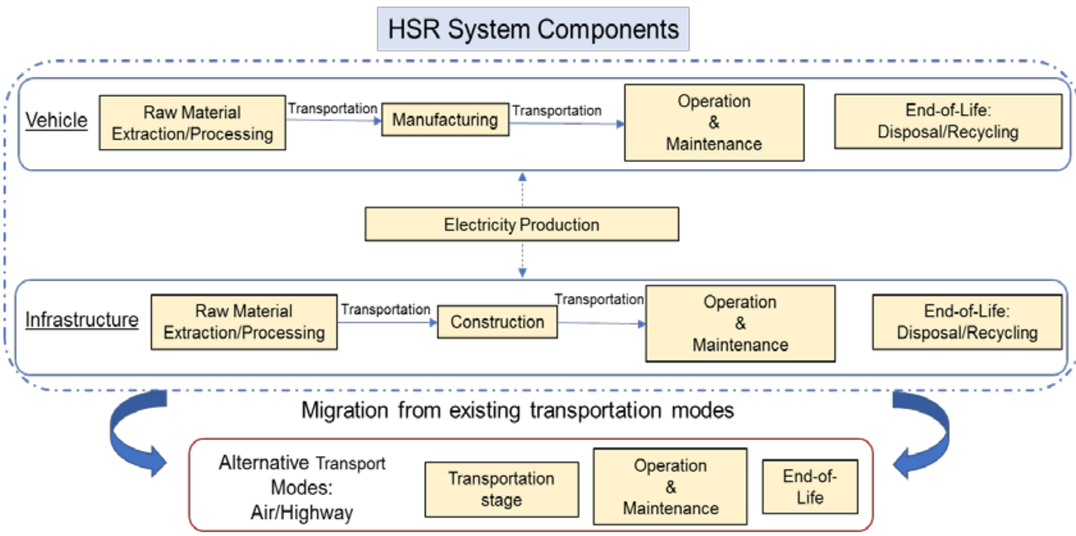


Figure 3. System boundary and unit processes for the LCA study of HSR system in Texas.

4.2. Life Cycle Inventory Analyses and Assumptions

This project's inventory is based on material balances between input and output. Therefore, the energy and raw materials used and the emissions are quantified for each step in the process. The products and processes can be compared and evaluated using Life Cycle Inventory (LCI) results. A complete list of input for vehicle and infrastructure modeling is listed in Table 3.

Table 3. Description of HSR system life cycle processes by phase.

Project Components	LCA Modeling	Major Materials	Energy Production /Resources
Vehicle	Material extraction/Processing (Locomotive and railcars under Japanese conditions)	Steel, aluminum, polyethylene, glass and resin.	Electricity medium voltage, heat, light fuel oil, heat, natural gas.
	Transportation (vehicle material during manufacturing phase)	The Shinkansen 700 vehicles being transported by boat from manufacturing company in Osaka, Japan to Galveston bay area in Houston.	Light and heavy fuel oil, heat, natural gas for material Transport using heavy trucks and existing rail.
	Manufacturing (parts and assembling)	Reinforced steel, steel, aluminum, copper, polyethylene, tempering flat glass, flat glass, alkyd paint.	Electricity medium voltage, heat, fuel, heat, natural gas, heat.
	Operations/Maintenance (vehicle running and maintenance)	Diesel, lubricant oil, Paraffin and Electricity from Texas Electricity Mix.	Local average electric (448.87MWh/daily) network mix, Light and heavy fuel and lubricants.
	Waste Disposal/Recycling	Steel, plastic, copper, glass, lubricants, resins diesel (heavy truck transportation and rail).	Electricity, light and heavy fuel.
Infrastructure	Material extraction/Processing	Concrete, cement, aggregate sand, steel, aluminum, copper.	Electricity medium voltage, light fuel oil and natural gas.
	Construction(Rail track, bridges, culvert, stations and power generation system)	Electricity and diesel for steel rail, railway fasteners.	Electricity medium voltage, light fuel oil and natural gas and heat (Electricity for lightning and power tools, fuel for heavy trucks, and power required for stations, signaling, substations and maintenance facilities).
	Operations/Maintenance	Diesel, gasoline, fuel oil, and Electricity.	Electricity, Light and heavy fuel.
	Transportation of personnel and material (heavy truck, passenger's truck existing rail light commercial trucks, single-unit short-haul and long-haul diesel trucks	Tire for tracks, lubricant and diesel.	Light and heavy fuel for heavy track and rail (passenger trucks, light commercial trucks and single-unit short-haul and long-haul diesel trucks).
	Disposal and recycling (runway material) and decommission of terminals under US condition	Steel, concrete, hydraulic fluids and cleaning products.	Electricity, light and heavy fuel.

For each component, the inventory base case begins with Ecoinvent v3 process for transportation services, adjusted to reflect the actual conditions of the Dallas-Houston HSR system. Other specific data such as electricity mix for operation phase, distance, material and energy were also included to reflect the number of maintenance services along the Dallas-Houston corridor. The project accounts for Shinkansen vehicles and infrastructure. The Shinkansen car consists of eight cars and a seating capacity of about 400 passengers. The infrastructure includes rail track, bridges, culvert, stations, Trainset Maintenance Facilities (TMF), and Maintenance-of-Way (MOW). The alternative model (road and air freight transportation) includes vehicle/aircraft lifetime correspondent to fuel amount in passenger kilometer traveled. All modules account for emissions during manufacturing, operation and maintenance, and the infrastructure construction of each system. The module process is consistent with LCA studies on HSR system across Europe, Asia, and the U.S. The material input for vehicle and infrastructure construction is listed Tables 3 – 5.

Table 4. Description of the material and average kilometers traveled per mode.

	Truck		**Rail**	
Material	**Average (miles)**	**Amount (tons)**	**Average (miles)**	**Amount (tons)**
Sub-Ballast	5	87,953	20	521,805
Ballast	5	206,925	20	1,227,642
Concrete Rail Ties (each)	5	699	-	-
Total Concert	8	767,661	-	-
Rail	7	53,266	20	1,4679
Excavation	3	667,392		-
Fill	5	2,249,949		-
Structural Steel	8	6,732	20	1,683
Reinforcing Steel	8	1,084,372	20	271,093
Waste Concrete	5	5,261	-	-
Waste-rebar	3	16,266	-	-
Sand	5	1,861,159	20	393,085
Cement	5	784,254	20	165,638
Gravel	5	205,3693	20	433,749

Table 5. Description of kilometers traveled for passenger transportation.

Construction Phase	**Vehicle Type**	**Average miles**
Track	Pickup Truck (1/2 -3/4 tons)	18,720,000
Station		
TMF		
MOV		

Ecoinvent database is not always categorized in a way that directly reflects input-output of product/process. Therefore, the research team made assumptions to allocate aggregated data to the most appropriate sector. Many of these assumptions are used to create the impact vectors, the values for the environmental effects and materials consumption. The set of data, allocated as weighted averages, are from data sources or other publications that represents industry sectors in North American, Europe, and in some cases, the globe.

Table 6 lists the main assumptions associated with the HSR model. However, most of this study input are actual project information retrieved from the *Dallas Houston High-Speed Rail Draft Environmental Impact Assessment* conducted by the U.S. Department of Transportation.

Table 6. Summary of the modeling assumptions.

Uncertain variables	Approaches
Train Specification	A typical trainset consists of eight cars carrying up to 400-seated passengers. Vehicle technology was based on that of the central Japan Railway Company We assumed a 25 years lifetime. Hour traveled retrieved from Texas Central website, a private railroad company proposing an HSR rail line between Dallas-Houston. Vehicle inventory: assessed using Ecoinvent's database as per Chester et al., 2013. Electricity and other operation inputs retrieved from the Dallas to Houston High-Speed Rail Draft Environmental impact statement prepared by the U.S. Department of Transportation. Vehicle manufacturing location assumed based on the existing manufacturing companies in Japan. Energy for operation includes Train, stations, TMFs and MOW facilities. Centerline geospatial data, from TxDOT, was used to calculate a city center-to-city center distance of 384.63 kilometers between Houston and Dallas.
Train Operation	Calculated based on the expected operation hours (18h/day), the number of trips a day (68) and trip duration. At the initial phase, the project will have seven trains performing five round trips a day.
Infrastructure	Construction emissions account for emissions from construction equipment, employee trips to the construction site and delivery of construction materials (hauling by both trucks and rail) to the material storage yards and to the construction sites and emissions from other on-road vehicles used during construction activities. This technical memorandum also provided information for: • Construction material quantities used in the emissions calculations. • Equipment lists by construction activity. • Detailed construction phase equipment quantities. • Track, stations, TMFs, and MOWs. • The route will be elevated viaducts (W/ bridges and no tunnels) The track choice is non-ballasted. Appropriate for high-speed with lifetime 50-60. Therefore, the chosen lifetime for infrastructure is 60 years. All stations have a total area of 60 acres. Excavation and fill material transported by heavy trucks along the build alternatives. Aggregates for concrete would come from quarries from within Texas.

References: (2, 8, 10, 21, 25)

The evaluation in transportation migration was performed taking into consideration the yearly average percentage of people traveling between I-45 corridors (4,400,000 passengers/year). Currently, I-45 highway is shared between car and bus with 89% and 2% of total passenger volume share respectively *(25)*. Car input reflects the manufacturing and road network for an average size gasoline cars in Texas. For this reason, this utilized module was a large size passenger car with engine capacity greater than two litter to account for the sport utility vehicles (SUVs) and trucks, common cars used in the region. A rate of 1.2 passengers per car was selected; a rate that influences the total overall emissions per passenger kilometer traveled. For bus, the module is a low sulfur diesel vehicle, with manufacturing and operation conditions of a bus engine in Europe. Aircraft transportation accounts for the remaining 9% of population modeled for the average capacity of 320 passengers. For HSR emissions, the calculation of pollutant accounts for a lifetime of 20 years of vehicle operation and 60 years of infrastructure operation.

To evaluate the net change in criteria air pollutants (CAPs), CO_2, and global warming impacts, results were analyzed in vehicle kilometers traveled (VKT) and passenger kilometers traveled (PKT). Equation 1 expresses the calculation for individual system emissions, where E is the emissions of pollutant in VKT per year, Te_i is total lifetime emission of a given pollutant, and Dt the total lifetime distance traveled (km/years).

$$E(VKT) = \frac{TE_i}{D_t} \qquad [1]$$

Equation 1 and 2 express the calculation for individual system emissions, where E is the total emissions allocated for material and energy use in PKT. Q is the total lifetime emission of a given pollutant for vehicle and infrastructure, p is 400 which represents the number of seats per vehicle, d is 386.243, the distance traveled between Dallas-Houston, R the vehicle utilization rate, and Y the service lifetime for vehicle and infrastructure. In addition, the study also examines the three most relevant categories for both vehicle and infrastructure. Out of the 15 mid-point categories in Impact 2002+ assessment method, the three most impacted areas include global warming (GW), respiratory inorganic (RI), and energy demand (E). The selected categories assess the significance of CAPs, GHG emissions and the energy use per passenger kilometers traveled with focus on pollutants like: carbon dioxide (CO_2), nitrox oxide (NOx), sulfur dioxide (SO_2) and particulate matter (PM).

To evaluate the different stages of vehicle and infrastructure and analyze the cause and effect chain of each pollutant, the results were obtained using the mid-point methodology of Impact 2002+. This method allows the trace of source contribution for individual pollutants, offering more detail to the study. Equations 2 and 3 represents the baseline to calculate mid-point emission in passenger per kilometers traveled.

$$E_{Vehicle} = \frac{Q_{Vehicle}}{p.d.R.Y_{Vehicle}} \qquad [2]$$

$$E_{Infrastructure} = \frac{Q_{Infrastructure}}{p.d.R.Y_{Infrastructure}} \qquad [3]$$

where:

$E_{vehicle}$ (PKT) = Vehicle emissions per Person Kilometers Traveled;
$E_{infrastructure}$ (PKT) = Infrastructure emissions per Person Kilometers Traveled;
Q = Vehicle lifetime emission of a given pollutant;

p = person (seat);
R= vehicle utilization rate;
$Y_{Vehicle}$ = Years of operation; and
$Y_{Infrastructure}$ = Years of operation.

The total distance traveled reflects the initial operating condition of two HSR vehicles with 8 cars and a seating capacity of 400 passengers. The vehicles are scheduled to operate 18 hours a day, leaving the other 6 hours of system maintenance and inspection. Considering that the HRS uses electricity as an energy source, the source of electricity mix scenarios on the environmental impact from the operation phase will also be analyzed during the vehicle's lifetime (20 years). Generally, the train operation does not generate direct emissions. However, the electricity generation and transition produce pollutants that can be minimized with the change in the electricity mix. Emissions for light-duty vehicles traveling to and from the station are not part of this study. The complete life cycle evaluation will account all emissions generated over the vehicle and infrastructure lifetime.

4.2.1. Material Extraction and Processing

Material extraction and processing are one of the most critical phases of any product life. Therefore, most of the product's emissions are determined by decisions made during the design phase of a product. Similarly, passenger vehicles are made of different materials, some of which are not always recyclable, increasing the total environmental burden of any product. This LCA inventory includes reliable data for all natural resources used, the processing and transportation phase referencing previous lifecycle study data, and inventory in the Ecoinvent v3 database. The HSR vehicle used in this study is the Shinkansen N700 trains, manufactured in Japan. Due to lack of information on Japan's vehicle inventory this assessment considers similar size train manufactured in Germany, which inventory is available in the Ecoinvent database, as per the approach used by (*10*). Most of the energy and material data reference the information on the Dallas-Houston HSR Environmental Impact Statement Report sponsored by the Department of Transportation and by the Texas Central Railroad (TCRR) engineers, which also provide the values for energy used during extraction and processing phases. The infrastructure data is a mix of previous studies and quantities of material used in the track, stations, maintenance, equipment, and service facilities.

The SimaPro processing module includes inputs of raw materials, energy, and on-site transportation of the product. A minor impact is allocated to transportation in the processing zone, because the route takes place in a very small distance, compared to the other transport processes. The HSR track choice is a non-ballast, with viaducts and bridges, above the threshold level, avoiding interference with the existing transportation system. For this reason, concrete and steel are the predominant materials in railway infrastructure. The track selection was based on infrastructure lifetime (50-60 yrs), safety, security and reliability. Moreover, it has been reported that fixed track construction consumes 89% less energy than the ballast track *(26).* This project does not include tunnels because of the flat surface along the Dallas-Houston region.

4.2.2. Manufacturing/Construction

The manufacturing of vehicle parts and infrastructure materials require carbon-based energy, which is associated with the release of CO_2, NO_x, SO_x, O_3, and PM emissions. For this study, the two Shinkansen vehicles are assumed to be manufactured in Germany using the available energy in the region. Input used for vehicle manufacturing were primarily electricity and the processed aluminum, steel, organic, and non-organic material such as glass, plastic and resign, which represents the vehicle's main material and manufacturing module from SimaPro®. The decision to import the vehicle outside the U.S was due to the fact that, at the moment, there is no Shinkansen vehicle manufacturing in the region. Infrastructure accounts for the total material and energy used during the 4 years of construction. The railway infrastructure, include track, bridges, culvert, stations, Trainset Maintenance Facilities (TMF), and Maintenance-of-Way facilities. Signal housings that monitor train traffic, signaling cables and power supply for equipment are also part of the infrastructure system. Vehicle manufacture emissions mostly originate from the energy used in the manufacturing process.

4.2.3. Transportation

Materials for track, stations, and other support facilities are transported to construction sites by diesel heavy pickup trucks and the Houston railroad connection system. Given the required materials, the extension of the track and the miles per passenger, it is expected to involve high consumption of energy (diesel and gasoline) and consequently a high percentage of fossil fuel emissions. Therefore, this study assumes that construction materials are obtained within the proximity of the track. On the other hand, the two Shinkansen vehicles were considered to be transported by boat from the Kinkisharyo manufacturing in Osaka, Japan to Galveston port via Panama Canal. Rail, reinforcement steel, structural steel, and aggregate are transported to the sites via rail. SimaPro calculates transportation emissions by multiplying the distance traveled by the weight of the materials. The average miles passengers and material used in the infrastructure construction and vehicle transport are shown in Tables 4 and 5.

4.2.4. Operation and Maintenance

This phase was modeled considering all the energy and material required to operate and maintain the railway system during the initial phase. Figure 4 shows the different modeling phases of the train in SimaPro, and the cascade compilation of train operation and maintenance phase.

The end-to-end route distance was estimated to be approximately 384.63 kilometers operated at the speed of 329.91 Km/h along most of the route, except in the vicinity of the stations. Initially, the trip is expected to take 1.7 hours with a 10-minute stop at Brazos Valley station for a total of 18 hours of operations and 6 hours of system maintenance and inspection – which results in an average of 68, one way, trips per day and an annual ridership of 6,155,360 passengers per year. The electricity consumption demand for the train is assumed to be a single phase running through a wiring installation above the track and distributed to each train using a catenaries distribution system. At the initial phase, the total electricity consumption is estimated to be 448.87 MWh. Electricity for the entire facility operation including maintenance is estimated to be 538.9 MWh, resulting in total power consumption of 998 MWh, assuming 5% loss. Three stations of 60 acres each are projected along the Dallas-Houston route. The stations are projected to give easy access to the city center of Dallas/Fort Worth, the Brazos Valley, and Houston *(25)*. Though this phase uses mostly electricity, during the 20 years, other products such as lubricates, diesel, paint, water and metals were also used, on a smaller scale.

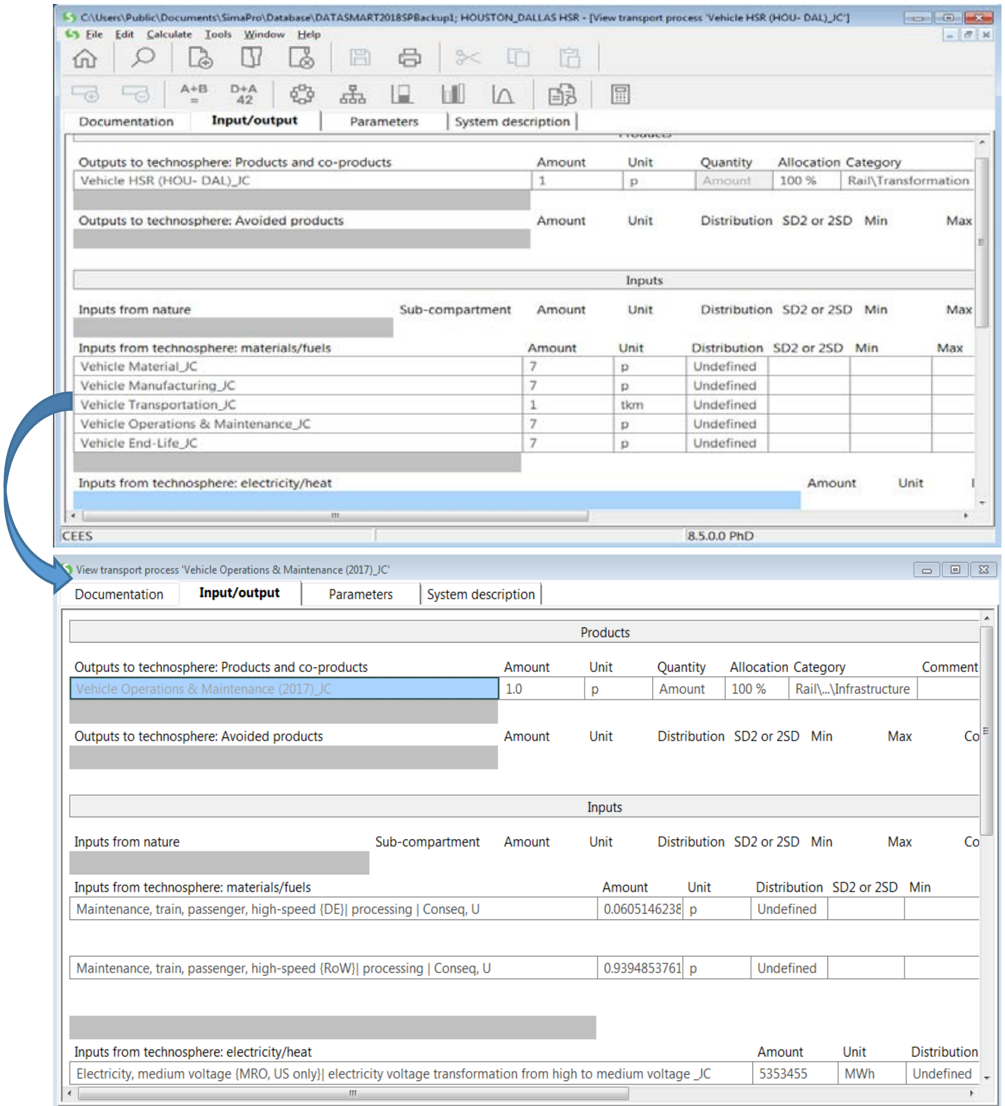


Figure 4. Illustrations of SimaPro cascade compilation of each process.

4.2.5. End-of-Life

The end-life assessment model was established considering the disposal and recycling mode of material and energy used throughout the life cycle phase. Considering the type of material used in vehicle construction, only a small amount of vehicle material was recycled. Most of the materials are scrapped and disposed of in the end-life phase. Materials which are part of stations and catenaries (steel and aluminum) are among the ones with the highest percentage of recycling rate. Energy consumption in vehicle scrapping and recycling process was retrieved from Ecoinvent3 database. Railway track, and road infrastructure are considered to be unutilized which results in zero end life effect. Since there is no data inventory for truck dismantling, the process suggests that the infrastructure is left on sight, at the end of life *(27)*.

4.3. Life Cycle Impact Assessment

There are many methods that characterize the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. Thus, for this study, the environmental impact was conducted using Impact 2002+ method of different transportation modes in comparison to the HSR system. Impact 2002+ provides viability process that associates the input emission inventory with 15-mid-point impact categories (Human toxicity, Respiratory inorganics, Respiratory organics, Ionizing radiation, Ozone layer depletion, Global warming, Terrestrial ecotoxicity, Aquatic acidification, Aquatic ecotoxicity, Acidification/nitrification, Aquatic eutrophication, and Land Occupation). Analyses of mid-point categories allow the research team to identify several exposure pathways and link concentrations of pollutants to possible tradeoffs in construction activities.

4.4. Interpretation of LCI and LCIA Results

This phase evaluates LCA results in relation to the defined goal and scope in order to reach conclusions and recommendations. The interpretation includes identification of any technical/methodological issues associated with inventory data and impact category selection. At this phase, limitations are analyzed and key assumptions documented with appropriate justification. Any missing emissions data for unit processes in the life cycle of the HSR system is substituted with appropriate data from HSR systems globally, subject to guidelines provided as per ISO 14040 standard.

5. ANALYSIS AND FINDINGS

5.1. Life Cycle Impact Assessment

This section outlines the life cycle impacts of the Dallas-Houston HSR system in terms of Impact 2002+ and mid-point categories (Table 7). By doing so, this study addresses the estimation of net change in GHG emissions and global warming potential as a result of HSR implementation. The resulting impacts across the 15 categories are based on defined boundaries and require inventory information established at the goal and scoping phase. Evaluating the total HSR system, the characterization assessment indicates that the vehicle is the largest contributor to the overall impact, accounting for more than 50% in 12 out of 15 mid-point categories. The significance of vehicle emissions results echo the amount of electricity used from fossil fuel generation (hard coal, lignite, and natural). For infrastructure material, such as copper, concrete, steel, rebar, and energy (electricity, fuel and lubricants) used during the four years of track and facility construction are the main contributor to the increase in emission. The increase in particulate matter, mostly from anthropogenic sources resulted in a high impact on human health and environmental damage potential. Global warming was impacted by hard coal/lignite mining operation, electricity and fuel consumption from heavy equipment, and the transportation of material to the construction site.

Table 7. Mid-point Impacts and relative contribution of vehicle and infrastructure in PKT.

	Impact category	Unit	Total Quantity	Vehicle[1]	Infrastructure[2]
a	Carcinogens	kg C_2H_3Cl eq	1.49E+08	62.64%	37.36%
b	Non-carcinogens	kg C_2H_3Cl eq	4.66E+08	40.22%	59.78%
c	Respiratory inorganics	kg $PM_{2.5}$ eq	17056764	95.85%	4.15%
d	Ionizing radiation	Bq C-14 eq	5.53E+10	97.99%	2.01%
e	Ozone layer depletion	kg CFC-11 eq	1250.64	51.69%	48.31%
f	Respiratory organics	kg C_2H_4 eq	1990505.20	66.26%	33.74%
g	Aquatic ecotoxicity	kg TEG water	1.09E+12	65.52%	34.48%
h	Terrestrial ecotoxicity	kg TEG soil	3.77E+11	56.09%	43.91%
i	Terrestrial acid/nutri	kg SO_2 eq	1.17E+08	83.77%	16.23%
j	Land occupation	m2org.arable	2.07E+08	34.48%	65.52%
k	Aquatic acidification	kg SO_2 eq	40190998	84.13%	15.87%
l	Aquatic eutrophication	kg PO_4 P-lim	9049321.90	74.63%	25.37%
m	Global warming	kg CO_2 eq	5.66E+09	92.77%	7.23%
n	Non-renewable energy	MJ primary	7.87E+10	92.83%	7.17%
o	Mineral extraction	MJ surplus	4.02E+09	18.63%	81.37%

[1]*Emissions were estimated for 20 years of vehicle lifetime;* [2]*Infrastructure at 60 years lifetime.*

Figure 5 below illustrates the cascade structure of the basic scenario used to calculate environmental impact with SimPro. As observed, the desired process (total emissions for the HSR system) is a result of train and infrastructure inputs. Moreover, each subsection has been analyzed separately to better assess the impact relative to vehicle and infrastructure. In all scenarios, the consumption of material and energy used is during the years of vehicle and infrastructure operation. The values in percentage represent the process contribution to the final process.

These results can also be translated in terms of mid-point category or as end-point (effect to human health, ecosystem, etc.).

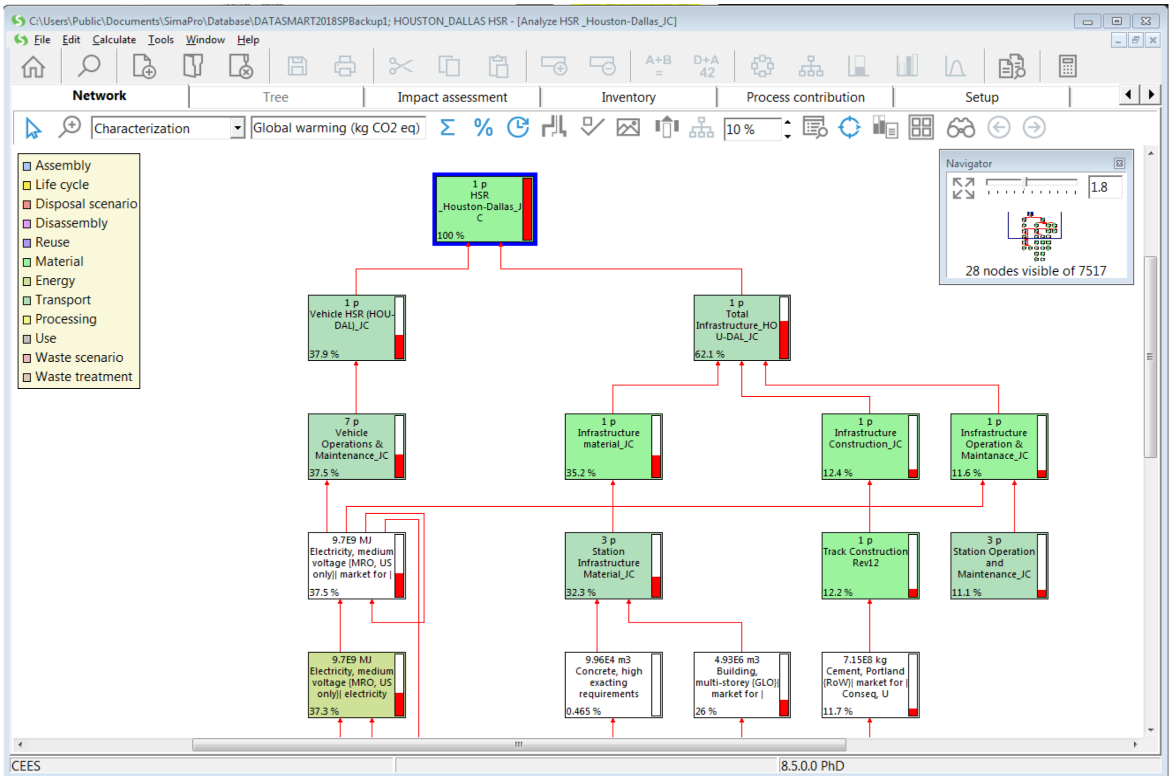


Figure 5. Illustration of HSR LCA process tree with SimaPro.

The distribution of mid-point impacts for the infrastructure is shown in Figure 6. Except for ionizing radiation and ozone layer depletion categories, the material extraction and processing phase is the leading contributor to environmental impact by a large margin. Operation & Maintenance (O&M) phase comes second, due to the large quantities of oil and gas products consumed during the 20 years of operation.

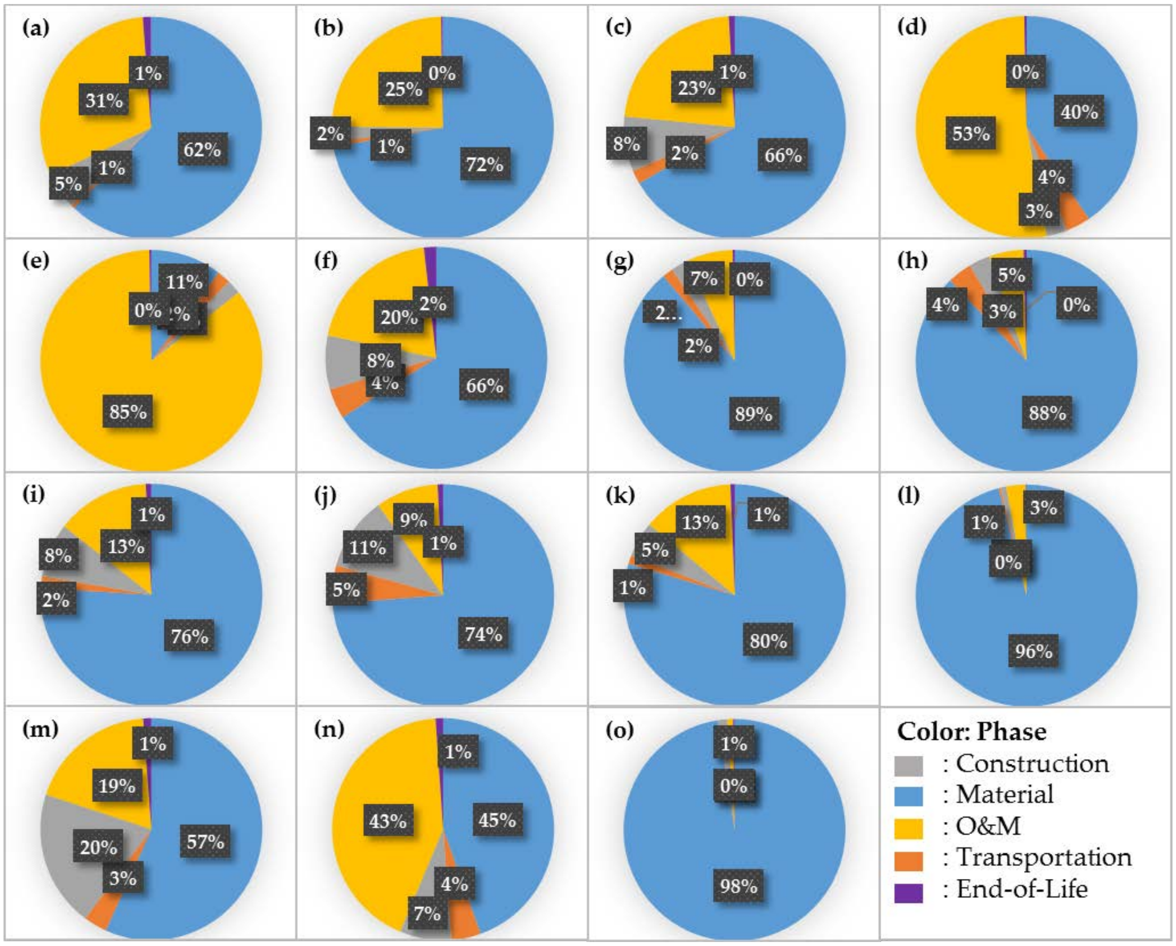


Figure 6. Distribution of phase wise mid-point impact for infrastructure.

Apart from the pollutants originating from mining, material processing and construction, the power source also influences the total system emission. Rail is frequently powered by electricity and depending on the source, low or high emission electrical generation system, the long term impact may be significant. A previous environmental assessment conducted in a nonrenewable source, such as coal power plant, has revealed higher emissions values than those from the renewable sources, like wind or hydroelectric *(28,29)*. Therefore, even though HSR has proven to be more efficient than other transportation modes (cars, plane) its long-term operation may be compromised by the available energy source in the region. Like other energy-related studies, the assessment of electricity and a higher average ridership are the main factors to minimize the GHG emissions per PKT. Figure 7 shows the cumulative energy demand for vehicle and infrastructure per PKT in the I-45 corridor.

I-45 high-speed rail system shows that the increase in global warming (carbon-related emissions) is strictly related to the increase in fossil fuel use, which suggests that the emissions by vehicle operation can be reduced by introducing a more sustainable energy source. The use of a carbon-intense mix will result in reduction proportion reduction in terms of emissions. Findings address Objective 5 which assesses the effect of source electricity mix scenarios on the environmental impact, resulting from HSR system operation phase.

At the end-point, the environmental impact results show that most of the contribution is allocated in the Human Heath category. The amount of particulate matter from infrastructure construction (excavation and mining), in addition to the use of electricity originated from fossil fuel such as coal, are the main factors contributing to the increase in human health.

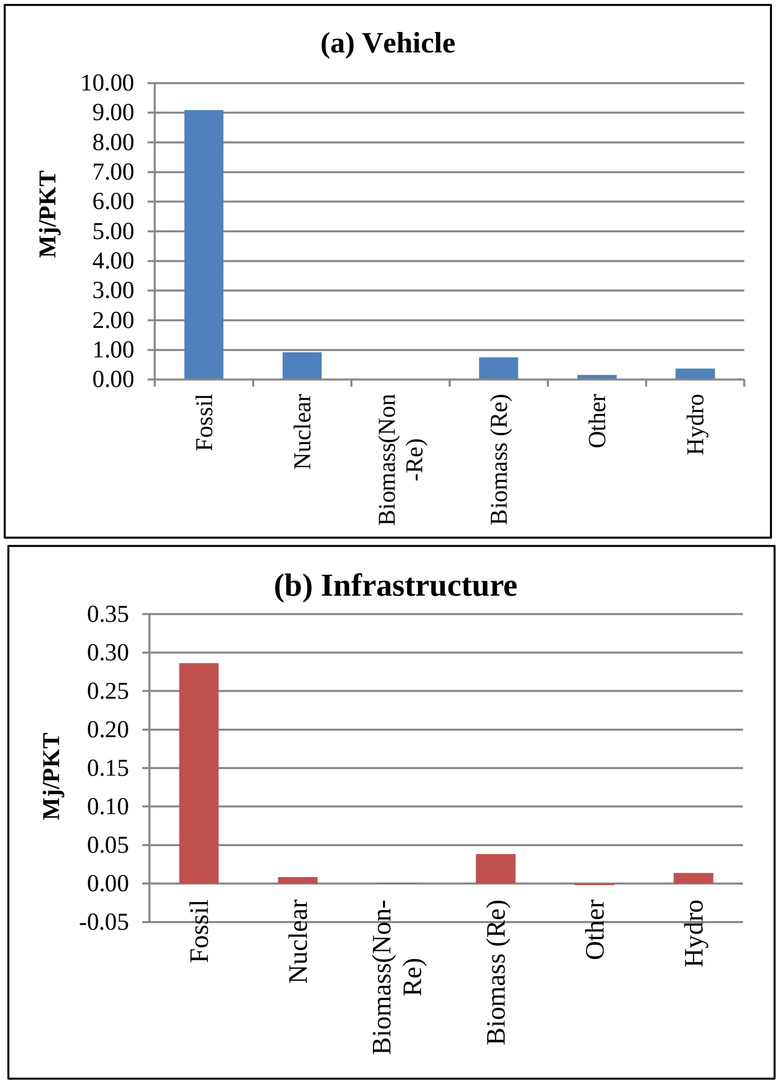
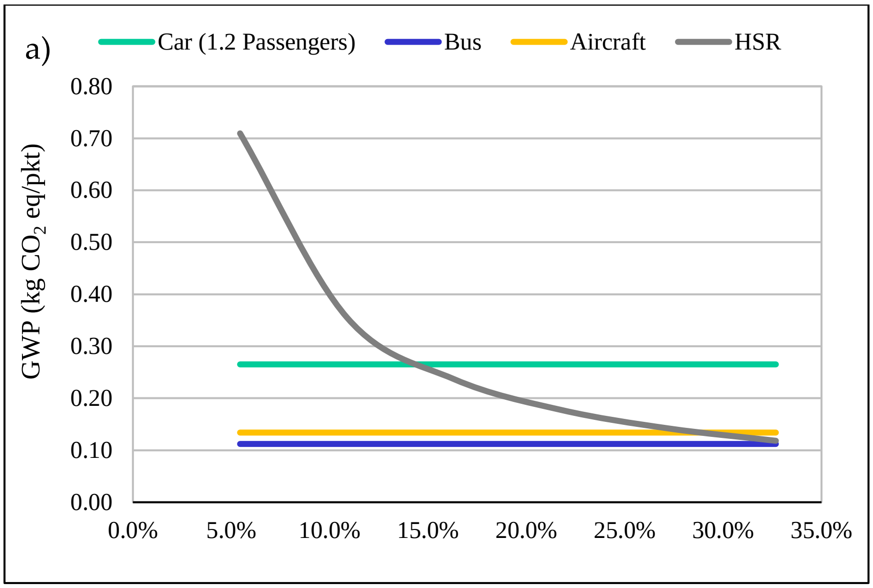


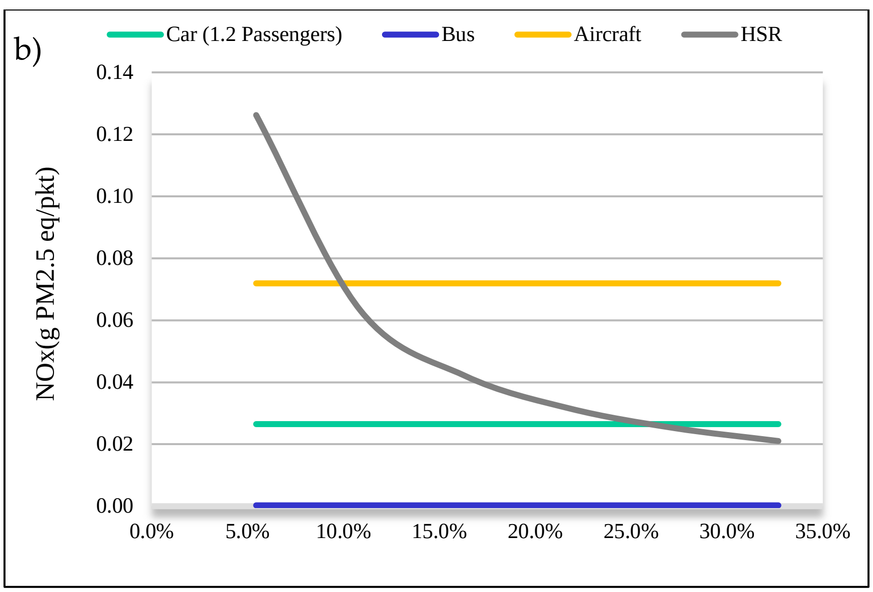
Figure 7. Cumulative Energy Demand for Vehicle and Infrastructure at 70% ridership.

5.2. Effect of Ridership Ratio

The effects on ridership and passenger migration to the HSR system control the environmental efficacy of the system. This analysis is depicted in Figure 8, which shows the cutoff levels for various transportation modes, addressing the requirement of Objective 4. From Figure 8(a), the minimum ridership ratio that is required for the HSR system to overcome the global warming potential compared to cars is around 12%. This cutoff point indicates that even at a low ridership level, the HSR system can outperform passenger cars in the HSR corridor. The principal reason for the low occupancy rate of 1.2 passengers/car in Texas. However, for the HSR system to be effective in comparison to bus and air transport the ridership level needs to increase to at least

25%. Regional air quality with the adoption of the HSR system can be improved at low ridership levels of 25% by outperforming NOx levels generated from cars and air travel. This would be a major boost to alleviating ozone problems in the nonattainment regions of Houston and Dallas. This study considers that all passenger cars used in the corridor are already fitted with the selective catalyst reduction technology for NOx control; thereby resulting in a major advantage for the HSR system. However, the HSR system performs very poorly in terms of $PM_{2.5}$ emission in comparison to cars and air travel, as observed in Figure 8(c). This anomaly is due to the heavy reliance on electricity produced from fossil fuels in the default SimaPro grid data. If the source electricity is shifted to a more renewable mixture, the problem of PM2.5 emissions could be negated. The highest quantitative input is from electricity production, so unless renewables are used in producing the electricity used to power the trains, PM2.5 emissions will not decrease. Although in terms of total energy consumed, the HSR system will be efficient at all ridership levels, as shown in Figure 8(d).





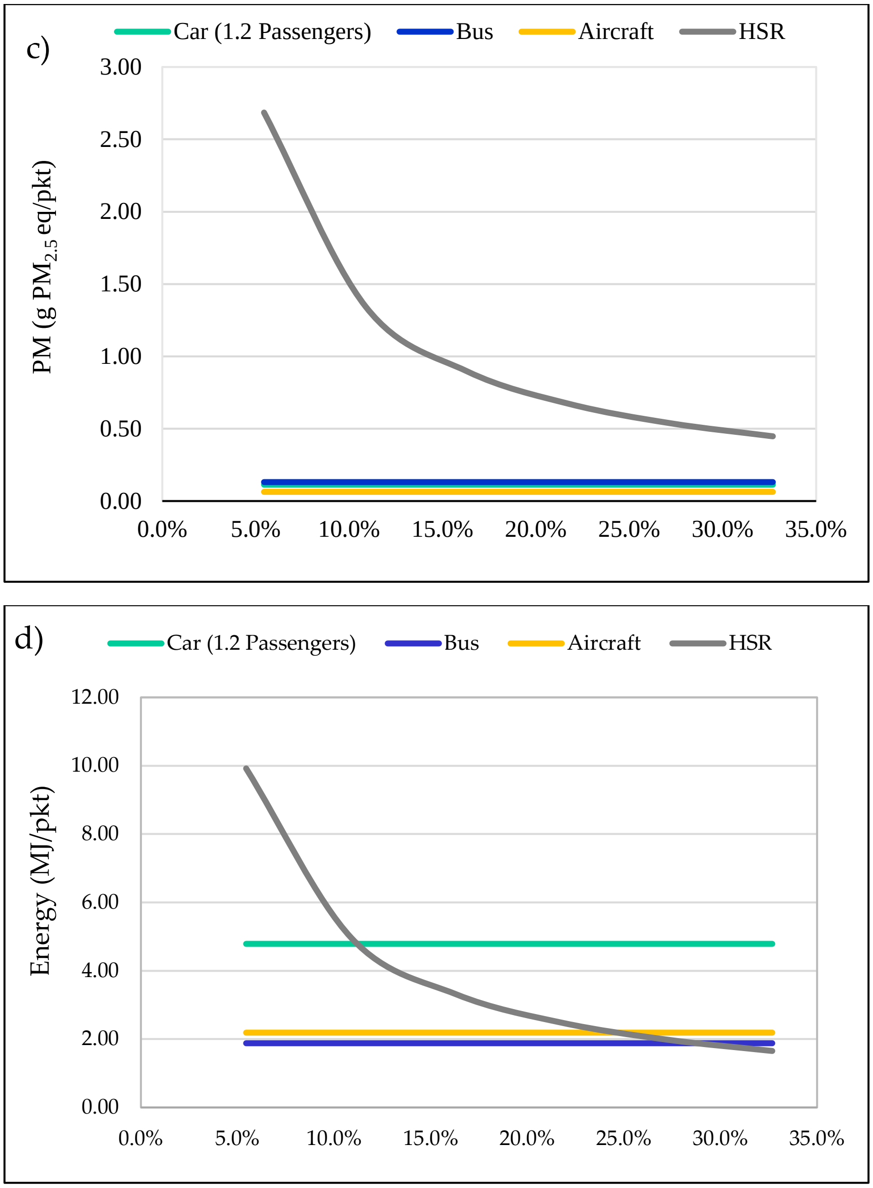


Figure 8. Effect of ridership levels on environmental efficacy of various categories (a) Global Warming Potential, (b) NOx, (c) PM2.5, and (d) Total Energy.

5.3. Sensitivity Analysis

This analysis was conducted to evaluate the environmental benefits resulting from the change in the source electricity mix. Operation and maintenance contribute the most in the overall vehicle emissions, and electricity mix is the main driver that increases pollutant emissions. Electricity mix varies by country and region.

The current U.S. and Texas electricity mix do not reflect the actual SimaPro® inventory. The U.S SimaPro electricity mix has the highest share for electricity from coal and lignite, which increase significantly the impact of vehicle and HSR system, in general. Whereas, the U.S. Electric Reliability Council of Texas (ERCOT) mix is mostly originated from gas sources, that have a much lower impact than electricity generated by coal or lignite. To evaluate the actual contribution of the main pollutants, the main vehicle emissions were assessed using the actual share of each fossil fuel source in Texas and the U.S.

Table 8 shows the difference in electricity mix for the base case (U.S. electricity mix) and the 2017 Texas Mix. Results show that the actual emissions for the HSR system will be much lower than the one calculated with Ecoinventv3 database.

Table 8. Ecoinventv3 electricity mix and the 2017 Texas Mix.

Energy Source	Base Case	Texas (ERCOT)
Hard coal	30.04%	19.33%
Hydro, Reservoir	1.09%	0.24%
Hydro, run-of-river	4.37%	0.00%
Lignite	33.01%	12.89%
Natural gas	0.32%	38.85%
Nuclear, boiling water reactor	5.42%	0.00%
Nuclear, pressure water reactor	10.63%	10.77%
Solar	0.00%	0.63%
Wind, <1MW turbine, onshore	1.11%	0.00%
Wind, >3MW turbine, onshore	0.11%	0.00%
Wind, 1-3MW turbine, onshore	13.18%	17.40%
Biomass	0.00%	0.15%
Net DC/BLT	0.00%	-0.27%
Biogas	0.72%	0.00%
Others	2.56%	0.01%
Total	100	100

Table 9 shows that vehicle operation will potentially reduce the CO_2 contribution by 64%, SO_2 by 78%, NO_x by 60%, and the N_2O emissions by 57%. Considering that the electricity mix is the main driver to the increase in vehicle emissions, by switching the Ecoinventv3 data with mix with the Electric Reliability Council of Texas (ERCOT), it expected an improvement in overall vehicle emissions. Reduction in vehicle emissions by changing the electricity mix to the less impacted source has previously been proven by other HSR/train environmental impact assessment conducted in Europe and North America, demonstrating to be one of the efficient ways to reduce the long term impact of the electricity mix. At the endpoint, the major reductions are observed in climate change (62%) and human health (44%). This result reflects the reduction in respiratory inorganic emissions (NO_x and SO_2) which normally coal electricity sources and fossil fuel use.

Table 9. Percentage of air emissions reduction with the change in electricity mix*

Pollutant	Unit/PKT	Base Case	U.S. 17	ERCOT 17	% Reduction (ERCOT 17)
CO_2	kg $CO_{2\ eq}$	12.68	8.03	8.08	36.3
SO_2	kg $PM_{2.5\ eq}$	0.002	0.002	0.002	21.7
$PM_{<2.5}$	kg $PM_{2.5\ eq}$	0.05	0.02	0.02	62.8
NO_X	kg $PM_{2.5\ eq}$	0.00	0.001	0.001	40.0
N_2O	kg $CO_{2\ eq}$	0.14	0.08	0.08	43.6

**The base case corresponded to the data in the Ecoinventv3 database for U.S. electricity mix: ERCORT (Electric Reliability Council of Texas), base case (U.S. Electricity Mix- Ecoinventv3, and % Reduction (Decrease in emission due to change from base case to Texas mix).*

5.4. Implementation Plan

To provide guidance to the stakeholders, policymakers and community leaders, we have developed a presentation listing the potential environmental benefits of the HSR system along the I-45 corridor. The presentation was developed as part of the implementation plan. The research team will make the presentation, final report available online and will attempt to contact the stakeholders for feedback.

Some recommendations include education to the public relative to the environmental benefits of HSR and the use of renewable energy for HSR system operation. Results from this study show that by reducing the population of passengers traveling by car we can improve air quality along the I-45 corridor. Moreover, the increase of the occupancy rate can significantly reduce the total environmental impact generated by construction of the HSR system.

6. CONCLUSIONS

Environmental impacts of the development of an HSR system along the I-45 corridor with Shinkansen N700 series trains were conducted. It was found that vehicle component is the largest contributory phase across 12 of the 15 mid-point impact categories (expect non-carcinogenic, land occupation, and mineral extraction). With the methodology described above, our research met the overall requirement of the proposed objectives by:

- Developing a systematic framework of Dallas-Houston HSR system. The framework defines all essential elements, in agreement with the standards, methods and guidelines established by the International Organization for Standardization (ISO 14040) of environmental life cycle assessment system.
- Estimation of the net change in GHG emissions and global warming potential (CO_2, eq) was realized by evaluating the energy and emissions per passenger-kilometers. This study found that vehicle component accounts for 14.50 $kgCO_2eq/PKT$, of which fossil-fuel usage during operation is the primary contributor with 98% of the GHG emissions. For the infrastructure component, 56.76% of GHG emissions are contributed by the construction phase (23.75 $kgCO_2eq/PKT$).
- Evaluating the benefits of air quality, by conducting a sensitivity and comparative analysis between the HSR system and other transportation modes, we concluded that the I-45 corridor will benefit from the reduction of CAPs and GHS emissions (which will consequently contribute to the air quality improvement in the region).
- Accessing the relevance of CAPs and GHGs emissions of the HSR system, relative to other modes of transportation. Based on these analyses, it was found that the minimum ridership levels required offsetting the environmental impact from conventional modes of transport, such as personal cars, bus and aircraft, are around 12% and 27% for GHG emissions and NOx emissions respectively.
- Analyzing the effect of source electricity mix on the environmental impacts from the operation phase. The results suggest that by increasing the percentage of renewable energy, in the train operation phase, will significantly reduce the impact of pollutants and GHGs emissions, in the region.
- The interaction process with stakeholders, policymakers and community leaders on the potential environmental benefits/costs of HSR mode of transportation in the U.S. is in progress yet. The PI intent to request a meeting with the Dallas –Houston Operation Company to present this study's findings and recombination.

6.1. Recommendations for Stakeholders

The I-45 corridor is the busiest route among 18 traffic corridors in Texas. The implementation of the HSR system provides benefits in the areas of environmental, safety, time, and commodity of passengers traveling between Dallas-Houston. However, for better environmental performance, this study recommends the following:

- Educate the public to increase the awareness of the environmental benefits of HSR. Increase of the occupancy rate will reduce the total environmental impact generated by the construction of the HSR system. In addition, it will:

    - Reduce the population of passengers traveling by car and plane, since more people would choose high speed trains, which consequently improves air quality.
    - Passengers will save time because of the use of efficient transportation, especially during rush hour and peak travel times.
- Improve mobility in the face of growth to mitigate population increase by 2050.
- Increase the use of renewable energy for HSR system operation.

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