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The Metallic Elephant in the Room: Short Range Flights, High-Speed Rail, and the Environment

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The Metallic Elephant in the Room: Short Range Flights, High-Speed Rail, and the Environment

by

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Report

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Community and Regional Planning

The University of Texas at Austin

May 2011

Dedication

Many people are blessed enough to have a very tough choice to make when choosing the person to whom this revered space should be dedicated. For me, luckily or unluckily depending on one's perspective, the choice was easy and obvious.

The term 'single parent' is not sufficiently descriptive in the social context of America in 2011. Single parents run the gamut from nouveaux-Independent Hollywood starlets to panicked poor everyday teenagers, and the situations that the children of these parents follow a similar continuum. My mother, Sharron Elaine Raibon, was on neither end of this continuum. However, as a young flight attendant, the new reality of single-parenthood did not mesh well with the demands of coast-to-coast travel three weeks of every month. As time passed, she chose to sacrifice the job she loved in order to be the parent that she felt would be necessary to raise a successful child, becoming an educator on the impoverished southeast side of Houston, Texas.

My mother was part of the first generation of her family to graduate from college. As an educator she embodied what it meant to be an inspirational American bootstrapper – from growing up in relative poverty in the 1960s to being a successful school administrator in Houston Independent School district in 2011. This example kept me from following a road many others in my situation have, and led me on a path that values education, good deeds, compassion, and independence.

In my dark times, my mother has offered unwavering support and compassion that has kept me motivated and focused, and determined to achieve the goals that I have set for myself. She has shown love in all of its forms, including the disciplinary tough love that many parents shy away from. It is a blessing to have such a dedicated person in my corner and I dedicate this culmination of my post-graduate studies to her.

Acknowledgements

First of all, I'd like to acknowledge that I would not be in a position to carry out any of my interests without the grace of God. Through Him, I have discovered that I am able to be successful at things that I would have never imagined I could have previously.

I also have a wide variety of people that I'd like to acknowledge. First of all, I want to thank my uncle, Mondy Raibon. My uncle was undoubtedly the driving force that led me to consider graduate education at the University of Texas. As a former Austin resident and member of The College Board, he, along with my mother, have stressed the value of and importance of education since as long as I can remember. He has helped me, more than any other person, use my time wisely and persevere at UT. His support has been invaluable.

The support of the School of Architecture faculty has also been as big of a factor in my matriculation here as any other. In particular, I'd like to thank Dr. Michael Oden, Dr. Ming Zhang, and Dr. Kent Butler. Dr. Oden was the original professor to reach out to me and provide the time for us to meet, leading me to choose UT. Without the kindness, tact, and honesty displayed by Dr. Oden, I may not have ever chosen to attend UT.

Dr. Zhang has been the biggest gift I could have asked for upon coming to the university. He and Dr. Butler have both been extremely patient with me over the last two years, and they have both helped me pursue some goals outside of the main goal of receiving a quality education and graduating. Dr. Zhang pushed me to travel with him to China to study high-speed rail, something I was initially reluctant to do. However, I relented and decided to go, and it turned into one of the most enriching, amazing experiences of my life. Dr. Zhang has helped me develop my professional and personal interests more than anyone else over the last two years. Dr. Butler provided me the opportunity to work with he, our student organization, and the Graduate School to enhance our recruitment of diverse applicants in the Community and Regional Planning Program, a directive that I believe we have made significant progress on. His tireless efforts to create a stronger, more diverse graduate school and planning program are goals I share and I appreciate his efforts.

I'd also like to acknowledge Lisa Loftus-Otway and Robert Harrison of the Center for Transportation Research here at the university. I hold Ms. Loftus-Otway personally responsible for introducing me to freight planning and bringing to my attention how large of a role it plays in our day-to-day lives, as well as the future of this country. She helped me diversify my interests in planning and recognize a problem I had honestly never thought about. She and Mr. Harrison have helped me develop as a professional by having me take a major role in delivering a large project to the Texas Department of Transportation. Their help has been invaluable to my professional development.

And last, but not least, I'd also like to extend a special thanks to Dr. Ming Zhang and Ms. Lisa Loftus-Otway for agreeing to serve as my committee for this report.

May 6, 2011

Abstract

The Metallic Elephant in the Room: Short Range Flights, High-Speed Rail, and the Environment

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The University of Texas at Austin, 2011

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It is of nearly universal acceptance that one of the pillars of American economic success over the course of the 20th century was the rapid development of infrastructure. Transportation infrastructure has been of particular importance in the rise of the United States and attributed to the spread of an increasingly mobile culture. Americans undoubtedly enjoy traveling, and the ability to do so with relative ease is of immense value to many.

In Texas, the majority of economic activity takes place within what is colloquially known as the "Texas Triangle", an area bounded by the large metropolitan areas of Houston, Dallas-Ft. Worth, and San Antonio. Intensive population growth in Texas, anchored by the triangle, has led to increasing road congestion on many routes, especially

along Interstates 35 and 10. This congestion, and the wasted time and money that comes with it, are of increasing concern to the future economic vitality of the state.

The Texas Triangle is also served by extensive aviation links via major airports in the major metropolitan areas, as well as smaller airports in other parts of the region. These flights, operated by American Airlines, Continental Airlines, and Southwest Airlines are frequent, but emit large amounts of greenhouse gases that contribute to ground level pollution and possibly climate change. High-speed rail has been considered by many to be a superior environmental option for intercity routes with lengths inherent to the Texas Triangle.

However, given the fact that Texas is the top emitter of carbon dioxide in the U.S.[1] and relies on an energy mix that is primarily fossil fuel powered; would a potential high-speed rail in Texas outperform the current air system environmentally, given similar passenger miles traveled? This report examines the environmental emissions of high-speed rail and compares it to the environmental emissions of our current aviation system, taking into account a life-cycle perspective.

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[1] (U.S. Environmental Protection Agency 2010)

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Glossary

BTS: Bureau of Transportation Statistics

CO_2: Carbon dioxide

EIO-LCA: economic input-output analysis based life-cycle analysis

EPA: United States Environmental Protection Agency

ERCOT: Electric Reliability Council of Texas

HSR: high-speed rail

kJ: kilojoule

kWh: kilowatt-hour

LCA: life-cycle analysis

LTO cycle: landing/take-off cycle

MWh: megawatt-hour

NO_x: nitrogen oxides

PMT: passenger miles traveled

SO_2: sulfur dioxide

VMT: vehicle miles traveled

WECC: Western Electricity Coordinating Council

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INTRODUCTION

Since the invention of the automobile in the early parts of the 20th century, Americans have been enamored with transportation. The United States, as the birthplace of the automobile and the airplane, has developed a culture of mobility unrivalled by many in the world. Americans have become known worldwide for big roads, big cars, and jet-setting in various locales.

However, the transportation system of the United States faces a perilous future. As the population (and therefore number of drivers) increases, congestion continues to increase faster than we can build new roads. Environmental concerns associated with increasing vehicle-miles traveled (VMT) have led to increasing concern about the sustainability of the proliferation of private automobiles worldwide. Revenues from fuel taxes have decreased for two primary reasons. The first is that the 20 cent/gallon Texas fuel tax and 18.4 cent/gallon federal fuel tax have not been raised since 1991 and 1993 respectively.[2] The other reason is increased fuel efficiency of the U.S. vehicle fleet. As the fuel efficiency of the fleet has increased, revenues brought in per passenger mile traveled (PMT) has decreased, limiting the amount of funding governments have available for new construction, maintenance, and repairs. Funding constraints are a significant threat both to maintenance of the current system as well as its future expansion. It is clear that transportation faces numerous challenges on many levels.

High-speed rail (HSR) has been gaining increasing popularity in years as a way to solve many of the United States' transportation problems in one fell swoop. It has been offered as a way to reduce U.S. dependence on foreign petroleum, by largely replacing short haul air trips with HSR trips and therefore decreasing the amount of Jet-A used in

[2] (Galbraith 2009)

the country. It has been promoted as a superior option in terms of safety, convenience, comfort, and in some cases even speed. All of these are undoubtedly strengths of HSR.

However, another argument that has been made by HSR advocates is that it is a more environmentally-friendly travel option than aircraft. This reasoning is born from the perception that aircraft, using petroleum as their primary fuel, emit more and are dirtier than a HSR line, using electricity as a power source on a per-passenger-mile basis.

The focus of this report is to determine if this is actually the case. Two key factors are often not taken into account when relative emissions are examined for either of these modes. The first is that the electricity emissions produced to operate and fuel HSR must be quantified in order to determine what is actually attributable to the HSR system. The second is that the emissions of all supporting activities must be quantified in order to gain a true understanding of what the environmental costs are for the mode. Examples of these supporting activities for HSR would include track construction, track maintenance, and station construction. For aviation, they would include activities such as aircraft maintenance, aircraft construction and airport maintenance.

The President of the United States, Barack H. Obama, has outlined his administration's policy of supporting new transportation initiatives such as HSR in the interest of renewing American infrastructure in general. On April 16, 2009, President Obama unveiled his national plan to bring HSR to a variety of corridors, and committing $8 billion to improving rail corridors, much of that going to HSR research and development.[3] Though the initiative of the Obama administration to pursue HSR has been seen favorably in some corners, the nation's immediate path toward fiscal austerity has dealt a series of blows to the President's vision. Three states have returned HSR money to

[3] (The White House 2009)

the administration, and the momentum of American HSR development has slowed with California remaining as the only state continuing to push forward with their planned system.

Though Texas is the largest state in the continental United States, the demand for intercity and interregional transportation largely centers on an area known as the Texas Triangle, located in east-central Texas. The Texas Triangle is normally defined, in transportation terms, as the area enclosed by and adjacent to Interstates 45, 10, and 35, and anchored by the metropolitan areas of Houston, Dallas-Ft. Worth, and San Antonio. Austin, Waco, and Bryan-College Station are also other key population centers within the Texas Triangle. Most trips in the state begin or end somewhere within the Texas Triangle area, and as a result, there is a strong air market between many of the Triangle cities. Due to the fact that none of the "vertices" of the Triangle are further than 250 miles away from one another, there is also significant automobile based commuting between the three cities.

Automobiles were not included in this analysis primarily due to the difficulty in accurately measuring the amount of automobile trips that originate or terminate in a specific area in a specific time. With air and rail modes, it is possible to realistically estimate ridership based on different known variables, but it is unrealistic to expect to do the same with private automobiles. Buses also compete with private automobiles and aircraft but were not included as the ridership information is not reliable. Ridership figures vary widely for buses across routes and times, and small operators are not adequately modeled.

In Texas, any HSR line is realistically at least fifteen years away. The state had a flirtation with HSR in the early 1990s that was ultimately undone by intensive anti-rail lobbying effort by the airlines, as well as potential cost overruns and opposition by landowners in prospective corridors. Since that time, progress on planning a potential HSR line in the state has been essentially nonexistent, with funding focusing on road construction and intraregional public transit.

Today, HSR in Texas is a hot topic among the academic and transportation communities. This study intends to examine whether HSR would be environmentally superior to the current air system. This will be done by comparing the total emissions of CO_2 and NOx emitted on a yearly, per-passenger-mile basis of the aviation system with the emissions of a theoretical HSR system. This is not intended to include any economic considerations and the economic impacts of building a new HSR system will not be examined.

CO_2 and NO_x were chosen as the gases of study because they are representative gases that can be quantified with reasonable accuracy and certainty. Many other greenhouse gases, such as $SO_{2,}$ are much more difficult to quantify via current methods, particularly for aviation applications. CO_2 and NO_x also have well-documented properties that are easily linked to ground-level pollution and the adverse health and environmental effects associated with them.

REVIEW OF LITERATURE

A perceived issue in the United States today is the question of how to reduce the nation's dependence on petroleum products for transportation applications. This question has been asked for decades in this country, and none of the price spikes, shocks, or discussions seen in the last 35 years about this topic have done much to change the status quo of immense importation of crude oil. Americans continue to buy vehicles and aircraft that use oil-derived products for fuel and lubrication.

While the vehicles driven in the United States are used for both intraregional and interregional travel, commercial aircraft are almost exclusively used for interregional travel. These aircraft, while fast, safe, and relatively efficient, also use an inordinate amount of fossil fuel, with jet fuel accounting for 10% of the resultant products of a typical barrel of oil consumed in the U.S.[4]

The discussion of how to reduce oil consumption in the United States often centers around improving the fuel economy of automobiles or supporting the development of alternative fuels for automobiles. Given the scale of automobile usage in the country, improvements in automobiles is undoubtedly critical to the success of consumption reduction efforts. However, many states see HSR as both a way to provide new capacity for highway congestion reduction while simultaneously providing an alternate travel choice for passengers that would ordinarily drive or fly. States such as California have policy motivations in the promotion of HSR as well, tying its success to the success of environmental legislation such as AB 32, a 2006 law that requires California to meet stringent greenhouse gas emissions goals by the year 2020. AB 32 also has incremental goals on the road to meeting new tighter greenhouse gas standards, and

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[4] (U.S. Department of Energy 2011)

many believe that HSR can bolster employment while improving environmental indicators related to travel in California.[5]

Carbon dioxide (CO_2)

The effect of human-caused CO_2 emissions into the environment is very controversial given the divergent data that has been collected on the topic. While there is no doubt that CO_2 emissions have increased substantially during the last 100 years or more, reconciling with the beginning of worldwide industrialization, there is little consensus as to the reason this is the case.

The world has been naturally warming for the last three centuries due to the Earth's recovery from an event known as the Little Ice Age. The Little Ice Age, while not a true ice age, was a period of cooling that lasted from approximately the beginning of the 16th century until approximately the beginning of the 19th century. It is defined as a period of colder than normal temperatures worldwide of up to about 1°C.

Since the Little Ice Age ended, temperatures on Earth have been rising steadily, with a larger than average jump in temperature rise observed toward the end of the 20th century. The cause of this rise is the point of conflict. Many have blamed CO_2 emissions that have risen sixfold on the sudden spike in temperature change rates.

The main argument against CO_2 being the primary cause of global climate change is that the increases in emissions of CO_2 tend to follow, not lead the increases in temperature.[6] This would mean that emissions of CO_2 are an effect, not a cause of global climate change.

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5 (Catz and Christian 2010)
6 (Soon, et al. 1999)

Despite the inconclusive nature of the relationship of the link between increased atmospheric CO_2 and global climate change, the heat-trapping ability of CO_2 has been demonstrated since the 19th century.[7] While the question of whether CO_2 is the causative agent of climate change remains to be seen, CO_2 has nonetheless become a symbol of climate change and the chief antagonist in the context of modern environmentalism. The likelihood that CO_2 is a key cause of global warming is high, and justifies its inclusion in this report as an emission of interest.

Nitrogen oxides (NO_x)

NO_x is a term that describes the nitrogen oxide compounds nitric oxide (NO) and nitrogen dioxide (NO_2). Unlike CO_2, the harmful properties of NO_x are well understood. NO_x has a variety of detrimental effects to human health, the environment, and plant life.

Below the troposphere (below 7-9 miles above sea level) presence of sunlight NO_x combines with volatile organic compounds (VOCs) to create smog and ground-level ozone. This ozone has the ability to penetrate sensitive lung tissues, especially in at-risk populations, and cause significant long-term damage. This type of pollution has many harmful effects on human and plant life, including chest pain, coughing, throat irritation, and congestion, as well as worsening conditions such as bronchitis, emphysema, and asthma.[8]

While NO_x creates ground level ozone, it ironically destroys ozone further up in the stratosphere. It is hypothesized that damage to the ozone layer has been primarily caused by emissions of NO_x over the years.[9] NO_x also mixes with water to cause acid

[7] (National Aeronautics and Space Administration 2010)
[8] (U.S. Environmental Protection Agency 2011)
[9] (Romano, Gaudioso and De Lauretis 1999)

rain. Acid rain tends to leave watersheds with high levels of nitrate, which is a health hazard, especially to infants.[10]

In Texas, the passage of State Senate Bill 7 in 1999, both deregulated the electricity market in the state, as well as mandating significant (50%) reductions in NO_x from grandfathered power plants as well as more strict requirements for any new point sources.[11] While its overall impact can be debated, it has undoubtedly done well in encouraging reduction in emissions of NO_x. Governor of Texas Rick Perry has estimated that the state has reduced NO_x emissions from ground-level sources by 46% between 2000 and 2008[12], while the U.S. Environmental Protection Agency (EPA) estimates an even steeper NO_x reduction of 60% between 2000 and 2007.[13] Though NO_x is emitted by ground-level sources such as refineries and power plants, the majority of NO_x in Texas is emitted by mobile sources, such as vehicles and aircraft. In the Dallas-Ft. Worth area alone, mobile sources are estimated to account for 73% of all NO_x emissions, with 27% attributable to industrial sources.[14] The ability of Texas to lower its NO_x emissions significantly will depend on the ability of the state to focus on mobile sources. HSR could provide a way to reduce our reliance on heavily NO_x emitting vehicles.

The Role and Rationale of Life Cycle Analysis

Life-cycle analysis (LCA) inventories, while not a new idea, have become more popular tools in recent years due to their ability to account for inputs not normally

[10] (Chesapeake Bay Journal 1997)
[11] (Metropolitan Partnership for Energy 2011)
[12] (State of Texas 2011)
[13] (U.S. Environmental Protection Agency 2010)
[14] (Texas Business for Clean Air Foundation 2008)

considered in the context of construction, operation, and maintenance of a mode of transportation.

The method chosen in order to undertake this case study was devised as a hybrid method that would yield an accurate result while still being able to use publicly available data. The primary document used to shape and draft the study was Mikhail Chester's 2008 doctoral dissertation, *Life-cycle Environmental Inventory of Passenger Modes in the United States.* Chester's dissertation is likely the most complete inventory in existence of life-cycle emissions and energy usage for transportation modes. Chester examined the energy usage of emissions for three modes (air, rail, and automobile) using a combination of two types of life-cycle analysis models. These two types are as follows:

1. A process model that quantifies resource inputs and environmental outputs based on unit process modeling and mass balance calculations, and
2. An economic input-output analysis based LCA (EIO-LCA) which integrates input-output analysis and environmental databases allowing for an inventory analysis showing the scope of the environmental outputs for the entire supply chain of a product or service.[15]

Chester chose to pursue a hybrid model that incorporates both of these types due to the fact that while process models are generally viewed as more precise models, they require a large amount of data and are a time- and cost-heavy method of completing LCA. The economic input-output based LCA offers a partial solution by utilizing traditional economic input-output analysis and adding environmental data to it. This allows for an effective quantification of the interdependencies between different sectors

[15] (Chester 2009)

that combine to create a good or service. Though it may not offer the detail of pure process based LCAs, the input-output analysis does allow for a more comprehensive environmental assessment.

Our goal is to utilize the methods pioneered by Chester's LCA to create a workable case study that will analyze the amount of pollution directly attributable to these two modes.

METHODOLOGY

Aviation Operating Emissions

Aviation data was procured from a variety of sources in the pursuit of creating a complete inventory of all flights serving the population centers of the Texas Triangle. The routes studied included:

- Houston (Bush IAH/Hobby) – Dallas/Ft. Worth (DFW/Love)
- Houston (Bush IAH/Hobby) – San Antonio (SAT)
- Houston (Bush IAH/Hobby) – Austin (AUS)
- Houston (Bush IAH/Hobby) – Waco (ACT)
- Houston (Bush IAH/Hobby) – Bryan/College Station (CLL)
- Dallas/Ft. Worth (DFW/Love) – Austin (AUS)
- Dallas/Ft. Worth (DFW/Love) – San Antonio (SAT)
- Dallas/Ft. Worth (DFW/Love) – Waco (ACT)
- Dallas/Ft. Worth (DFW/Love) – Bryan/College Station (CLL)

American Airlines, Continental Airlines, and Southwest Airlines, the three carriers that serve intercity Texas routes, have publicly available schedules for up to a year in advance.[16]

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[16] (accessed via www.aa.com, www.continental.com, and www.southwest.com)

Route	Flights per day	Actual Passengers (2009)	Estimated Passengers (2010)	Estimated PMT (2010)
HOU-DAL	104	2,910,797	3,207,620 (+9%)	750,910,850
HOU-SAT	32	N/A	1,234,576	235,522,528
HOU-AUS	30	N/A	1,095,365	156,533,900
HOU-ACT	8	N/A	78,840	12,535,560
HOU-CLL	14	N/A	137,970	10,209,780
DAL-AUS	53	2,028,399	2,148,390 (+6%)	408,194,100
DAL-SAT	57	2,116,049	2,299,500 (+8%)	567,976,500
DAL-ACT	8	N/A	121,910	10,971,900
DAL-CLL	6	N/A	100,010	16,401,640
TOTAL	**312**	**N/A**	**10,424,181**	**2,169,256,758**

Table 1 - Flight profile of Texas Triangle routes, March 18, 2011

Using the information for a typical day (in this case chosen as March 18, 2011), all flights between Texas Triangle cities were recorded, along with appropriate requisite information about them, such as the number of flights per day, aircraft type, distance between airports, flight time, and the number of seats on the airplane. Load factors for aviation were taken at an average of 80%, reflecting increasing load factors on U.S. airlines in recent years. Assuming an 80% load factor, an estimate of the amount of annual passenger seat miles traveled on these routes could be obtained.

The three busiest routes (HOU-DAL, DAL-SAT, DAL-AUS) have available published passenger numbers from 2009 via the Bureau of Transportation Statistics

(BTS). The existing 2009 passenger numbers tend to corroborate the viability of the 2010 estimates using an 80% load factor – the estimates show a rise of 6-9% PMT for the three busiest routes

Specific aircraft type information was available for Continental and American Airlines; however this was not the case with Southwest Airlines. Since Southwest only operates different variations of one aircraft type, cockpit commonality allows the airline to swap aircraft depending on loads and operational considerations. As a result, the company does not specify the aircraft type on their schedules.

In order to calculate emissions information of an aircraft on a passenger mile basis, it is first necessary to know the passenger capacity of the aircraft in question. Since this was not possible with the data given, it was chosen to use Southwest's average aircraft capacity (136 seats) as the value for passenger seat-mile calculations. This same method was used to estimate NO_x emissions factors and fuel usage for the Southwest fleet. All other airlines use the actual capacity of the specific aircraft serving each particular route.

After compiling general flight scheduling data, information about emissions related to aircraft operations was gathered. Aircraft emissions are an evolving area of study, as the nature and potential harm of aircraft emissions are not fully understood. Aircraft, as a result of flying in the high troposphere and low stratosphere, emit pollutants into the upper areas of the atmosphere more quickly and directly than ground-based pollution sources. The magnified effect of pollution generated at high altitudes is not completely quantified, but the Intergovernmental Panel on Climate Change estimates that CO_2 emissions increase the amount of external radiative forcing, or net change in irradiance of different layers of the atmosphere, by a factor of 3.5.[17] Aircraft operations alone are estimated to comprise 3.5% of all global greenhouse gas emissions, with 60% of that attributable to civil aviation.[18] This is prior to accounting for any life-cycle emissions attributable to the operations of aircraft. Therefore the true amounts of emissions that are linked to aviation worldwide are likely significantly higher.

The International Civil Aviation Organization (ICAO) maintains the ICAO Engine Emissions Databank, the most comprehensive database of turbofan and turbojet technical emissions data. The Swedish Defence Research Agency FOI maintains a similar database for turboprop aircraft. This data includes measurements of emissions of NO_x and CO, as well as information of fuel usage and smoke production. It presents this data for four phases of flight (takeoff, climb, approach, idle) as well as for the landing-takeoff (LTO) cycle.

The LTO cycle is defined by ICAO as the cycle time when an aircraft enters the atmospheric mixing zone and lands, taxi time in, landing time at the gate, taxi idle out to the takeoff runway, takeoff, and climb through the atmospheric mixing zone.[19] The atmospheric mixing zone is the height below which pollutants emitted into the atmosphere can have an effect on ground level concentrations of pollutants.

It is useful to separate LTO cycle calculations from cruise calculations when inventorying emissions or fuel usage for two key reasons. First, LTO cycles tend to consume a much larger share of fuel than do other phases of flight, as a percentage of time spent in the phase. Separating the LTO fuel usage from the climb, cruise, and descent fuel usage would yield more precise estimates of energy usage and therefore

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[17] (Eggleston, et al. 2006)
[18] (Lee, et al. 2009)
[19] (Wade 2002)

more precise estimates of emissions. Secondly, turbine engines are much more efficient at higher altitudes, reflected by a higher emissions profile at low altitudes. Some gases, such as methane, are even produced by turbine engines at low altitudes, but consumed by the engine at high altitudes.[20] The LTO cycle data reflects the measured differences in these emissions.

NO_x emissions attributable to aircraft vary widely among aircraft engines as their prevalence depends primarily on engine technology. Older generation turbine engines are much more polluting than contemporary engines of similar thrust ratings. This can be seen by comparing the emissions profiles of the McDonnell Douglas MD-80 with the current generation Boeing 737. Together, these two make up 74% of all intercity Texas Triangle flights. The Pratt and Whitney JT8D's of the MD-80, a 1970s era design, emits an average of 12.3 kg of NO_x/LTO, compared to 8.3 kg of NO_x/LTO for the CFM International CFM56 engines featured in current generation 737s.[21] However, the variable nature of NO_x emissions does not apply to CO_2. Production of CO_2 is a component of the energy released from Jet-A fuel and is 3.15 kg CO_2/kg fuel burned, with small variations for fuel quality and environmental conditions.[22] Therefore, the amount of estimated CO_2 emissions was found by simply finding the amount of estimated fuel used and multiplying it by that factor.

Estimated NO_x emissions attributable to Texas Triangle intercity flights was obtained by multiplying the appropriate cruise emission factors by the estimated amount of cruise fuel used during the flight, and adding this to the estimated amount of NO_x emitted during the LTO cycle. This was then summed to yield the total amount of

[20] (Federal Aviation Administration and U.S. Environmental Protection Agency 2009)
[21] (International Civil Aviation Organization 2007)
[22] (European Environment Agency 2009)

emissions for this subset of flights, and divided by the estimated number of passenger miles traveled in order to obtain an estimate of the total amount of aviation emissions per passenger mile traveled (PMT) for the operating stages of the flight.

Aviation Non-operating Emissions

Chester's LCA of the non-operating emissions associated with air transport was modeled as an EIO-LCA, and consisted of three elements: vehicles, infrastructure, and fuel production/delivery.[23] For the purposes of this study, all activities are further grouped into operating activities and non-operating or external activities, shown below:

- Operating Activities:
  - Auxiliary Power Unit (APU) Operation
  - Startup
  - Taxi-out
  - Takeoff
  - Climbout
  - Cruise
  - Approach
  - Taxi-in
- Non-operating Activities (External Activities):
  - Aircraft manufacturing
  - Engine manufacturing
  - Auxiliary power unit (APU) operation

[23] (Chester 2009)

- Aircraft maintenance
    - Lubrication and fuel system
    - Battery
    - Chemical application
    - Parts cleaning
    - Metal finishing
    - Coating application
    - Painting
    - Depainting
    - Engine maintenance
- Operation of airport lighting
- Operation of ground service equipment
- Airport maintenance
- Runway maintenance
- Tarmac maintenance
- Parking construction/maintenance
- Production and inventorying of fuel

Chester's aircraft operating emissions are modeled after only three aircraft types: the Embraer 145 (small), the Boeing 737 (medium), and the Boeing 747 (large). One way to carry out this study would be to model the data for Texas using only the generalized emissions given for a small, medium, or large aircraft type. However, this method was rejected in favor of the more detailed method of substituting data for the actual aircraft used on the routes. As the emissions data collected from the airlines, ICAO, and the EEA yielded more specific data for each aircraft type represented in this study than did Chester's general model, that data was used instead. This created a situation where the figures related to operations was based on actual airline, ICAO, and EEA data, while the non-operational life-cycle data was developed by Chester using generic aircraft size classes. This could have potentially been problematic if Chester's generic data was inappropriate for the aircraft types used on Texas Triangle routes. However, comparing Chester's generic operational data to the actual operational data did not yield large differences, implicitly corroborating the accuracy of both sets of data.

Airport construction was omitted from the LCA because airports in the Texas Triangle region have been built throughout different time periods and using different methods. Additionally, the markets served in this analysis all have mature airports. The only significant construction activity in the last decade at any of the eight airports seen in this study was the opening of a new east-west runway at Bush Intercontinental Airport in Houston in late 2003.[24] As a result of these factors, there was little value in adding this factor into the LCA.

Deicing fluid production and distribution was omitted due to the low prevalence of icing conditions in the particular portion of Texas examined, leading to negligible usage of deicing fluid.

Chester's EIO-LCA specifies the amount of energy that each process uses, as well as the amount of NO_x (among other pollutants) emitted per unit of energy used given a general U.S. energy mix.[25] Location does not make a large difference in the amount of energy used by a process; however the amount of pollutants emitted per unit of energy

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24 (American Society of Civil Engineers 2004)
25 (Chester 2009)

produced varies widely across the country. The Electric Reliability Council of Texas (ERCOT) has made tremendous strides in taking measures to cut pollution levels in the state related to power generation. Between 2000 and 2007, CO_2 emissions per megawatt-hour (MWh) have dropped 15% and NO_x emissions have plunged 68% in ERCOT's area of responsibility. As a result, Texas now enjoys 4% lower average CO_2/MWh levels and 68% lower NO_x/MWh levels than does the country as a whole.[26] Therefore, NO_x emissions seen by Chester in the California context would be significantly lower in Texas. This translates to 41% of the average emissions seen elsewhere, leading to that number being used as the NO_x emissions factor for aviation's non-operating emissions.

The summation of energy usage, given in kilojoules per passenger mile traveled (kJ/PMT), was converted to MWh, and the ERCOT NO_x and CO_2 emission factors[27] were applied to give an estimate of current emissions associated with aviation non-operating emissions. This was then added to the estimate of current operating emissions to yield an estimate of total emissions associated with intercity flights in the Texas Triangle.

Rail Emissions

Since high-speed rail is currently unbuilt in Texas, and no other U.S. system exhibits the level of service desired in any new HSR application, a set of assumptions was required in order to set the parameters of how to approach creating a reasonable LCA in this instance. High-speed rail systems in Europe and Asia provide a good baseline for

[26] (U.S. Environmental Protection Agency 2010)
[27] (taken from eGRID summary tables)

vehicle operating data. The particular data of interest in this study was energy consumption for trains, given on a per vehicle mile traveled (VMT) or per PMT.

In order to determine energy consumption, it was first necessary to determine what type of train would be used in a potential Texas HSR system. HSR trainsets vary widely worldwide in size, weight, energy consumption, and passenger capacity. For example, the Japanese Shinkansen 700 series trainset carries over 1,300 passengers per train, while the international Eurostar carries 750[28] and the Spanish AVE trainset carries only 313.[29] Larger trainsets, while generally more efficient on a per seat basis than are smaller trainsets, also have a corresponding increase in tare weight, which causes a higher rate of absolute energy use. Low load factors on large trains would have a higher energy usage per PMT than would a smaller train with an equal number of passengers, and thus a higher load factor. Therefore, it is imperative that the train used for any particular system is correctly sized for that system in order to avoid the possibility of running trains that are too large for the amount of demand.

In the case of Texas, a small train would be ideal for several reasons. First, the population of Texas, at 25 million, is significantly smaller than places with current high-speed rail systems such as Japan (127 million) or France (63 million), despite being bigger in physical size than Japan and relatively equal in size to France.[30] Secondly, Texas is well connected to the wider U.S. aviation system, which offers much more extensive connections to destinations outside of the state, and enhancing the benefits of air travel, assuming that the future Texas HSR does not code-share with the airlines. Also, in order to offer frequencies that would be competitive with frequencies currently

[28] (Davies 2009)
[29] (Jorgensen and Sorenson 1997)
[30] (figures from CIA World Factbook, accessed March 25, 2011)

offered by airlines, a large train would likely have extremely low load factors, whereas a smaller train's higher load factors would be better for energy usage per PMT, as well as better for the public relations campaign of the HSR system. Finally, Texas cities are much lower density than are the cities in many other countries with HSR. Combined with the relatively robust road infrastructure of the state, automobile trips are expected to be stiff competition for Texas HSR routes in the future, something that cannot be said about denser nations such as Japan.

Taking the preceding facts into account, it was chosen to create an LCA based on a future train similar in specifications to the current Spanish Alta Velocidad Española (AVE) trainset. The AVE train is among the smallest and lightest HSR trains worldwide, with average energy consumption comparable to the French and Italian systems, and slightly higher than the German ICE train. The operating specifications of this train are as follows[31]:

Passenger Capacity:	313 (8 passenger cars, 2 locomotives)
Empty (Tare) Weight:	392 tonnes (431 tons or 862,000 lbs)
Average Loaded Weight:	415 tonnes (457 tons or 914,000 lbs)
Energy Consumption:	15.88 kWh/train/km (25.57 kWh/train/mi)
Specific Energy Consumption:	135.6 kJ/tonne/km (198.7 kJ/ton/mi)
Top Speed:	300 km/h (186 mph)

Table 2 - Specifications of Spanish AVE trainset

[31] (Jorgensen and Sorenson 1997)

While the type of trainset is used to determine operating emissions, other life-cycle emissions of a potential Texas HSR are estimated using the results found by Chester. Chester's LCA uses the 2006 version of the process-based LCA software SimaPro. SimaPro uses a representative trainset (in this case a combined system of German and Swiss HSR) to provide data necessary to determining life-cycle costs of a variety of activities associated with HSR. In order to make this data applicable to a potential Texas HSR, the effects of ERCOT's energy mix must be substituted for the California mix used by Chester. The activities associated with the operating and non-operating phases of the LCA are as follows:

- Operating
    - Active Operation
    - Idle Operation
    - HVAC Operation
- Non-operating
    - Vehicle
        - Manufacturing
        - Maintenance
        - Cleaning
        - Flooring
    - Infrastructure
        - Station
            - Construction
            - Lighting
            - Escalators

        - Train Control
        - Parking Lot Lighting
        - Maintenance
        - Cleaning
        - Parking
        - Miscellaneous
    - Track
        - Construction
        - Maintenance
- Fuel
    - Supply Chain
        - Vehicles
        - Infrastructure
    - Transmission and Distribution Losses
        - Vehicles
        - Infrastructure

The approach utilized for this task was to examine the United States Environmental Protection Agency (EPA) data that allowed comparison of the energy mix of ERCOT with those of the State of California, as well as the Western Electricity Coordinating Council (WECC). The reason that both the State of California and WECC were examined is that California only generates an estimated 65% of the electricity it consumes, importing the other 35% from the other states that comprise WECC.[32]

[32] (U.S. Environmental Protection Agency 2010)

Therefore, when determining an appropriate factor adjustment to use in order to correct emissions for a potential California system with the emissions for a potential Texas system, the California system was measured at 65% California electricity, and 35% WECC electricity. The amount of CO_2 and NO_x Texas emits per unit of CO_2 and NO_x emitted on average by these two entities at a 65/35 split were applied to the emissions factors given in Chester's LCA, creating an inventory of all emissions related to the non-operating phases of high-speed rail and corrected to represent the current Texas energy mix.

After determining an estimate of the non-operation based emissions of CO_2 and NO_x, it was next necessary to construct a realistic, theoretical rail schedule to simulate a timetable that could compete with air on a time basis. While rail cannot possibly compete with the block times offered by nonstop flights on nearly any city pair, it makes up for this via increased comfort, the potential of increased productivity (depending on the equipment featured), and the ability for passengers to show up for a train much later than they could if they were flying. Total door-to-door travel times of HSR routes have shown to be competitive with airline travel.[33] Three options on the physical layout of the HSR are shown. All calculations follow a schedule based on Option A.

[33] (Air Guide 2006)

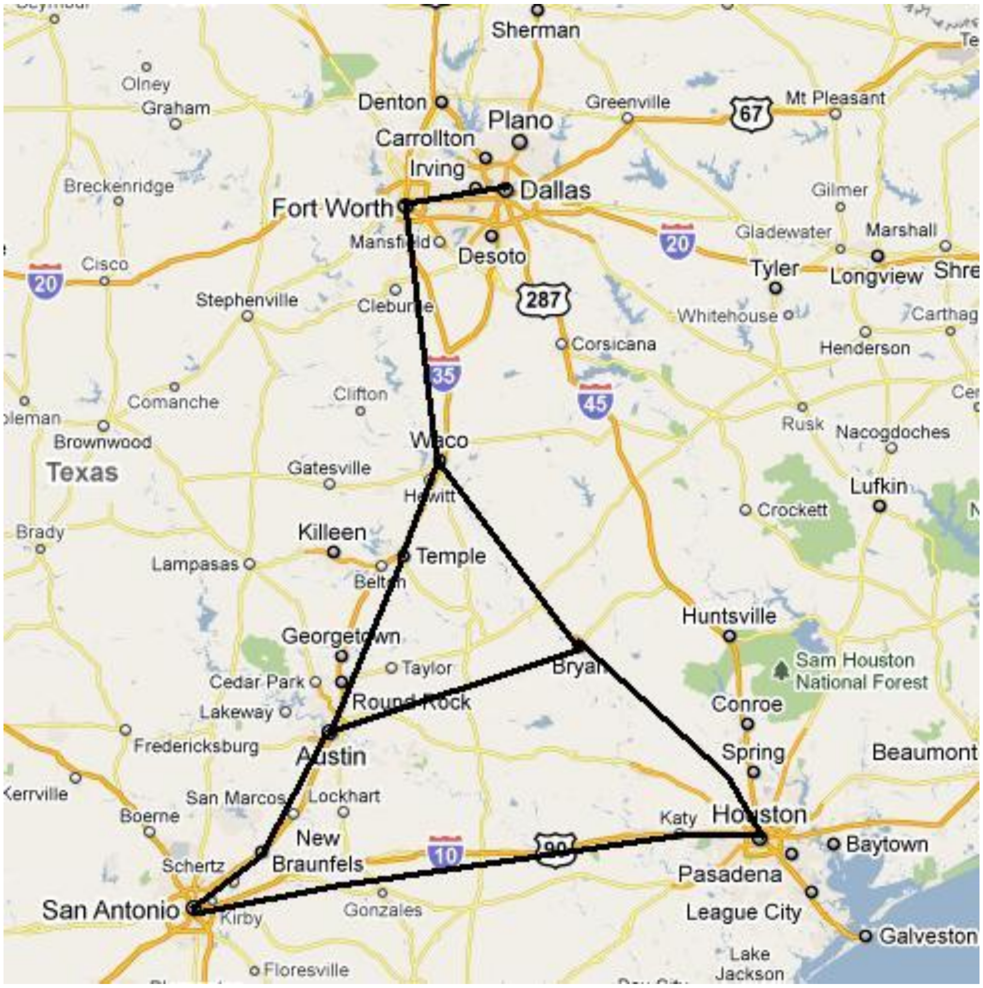

Illustration 1 - Option A – 754 miles of track

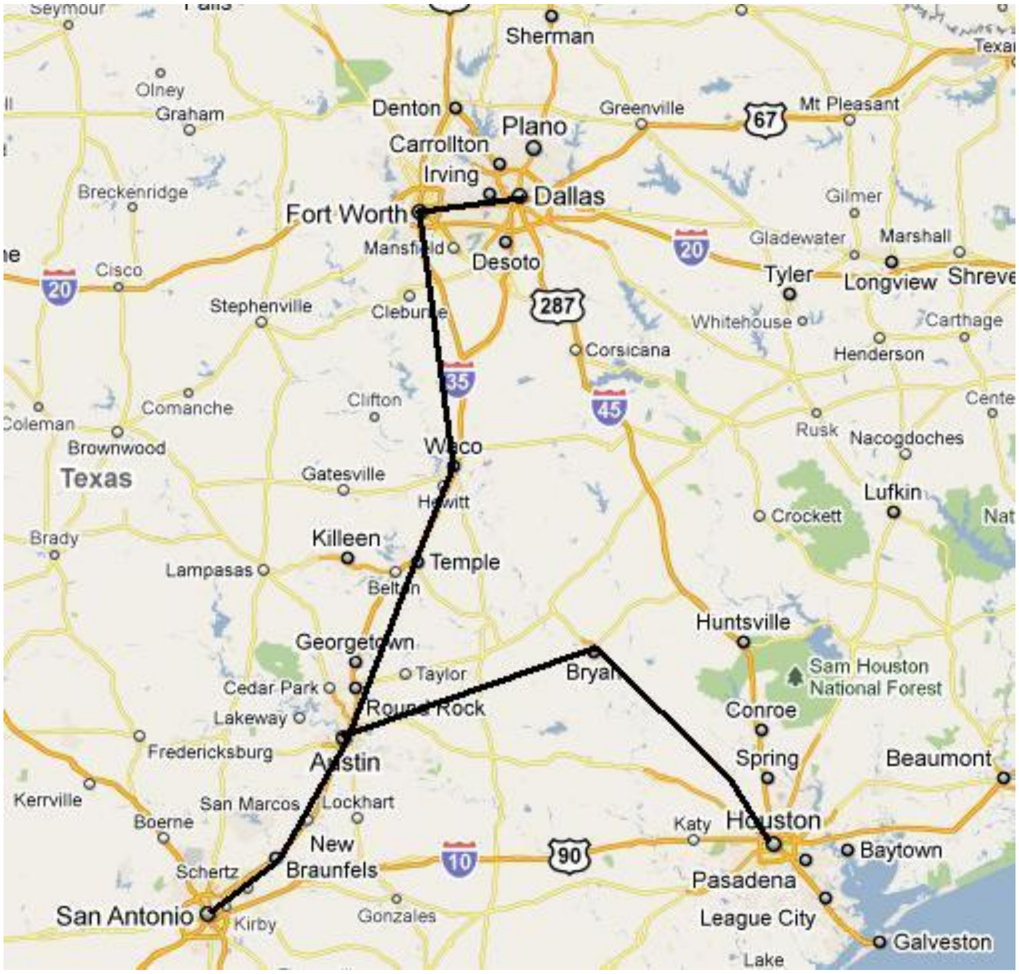

Illustration 2 - Option B – 562 miles of track

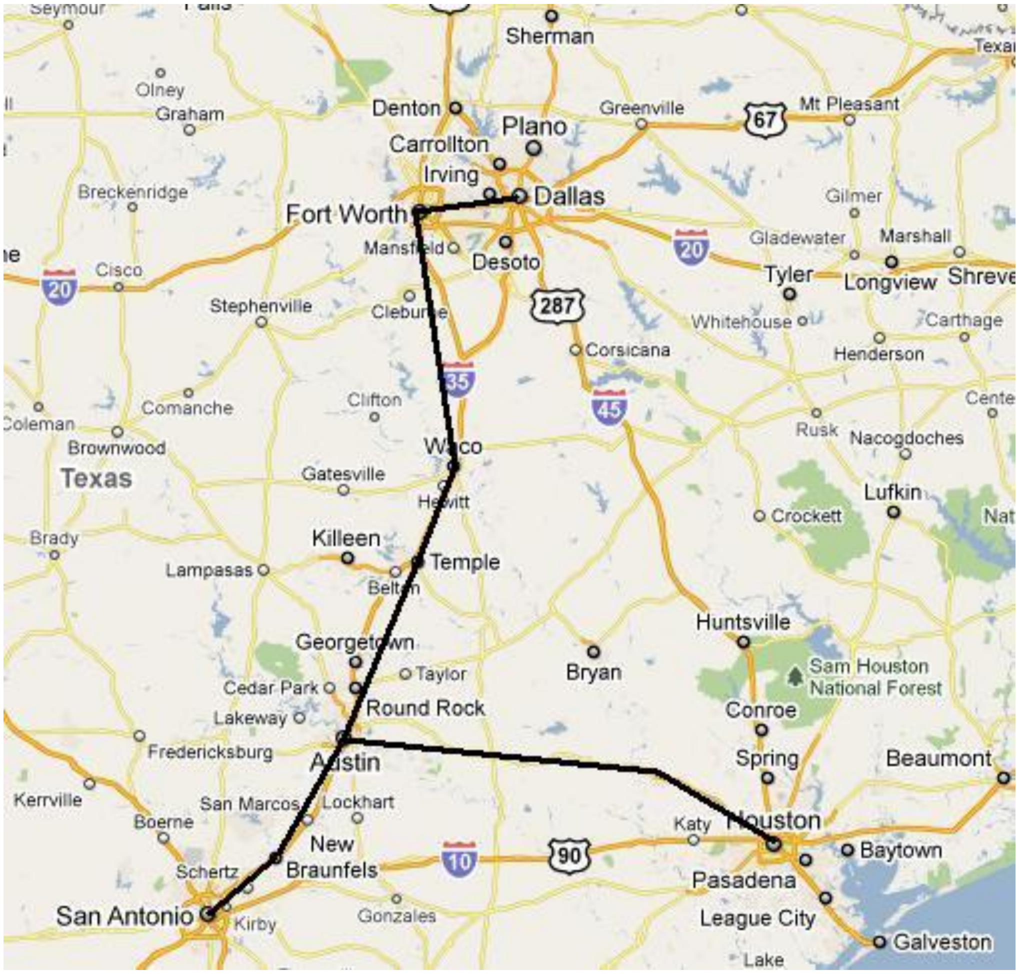

Illustration 3 - Option C – 427 miles of track

The airlines in Texas currently serve the markets intended to be served by a future HSR with daily flights at high frequencies, with 312 nonstop flights per day being operated on the routes under study. The initial rail schedule that has been devised was done with the following criteria in mind:

1. Size the system to allow for at least equal passenger capacity to what the airlines currently offer.
2. Keep frequencies high enough to compete with the frequencies operated by the airlines on the high density routes. (HOU-DAL, DAL-SAT, DAL-AUS)
3. Ensure all small markets are served from large markets at least at the frequency they are served by the airlines.

The rail schedule devised consists of four routes that begin and end at each of the four major metropolitan areas, consisting of 124 train departures per day. Trains will operate a mixture of express routes (non-stop end to end), suburban-collector routes (city and suburban stops, then relative express service in between), and collector routes (making all stops).

Using this schedule, three estimates of emissions were done, using average load factors of 40%, 55%, and 70% for the train. The 40% level represents a light average systemwide load factor. This is meant to simulate the initial operation of the train and the expected light loads as people get familiar and comfortable with the mode. The 55% level represents an intermediate level of loading, which represents a maturing system as passengers make a large scale switch from the automobile and air to rail. The 70% level represents the desired loads of a fully mature system as well as representing a passenger throughput level that would signal a large scale mode switch from air and road to rail. It also closely parallels the average load factor for successful high speed rail systems.[34]

Since the amount of energy used per unit of distance the train travels is known, this factor was applied to the distance of the route to find the average amount of energy

[34] (Davies 2009)

used on the route. This was then multiplied by the emissions factors for CO_2 and NO_x to find the total amount of estimated emissions applicable to the trip, and projected out over a year. Dividing this figure by total amount of estimated PMT on the system yields an estimate of yearly emissions per PMT for the operating phases of a potential Texas HSR.

RESULTS

Application of the above methodology yielded an estimate that strongly suggests that the CO_2 and NO_x emissions of a future Texas high-speed rail system would be lower than the current amount of these gases emitted by the current system of intercity flights. All data is based on a scheduling base year of 2011, using 2007 energy and emissions data (the latest available).

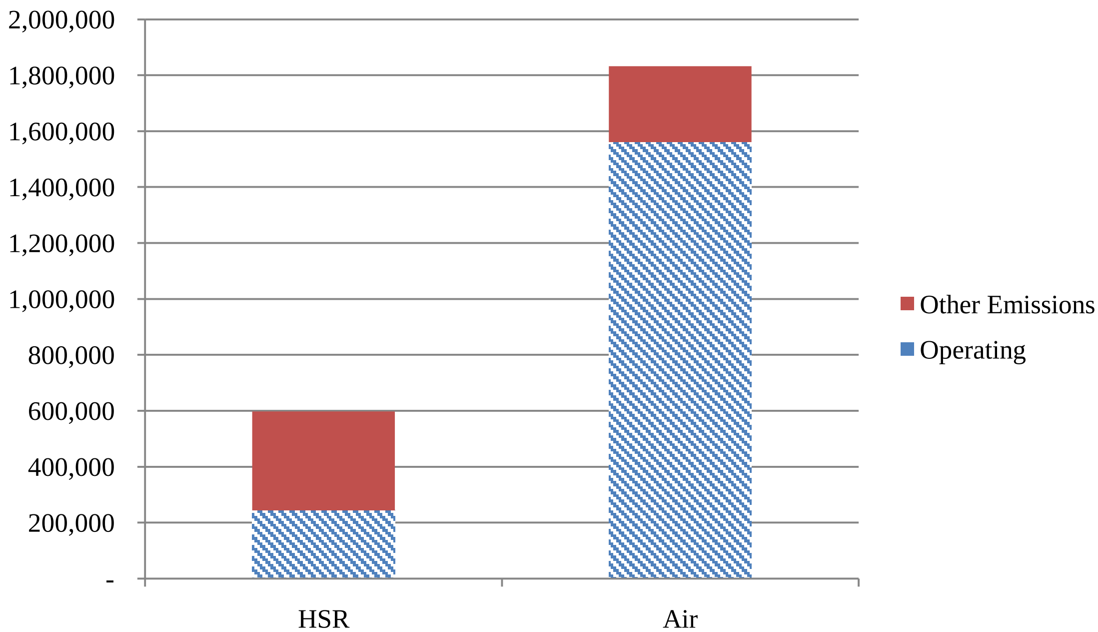

Figure 1 - Estimated Annual Energy Used, in MWh

As figure 1 demonstrates, a potential HSR system in Texas is estimated to use approximately ⅓ of the total annual energy that airlines currently use to move people between the metropolitan areas of the Texas Triangle. This is due to the fact that the LTO cycle uses a disproportionate amount of energy with respect to the time that an aircraft is in a mode.[35] For the short range flights exemplified by the routes studied here, these phases of flights represent an even larger portion of the total flight than they do for medium or long-haul segments.

In terms of estimated amount of energy used per PMT, HSR at all load factors significantly outperforms rail. As shown in Figure 2, even at an 80% load factor, aircraft in the Texas Triangle use almost twice the amount of energy (49% more) per passenger mile traveled than does HSR.

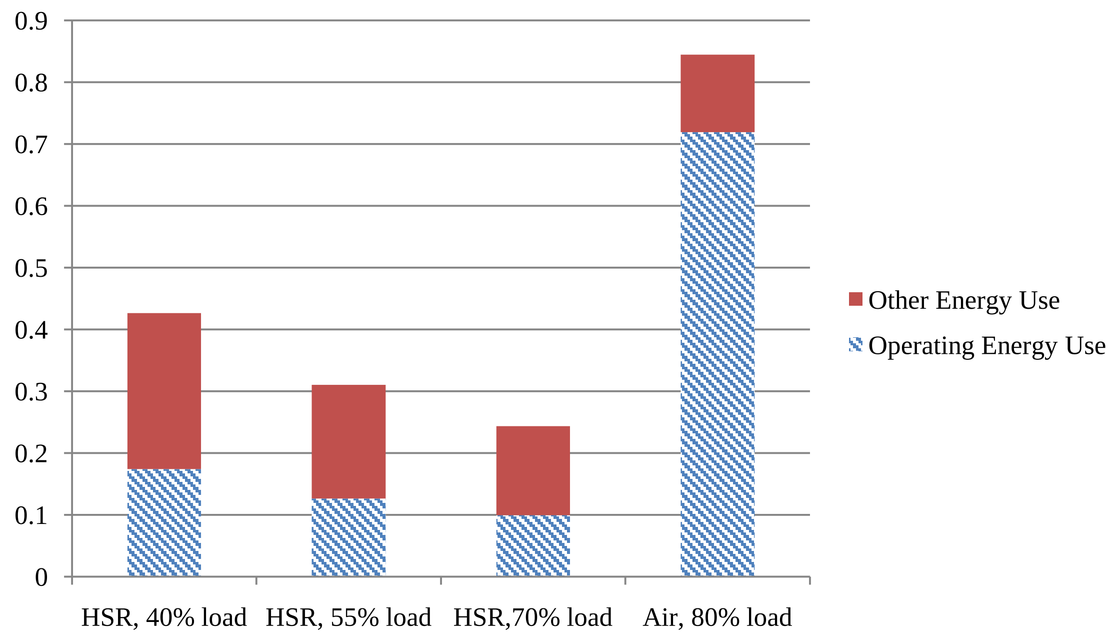

Figure 2 - Estimated Annual Energy Usage, in kWh/PMT

According to Figure 3, annual CO_2 production attributable to Texas Triangle intercity flights is estimated at 1.67 billion pounds in 2010. This represents approximately

[35] (European Environment Agency 2009)

0.3% of the estimated 530 billion pounds of CO_2 emitted by Texas during the process of electricity generation annually.[36] Of these 1.67 billion pounds, 80% (1.33 billion pounds) are emitted during operating phases of flight, while the other 20% (340 million pounds) are emitted as a result of other activities associated with the process of civil aviation in support of these flights.

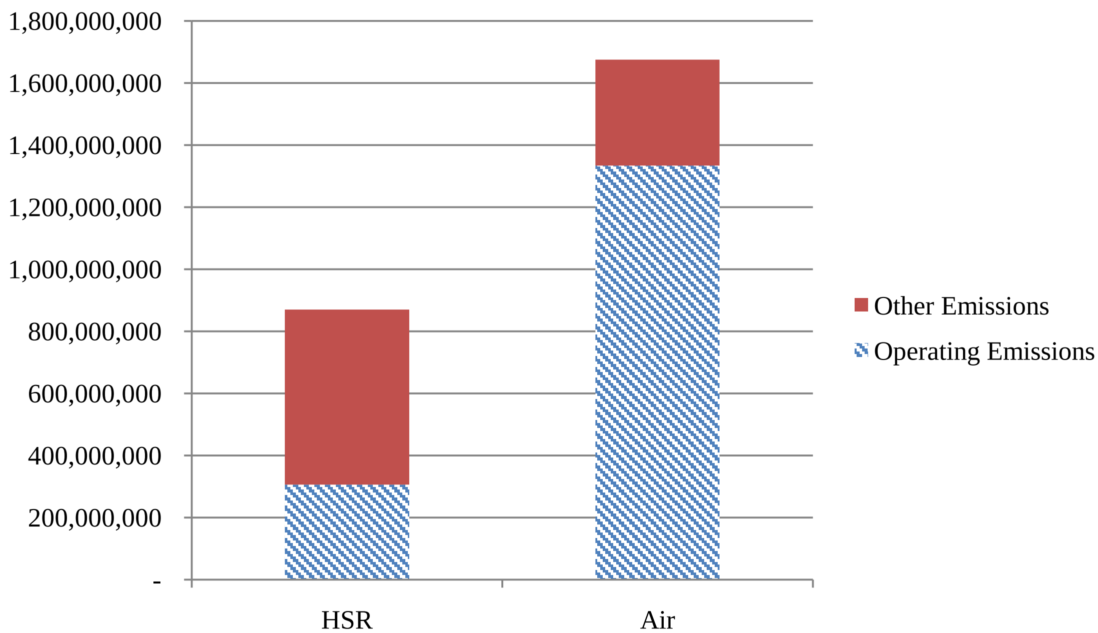

Figure 3 - Estimated CO_2 Emissions of HSR and Airline Travel, in pounds

Using the given parameters for an HSR train and following the daily schedule developed by the research team, HSR's potential yearly emissions of CO_2 are much lower, totaling an estimated 870 billion pounds, or 52% of what yearly air travel emits between the Texas Triangle cities. However, unlike air travel where the operation of the

[36] (U.S. Environmental Protection Agency 2010)

actual airplane produces the most CO_2, most carbon dioxide produced by HSR is produced outside of the operating cycle of the train, with only 35% (305 million pounds) of emissions attributable to direct operation.

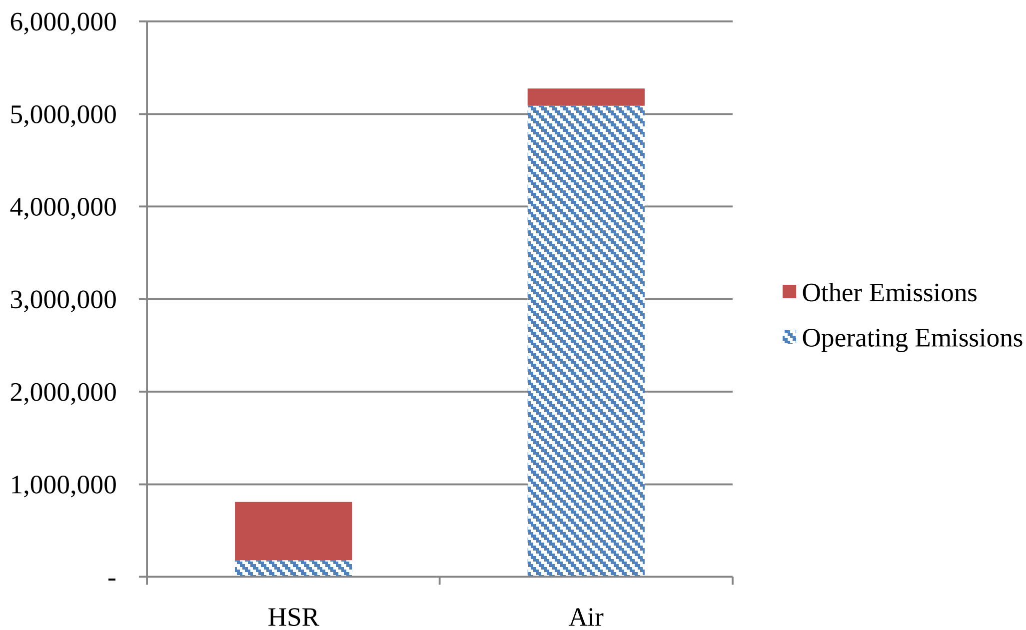

Figure 4 - Estimated Annual Emissions of NO_x, in pounds

In the case of NO_x, the divide between the performance of HSR and the performance of air travel is even starker. Figure 4 shows total annual NO_x emissions attributable to a Texas HSR system are estimated at 809,000 pounds, compared to 5.3 million pounds for aviation, a difference of more than six times. However, the NO_x emissions attributable to aviation are heavily skewed toward the operational side, with 96% (5.1 million pounds) of all emissions related to the direct operation of aircraft. HSR is the opposite situation, with 78% (629,000 pounds) of NO_x emissions attributable to non-operating elements of HSR operation.

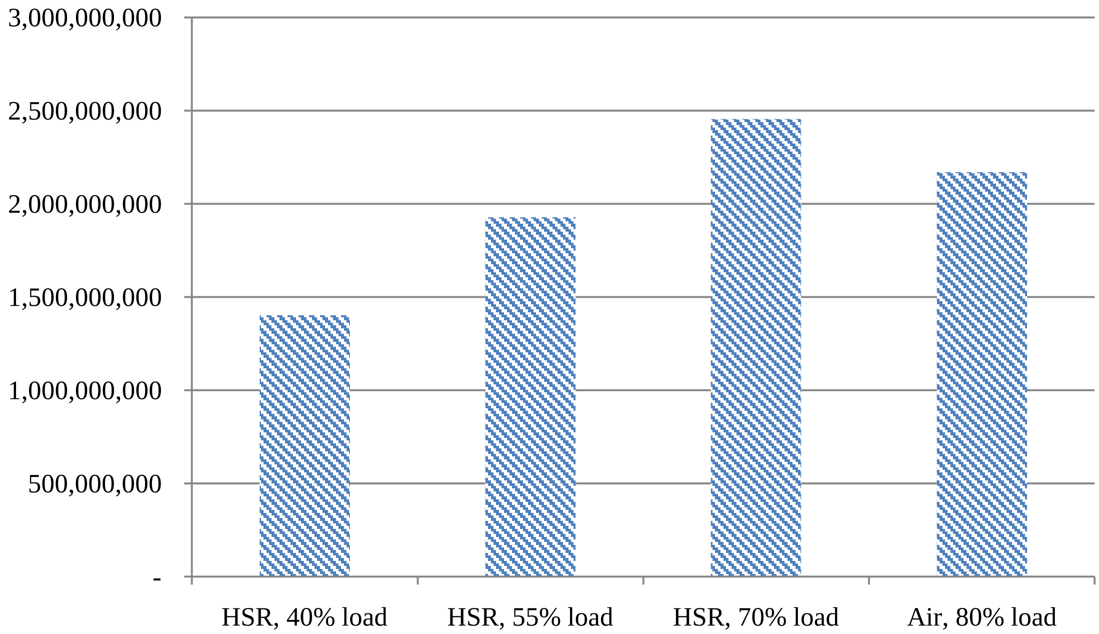

Figure 5 - Estimated PMT Between Texas Triangle Cities

On a per passenger mile basis, the HSR system is estimated to emit less CO_2 and NO_x than the current aviation system is by a wide margin. It is notable that all three of the chosen load factors for rail outperform the aviation system with an 80% load factor as shown in Figure 5.

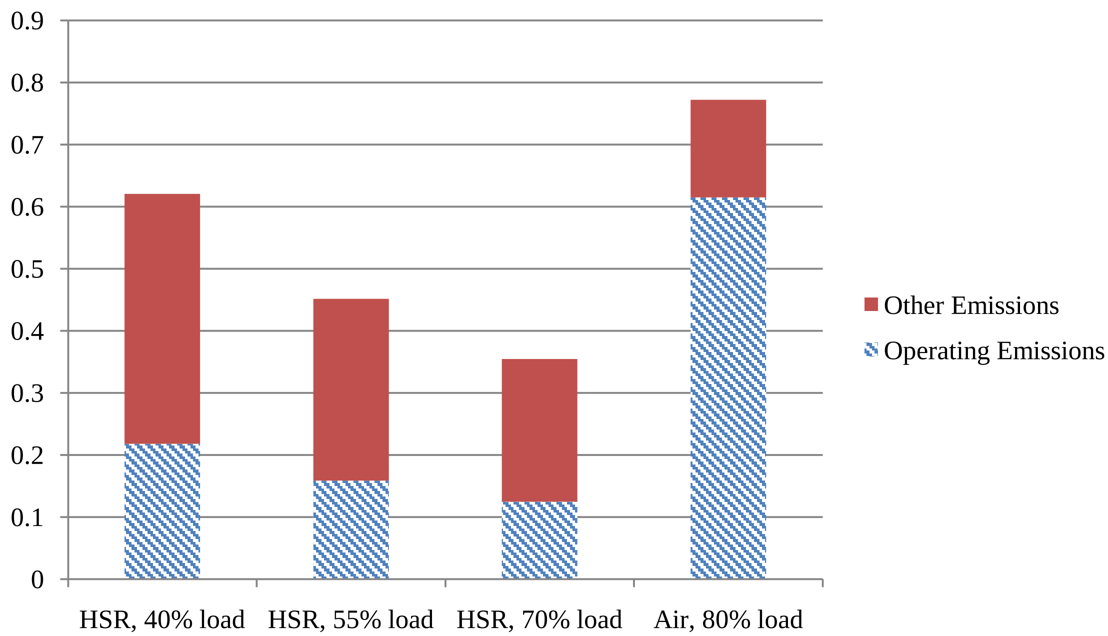

Figure 6 - Estimated Annual CO_2 Emissions, in pounds/PMT

As can be seen in Figures 6 and 7, at a 40% load factor, the train emits 20% less CO_2 and 76% less NO_x than does aviation at an 80% load. At a 70% load factor, the train's advantage grows, and it emits 55% less CO_2 and 86% less NO_x than does an equivalent airplane trip.

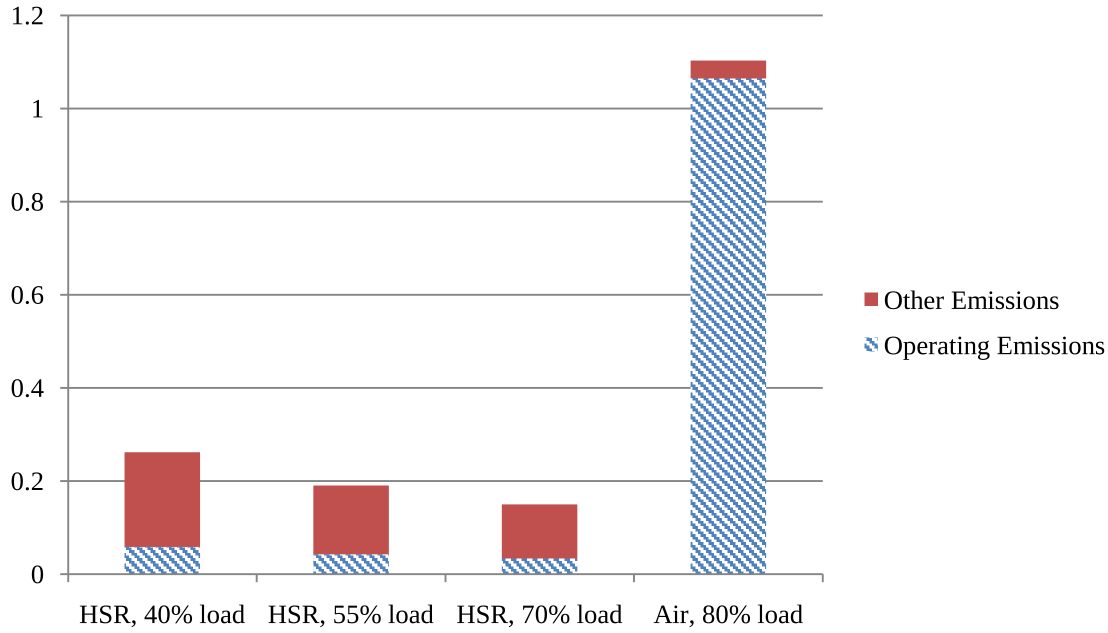

Figure 7 - Annual Estimated NO_x Emissions, in grams/PMT

DISCUSSION OF RESULTS

Using this methodology, high-speed rail comes out a clear winner when comparing energy usage, CO_2 emissions, and NO_x emissions (both total and per PMT). However, air still has a slight advantage in total travel time. However, one should keep in mind that this advantage does not take into account external elements of a trip that contribute to the total time spent on the trip. These elements mostly apply to aircraft travel and include security checks, waiting time for baggage claims, and boarding/deboarding time. With all of these external elements accounted for, the difference in travel time between HSR and air narrows further.

Route	Estimated HSR time	Actual Air time
HOU-DAL	1:48-2:36	0:55-1:20
HOU-SAT	1:06-2:06	0:53-1:04
HOU-AUS	1:00-1:24	0:45-0:58
HOU-ACT	1:06-1:36	1:04-1:06
HOU-CLL	0:30-0:42	0:46-0:51
DAL-AUS	1:12-1:42	0:50-1:00
DAL-SAT	1:42-2:24	1:00-1:10
DAL-ACT	0:42-1:00	0:40-0:45
DAL-CLL	1:18-1:48	0:50-0:60

Table 3 – Estimated Time Enroute by mode

Energy Usage

HSR is estimated to use about 33% of the energy currently used by aircraft travel. Of this energy, only about 41% (244,000 MWh) is used during the operating stages, with the other 59% being used during other parts of the life-cycle.

The likely reason for this is the significant amount of new infrastructure which must be built in order to support the operation of a new HSR system. When Chester and Horvath carried out their LCA, they amortized construction emissions over a period of years, until a reconstruction of the element was necessary. For some elements this period was 25 years, for others 50 years, and for others 100 years.[37]

The major point to be taken away from this is that the amount of non-operating emissions associated with an HSR system are high primarily due to the significant emissions attributed to the construction of new infrastructure. Air shows a completely inverse relationship. Since air travel in Texas is essentially mature, most (85%) of energy usage associated with air travel is used during the operating phase.

CO_2 Emissions

The amount of carbon dioxide emitted as a result of building and operating HSR is also lower than the operation of the current aviation system, however the advantage over air is lower and more dependent on strong loads. While an HSR loaded at 40% would emit approximately 80% of the CO_2 per PMT as air does, that same train loaded at 70% would emit only 45% of the CO_2 per PMT of an equivalent aircraft.

The train emits less CO_2 during its operating stages (35%) than it does during the other phases of its life cycle (65%), paralleling its behavior with energy usage. Again,

[37] (Chester and Horvath 2010)

this speaks to the massive infrastructural inputs that will inevitably create significant environmentally harmful outputs.

It is important to remember that CO_2 emitted by HSR has the potential to be further reduced in the future through a change in the energy mix of the state. If renewable energy is a large part of Texas' energy future, the amount of CO_2 emitted upon construction and the beginning of the operation of an HSR system would be much less. Aircraft, on the other hand, have very little leeway to further reduce CO_2 emissions, as the CO_2 emitted during aircraft operations is a result of the combustion of kerosene fuel, and thus can only be reduced via a parallel reduction in fuel consumption.[38]

NO_x Emissions

Emissions of NO_x are the most visible disconnect between the HSR and air systems, with HSR expected to produce only a small portion of NO_x emissions compared to air. At 40% load, the HSR is expected to produce 24% of the NO_x that air does on a per PMT basis. At a 70% load, this share is expected to drop to only 14%.

NO_x emissions are a much better known quantity than CO_2, having been associated with ground level ozone and smog for decades. Therefore, efforts by different entities to cut NO_x emissions, especially at stationary sources, have been much more successful than has the burgeoning movement to cut CO_2. Since the passing of S.B. 7, ERCOT and individual plant operators have invested heavily in both pre- and post-combustion NO_x control technology. Technologies such as staged combustion reduce NO_x pre-combustion, while selective catalytic reduction and selective non-catalytic reduction work to reduce NO_x post-combustion.

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[38] (European Environment Agency 2009)

SUMMARY AND AREAS FOR FURTHER STUDY

The results of this study show that a HSR system in Texas would be vastly superior to the current air system in terms of our three measurables: energy usage, CO_2 emissions, and NO_x emissions. Analyzing this from the environmental and quality of life standpoints, it would be prudent for policymakers and leaders in the state to seriously consider studying a future HSR system to move people around the state. It would use much less right of way than would new freeway lanes, while simultaneously providing significantly more capacity. It could in many cases be added to existing highway corridors running in medians or perhaps using an elevated design.

One of the major drawbacks to HSR is the emissions related to the amount of new construction that must be undertaken in order to build the system. These emissions are, however, an extremely high one time only charge that must be taken into account. However, on the positive side, the construction of a HSR system in Texas would lead to many new jobs as well as new competition for the airlines. While the airlines may correctly view HSR as a competing mode and perhaps even an existential threat to their business, partnerships between airlines and the potential HSR operator may be able to strengthen both systems via interlining or code-sharing agreements.

However, the energy usage and environmental performance of HSR is only a small portion of the criteria to be considered when choosing how to proceed forward.

The primary consideration which should be taken into account is fuel sources and their accompanying life cycle emissions. The fuel source of future power plants in the ERCOT region and alternative aviation fuels are two topics which have the potential to dramatically reshape the relationship of the emissions profiles of HSR and air travel. While the widespread adoption in the ERCOT region of aggressive scrubbing technology has significantly reduced NO_x emissions, CO_2 emissions related to ground-based power sources can only be significantly reduced by carbon sequestration or by large-scale replacement of coal and natural gas power plants.

In Texas, the bulk of new renewable energy would likely be generated by wind or nuclear sources. These would allow a potential HSR system to draw more renewable energy as a percentage of its total usage, and therefore lower the carbon footprint of operating the entire system. However, in the absence of rapid technological progress, heavy investment in replacing coal and natural gas fired generating capacity with wind and nuclear capacity would be the most feasible way of further lowering both operational and non-operational emissions of HSR.

Equally critical is the burgeoning development of alternative aviation fuels. Alternative aviation fuels can come from a variety of sources such as plant oils, biomass and animal fats, as well as from fossil sources such as natural gas. This is an area of significant study recently in the aviation industry, as airlines and militaries want to diversify their sources of aviation fuel in the face of high petroleum prices and potential supply disruptions.[39]

The ability to see large scale production of alternative aviation fuels will hinge on a different variable than will the ability to replace fossil fuel ground-based power. A major barrier to the feasibility of mass production of these fuels is the lack of a process that can produce large amounts of fuel sustainably. Again, the pace of technological progress and financial investment will determine how quickly this can impart significant influence on the very real problem of aviation fuel life-cycle emissions. Quantification of

[39] (Stratton, Wong and Hileman 2010)

how much of an impact these fuels could have cannot be completed without a commercialized process in place.

Other key fields of study which should be taken into account are:

- Financing mechanisms
- Feasibility of partnerships/interlining with airlines
- Forecasting of the effect of automobile competition

The flights between the Texas Triangle cities are an economic lifeblood of the state and comprise key portions of the national air network. They are predictable, convenient, and fast. They are also extremely harmful to the environment of Texas, and more indirectly, the entire planet. With the State of Texas's large investment in decreasing emissions from ground-based power plants, HSR could provide a safer, more comfortable, more energy efficient, and more environmentally friendly system to transport people between the population centers of the state. HSR should be used for more short routes in the United States, leaving air to what it does best – unparalleled speed for medium and long-haul transportation.

Appendices

Appendix A – Texas Triangle Air Travel Emissions Characteristics, 2010

	HOU-DAL	HOU-SAT	HOU-AUS	HOU-ACT	HOU-CLL
CO2	191,642,031.63	62,842,621.59	49,567,700.07	2,550,697.38	2,729,483.51
NOX	685,051.79	236,190.05	183,815.52	7,662.83	7,629.15
Pax (Est. 2010)	3,207,620	1,234,576	1,095,365	78,840	137,970
Pax (2009)	2,910,797				
PMT	750,910,850.00	235,522,528.00	156,533,900.00	12,535,560.00	10,209,780.00
	DAL-AUS	**DAL-SAT**	**DAL-ACT**	**DAL-CLL**	
CO2	129,393,382.39	160,969,024.13	2,639,412.09	2,792,949.71	
NOX	489,609.79	607,285.60	9,590.04	10,396.34	
Pax (Est. 2010)	2,148,390	2,299,500	121,910	100,010	
Pax (2009)	2,028,399	2,116,049			
PMT	408,194,100.00	567,976,500.00	10,971,900.00	16,401,640.00	
	TOTAL(kg)	**TOTAL (lb.)**			
CO2	605,127,302.48	1,333,700,574.67			
NOX	2,237,231.12	4,930,857.38			
Pax (Est. 2010)	10,424,181				
Pax (2009)					
PMT	1,957,128,978.00	212,127,780.00	2,169,256,758.00		
	total medium	**total small**	**total PMT**		

Appendix B – External Aviation Operating Costs (red denotes internal costs that are accounted for via operational data)

AVIATION OPERATING COSTS	Energy Used	NOx		TOTAL Energy Used		TOTAL NOx		TOTAL CO2
Activity (per PMT)	**(kJ/PMT)**	**(mg/PMT)**	**(w/ TX EF)**	**(kJ)**	**(mWh)**	**(kg)**	**(lbs)**	**(lbs)**
SMALL AIRCRAFT (ERJ-145)								
Airport Operations								
Operation of Runway Lighting	2.7	0.92	0.38	572,745,006	159	80	177	199,279
Operation of Ground Support Equipment	33	25	10.28	7,000,216,740	1,945	2,180	4,804	2,435,628
Airport Maintenance								
Airport Maintenance	0.057	0.015	0.01	12,091,283	3	1	3	4,207
Runway Maintenance	1.3	0.64	0.26	275,766,114	77	56	123	95,949
Tarmac Maintenance	3.4	1.7	0.70	721,234,452	200	148	327	250,944
Manufacturing								
Aircraft Production	140	24	9.86	29,697,889,200	8,249	2,092	4,612	10,332,968
Engine Production	48	8.6	3.53	10,182,133,440	2,828	750	1,653	3,542,732
Aircraft Operations								
APU Operation	31	8.9	3.66	6,575,961,180	1,827	776	1,710	2,288,014
Taxi	400	33	13.56	84,851,112,000	23,570			
Takeoff	100	46	18.91	21,212,778,000	5,892			
Climbout	270	100	41.10	57,274,500,600	15,910			
Cruise	2,300	390	160.29	487,893,894,000	135,526			
Approach	180	31	12.74	38,183,000,400	10,606			
Taxi-in	150	12	4.93	31,819,167,000	8,839			
Aviation Fuel Production and Distribution	340	54	22.19	72,123,445,200	20,034	4,708	10,376	25,094,351
Aircraft Maintenance								
Lubrication and Fuel Systems	12	0.37	0.15	2,545,533,360	707	32	71	885,683
Battery	1.4	0.24	0.10	296,978,892	82	21	46	103,330
Chemicals	4.7	0.47	0.19	997,000,566	277	41	90	346,892

Parts/Cleaning	4.1	0.51	0.21	869,723,898	242	44	98	302,608
Metal Finishing	6.9	0.48	0.20	1,463,681,682	407	42	92	509,268
Coating/Application	3.1	0.38	0.16	657,596,118	183	33	73	228,801
Depainting	6.9	0.48	0.20	1,463,681,682	407	42	92	509,268
Painting	9.2	1.2	0.49	1,951,575,576	542	105	231	679,024
Engine	3.4	0.61	0.25	721,234,452	200	53	117	250,944
Other Ops								
Parking Ops	14	5.7	2.34	2,969,788,920	825	497	1,095	1,033,297
TOTAL SMALL				**862,332,729,761**	**239,537**	**11,701**	**25,790**	**49,093,186**
MEDIUM AIRCRAFT (737)								
Airport Operations								
Operation of Runway Lighting	2.6	0.91	0.37	5,088,535,343	1,413	732	1,613	1,770,485
Operation of Ground Support Equipment	33	25	10.28	64,585,256,274	17,940	20,110	44,321	22,471,543
Airport Maintenance								
Airport Maintenance	0.057	0.015	0.01	111,556,352	31	12	27	38,814
Runway Maintenance	1.3	0.63	0.26	2,544,267,671	707	507	1,117	885,243
Tarmac Maintenance	3.3	1.7	0.70	6,458,525,627	1,794	1,367	3,014	2,247,154
Manufacturing								
Aircraft Production	41	7.2	2.96	80,242,288,098	22,290	5,792	12,765	27,919,190
Engine Production	8.2	1.5	0.62	16,048,457,620	4,458	1,207	2,659	5,583,838
Aircraft Operations								
APU Operation	20	2	0.90	39,142,579,560	10,873	1,770	3,900	13,619,117
Taxi	140	12	4.93	273,998,056,920	76,111			
Takeoff	40	15	6.17	78,285,159,120	21,746			
Climbout	100	35	14.39	195,712,897,800	54,365			
Cruise	2,100	500	205.50	4,109,970,853,800	1,141,659			
Approach	70	13	5.34	136,999,028,460	38,055			
Taxi-in	52	4.4	1.81	101,770,706,856	28,270			
Aviation Fuel Production and	250	40	16.44	489,282,244,500	135,912	32,175	70,914	170,238,961

Distribution								
Aircraft Maintenance								
Lubrication and Fuel Systems	12	0.39	0.16	23,485,547,736	6,524	314	691	8,171,470
Battery	1.5	0.24	0.10	2,935,693,467	815	193	425	1,021,434
Chemicals	4.8	0.48	0.20	9,394,219,094	2,610	386	851	3,268,588
Parts	4.3	0.52	0.21	8,415,654,605	2,338	418	922	2,928,110
Metal Finishing	7.1	0.49	0.20	13,895,615,744	3,860	394	869	4,834,787
Coating/Application	3.2	0.4	0.16	6,262,812,730	1,740	322	709	2,179,059
Depainting	7.1	0.49	0.20	13,895,615,744	3,860	394	869	4,834,787
Painting	9.5	1.2	0.49	18,592,725,291	5,165	965	2,127	6,469,081
Engine	5.6	1	0.41	10,959,922,277	3,044	804	1,773	3,813,353
Other Ops								
Parking Ops	14	5.7	2.34	27,399,805,692	7,611	4,585	10,105	9,533,382
TOTAL MEDIUM				**5,735,478,026,381**	**1,593,188**	**72,446**	**159,672**	**291,828,394**
TOTAL ALL				**6,597,810,756,142**	**1,832,725**	**84,148**	**185,462**	**340,921,580**

Appendix C- High Speed Rail Operating Energy Cost Estimates

HSR OPERATING ENERGY COSTS							
	Distance (nm)	**Distance (sm)**	**Distance (km)**	**Time (@120mph)**	**Time (@150 mph)**	**Time (@170 mph)**	**Energy Req'd**
Route							(135kJ/tonne*km)
Houston							
Woodlands	25	29	40	**0.24**	**0.19**	**0.17**	2,255,006.25
College Station	51	59	82	**0.49**	**0.39**	**0.35**	4,600,212.75
Temple	62	71	100	**0.59**	**0.48**	**0.42**	5,592,415.50
Waco	30	35	48	**0.29**	**0.23**	**0.20**	2,706,007.50
Fort Worth	72	83	116	**0.69**	**0.55**	**0.49**	6,494,418.00
Dallas	28	32	45	**0.27**	**0.21**	**0.19**	2,525,607.00
TOTAL	268	308.2	431.48	**2.57**	**2.05**	**1.81**	**24,173,667.00**
Dallas							
Fort Worth	28	32	45	**0.27**	**0.21**	**0.19**	2,525,607.00
Waco	72	83	116	**0.69**	**0.55**	**0.49**	6,494,418.00
Temple	30	35	48	**0.29**	**0.23**	**0.20**	2,706,007.50
Austin	50	58	81	**0.48**	**0.38**	**0.34**	4,510,012.50
San Marcos	25	29	40	**0.24**	**0.19**	**0.17**	2,255,006.25
New Braunfels	15	17	24	**0.14**	**0.12**	**0.10**	1,353,003.75
San Antonio	25	29	40	**0.24**	**0.19**	**0.17**	2,255,006.25
TOTAL	245	281.75	394.45	**2.35**	**1.88**	**1.66**	22,099,061.25
San Antonio							
Seguin	30	35	48	**0.29**	**0.23**	**0.20**	2,706,007.50
Katy	112	129	180	**1.07**	**0.86**	**0.76**	10,102,428.00
Houston	25	29	40	**0.24**	**0.19**	**0.17**	2,255,006.25
TOTAL	167	192.05	268.87	**1.60**	**1.28**	**1.13**	15,063,441.75
Austin							
College Station	73	84	118	**0.70**	**0.56**	**0.49**	6,584,618.25
Woodlands	51	59	82	**0.49**	**0.39**	**0.35**	4,600,212.75
Houston	25	29	40	**0.24**	**0.19**	**0.17**	2,255,006.25
TOTAL	149	171.35	239.89	**1.43**	**1.14**	**1.01**	13,439,837.25
San Antonio							
New Braunfels	25	29	40	**0.24**	**0.19**	**0.17**	2,255,006.25
San Marcos	15	17	24	**0.14**	**0.12**	**0.10**	1,353,003.75
Austin	25	29	40	**0.24**	**0.19**	**0.17**	2,255,006.25
College Station	73	84	118	**0.70**	**0.56**	**0.49**	6,584,618.25
Woodlands	51	59	82	**0.49**	**0.39**	**0.35**	4,600,212.75
Houston	25	29	40	**0.24**	**0.19**	**0.17**	2,255,006.25
TOTAL	214	246.1	344.54	**2.05**	**1.64**	**1.45**	19,302,853.50

Appendix D – External Energy Consumption, HSR (Red denotes operational components. These are accounted for using AVE data.)

Ext. Energy Consumption	**Energy Used**	**NOx**		**TOTAL Energy Used**		**TOTAL NOx**		**TOTAL CO2**
	(kJ/PMT)	**(mg/PMT)**	**(with TX EF)**	**(kJ)**	**(mWh)**	**(kg)**	**(lbs)**	**(lbs)**
Vehicles								
Vehicle Manufacturing	3.70	0.47	0.45	9,079,583,446	2,522	1,096	2,415	
Active Operation	1,200.00	34.00	32.30					
Idle Operation	30.00	0.84	0.80					
HVAC Operation	64.00	1.80	1.71					
Maintenance	2.40	0.21	0.20	5,889,459,532	1,636	490	1,079	
Cleaning	0.01	0.00	0.00	24,048,626	7	1	1	
Flooring Maintenance	0.15	0.02	0.02	368,091,221	102	51	113	
Infrastructure								
Station Construction	0.90	0.37	0.35	2,208,547,325	613	863	1,901	
Station Lighting	0.01	0.00	0.00	29,447,298	8	1	2	
Station Escalators	0.01	0.00	0.00	13,496,678	4	0	1	
Station Train Control	15.00	0.42	0.40	36,809,122,077	10,225	979	2,158	
Station Parking Lights	1.60	0.05	0.04	3,926,306,355	1,091	107	236	
Station Misc.	0.00	0.00	0.00	7,116,430	2	0	0	
Station Maintenance	0.95	0.39	0.37	2,331,244,398	648	909	2,004	
Station Cleaning	0.01	0.00	0.00	24,048,626	7	1	1	
Station Parking	4.00	1.60	1.52	9,815,765,887	2,727	3,730	8,221	
Track/Power Construction	320.00	110.00	104.50	785,261,270,976	218,128	256,437	565,187	
Track Maintenance	8.10	0.55	0.52	19,876,925,922	5,521	1,282	2,826	
Fuel								
Supply Chain (Vehicles)	180.00	8.00	7.60	441,709,464,924	122,697	18,650	41,105	
T&D losses (Vehicles)	120.00	0.30	0.29	294,472,976,616	81,798	699	1,541	
Supply Chain (Infrastructure)	2.40	0.10	0.10	5,889,459,532	1,636	233	514	
T&D losses (Infrastructure)	1.50	0.00	0.00	3,680,912,208	1,022	9	20	

				1,621,417,288,077	**450,394**	**285,538**	**629,326**	**564,149,626**

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