Sustainability of Intercity Transportation Infrastructure:

Assessing the Energy Consumption and Greenhouse Gas Emissions of High-Speed Rail in the U.S.

By

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved July 2011 by the
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ARIZONA STATE UNIVERSITY

August 2011

ABSTRACT

In the U.S., high-speed passenger rail has recently become an active political topic, with multiple corridors currently being considered through federal and state level initiatives. One frequently cited benefit of high-speed rail proposals is that they offer a transition to a more sustainable transportation system with reduced greenhouse gas emissions and fossil energy consumption. This study investigates the feasibility of high-speed rail development as a long-term greenhouse gas emission mitigation strategy while considering major uncertainties in the technological and operational characteristics of intercity travel. First, I develop a general model for evaluating the emissions impact of intercity travel modes. This model incorporates aspects of life-cycle assessment and technological forecasting. The model is then used to compare future scenarios of energy and greenhouse gas emissions associated with the development of high-speed rail and other intercity travel technologies. Three specific rail corridors are evaluated and policy guidelines are developed regarding the emissions impacts of these investments. The results suggest prioritizing high-speed rail investments on short, dense corridors with fewer stops. Likewise, less emphasis should be placed on larger investments that require long construction times due to risks associated with payback of embedded emissions as competing technology improves.

DEDICATION

For Ellen –

Thanks for your incredible support.

ACKNOWLEDGEMENTS

This thesis could not have been completed without the help of many individuals. First and foremost I thank my committee members (Eric, Jon, and Bob) for providing much guidance and enlightening discussions on the research topic. I'd also like to thank the colleagues I spent a summer with at Regional Plan Association, particularly Petra Todorovich and Yoav Hagler with America 2050 who gave me a great first-hand experience in the national transportation policy world. I am also indebted to Mikhail Chester for some engaging discussions on life-cycle assessment of transportation and for the data necessary to complete my analysis. I would also like to thank Paul Denholm for sharing details about his research on renewable energy adoption. Ram Pendayala provided guidance on ridership modeling. I am grateful to the IGERT community and my mentor, Nancy Grimm for constructive feedback on initial research directions. I would also like to thank all of the faculty and staff at the School of Sustainability who provided a very enriching two years and have helped me find a new path in the academic world. This work was partially supported through the National Science Foundation under Grant No. 0504248, IGERT in Urban Ecology. Additional support also came from a Research Assistantship through the Global Institute of Sustainability.

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I. INTRODUCTION

A. Intercity Travel and Greenhouse Gas Emissions

Over the next 50 years, the most dangerous levels of anthropogenic global warming (exceeding 2°C) will arise only with greenhouse gas (GHG) contributions from emissions sources yet to be built (Davis, Caldeira, & H. D. Matthews, 2010). Thus, determining which forms of new energy infrastructure can deliver services while minimizing emissions is a key problem for engineers and policy-makers seeking to mitigate climate change. In particular, the emissions contribution from infrastructure projects with long lifetimes should be given careful consideration before their construction.

A subset of this long-lived energy infrastructure is within the passenger transportation sector, which currently contributes to roughly 20% of U.S. greenhouse gas emissions as illustrated in Figure 1 (U.S. EPA, 2011). In recent years, scientists and policymakers have grappled with finding appropriate strategies to provide mobility while reducing greenhouse gas emissions (Transportation Research Board, 2011). A particularly vexing portion of existing transportation emissions is that of intercity travel, or trips between urban centers that cannot be accommodated by local services. As the world economy continues to globalize and populations continue to urbanize, intercity travel only seems poised to increase in necessity (Figure 2).

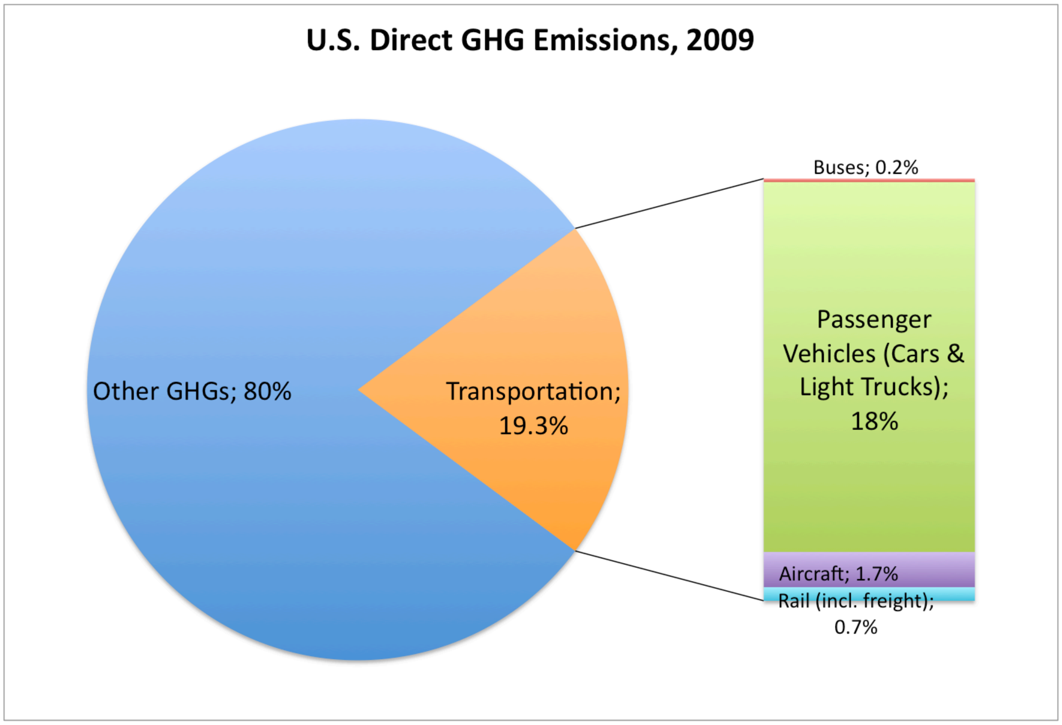

Figure 1. Inventory of U.S. Greenhouse Gas Emissions for 2009 (U.S. EPA, 2011).

Yet certain challenges inherent to intercity travel make it difficult to manage as a contributor to greenhouse gas emissions. For instance, emissions from intercity trips are difficult to attribute to particular political jurisdictions (Ramaswami, Hillman, & Janson, 2008). Emerging tools for transportation emissions accounting may play a role in improving policies related to infrastructure development. Contributing to this toolbox is one objective of this study.

Current estimates suggest that long-distance trips (>50 miles) make up about a third of all distance traveled by passengers in the

U.S. (Hu & Reuscher, 2004; U.S. Department Of Transportation Bureau of Transportation Statistics, 2006). Combining these statistics with data in Figure 1 gives a rough approximation that about ~7% of U.S. GHGs come from long-distance travel (assuming travel for long and short distance has roughly the same footprint per distance traveled). This contribution (~440 Tg CO_2eq) and opportunity for mitigation is on par with the national emissions contributions of Mexico or Italy.

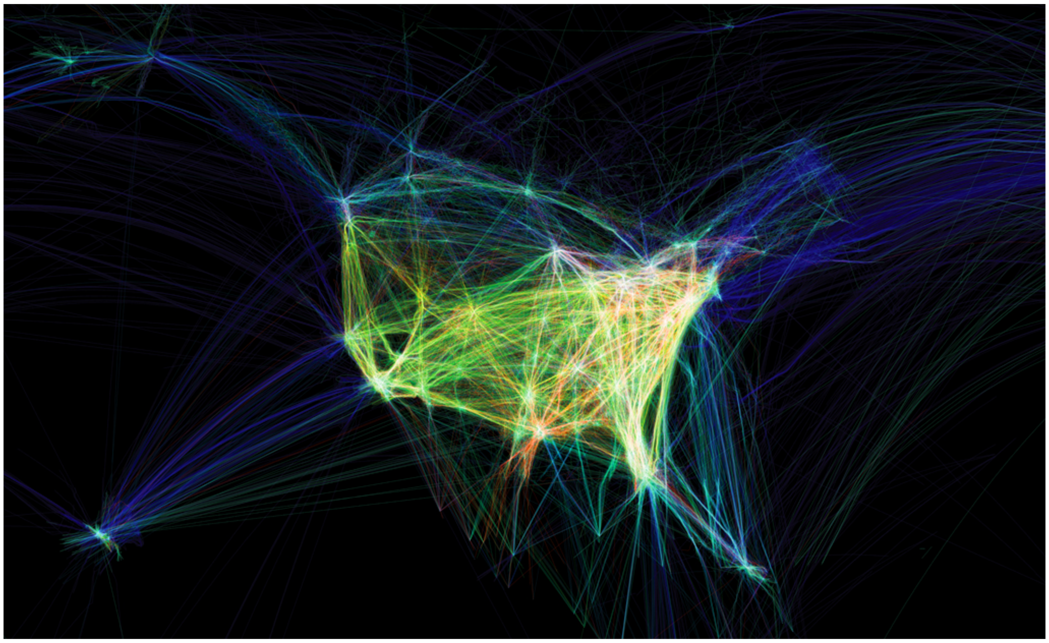

Figure 2. Visualization of flight paths across the U.S. illustrates both the global nature and urban centeredness of the transportation network (Koblin, 2006).

B. High-Speed Rail development in the U.S.

High-speed rail has emerged as one of several large-scale infrastructure initiatives with purported benefits for climate change mitigation. In a recent strategic plan, the U.S. Department of Transportation identified reduction in energy use and greenhouse gas emissions as a primary benefit of developing a national high-speed rail network (U.S. Department Of Transportation, 2009a). Several independent groups have supported high-speed rail for this reason, (e.g. California High-Speed Rail Authority, 2009a; Center for Clean Air Policy, 2006). California has perhaps the most progressive approach to greenhouse gas mitigation of any state, with its landmark law, the AB32 Global Warming Solutions Act. High-speed rail was included as an integral part of the scoping plan for California's mitigation effort (Adams, Nichols, & Goldstene, 2008). Meanwhile, President Barack Obama and Transportation Secretary Ray LaHood have indicated that high-speed rail is a priority for their administration and Congress has already appropriated large amounts of federal funding towards the newly established High Speed Rail Intercity Passenger Rail Program (HSIPR, Figure 3). These appropriations included $8 billion from the American Recovery and Reinvestment Act (ARRA) of 2009.

High-speed rail, typically defined as passenger service that exceeds 250 km/hr, was first adopted in Japan in the 1960s (US

Government Accountability Office, 2009). Systems have since been built in many countries, including Spain, France, Germany and England, South Korea and China with many more proposed or under construction around the world. As the U.S. developed funding programs for high-speed rail on a timeline to meet ARRA requirements, policy-makers did not have the opportunity for a more systematic planning process that investigates the full range of possible benefits and costs these investments would cause. Research and advocacy groups such as America 2050 have attempted to address the lack of robust criteria for evaluating high-speed rail projects through a series of studies (Hagler & Todorovich, 2009; Todorovich & Hagler, 2011). A central question asked in these studies was "Where does high speed rail work best?" A variation of this question should be "Where does high-speed rail work best for sustainability?" In this study, I will attempt to explore the sustainability dimensions of high-speed rail by developing a new method for modeling the greenhouse gas emissions of high-speed rail projects. The model is then applied to three proposed high-speed rail corridors in the U.S.: California, the Northeast Corridor, and Chicago-St. Louis-Kansas City (see Figure 3). Sensitivity of the model is tested under a variety of possible future technological and operational scenarios.

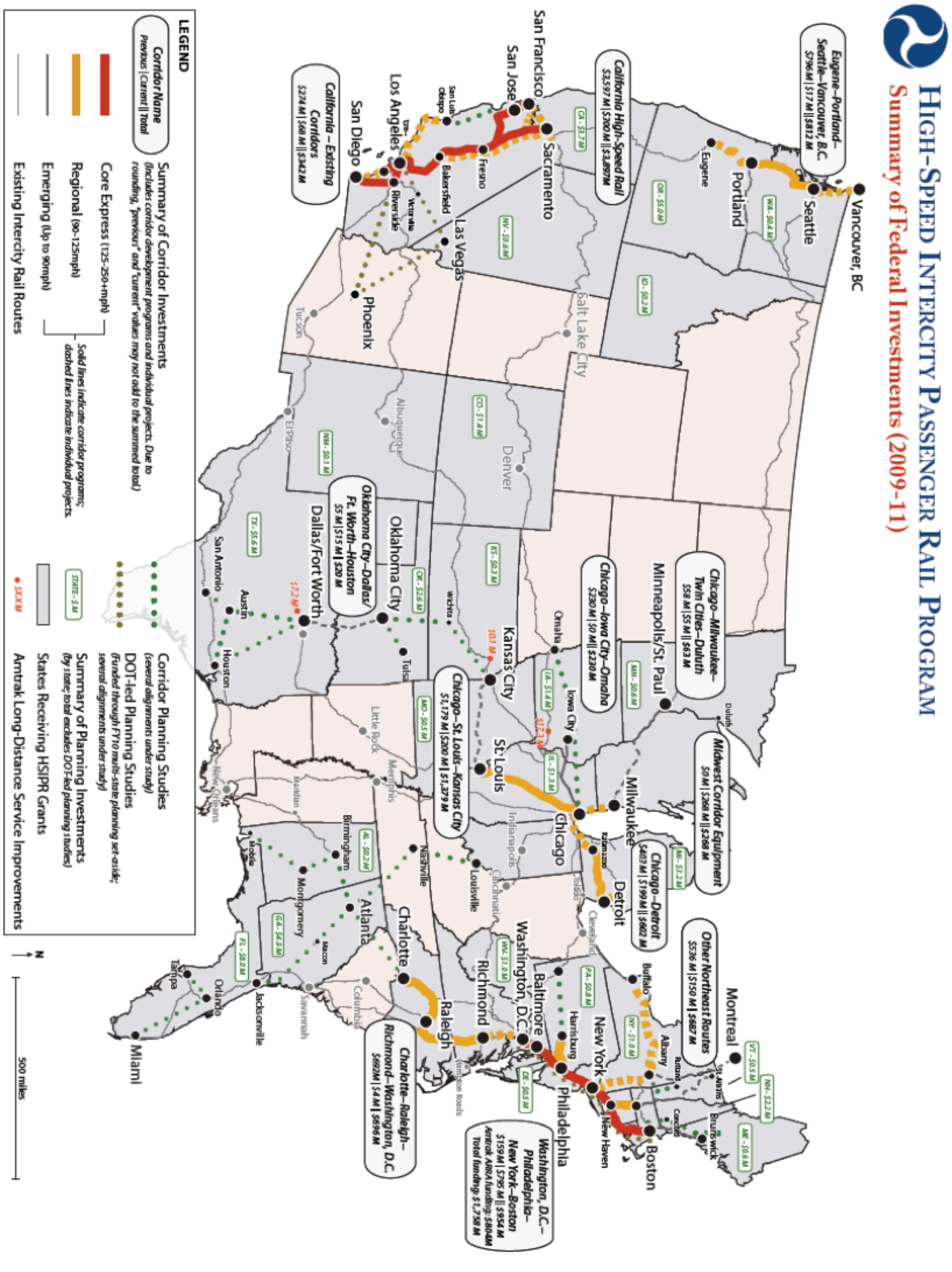

Figure 3. Summary of Federal High-Speed Intercity Passenger Rail Program (HSIPR) investments as of July, 8 2011 (U.S. Department Of Transportation, 2011).

C. Weighing Costs and Benefits in Life-Cycle Assessment of High-Speed Rail:

When considering the life-cycle costs of any process it's important to consider the benefits derived in exchange for those costs. High-speed rail is purported to provide a suite of benefits to society in exchange for its costs. The benefits frequently cited to stem from this investment include:

- New jobs created through construction and operation of the system and surrounding stations;
- Economic growth through increased transportation capacity; faster and cheaper travel between nearby cities;
- Enhanced regional connectivity that fosters regional identity, enhances quality of life, allows for more mobility, and increases business opportunities in the corridor;
- Environmental benefits due to reduced energy, emissions, and oil consumption;
- Increased system performance through added capacity that reduces burden on other modes and alleviates congestion.

These benefits are diagrammed in Figure 4.

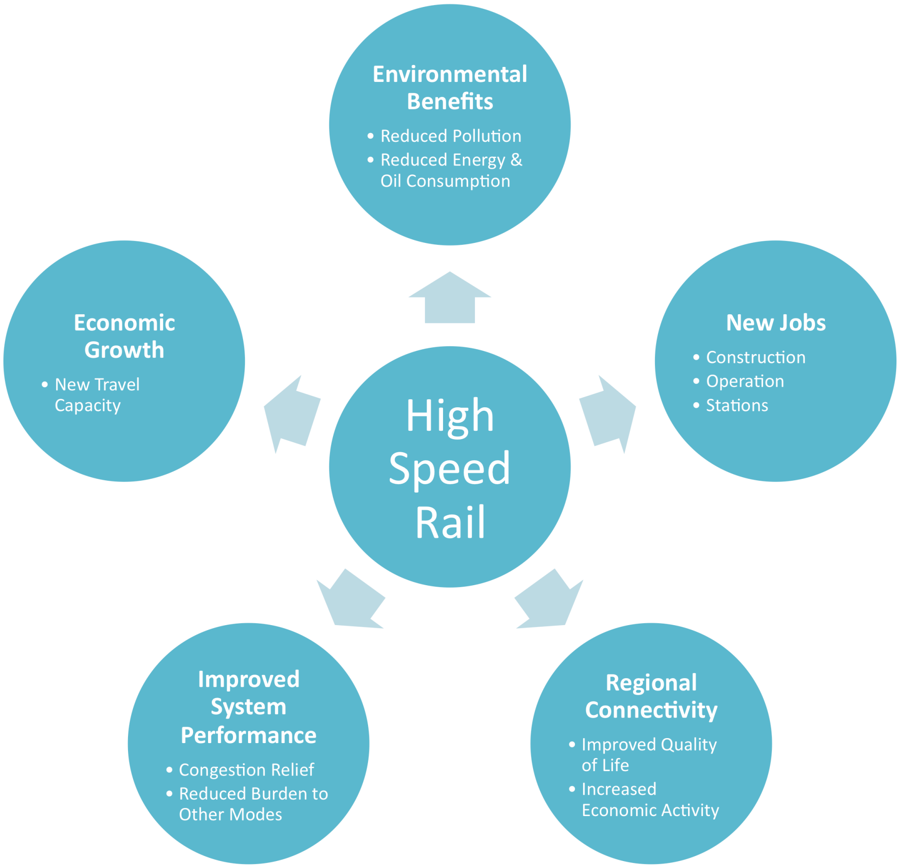

Figure 4. Diagram of perceived benefits derived from high-speed rail.

This study's analysis is constrained to only one portion of this overall picture: the environmental benefits – namely greenhouse gas emissions – associated with the distance traveled by passengers on high-speed rail. The magnitude of these environmental benefits should not be seen as the sole reason to support or oppose high-speed rail. Rather, the anticipated pollution benefits are one of many attributes that must be scrutinized through comprehensive cost-benefit analysis. However, in order to focus this study, this benefit is considered in isolation. Even if environmental benefits from high-speed rail are minimal, it’s very possible that the costs of high-speed rail are justified for other reasons. Indeed, larger political and economic drivers are likely to be more influential upon any rail investment decision. For example, many transportation engineers claim our highway and airport systems are beyond capacity and new infrastructure like high-speed rail is needed to enable a transportation system that maintains economic and population growth. However, despite any common arguments for or against high-speed rail, an appropriate measurement of its environmental impacts can help contribute to a more meaningful discussion of the true costs and benefits.

Recently, political contention over government spending and fiscal constraints may push high-speed rail in the U.S. further from reality. However, the methodology in this study can be instructive beyond this immediate case. In general, it provides a novel framework for long-term infrastructure assessment under uncertainty. This is especially important in a fiscally constrained environment in which benefits from public expenditures must be carefully assessed to ensure maximum benefits. For example, we might be interested in knowing if more local investments are preferable to large-scale high-speed rail systems. Furthermore, other nations are moving forward with high-speed rail, most notably China. China has prioritized economic growth but more recently shown interest in building its clean technology sector – both challenges that are conceivably addressed through is ambitious high-speed rail program. However, recent revelations of corruption show that China's system has not been without problems, notwithstanding any environmental considerations (Johnson, 2011). Furthermore, the environmental benefits of China's high-speed rail system may be hampered by the country's strong reliance on coal as a primary energy source. A full life-cycle assessment, utilizing the framework in this study could be useful for Chinese officials interested in determining the benefits of expanding their system. Both China and the U.S. could learn from each other's experience and research regarding high-speed rail.

II. LITERATURE REVIEW & STUDY OBJECTIVES

A. Functional units for transportation life-cycle assessment

Sustainability life-cycle assessments for passenger transportation often compare travel by using vehicle-kilometers (VKM) or passenger-kilometers (PKM) as a functional unit (M.V. Chester & Horvath, 2009; Eriksson, Blinge, & Lovgren, 1996; Kennedy, 2002; a Schafer, Heywood, & Weiss, 2006; Spielmann & Scholz, 2005). For instance, the marginal greenhouse gas impacts of transportation can be described as CO_2/PKM[1], the carbon dioxide emissions created from a passenger traveling one kilometer. This measure is intuitive for comparing the impacts of different transportation technologies. For example, emissions from public transit often compare favorably to automobiles in providing travel (PKM) over the same distance (Hodges, 2009). However, CO_2/PKM has many limitations as a unit of analysis. In this study, I will attempt to build upon the usefulness of CO_2/PKM as an intuitive metric by addressing some of these limitations. I develop an approach that accounts for the long-term nature of transportation infrastructure investments, a characteristic that ultimately affects emissions performance as new technologies and

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[1] In this study, all instances of "CO_2" actually refer to CO_2eq -- the carbon dioxide equivalent of greenhouse gas emissions based on 100-year global warming potentials.

utilization patterns develop over time. I then apply this analytical framework to model the relative emissions advantages of high-speed rail as technologies improve. I use the model to evaluate a set of proposed high-speed rail corridors in the U.S.

B. Confronting limitations of CO_2/PKM

1. Non-equivalence of modes

One obvious drawback of CO_2/PKM as a unit for life-cycle assessment is that transportation modes differ drastically in terms of the value and quality of service for equivalent distances traveled. Airplanes offer the advantage of speed, which is not directly comparable to other modes in terms of PKM. Similarly, trains and buses offer non-PKM benefits such as greater productivity during travel and ease of use for disabled and elderly passengers. Studies that incorporate models of the implicit value or utility of these travel modes are needed to disentangle these differences, and are a major focus of transportation modeling (Cervero, 2002). Addressing this problem is beyond the scope of this study, but I acknowledge that any CO_2/PKM comparison is an inherently limited way to compare the benefits transportation investment brings compared to the cost of increased emissions.

Despite these caveats, CO_2/PKM may still be a useful tool for assessing the aggregate emissions impacts that arise as a consequence of a proposed transportation investment. However, I must concede that this evaluation is limited to emissions impacts alone and that this is only one of many possible costs or benefits a transportation investment will achieve.

2. Uncertainty in technological progress

An inherent quality of public infrastructure projects is that they are long-lived, often lasting decades. Indeed, part of the value of public infrastructure comes from its long lifetime, during which initial investment costs can be recovered through societal benefits, many times over in some cases (Partership for New York City, 2003). However, this long timeframe also places great uncertainty on the environmental outcomes (costs and benefits) that any particular project may bring. Even after constituent parts are replaced, transportation networks can live on, potentially giving rise to undesirable technology lock-in that limits choices in the future. Thus special attention must be given when evaluating wholly new transportation projects where the core technology (and those of competing modes) could change significantly over the lifetime of the asset. For example, investment in a high-speed rail corridor may compare favorably on a CO_2/PKM basis during its construction, but changes in vehicle technologies for automobiles or airplanes over the next 20 years might supersede that advantage. Addressing this uncertainty requires an analytical framework that can anticipate future technological changes.

3. Uncertainty in utilization

Another problem with CO_2/PKM as a functional unit is that there is great uncertainty in how transportation investments will be utilized in the future. This has been documented extensively in transportation modeling studies. For example, a recent analysis indicated major uncertainties in ridership studies of the high-speed rail corridor being developed in California that could jeopardize its cost-effectiveness (Brownstone, Hansen, & Madanat, 2010). Beyond ridership, other operational characteristics such as the speed of trains and number of stops can also influence overall energy consumption, and thus emissions. Furthermore, adoption rates for new transportation technologies such as plug-in hybrid electric vehicles (PHEVs) can influence the relative CO_2 advantage high-speed rail yields. Uncertainty in utilization of transportation suggests developing a framework that can isolate non-ridership components and illuminate sensitivities to different utilization patterns. I use the model developed in this study to explore these sensitivities.

4. Marginal impact of large-capital projects

Typically, life-cycle studies find the average of production impacts for a function unit of the product or service. For example, the emissions embedded in the concrete used to construct a railroad track are amortized over the lifetime of the track and then divided among the annual ridership (PKM).

Yet, including transportation infrastructure as a marginal unit suggests that these impacts change per unit of travel on that mode. In reality, these large-scale investments are lumpy fixed costs that are spaced many years apart, and their impacts reflect one-time events that do not scale linearly with demand (i.e. ridership). Thus, a framework is needed that can evaluate infrastructure components of transportation projects that addresses the shortcomings of this marginal unit approach.

C. Previous Life-cycle Studies on High-Speed rail

In recent years, comprehensive life-cycle studies of transportation have been conducted and currently serve as a baseline for comparing modes including high-speed rail (M. Chester & Horvath, 2008; 2010). Crucially, these studies account for the upstream impacts of transportation including construction of infrastructure, vehicle manufacturing, maintenance, and other embedded components, in addition to normal vehicle operation. Upstream components are estimated through hybrid economic input-output life-cycle assessment (EIO-LCA) methods (Williams, Weber, & Hawkins, 2009), which are increasingly used to account for construction projects incorporating disparate elements that cannot be traced to the original production source (Sharrard, H. S. Matthews, & Ries, 2008).

Transportation life-cycle studies have confirmed that operational energy is often the dominant contributor to life cycle impacts (M.V. Chester & Horvath, 2009). This is true in the case of California's proposed high-speed rail system, for which the largest contributor to energy and greenhouse gas emissions is estimated to be from vehicle operation (i.e. electricity for traction), followed by infrastructure construction (i.e. track and power delivery systems), and fuel production (M. Chester & Horvath, 2010). Additionally, these studies consider a wide range of passenger load factors, which have a significant influence on emissions/energy impact per PKM.

Another recent study also considered the greenhouse gas impact of high-speed rail by constructing scenarios to estimate the potential for emissions reduction (Kosinski & Deakin, 2011). In each scenario, the overall reduction from high-speed rail was relatively small and accounted for ~1% of U.S. total emissions. This is in line with my estimate that ~7% of GHGs are from intercity passenger travel, knowing that the candidate market for high-speed rail is only a fraction of this.

D. System Boundaries

A standard practice in life-cycle assessment is a proper definition of system boundaries. The diagram below (Figure 5) highlights the parts of the system included in this assessment of high-speed rail. According to previous life-cycle studies, the largest components contributing to energy and pollution impacts in high-speed rail are vehicle operation followed by infrastructure construction (Chester & Horvath, 2008; 2010). After infrastructure, fuel production is the next most-significant area. However, the studies reviewed suggest it is a fairly small component so I chose not to include it to simplify the analysis. The remaining components are much smaller by comparison. For alternative transportation modes, including automobiles and airplanes, system boundaries were chosen that exclude infrastructure (e.g. roads, see Figure 6). This was based on the assumption that most air and road transportation modes in the U.S. include largely built-out systems that require some expansion and maintenance but not entirely new construction as is the case for high-speed rail. A more complete life-cycle assessment that includes these marginal expansions such as addition of new highway lanes should be considered for future analysis. Note that for automobiles and aircraft, operation is still the largest component, yet vehicle manufacture makes up a more significant fraction of the full life-cycle impacts than in trains.

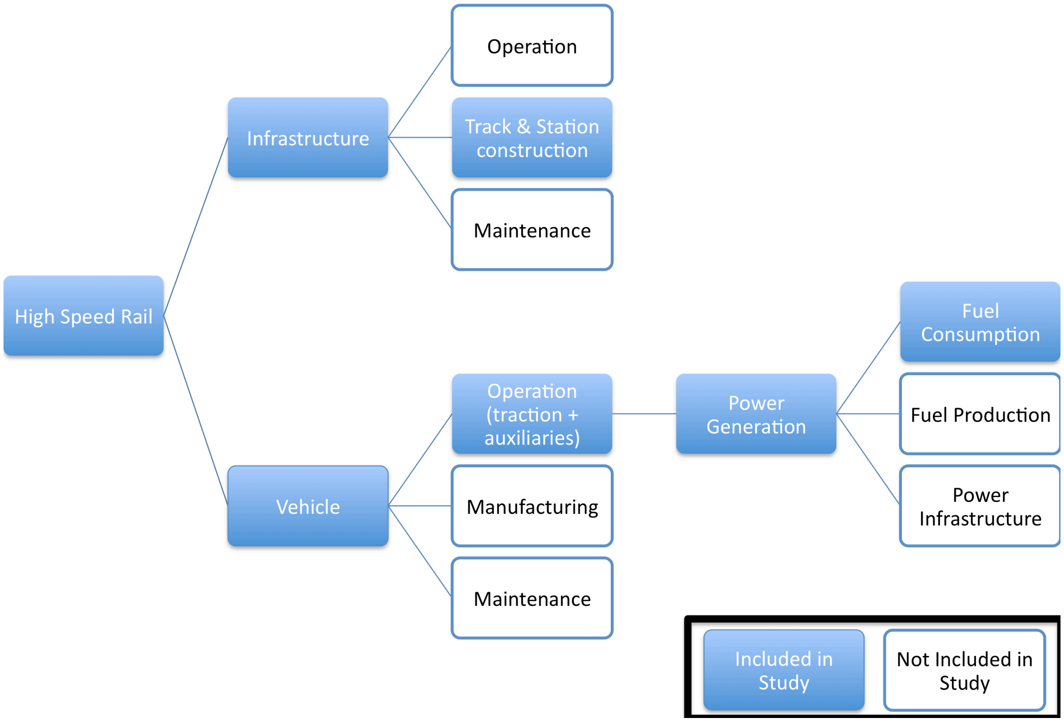

Figure 5. System Boundaries Defined for Life-Cycle Assessment of High-Speed Rail in this Study.

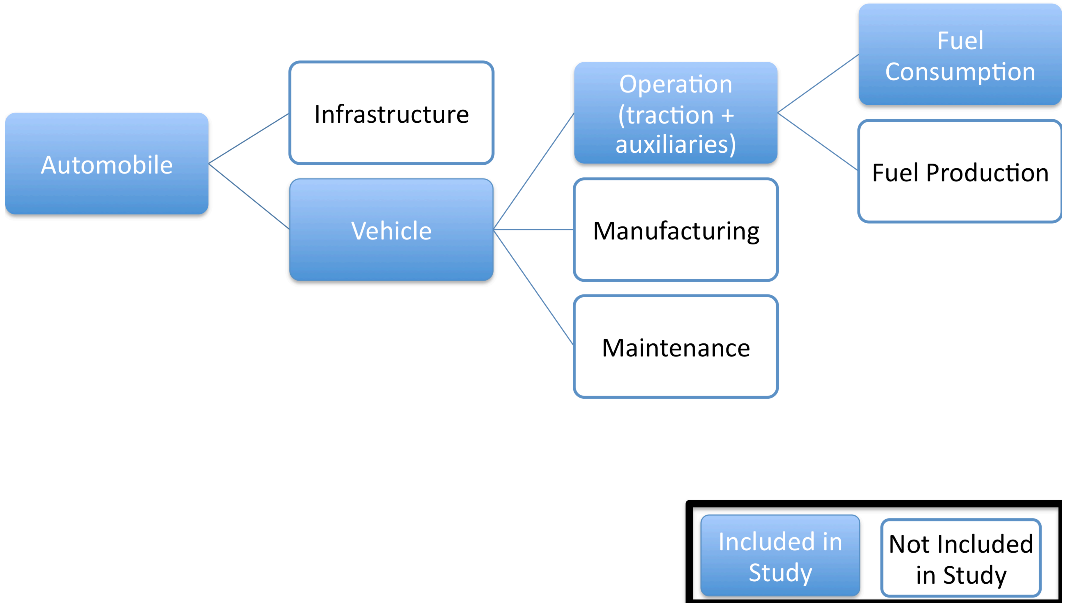

Figure 6. System Boundaries Defined for Life-Cycle Assessment of Alternative Transportation Modes in this Study.

E. Present Study Objectives

The studies summarized above contribute greatly to the discussion of high-speed rail as a potential piece in a sustainable transportation system. I build upon this analysis by addressing some additional questions regarding high-speed rail and life-cycle methodology issues more generally. For instance, the literature on transportation life-cycle assessment reveals operational energy as a dominant driver of impacts, but often does not consider what components of those energy losses are subject to change, through variation in either technological or operational parameters.

There is a wealth of literature on technological forecasting for specific vehicle technologies (particularly automobiles), but these studies often do not consider multiple modes simultaneously. Thus there is no understanding of how high-speed rail is likely to progress relative to other possible intercity travel modes. Furthermore, these studies have considered a single corridor (California) and broader impacts for a national program. Incorporating additional regions into the analysis could be insightful for understanding transportation's relationship to existing capital infrastructure particularly the power grid.

Finally, ridership and load factor have been considered major sources of uncertainty in marginal impacts per PKM, but many other operational and technological parameters also contribute to uncertainty of high-speed rail's impact. Weighing the relative influence of these parameters could help set guidelines for maximizing the environmental benefit, and minimizing the impact of high-speed rail.

With these concerns in mind, the following primary objectives were pursued in this study:

Objective 1: Develop a methodology to estimate the marginal CO_2 impacts of intercity transportation modes under technological uncertainty.

Objective 2: Apply this methodology to understand how technological progress may affect the relative emissions costs/benefits of high-speed rail.

Objective 3: Apply this methodology to understand the carbon benefits of high-speed rail in specific corridor proposals, while incorporating life-cycle costs of construction.

III. METHODOLOGY

A. Analytical Framework for Forecasting Emissions From High-Speed Rail

The framework I use to evaluate emissions impacts of high-speed rail consists of two discrete analyses. The first employs a technology forecasting method to compare intercity travel modes. The second employs a life-cycle carbon payback calculation to evaluate the effectiveness of specific high-speed rail corridors.

1. $\Delta CO_2/PKM$: A tool for technology comparison

In the U.S., high-speed rail represents a novel mode of transportation. Thus, upon construction, all high-speed rail travel (PKM_{HSR}) will be comprised of travelers from other modes (PKM_{ALT}) plus any induced travel not previously undertaken. I base my analysis on a desire to understand the marginal difference in emissions (ΔCO_2) when a person switches to high-speed rail from a competing mode of travel, expressed as follows:

$$\Delta CO_2/PKM = CO_2/PKM_{HSR} - CO_2/PKM_{ALT} \qquad \text{Equation 1}$$

where CO_2/PKM_{HSR} represents the added carbon footprint of high-speed rail travel and $CO2/PKM_{ALT}$ represents the carbon avoided from other modes of travel. $CO2/PKM_{ALT}$ in turn is an aggregation of each alternative:

$$CO_2/PKM_{ALT} = \alpha_1 [CO_2/PKM_{mode\ 1}] + \alpha_2 [CO_2/PKM_{mode\ 2}] + \ldots + \alpha_n [CO_2/PKM_{mode\ n}] \qquad \text{Equation 2}$$

Where α_i represents the fractional share of high-speed rail ridership derived from each mode ($\alpha_1 + \alpha_2 + \ldots + \alpha_n = 1$). One α-value represents the fraction of induced travel that would not have occurred otherwise (See Chapter VI for detailed information on α values). For induced travel, I assign $CO_2/PKM = 0$, reflecting the fact that these passengers do not reduce emissions elsewhere in the economy. Higher induced travel from a new rail corridor may reflect societal benefits in terms of additional economic activity, including population growth. However, it also tends to reduce $\Delta CO_2/PKM$ and thus decreases the overall intensity of the environmental benefit caused by the rail investment.

Policy arguments that refer to the climate benefits of high-speed rail rely on the implicit assumption that marginal impact of high-speed rail is less than that of alternative modes (i.e. $\Delta CO_2/PKM < 0$). Thus as passengers utilize high-speed rail instead of other transportation modes, the emissions benefits realized over time reflect the magnitude of $\Delta CO_2/PKM$, as well as the amount of travel (PKM) that uses high-speed rail instead of other modes.[2] To understand how technological change and operational characteristics affect this benefit, a model was developed to evaluate high-speed rail in comparison to alternative (existing) intercity travel technologies over time. The model projects the performance of each mode's CO_2/PKM value over time (and thus $\Delta CO_2/PKM$) based on assumptions about feasible improvements in each technology's performance. It's important to note that for early years (i.e. before 2020), $\Delta CO_2/PKM$ is more of a conceptual value since there is no high-speed rail on schedule to be completed by then.

To better identify and constrain uncertainties in the time progress of CO_2/PKM , I decompose the term into three constituent parts whose time evolution can be separately evaluated as components of the model:

$$CO_2/PKM = CO_2/kWh \times kWh/VKM \times VKM/PKM \quad \text{Equation 3}$$

a) CO_2/kWh:

This term represents the carbon intensity of primary energy sources used for intercity transportation and is detailed in Chapter IV. It reflects the fuel mix of electricity generating plants in a particular region. Changes in this parameter for electric vehicles reflect improvements in power plant efficiencies (heat rates) and adoption of

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[2] Net CO_2 in a given year is the product $\Delta CO_2/PKM$ and PKM.

low-carbon energy sources. Changes to the carbon intensity of liquid fuels, such as adoption of advanced biofuels, were not considered.

b) kWh/VKM

This term represents the energy intensity of travel for a particular vehicle technology and is detailed in Chapter V. Changes here reflect feasible improvements in transportation technology under thermodynamic constraints (i.e. minimum losses from energy conversion).

c) VKM/PKM

This term reflects utilization of passenger modes and is detailed in Chapter VI. Values for each mode are based on historical patterns and observed statistics. In the short run, it's unlikely that a perfect one to one relationship exists between passenger travel and vehicle travel. For example, one less passenger traveling between two cities may not cause any fewer airplane flights. However, in the long run, we assume an aggregate effect that is close to a linear relationship. In other words, it is assumed that carriers on a competitive system will manage their vehicle operations toward a target efficiency (load factor), and thus the number of vehicle trips will be directly proportional to the number of passengers. A further review of the elasticity between passenger loads and vehicle travel is warranted.

2. Payback Times: A tool for policy analysis

Many life-cycle studies incorporate not just the operational impacts of transportation (which are captured by $\Delta CO_2/PKM$), but also the life-cycle impacts associated with upstream components like track construction, e.g. (Mikhail V Chester & Horvath, 2009). Typically, life-cycle studies find the average impact of production for each functional unit (in this case, PKM). However, for long-lived infrastructure I adopt a different approach in order to account for uncertainties described in Section II.B. As noted, converting construction costs to marginal units may obscure the lumpy nature of transportation infrastructure, with large construction impacts occurring at the beginning that are then averaged over decades of operation. Since greenhouse gases have long atmospheric lifetimes and can be considered "stock pollutants," many recent life cycle studies have instead used payback times as an alternative method for evaluation (M. Chester & Horvath, 2010; Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008). I adopt payback times as a useful way of assessing the stream of costs and benefits a high-speed rail investment provides relative to the upfront environmental costs of production. However, in order to calculate paybacks I also need to know details about initial construction and ridership.

a) Construction Impacts

The initial construction of a high-speed rail system includes large amounts of concrete, steel, and power delivery systems, which have embodied energy and emissions in their production. The magnitude of the construction-embodied emissions can be approximated from knowing a marginal quantity of life-cycle emissions per kilometer of track length. Data on marginal emissions per kilometer of track material were obtained from the author of life-cycle studies of California's proposed high-speed rail system (M. Chester & Horvath, 2010). These results were generalized for all new high-speed rail track construction, although it is likely that regional variations would arise from differing construction needs.

It's important to note that high-speed rail experiences long construction phases before any passenger service is realized. For example, current business plans for the California High-Speed Rail (CAHSR) estimate that initial revenue service will not commence until 2020 (California High-Speed Rail Authority, 2009a). For analysis of payback time, construction-related emissions were simplified to portray one-time pulse at the beginning of the modeled time period.

b) Ridership

Ridership estimates for public transportation are typically developed through extensive travel demand modeling efforts. As an illustration, the process undertaken by the CAHSRA is described briefly:

The CAHSRA hired transportation consultants Cambridge Systematics to develop ridership forecasts for the proposed CAHSR project (California High-Speed Rail Authority, 2009b). This ridership study is one of the most robust for high-speed rail in the U.S. and reflects development over many years and several rounds of peer review. Cambridge achieved its estimates through two main efforts: a *model development* phase and a *model validation* phase.

Model development: In the model development phase, intercity travelers in California were surveyed. Travelers were asked questions about the mode they would choose given hypothetical values for time, cost, frequency, and so on. These stated preferences were used to develop a ridership forecast model incorporating mode choice, historical travel patterns, population projections and economic projections.

Model validation: After the model was developed, its parameters were adjusted to achieve agreement with observed travel market data, and to reflect the expert judgment of the model developers. The observed market mode shares were largely determined through a combination of Department of Transportation air ticket sample data, the American Travel Survey, and other travel surveys.

According to Cambridge Systematics, the practices used to develop these projections were in accordance with standard industry practices. However, the projections have also been criticized and may call into question the project's cost-effectiveness (Brownstone et al., 2010). Because high-speed rail is a novel form of transportation in the U.S., there is sufficient uncertainty about ridership in understudied corridors to take caution. Indeed, the lack of similarity between urban form in the U.S. and the locations of successful high-speed rail systems worldwide (e.g. Japan) gives ample reason for concern when considering ambitious ridership projections. There may be some exceptions to this rule, such as dense corridors in the Northeast U.S., and transit-centric cities in the Pacific Northwest. Nonetheless, I am wary of the limitations in ridership projections when conducting my payback analysis. In any case, having previously isolated $\Delta CO_2/PKM$ – the technology component -- we can be more confident about the meaning of ridership sensitivity analysis.

3. Timing and trajectory of emissions

In addition to simple payback times, there are additional ways to consider the timing and trajectory of emissions costs/benefits to high-speed rail (Figure 7). In addition to magnitude of emissions, the timing of drawdown (which is partly determined by $\Delta CO_2/PKM$) matters a great deal as well. Some investments with small infrastructure needs could yield relatively short paybacks but slow long-term payoffs. Likewise, investments with greater upfront construction costs may yield higher payoffs, but with greater risk and uncertainty. I will discuss these principles informally. Converting carbon costs to a monetary value could allow decision-makers to prioritize different investments by exploring the net present value and rate of return for carbon savings.

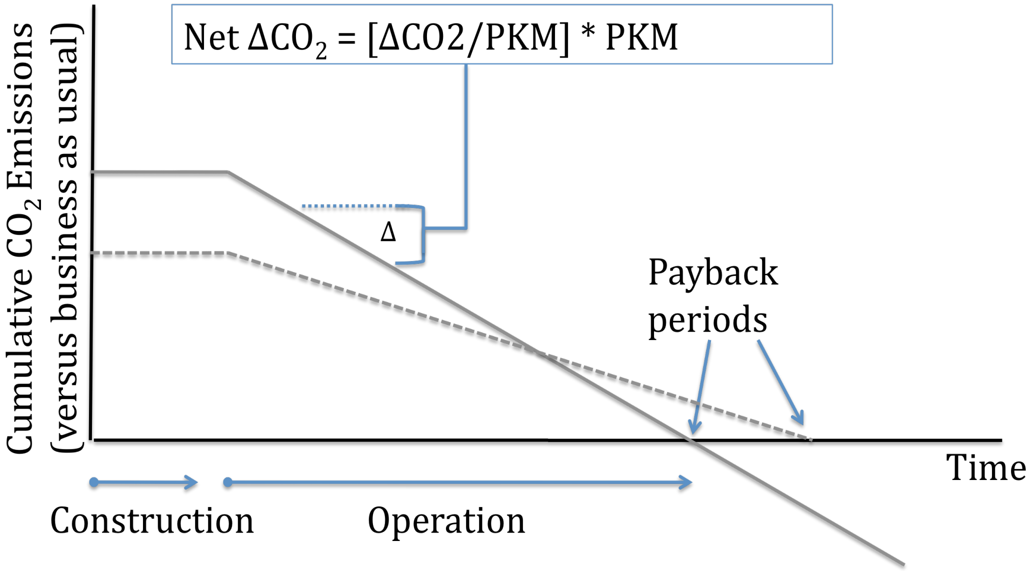

Figure 7. A schematic of a possible emissions trajectories for high-speed rail emissions payback.

IV. FORECASTING THE CARBON INTENSITY OF ENERGY SOURCES

A. Uncertainties in emissions of electricity generation

This chapter describes the CO_2/kWh component of the model, which represents the carbon intensity of primary energy sources used to power intercity travel. The objective of this analysis is to understand how technological changes and uncertainties affect the carbon emissions associated with a marginal unit of energy consumption for transportation. Liquid fuels in wide use for transportation today (e.g. gasoline) are mainly fossil-derived and have relatively fixed values for CO_2/kWh, which should persist absent breakthroughs in advanced biofuels. However, changes to CO_2/kWh become salient when considering a transition to electrically powered transportation modes such as high-speed rail or electric automobiles. Electricity is produced from a wide variety of primary energy sources that evolve over time. The nature of the electricity market makes quantifying the marginal impacts a challenge for several reasons.

Foremost among these challenges is the fact that electricity consumption does not necessarily coincide with electricity generation since electrons can be transmitted over long distances. Thus, emissions factors[3] for electricity consumption within a specific geography are subject to uncertainty related to the choice of spatial aggregation of grid generation sources. This problem has been thoroughly addressed in recent studies (Weber, Jiaramillo, Marriott, & Samaras, 2010), including an attempt that was made to reduce this uncertainty by modeling the primary energy sources associated with electricity consumption (opposed to generation) at the state level (Marriott, H. S. Matthews, & Hendrickson, 2010).

Another major challenge to quantifying the impact of marginal electricity consumption is the presence of temporal variations. Electricity markets typically meet demand with least-cost generation sources giving rise to different fuel mixes for peak and baseload power consumption. Thus the carbon intensity can differ by time of day.

A final challenge is considering the outcome of the overall increase or decrease in electricity demand associated with transportation. Indeed, increased electricity demand from electric trains or cars will undoubtedly lead to an increase in marginal output of electricity in the short run. But perhaps a more significant effect is the impact on long-run demand for generation capacity, which has the potential to alter the fuel mix. As some supporters of high-speed rail technology have suggested, the new energy demands imposed by high-

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[3] Emissions factors represent the emissions (e.g. CO_2) generated per unit of fuel or electricity (e.g. kWh)

speed rail might be met entirely through the addition of new renewable sources (Navigant Consulting, 2008), although this is by no means a certainty.

Despite the challenges described above, I attempt to formulate some constraints on how emissions from electricity for transportation might evolve in particular intercity travel corridors. These estimates rely on a few simplifying assumptions:

1. Current state-level electricity fuel mixes (for consumption) can be approximated by using the findings of Marriott et al., 2010.

While data is readily obtainable on power generation locations, the location where that power is consumed is more difficult. To model a baseline "consumption mix" of energy sources based on where the energy is used (opposed to where it's generated) I used data from Marriot et al., 2010. This particular study used a spatial optimization technique to model the resource mix used to produce electricity consumed in U.S. states.

2. This consumption mix is representative of the generation present during the times of day that intercity travel occurs.

Since the study does not differentiate between peak and baseload consumption patterns, I assume that the changes between the two do not play a large role in the fuel consumed by transportation. This is a data limitation more than a methodological preference.

3. New intercity travel plays a minimal role in overall capacity additions;

Instead, I assume that the capacity market for electricity is mostly dominated by other policies and market trends such as adoption of renewable portfolio standards.

4. Plant efficiencies are similar to national averages

I assume that national statistics for power plant efficiency apply to all regions equally.

Developing accurate forecasts of future energy markets is notoriously difficult and may indeed be a futile effort (Smil, 2005). Thus I acknowledge that any attempt to predict electricity generation capacity will likely have severe limitations and should not be construed as an attempt to predict reality. Instead, my purpose here is to develop a reference scenario that models a *possible* trajectory for the carbon intensity of electricity. This trajectory can then be tested against other scenarios, and in particular against decisions to build high-speed rail corridors. Carbon emission reductions and payback times associated with electrically powered transportation are sensitive to future developments in electricity generation, and these sensitivities are explored in this portion of the model.

B. Modeling emissions of current and future electricity generation

Using assumptions specified above, CO_2/kWh for a specific region are modeled, adapting a general approach used in a previous study (Denholm, Margolis, & Milford, 2009) as follows:

$$CO_2/kWh\ (t) = \sum_i f_i\ (t) \times EF_i \times \eta_i\ (t) \qquad \text{Equation 4}$$

Where $f_i\ (t)$ = the fraction of electricity produced from resource i at time t, and $f_1 + f_2 + \ldots + f_n = 1$.

EF_i = emissions factor of resource i (in kg CO_2eq/BTU), and

$\eta_i\ (t)$ = power plant heat rate, expressed in the energy content (BTU) of resource i per kWh produced.

1. Emission Factors, *EF*

For some energy resources (e.g. hydro, nuclear, wind), $EF=0$. The two most common non-zero resources are natural gas and coal (petroleum makes up a small portion of U.S. generation capacity and is not included in this model). These emissions factors do not evolve over time, though in theory they might be reduced through carbon capture and sequestration. Emissions factors used are shown in Table 1.

Table 1. Emissions factors for common fuels (Data Source: Energy Information Agency)

Fuel	**Emission Factor (kg CO2/million BTU)**
Coal	93.4
Natural Gas	53.1
Gasoline	70.7
Jet Fuel	70.9

2. Generation Fractions, *f*

At t=0, each $f_i(t)$ value reflects the consumption modeled in (Marriott et al., 2010) as stated above. Each fraction changes over time reflecting investments in new generation sources and retirement of existing generation sources. Predicting these dynamics is beyond the scope of this study. Indeed, such resource planning efforts are usually undertaken by experienced specialists within the electric utility industry and typically require costly proprietary modeling software. However, I choose to approximate how these fractions might change in light of public policies that are already enacted. Renewable portfolio standards (RPS) already adopted in many U.S. states mandate that a specified amount of retail electricity sales be supplied by renewable energy sources (North Carolina State University Solar Center, n d).

The fraction of renewable sales increases over time as illustrated in Figure 8.

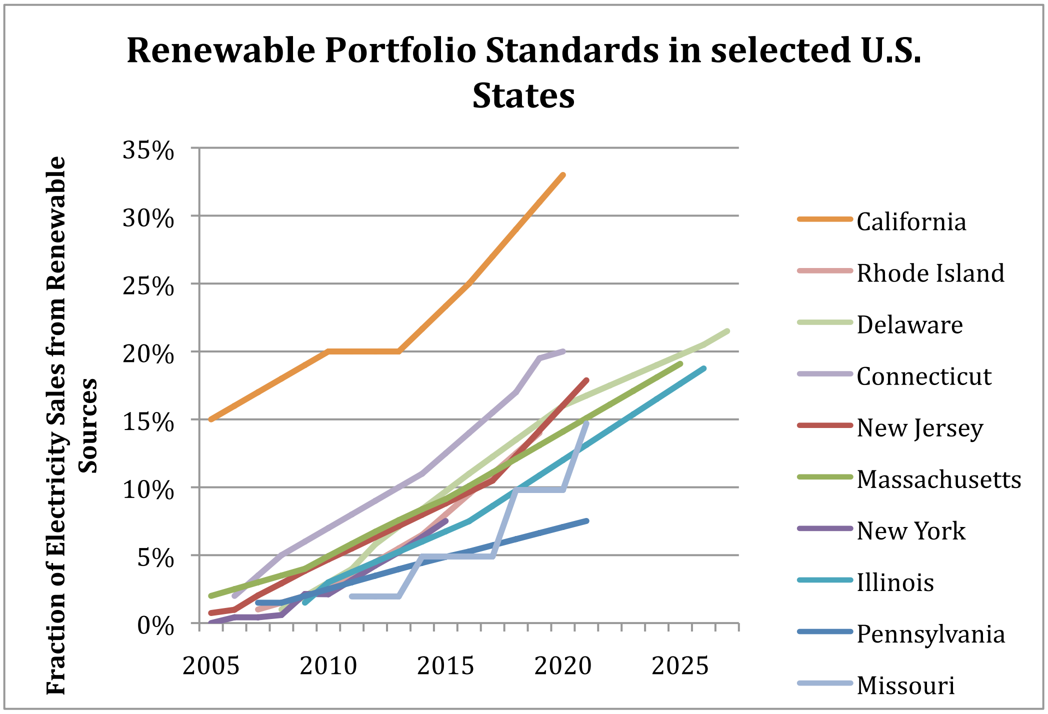

Figure 8. Fraction of electricity sales from renewable sources according to state renewable portfolio standards (Data Source: North Carolina State University Solar Center, DSIRE database).

While there is uncertainty over whether these standards will be met, or whether the policies will be maintained, most are legally binding and represent a best guess of the minimum expected changes to the electricity consumption resource mix. It's also possible that these policies will be strengthened as time goes on.

I incorporate renewable portfolio standards into the model by hypothesizing that existing fossil generation fractions (f_{coal} and f_{natgas})

will be reduced proportionally to the increase in renewable sources. The schedule of fossil energy replacement by photovoltaic (PV) generation in the Western U.S. has been explored in some recent studies (Denholm et al., 2009; Drury, Denholm, & Margolis, 2009). These studies conclude that natural gas generation is likely to be replaced first at low PV market penetration with increasingly higher replacement of coal as overall PV penetration increases. Understanding how these replacement rates evolve for renewable portfolio standards (including generation sources other than PV) is a complex question and well beyond the scope of this study. Thus I assume that the increased renewable fraction ($f_{renewable}$) replaces both major fossil fractions (f_{coal}, and f_{natgas}) in equal measure, even though this as an unlikely outcome. It's assumed that renewable resources will not replace existing low-cost energy sources such as nuclear or hydroelectric power.

3. Heat rates, η

While f evolves with changes in generation sources, specific power plant technologies may also evolve over time as efficiencies improve. Such changes have occurred in recent history, particularly for natural gas plants, as illustrated in Figure 9.

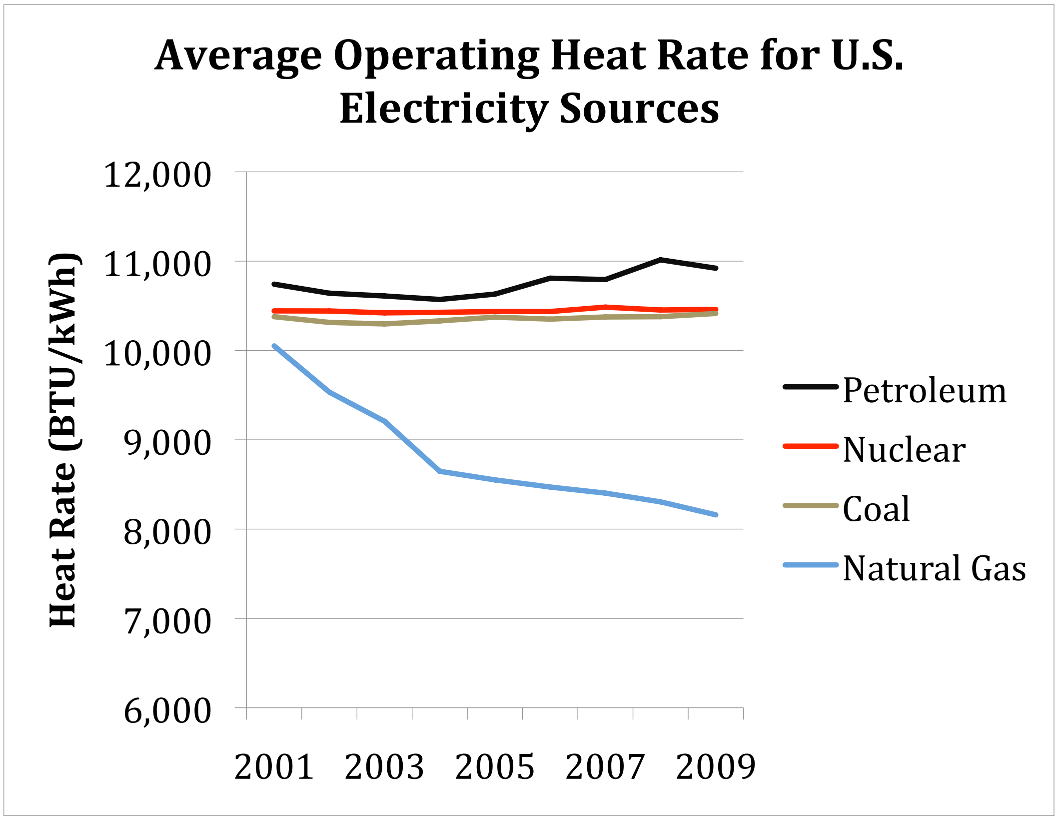

Figure 9. Average heat rates electricity generating units in recent years (Data Source: Energy Information Administration).

Combined cycle gas turbine plants have been purported to achieve heat rates as low as 5,690 BTU/kWh (GE-Energy, 2010), corresponding to ~60% efficiency. Use of cogeneration plants could enable plants to reach even higher efficiencies over time. Thus, I assume the overall heat rate (η_{natgas}) for natural gas generation will continue to decline in coming years as new generating capacity is brought online and existing plants are retrofitted. Furthermore, addition of renewable resources will typically replace the costliest plants first, which typically have lower efficiency. I assume a modest annual 0.5% decrease in natural gas plant heat rates, achieving an average of 6,677 kWh/BTU by year 2050. Similarly I assume coal plant heat rates to improve 0.1% annually, reaching 10,005 kWh/BTU by 2050.

4. Transmission Losses

In addition to energy lost through inefficiencies at the generation source, energy is also lost through grid transmission and distribution. Equation 4 is corrected for transmission losses as follows:

$$CO_2/kWh_{delivered} = (1-l_j)\ CO_2/kWh_{generated} \qquad \text{Equation 5}$$

Where l represents the transmission losses (%) in location j. Transmission losses were estimated from the values reported in the EPA eGRID2010 database (E.H. Pechan & Associates, 2008).

C. Forecast results

The parameters described above in Section B were combined to derive forecasts of state level changes to CO_2/kWh. Some examples of these estimates are illustrated in Figure 10. The modeled values are most prominently influenced by the starting resource mix and stringency of renewable portfolio standards.

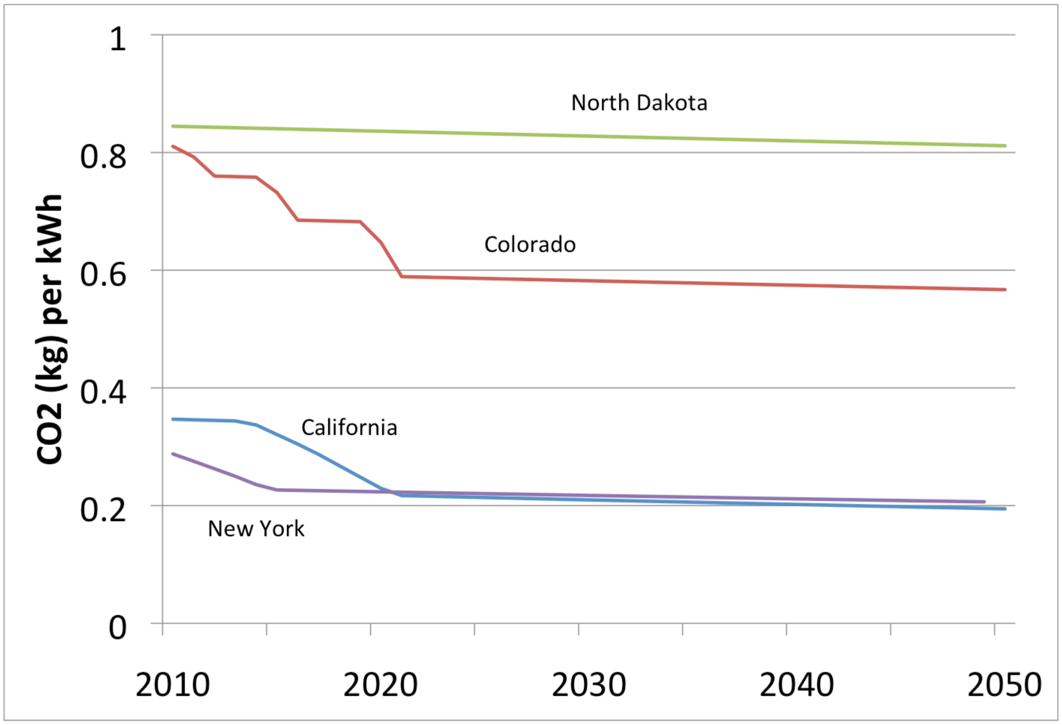

Figure 10. Forecasted CO_2/kWh transitions for four states (California, Colorado, North Dakota, and New York). These examples were selected to illustrate a range of fuel mixes and renewable portfolio standards.

CO_2/kWh values for the specific rail corridor assessments were derived by summing distance-weighted averages of CO_2/kWh for each state crossed in the rail corridor. Corridor segment lengths were computed in ArcGIS using rail network data provided courtesy of the Regional Plan Association. The time evolutions for the three corridors (California, Northeast Corridor, and Chicago-St. Louis-Kansas City) are shown in Figure 11.

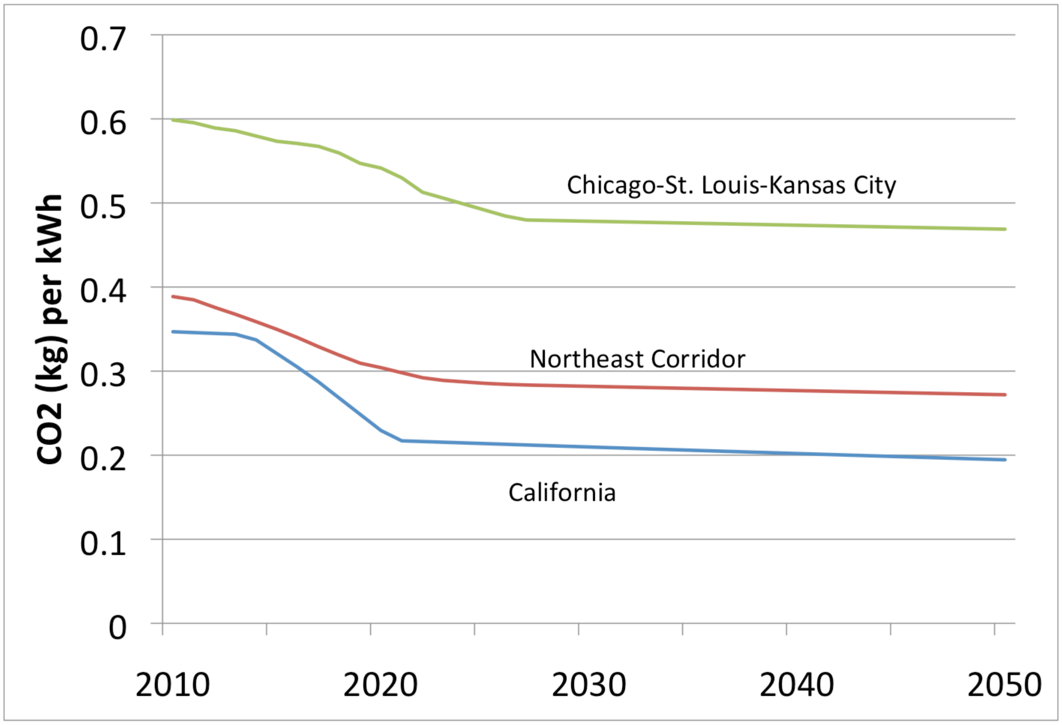

Figure 11. Forecasted CO_2/kWh values for three high-speed rail corridors (California, Northeast Corridor, & Chicago-St. Louis-Kansas City). Most renewable portfolio standards do not extend beyond 2025, thus contributing to the flatness of each curve in later years.

V. FORECASTING ENERGY REQUIREMENTS FOR INTERCITY VEHICLE TECHNOLOGIES

A. Overview

This chapter describes the kWh/VKM component of the model, which represents the overall energy requirements for intercity vehicles. The primary objective of this analysis to understand the evolution of kWh/VKM over time for intercity transportation technologies. First I will explain the approach used to forecast kWh/VKM for train technology. I will then move on to automobiles and planes.

A second objective of this analysis is to understand how close travel modes are to nearing theoretical minimum energy requirements, and thus how much room for improvement each travel mode has as vehicle technology improves. In energy terms, intercity vehicle kilometers traveled (VKM) can be thought of as the energy output, or useful work, that results from the overall energy input (kWh) of electricity or fuel combustion. At a minimum, the energy inputs needed to power a rolling vehicle must be sufficient enough to overcome the forces resisting motion, namely friction (rolling resistance), aerodynamic drag, and inertia. Aircraft, needless to say, are governed by much different energy losses and are treated separately.

B. High-speed Trains

The energy expended to overcome friction and drag is lost and not recoverable. Meanwhile, energy spent overcoming inertia, is not immediately dissipated but is converted to the kinetic energy of the moving vehicle. In modern trains, much of this kinetic energy is lost during braking. Theoretically, all the kinetic energy can be recovered; however, there are practical limitations to this I will explore later.

Resistance to gravitational forces was omitted in the model. For simplicity, I assume that intercity travel typically has an equal number of trips in both directions. Thus any energy spent overcoming gravitational resistance during uphill travel is stored as potential energy and recouped during downhill travel.

Beyond these fundamental forces, additional energy losses also arise from inefficiencies at each stage of energy conversion that makes up a vehicle technology. For example, in an internal combustion engine, not all of the energy from gasoline is transferred to the transmission (and subsequently to the wheels), with a typical conversion efficiency of less than 30% or $\eta<0.3$ (R. U. Ayres, L. W. Ayres, & Warr, 2003).

Each of the energy losses described above is reducible to varying degrees; some losses are near their theoretical limits and others have much room for improvement. While it is impossible to predict exactly how or when such reductions (or increases) in energy loss might occur, I can use the basic equations of motion and conversion efficiencies reported in the literature to gain some understanding of future prospects for vehicle energy requirements.

To model the primary energy output required for high-speed rail vehicles, I first summed the energy losses, expressed in kWh/VKM, as follows:

$$kWh/VKM = (kWh/VKM_{drag} + kWh/VKM_{friction} + kWh/VKM_{inertia})/\eta + kWh/VKM_{aux} \qquad \text{Equation 6}$$

Where η = the conversion efficiency of power that is input from the incoming power line (caternary line) and output to the train's wheels. I will now explore each of these components individually.

1. Power Requirements for Friction (Rolling Resistance)

Equation 7 describes the instantaneous power required to overcome rolling resistance:

$$P_{roll} = C_{rr} * m * g * v \qquad \text{Equation 7}$$

Where P = power output in watts,

C_{rr} = a dimensionless coefficient of rolling resistance,

m = vehicle mass in kg,

$g = 9.8\ kg^{-1}\ m\ s^{2}$, the constant for gravitational acceleration, and

v = vehicle speed in m s^{-1}. Dividing each side of

Equation 7 by v, the energy expenditure over a marginal unit of distance (kWh/VKM) becomes:

$$kWh/VKM = C_{rr} * m * g \qquad \text{Equation 8}$$

The resulting energy requirement is independent of speed and is dependent solely on C_{rr} and m. In physical terms, C_{rr} represents the degree of wheel deformation upon the rolling surface. For high-speed rail, steel wheels upon railroad tracks yield very little deformation with typically reported values near 0.001 to 0.002, an order of magnitude less than many automobiles (MacKay, 2009; Nice, n d). Maglev trains could reduce the friction, but powering an electromagnetic field would add to energy requirements. This technology is also prohibitively expensive over long distances. For the model, I assume that there is relatively little room for improvement in this parameter, and do not change it in my forecasts.

Typical train masses range from 400 to 800 kg per seat (Nolte & Würtenberger, 2003), though in some cases they are well over 1000 kg per seat (Ostlund, 1998). For m, in the reference case, I assume a typical mass of 60 kg per seat, which for a 1,200 passenger high-speed train (as proposed by the California High Speed Rail Authority) is equal to 720,000 kg. Reduction in m is feasible through use of lightweight vehicles and materials and can be tested as a variable component in the model.

In addition to rolling friction, there is also some small resistance due to track curvature, although because rolling resistance is a small energy loss, track curvature was not included for simplicity.

2. Power Requirements for Aerodynamic Drag:

Equation 9, below, describes the instantaneous power required to overcome aerodynamic drag:

$$P_{aero} = \frac{1}{2} \rho * v^3 * A * C_d \qquad \text{Equation 9}$$

Where ρ = 1.22 kg m-3, the constant for air density,
v = vehicle speed in m s-1,
A = the vehicle's frontal area, in m2
Cd = a dimensionless coefficient of drag.

As with rolling resistance, dividing each side by v to find energy consumption per distance yields:

$$kWh/VKM = \frac{1}{2} \rho * v^2 * A * C_d \qquad \text{Equation 10}$$

Here, the energy requirements increase with the square of the vehicle's velocity. Since trains do not travel at constant speed, an accurate modeling of the energy output would require integrating P_{aero}

over time for the train's drive cycle. This requires specific knowledge of v is a function of time as determined by the train's specific drive cycle. Since true drive cycle patterns will vary in each case, a simplified model of P_{aero} was estimated by assuming the train travels at maximum speed (v_{max}) across most of the route distance and applying a correction factor (ξ=0.85) to v_{max} to account for periods that the train traveled below this speed. This correction factor was approximated from a preliminary engineering specification for California high-speed train speed profile illustrated in (Deutche Eisenbahn Consulting, 2000). Sensitivity of ξ, as well as v_{max}, are tested in the model. Furthermore, we anticipate that top train speeds (v_{max}) could increase over time as technology improves. While v_{max} = 300 km/hr for many high-speed train systems, some are already claiming top speed of 350 km/hr (Dingding, 2011).

A typical value for the cross-section surface area, A, for high-speed trains has been reported in the literature as 12 m^2 (Alvarez, 2010). I assume that there is very little opportunity to change this parameter. Meanwhile, literature values of C_d for trains are typically near 1.2 with theoretical future reductions down to 0.9 through streamlining (Sandia National Laboratories, 1995).

As speed increases, the energy required to overcome forces of aerodynamic drag and inertia increases exponentially, while rolling resistance is constant over all speeds and is most significant at low speeds. Typical top train speeds are 300 km/hr, near the right hand edge of the chart in Figure 12.

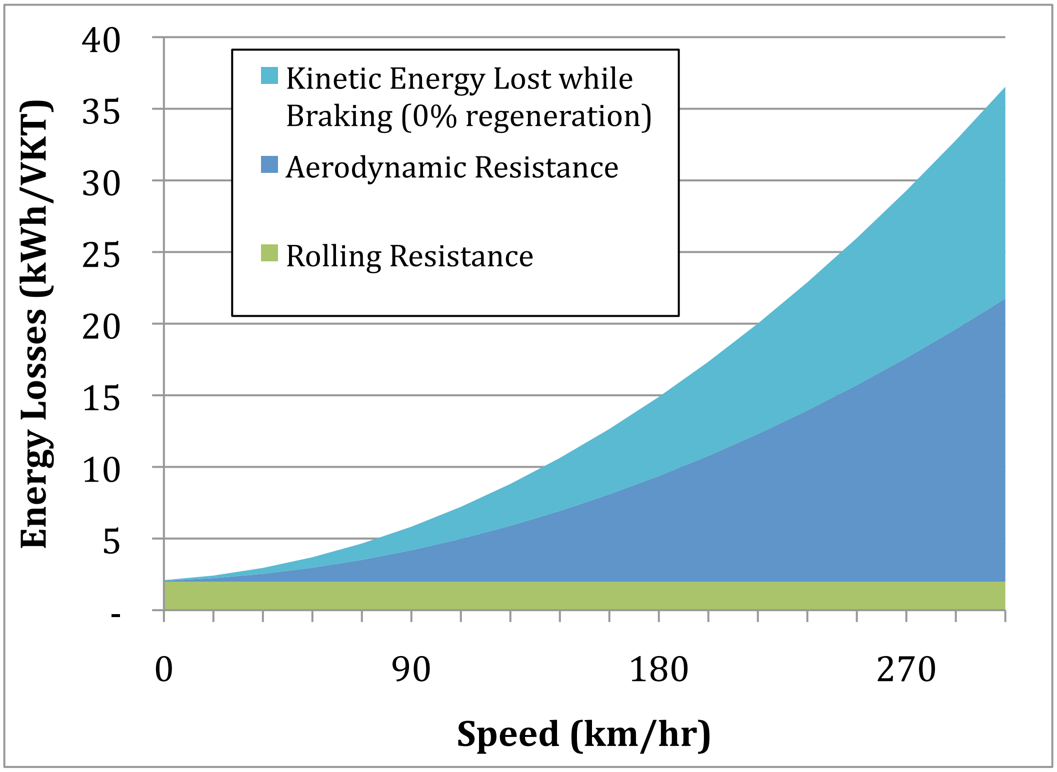

Figure 12. Energy losses as a function of train speed. Parameters used to model these values are shown in Table 2. This chart shows a basic case with no regenerative braking and no correction for speed homogeneity.

3. Power requirements for kinetic energy and braking

Energy used to overcome inertia is converted to kinetic energy, according to the well-known formula:

$$KE = \frac{1}{2} m v^2 \qquad \text{Equation 11}$$

a) Braking Technologies

The kinetic energy shown in Equation 11 is dissipated as the train slows down and is either lost or recovered through regenerative braking. Throughout the twentieth century, most trains used some form of mechanical braking system such as the air brake system originally invented by George Westinghouse, or dynamic braking system where electric power is dissipated as heat in rheostatic resistors. In each case, as the train's brake is applied a force slows the speed and the kinetic energy is lost as heat (Hasegawa & Uchida, 1999). Modern trains that use electric traction motors enable the possibility of recovering kinetic energy through regenerative braking. When operated in reverse, the traction motor can slow the train while returning energy to the original power source (the grid) or a temporary storage medium (on-board or remote) such as a battery or flywheel. Ideally, regenerative braking would work well enough for trains to recover all of their kinetic energy at maximum speed. However certain limitations apply:

- Regenerative braking often cannot absorb kinetic energy fully enough to slow moving trains in a sufficient amount of time. Thus, in most cases a combination of electric braking and air/dynamic braking (known as blended braking) is applied.

Energy losses occur corresponding to the component of mechanical braking force required.

- Inefficiencies occur in conversion of regenerated braking energy. Just as each stage of energy conversion to the wheels yield inefficiencies, so does energy conversion back to the grid or storage device. Conversion efficiency in both directions is roughly equivalent (Nolte & Würtenberger, 2003)
- Energy cannot always be returned to the power source (the grid). In some cases the catenary is not receptive to power either because of existing power flows, or inadequate transformer technology (Gunselmann, 2005).
- Current technologies for energy storage are not fully developed and may lack the capacity to absorb large amounts of kinetic energy quickly (Hillmansen & Roberts, 2007).

Although they are not widely adopted, literature estimates suggest that railway regenerative braking technologies have achieved 35% regeneration rates in recent years (Ishida & Iwakura, 1998). Development of hybrid electric trains with storage capacity, using current technologies, has been estimated to be capable of 40% regeneration rate (Hillmansen & Roberts, 2007). Modeling studies have shown that regeneration in excess of 60% might be achievable with flywheel storage but the necessary storage capacity exceeds the capability of current technologies (Miller & Peters, 2006). I estimate that regeneration rates for a typical high-speed train would reach 50% by 2050, and sensitivity tests are conducted.

b) Train Operation

While Equation 11 describes the kinetic energy of a train moving at a particular speed, determining the marginal energy loss over a certain distance (kWh/VKM) also requires information about the train's operation. Specifically, one needs to understand how much and how frequently the train accelerates. Frequency of acceleration is assumed to be proportional to the number of stops along a route. Meanwhile, to calculate the magnitude of acceleration, each trip segment was approximated by assuming a train starts at a station (at rest), accelerates smoothly to v_{max}, and then decelerates smoothly to rest at the next station. This assumes that after acceleration, speed is constant, with minimal fluctuations before approaching the station. A truly accurate representation would require knowledge of the speed profile to account for minor speed variations en route. These fluctuations give rise to additional energy losses and thus using v_{max} likely underestimates the amount of kinetic energy losses dissipated. However, for the purpose of this model, I assume these deviations are small and choose to ignore them.

From Equation 12, I can derive the marginal energy loss per unit of distance, incorporating factors for operating characteristics and braking technology:

$$kWh/VKM = \frac{1}{2}\, m\, v_{max}{}^{2} * (N/L) * (1\text{-}\beta) \qquad \text{Equation 12}$$

Where v_{max} = train's top speed

L = route length,

N = number of stops, and

β = brake recovery efficiency.

(N/L) can also be substituted for (D^{-1}), where D is the average distance between train stops. D is estimated for three U.S. corridors based on planning documents that suggest possible routes and stations (Table 2). As a basis of comparison, one proposed Dutch high-speed rail system had D=47 (Vanwee, Vandenbrink, & Nijland, 2003).

Table 2. Average stop distance based on proposed routes and stops in three modeled high-speed rail corridors (Amtrak, 2010; California High-Speed Rail Authority, 2009a; Midwest High Speed Rail Association, 2011).

Corridor	Longest Route Segment	Estimated Number of Stops	Average Stop Distance (D)
California	919 km (San Diego to San Francisco)	~19	52 km
Northeast Corridor	732 km	~18	41 km
Chicago-St. Louis-Kansas	901 km	~9	100 km

City			

4. Energy delivery & power train efficiencies

Delivering power to the wheels of a high-speed train requires that power travel through several steps summarized in Figure 13.

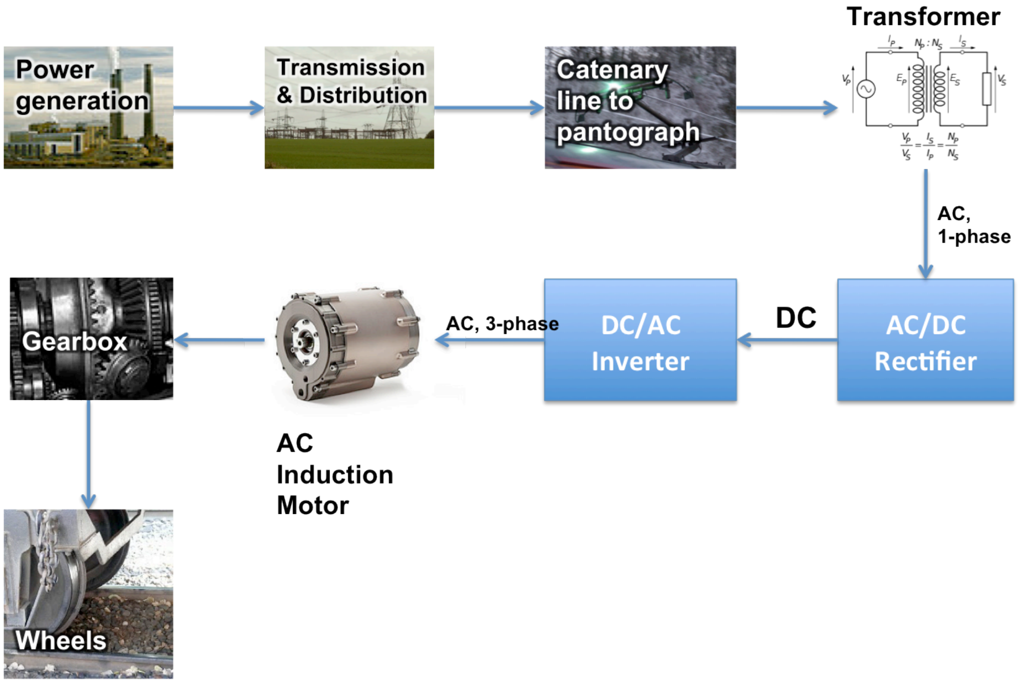

Figure 13. Illustration of a typical sequence of power conversion in modern electric train technology.

For most of these steps, power delivery is not perfectly efficient, and some energy losses occur. However, many of the technologies involved in electric trains are very mature and efficiencies are approaching their thermodynamic limits. For example, typical induction motors have efficiencies exceeding 90%. Conversion efficiencies and potential improvements for each component are described in detail in several recent studies (Gunselmann, 2005;

Meibom, 2001; Nolte & Würtenberger, 2003) and at www.railway-energy.org. As noted by Nolte and Wurtenberger (2003), the total conversion efficiency in electric trains from catenary (overhead line) to wheels is approximately 85%. Based on knowledge from these sources, my model approximates the efficiency could increase to 90% by 2050.

In addition to these conversion steps, some energy is also diverted before it reaches the wheels to support auxiliary energy uses such as lighting and cabin HVAC systems. Energy requirements for these uses are estimated by Rozycki, Koeser, & Schwarz (2003) and reported to be approximately 1.35 kWh/VKM.

5. Prospects for reducing high-speed rail energy consumption

To grapple with the complexity of many possible futures in train technology development, two possible technology cases were constructed to bound future energy requirements. The first case, "2011 Reference," reflects the starting point and includes parameters for existing train technology as reported in recent literature, as if it were operating today. The second case "2050 Optimal," is a forecasted scenario that anticipates development towards "optimal" technology parameters in each category through year 2050. For example, streamlining to reduce drag has potential to reduce C_d, but the extent of these reductions are likely to face practical limits as described in (Sandia National Laboratories, 1995) and may soon approach an "optimal" asymptotic value near $C_d \approx 0.9$. Thus changes in several parameter values over time are estimated with a generalized formula for exponential decay towards the optimal value:

$$\theta(t) = \theta_{optimal} - (\theta_{optimal} - \theta_{Initial}) * e^{-rt} \qquad \text{Equation 13}$$

Where $\theta(t)$ is the parameter at time t,

$\theta_{optimal}$ is the "optimal" parameter value,

$\theta_{Initial}$ is the initial parameter value, and

r is an estimated rate of improvement (I use r=0.1 in each case).

Key parameters for each technology case are summarized in Table 3. The resulting changes in marginal energy loss, according to the model, are illustrated graphically in Figure 14.

Table 3. Technology parameters for current and future technology cases

Description	**Parameter**	**2011 Reference Value (Current)**	**2050 Optimal Value (Forecast)**
Coefficient of Rolling Resistance	C_{rr}	0.001	No change
Mass (kg)	m	720,000	600,000
Frontal Area (m^2)	A	12	No change
Coefficient of Drag	C_d	1.2	0.9
Maximum speed (km/hr)	v_{max}	300	330
Speed homogeneity	ξ	0.85	No change
Distance Between Stops (km)	D	30	No change
Brake regeneration rate	ß	0	0.50
Power Conversion Efficiency	η	0.85	0.90

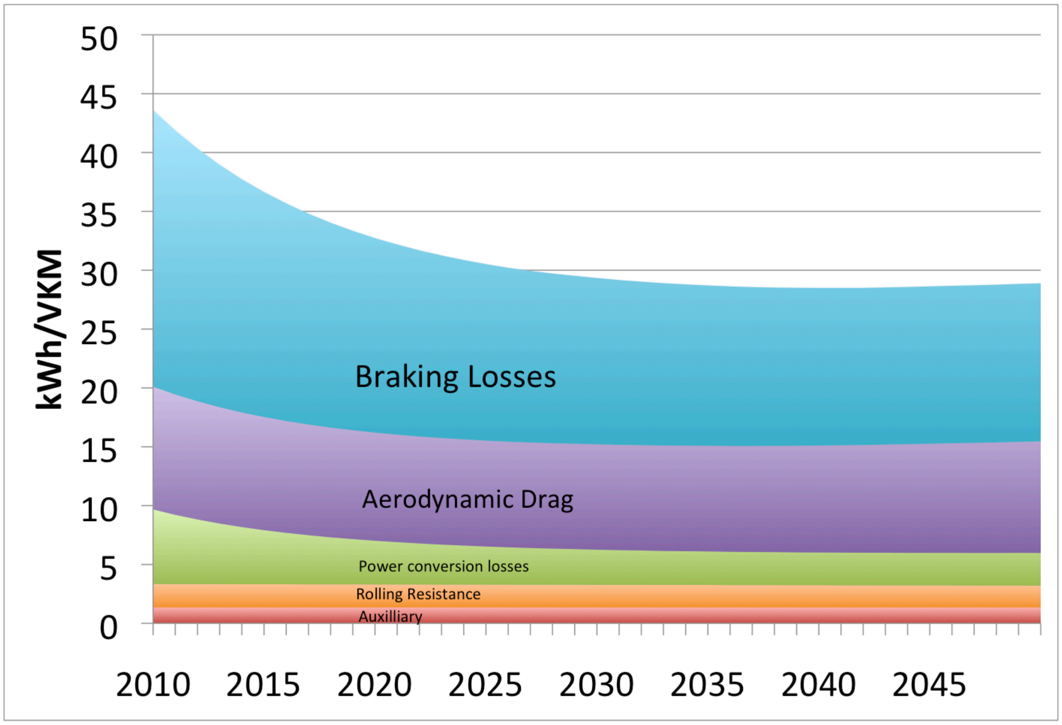

Figure 14. A modeled projection of future energy losses for high-speed train technology reflecting the transition from 2011 Reference technology case to the 2050 Optimal technology case.

C. Personal Automobiles

1. Power Requirements

Energy requirements for personal automobiles can be computed using a methodology similar to that described in section A to find the corresponding minimum requirements for rolling resistance, aerodynamic drag, and braking losses. Physical parameters are specified in Table 4 by drawing upon literature sources. Auxiliary losses were estimated to be 0.3 kW in accordance with estimates from (van Vliet, Kruithof, Turkenburg, & Faaij, 2010).

The operational characteristics for automobiles differ from the trains. Most obviously, typical speeds are much slower. Additionally, there is much greater potential for speed variability, which complicates the estimation of energy losses due to kinetic energy and braking. I estimated a typical intercity vehicle trip by modifying the standardized EPA STFP US06 drive cycle, which is normally used to describe aggressive highway driving (U.S. Environmental Protection Agency, n d). A segment of the drive cycle at highway speeds was repeated until it reflected a full cycle distance of nearly 100 km. From this drive cycle I approximate v_{max} as the median speed, approximately 105 km/hr (~65 mi/hr), which is used to estimate the energy losses for aerodynamic drag. Upon calculation of the drag losses for each timestep in the drive cycle, I find the median speed to be a very close approximation of the true automobile energy losses. Thus, this method was used in place of the correction factor used for trains. The distance between stops is also not limited to a fixed schedule and may include stops for rest and refueling. I estimate the average stopping distance to be about 100 km in correspondence to the selected drive cycle.

Table 4. Physical parameters for passenger automobile characteristics. Most values were derived from those reported in (van Vliet et al., 2010)**. *m* and *A* were adjusted upwards to reflect the larger automobile sizes among American vehicle fleets.**

Description	Parameter	ICE	EV (based on EV1)
Coefficient of Rolling Resistance	C_{rr}	0.01	0.008
Mass (kg)	m	1500	1347
Frontal Area (m^2)	A	2.5	1.89
Coefficient of Drag	C_d	0.32	0.2
Median speed (km/hr)	v_{max}	105	105
Distance Between Stops (km)	D	100	100

Because of the speed fluctuations inherent in highway driving, the drive cycle intervals that represent acceleration (net increase in kinetic energy) account for a much greater energy requirement than they otherwise would under a gradual acceleration to maximum speed as illustrated in Figure 15.

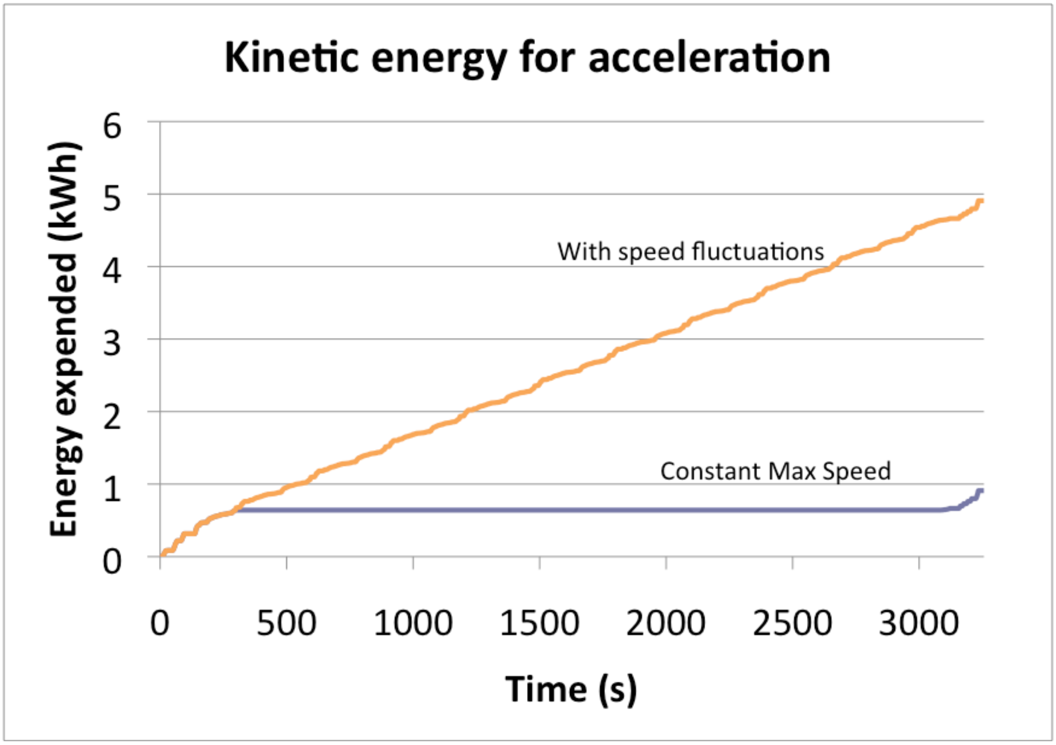

Figure 15. Kinetic energy for acceleration of a 1500 kg automobile traveling according to the modified drive cycle. This assumes that zero energy is recovered through regenerative braking.

Thus, over long distances the kinetic energy term is more dependent on speed fluctuations than it is on maximum speed. Based on this customized drive-cycle analysis, I approximate the kinetic energy requirement of a 1500 kg and 1347 kg automobile to be 0.053 and 0.48 kWh/km respectively.[4] The cumulative energy losses from rolling resistance, kinetic energy, and aerodynamic drag are illustrated in Figure 16 as a function of average speed.

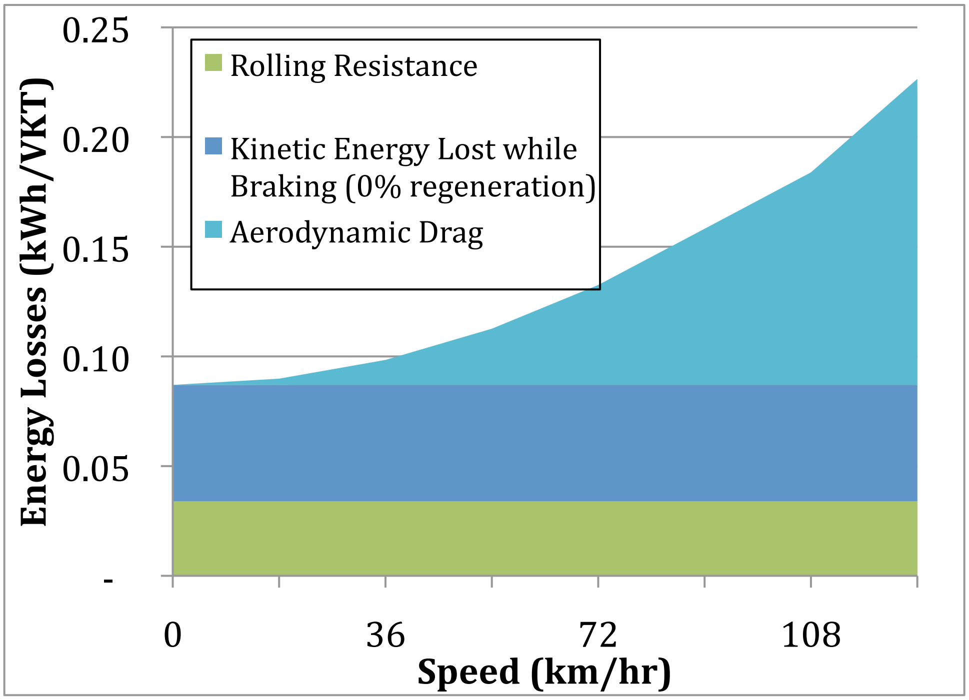

Figure 16. Physical energy losses for a 1500 kg automobile traveling according to the modified drive cycle.

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[4] This assumes there is no energy recovered through regenerative braking.

As a comparative example, consider a 1200 person train at half capacity (600 passengers) traveling at 300 km/hr. Using parameters for the 2011 Reference case, aerodynamic drag requires approximately 0.015 kWh/km per seat or 0.030 per passenger. In contrast, a single-occupancy automobile traveling at 105 km/hr requires about 0.10 kWh/km per person to overcome drag. Similarly, kinetic energy for a train accounts for approximately 0.04 kWh/km per passenger compared to 0.05 kWh/km for an automobile. In each case, trains perform better than automobiles on a per person basis, but are still within an order of magnitude. It is not outside the realm of possibility that minor changes to speed, passenger load, and drag, in either technology could lead to the basic energy requirements becoming nearly equivalent.

2. Vehicle technologies and power conversion

While the physical characteristics that dictate the power requirements may not be appreciably different between automobile technologies, there are several distinct differences that arise from power conversion technologies to consider. Conventional gasoline internal combustion engines (ICEs) have been observed to achieve approximately 31% efficiencies at highway speeds (R. U. Ayres et al., 2003). This does not include energy losses from idling or transmission. Many technologies exist that could reduce energy losses at each stage of this chain such as direct fuel injection, turbo-charging, integrated starter generators, continuously variable transmissions, etc. Efficiencies for ICEs are significantly lower than the efficiencies associated with the motors used to power battery electric vehicles (BEVs) or hybrid-electric vehicles (HEVs), which are typically near 90% efficiency (van Vliet et al., 2010). Both combustion engines and electric motors also have energy losses associated with their transmissions (η=0.80 to 0.94), which increase overall conversion losses beyond the engine or motor. Additionally, battery electric vehicles also have inefficiencies associated with charging and discharging the battery. However, batteries provide energy storage, which offers the potential for regenerative braking.

3. Electric Vehicle Range Limitations and Market Penetration

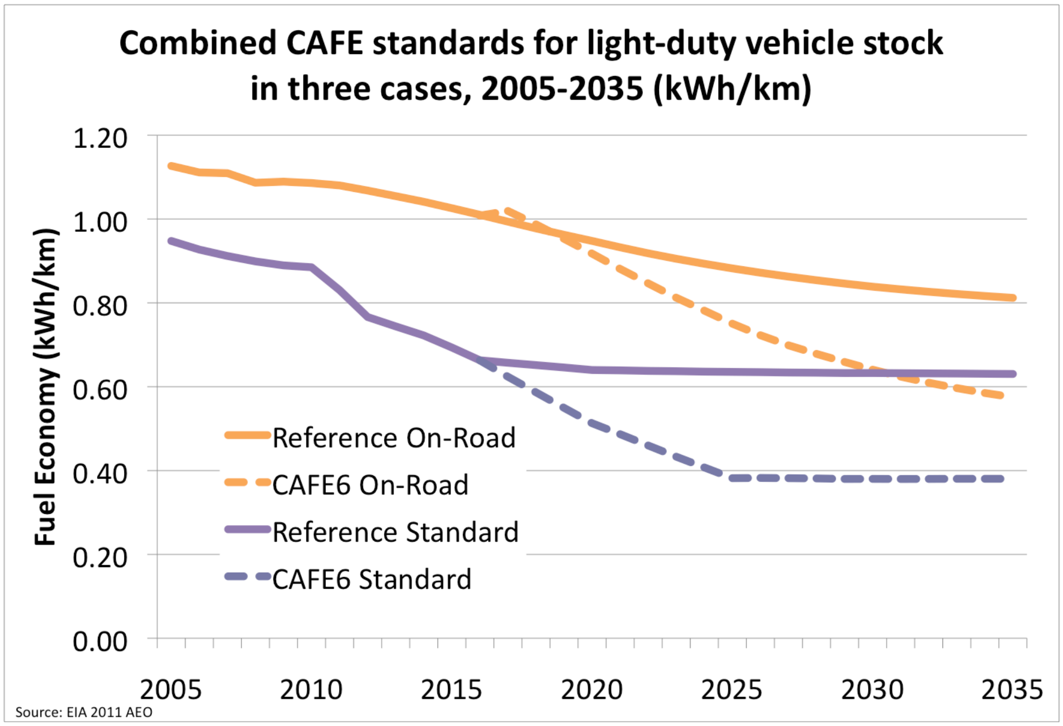
It's important to note that electrically driven vehicles currently have limited battery storage capacities that restrict their use for the long-distance trips associated with intercity travel. This could be overcome with the advent of technologies such as battery switching stations, larger battery storage capacities, or faster charging. For example, companies such as Project Better Place are currently building infrastructure for battery switching stations (Better Place, 2011). The company Tesla plans to release a new electric car model with a range up to 300 miles (Tesla Motors, 2011). Furthermore, current PHEVs such as the Chevy Volt allow for extended range via a combustion engine. Thus a portion of the trip would be powered using a battery-powered electric motor, but this portion is range-limited to about 40 miles.

Because of these range limitations, I assume that electric drives can only account for a fraction of the inter-city trip distance traveled by personal automobiles, even in a scenario with high PHEV/EV market penetration. This is accounted for in $\Delta CO_2/PKM$ by splitting α for automobiles into a fraction for electric drive and a fraction for combustion engine drive.

Furthermore, I explore kWh/VKM under two possible technology scenarios for electrically driven automobiles. In one scenario, electricity powers the car for an entire 300 km trip and in the other battery electricity powers the car for ~40 miles (60 km) and the remaining duration utilizes a gasoline powered hybrid engine. This 40 miles duration is similar to current technology used in the Chevy Volt PHEV. Parameters for each portion reflect those used for electric drive and hybrid technology used in isolation.

4. Impact of fuel economy standards on future energy requirements

In the U.S., Corporate Average Fuel Economy (CAFE) standards play a significant role in the energy consumption of the automobile vehicle fleet. These standards dictate the average fuel economy of new vehicles sold in a given year. Because the standard only applies to new vehicles, there is a discrepancy between the current standards and the actual on-road fleet fuel economy due to the time it takes for a vehicle fleet to turn over and thus for market penetration of new vehicle technologies to occur. Figure 17 illustrates this dynamic for two scenarios modeled by the Energy Information Administration (EIA).



Source: EIA 2011 AEO

Figure 17. Vehicle fleet fuel economy projections from the EIA 2011 Annual Energy Outlook (US Energy Information Administration, 2011). **Solid lines represent the AEO Reference Scenario that includes only CAFE standards that exist today, while dashed lines represent the CAFE6 scenario in which fuel economy standards (in miles per gallon) increase 6% annually through 2025. The blue line represents the fuel economy for new vehicles according to the standard while**

the orange line represents on-road performance of the vehicle fleet.

5. Comparing vehicle technologies

To illustrate the energy losses for different automobile technologies, I calculate energy losses for four hypothetical vehicle types. Regenerative braking and power-train efficiencies used are shown in Table 6 and were approximated from values in the literature (R. U. Ayres et al., 2003; Åhman, 2001). Physical parameters in Table 4 were used, which are based on (van Vliet et al., 2010). HEV and PHEV were assumed to have values similar to ICE.

Table 5. ICE efficiency for vehicles traveling on highways is from (R. U. Ayres et al., 2003) **and includes losses from engine, idling, transmission, & accessories. Power train efficiency for PHEV(60+240) represents a combination of EV for 60 km of a trip and HEV for the remaining duration assuming a 300 km intercity trip.**

Description	Para-meter	ICE	HEV	PHEV (60 +240 km)	EV (300 km)
Regenerative braking recovery rate	ß	0	0.30	0.30	0.30
Power-train Efficiency	η	0.20	0.30	*	0.72

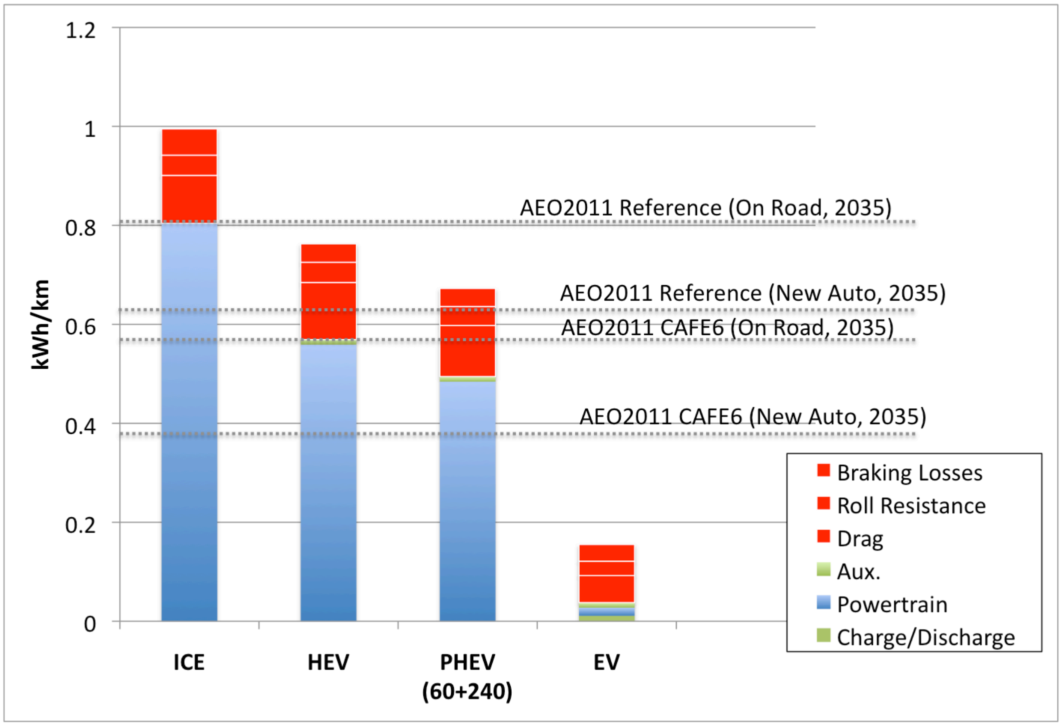


Figure 18. Comparison of estimated energy requirements for current vehicle technologies and forecasts of energy requirements that match technology standards for new vehicles. ICE represents the current fleet of predominantly internal combustion engines, HEV is a hybrid engine technology, PHEV (60+240) is a plug-in hybrid engine that drives 60 km on a battery charge and the remaining part of the trip using a hybrid, and EV represents a battery electric vehicle. "Incompressible" energy requirements for braking, rolling resistance, and drag are noted in red.

As Figure 18 illustrates, there is a wide range in the energy requirements for vehicle technologies that exist today. The current fleet of on-road vehicle technologies used will not meet fuel economy standards to be implemented in the coming years, but there are existing technologies that will be able to meet those standards. Implementation of more efficient vehicle technology appears to be driven in large part by the standards, not necessarily the best available technology. Additionally, automobile technology does not appear to be nearing fundamental physical constraints in terms of energy efficiency. Given these observations, I did not try to estimate precisely which technology changes might occur since there are many to choose from. Instead, to estimate $CO2/PKM_{auto}$ over time I relied on a forecast developed by EIA for vehicle fuel economy according to their 2011 Annual Energy Outlook CAFE 6% scenario. These values are illustrated in Figure 17 above.

D. Airplanes

Airplane fuel usage per available seat kilometer (ASK) has historically declined over time (Figure 19). This decline is related to increases in capacity, improvements in airplane technology, and more efficient operations.

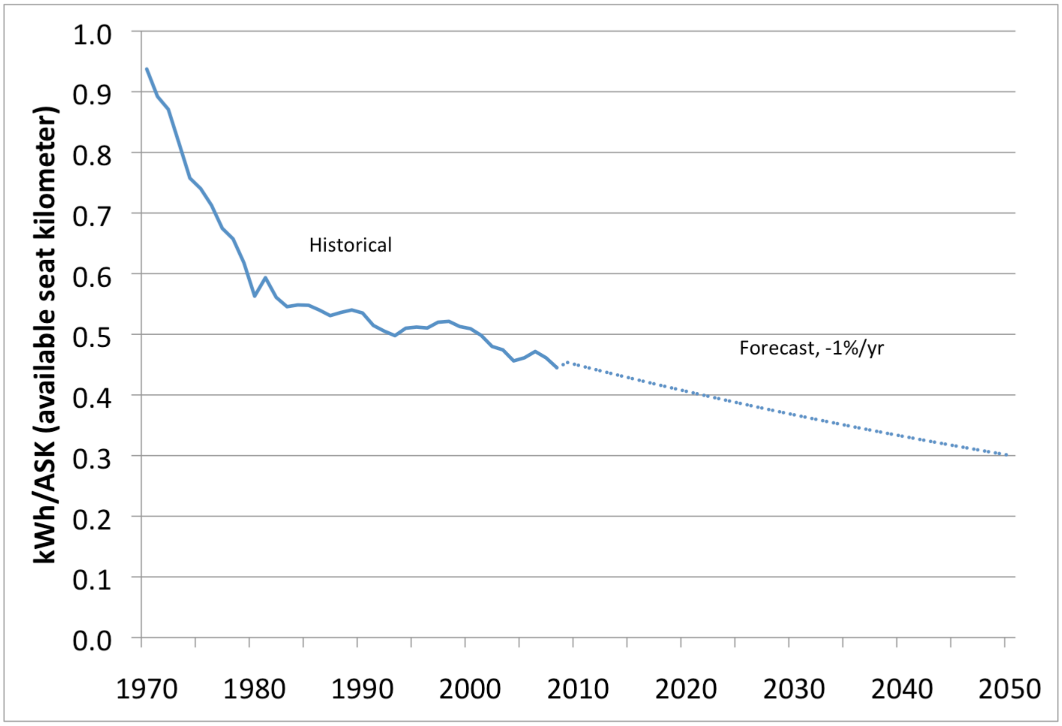


Figure 19. Historical and forecasted energy efficiency of U.S. domestic passenger aircraft. Historical data were taken from (U.S. Department of Energy, 2010)**. Forecast was based on findings of** (Lee, Lukachko, Waitz, & A. Schafer, 2001)**, which suggest a reduction in energy usage per available seat kilometer by ~1% annually. I don't anticipate any changes in passenger load factors or aircraft capacity.**

Existing technological forecasting studies of energy consumption in airplanes informed the analysis undertaken to develop the estimates shown in Figure 19. I adopted the approach described by (Lee et al., 2001), whereby the energy usage (in MJ) per available seat kilometer (ASK) is derived from the Breguet range equation. This equation is commonly used to estimate the distance, *R*, an aircraft can travel at constant speed, and level flight, and can be modified to calculate energy consumption:

$$E_{\mathrm{U}} = \frac{Q \cdot W_{\mathrm{f}}}{\mathrm{Seats}} \cdot \frac{g \cdot \mathrm{SFC}}{V(L/D)} \cdot \frac{1}{\ln\left(1 + \frac{W_{\mathrm{f}}}{W_{\mathrm{p}} + W_{\mathrm{s}} + W_{\mathrm{r}}}\right) \cdot \eta_{\mathrm{ft}}},$$

Where Eu = Energy usage in MJ per available seat kilometer (ASK),

Q = lower heating value of jet fuel,

SFC = specific fuel consumption,

L/D = lift-to-drag ratio,

W_f = Weight of fuel,

W_p = Weight of payload,

W_s = Weight of structure,

W_r = Weight of reserve,

V = Speed,

η_{ft} = flight time efficiency.

The equation identifies technological parameters, such as SFC and L/D that are subject to incremental improvements over time. Other factors, such as number of seats and flight time efficiency relate to operational characteristics. Combined, the technological improvements were estimated to yield a 1-2% annual change in E_U through 2025 (Lee et al., 2001). For forecasting to 2050, I assume the lower bound of this range (1% annual decrease in E_{U}). kWh/PKM can then be determined as follows:

$$kWh/PKM = kWh/ASK * ASK/PKM$$

Where $(ASK/PKM)^{-1}$ is the load factor. Load factors for passenger aircraft are described in detail in Chapter VI.

VI. FORECASTING UTILIZATION

In this chapter I describe the VKM/PKM component of the model, which represents the marginal unit of vehicle travel required for each unit of passenger travel. I also explore ridership forecasts for high-speed rail and the fractional sources of that ridership (α) that help determine ΔCO_2/PKM

A. Vehicle Passenger Loads

Conceptually, it's easier to understand the expression VKM/PKM as its inverse PKM/VKM, which is the number of passengers in a vehicle. PKM/VKM in turn is dependent on the capacity of the vehicle as designed (i.e. number of seats) and the number of seats filled:

$$PKM/VKM = CAP * \lambda \qquad \text{Equation 14}$$

Where CAP = available seat capacity per vehicle and

λ = a load factor (fraction of seats filled).

Increasing both of these variables will help maximize ΔCO_2/PKM, though each has unique considerations. An increase in the capacity of public transport modes can be accomplished through better space utilization or increasing the vehicle size. In energy terms, increases in vehicle size must be weighed against increases in mass. Changes in the load factor, λ, are affected by economic and behavioral conditions that give rise to higher or lower travel demand. For a publicly owned or operated transportation system (characteristic of many high-speed rail systems), considerations other than cost effectiveness could influence the overall number of trips scheduled. For example, operating additional trips on a route could boost total ridership by providing more travel options but it might do so at the expense of decreasing the load factor for each individual trip. At the same time, some intercity travel demand studies note a "threshold" effect where a sufficient number of trips are necessary to support robust ridership (Washington State Department of Transportation, 2006). In any case, the location of public transport systems is crucial to ensure sufficient travel demand as trips within a given corridor increase. This is explored thoroughly for high-speed rail by Todorovich and Hagler (2011).

1. High-speed rail

Capacity

A recent review of high-speed rail characteristics show typical seating capacities in European trains ranging from 329 seats to 627 (Campos & de Rus, 2009). In Japan, high-speed trains typically have higher capacities, with 800-1200 seats. The world's highest capacity train has been cited as the E4 Shinkansen with approximately 1600 passengers. In the U.S., the California high-speed rail system is anticipated to have a train capacity of 1175 (California High-Speed Rail Authority, 2008). For the 2011 Reference case, I approximate train capacities to be similar to the California projection and use a standard capacity of 1200 seats per train, consistent with the assumptions used by Chester and Horvath (2010).

Load Factor

On European high-speed rail systems load factors typically range between 0.4-0.5 (Vanwee et al., 2003). In Germany, observed load factors are close to this range, with Deutsche Bahn recently achieving load factors of 0.51 and 0.55 on two of its ICE lines (Deutsche Bahn, 2010). In Japan, load factors are typically higher, with a recent study citing Shinkansen load factors ranging from 0.61 to 0.79 (Nakagawaa & Hatoko, 2007).

In the U.S., Amtrak passenger service shows patterns similar to Europe, with load factors ranging from 0.40 to 0.60 that vary seasonally (U.S. Department Of Transportation Bureau of Transportation Statistics, 2011). For modeling purposes I use a load factor of 0.50 in the 2011 Reference scenario and test its sensitivity from 0.20 to 0.81. The upper bound approximates the load factor typically found on U.S. airlines and is intended to estimate the "natural" load factor found on intercity travel corridors serviced by competitive private firms.

2. Automobiles

Automobile trip passenger loads (PKM/VKM) were estimated form survey data from the National Household Travel Survey shown in Table 6 (U.S. Department Of Transportation, 2009b).

Table 6. Average Vehicle Occupancy (passengers per vehicle) based on 2009 National Household Travel Survey data.

Trip Purpose	2001	2009
To/From Work	1.14	1.13
Shopping	1.79	1.78
Family/Personal Errands	1.83	1.84
Social & Recreational	2.03	2.20
All Purposes	*1.63*	*1.67*

My model assumes an automobile occupancy of 1.67 reflecting the 2009 datum for "All Purposes" (Table 6). Presumably the majority of intercity trips diverted to high-speed rail would be business trips. This could lead to a greater share of diverted trips from single occupancy vehicles, as opposed to trips for leisure or personal use. A lower passenger load would tend to increase CO_2/PKM_{auto} and $\Delta CO_2/PKM$.

3. Airplanes

After deregulation in the late 1970s, the average number of seats in U.S. passenger aircraft has generally declined, possibly reflecting more regional travel as airlines gravitated towards a "hub-and-spoke" business model which takes advantage of hub consolidation to allow more frequent flights with shorter distances. I use a seat capacity of 115 in my model, which is held constant reflecting a recent stabilization since 2002. The hub-and-spoke pattern has also allowed for more efficient use of aircraft, and thus increased load factor. For example, airplanes typically had a load factor between 50-60% in the 1960s and 1970s (Figure 20). Today the load factor for aircraft is close to 80% and is projected to stay near that for the next few decades (Transportation Research Board, 2011). If deregulation is truly a driver of load factors for intercity travel, and this applies to train travel, then one can also examine the carbon penalty of a regulated intercity travel market. In particular – I use my sensitivity analysis of load factors to explore the carbon penalty associate with a decrease in load factor from 80% (competition) to 50% (no competition).

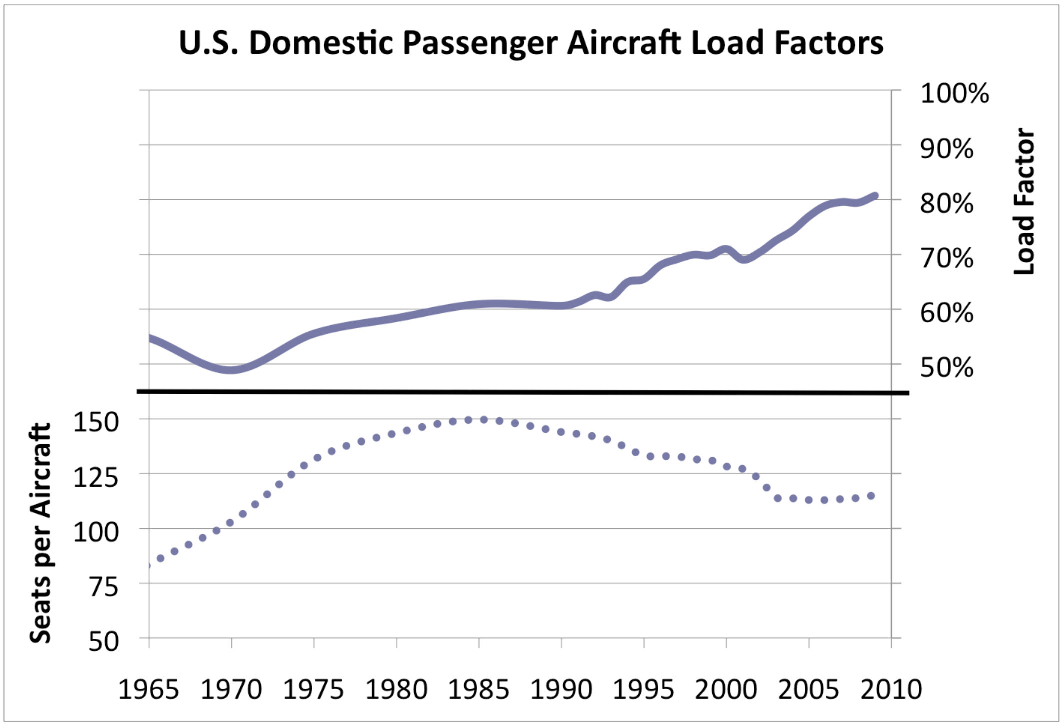


Figure 20. Load factors and available seats for domestic passenger aircraft over time. Data were taken from Bureau of Transportation Statistics, National Transportation Statistics, Table 4-21, 2011.

B. High-Speed Rail Ridership

As discussed in Chapter III, ridership is a necessary parameter for assessing the payback period for achieving net reduction in greenhouse gas emissions (compared to business as usual). Ridership, trip distance, and ΔCO_2/PKM together govern the speed of reduction over time.

As described in Chapter III, there is reasonable uncertainty in ridership forecasts for high-speed rail corridors in the U.S. A thorough review or critique of these forecasts is outside the scope of this study. However, in order to apply my model to specific project proposals I incorporate data from a small number of these forecasts as a starting point for analysis. These data are shown in Figure 21. I then explore the sensitivity of emissions benefits in relation to possible changes in these ridership outcomes. In general, I place a greater degree of confidence in the California projections since they have been subject to more formal modeling and peer review.

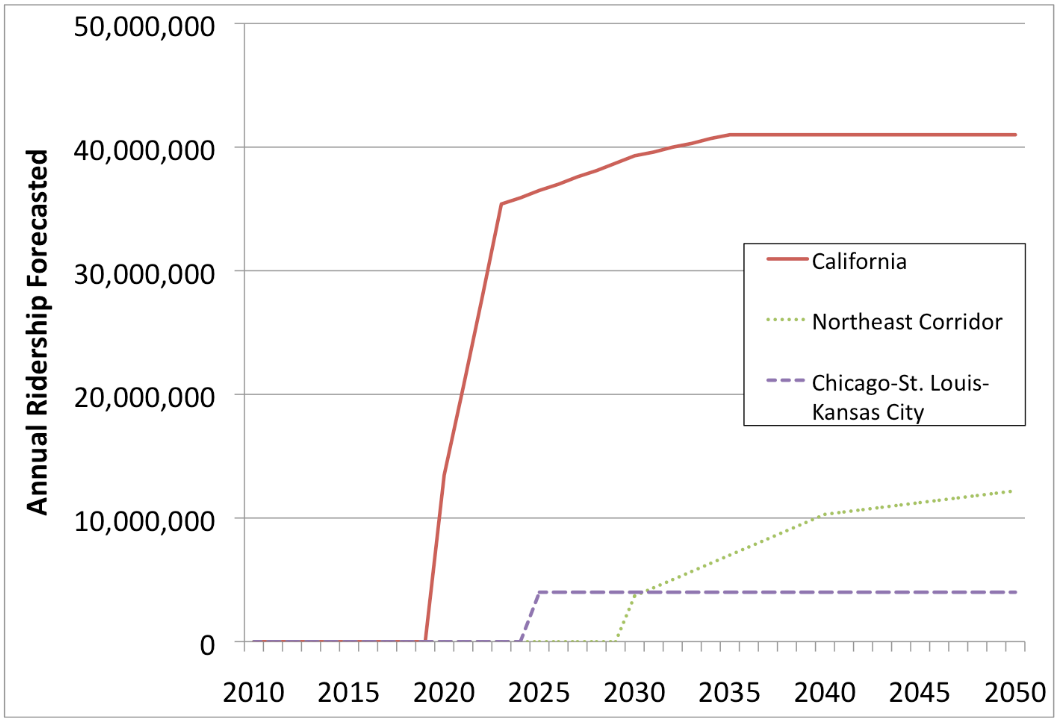


Figure 21. Ridership projections used to model payback times for carbon embedded in high-speed rail infrastructure. These projections include rigorous modeling studies (CA),

basic market estimates (CHI), and figures from a coordinated corridor growth strategy (NEC).

California

California ridership forecasts have been modeled for a range of possible scenarios that vary the prices of competing modes and preferences among customers. Figure 21 shows ridership projections developed by CAHSR Authority and reported to the CA state legislature in the business plan as a likely expected outcome (California High-Speed Rail Authority, 2009a). This scenario assumes rail ticket prices are held at 83% of airfares between cities in the corridor. Annual ridership was held constant at 41 million for the years after 2035.

Northeast Corridor

According to a recent document published by Amtrak, high-speed rail would increase rail ridership on the Northeast corridor to 33.7 million annually over the 23.4 million expected under business as usual (Amtrak, 2010). The methodology and uncertainty associated with these estimates was not published. Amtrak projected ridership statistics for three future years after high-speed rail: 2030, 2040, and 2050. I interpolated the intermediate years assuming a linear growth rate.

Chicago-St. Louis-Kansas City

A preliminary estimate of possible ridership on the Chicago to St. Louis corridor commissioned by the Midwest High Speed Rail Association was used to estimate ridership on this route (TranSystems, 2010). This report was not a detailed ridership model, but rather a preliminary estimate of market potential. Thus a single value for overall ridership potential from this study was used for all dates after the proposed completion of the system. Since the study did not include the St. Louis-Kansas City portion, I assumed an increased ridership from including this additional leg of the corridor. This increase was estimated to be 60% above the study estimate, reflecting the relative ridership potential indicated by the scoring system in (Todorovich & Hagler, 2011).

C. Sources of High-Speed Rail Ridership

To generate these ridership forecasts, travel demand studies often employ a methodology that estimates a particular diversion for each mode. New travel demand is generated from travel diverted from existing modes or else it is induced. The aforementioned California and Northeast Corridor studies each indicate the sources of new travel. For Chicago to Kansas City I use preliminary estimates from the 1997 High Speed Ground Transportation Study. The diversion rates are summarized in Table 7. These diversion rates were assigned to corresponding values of α, as outlined in Chapter III.

Table 7. Trip diversion rates from various modes to high-speed rail as reported by Cambridge Systematics, Amtrak, and U.S. DOT.

Mode Source of HSR Ridership	Fraction of HSR Passengers		
Corridor	California	Northeast Corridor	Chicago-St. Louis-Kansas City
Auto	76%	47%	30%
Air	15%	23%	43%
Induced	2%	30%	8%
Conventional Rail	7%	--	18%
Bus	0%	0%	1%
Total	100%	100%	100
Data Source	(Cambridge Systematics Inc., 2007)	(Amtrak, 2010)	(Peña et al., 1997)

VII. RESULTS & ANALYSIS

A. Evolution of ΔCO_2/PKM with technological progress

Recall that a central objective of this analysis is to understand how technological progress affects the CO_2 advantage of high-speed rail over time. Figure 22 illustrates how CO_2/PKM for several intercity transportation modes will evolve if improvements occur according to the technological progress scenarios outlined in Chapters IV through

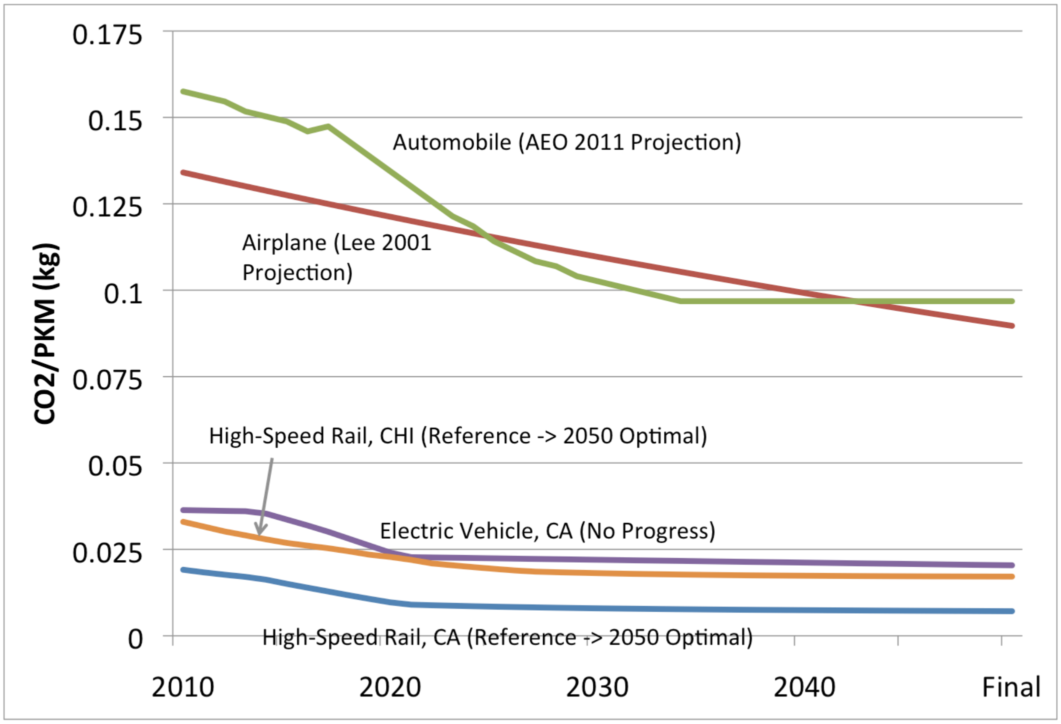


Figure 22. Forecast of CO_2/PKM for intercity travel technologies. Automobile and airplane data are derived from forecast. Electric vehicle data shown does not include any technological progress and uses parameters in Tables 4 & 6. The high-speed rail data portray technological progress towards a 2050 Optimal case as outlined in previous chapters.

VI. This time series represents the operational impact only and does not incorporate life-cycle construction impacts. To reiterate, the electricity grid progresses according to state renewable portfolio standards, high-speed rail technology progresses from the 2011 Reference case to the 2050 Optimal case, automobile technology progresses according to the EIA AEO 2011 projections, airplane technology progresses according to the Lee 2001 projections, and electric vehicles experience no progress and are included for reference. In this figure, the relative distance between each line represents the value of ΔCO2/PKM for a passenger switching between two modes.

Under the specified assumptions, a marginal unit of travel (PKM) using high-speed rail holds a clear advantage over conventional travel technologies (automobiles and airplanes) well into the future. However, this advantage diminishes over time (ΔCO_2/PKM declines) because the non-rail modes are expected to improve considerably faster than high-speed rail itself. Indeed, this is evident in the fact that most of the energy losses for train travel described in Chapter V are from generally irreducible physical parameters like aerodynamic drag. By contrast, for conventional automobiles, most of the energy losses result from inefficiencies in the power train and are subject to substantial improvement.

The ultimate case for improvement in automobile performance would be battery electric vehicles. As these results illustrate, high-speed rail emissions are comparable on a PKM basis to battery electric vehicles even if there is no progress in BEVs beyond current technologies. While long-distance travel is not possible with current BEV technologies, improvements to battery life and battery switching infrastructure are under development that could enable BEV to be a viable intercity mode. This analysis suggests negligible carbon benefits to high-speed rail in the event of widespread BEV adoption. If life-cycle infrastructure costs were taken into account under such a scenario, it is possible that high-speed rail would be more costly from an emissions perspective. However, even in the event of high adoption rates, electric vehicles are fundamentally limited by long fleet turnover times. In comparison, high-speed rail acts as a disruptive technology since, despite long construction phases, there is no significant time lag for individual adoption.

B. Identifying the drivers of CO_2/PKM sensitivity in train technology

While Figure 22 presents a possible outcome, one could envision many possible futures for vehicle technology, operation, or adoption that would dramatically change the trajectories of CO_2/PKM. A sensitivity analysis of key model parameters sheds light on which specific changes have the most profound influence on overall emissions performance. Since my primary focus is the implementation of high-speed rail technologies, I focus on illustrating sensitivities to the components of that particular technology in Figure 23.

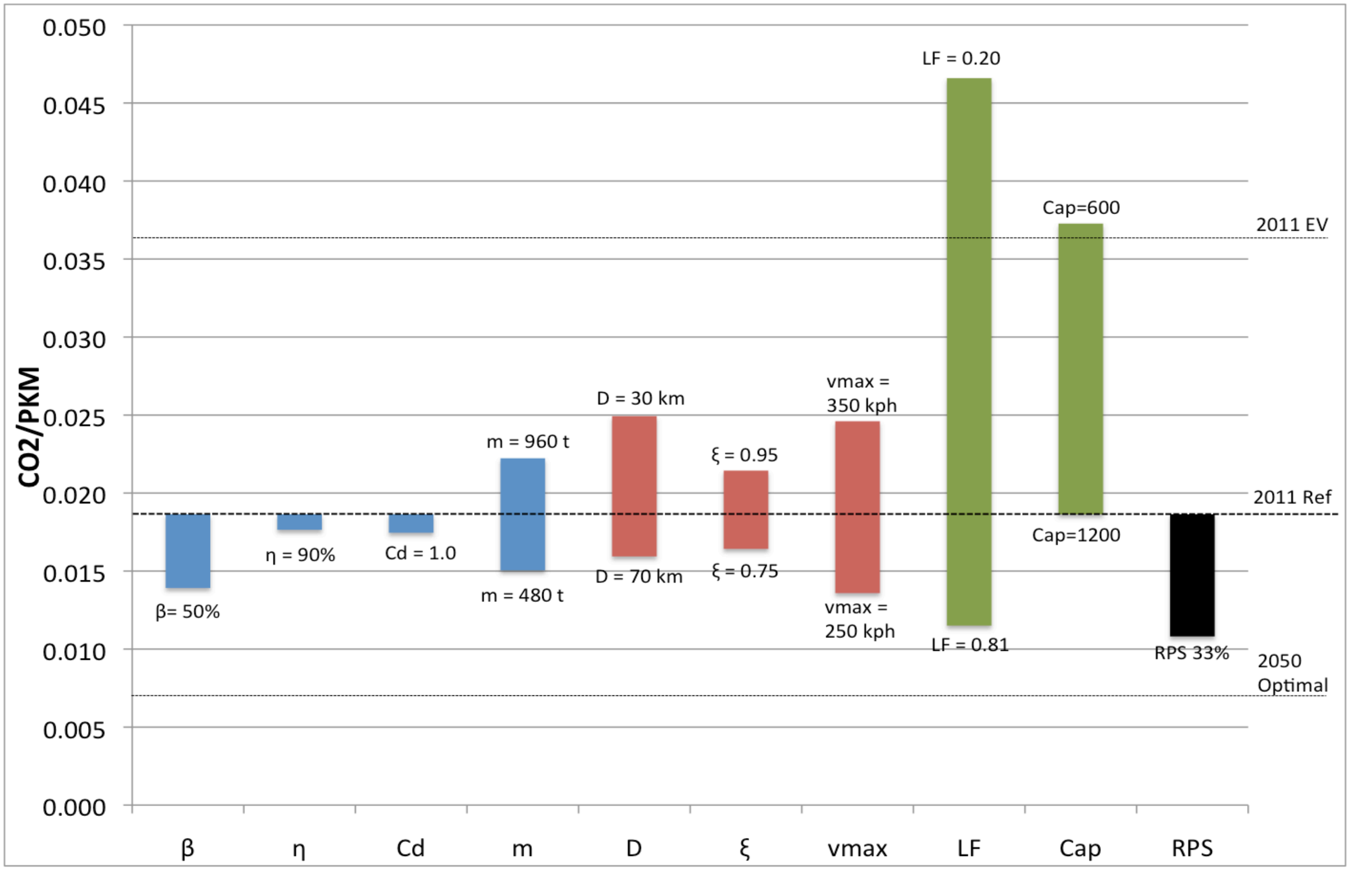


Figure 23. Sensitivity of CO_2/PKM for high-speed rail technology in the 2011 Reference Case (CA corridor). Each bar represents the range of CO_2/PKM upon variation of single parameter shown on the x-axis. Parameter ranges are labeled at endpoints. Colors represent different types of parameters, blue=technology, red=operation, green=passengers, black=electricity grid. β = regenerative braking, η = power conversion efficiency, Cd = drag coefficient, m = mass, D = average stop distance, ξ = speed homogeneity, vmax = maximum speed, LF = load factor, Cap = capacity and RPS = renewable portfolio standard. 2050 Optimal high-speed rail and 2011 EV technologies are shown for comparison.

Several parameters are notable for the variation (and thus uncertainty) they produce in the results. Operational parameters such as stop distance, speed, and load factor appear to be responsible for the largest variations. Meanwhile, regenerative braking and carbon intensity of the electric grid (via renewable portfolio standards) also play a large role. It's possible that the combined effects of several parameters could cause high-speed rail to become more greenhouse gas intensive than other modes of intercity travel.

As an illustrative example of an extreme case, CO_2/PKM for a hypothetical high-speed rail system on the Chicago-St. Louis-Kansas City corridor would break-even with CO_2/PKM for 2011 air travel upon the following concurrent changes to the 2011 Reference case:

- Load Factor reduced from 0.50 to 0.40,
- Capacity reduced from 1200 to 400 seats per train,
- Speed increased from 300 km/hr to 350 km/hr,
- Mass increased from 600 kg/seat to 800 kg/seat,
- Average stop distance decreased from 50 km to 30 km.

It should be noted however that under this extreme starting condition, rail technology improvements will have a more profound influence and may cause a rapid decline in CO_2/PKM.

C. Regional Differences

While part of the performance of high-speed rail is dependent on the state of technology and how it is operated, some qualities that govern performance vary regionally -- most notably the carbon intensity of the electricity grid and the sources of high-speed rail ridership. This distinction is important for policy-makers considering the greenhouse gas reduction potential of intercity rail investments. As an illustration, the time variation in $\Delta CO_2/PKM$ for three possible rail corridors is shown in Figure 24.

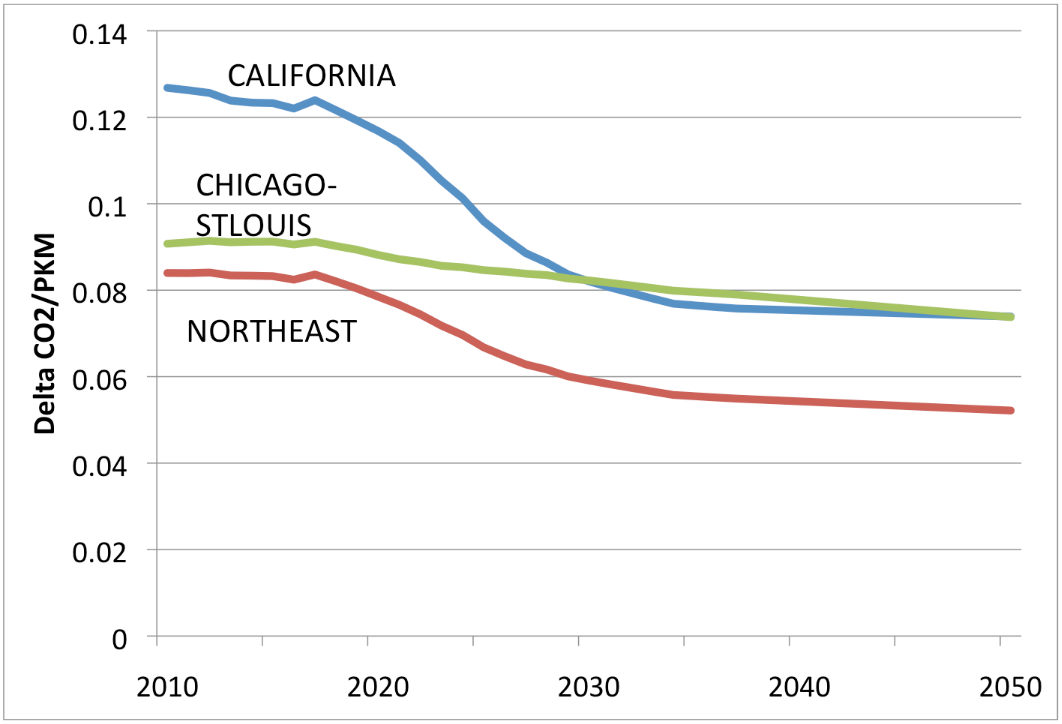


Figure 24. A time series of ΔCO2/PKM forecasts for three different high-speed rail corridors.

California leads throughout, primarily due to the low carbon intensity of its electricity and strong renewable portfolio standards.

The higher ΔCO_2/PKM in the early years reflects the large share of ridership diverted from automobiles, which have a high initial $CO2_2$/PKM that drops quickly in subsequent years. It's important to note that marginal impacts in the earliest dates are only theoretical since each corridor will not be built or operated for many years. However, the decline in ΔCO_2/PKM is illustrative of a potential pitfall in estimating high-speed rail mitigation potential. Namely, calculations of greenhouse gas reductions using current fuel efficiencies will over-state the carbon savings possible since fuel economies will continue to improve through the planning and construction process. The Northeast corridor lags behind Chicago-St. Louis-Kansas City, despite a cleaner power grid, in part because it has a high number of riders that are predicted to be induced (rather than diverted) and thus will not reduce emissions from other modes.

D. Payback Times for high-speed rail corridors under consideration

In addition to marginal impacts of high-speed rail indicated by ΔCO_2/PKM, a paramount goal of greenhouse gas mitigation is to reach a state of lower cumulative emissions relative to business as usual (BAU). Figure 25 illustrates net CO_2 emitted (when compared to BAU) for each corridor under the specified assumptions about technological progress and ridership in Chapters IV-VI. Furthermore, the initial emissions embodied in construction were included as an initial pulse. Modeling net CO_2 emissions this way provides an intuitive means for understanding the carbon payback time horizons of the three corridors in this study.

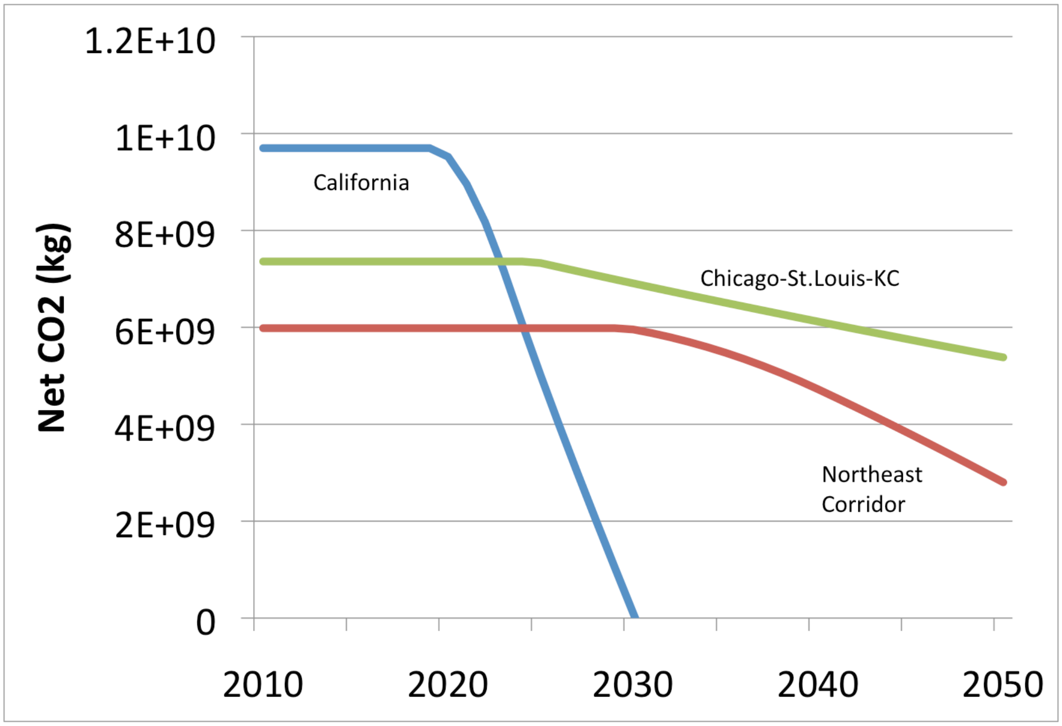


Figure 25. Net CO2 emissions for three representative high-speed rail corridors based on technology and ridership scenarios outlined in this study's methodology. The different curve shapes represent radically different outcomes in terms of carbon mitigation. The flat value at the beginning of each curve's trajectory reflects the initial CO_2 embedded in the infrastructure of the corridor.

These results show that under some scenarios high-speed rail projects (e.g. Northeast Corridor and Chicago-St. Louis-Kansas City) can take a long time to pay back the greenhouse gas impacts of the initial investment. If these costs and benefits are monetized and discounted for present value, this outcome could be further exaggerated. A closer look at these corridor payback trajectories reveals some important considerations for the sustainability performance of high-speed rail planning.

Technological Progress versus Operational Changes:

Of the corridors modeled, California alone had a payback time within the 40-year time horizon considered, despite having a higher initial upfront infrastructure cost. This is due to both the higher ridership projections incorporated in the model and the higher $\Delta CO_2/PKM$ as indicated in Figure 24. While ridership has an overwhelming influence in determining the payback time for all corridors, technological and operational factors can also play a meaningful role. In particular, when multiple technological and operational factors are changed in combination they can yield significant effects on the CO_2 payback that may even be comparable to major changes in ridership.

As an example, I explored alternative scenarios for California in which rail experienced 1) no technological progress in train technology, 2) a service pattern comprised of smaller trains with fewer passengers and more frequent stops, and 3) a combination of these factors. Figure

26 illustrates the payback under the baseline scenario, these three alternative scenarios, as well as a 50% reduction in projected ridership for reference purposes.

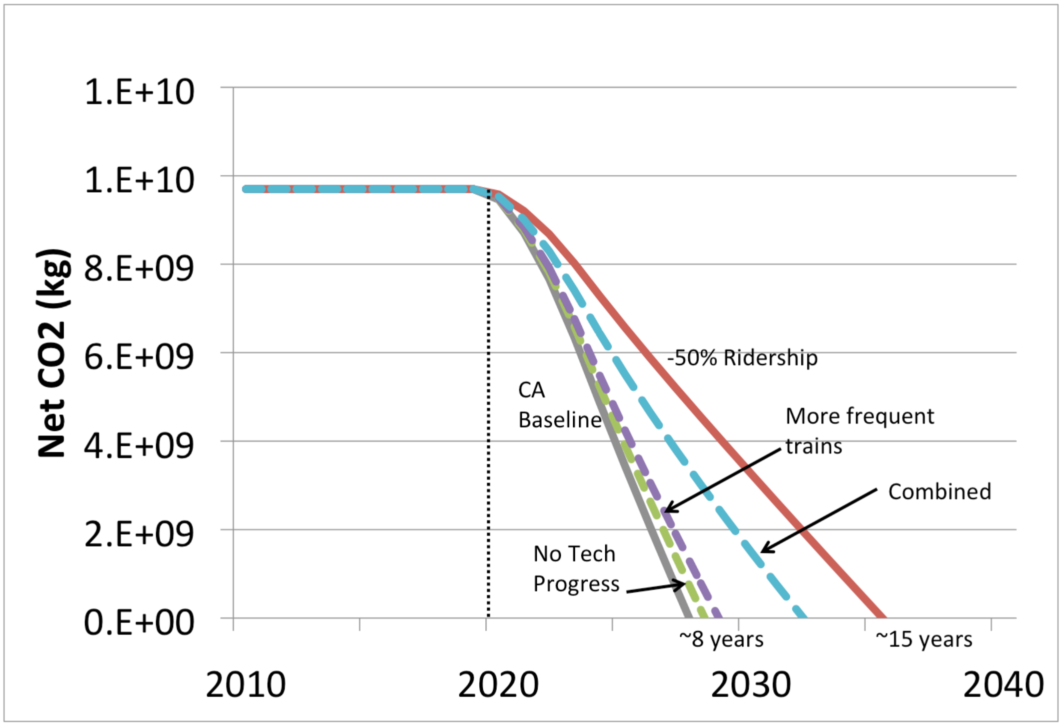


Figure 26. Modeled emissions trajectory and payback time for the California high-speed rail corridor with changes in technology and operation. Scenarios modeled included: 1) Baseline (solid grey), 2) high-speed rail experiences no technological progress (dashed green), 3) high-speed rail is operated with fewer passengers and frequent stops (dashed purple), 4) a combination of 2 and 3 (dashed blue), and 5) a 50% decrease in projected ridership (solid red).

It's evident that either technological or operational changes in isolation do not yield a significant delay to payback times, however in combination they can delay payback by several years.

Ridership Sources

A surprising outcome of this analysis is the poor performance of the Northeast Corridor. Indeed, the Northeast Corridor is generally recognized as being one of the most viable places to implement high-speed rail due to its high concentration of population and other factors conducive to ridership (Todorovich & Hagler, 2011). However, the Northeast Corridor, more than any other part of the U.S., already experiences a significant share of rail traffic and thus the new rail system would only add passengers beyond this existing ridership.

Additionally, high-speed rail on the Northeast Corridor is projected to start operations at a much later date than California. If the system were developed along the timeline envisioned by Amtrak, initial high-speed rail ridership would not commence until nearly 10 years after California. In light of this fact, one could argue that comparing the two puts the Northeast at an unfair disadvantage due to this time lag. However, time lags cannot be discounted from a decision-making process precisely because the technological progress that occurs during the planning and construction phase could severely reduce high-speed rail's competitive advantage. While upfront emissions are a certainty, the timing and magnitude of the payback is less certain and ought to be weighed against other potential mitigation investment opportunities (assuming investment dollars are fungible).

Another reason for the Northeast's long payback period is that the projected increases in ridership above current levels are currently hypothesized to be primarily from induced riders leading to a small ΔCO_2/PKM even if ridership is significant. To explore this phenomenon, I considered a scenario in which the sources of ridership were modified so that the number of induced riders instead came from automobiles (Figure 27).

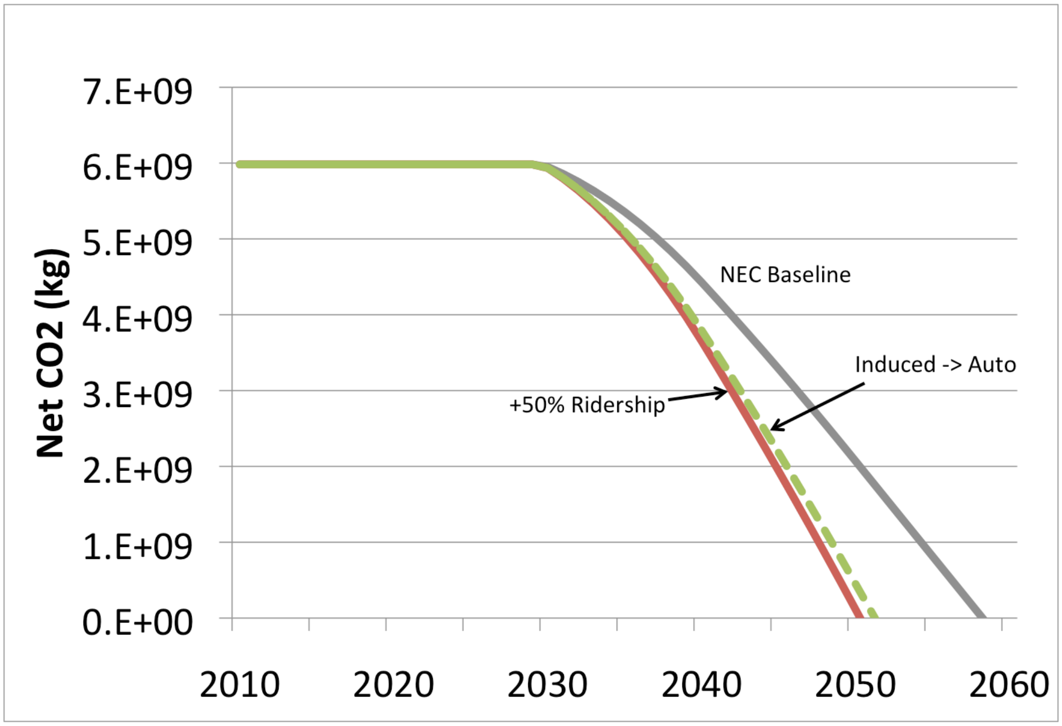


Figure 27. Modeled emissions trajectories and payback times for the Northeast corridor with changes in ridership source. Three scenarios are modeled, 1) a baseline scenario (solid gray), 2) a scenario in which the induced ridership

instead came from automobiles (dashed green), and 3) a 50% increase in projected ridership (solid red).

Indeed under this scenario, payback is noticeably shortened to a degree roughly equivalent to a 50% increase in projected ridership. This result demonstrates that high-speed rail emissions mitigation is dependent on not just how many riders exist, but where those riders come from. Coordinated policies to encourage travelers to switch to high-speed rail from carbon intensive modes could increase its effectiveness for emissions mitigation. These measures could include some that decrease the attractiveness of other modes such as road-pricing or increase the attractiveness of high-speed rail through non-travel benefits such as on-board amenities. Other options to encourage switching to rail might include efforts to equalize convenience of access and egress through local transportation connectivity.

Electric Vehicles

As a final exploration of technological uncertainty in relation to high-speed rail, I considered a scenario that envisions widespread adoption of electric vehicles. As indicated earlier (Figure 22), electric vehicles have a CO_2/PKM that could put them in competition with high-speed rail in terms of carbon mitigation. However, they also have a lag time to achieve substantial market penetration. Currently, vehicle scrap rates are around 5-6% annually and appear to be declining (Figure 28). This implies a full fleet replacement rate of around 15-20 years. Thus, for example, under an optimistic scenario in which 50% of all new cars sold are electric, it would only be possible to reach a 50% share of automobiles by 2025 at the earliest. The EIA AEO 2011 projects the share of the vehicle fleet comprised of unconventional vehicles through 2035 for their CAFE6 scenario. I used this scenario to model payback times for California high-speed rail, assuming all unconventional sales were electric vehicles (Figure 29).

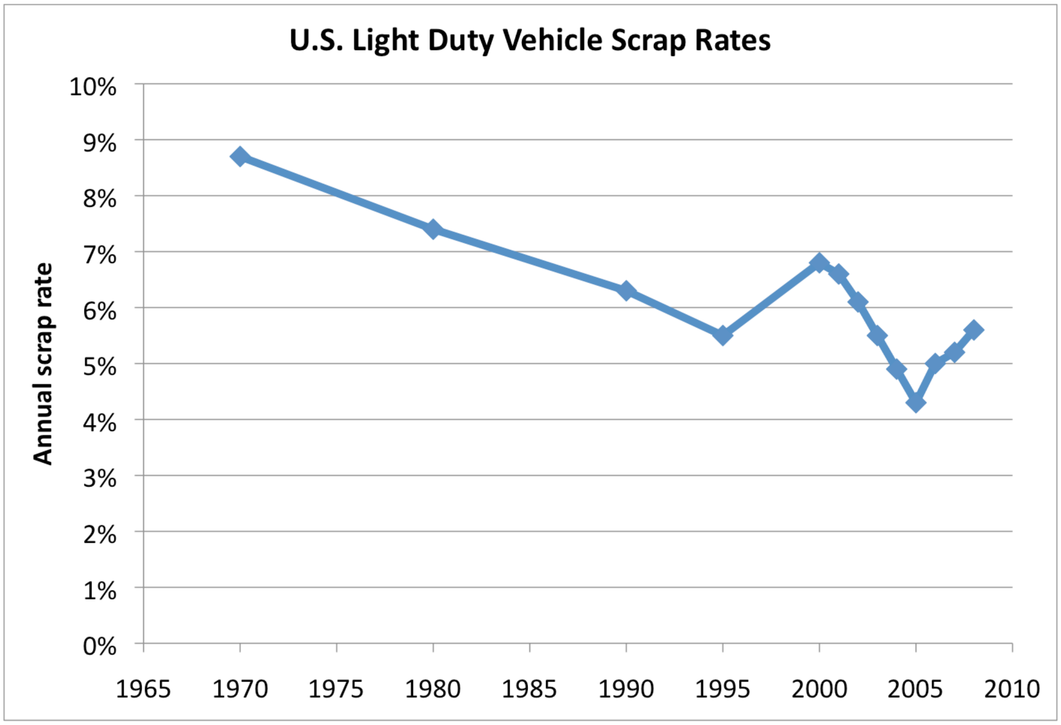


Figure 28. Historical changes in fleet scrap rates for light-duty vehicles in the U.S. (R. L. Polk & Co., 2010).

This particular scenario achieves a 33% unconventional vehicle fleet share by 2025, and 51% by 2035. The small increase in payback time indicates that electric vehicle adoption may not be a significant risk to carbon mitigation through high-speed rail in corridors like CA that are well on their way to becoming a reality. However, if there are significant delays in construction and implementation, or high-speed rail is considered in locations where it might take longer, the emissions benefits of high-speed rail could be significantly reduced.

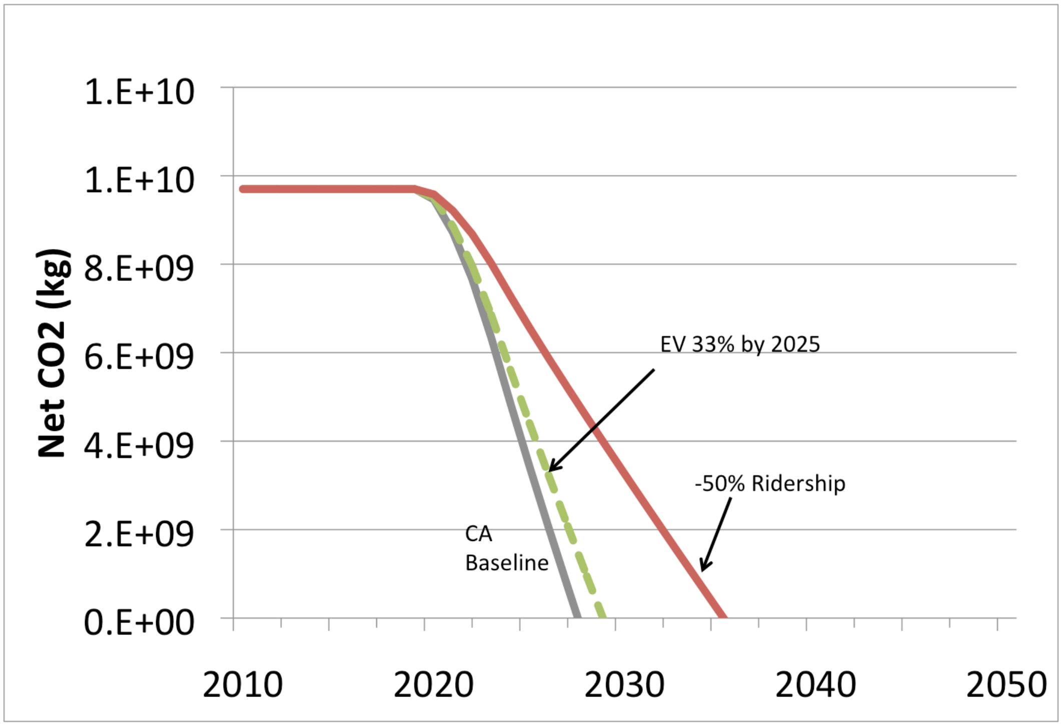


Figure 29. Modeled emissions trajectory and payback time for the California high-speed rail corridor with high electric vehicle adoption. Scenarios included: 1) Baseline (solid grey), 2) widespread electric vehicle adoption (dashed green), 3) a 50% decrease in projected ridership (solid red).

VIII. CONCLUSIONS & POLICY RECOMMENDATIONS

A. Conclusions

In the U.S., large-scale investments like high-speed rail become politically charged topics due to the fact that they require significant public spending. Indeed, because so much is typically at stake for each project, it's essential for decision-makers to have the clearest sense of possible costs and benefits. While sustainability concerns like energy and emissions may not be the primary considerations behind high-speed rail projects, these benefits are certainly a prominent part of the public discussion and high-speed rail's image as a clean technology. I believe the results of this study add to this discussion and solidify some key facts:

1) High-speed rail's marginal contribution to greenhouse gas emissions (per PKM) is similar to that of electric automobiles. Meanwhile, high-speed rail offers significantly lower marginal emissions when compared to airplanes and conventional automobiles. This holds true even in the advent of likely technological progress scenarios in each of those modes (assuming typical load factors for all modes).

2) The relative advantage of high-speed rail for reducing energy and emissions may decrease over time as the gap between rail and other transportation modes narrows from technological progress. This is most important in areas with a high expectation of ridership derived from automobiles.
3) From a sustainability perspective, high-speed rail corridors might be considered a risky investments for the following reasons:
    a. Each corridor has a large upfront carbon cost embedded in materials for construction. Unlike life-cycle costs of short-lived goods, these lumpy investments do not scale easily with demand (i.e. ridership). Track construction cannot be pared back if riders turn out to be fewer than expected.
    b. Life-cycle payback is dependent on operational and behavioral characteristics that are hard to predict (including ridership)
    c. There is little room for technological improvement in rail technologies. Many of the components are near their maximum thermodynamic efficiency.
    d. Rapid widespread adoption of electric vehicles with long ranges could undermine high-speed rail's

relative advantage in terms of energy and emissions. On the other hand, such adoption is hampered by slow vehicle fleet turnovers. High-speed rail, if implemented quickly enough, could provide a positive disruptive influence since it does not require the time lag associated with new vehicle purchases. The environmental performance of high-speed rail projects is sensitive to a number of factors beyond ridership including: speed, number of stops, load factor and capacity, ridership, and (to a much lesser extent) technological progress.

4) Regional variation in existing energy and transportation markets plays a big role in the greenhouse gas mitigation potential of high-speed rail projects, and offers a possible screening metric to supplement current considerations. These screening metrics should consider life-cycle impacts of the investments in addition to operation.

B. POLICY Recommendations

Based on the analysis put forward in this study, it seems improbable, or very uncertain, that many high-speed rail investments will lead to appreciable emissions reductions on any short timescales.

If maximizing greenhouse gas reductions is a goal for state and federal policy-makers, then high-speed rail investments should be targeted towards corridors that not only have high ridership potential, but also high ΔCO_2/PKM and can be implemented quickly. Otherwise, it may be difficult to justify any of high-speed rail's costs by appealing to environmental benefits. Under some scenarios, it's possible that high-speed rail projects wont pay back the initial construction-related emissions for decades. Therefore, decision-makers should take caution when making these choices in the event that they do not pay off as expected.

If policy-makers do commit to making high-speed rail investments, certain guidelines can help maximize the emissions benefits or at least minimize negative outcomes. For instance, emissions reductions could increase by prioritizing corridors with high probability of mode switching (versus induced ridership), shorter track lengths, fewer stops, and strong renewable portfolio standards. A national strategy that initially targets smaller segments, in densely populated areas also seems advisable to avoid riskier large investments that may not have a guaranteed payback.

Decision-makers should also establish clear guidelines on operational practices that can reduce CO_2/PKM such as maximizing load factors and reliance on fewer stops.

Finally, decision-makers should weigh the fact that electric vehicles may be a promising alternative to high-speed rail from a greenhouse gas emissions perspective. If high-speed rail development time exceeds the time needed for electric vehicle technologies to mature to allow intercity travel, then perhaps redirecting public funding for electric vehicle charging infrastructure is warranted.

C. Additional Economic Considerations

The analysis in this study raises very fundamental questions about how our society envisions its future infrastructure investments if climate is deemed a major concern. Indeed the benefits offered by high-speed rail in terms of emissions reductions may be significant assuming intercity travel remains constant, ridership is high, and mode switches are made. However, if additional travel and economic growth occurs from high-speed rail, it's possible these reductions would be simply offset by the increase in energy demand. Unlike other pollutants, greenhouse gases contribute to a global stock of pollutants. Thus the relative emissions intensity of any activity is ultimately meaningless if absolute emissions continue to rise from increased growth in population and economic activity. Meanwhile, discussion of curtailing growth seems fundamentally at odds with any public sentiment and unlikely to gain traction in the near term.

This reality lends support for economy-wide policies such as carbon pricing policies. However, even under such circumstances, various market failures in the transportation sector may lead to a failure to capture the true potential for low-cost carbon mitigation. This study illustrates some of these stumbling blocks, most notably through the long delays between initial investments and eventual payoffs in terms of carbon emission saved.

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