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Impacts of climate change on operation of the US rail network

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A B S T R A C T

The rail network in the US is the largest network within any single country at 140,000 miles of Class 1 tracks. The network is predominantly focused on freight traffic with the exception of key passenger corridors along the eastern seaboard and in the upper Midwest. This extensive rail network enhances connectivity, but also raises the question of potential vulnerability to climate changes over the next century. Specifically, projected changes in temperature highlight the vulnerability of tracks to temperature increases and the accompanying issue of track expansion, which under current operating policies can lead to train delays, and in the most extreme cases can lead to derailments. In this study, the issue of potential impacts to the rail network are analyzed in terms of the cost of potential increases in delays that will occur due to responses of train network operators to temperature increases. Impacts analyzed using a range of climate models indicate that the rail network may incur an increase in delay-minute costs over typical historic costs of between $25 and $45 billion cumulatively through 2100 under a low greenhouse gas emissions future, and between $35 and $60 billion under a high emission scenario. However, these costs could be reduced by up to an order of magnitude if current sensor technologies are incorporated into tracks, coupled with refinements to current speed reduction policies that better leverage temperature monitoring capabilities.

1. Introduction

The primary freight and passenger rail network in the US comprises 140,000 miles of Class 1 rails operated by seven railroad companies (Federal Railroad Administration, 2016). The rail network carries 40% of the freight by distance traveled and 16% of the freight by weight each year. Put into context, each person in the US requires 40 t of freight to be moved each year either through direct goods purchased or indirectly through bulk products such as coal which are required to generate electricity for individual users (Federal Railroad Administration, 2016). The cost-effectiveness of rail transport and year-to-year dependence on the rail network places the system within the scope of critical infrastructure that should be evaluated for its continued reliability and effectiveness under climate change.

Climate change projections indicate that the number and severity of heat related events will increase both in number as well as geographically, increasing concerns of impacts of climate change on the railroad infrastructure (Ford et al., 2015). Climate change is a threat to the rail network due principally to projected temperature increases, though indirect effects from changes in precipitation could also be important. Thermal threats are due to the susceptibility of tracks to damage during periods of elevated temperatures that exceed the operating conditions in the geographic location in which it was installed. Specifically, the steel tracks are designed to operate in a narrow range that is based on the temperature in which it is originally laid, known as the Design Neutral Temperature. When this temperature is exceeded, the ability of the steel rails to support rail traffic begins to degrade. At extreme heat conditions, the continuously welded rail tracks that make up the modern rail system will buckle due to expanding metal. For example, a typical welded length of 1800 feet of rail can expand up to 1 in. per ten degrees of temperature increase (Wolf, 2005). In extreme heat conditions where temperature increases can be several times that, expansion and offset can quickly exceed several inches which will lead to derailment if undetected. These expansion conditions are known as “sun kinks” and will lead to failure if rail traffic is not reduced until temperatures decline.

The complicating factor of climate change for the rail network is that the frequency and magnitude of these extreme heat conditions is projected to increase, significantly in some instances, which increases the risk of failures due to track expansion. Currently, the accepted

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practice for addressing these heat events is to reduce the traffic on the affected areas by reducing the speed of the trains, or in extreme events, stopping traffic completely for a period of time (Chagnon, 2006). The intent of these practices is to reduce the stress on the weakened tracks during the highest temperature points during the day. The byproduct of these practices is a delay in rail traffic as trains are forced to reduce speed or wait until temperatures return to a normal operating level. The questions addressed in this study are: to what extent could these delays increase through the end of the century based on changes in temperature; and how could current technologies and changes in operating practices mitigate these effects.

2. Background

The issue of temperature impact on rails is not a current phenomenon. The issue was identified repeatedly through the late 19th and early 20th centuries by researchers including Ryan (1946), Champion (1947), and Hay (1957, 1982). The primary factor identified in the early studies focused on the joints between the rail sections. Prior to a change that began to occur in the 1950s and 1960s, rail tracks were characterized by a jointed construction process. In this design, segments of track ranging from 30 to 60 feet were laid and then joined through the use of plates with a gap left between the segments to allow for expansion. However, significant variations in temperature above the neutral temperature at which the track was laid would lead to misalignment between the sections due to excessive expansion and contraction of the rails.

A change in the design of tracks from the jointed design to the modern Continuous Welded Rail (CWR) reduced the likelihood of misalignment due to temperature, but it did not eliminate the issue. In the new design, sections of rail are welded together to create a single span of a quarter mile or more. This reduces the noise associated with rails and creates an integrated rail surface that reduces wear on the wheels and allows higher speeds. From the perspective of temperature, the CWR design increased the risk of track deformations referred to as "sun kinks."

Sun kinks are deformations that are introduced in rail when the weight of train cars put stress in areas that are weakened due to excessive heat (Kish and Samavedam, 2013). In these situations, the rails are weakened when the track temperature increases beyond the expected operating temperature as established by the neutral temperature, or the temperature at which the rail was originally laid. When rails are weakened, the downward and outward stress from the weight of the rail cars will push the rails out of alignment. Currently, there is no accepted method to prevent this deformation as rail material is manufactured to a global standard that is both cost-effective and long-lasting. However, to ensure safety and reduce the occurrences of these sun kinks, a standard practice has been established of both reducing and slowing traffic during periods of high temperature (Chagnon, 2006).

The use of temperature-based safety practices has increased in the last decade in many locations. In Great Britain, the number of delays due to heat events continues to rise and has resulted in notable occurrences, such as in 2003 when 137 railway buckles occurred compared to an annual average of 30–40 (Dobney et al., 2008). Similarly, in the US, the occurrence of heat-related delays has increased as the number of extreme heat events has similarly increased (Bruzek, Biess and Al-Nazer, 2013). In both cases, the resulting delays have impacted industries as diverse as agriculture, energy, and automotive. The seven primary railroad companies have adopted a practice of slowing rail traffic during hours when temperatures exceed what is considered safe operating conditions. The specific amounts of reduction vary between the railroad companies from an absolute reduction to a relative reduction below a prescribed maximum operating speed. In either case, the rules intend to prioritize safety but impact operational efficiency. Although these practices have been in place for an extended period of time, increasing occurrence of heat events have brought these practices into greater visibility (Ferranti et al., 2016; Palin et al., 2013). In response to these increasing delays, efforts have moved forward on several fronts including track design, sensor development, and the modification of existing rules in attempts to mitigate the effect of increasing temperatures.

Of the advances in reaction to temperature-based delays, sensor development is having the greatest initial impact. The changes in track design and materials may have an impact over the long-term, but changing the current track design specifications may prove too difficult and expensive to implement in the near-term or mid-term. Similarly, changing practices that may impact human safety will require strong supporting evidence. Therefore, the development of new temperature-sensors and associated electronic communication capabilities may provide the near-term advance required to offset the increasing temperature profiles (Hodge et al., 2015). This near-term potential is being realized by the greater availability of sensors by a number of manufacturers (Davis, 2014).

3. Project methodology

This study estimates the impact of temperature increases on railroad infrastructure and evaluates adaptation measures to alleviate the impact of the potential changes. The current rail study focuses on determining the potential risk to the Class I rail network in the US from climate change. To accomplish this task, the study methodology incorporates a model-based approach that combines climate change projections with current data on rail inventory and volume. In this approach, the current rail system is stressed with future climate projections to determine the potential vulnerabilities that exist in the physical structure and the associated operations. Additionally, the potential for building resiliency into the system through technological advances is explored in terms of the reductions in delay-minutes that can be achieved. The modeling approach encompasses three primary steps; 1) estimate rail inventory and traffic volumes; 2) develop climate scenarios to span a range of future outcomes; and 3) estimate historic (baseline) and projected future climate risks to the rail network, measured by delay minutes and monetary terms, and potential savings that could be realized with emerging technologies.

3.1. Rail inventory and volumes

The primary source for the rail inventory used in the current study was the National Transportation Atlas Database (NTAD) (Bureau of Transportation Statistics, 2015). From this source, GIS shapefiles were obtained for the railroads, rail bridges, and rail stations. The rail lines shapefile is a comprehensive file of all railroad tracks in the US. Only active main line and sub main line (definitions provided in the GIS file as well as standard terminology for rail ones) track were included in this analysis.

In addition to the base inventory of the rail system, the volume of traffic within the system was required to model the cost of delays for distinct geographic areas. The Federal Railroad Administrations (FRA) Office of Safety Analysis website regularly updates highway-rail crossing data for all rail lines in the US along with numerous safety-related parameters. The number of trains passing each crossing during the day is compiled based on the information received from railroad owners and operators.

The highway-rail crossings data indicated that for the rail lines under consideration, 152,656 unique highway-rail crossings had daily rail volume data. Each rail crossing has corresponding GIS coordinates, and therefore can be allocated into a specific climate grid. The average number of daily trains passing through each grid was calculated from the volume data to provide the base number of trains that would be impacted in each grid cell from each projected climate event. For the 2522 grid cells that contain non-zero train traffic volume, the train traffic ranged from 1 to 141 trains per day. Combining this number with the temperature projections described below, the model could project how many train trips would be affected by projected changes in temperature. The discussion on regional impact reflects the variation in this volume and climate variation.

3.2. Climate projections

The climate projections used in the current study follow from the overall methodology being used in the second phase of the Climate Change Impacts and Risk Analysis (CIRA) project (EPA, 2015) – two "Representative Concentration Pathways" (RCPs) capture a range of plausible Greenhouse Gas (GHG) emission futures and are simulated in five General Circulation Models (GCMs). The RCPs, originally developed for the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report, are identified by their approximate total radiative forcing in the year 2100, relative to year 1750: 8.5 W/m^2 (RCP8.5) and 4.5 W/m^2 (RCP4.5). RCP8.5 implies a future with continued high emissions growth with limited efforts to reduce GHGs, whereas RCP4.5 represents a global GHG mitigation scenario. Comparing outcomes under RCP8.5 with those of RCP4.5 not only captures a range of uncertainties and plausible futures, but also provides information about the potential benefits of global GHG mitigation (i.e., how significant greenhouse gas emissions mitigation can avoid or reduce impacts that are expected under RCP8.5).

The fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) developed a large inventory of climate simulations using GCMs driven by the RCP forcing scenarios. To provide localized climate projections suitable for estimating impacts to rail infrastructure and to bias correct the projections to improve consistency with the historic period (defined in this analysis as 1986–2005), the Localized Constructed Analogs dataset (LOCA) (Bureau of Reclamation, 2016) was employed. The LOCA projections are the primary dataset being used in the forthcoming Climate Science Special Report of the U.S. Global Change Research Program's Fourth National Climate Assessment. The LOCA downscaled dataset provides daily maximum and minimum temperatures, and daily precipitation values at 1/16 degree resolution from 2006 to 2100, along with a historical dataset extending back to 1950. The dataset was consolidated into ½ degree resolution to correspond with the rail network inventory.

As in most impacts work, the selection of a subset of GCMs was necessary due to computational and resource constraints. Five GCMs were chosen with the intent of ensuring that the subset captures a large range of the variability in climate outcomes observed across the entire CMIP5 ensemble. The five selected GCMs from CMIP5 (CCSM4, GISS-E2-R, CanESM2, HadGEM2-ES, and MIROC5) cover a large range of the variability across the entire ensemble in terms of annual and seasonal temperatures (Table 1).

Table 1
Change in average maximum summer temperature (°C).

RCP	Model	2030	2050	2070
RCP 4.5	CANESM2	2.22	3.13	3.75
	CCSM4	2.18	2.65	3.38
	GISS-E2-R	1.16	1.83	2.07
	HadGEM2-ES	2.65	4.00	4.67
	MIROC5	2.10	2.81	3.36
RCP 8.5	CANESM2	2.51	3.99	5.25
	CCSM4	2.44	3.62	4.79
	GISS-E2-R	1.46	2.47	3.51
	HadGEM2-ES	3.03	5.14	7.02
	MIROC5	2.16	2.89	4.57

3.3. The software modeling environment

The analysis of the rail system for climate impacts centered around the use of the Infrastructure Planning Support System (IPSS). The IPSS tool incorporates engineering knowledge, stressor-response algorithms and climate projections to quantify potential vulnerabilities resulting from climate change for numerous infrastructure types (Chinowsky and Arndt, 2012). Damage and replacement costs associated with increased vulnerability and adaptation options are quantified and represent the incremental change in expenditures associated with projected climate change for each environmental stressor and infrastructure type examined. As such, the effect of climate change can be isolated from historical baseline maintenance costs. The IPSS system has been used to examine infrastructure in a wide range of US contexts such as Alaskan infrastructure, national road network analysis, and local storm surge analysis (Melvin et al., 2016; Chinowsky et al., 2013). These studies are in addition to international contexts including national studies throughout Africa and Asia (Schweikert et al., 2014; Espinet et al., 2016).

For the current study, the IPSS system was used to determine the impact of temperature changes on the physical rail structure of the overall rail network. Although climate change also impacts precipitation levels, the key concern in terms of rail operations is the projected increase in track temperatures. This concern is due to the softening of rails and the associated physical damage that is caused by increased temperatures.

Quantifying the impact of increased temperatures on the rail system incorporates two components; determining the potential increases in buckling failures, and estimating the potential increases in temperature-based delays. The former is required to determine the increased likelihood that track buckles will result in subsequent operation delays. The increase in buckling potential triggers an accepted operating procedure that requires trains to reduce speed during conditions which may result in increased buckling. Once the potential for increased buckling is identified, the second element estimates potential increases in rail delays in accordance with the operating procedures that reduce speeds due to safety considerations. Given the combination of projected buckling occurrences and projected increases in delays, delay-minutes can be used to provide the metric of impact for the overall rail network. Once the delay-minutes are determined for each segment of track, the delay minutes can be changed to cost impacts as the cost of delay can be determined for both passenger and freight trains based on documented industry cost factors. In this manner, the final impact of temperature increases is presented as specific cost impacts.

3.3.1. Current operating procedures

Currently, railroads utilize operating procedures that incorporate speed restrictions to avoid track buckling events due to high temperatures. However, each railroad operator sets different speed orders for these high temperature events. These restrictions are put in place with a blanket reduction in speed for operations occurring in these areas when the expected daily high exceeds a temperature that is deemed unsafe. These restrictions typically occur in the afternoon and early evening between 1 pm and 7 pm (Virginia Department of Rail and Public Transport, 2008). Table 2 details railroad specific heat restrictions (Chagnon, 2006).

These operating procedures result in operating delays (Historic Delays) due to fluctuations is weather on an annual basis. Although these delays have been increasing in recent years due to increases in summer temperatures, the operating procedures have remained consistent. However, the projected increases in temperatures due to climate change are challenging the ability of rail operators to retain current operating practices. The current study uses these historic practices to establish the vulnerability of the system to climate change and uses an adaptation option to change these procedures to reduce the potential impact of temperature increases.

Table 2
Railroad heat restrictions.

Railroad	Temperature (°F)	Restricted speed
Amtrak	95°	Passenger: Max 80 mph
BNSF	85–115°	Passenger: 70 mph to 50 mph Freight: 50 mph to 40 mph
CN	95°	Passenger: Max 65 mph
CSX	85°	20 mph reduction from posted speed
UP	100–115°	Passenger: 50 mph Freight: 40 mph

3.3.2. Delay minute comparisons

The concept of delay-minutes has been introduced in previous studies to compare impacts on rail transport (Dobney et al., 2008; US Climate Change Program, 2008). In this method, the estimated railroad delay is determined based on the difference in the time required to complete a trip at the maximum posted speed and the actual time taken for the trip (Cambridge Systematics, 2007). This difference is then multiplied by the cost of delay to calculate the impact of reduced speeds.

Existing literature provides different approaches to calculate rail delay from extreme heat events (Dobney et al., 2008; Nemry and Demirel, 2012). This study calculates train delay minutes at a grid level in accordance with the granularity of the climate projections. Since impacts are limited to estimates at the grid level, impacts are averaged over the inventory in that grid cell to reflect the granularity of the projection. In this grid approach, the generalized approach is summarized as follows:

$$TDM_g = (L_g/S_r - L_g/S_o)*60*H_d/H_o \tag{1}$$

where

TDM_g	Train Delay Minutes per grid
S_r	Reduced Speed
S_o	Base speed
L_g	Total length of rail traveled per grid
H_d	Hours of speed order
H_o	Hours of rail road operation

In this method, train delay minutes are first calculated based on a speed restriction, the length of track in the grid, and the number of hours in which the speed order will be put into effect. The specific speed restriction used in the current modeling effort corresponds to the BNSF details seen in Table 1 as they incorporate both freight and passenger safety rules.

Once the total delay minutes are calculated on a per grid basis, the delay minutes per year are calculated by multiplying the delay minutes per grid by the average volume of trains per grid and the number of incident days per grid. An incident day being defined as a day in which a speed order is put into place.

$$DM_g = TDM_g*T_d*I_d \tag{2}$$

where

DM_g	Delay Minutes per grid per year
TDM_g	Train Delay Minutes per grid
T_d	average number of trains per day
I_d	number of incident days

Finally, the delay minutes are quantified as costs using the following equation.

$$C_d = C_m*DM_g \tag{3}$$

where

C_d	Cost of delay
C_m	Cost per minute of delay
DM_g	Delay Minutes per grid per year

The specific delay costs for bulk, intermodal and passenger trains are detailed in the cost modeling section. The cost of delay is aggregated to the grid level by adding the cost of delay for different train types.

3.3.3. Design neutral temperature and track temperature

While the operating procedures put in place by the rail operators provide a broad guideline for implementing speed reduction, the guidelines also suffer from a lack of specificity for local conditions. This is generally due to the challenge of isolating risks to local rail conditions. Specifically, the challenge to improving operating procedures is the challenge to identify track temperatures at individual locations. However, research into the effects of temperature on rails provides a basis for modeling potential damages as well as the potential savings that can be achieved through adaptations.

The modeling of historic and potential delays based on a sensor technology approach rather than a temperature procedure approach begins with the concept of Design Neutral Temperatures. The Design Neutral Temperature or Stress Free Temperature (SFT) of rail is the temperature for which the rail was intended to operate in stress free condition. This is typically considered the temperature when the rail was installed in a particular location and is considered the neutral temperature at which the rail functions at an optimum level. This temperature also determines the threshold at which the rails are likely to experience softening and bending due to the longitudinal forces on the rail. The stress free temperature that is used in design is generally 75% of the expected maximum temperature of the region. This is also known as the ¾ T_{max} rule and can be seen in Eq. (4) (Nemry and Demirel, 2012).

$$SFT = \frac{3}{4}*T_{max} \tag{4}$$

The stress free temperature will gradually reduce with age due to a variety of causes such as typical movement and shifting of the rails. In order to account for this degradation in the current effort, the average baseline SFT for the lower 48 states was compared to the typical SFT distribution in order to calculate a degradation factor (Kish and Samavedam, 1999). This factor was applied to more accurately reflect the SFT of the overall rail network.

The second critical number that is required in the rail analysis is the track temperature at a given point in time. The track temperature provides the basis for the likelihood of failure of steel tracks under a combination of heat and stress. The track temperature is thus used as the main indicator of the likelihood that the rail will fail under different operating scenarios. While the optimum practice is to measure track temperature at multiple locations through temperature sensors, the amount of track owned by each railroad company is substantial, which has made the widespread use of temperature sensors difficult from a cost-benefit perspective. Therefore, a relationship between air and track temperature has been developed to compensate for the lack of sensor data and approximate the track temperature. The relationship between ambient air temperature and track temperature can be seen in Eq. (5) (Dobney et al., 2008).

$$T_{rail} = \frac{3}{2}*T_a \tag{5}$$

Using Eqs. (#4) and (#5), the SFT for any region can be calculated using a maximum operating ambient air temperature from the climate scenario projections. Researchers have concluded that an approximation for this operating temperature is the projected average maximum temperature for the summer period (US Climate Change Program, 2008). Thus, for each grid section in the study, the maximum temperature from the three-month summer period in that grid is used as the maximum temperature with the process repeated for each year under consideration. Once a SFT is calculated for each grid location, a delay-minute cost can be calculated for both historic and future conditions using the modeling approach detailed in the next section.

3.3.4. Impact and adaptation modeling

The determination of delay minutes due to temperature events provides the basis for comparing the potential benefits of implementing adaptation measures. Specifically, the potential savings from adaptation methods can be calculated in terms of delay-minute savings. In the current study, this adaptation is based on a risk-based speed reduction methodology proposed by the FRA (Kish and Samavedam, 2013). The focus of this methodology is the installation and use of temperature sensors to better monitor the area and time when speed and traffic reductions are required in a geographic location.

The sensor technology is translated into an adaptation calculation based on a risk-based perspective. At the core of the perspective is the threshold where buckling risk can be implemented. Specifically, there are three important thresholds for the proposed speed order methodology; 1) $T_{b,min}$ represents the maximum track temperature in which there is no risk for buckling, 2) $T_{b,max}$ represents the temperature at which certain buckling will occur, and 3) the temperatures between $T_{b,min}$ and $T_{b,max}$ have an associated probability of bucking, which is dependent on energy needed to buckle the track and decreases as $T_{b,max}$ increases.

For the purpose of track safety, $T_{allowable}$ is the maximum allowable temperature above the neutral temperature of the rail that is considered safe. Investigations of the ERRI committee have shown that $T_{allowable}$ should be the temperature at 50% of buckling energy which can be calculated using Eq. (6) (Esveld, 1998).

$$T_{allowable} = T_{b,min} + 0.25(T_{b,max} - T_{b,min}) \tag{6}$$

The probability of buckling is then based on a relationship between buckling energy and ΔT (Kish and Samavedam, 2008). As the temperature approaches $T_{b,max}$ the additional energy required to buckle the track decreases exponentially. Therefore the maximum amount of additional energy required to cause buckling occurs at $T_{b,min.}$ At $T_{b,max}$, no additional energy is required for the track to buckle, therefore buckling will be certain (Buckling Probability, $P_b = 1$). At $T_{b,min}$ the level of buckling energy needed is significant and therefore must be caused by added mechanical energy. We can assume that at $T_{b,min}$, P_b is equal to 0 because we have established that if ΔT is less than $T_{b,min}$ then there is no risk of buckling. However, P_b varies exponentially between $T_{b,min}$ to $T_{b,max}$ as buckling energy varies with temperature. The exponential equation for P_b is detailed in Fig. 1.

Given the relationships in Fig. 1, a reduction in speed to avoid buckling can be calculated based on temperatures using Eq. (7) (Kish and Samavedam, 2008).

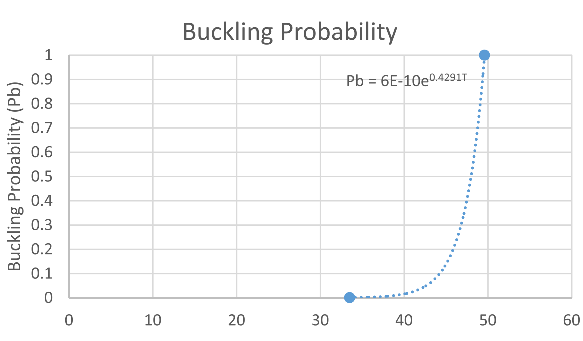

Fig. 1. Buckling probability (P_b).

$$\frac{V_r}{V_{max}} = \left(1 - \frac{P_b(T)}{P_b(T_L)}\right)^{.5} \tag{7}$$

where

V_r	Reduced speed
V_{max}	Permissible maximum authorized line speed
$P_b(T)$	Buckling probability at track temperature, T
$P_b(T_L)$	Buckling probability at limiting temperature, T_L

The limiting temperature for track safety is therefore the maximum allowable temperature ($T_{allowable}$) above the neutral temperature of the rail.

In extreme temperature scenarios, the risk-based methodology will recommend a speed order of 10 mph, far below common practice. This limits the number of buckling events considerably, but increases the delay minutes. As the approach adopted for the current study does not allow for an increase in number of buckling events, the model limits the risk-based speed order to 40 mph which remains consistent with common practice. It is also estimated that sensors which are more sensitive and able to capture small changes at higher temperatures will be developed in the near future. Therefore, the assumption of using risk-based speed order of 40 mph is conservative and attempts to accommodate for potential advancements in sensor technology.

3.3.4.1. Cost modeling. The impact of climate change on rails differs from other types of infrastructure in that the degradation that occurs in rails is different from the types of degradation found in elements such as paved roads. Specifically, in the case of temperature and asphalt roads, asphalt roads may experience increased cracking due to increased temperatures, but a failure of the road due to that stress is unlikely. In contrast, increased temperatures can lead directly to catastrophic failures of rails due to misalignments or deformations. Operating procedures attempt to eliminate this potential through the speed reduction orders. The translation of these operating procedures into delay-minutes and subsequently to cost impacts provides the quantitative comparator that can be used to determine the financial impact of projected climate change.

The basis of delay-minute costs lies in the total cost of a delay when a train is impacted by temperature. The methodology used by Lovett et al. (2015) estimates the cost of delay for freight trains to the railroad company and public. The cost to the railroad company includes the cost of crew, cars (separated by type), locomotives, lading, and fuel. The costs to the public are primarily due to a combination of locomotive emissions attributed to additional operation time and car traffic delay at level railroad crossings. Various components of ownership and operation costs in this methodology are based on the American Association of Railroads' (2016) Analysis of Class 1 Railroads.

In the current study, the elements of delay costs are based on the Lovett et al. (2015) methodology, but several adjustments are made to provide a national foundation for the model. As detailed, each of the changes or extensions are based on previous studies or documented costs.

1. The cost of fuel used by locomotives is calculated as $185 per hour in Lovett et al. (2015) for the SD-70 Locomotive, but the amount of fuel used depends on the notch at which the locomotive operates to maintain a certain speed. Since delay related to heat will reduce the train speed, the cost of locomotive fuel is increased to reflect the reduced speed of 40 mph. The cost of fuel used by locomotives is adjusted accordingly to $128.2/hour for each additional hour of operation.

Table 3
The cumulative projected cost of climate change impacts on the rail system 2016–2099 based on delay-minutes. Figures are in billions USD, discounted at 3%.

	RCP4.5	RCP8.5
Baseline	$76.65	
CANESM2	$121.66	$132.55
CCSM4	$113.02	$123.36
GISS-E2-R	$103.54	$113.19
HadGEM2-ES	$124.58	$138.51
MIROC5	$118.59	$126.91

2. The ratio of bulk vs intermodal traffic is estimated using monthly rail traffic data from the American Association of Railroads. The data includes average weekly carloads for each month from 2013-present for intermodal and bulk units (American Association of Railroads, 2016)
3. The delay costs to the public associated with traffic delays incurred at level-crossings, and CO_2 emissions are excluded in the current study.
4. The value of passenger delay is considered to be 1.5 times line-haul travel time based on travel times provided by the US DOT.
5. The study assumes 6% of total trips are business trips with the passenger value of delay being $52/hour/passenger (Talebian and Zou, 2015).

4. Study results

The results of this study provide a comparison of historic approaches to rail safety versus the potential benefit of investment in emerging technologies such as sensors. In each case, the results use the cost of delay-minutes to determine the potential impacts of climate change on rail operation and adaptation savings.

Table 3 provides an overview of the cumulative vulnerability of the rail system during the study period (2016–2099) for the five climate models and the baseline. The baseline cost represents the monetary cost of delays that are anticipated due to temperature events that occur based on a continuation of historical climate patterns. These events do not include temperature increases due to projected climate change, and therefore both RCPs have the same baseline costs of $73.03B between 2016 and 2099.

The five entries below the baseline represent the cumulative costs anticipated from the five climate models and two RCPs. As illustrated, the RCP8.5 scenarios result in a higher cost since emissions continue to rise throughout the 21st century in RCP8.5, whereas emissions in RCP4.5 peak around 2040 (Meinshausen et al., 2011). However, within the RCP8.5 results there is a 22.3% difference between the lower estimate of $113.19B (GISS-E2-R) and the upper estimate of $138.51B (HadGEM2-ES). This difference represents the uncertainty or risk that is related to selecting one of the different GCM models as the basis for making resiliency decisions.

Similar to the RCP8.5 results, the RCP4.5 results contain a variance in the total amount. At the high end, the RCP4.5 results under the HadGEM2-ES model project a $124.58B cost, which is 20.3% higher than the lower estimate of $103.54B (GISS-E2-R) for RCP4.5. When placed in the overall context of the combined scenarios, this creates a difference of $34.97B between the lowest RCP4.5 scenario and the highest RCP8.5 scenario.

4.1. Vulnerability by era

The cumulative totals provide a broad perspective of the climate impacts on the rail system. Putting these results in a temporal context provide an indication of when these impacts will occur in the span of the study. Fig. 2 provides an indication of this timeline through the use of five undiscounted eras. The first era includes four years from 2017 to 2020, followed by four eras of 20 years each centered around years 2030, 2050, 2070 and 2090.

As illustrated, several key points are seen through the data. First, four of the five RCP8.5 scenarios have a greater impact than their corresponding RCP4.5 scenarios by the end of the century. Second, the impact grows throughout the study period with each era having a greater impact than the previous era. This fact reflects the projected rise in temperature across the US throughout the span of the study.

Finally, the difference between the two RCPs increase over time. In Era 1, the gap between the highest and lowest scenarios is $0.37B annually which increases to $4.20B in Era 5. This gap is indicative of the uncertainty associated with climate scenarios and reflects the importance of viewing the data over the ensemble of scenarios to determine an appropriate adaptation scenario.

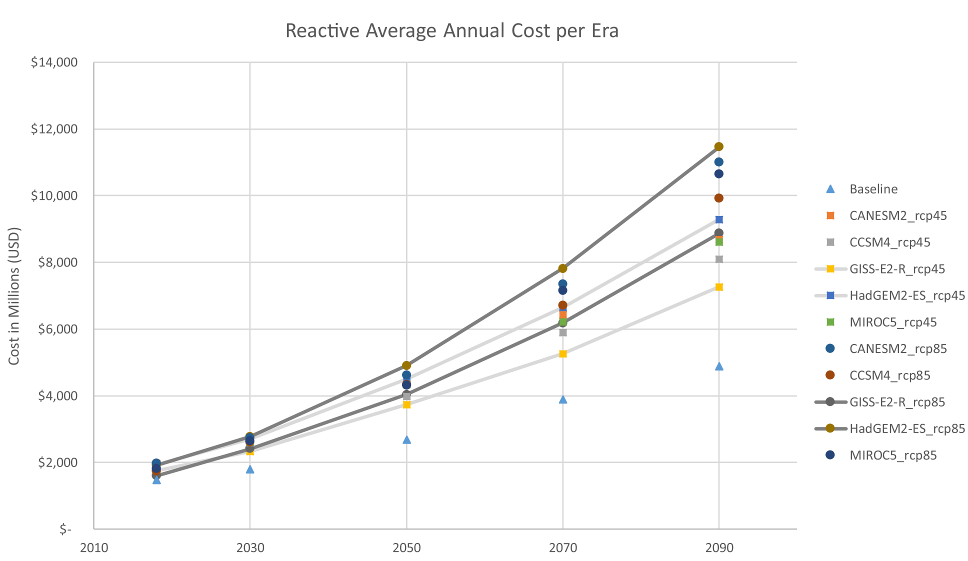

Fig. 2. The average annual cost of climate change impacts on the rail system per era based on delay-minutes. The lines indicate the minimum and maximum of the two RCP scenario groups. Figures are in millions USD undiscounted.

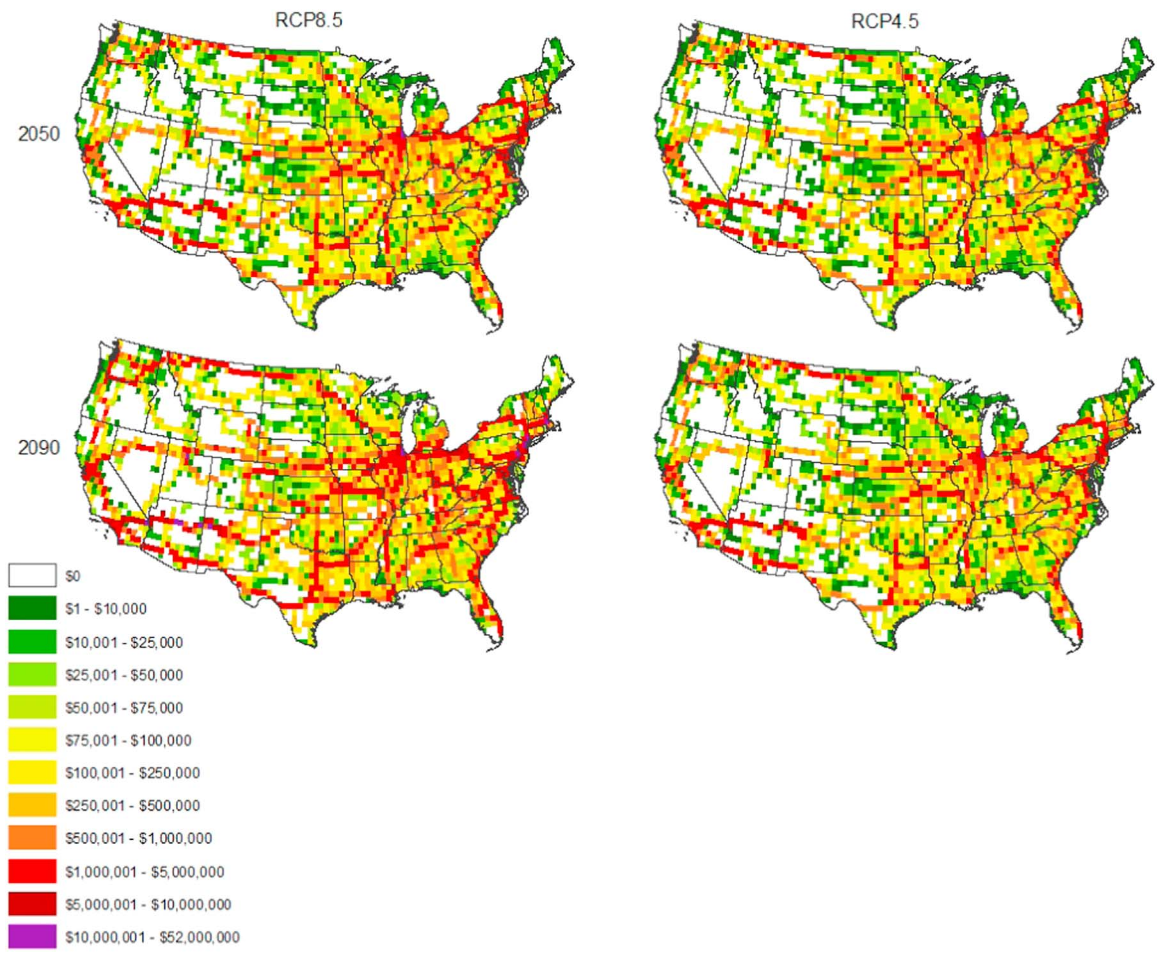

Fig. 3. The average annual costs for the eras containing 2050 and 2090, by geographic region. Costs are undiscounted 2015 USD.

Table 4
The cumulative projected cost of climate change impacts on the rail system 2016–2099 based on delay-minutes. Comparison between reactive and proactive adaptation approaches. Figures are in billions USD, discounted at 3%.

	Reactive		Proactive	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Baseline	$73.03		$3.00	
CANESM2	$121.66	$132.55	$6.15	$11.34
CCSM4	$113.02	$123.36	$7.29	$14.77
GISS-E2-R	$103.54	$113.19	$4.10	$6.60
HadGEM2-ES	$124.58	$138.51	$12.60	$29.24
MIROC5	$118.59	$126.91	$7.56	$10.85

4.2. Vulnerability by region

Fig. 3 illustrates the potential impact of climate on a geographic basis. As illustrated, the majority of the system is impacted, however specific regions including the Northeast, the upper Midwest and the South are anticipated to experience the greatest impacts. The reason for this impact is a combination of the rail network density, the neutral temperature at which the rails were laid, and the relative increase in temperature projected by the model in these areas.

In terms of the neutral temperature, the areas with the greatest projected impact lie where the base (or neutral) temperatures are in the milder range. The northern sections of the US as well as the coastal areas have lower average temperatures and thus have a lower neutral temperature. This lower temperature results in greater vulnerability to temperature increases as the sensitivity to changes increases in proportion to the lower neutral temperature.

Regions, such as the upper Midwest and Chicago that are projected to incur the greatest absolute increases in summer temperatures also incur the largest increases in delay-minutes. This increase, combined with the lower neutral temperature, results in even greater increases in delay-minutes.

4.3. Potential for adaptation to reduce impacts

As described previously in the methodology, the costs due to train delay are reduced through the enhanced identification of track temperatures that exceed normal operating parameters. Through this identification, delays would be reduced by minimizing the spatial area where delays are expected as well as using a risk-based approach to adjusting the severity of the speed reduction order according to specific temperature and track conditions.

The reduced delay costs using the sensor approach are illustrated in Table 4 and Fig. 4. Fig. 4 illustrates the totals (discounted at 3%), which show a reduction in delay costs through each era of the study through 2099 for both the RCP4.5 and 8.5 scenarios. The proactive approach places the annual average costs in the first three eras for the majority of scenarios to below $500 million, and below $2 billion for all but one scenario in the fifth era. This is in contrast to the reactive approach where the final era costs range between $6 and $12 billion as an average annual cost.

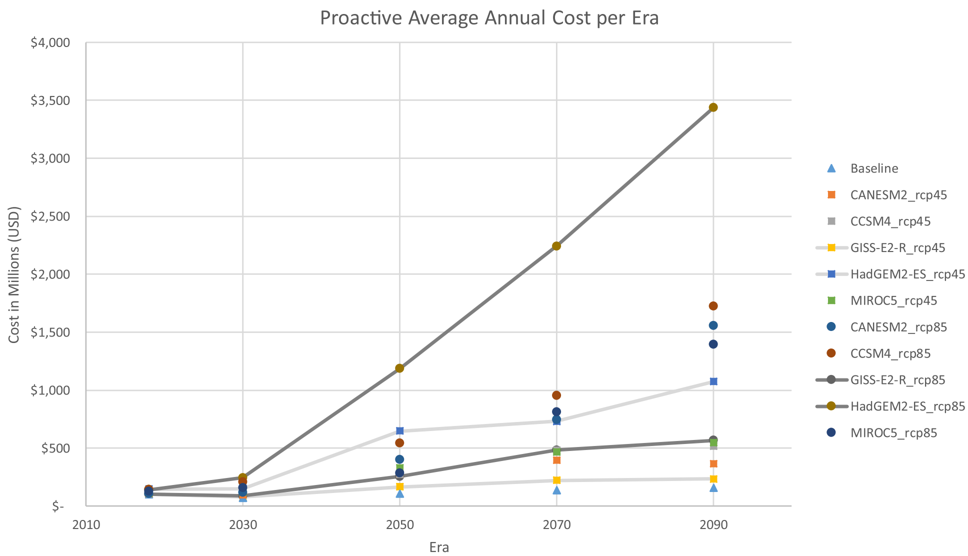

Fig. 4. The average annual cost of climate change impacts on the rail system per era based on delay-minutes for the adaptation approach. The lines indicate the minimum and maximum of the two RCP scenario groups. Figures are in millions USD undiscounted.

The greater variability seen in the proactive approach is a function of the greater sensitivity that the sensor approach provides for operating procedures around delays. In contract to the broad approach for delays adopted currently in the reactive approach, the targeted delays in the proactive approach allow a railroad company to limit delays to areas that are experiencing delays at a specific time. However, this approach highlights the difference in temperature projections between the different climate scenarios. The higher scenarios resulting in larger costs as the proactive approach customizes the delays in a more targeted manner.

5. Conclusion

The current study highlights the potential vulnerability of the US rail system to projected temperature increases from climate change. Depending on the climate scenario selected, the cumulative impacts based on delay-minute costs can range from $103 to $138 billion by 2100 at a 3% discount rate. The increase is noticeable within the first two eras with the costs increasing throughout the study. This near-term impact establishes the motivation to explore alternative solutions for reducing the projected impact. Although long-term impacts are notable, it is in fact the concern for near-term impacts that creates the motivation for considering adaptation options including that put forward in this paper.

The current study estimates reduced delay costs through the use of sensor technology combined with changes to operating procedures to demonstrate a possible path to reduce climate impacts. In this approach, the focus is placed on using the sensor technology to reduce delays by focusing speed restrictions to specific spatial locations rather than having broad speed reduction procedures. Although an investment in sensor technology may be a significant investment today due to the amount of track that requires coverage, the adaptation approach can lead to significant system-wide reduction in train delay costs over the century. In particular, geographic areas such as the Southwest that are anticipating significant temperature increases can achieve notable benefits through the sensor approach.

The sensor and operating procedure approach is not the only approach to reduce train delay costs due to climate change. Continuing innovations in track management and potential changes in track materials may provide additional opportunities. These innovations may lead individual rail companies to adopt different solutions depending on their needs and budgets. Additionally, rail lines that anticipate implementing new rail technologies, such as high-speed rail, or that focus on specific types of freight, may implement new technologies optimized for those options.

Although the focus of this study was on temperature effects, additional climate change considerations can affect the vulnerability of the rail system. Precipitation changes could result in flooding that affect bridge stability and thus require additional investment to stabilize railroad bridges. Additional costs could result from increased intensity of precipitation events that could result in flash flooding and wash outs in localized areas. Similarly, increased threats from wildfires and hurricanes could exacerbate potential vulnerabilities as they intensify climate change impacts. These considerations should not be overlooked in overall considerations of rail vulnerability.

Additionally, the methodology embedded in this study is extensible to contexts where the train volume varies between freight and passenger traffic or other variabilities. This flexibility is due to the base idea of the study that delays are caused by track safety concerns. These safety concerns vary by degree of temperature impact and thus are flexible to any type of variance in type of volume. The change in type of volume is a costing issue which is separate from the underlying methodology employed in the study.

In summary, the message from this study is that the US rail system is expected to face notable increases in delay-minutes due to projected increases in temperature from climate change. These changes are anticipated to begin appearing within the next decade. However, the potential impact of these changes can be mitigated with investment in existing technologies and incorporating the use of sensors into the speed reduction practices of railroad companies. Investment in these technologies could reduce delay costs by an order of magnitude or more on an annual basis.

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