

Thank you to our Patrons



We will begin our presentation in a few minutes...





Passenger and Freight Rail Systems are Being Compromised by Climate Change:

How Proactive Data-Driven Engineering Can Help Owners Adapt

Jake Helman, Principal Consultant

Agenda

1 »

Climate impacts on engineering and the rail system

2 »

How can we address climate impacts in engineering through a data-driven approach?

3 »

A data-driven approach to resilience in the rail sector

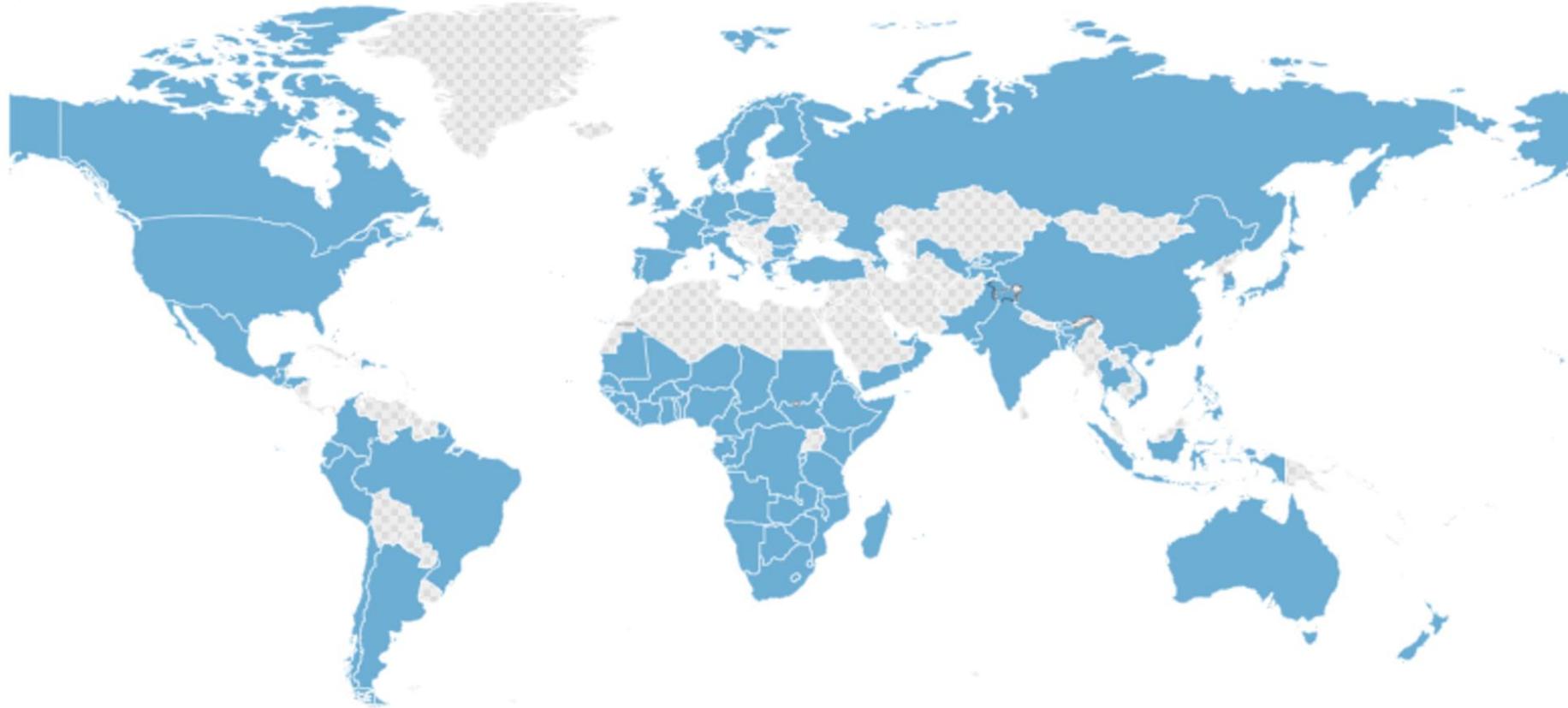
4 »

Other applications of the data-driven approach

Who is Resilient Analytics?

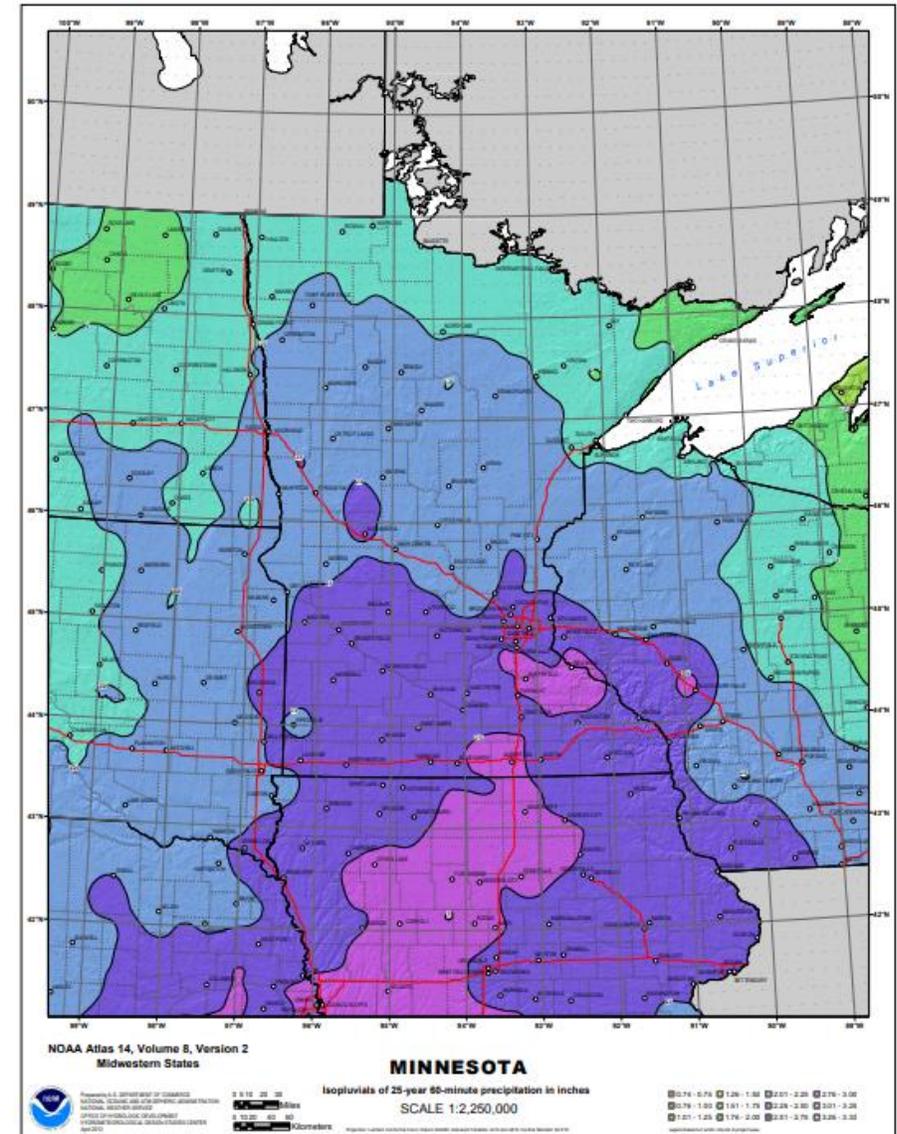


Clients and Analysis Area



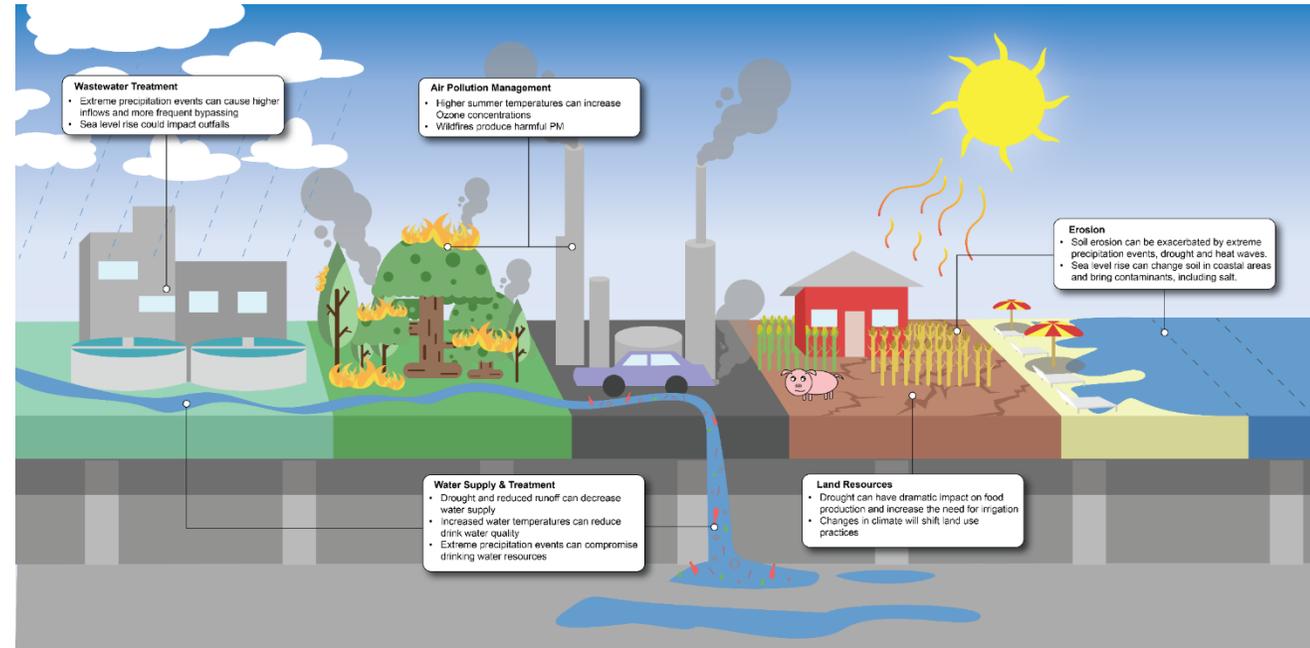
Climate in Engineering Design

- Climate has always been a factor in engineering design
 - Wastewater treatment inflow
 - 5-year and 25-year 60-minute precipitation
 - Retention pond
 - System should be designed for the maximum wet year and minimum evapotranspiration year of record
- Why are we designing the infrastructure of the future to past climate conditions?
 - Historically that is the only data we had to go off
- Climate modeling changes that narrative
- We now have the capability to design the infrastructure of the future to projected climate conditions



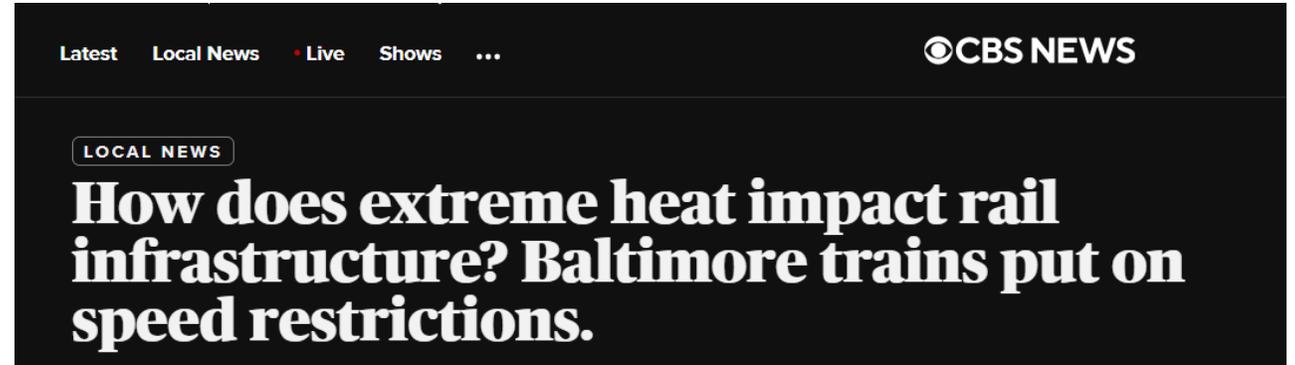
Climate Impacts on Infrastructure

- Climate impacts every engineering discipline
 - Acute risk: damage from catastrophic event
 - Example: Damage from hurricane
 - Operational risk: chronic risk to infrastructure and ops
 - Example: Shortened pump motor lifespan
- Impacts can be modelled and quantified for more informed decision making



Climate Impacts on the Rail System

- Federal Rail Association (FRA) Focus Area II: Resilient Infrastructure
 - Hurricanes, tornados, extreme precipitation, sea level rise and **extreme heat**
- Extreme heat can cause damage and delay
 - Buckled rail → delay and/or derailment
 - Heat restrictions begin between 85°F and 95°F
- Secondary Impacts
 - Supply chain disruption
 - Environmental impacts
- By mid century, many locations in the US will see huge increases in extreme heat events
- Turning risk into opportunity



EXTREME WEATHER

Amid extreme heat, US infrastructure and transportation systems buckle under pressure

"Our infrastructure was not built for the climate of the future," Radley Horton said. "A lot of our infrastructure, at this point, is also very old. Some of it is beyond its intended lifetime."

Jul 12, 2024 - Transit

Heat waves cause Amtrak travel delays, slow Metro

Market Drivers and Opportunity

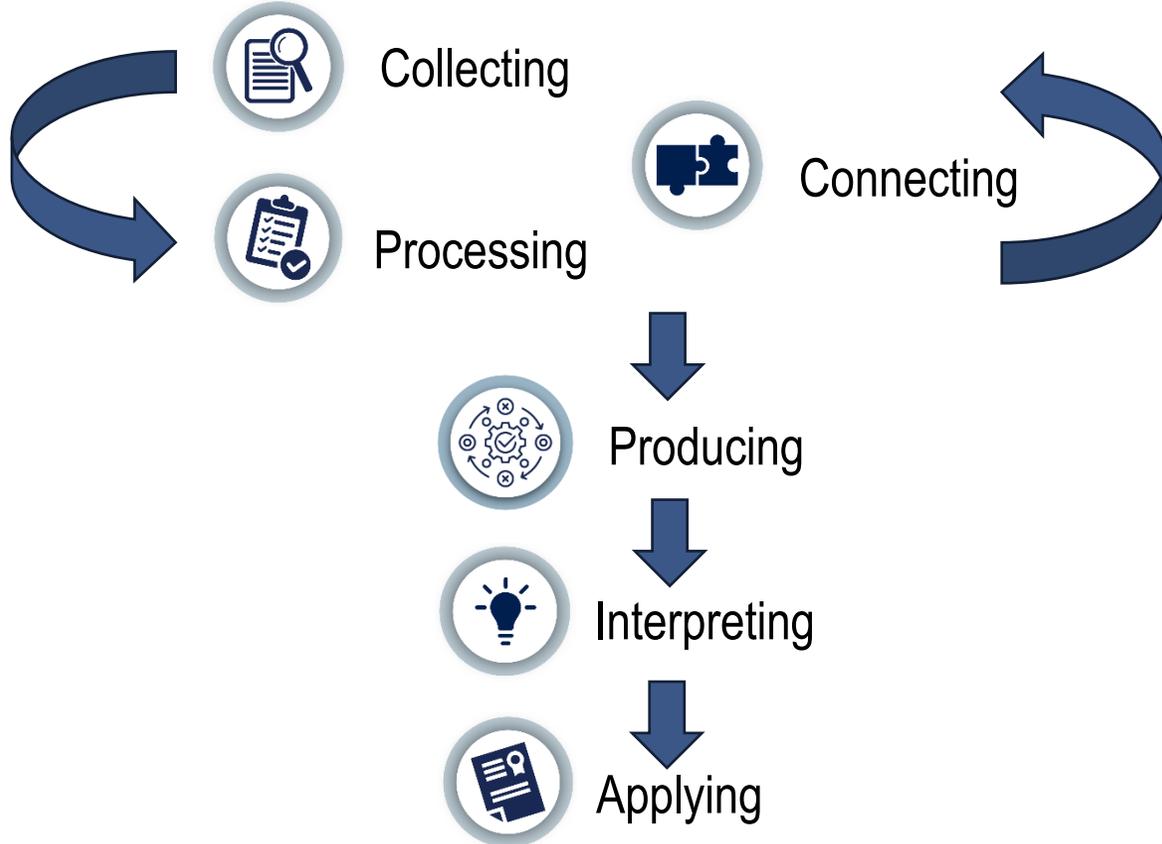
- Climate change is no longer an abstract concept
- Engineers need to be prepared for this, and it needs to be done correctly
- There is an opportunity to become a trusted partner with owners who understand climate risks and are ready to implement this new risk metric



How can we address climate impacts in engineering?



A Data-Driven Approach to Resilience



Actionable Results



Custom



Operational



Cost Driven



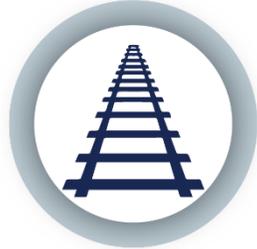
Meets Goals



Collecting



Climate Data



Infrastructure Data



Cost Data



Spatial Data



Methodological Data



Physical Data



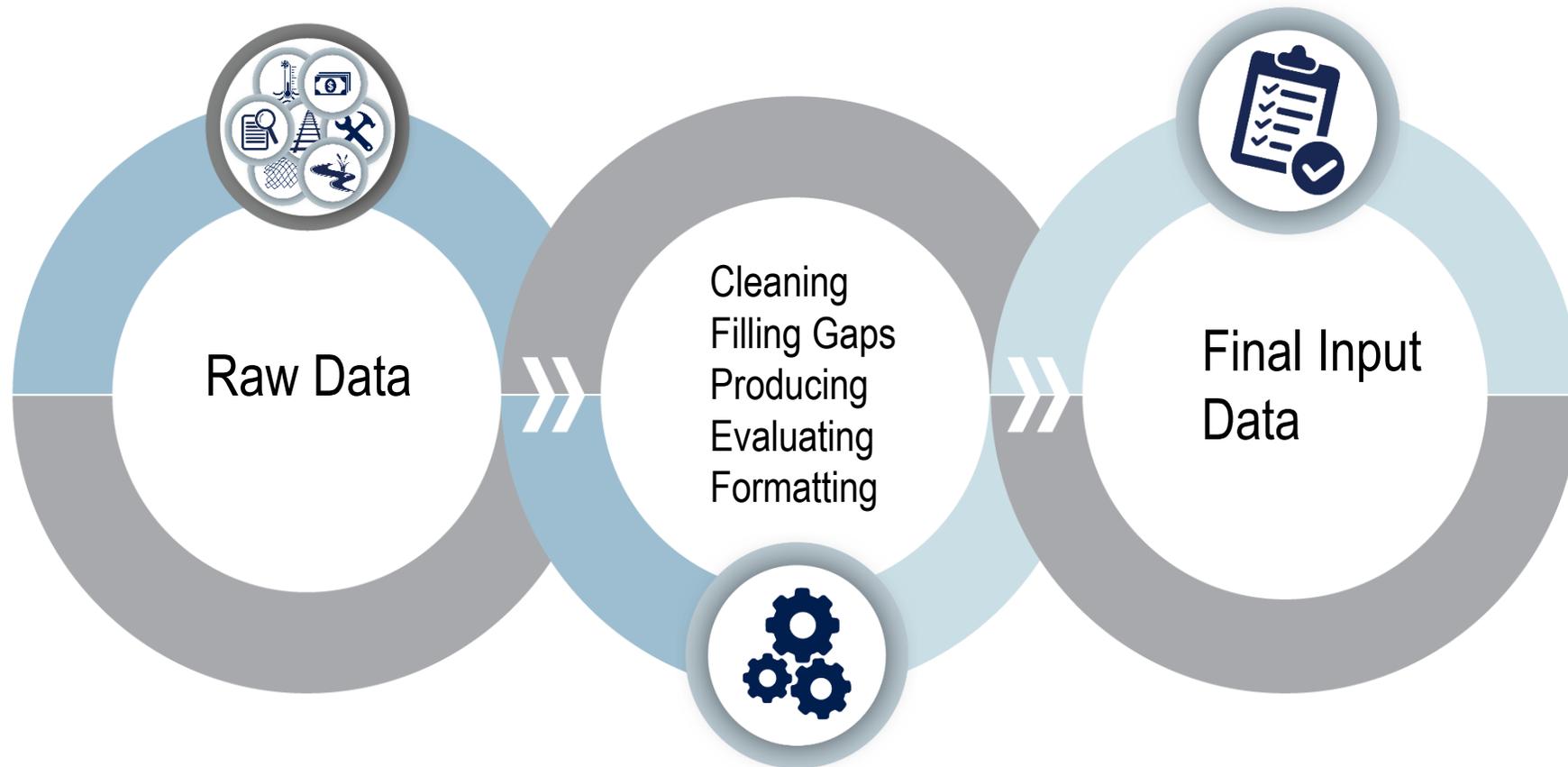
Impact Data

Data Structure

- Data Sources
- Data Format
- Data Size
- Data Updates



Processing





Connecting

- Development of the project method
 - Connecting all the data streams
 - Establish analytical structure
 - Stressor response functions
 - Model boundaries and assumptions
 - Establish data to be produced
 - Derived climate variables
 - Infrastructure variables
 - Cost scenarios
 - Establish the final metrics
 - Drive the narrative of interpretation
- Iterative Process → Can go back to collect and process





Producing



Develop



Iterate



Validate



Interpreting



- Establish categories of interpretation
 - Spatial, Ownership, Time, Scenario, Climate Model, Asset Type



- Synthesize results to create succinct data

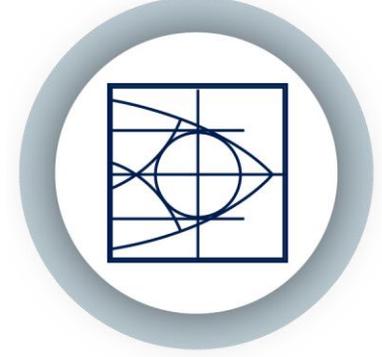
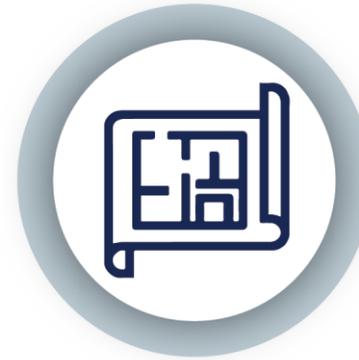


- Establish key trends, patterns and insight



Applying

- **Deliverables such as**
 - Comprehensive vulnerability assessment
 - Resilience improvement plan
 - Engineering resilience assessments
 - Technical report
- **Which can include**
 - Asset vulnerability and risk
 - Project prioritization
 - Changes in design standards
- **In many formats**
 - Report
 - GIS
 - Interactive tool
- **Consistent with other initiatives**





Actionable Results



Custom



Operational



Cost Driven



Decision Making

Summary so far

1»

Climate impacts engineering design and infrastructure

2»

Extreme heat causes damage and delay in the rail system and extreme heat events are projected to increase

3»

A data-driven approach utilizes numerous data streams to create actionable data

4»

A data-driven approach can help quantify sectoral impacts of climate change

Pause for Questions





A Data-Driven Approach to Resilience in the Rail Sector





Project Background

- The Climate Change Impacts and Risk Analysis (CIRA) for the U.S. EPA
 - Impacts across 22 sectors including rail, roads, bridges
 - Enables cross sectoral comparison
- It is designed to estimate physical and economic damages of climate change in the United States under different climate scenarios.



	Scope of Physical Analysis	Economic Valuation of the Impact	
HEALTH			
Air Quality	Future ozone concentrations and resulting number of premature deaths	Value of a statistical life (VSL)	in of the
Aeroallergens	Change in oak pollen season length and concentrations, and resulting number of emergency department visits for asthma	Emergency department cost-per-visit	
Extreme Temperature Mortality	Number of premature deaths attributable to extreme hot and cold temperatures in 49 cities	VSL	costs (sts)
Labor	Lost labor supply hours due to changes in hot and cold temperature, including extreme temperatures	Lost Wages	ated in (ings)
West Nile Virus	Impact of temperature on number of West Nile Neuroinvasive Disease cases	VSL and hospitalization costs	ffset ty index
Harmful Algal Blooms	Change in occurrence of cyanobacterial harmful algal blooms in 279 reservoirs	Lost consumer surplus from reservoir recreation	
Domestic Migration	Percent change in population	N/A	
INFRASTRUCTURE			
Roads	Vulnerability of paved, unpaved, and gravel roads to changes in temperature, precipitation, and freeze-thaw cycles	Reactive or proactive repair or reconstruction costs to maintain level of service	ket and
Bridges	Vulnerability of non-coastal bridges to changes in peak water flow	Costs of proactive maintenance and repairs to maintain level of service	
Rail	Vulnerability of the Class 1 rail network (passenger and freight) to changes in temperature	Costs of delays (reduced speed and traffic) to railroad companies and to public, and proactive adaptation costs to install sensors	ar welfare
Alaska Infrastructure	Vulnerability of roads, buildings, airports, railroads, and pipelines to changes in permafrost thaw, freeze-thaw cycles, precipitation, and precipitation-induced flooding	Reactive and proactive adaptation expenditures to maintain level of service	
Urban Drainage	Change in urban drainage volume from more intense rainfall and increased runoff in 100 cities	Proactive adaptation costs to implement stormwater best management practices	
Coastal Property	Vulnerability of on-shore property to sea level rise and storm surge	Value of abandoned property and costs of protection	
	Wildfire	Change in terrestrial ecosystem vegetative cover and acres burned on non-agricultural, rural lands.	Response costs
	Carbon Storage	Terrestrial carbon flux (storage and annual flows) in metric tons	N/A



Rail Background

- 140,000 miles of Class 1 rails
- \$80-billion freight rail industry
- Passenger carries 30 million people annually
- Rail is susceptible to damage under extreme heat events
- Climate change indicates an increase in the number and severity of extreme heat events



Collecting



Climate Data: LOCA



Infrastructure Data: Rail inventory and volumes



Cost Data: Unit costs, delay costs, other costs



Spatial Data: Grid, state and regional boundaries



Methodological Data: Operating procedures, stressor response functions



Physical Data: NA



Impact Data: Buckling data for validation

Collecting: Climate Data

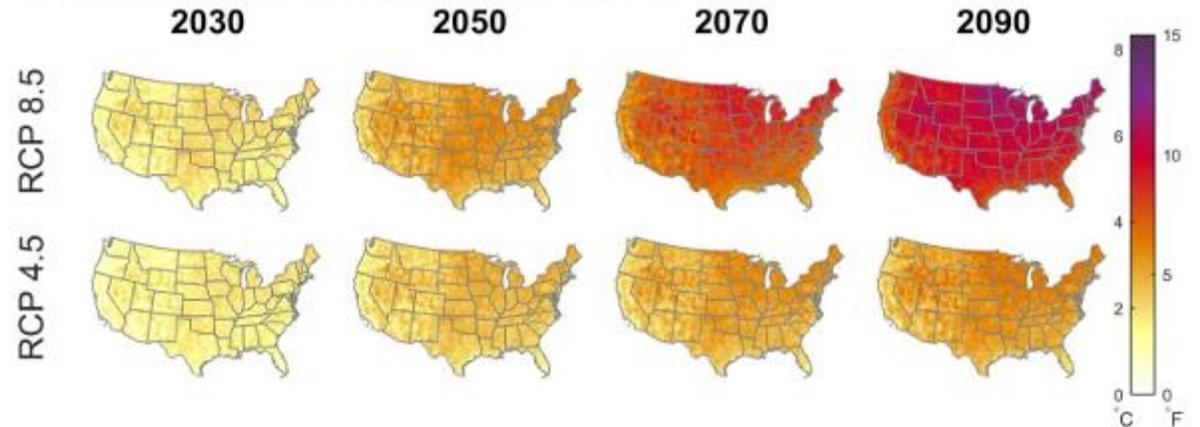


- Consistent with CIRA
- Localized Constructed Analogs (LOCA)
 - 5 representative models
 - Two Representative Concentration Pathways (RCPs) and observed baseline
 - Daily maximum temperature
- NetCDF format
- Approximately 1.2 billion data points

Table 1.1. CMIP5 GCMs Used in the Analyses of this Technical Report

Center (Modeling Group)	Model Acronym	Availability		References
		LOCA	SNAP	
Canadian Centre for Climate Modeling and Analysis	CanESM2	X		Von Salzen et al. 2013 ²¹
National Center for Atmospheric Research	CCSM4	X	X	Gent et al. 2011 ²² Neale et al. 2013 ²³
NASA Goddard Institute for Space Studies	GISS-E2-R ²⁴	X	X	Schmidt et al. 2006 ²⁵
Met Office Hadley Centre	HadGEM2-ES	X		Collins et al., 2011 ²⁶ Davies et al. 2005 ²⁷
Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	X		Watanabe et al. 2010 ²⁸

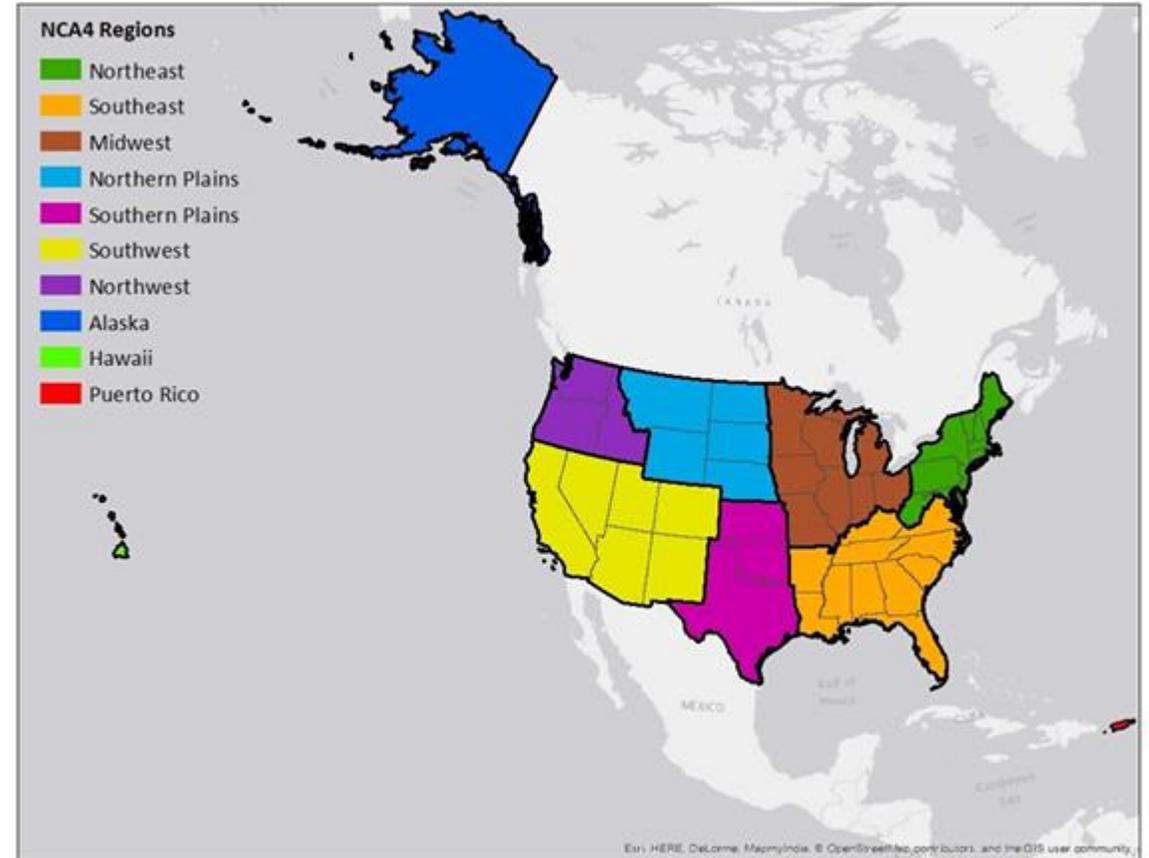
Figure 1.7. Change in Mean Annual Temperature Relative to the Reference Period (1986-2005) across the Contiguous U.S. (Average across the Five LOCA GCMs)



Collecting: Spatial Data



- Climate data grid
 - Native LOCA grid is 1/16th degree
- National Climate Assessment (NCA) Regions
- Conversion by weighted average



Collecting: Methodological Data



- Operating procedures for reactive adaptation
- Equations to estimate:
 - Stress Free Temperature (SFT)
 - Rail temperature
 - Expected buckling probability
 - Delay

RISK ANALYSIS BASED CWR TRACK BUCKLING SAFETY EVALUATIONS

Andrew Kish

Gopal Samavedam

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



U.S. Department of
Transportation
**Federal Railroad
Administration**

Track Buckling Prevention: Theory, Safety Concepts, and Applications

Collecting: Impact Data



- Buckling data for validation
- Limited data but serves as a ground truth
- More details on the validation to come later

MODELLING THE IMPACTS OF CLIMATE CHANGE ON CITIES: ECONOMIC COSTS OF RAIL BUCKLE EVENTS



ARCADIA FACTSHEET 9

Contact: jim.hall@eci.ox.ac.uk katie.jenkins@ouce.ox.ac.uk

As the effectiveness of a cities transport system is central for business, employees, and economic competitiveness damage to the system could be severe and far-reaching. In the UK high temperatures can directly damage railway lines due to buckling. This factsheet outlines a method for estimating the frequency of future buckle events under climate change. Economic costs of rail buckles are estimated and benefits of improved rail infrastructure assessed.



Context

- Railway networks are associated with an increased occurrence of rail buckling during high temperatures.
- A buckle can be defined as a track misalignment serious enough to cause derailment, which can be caused by forces produced by the metal expanding under high temperatures and by subsequent disturbance caused by a train.
- Speed restrictions are introduced when certain temperature thresholds are passed to reduce the risk of derailment.
- Theoretically, well maintained track should not be vulnerable to buckling up to ambient temperatures of -39.3°C . However, severe buckles have been reported to occur when the maximum daily temperature is over 25°C .
- The majority of severe events occur over 27°C in London and the South-East, suggesting that track is of poorer condition.
- During the 2003 summer heatwave 137 buckle events were reported, at a cost of $\sim\text{£}2.5$ million for repairs and delays. Extensive buckle related delays were also seen during the 2006 heatwave event.

Method

- The study provides an assessment of the number of days when one or more buckle events could occur in the study area and associated repair costs.
- Spatial temperature data from the urban spatial Weather Generator is used to facilitate an analysis of rail buckling under future climate change.
- Based on a study of historic buckle events and the corresponding temperature at the Heathrow weather station, it is assumed that buckle events could occur across London where daily maximum temperature (TMax) exceeds 27°C (Fig. 1).
- The probability of one or more buckle events occurring on a day when the temperature threshold is passed is estimated based on published studies.
- The cost of repairs following a rail buckle are estimated as $\text{£}10,000$ per buckle.

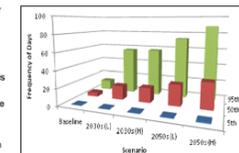
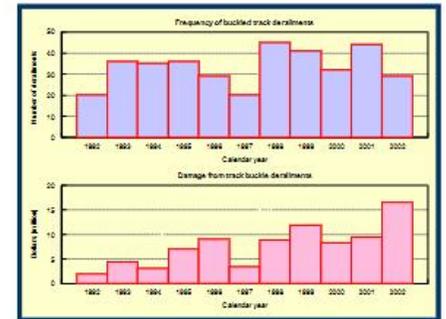


Fig. 1: The annual frequency of days which exceed 27°C at the grid cell corresponding to Heathrow for the baseline, 2030s and 2050s time periods and high (H) and low (L) emission scenarios. Results are provided at the 5th, 50th, and 95th percentile, reflecting the range of results provided by the urban spatial Weather Generator

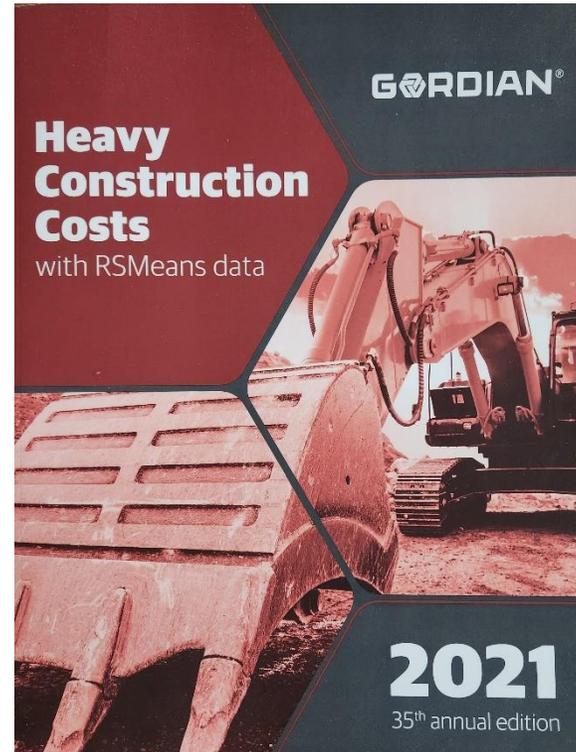


Track buckling illustrations and accident statistics

Collecting: Cost Data



- Cost of delay for slowdown
 - Passenger unit cost
 - Business vs pleasure
 - Bulk vs intermodal unit cost
 - Cost of crew, locomotives, and fuel.
 - Cost to public
- Cost of delay from repair
 - Passenger unit cost
 - Business vs pleasure
 - Bulk vs intermodal unit cost
 - Cost of crew, locomotives, and fuel.
 - Cost to public
- Cost of repair



U.S. Department of
Transportation
Office of the Secretary
of Transportation

Under Secretary for Policy

1200 New Jersey Avenue, S.E.
Washington, DC 20590

July 9, 2014

MEMORANDUM TO: Secretarial Officers
Modal Administrators

From: Peter Rogoff 
Acting Under Secretary for Policy, x64540

Prepared by: Roberto Ayala
Economist, Office of Economic and Strategic Analysis, x64825

Subject: Revised Departmental Guidance on Valuation of Travel Time in
Economic Analysis

The value of travel time is a critical factor in evaluating the benefits of transportation infrastructure investment and rulemaking initiatives. Reduction of delay in passenger or freight transportation is a major purpose of investments, and rules to enhance safety sometimes include provisions that slow travel. As the Department expands its use of benefit-cost analysis in evaluating competitive funding applications under such programs as the TIGER Grant program and the High-Speed Intercity Passenger Rail program, it is essential to have appropriate, well-reasoned guidance for valuing delays and time savings.

This version of the guidance updates the value of travel time savings with median household income information from the 2012 US Census Bureau and salary information from the Bureau of Labor Statistics Occupational Handbook 2012. The household income data are drawn from the Census Bureau's American Community Survey, and are not released until the September following the year in which they are collected; the 2012 data are thus the most recent data available. The percentages of earnings used to determine the value of travel time savings (shown in tables 1 and 2) remain unchanged. The revised dollar values of travel time savings are shown in tables 3, 4, and 5. We have also revised our estimate of future growth in real incomes based on revised projections from the Congressional Budget Office (see page 14).

DOT published its first guidance on this subject, "Departmental Guidance for the Valuation of Travel Time in Economic Analysis," on April 9, 1997, to assist analysts in developing consistent evaluations of actions that save or cost time in travel. That memorandum recommended an array of values for different categories of travel, according to purpose, mode and distance. For each category, the Guidance specified a percentage of hourly income that would normally be used to determine the value per hour of savings in

Processing

- **Cleaning**

- Only include Class 1
- Only include operational
- Eliminate rail outside of US

- **Filling Gaps**

- Missing volumes
- Look to surrounding grids

- **Producing**

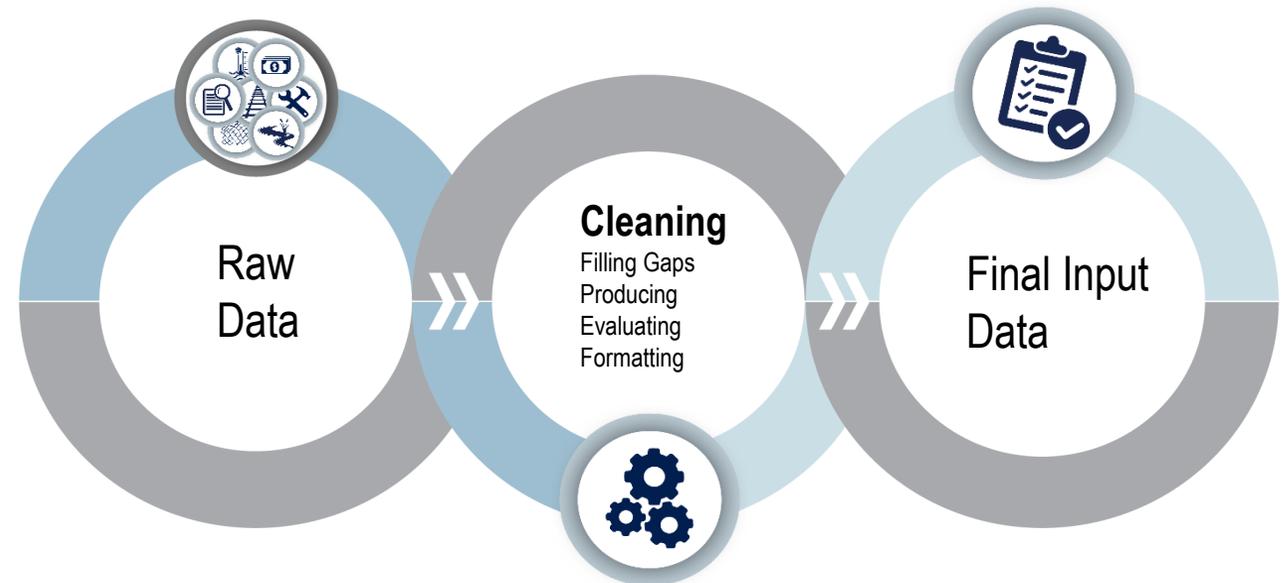
- Passenger vs freight ratio

- **Evaluating**

- Rural vs urban traffic volumes

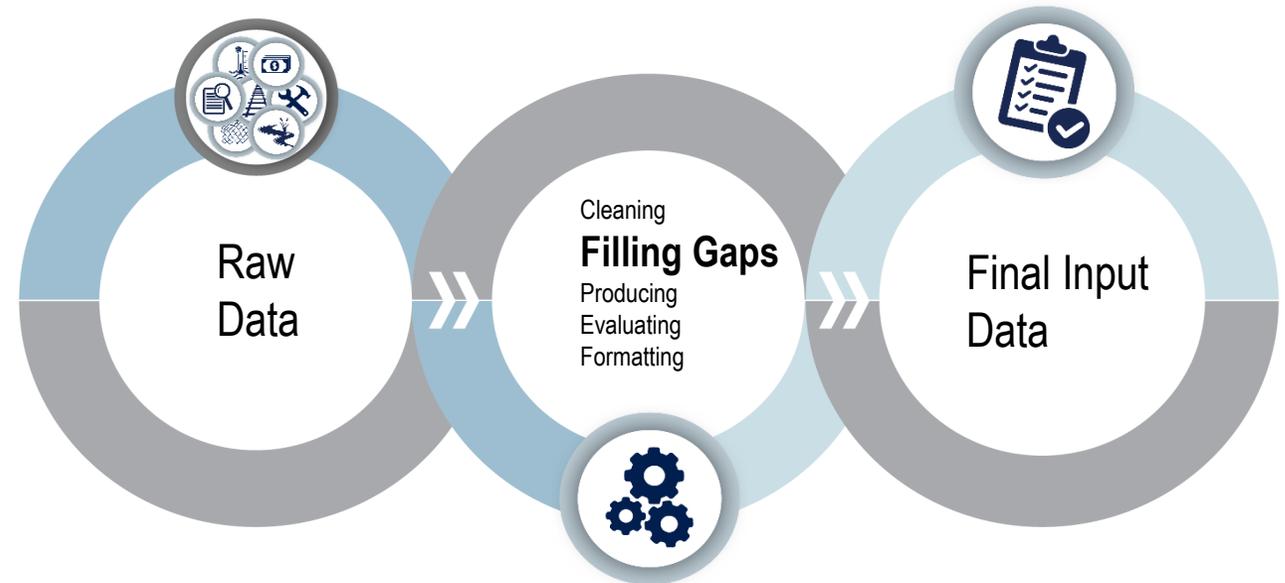
- **Formatting**

- Grid level tables for reading



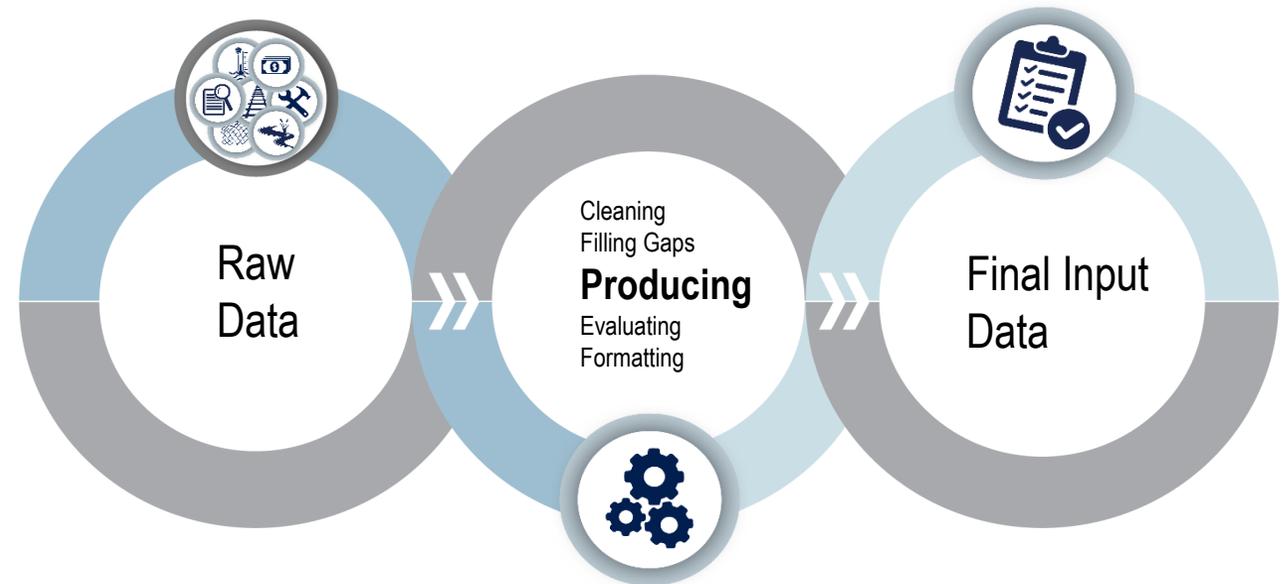
Processing

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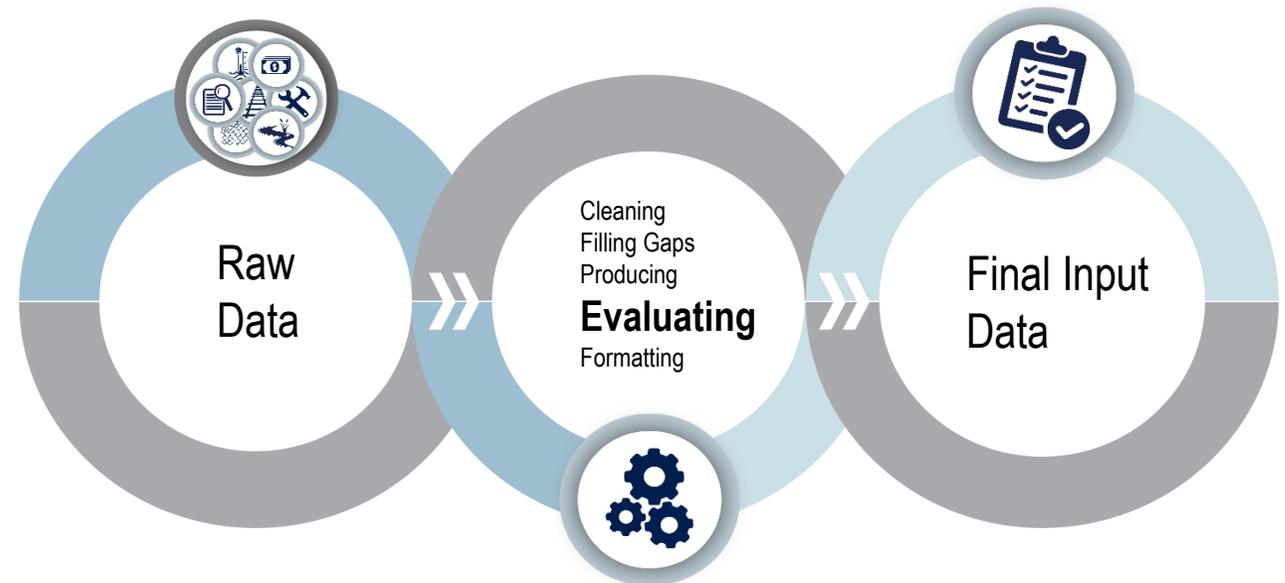
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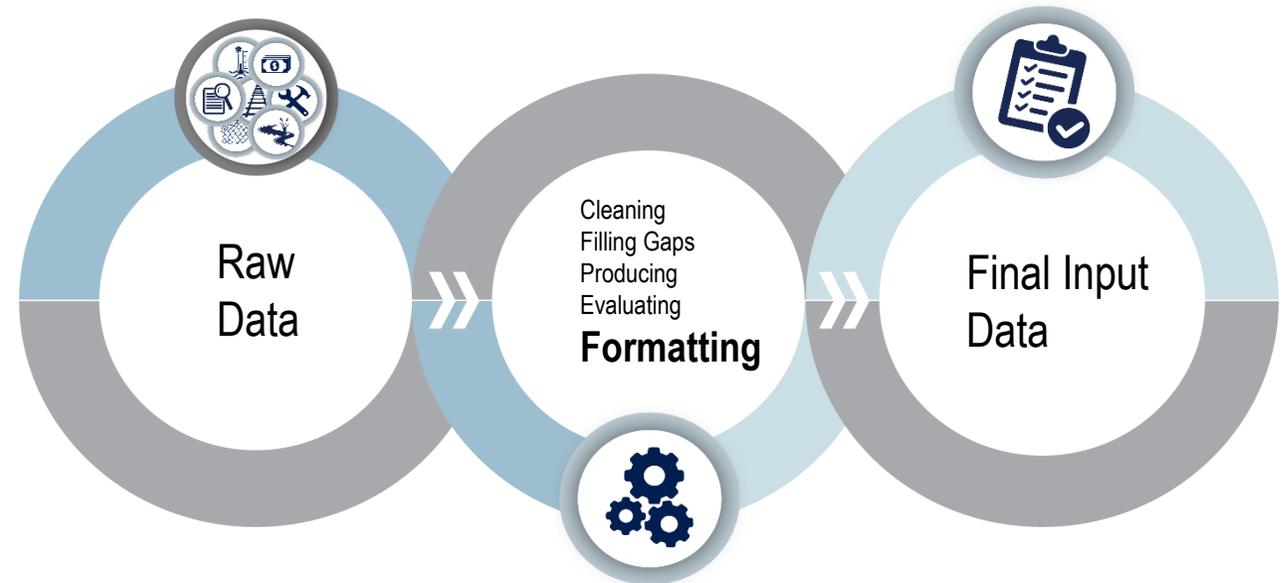
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Summary so far

1»

The rail analysis is designed to estimate physical and economic damages of climate change

2»

Rail system is a \$80 billion dollar industry that carries 30 million people annually

3»

Many data sources had to be collected and processed for the analysis

Pause for Questions



Connecting

- Establish analytical structure
 - Three adaptation scenarios laid out by CIRA
 - **5 cost and impact scenarios**
 - Costs not included
- Iterative and parallel process → can go back to collecting and processing

	No Adaptation	Reactive Adaptation	Proactive Adaptation
Rail			
Costs include	<ul style="list-style-type: none"> • Costs of replacing track to repair lateral alignment defects in the buckling zone and costs of re-aligning rail in adjoining zones 	<ul style="list-style-type: none"> • Costs of replacing track to repair lateral alignment defects in the buckling zone and costs of re-aligning rail in adjoining zones • Costs of delays that occur due to track buckling and repair, as well as delays associated with blanket speed reductions 	<ul style="list-style-type: none"> • Costs of purchasing, installing, and maintaining the track temperature sensors, and related software infrastructure • Costs of delays associated with risk-based speed reductions
Costs do not include	<ul style="list-style-type: none"> • Costs of derailment that may result from track buckling • Costs of routine (non-climate driven) track maintenance, including winter maintenance 	<ul style="list-style-type: none"> • Costs of derailment that may result from track buckling • Costs of developing and implementing the speed orders • Costs of routine (non-climate driven) track maintenance 	<ul style="list-style-type: none"> • Costs of routine (non-climate driven) track maintenance

Connecting

- Stressor response functions

Expected buckling events

$$e_b = (P_b \times P_T \times n_t \times 365 \times L) / (L_t) \quad (1)$$

where

- P_b probability of buckling at rail temperature
- P_T annual rail temperature frequency
- n_t number of trains per day
- L total length of track
- L_t length of train

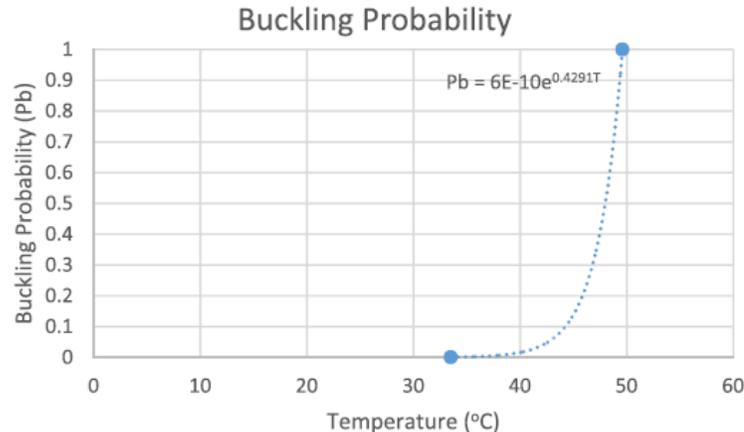


Fig. 1. Buckling probability (P_b).

Reactive Delay

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

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

$$DM_g = TDM_g * T_d * I_d \quad (2)$$

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

Proactive Delay

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

where

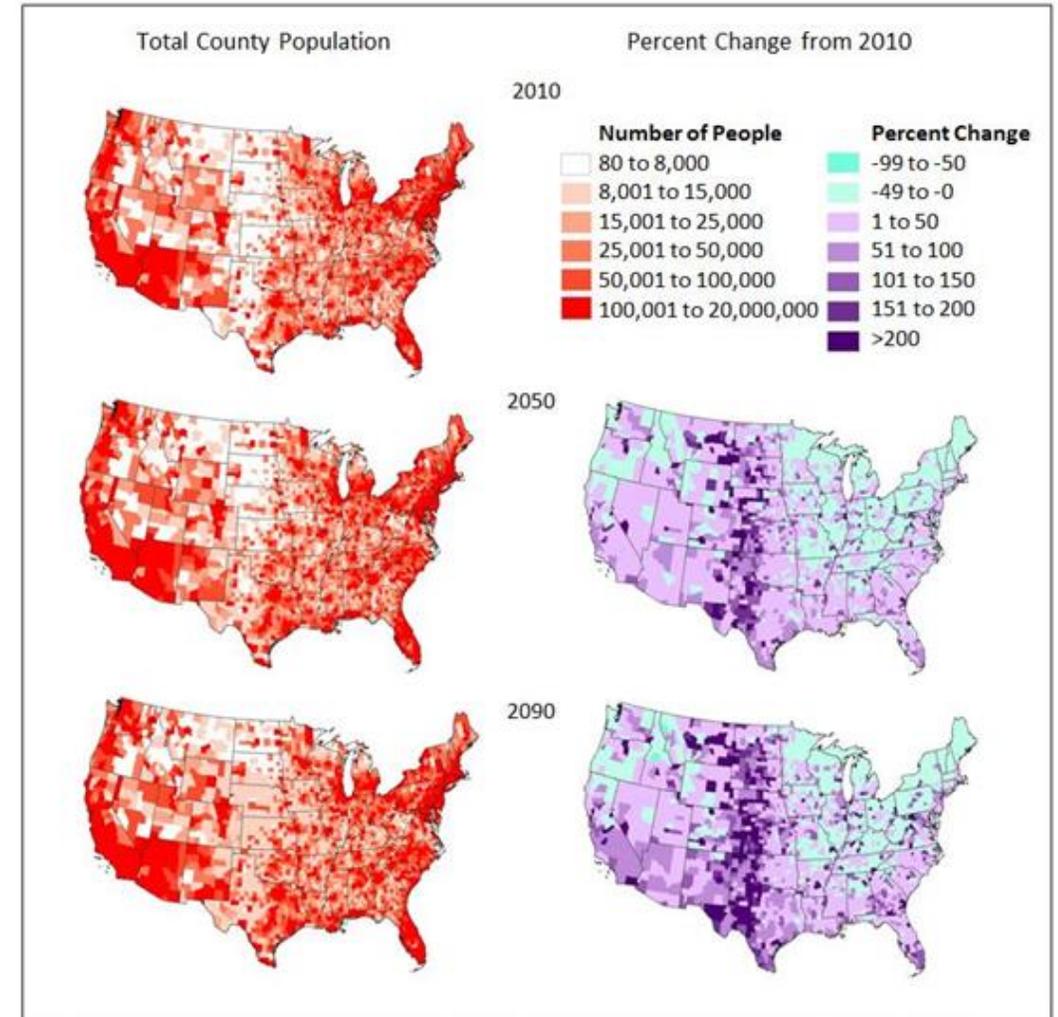
- V_r Reduced speed
- V_{max} Permissible maximum authorized line speed
- P_b(T) Buckling probability at track temperature, T
- P_b(T_L) Buckling probability at limiting temperature, T_L

Connecting



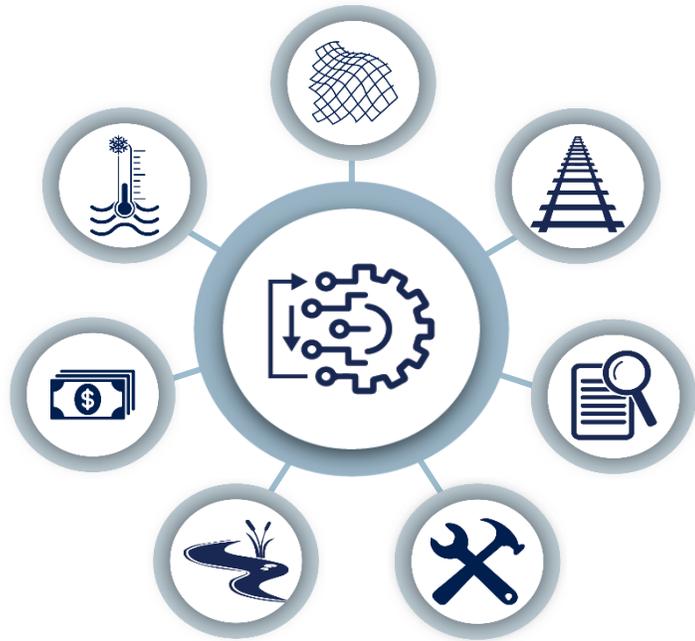
- Model boundaries and assumptions
 - Baseline period is from 1950 to 2005
 - Subset of baselines
 - ½ degree resolution
 - 20-year era level reporting in 2030, 2050, 2070 and 2090
 - Undiscounted and 3% discount rate
 - Costs adjusted for population and GDP growth
 - Do not quantify derailment
 - **Many other highly specific assumptions**

Figure 1.4. Projected County-Scale Population Change



Connecting

- Data to be produced
- Calculations often validated by hand before producing model



Derived climate variables

1. Restriction events
2. Average max summertime temperature
3. Min, allowable and max temperature for Eb
4. Pt for Eb

Infrastructure variables

1. Rail temperature $T_{rail} = \frac{3}{2} * T_a$
2. Rail SFT (vintaging) $SFT = \frac{3}{4} * T_{max}$
3. Pb and Eb (reactive and proactive)
4. Risk base speed reduction

Final Metrics

1. No Adaptation: DM from buckling, repair cost from buckling
2. Reactive: DM for speed order, DM from buckling, repair cost from buckling
3. Proactive: DM from risk-based speed order, investment cost

Producing



- Development of model
 - Over 1500 lines of code contained in 10 scripts and functions
- Iteration of model
 - QC process continues as figments emerge in the model
 - Over 50 runs saved

```
1
2 %This script will run and save all rail analyses
3 dirMain = cd;
4
5 out_folder=inputdlg(' Name the folder you would like to save the results in?');
6 mkdir(char(fullfile(cd,out_folder)))
7
8 dirData = char(fullfile(cd,out_folder));
9
10 %Reactivi 302
11 cd('Reac: 303
12 New_Reac: 304
13 cd(dirMa: 305
14 %Bucklinj 306
15 cd('No A: 307
16 Eb_calc_! 308
17 cd(dirMa: 309
18 %Bucklinj 310
19 cd('Proa: 311
20 Eb_calc 312
21 cd(dirMa: 313
22 314
23 %Output : 315
24 cd('Outp: 316
25 EPARailO: 317
26 318
27 cd(dirMa: 319
302
303 %Eb for CC reactive scenario
304 Eb_mile_cc_adjust = zeros(num.crus,num.years,num.years,num.models,num.scenarios);
305
306 for scen = 1:num.scenarios
307     for model = 1:num.models
308         %Set directories and load in data
309         cd(cc_dir)
310         filename = strcat(cc_names(model),'-scenario(scen),'_tmaxmax.mst');
311         function [ edges, num_thresh ] = PDF_f_5( tmax )
312
313         %create evaluation parameters
314         x_min = floor(min(tmax));
315         x_max = ceil(max(tmax));
316         min_edge = floor(x_min/5)*5;
317         max_edge = ceil(x_max/5)*5;
318         x_range = x_max-x_min;
319         edge_range = max_edge-min_edge;
320         num_edge = edge_range/5;
321
322         edges = zeros(1,num_edge+1);
323         edges(1) = floor(x_min/5)*5;
324         edges(num_edge+1) = ceil(x_max/5)*5;
325
326         for i=2:num_edge
327             edges(i) = edges(i-1)+5;
328         end
329
330         [_,edges] = histcounts(tmax,edges);
331
332         tmax_sort=sort(tmax);
333
334         num_thresh = zeros(1,length(edges)-1);
335         for i=1:length(edges)-1
336             logic2 = tmax>edges(i);
337             logic3 = tmax<edges(i+1);
338             logic = logic2.*logic3;
339             num_edges=sum(logic);
340             num_thresh(i) = num_edges;
341         end
342     end
343 end
```

Producing



- Sensitivity
 - Testing broad assumptions
 - Time of slow order
 - Train speed
 - Restrict Temperature
- Validation
 - Compare output to impact data
 - Used buckling events per mile for comparison
 - Reactive buckling events per mile within 15%
 - No adaptation events 70% higher



No Adaptation					
	Avg. Number of Annual Buckling Events (2018 to 2099)		Annual Cost of Repairs (2018 to 2099, millions \$2018, i		
	RCP 4.5	RCP 8.5		RCP 4.5	RCP 8.5
Historic	802		Historic	\$ 15.8	
CANESM2	2,989	7,696	CANESM2	\$ 58.8	\$ 151.5
CCSM4	4,921	12,772	CCSM4	\$ 96.8	\$ 251.3
GISS-E2-R	1,921	3,500	GISS-E2-R	\$ 37.8	\$ 68.9
HadGEM2-ES	8,495	35,130	HadGEM2-ES	\$ 167.2	\$ 691.3
MIROC5	4,783	8,901	MIROC5	\$ 94.1	\$ 175.2
Average	4,622	13,600	Average	\$ 91.0	\$ 267.8

Reactive Adaptation					
	Avg. Number of Annual Buckling Events (2018 to 2099)		Annual Cost of Repairs (2018 to 2099, millions \$2018, i		
	RCP 4.5	RCP 8.5		RCP 4.5	RCP 8.5
Historic	389		Historic	\$ 7.6	
CANESM2	1,855	5,352	CANESM2	\$ 36.5	\$ 105.3
CCSM4	3,441	9,721	CCSM4	\$ 67.7	\$ 191.3
GISS-E2-R	1,165	2,204	GISS-E2-R	\$ 22.9	\$ 43.4
HadGEM2-ES	6,077	28,260	HadGEM2-ES	\$ 119.6	\$ 556.1
MIROC5	3,307	6,439	MIROC5	\$ 65.1	\$ 126.7
Average	3,169	10,395	Average	\$ 62.4	\$ 204.8

Proactive Adaptation					
	Avg. Number of Annual Buckling Events (2018 to 2099)		Annual Cost of Repairs (2018 to 2099, millions \$2018, i		
	RCP 4.5	RCP 8.5		RCP 4.5	RCP 8.5
Historic	0		Historic	\$ 0.0	
CANESM2	0	0	CANESM2	\$ 0.0	\$ 0.0
CCSM4	0	0	CCSM4	\$ 0.0	\$ 0.0
GISS-E2-R	0	0	GISS-E2-R	\$ 0.0	\$ 0.0
HadGEM2-ES	0	0	HadGEM2-ES	\$ 0.0	\$ 0.0
MIROC5	0	0	MIROC5	\$ 0.0	\$ 0.0
Average	0	0	Average	\$ 0.0	\$ 0.0

Proactive Adaptation with 20% Buckling Events					
	Avg. Number of Annual Buckling Events (2018 to 2099)		Annual Cost of Repairs (2018 to 2099, millions \$2018, i		
	RCP 4.5	RCP 8.5		RCP 4.5	RCP 8.5
Historic	78		Historic	\$ 1.5	
CANESM2	371	1,070	CANESM2	\$ 7.3	\$ 21.1
CCSM4	688	1,944	CCSM4	\$ 13.5	\$ 38.3
GISS-E2-R	233	441	GISS-E2-R	\$ 4.6	\$ 8.7
HadGEM2-ES	1,215	5,652	HadGEM2-ES	\$ 23.9	\$ 111.2
MIROC5	661	1,288	MIROC5	\$ 13.0	\$ 25.3
Average	634	2,079	Average	\$ 12.5	\$ 40.3

Summary so far

1»

The rail analysis methodology is rooted in research performed by the FRA and US DOT

2»

The analysis aims to quantify 3 cost scenarios

3»

Sensitivity and validation are critical to modeling success

Pause for Questions



Interpreting



- Establish categories of interpretation



- **Spatial**
- Ownership
- **Time**
- **Scenario**
- Climate Model
- Asset Type

- Create succinct data

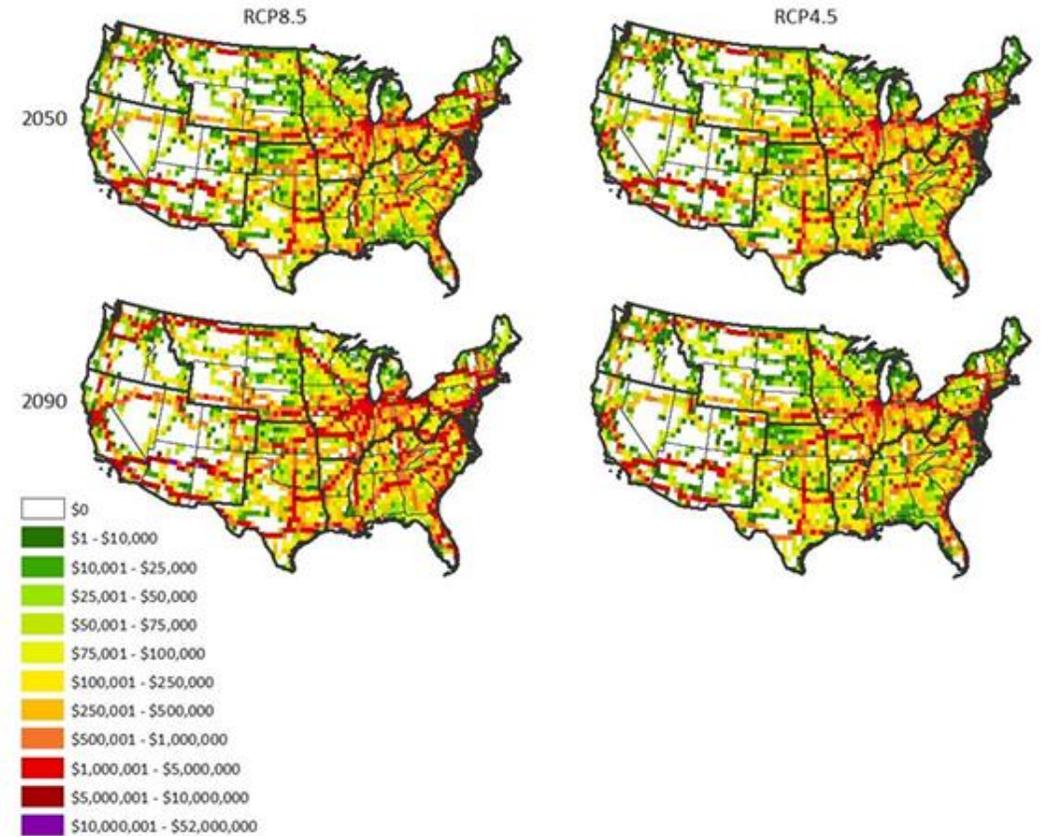


- Establish key trends, patterns and insight



Figure 12.1. Average Annual Reactive Adaptation Costs to the U.S. Rail Network

The maps display the change in reactive adaptation costs relative to the reference period (1950-2013) for the five-GCM average (\$2015, undiscounted) in 2050 (2040-2059) and 2090 (2080-2099).



Interpreting



• Key insights

- Large increase in costs under all scenarios
- No Adaptation shows a large increase in buckling events, delay and cost
- Reactive adaptation shows a large increase in speed orders but helps to offset buckling events
- The Proactive Adaptation scenario shows the risk-based speed orders dramatically reduces the delay cost
- In general, the highest costs are projected to occur in the Southeast and Midwest.

Table 2 Average annual change in costs relative to the baseline (1986–2005) (5-GCM average, billions \$2018, undiscounted)

Infrastructure sector and scenario	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Rail				
No Adaptation	\$11.3	\$5.8	\$45.4	\$8.5
Reactive Adaptation	\$10.2	\$5.4	\$35.9	\$6.6
Proactive Adaptation	\$0.9	\$0.4	\$3.3	\$0.7

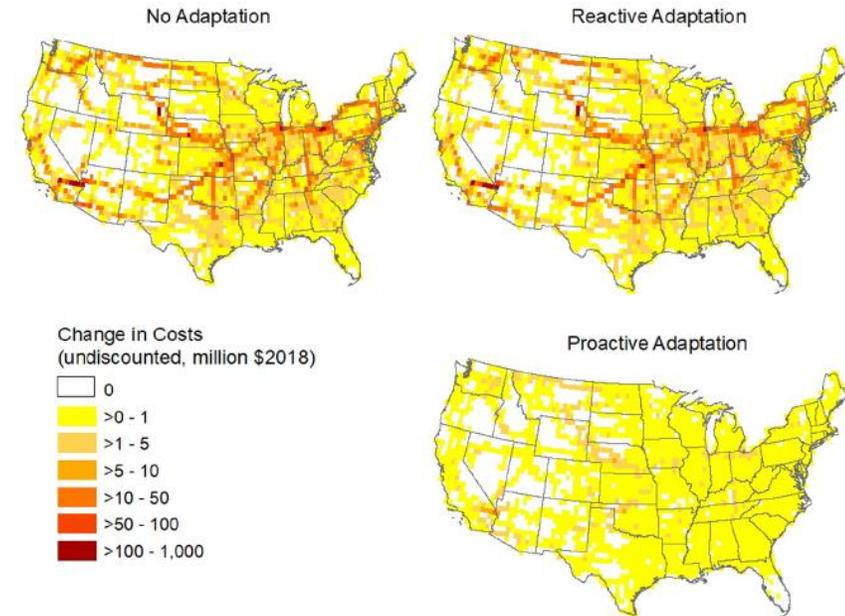
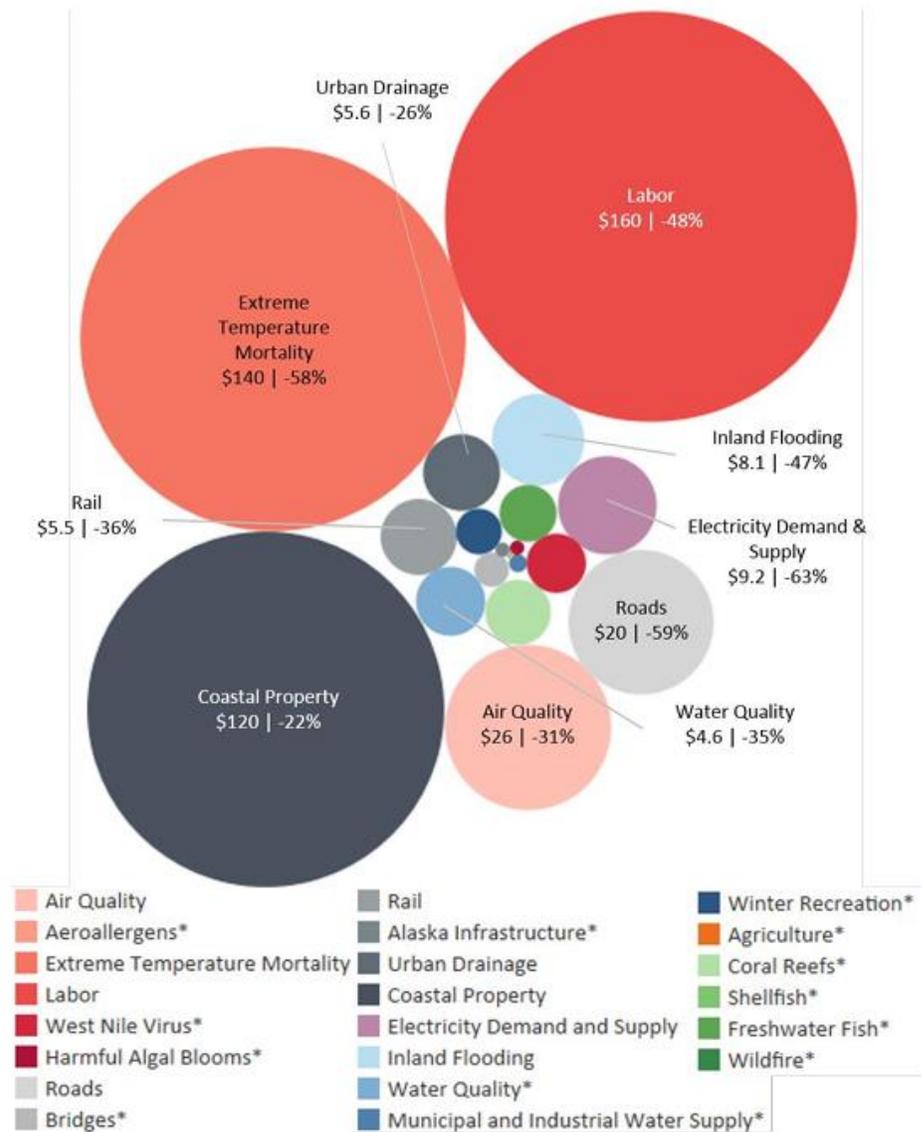
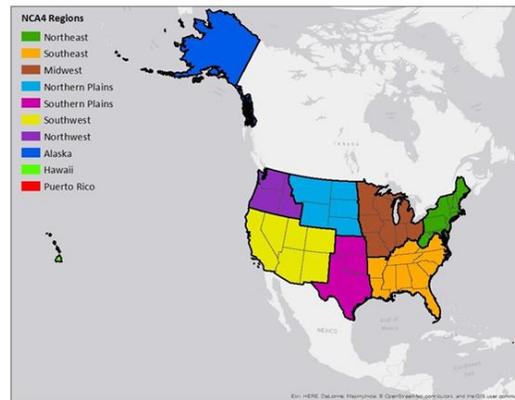


Fig. 1 Change in costs to the U.S. rail network in 2090 relative to baseline (1986–2005) under RCP8.5 (undiscounted, \$2018)

Interpreting

- Key insights across sectors
- How does rail compare to other sectors nationally?
 - 9th highest economic damage
 - 5th highest reduction when comparing RCP 4.5 to RCP 8.5
- Where does rail have the largest relative impact?
 - 3rd in Northern Plains
 - 5th in Midwest



Applying



• Deliverables

- Multi-Model Framework for Quantitative Sectoral Impacts Analysis
 - A Technical Report for the Fourth National Climate Assessment
- Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development
 - Climatic Change
- Impacts of climate change on operation of the US rail network
 - Transport Policy
- Framework for Evaluating Damages and Impacts (FrEDI) data structures

• Which includes

- Asset vulnerability and risk
- Benefit-cost analysis
- Adaptation policy

• In many formats

- 1 Technical report
- 2 published articles
- Data structures (.mat to .R)

Climate Change (2021) 167:44
<https://doi.org/10.1007/s10584-020-03170-w>

Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development

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Received: 4 September 2019 / Accepted: 17 July 2021 / Published online: 19 August 2021
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Abstract
 Changes in temperature, precipitation, sea level, and coastal storms will likely increase the vulnerability of infrastructure across the USA. Using models that analyze vulnerability, impacts, and adaptation, this paper estimates impacts to railroad, roads, and coastal properties under three infrastructure management response scenarios: No Adaptation; Reactive Adaptation; and Proactive Adaptation. Comparing damages under each of these potential responses provides strong support for facilitating effective adaptation in these three sectors. Under a high greenhouse gas emission scenario and without adaptation, overall costs are projected to range in the \$300s of billions annually by the end of this century. The first (reactive) tier of adaptation action, however, reduces costs by a factor of 10, and the second (proactive) tier reduces total costs across all three sectors to the low \$10s of billions annually. For the rail and road sectors, estimated costs for Reactive and Proactive Adaptation scenarios capture a broader share of potential impacts, including selected indirect costs to rail and road users, and are consistently about a factor of 2 higher than prior estimates. The results highlight the importance of considering climate risks in infrastructure planning and management.

Keywords: Rail · Roads · Coastal development · Infrastructure · Proactive/adaptation

1 Introduction

Climate change is affecting infrastructure systems across the USA in far-reaching ways, and impacts are projected to worsen over time in many regions. Extreme temperature and

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12. RAIL

12.1 KEY FINDINGS

- Increasing temperatures are projected to result in significant damages to the U.S. rail system. In response to increased risks of rail cooling, rail operators will be forced to reduce speeds, causing economic damages associated with slower freight and passenger rail. Average cumulative economic damages through 2100 are estimated at \$50 billion under RCP2.6 and \$40 billion under RCP4.5.
- Well-timed proactive adaptation is projected to reduce average cumulative discounted costs through 2100 to \$22 billion under RCP2.6 and \$4.3 billion under RCP4.5.

12.2 BACKGROUND

The U.S. rail network is a critical component of the nation's infrastructure system, connecting U.S. consumers with agriculture, economics, logistics, and manufacturing across the nation and the world.¹ Climate change affects the rail network primarily through projected temperature increases across the U.S. Passenger and freight trains are susceptible to damage during periods of extreme heat, which are expected to increase in frequency as a result of climate change. Specifically, when exposed to temperatures outside of the range of normal operating conditions, steel rail expands and can undergo a displacement or buckling called a "sun kink," increasing the risk of derailments and leading to costly maintenance expenditures and train delays.²

12.3 APPROACH

The purpose of this analysis is to determine the potential risk of climate change to the Class I rail network in the U.S., which comprises 46,000 miles operated by seven railroad companies and carrying both freight and passenger trains.³ To model the existing rail network, the analysis relies on granular data from the National Transportation Data Gateway (NTDG) for active main line and sub main line tracks.⁴ Average daily train traffic volume is derived based on "highway" crossing data from the Federal Railroad Administration's (FRA) Office of Safety Analysis.⁵

The analysis uses the Infrastructure Planning Support System (IPSS) tool, which incorporates engineering knowledge, climate-response algorithms, and climate exposures, to quantify impacts of climate change to the rail system resulting from climate change.⁶ The tool quantifies the costs of reactive adaptation and proactive adaptation under RCP2.6 and RCP4.5 for each of the five ICMA, and represent impacts above and beyond what is spent on periodic maintenance. The reactive adaptation costs are

¹ U.S. Dept. of Transportation, United States Department of Transportation, Federal National Administration, Available online at <https://www.transportation.gov/>

² U.S. Dept. of Transportation, United States Department of Transportation, Federal National Administration, Available online at <https://www.transportation.gov/>

³ U.S. Dept. of Transportation, United States Department of Transportation, Federal National Administration, Available online at <https://www.transportation.gov/>

⁴ U.S. Dept. of Transportation, United States Department of Transportation, Federal National Administration, Available online at <https://www.transportation.gov/>

⁵ U.S. Dept. of Transportation, United States Department of Transportation, Federal National Administration, Available online at <https://www.transportation.gov/>

⁶ U.S. Dept. of Transportation, United States Department of Transportation, Federal National Administration, Available online at <https://www.transportation.gov/>

Transport Policy (2020) 102:191
 Contents lists available at ScienceDirect
Transport Policy
 journal homepage: www.elsevier.com/locate/transportpol

Impacts of climate change on operation of the US rail network

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ABSTRACT
 The rail network in the US is the largest network within any single country at 160,000 miles of Class I tracks. The network is predominantly located in freight tracks with the exception of freight and passenger corridors along the eastern seaboard and in the upper Midwest. This extensive rail network enhances connectivity, but also poses the question of potential vulnerability to climate change over the next century. Specifically, projected changes in temperature highlight the vulnerability of steel to temperature increases and the accompanying issue of track expansion, which under current operating practices can lead to train delays and in the most extreme case can lead to derailments. In this study, the issue of potential impacts to the rail network are analyzed in terms of the cost of reactive adaptation, proactive adaptation, and no adaptation. The rail network operates at approximately 100 miles per hour, and the expansion of steel tracks under a high greenhouse gas emission scenario is projected to range from 100 to 400 billion under a high emission scenario. However, these costs could be reduced by up to an order of magnitude if current asset management techniques are incorporated into tracks, coupled with adjustments to current speed reduction policies that better manage temperature resulting expansion.

1. Introduction
 The primary freight and passenger rail network in the US comprises 160,000 miles of Class I tracks operated by seven railroad companies (Federal Railroad Administration, 2018). The rail network carries 40% of the freight by volume (measured in tons) and 10% of the freight by weight each year. For this context, each person in the US requires 40 t of freight to be moved each year either through their goods purchased or indirectly through bulk products such as coal which are required to generate electricity for industrial uses (Federal Railroad Administration, 2018). The cost-efficiency of rail transport and cost-to-mile dependence of 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 geographic reach, increasing concern of impacts of climate change on the rail network (Eli et al., 2013). Climate change is a threat to the rail network due primarily to projected temperature increases, though indirect effects from changes in precipitation could also be important.

Thermal strains 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 used throughout to operate in a narrow range that is based on the temperature in which it is originally laid, known as the design normal 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 1000 feet of rail can expand up to 1.5 inches per degree of temperature increase (Vick, 2013). In extreme heat conditions where temperature increases can be several times that, expansion will offset one quickly moved across tracks which will lead to derailments if unhandled. 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 locations, which increases the risk of failure due to track expansion. Currently, the accepted

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<https://doi.org/10.1016/j.tranpol.2020.102191>
 Received 7 December 2019; Received in revised form 26 March 2020; Accepted 21 May 2021
 Available online 29 May 2021
 0967-0702/© 2021 The Author. Published by Elsevier Ltd. This is an open access article under the [CC BY 4.0 International license](http://creativecommons.org/licenses/by/4.0/).

FrEDI Framework for Evaluating Damages and Impacts





Actionable Results

- What does this mean for the rail sector?



Climate change will have a big impact on current rail operation



Current operating procedures are relatively effective



Proactive adaptation can save owners billions



Actionable Results

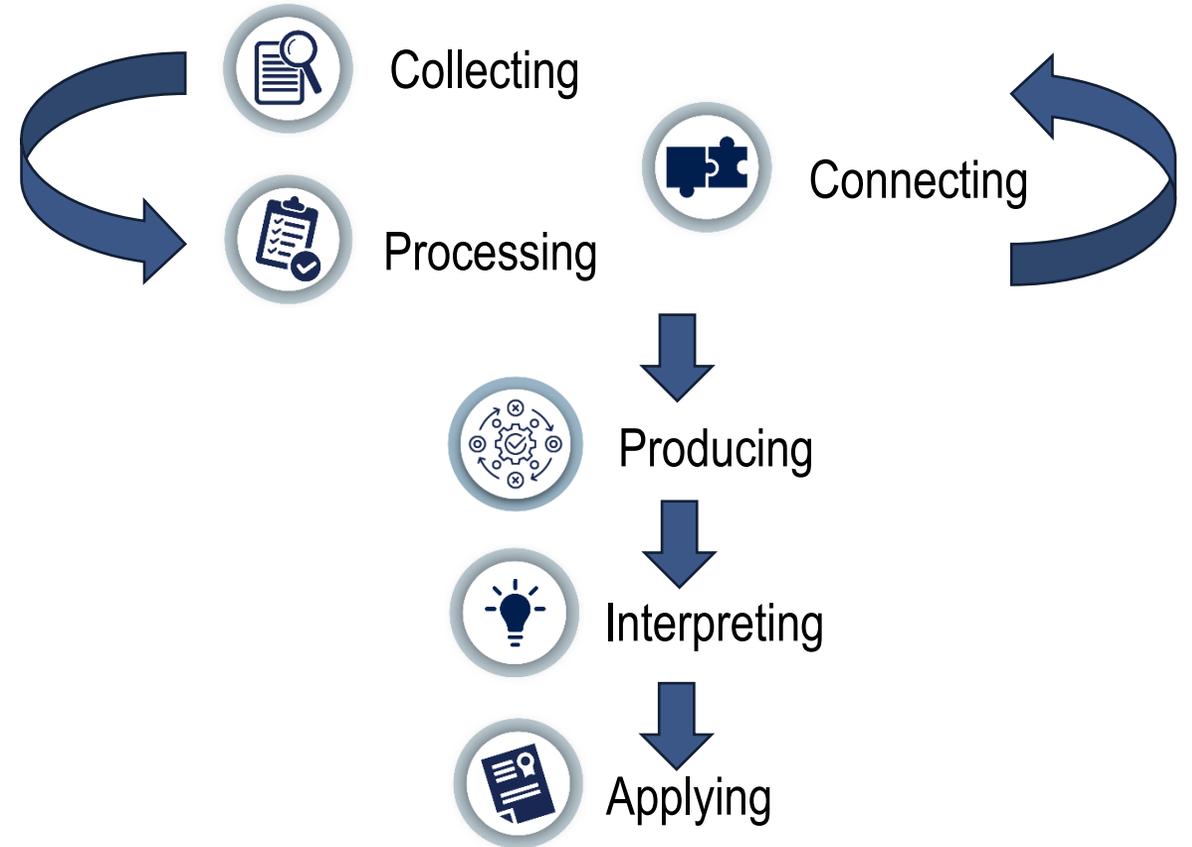
- What types of proactive adaptation have we seen?
 - Paint the rails white
 - Passive temperature control
 - Reinforced foundation and other design alterations
 - Rail sensor network
 - Live temperature monitors
 - Predictive rail temperature monitors
 - Stress free monitors
 - Longitudinal Stress Monitor





Other Applications

- This model has been applied for the Canadian Government and New York State Energy Research and Development Authority
- This framework can be applied across:
 - Sectors
 - Scales
- Other applications
 - Water Utility Climate Alliance
 - Arizona DOT
 - Hillsborough Florida MPO





Other Applications

- Anything you want!
- Climate impacts almost everything
- You just need good data that puts all the pieces together





Summary

- A data driven approach can help streamline, connect and produce actionable data
- There is a lot of data, and it is constantly being produced
- When applied to the rail sector we discovered
 - ① • Climate change will have a big impact on current rail operation
 - ② • Current operating procedures are relatively effective
 - ③ • Proactive adaptation can save owners billions
- More and more innovative technologies will help mitigate the impacts of climate change

Questions and Discussion



Contact

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