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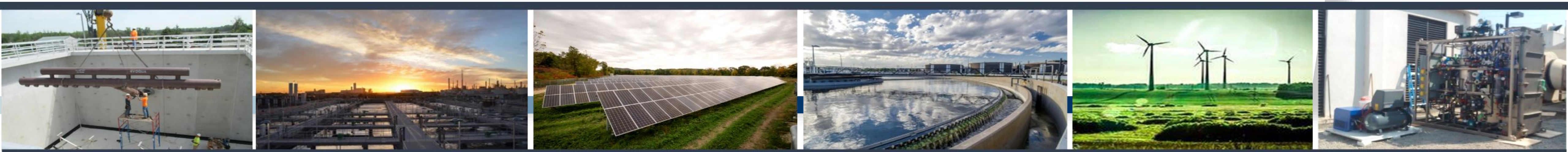
carollo
BLACK & VEATCH
CDM Smith
DSWA Delaware Solid Waste Authority
Los Angeles County Sanitation Districts Converting Waste Into Resources
Stanley Consultants
LA DWP Los Angeles Department of Water & Power

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



Leadership and Excellence in Environmental Engineering and Science

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?

RESILIENT
ANALYTICS

2006

Research and consulting in financial climate impact analysis since 2006

- Data driven decision support for resilient infrastructure
- Based engineering design
- Adapt versus react financial impact
- Full spectrum of assets

2022

Stanley Consultants acquisition

Stanley Consultants INC.

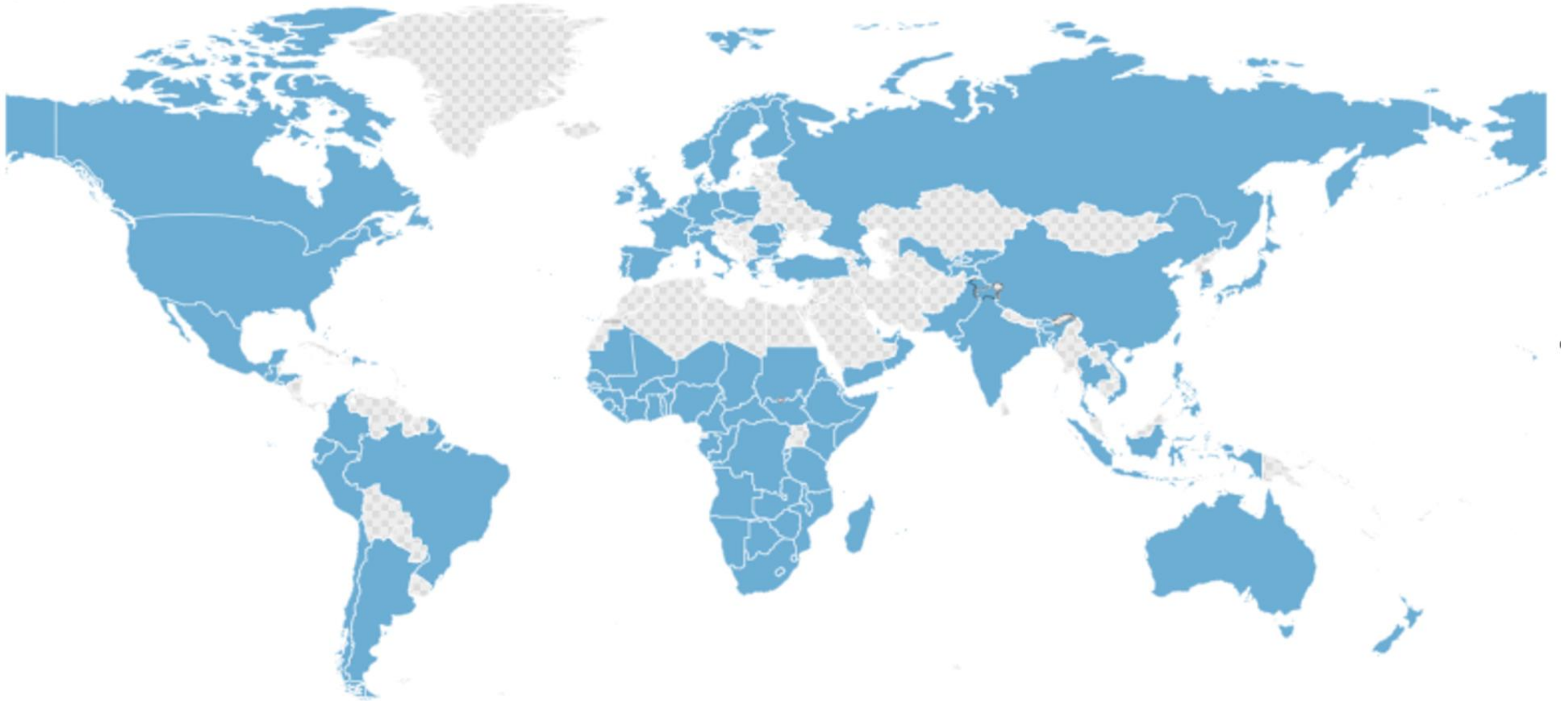
2016

RA incorporated

- International (WB, UN), National (EPA), Local (Counties and Cities), and Private Clients
- 30 peer-reviewed publications
- Multiple peer-reviewed committees

2014

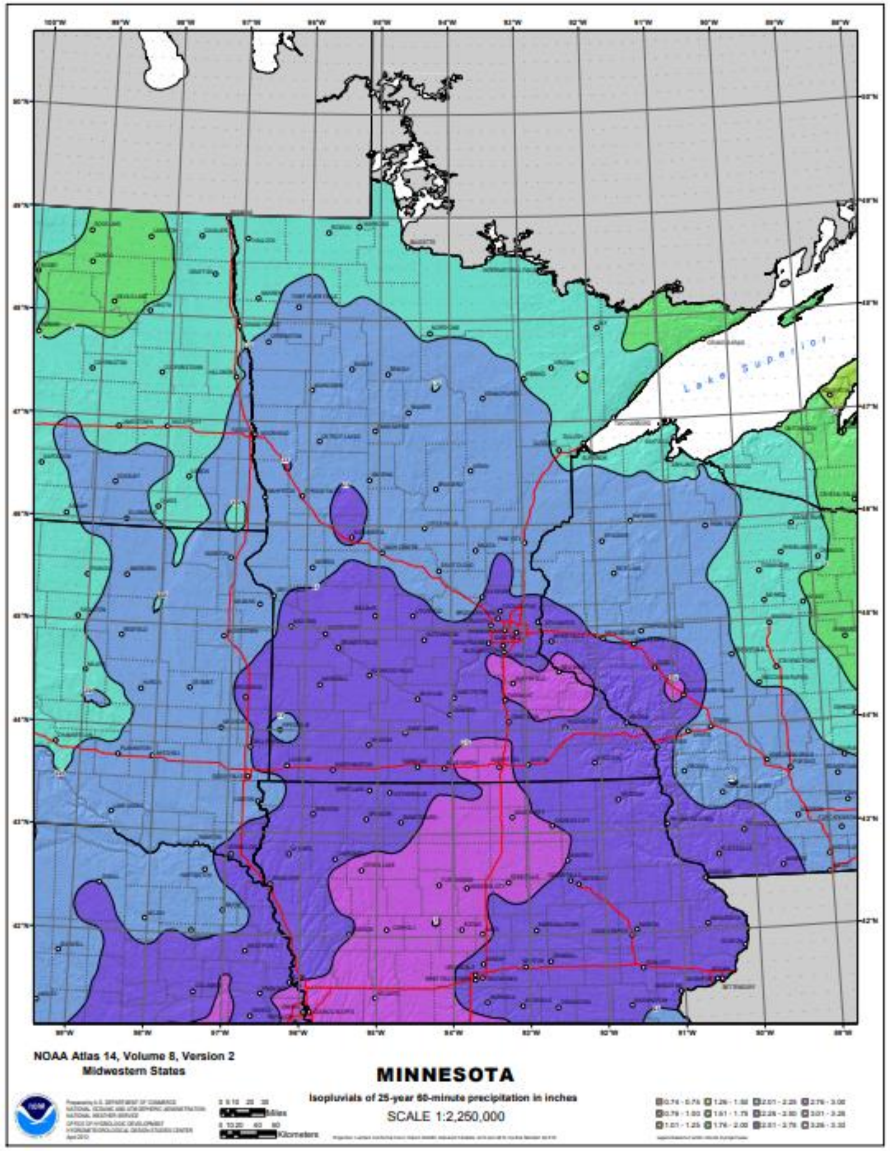
Clients and Analysis Area



United Nations · The World Bank · EPA United States Environmental Protection Agency · New York State of Opportunity | NYSERDA · Arizona ADOT · Water Utility Climate Alliance · Hillsborough MPO Metropolitan Planning for Transportation · MIT Massachusetts Institute of Technology · Boulder County · City of Boulder · Hanes

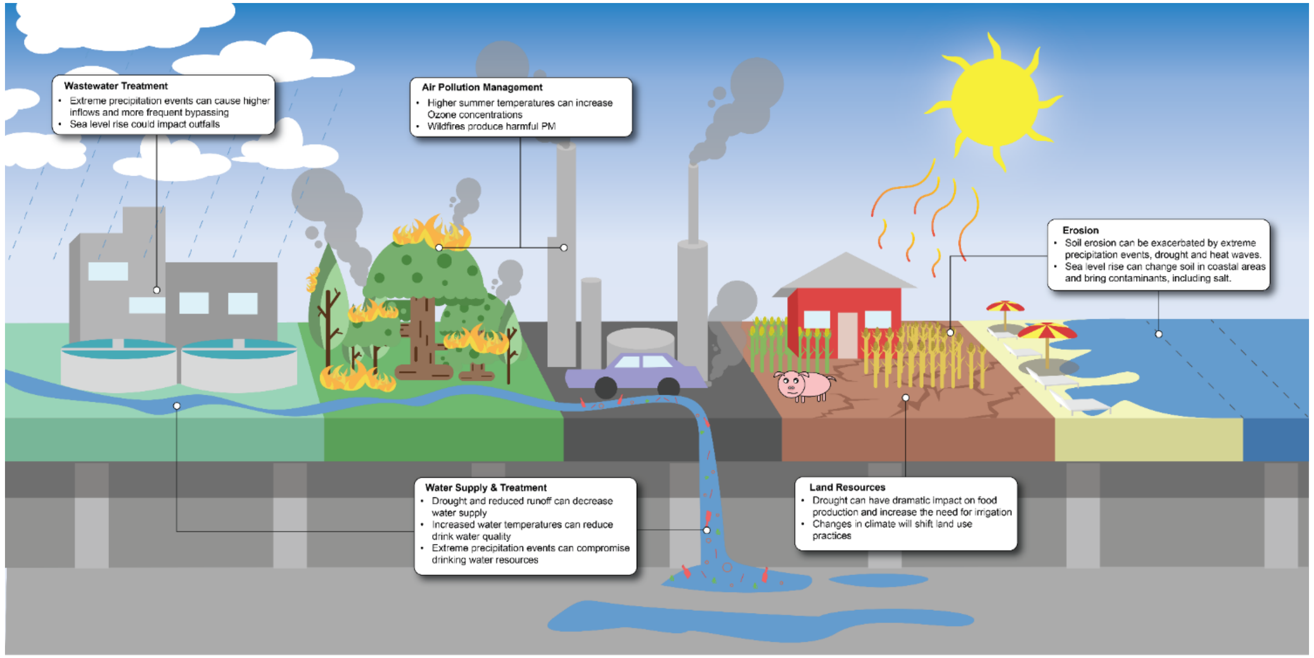
Climate in Engineering Design

- 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

Latest Local News • Live Shows ... CBS NEWS

LOCAL NEWS

How does extreme heat impact rail infrastructure? Baltimore trains put on speed restrictions.

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

- Collecting
- Processing
- Connecting
- Producing
- Interpreting
- Applying

Actionable Results

- Custom
- Operational
- Cost Driven
- Meets Goals

Collecting

Climate Data

Infrastructure Data

Cost Data

Spatial Data

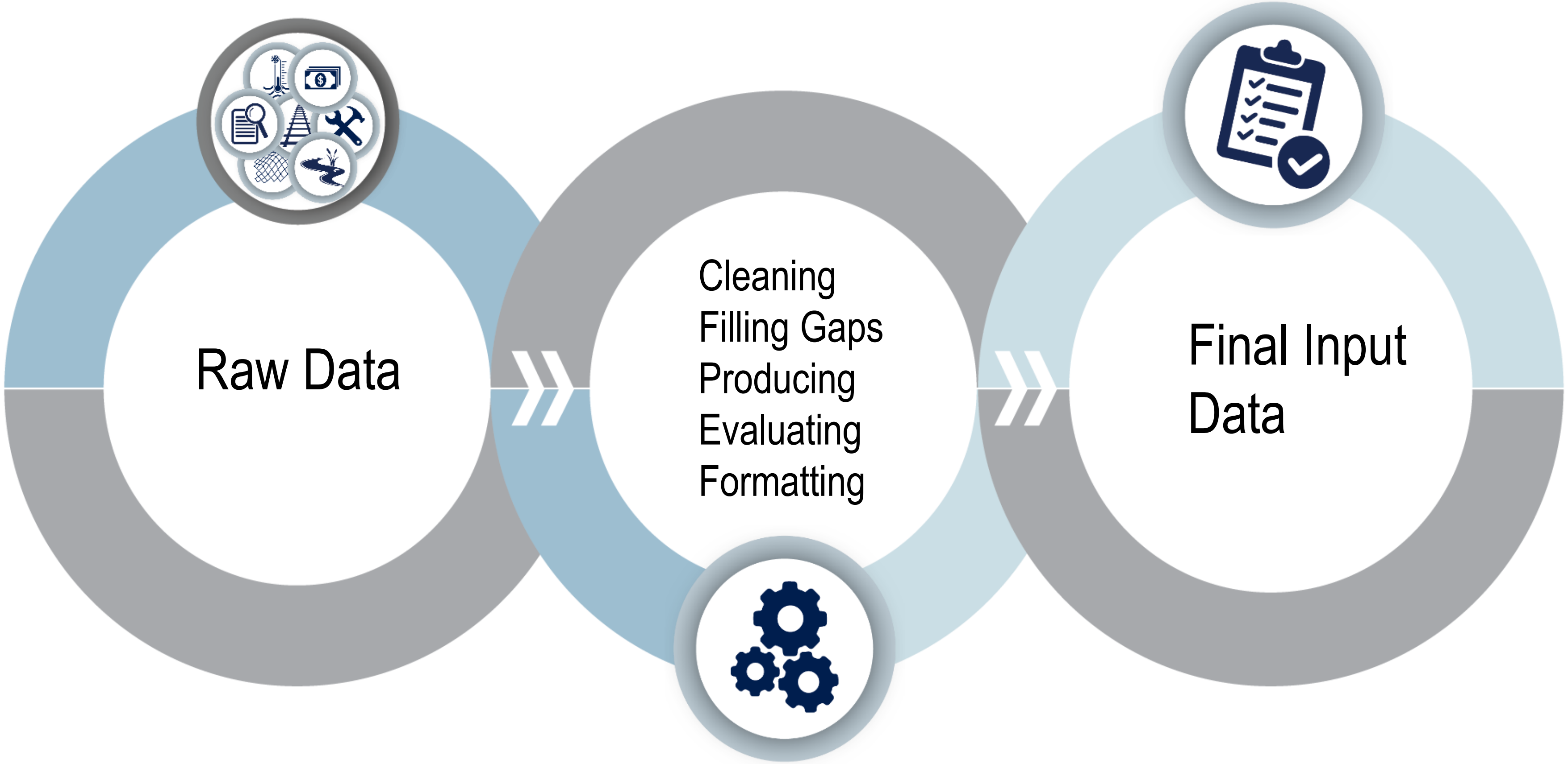
Methodological Data

Physical Data

Impact Data

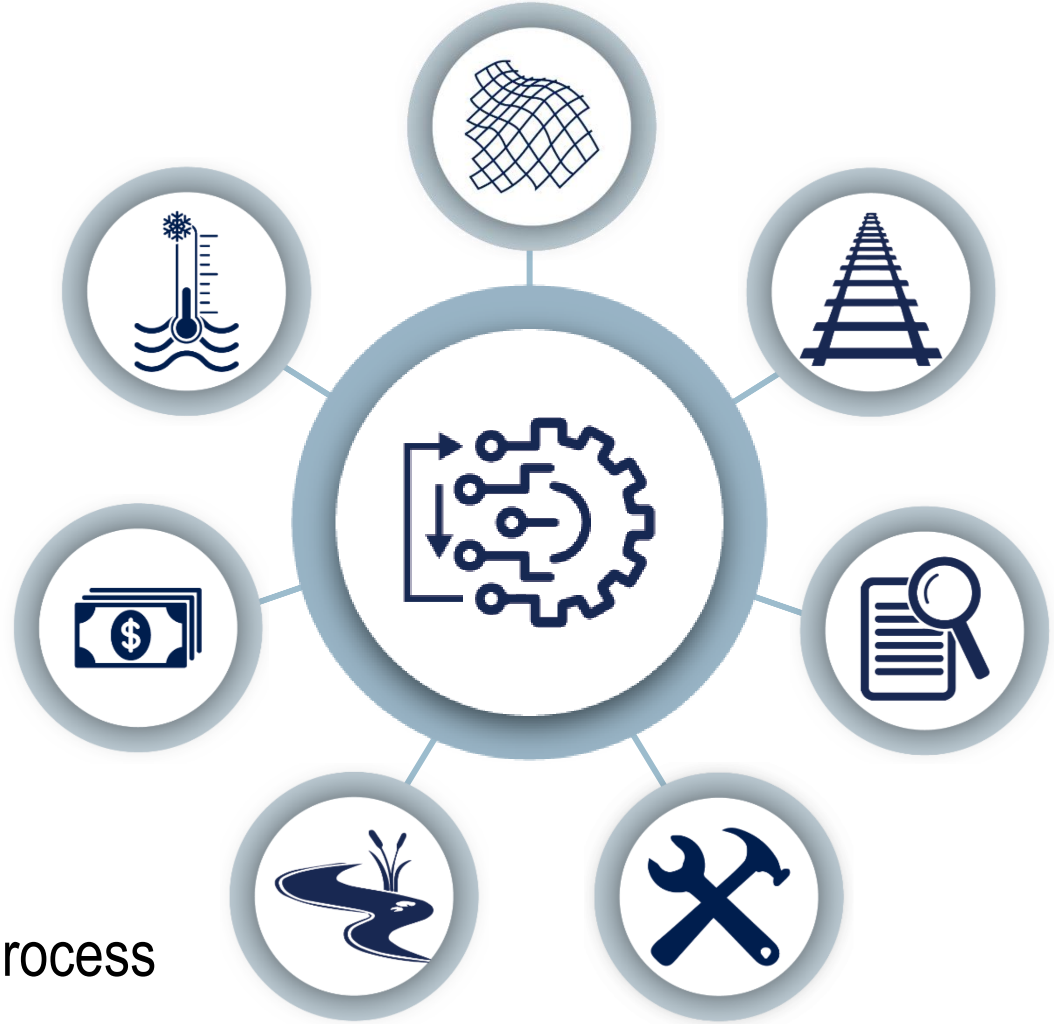
Data Structure
- Data Sources
- Data Format
- Data Size
- Data Updates

Processing


Raw Data
Cleaning
Filling Gaps
Producing
Evaluating
Formatting
Final Input Data

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

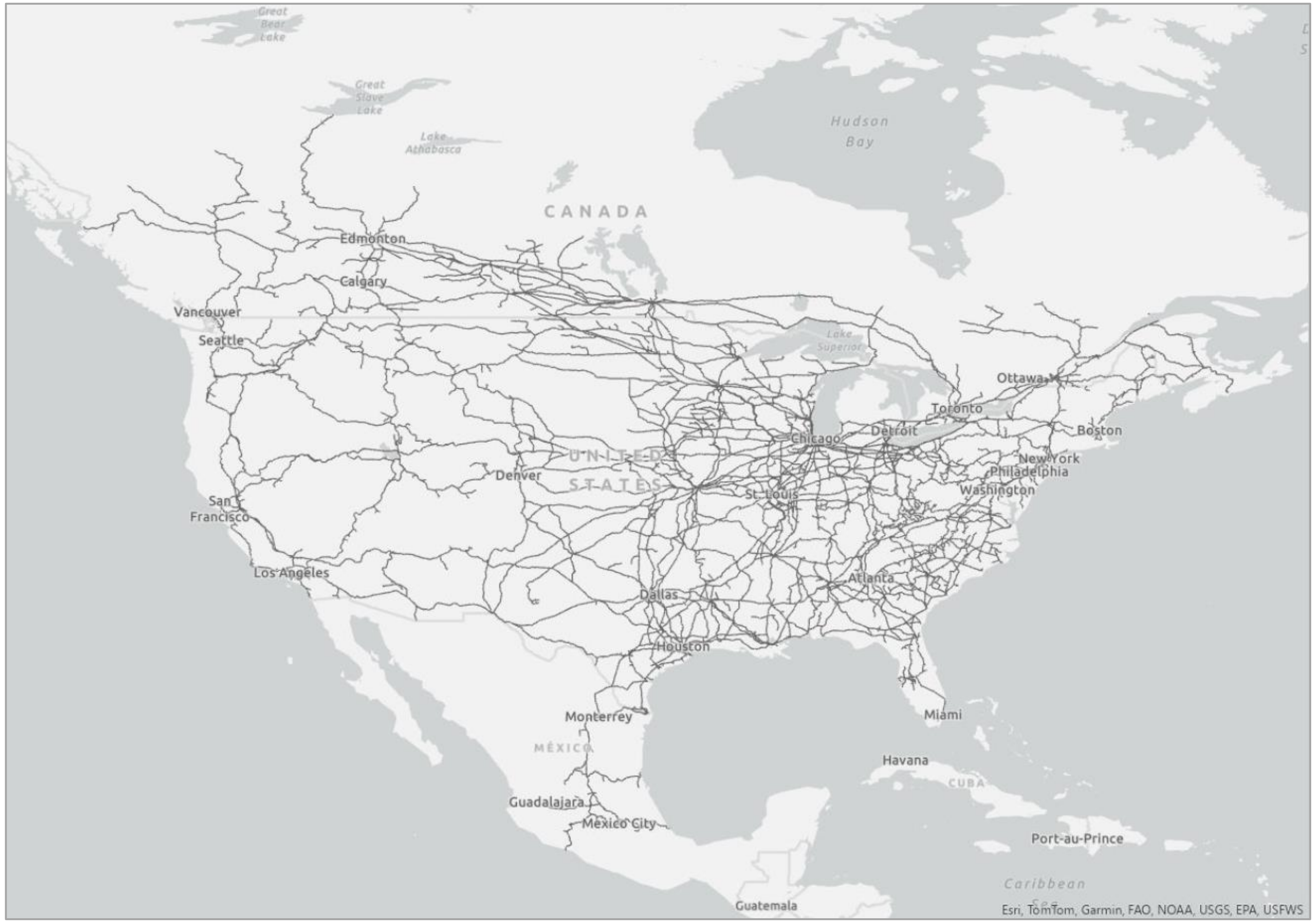
Project Background

- 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)
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
Labor	Lost labor supply hours due to changes in hot and cold temperature, including extreme temperatures	Lost Wages
West Nile Virus	Impact of temperature on number of West Nile Neuroinvasive Disease cases	VSL and hospitalization costs
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
★ **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
★ **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

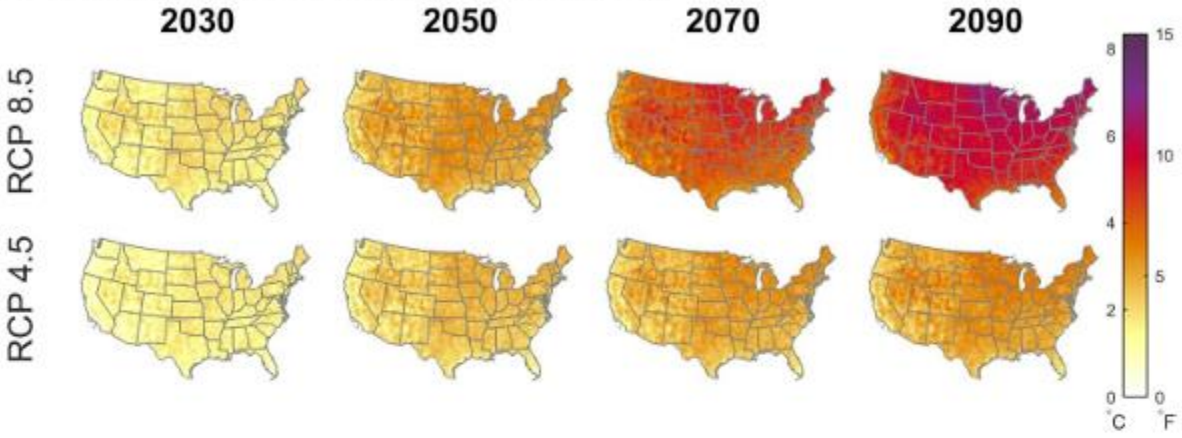
Collecting: Climate Data

- 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

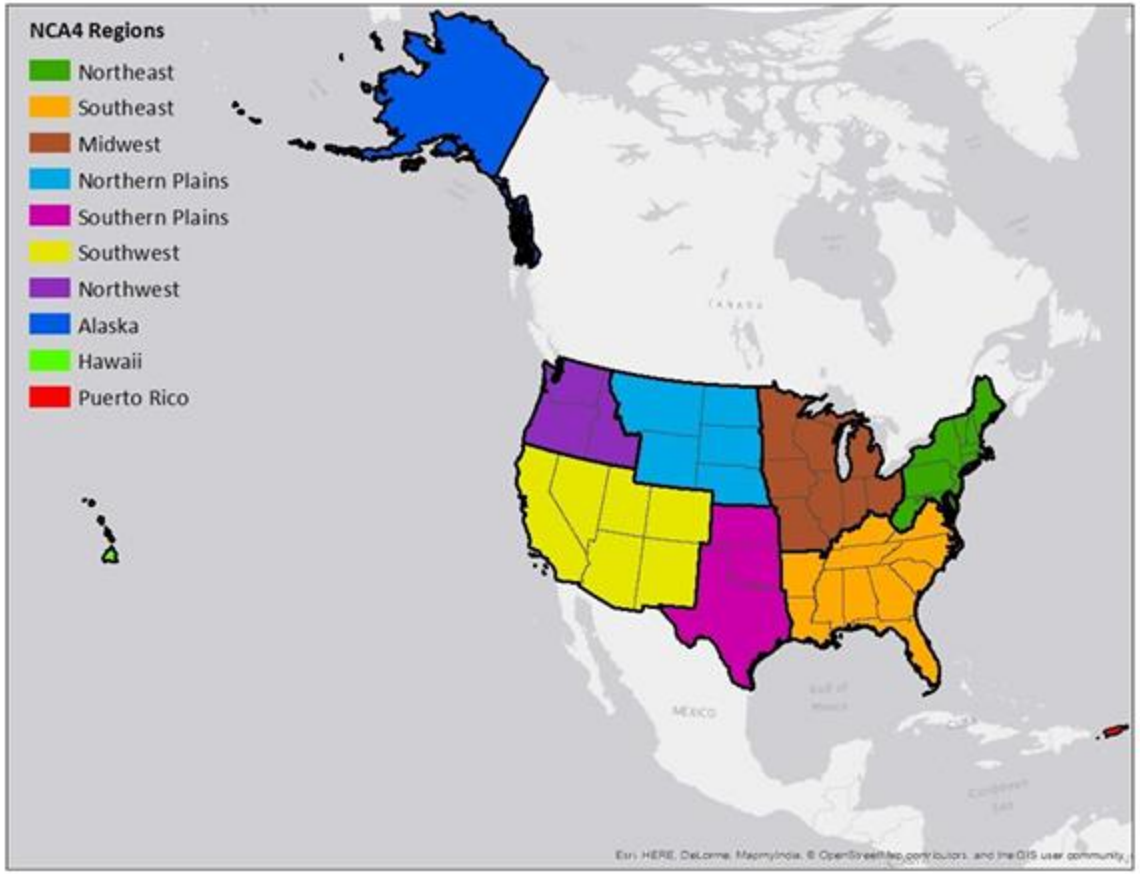
Center (Modeling Group)	Model Acronym	Availability LOCA	Availability SNAP	References
Canadian Centre for Climate Modeling and Analysis	CanESM2	X		Von Salzen et al. 2013[21]
National Center for Atmospheric Research	CCSM4	X	X	Gent et al. 2011[22] Neale et al. 2013[23]
NASA Goddard Institute for Space Studies	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)



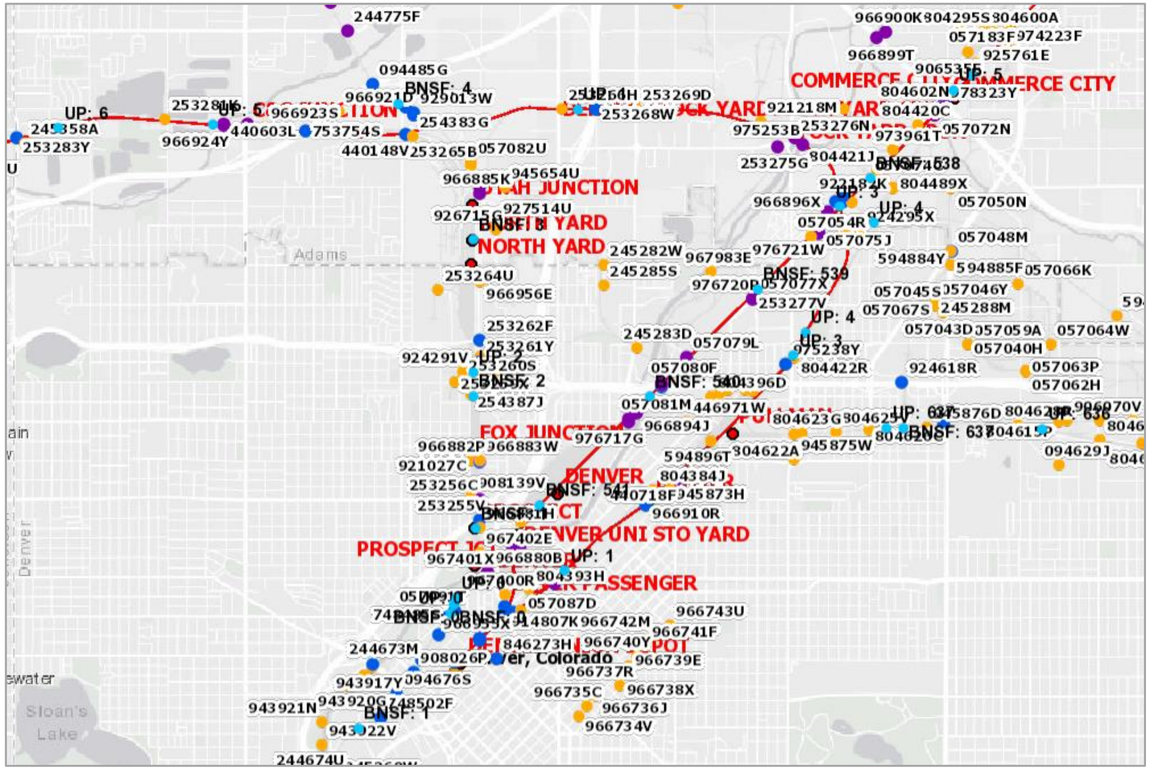
Collecting: Spatial Data

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



Collecting: Infrastructure Data

- Rail inventory from the National Transportation Atlas Database (NTAD)
  - Length of Class 1 rail
  - Track rights → used to estimate passenger vs freight
- Traffic volume from FRA highway-rail crossing
  - 152,000 unique crossings
  - Daily rail volume



RESILIENT ANALYTICS

Collecting: Methodological Data

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

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

RISK ANALYSIS BASED CWR
TRACK BUCKLING SAFETY EVALUATIONS

Andrew Kish Gopal Samavedam

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 ~£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 £10,000 per buckle.

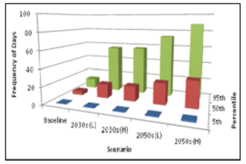
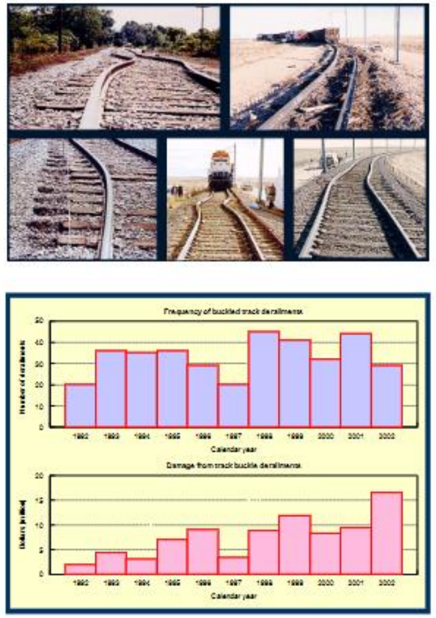


Fig. 1: The annual frequency of days which exceed 27°C at the grid cell corresponding to Heathrow for the baseline, 2030s and 2050s time periods and high (H) and low (L) emission scenarios. Results are provided at the 5th, 50th, and 95th percentile, reflecting the range of results provided by the urban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

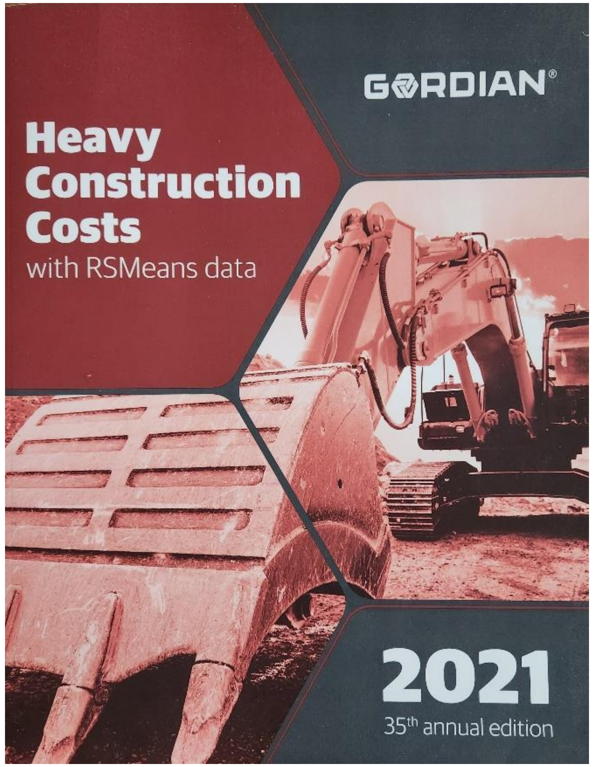


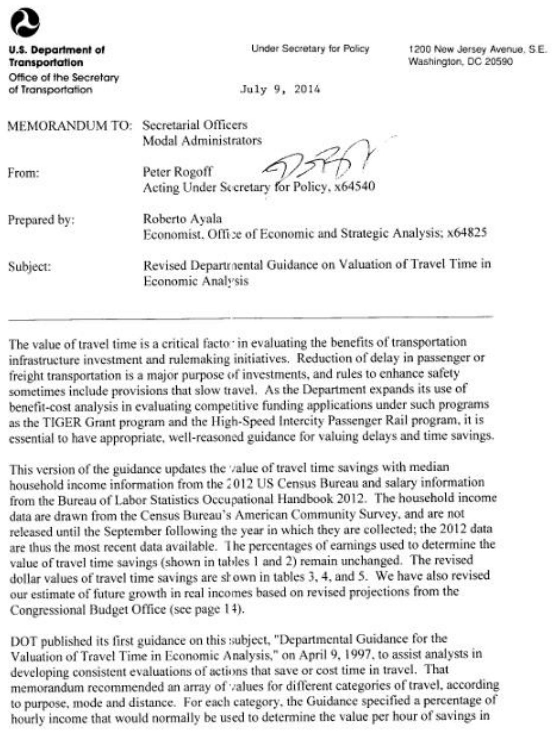
Track buckling illustrations and accident statistics

3

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

---

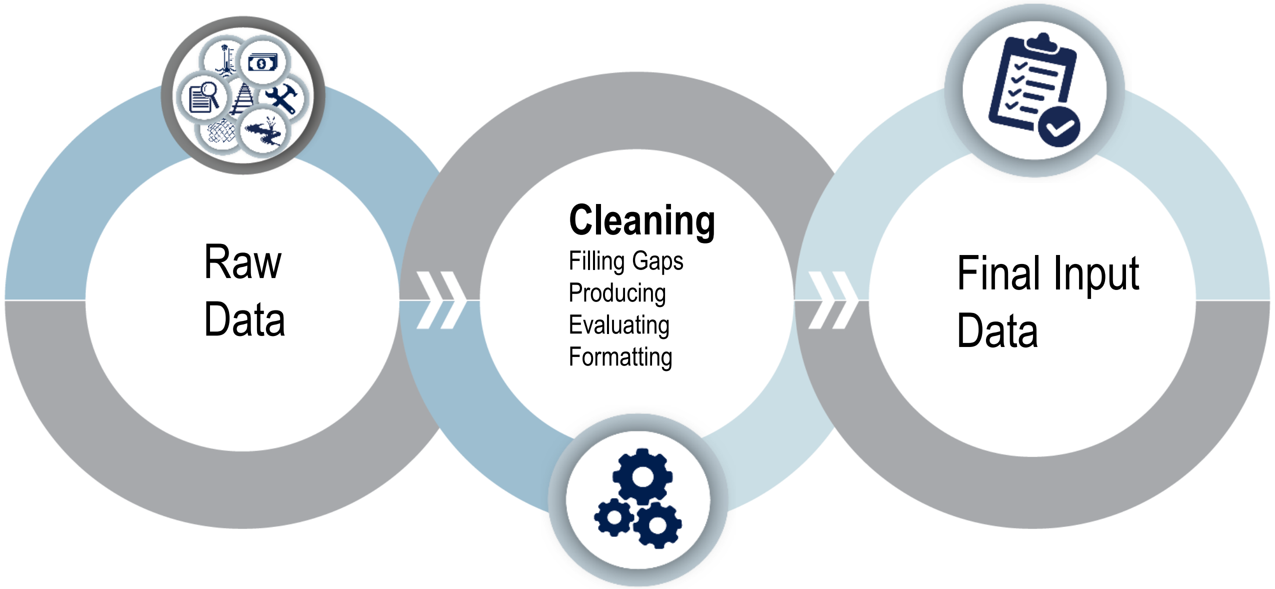
The value of travel time is a critical factor in evaluating the benefits of transportation infrastructure investment and rulemaking initiatives. Reduction of delay in passenger or freight transportation is a major purpose of investments, and rules to enhance safety sometimes include provisions that slow 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



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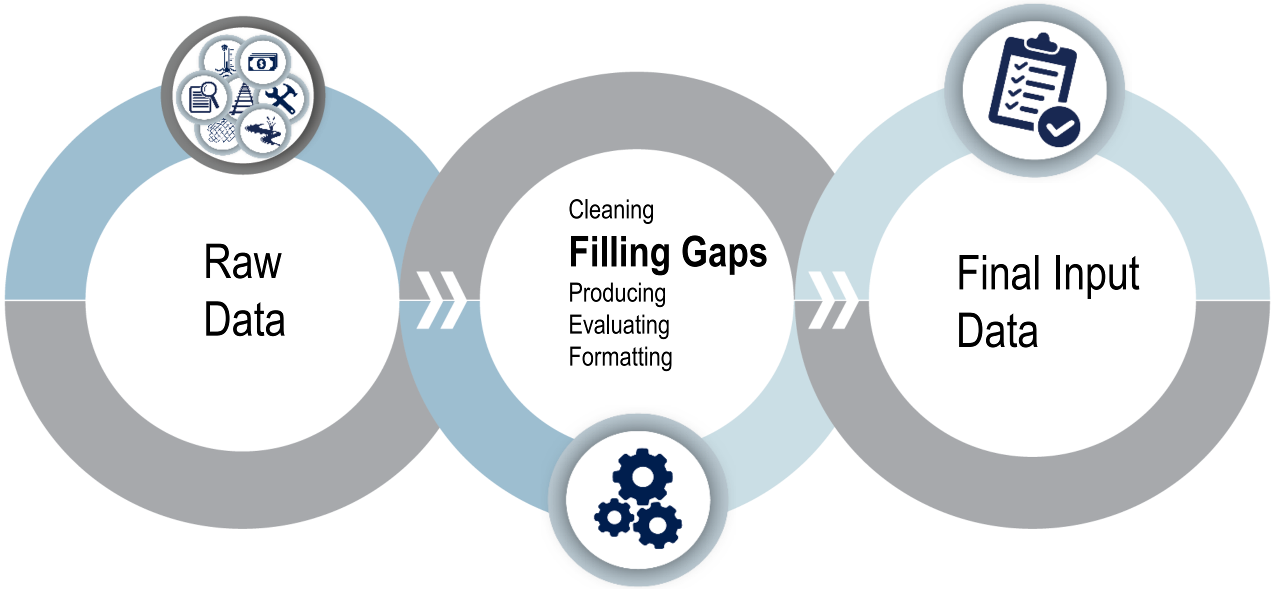

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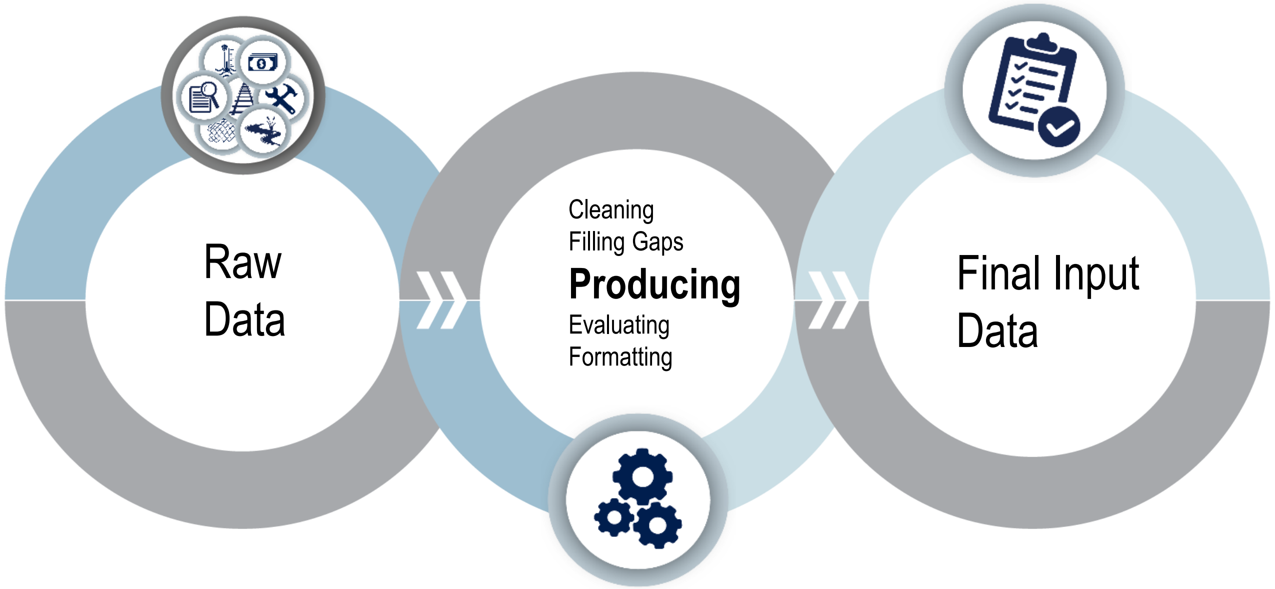

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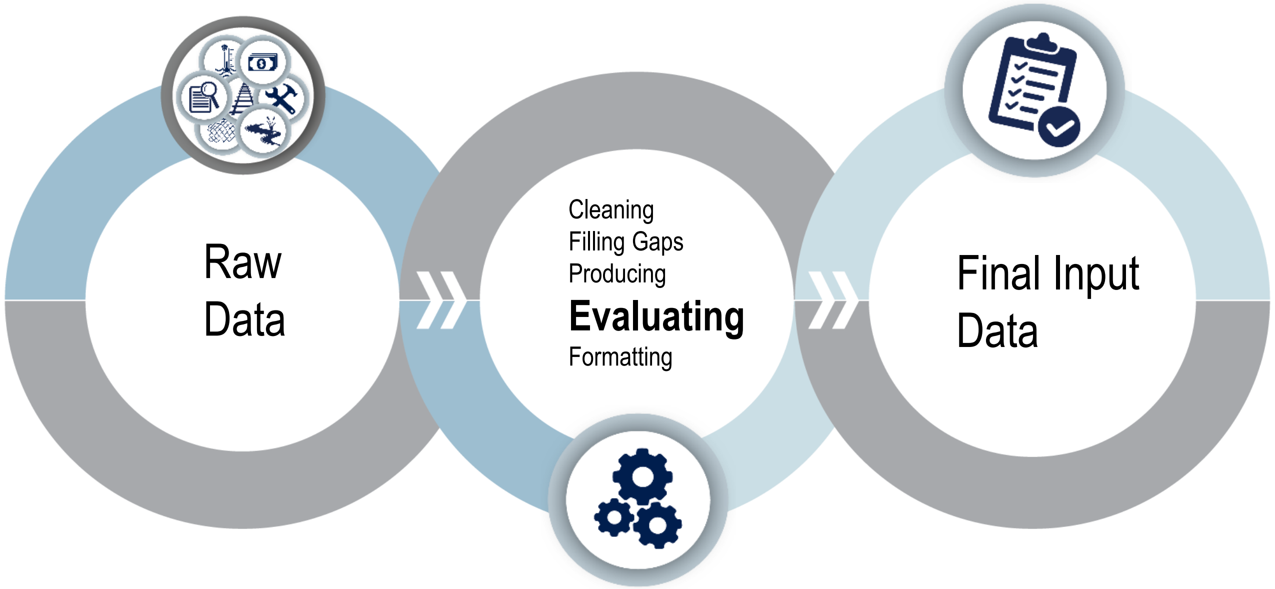

Processing

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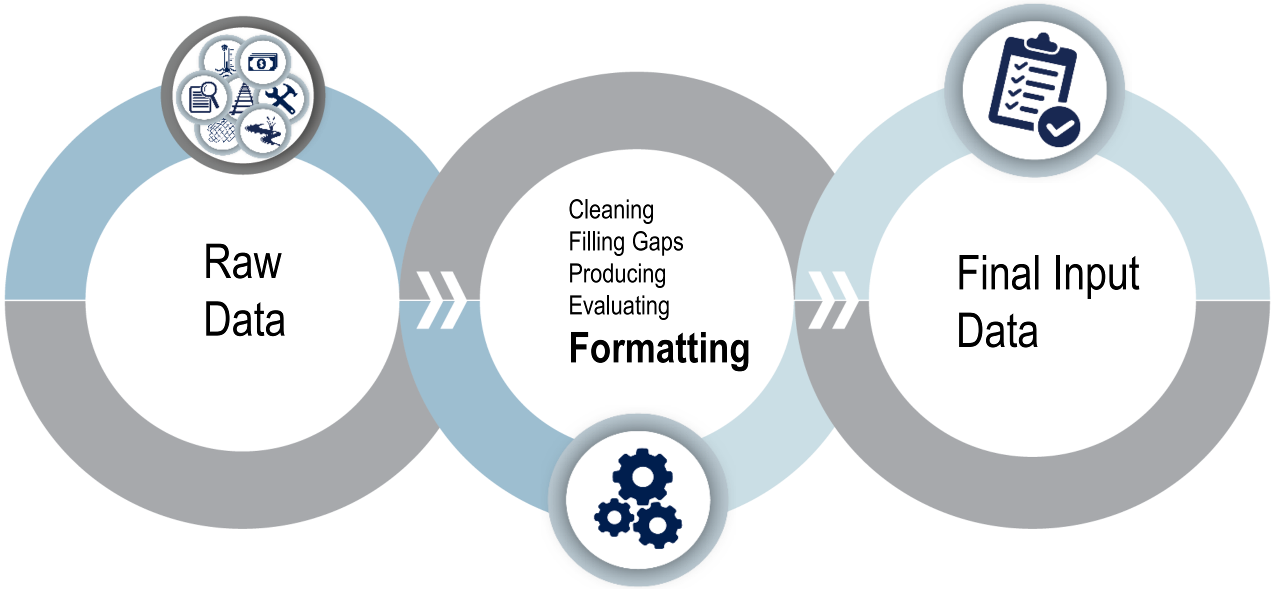


Summary so far

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	1 • Costs of replacing track to repair lateral alignment defects in the buckling zone and costs of re-aligning rail in adjoining zones 2 • Costs of delays that occur due to track buckling and repair	• Costs of replacing track to repair lateral alignment defects in the buckling zone and costs of re-aligning rail in adjoining zones 3 • Costs of delays that occur due to track buckling and repair, as well as delays associated with blanket speed reductions	4 • Costs of purchasing, installing, and maintaining the track temperature sensors, and related software infrastructure 5 • Costs of delays associated with risk-based speed reductions
Costs do not include	• Costs of derailment that may result from track buckling • Costs of routine (non-climate driven) track maintenance, including winter maintenance	• 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	• 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

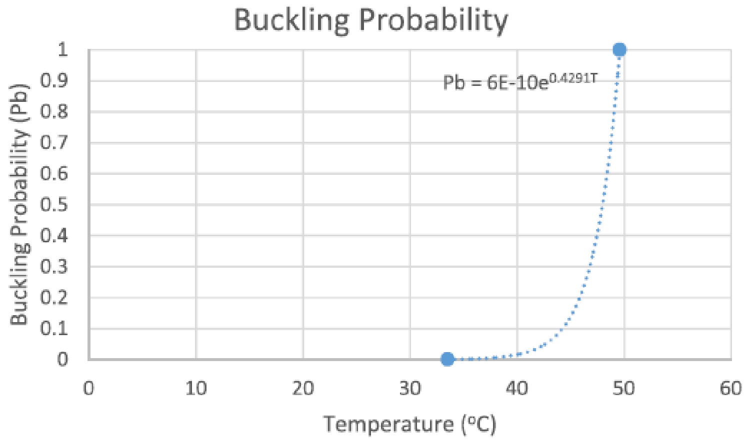


Fig. 1. Buckling probability (P_b).

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

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

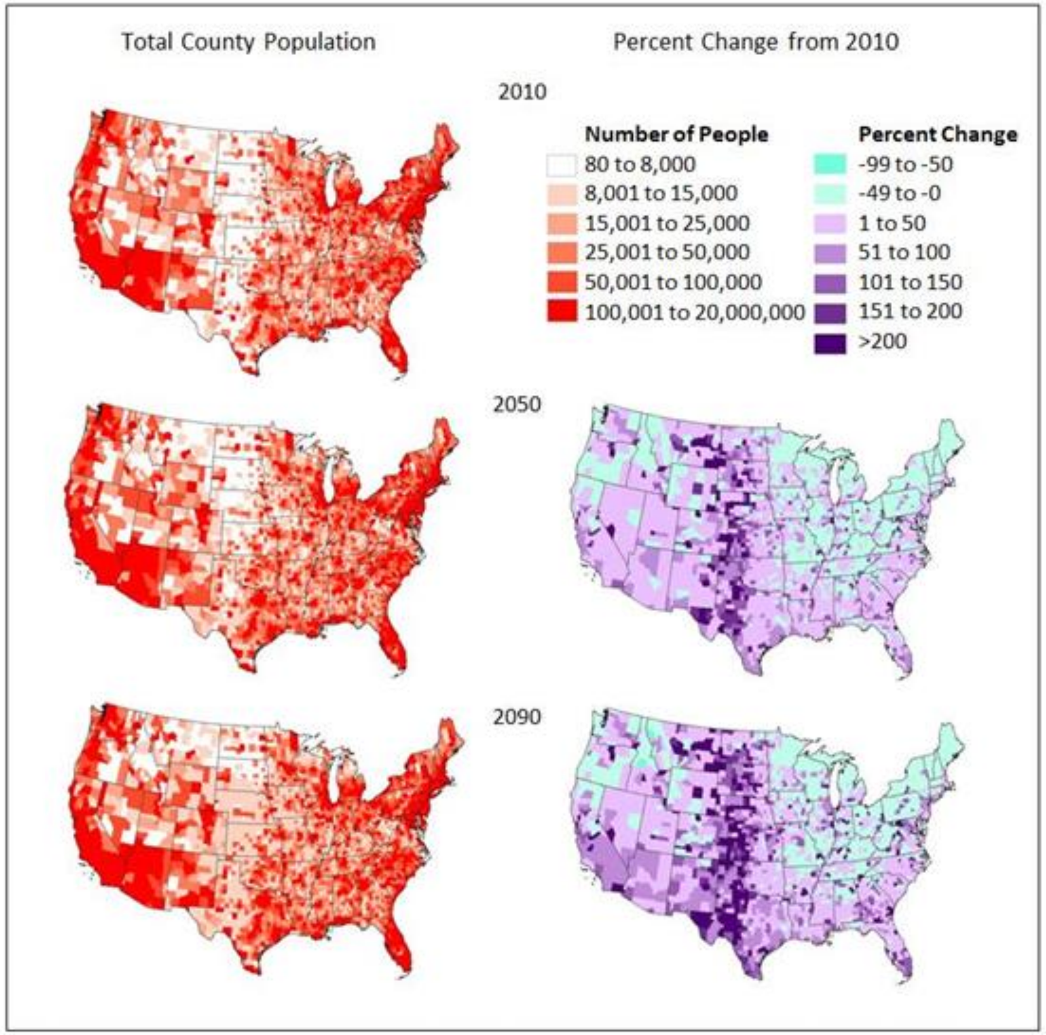
where

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

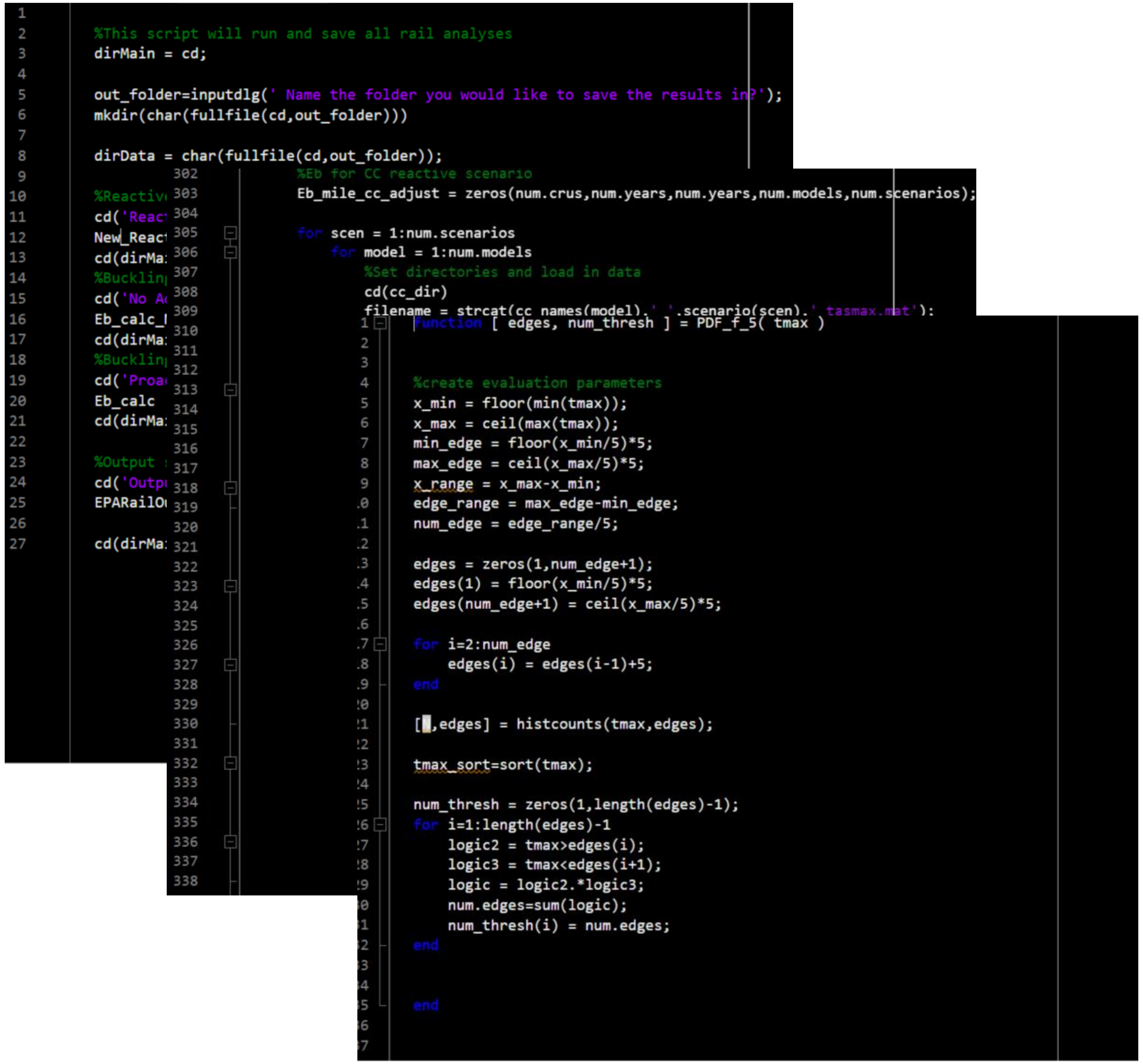
1. Rail temperature $T_{rail} = \frac{3}{2} * T_a$
2. Rail SFT (vintaging) $SFT = \frac{3}{4} * T_{max}$
3. Pb and Eb (reactive and proactive)
4. Risk base speed reduction

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



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)	RCP 4.5	RCP 8.5
Historic	802	
CANESM2	2,989	7,696
CCSM4	4,921	12,772
GISS-E2-R	1,921	3,500
HadGEM2-ES	8,495	35,130
MIROC5	4,783	8,901
Average	4,622	13,600

Annual Cost of Repairs (2018 to 2099, millions $2018,	RCP 4.5	RCP 8.5
Historic	$ 15.8	
CANESM2	$ 58.8	$ 151.5
CCSM4	$ 96.8	$ 251.3
GISS-E2-R	$ 37.8	$ 68.9
HadGEM2-ES	$ 167.2	$ 691.3
MIROC5	$ 94.1	$ 175.2
Average	$ 91.0	$ 267.6

Reactive Adaptation

Avg. Number of Annual Buckling Events (2018 to 2099)	RCP 4.5	RCP 8.5
Historic	389	
CANESM2	1,855	5,352
CCSM4	3,441	9,721
GISS-E2-R	1,165	2,204
HadGEM2-ES	6,077	28,260
MIROC5	3,307	6,439
Average	3,169	10,395

Annual Cost of Repairs (2018 to 2099, millions $2018,	RCP 4.5	RCP 8.5
Historic	$ 7.6	
CANESM2	$ 36.5	$ 105.3
CCSM4	$ 67.7	$ 191.3
GISS-E2-R	$ 22.9	$ 43.4
HadGEM2-ES	$ 119.6	$ 556.1
MIROC5	$ 65.1	$ 126.7
Average	$ 62.4	$ 204.6

Proactive Adaptation

Avg. Number of Annual Buckling Events (2018 to 2099)	RCP 4.5	RCP 8.5
Historic	0	
CANESM2	0	0
CCSM4	0	0
GISS-E2-R	0	0
HadGEM2-ES	0	0
MIROC5	0	0
Average	0	0

Annual Cost of Repairs (2018 to 2099, millions $2018,	RCP 4.5	RCP 8.5
Historic	$ 0.0	
CANESM2	$ 0.0	$ 0.0
CCSM4	$ 0.0	$ 0.0
GISS-E2-R	$ 0.0	$ 0.0
HadGEM2-ES	$ 0.0	$ 0.0
MIROC5	$ 0.0	$ 0.0
Average	$ 0.0	$ 0.0

Proactive Adaptation with 20% Buckling Events

Avg. Number of Annual Buckling Events (2018 to 2099)	RCP 4.5	RCP 8.5
Historic	78	
CANESM2	371	1,070
CCSM4	688	1,944
GISS-E2-R	233	441
HadGEM2-ES	1,215	5,652
MIROC5	661	1,288
Average	634	2,079

Annual Cost of Repairs (2018 to 2099, millions $2018,	RCP 4.5	RCP 8.5
Historic	$ 1.5	
CANESM2	$ 7.3	$ 21.1
CCSM4	$ 13.5	$ 38.3
GISS-E2-R	$ 4.6	$ 8.7
HadGEM2-ES	$ 23.9	$ 111.2
MIROC5	$ 13.0	$ 25.3
Average	$ 12.5	$ 40.9

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

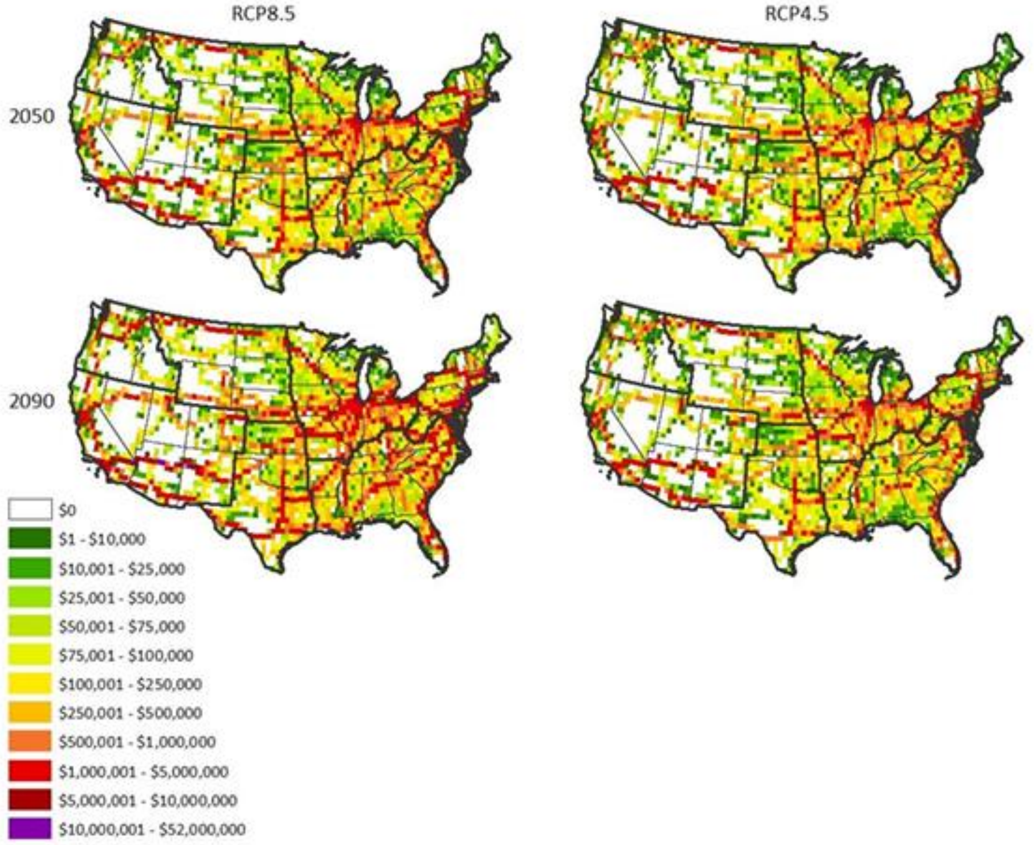
Pause for Questions

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

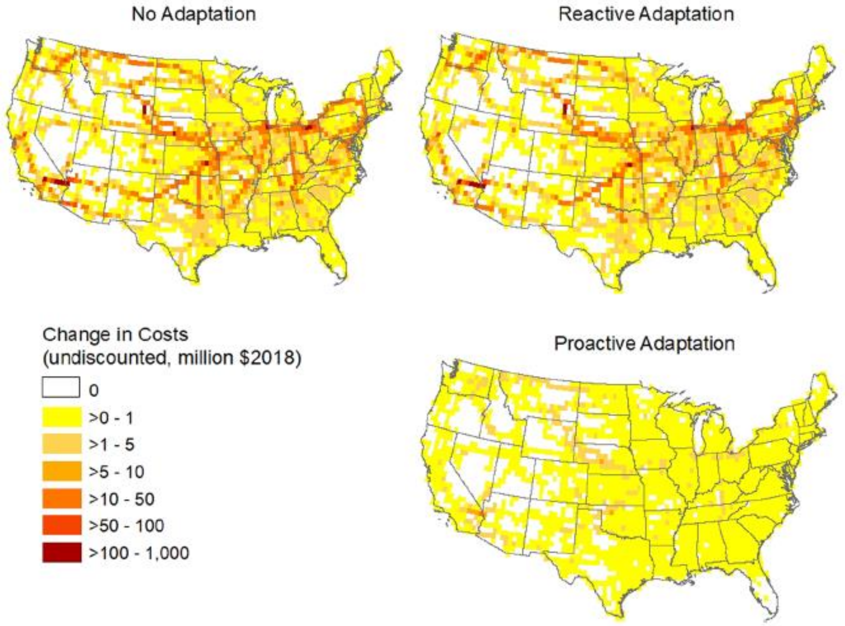
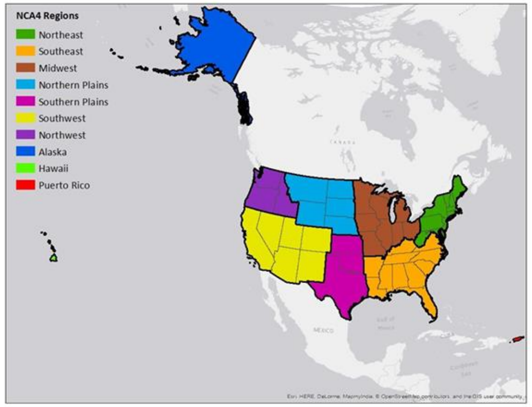
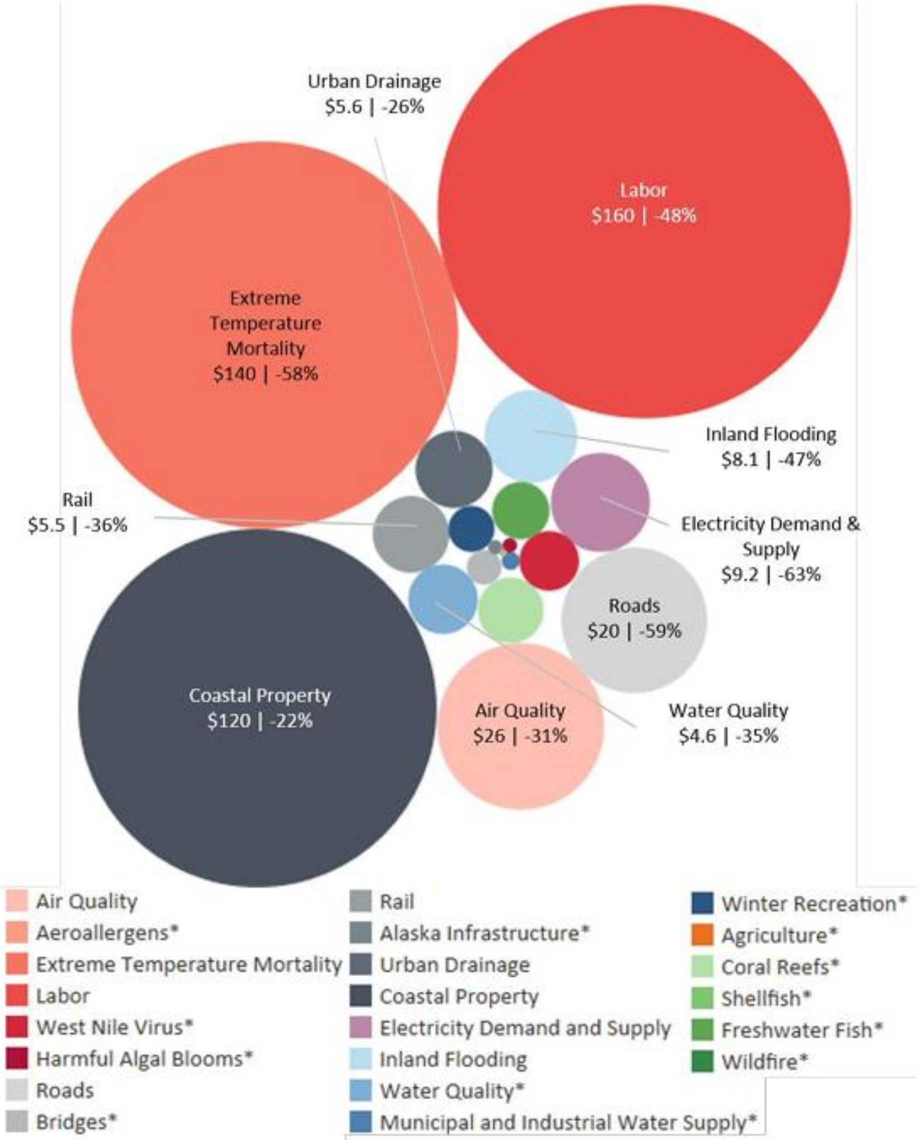


Fig. 1 Change in costs to the U.S. rail network in 2090 relative to baseline (1986–2005) under RCP8.5 (undiscounted, $2018)

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

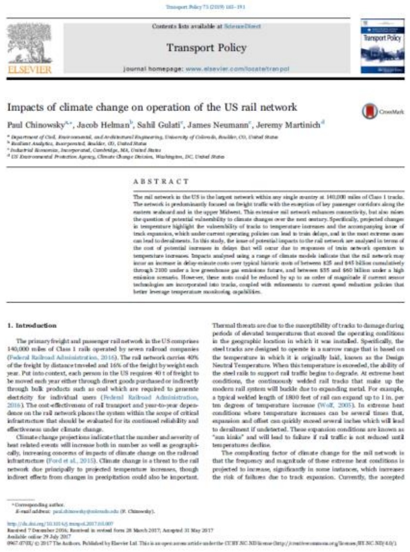
- **Deliverables**
  - Multi-Model Framework for Quantitative Sectoral Impacts Analysis
    - A Technical Report for the Fourth National Climate Assessment
  - Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development
    - Climatic Change
  - Impacts 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 effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development

James E. Neumann · Paul Chinowsky · Jacob Helman · Margaret Black · Charles Fant · Kenneth Strzepek · Jeremy Martinich

Abstract

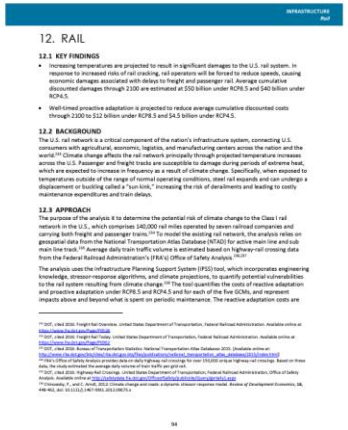
1 Introduction


Transport Policy

Impacts of climate change on operation of the US rail network

ABSTRACT

1. Introduction


12. RAIL

RESILIENT ANALYTICS

Stanley Consultants

Actionable Results

- What does this mean for the rail sector?

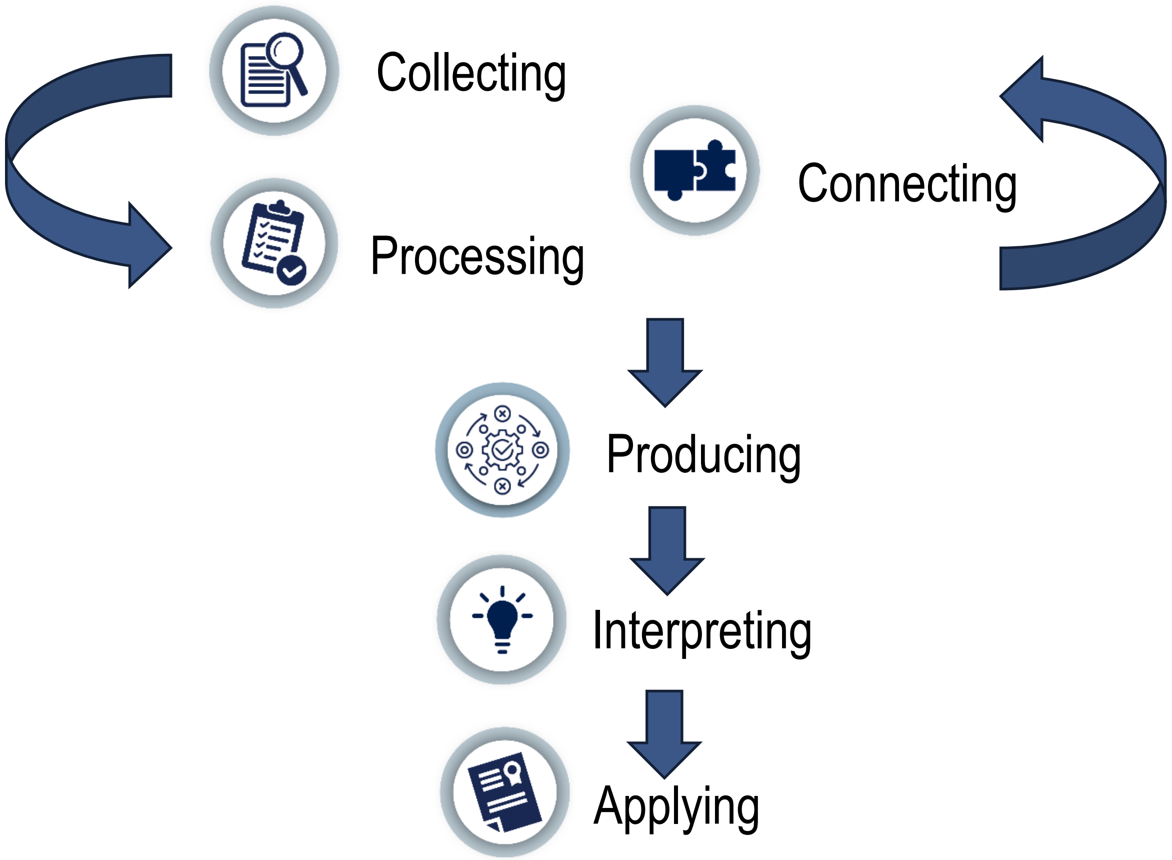
1. Climate change will have a big impact on current rail operation
2. Current operating procedures are relatively effective
3. Proactive adaptation can save owners billions

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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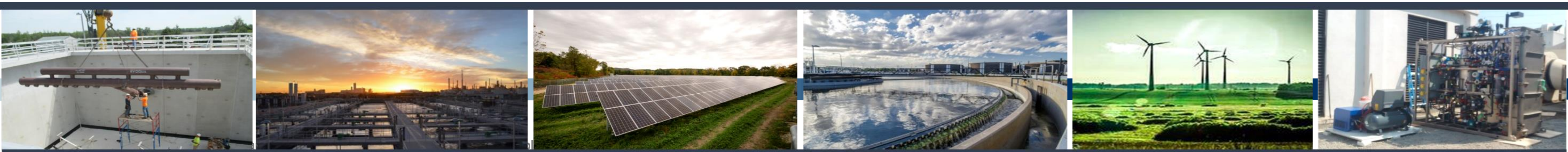

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