TURNER-FAIRBANK HIGHWAY RESEARCH CENTER

Long-Term Bridge Performance Program

Status Update and LTBP Deterioration Modeling Framework

2016 Midwest Bridge Preservation Partnership
October 5, 2016
Milwaukee, WI

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LTBP Program Coordinator
Long-Term Bridge Performance Program
Federal Highway Administration

Long-Term Bridge Performance Program

U.S. Department of Transportation
Federal Highway Administration

Long-Term Bridge Performance Program

- Status Update
- Data Management
- LTBP Analysis
- Moving Forward

LTBP Program

Long-Term Bridge Performance Program

Projects at a Glance

Rutgers

- Data-Driven Modeling
- Bridge Portal
- Field Data Collection
- Legacy Data Mining
- Other Projects – Drone

PB

- NW – SW visual inspection

Michael Baker

- Gulf Visual inspection, material sampling

PSI

- Legacy Data Mining

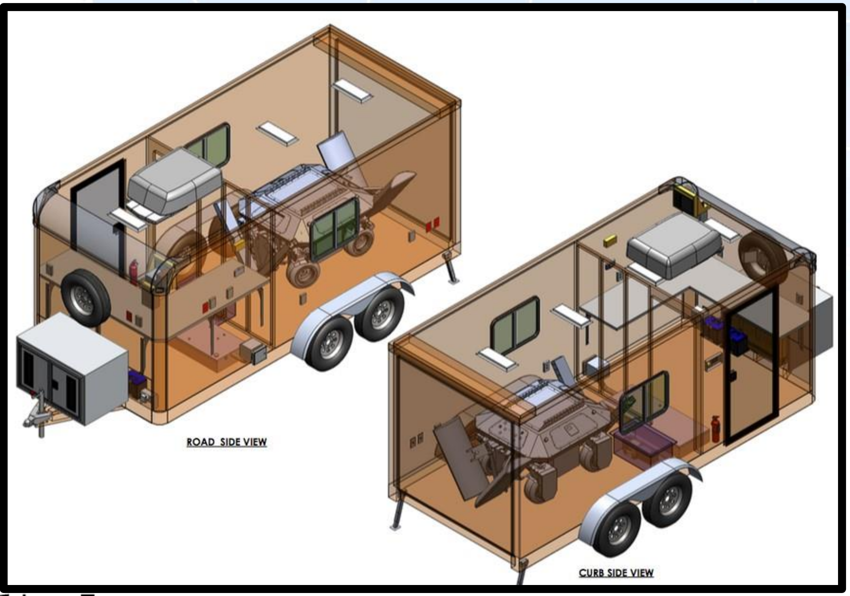
Pennoni

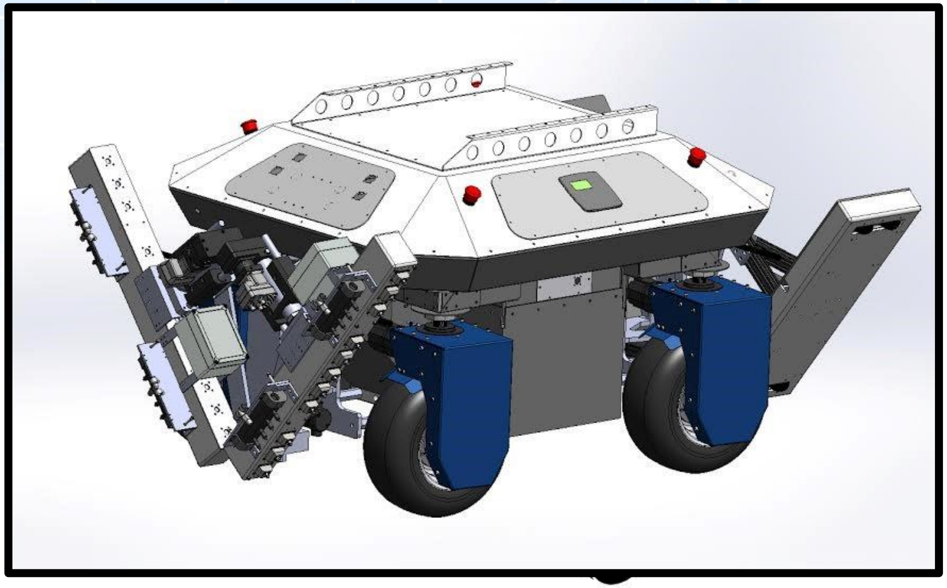
- WIM
- LTBP Performance Index
- Develop an accelerated testing bridge DB
- Website & Newsletter
- Protocol Publication
- RABIT Acquisition

Long-Term Bridge Performance Program

Automated Data Collection RABIT™ Bridge Deck Assessment Tool

- Procurement of four autonomous robotic bridge deck assessment tools inclusive of training to LTBP contractors for the proper deployment of the technology in field data collection activities





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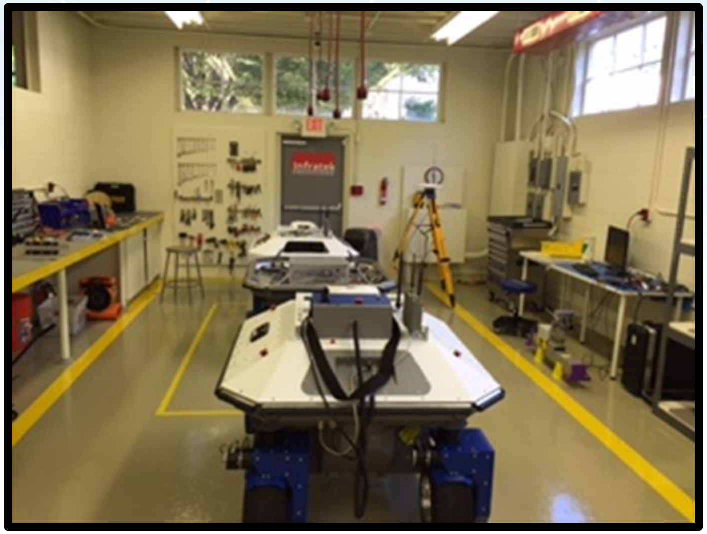
RABIT™ Bridge Deck Assessment Tool

Status:

- Development of the software is on-going
- User Manual and Training Curriculum in development
- Validation of RABIT #1 scheduled for September – October.
- Robotic platform for RABIT #2 arrived



Long-Term Bridge Performance Program

- Status Update
- Data Management
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LTBP Program – Bridge Portal Update

- Version 1.1 of the LTBP Bridge Portal is currently in the process of being deployed and will be available through FHWA network (UPACS) very soon.

Version 1.1 currently being deployed

Version 2 expected in 2017

Long-Term Bridge Performance Program

- LTBP Data Collection
- Data Management
- LTBP Analysis
- Moving Forward

Long-Term Bridge Performance Program

Refined Data Analysis, Modeling, and Interpretation Framework

Key Underlying Assumptions

- **Time is the most significant influence over bridge performance for any set of input and attributes**
- **The available NBI and NBE data may have errors and variability, but no bias – that is, the mean predictions derived from these data are (on average) representative of the true behavior**
  - At this stage this assumption is made for untreated bridge decks, and will need to be revisited for other elements

Framework Characteristics

- **Adaptive – has the ability to learn and adapt as new data become available (i.e. to modify, replace, or verify the key assumptions above)**
- **Comprehensive – is cast in general terms so as to be applicable to a diverse set of performances**
- **Efficient – makes use of all of the diverse data being collected by the LTBP Program**

Long-Term Bridge Performance Program

Two-Pronged Approach

Top Down

- Makes use of data available across the entire population of bridges located within clusters
- Employs probabilistic and/or deterministic models to generate deterioration curves based on this data
- Essentially provides a broad context to compare the bridges subjected to higher resolution data collection

Bottom Up

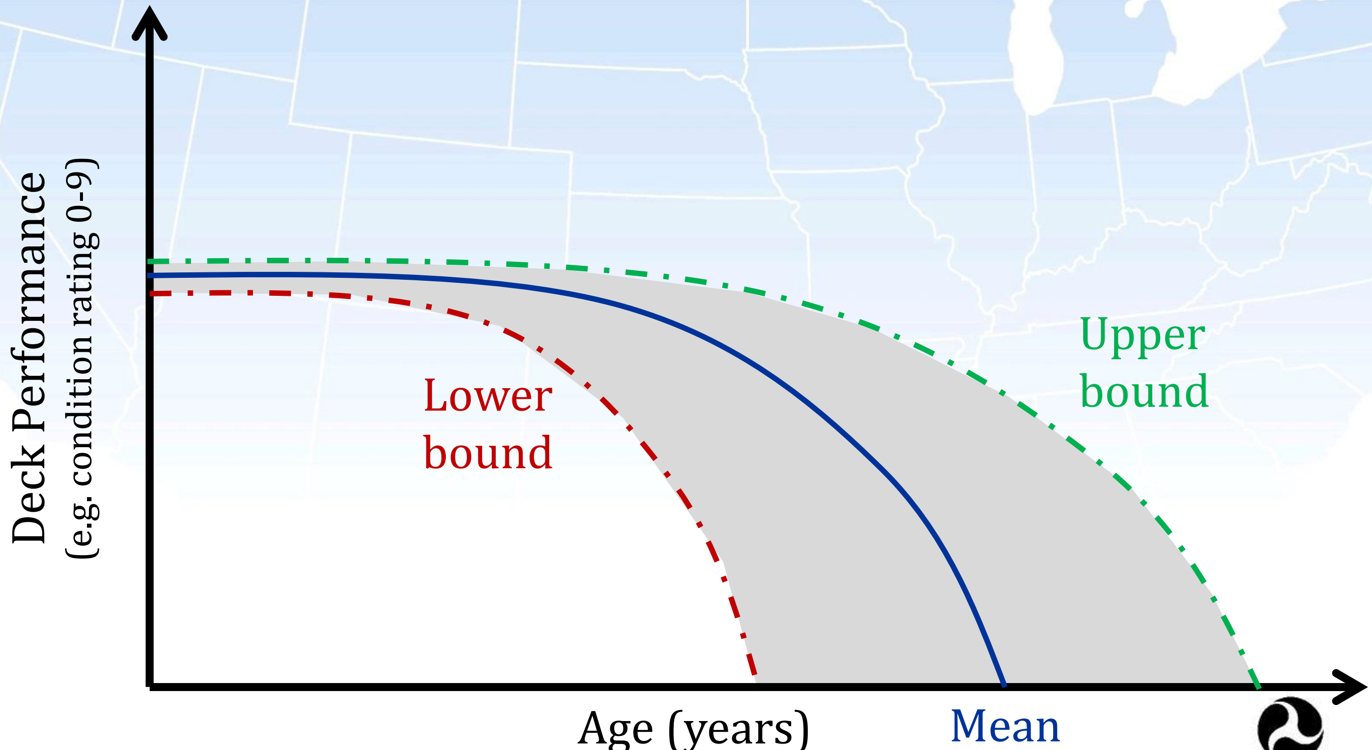
- Makes use of data available from legacy data collection, visual inspection, NDE, SHM, material sampling, etc.
- In some cases, the bottom up data maybe "translated" to the NBI/NBE scale to be located with respect to the top-down model
- Through comparison with the top-down models, the level of over- or under-performance of specific bridges can be quantified
- Provides a wealth of data and information to develop and validate quantitative explanations as to why certain bridges over- or under-perform

Step 1 – Top-down deterioration modeling

Approaches may include:

Deterministic – Heuristic-based models, Wenzel et al.

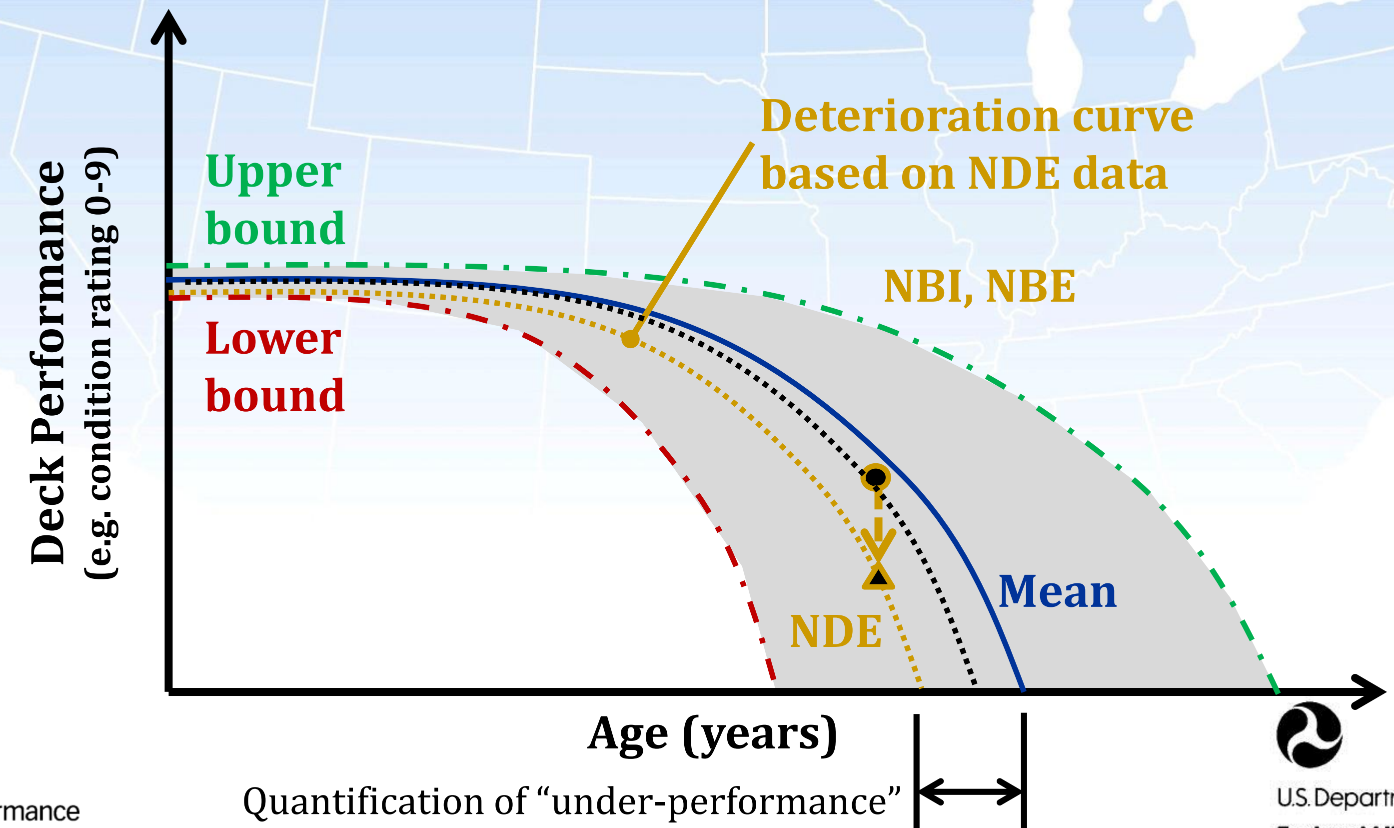
Probabilistic – Markov, Weibull, Hoatian et al., etc.



Step 2 – Locate the specific bridge within the top-down deterioration predictions

Direct use of NBI and/or NBE

Or use of other data such as NDE "translated" to the NBI/NBE scale



Step 3 – Quantify explanatory variables

Quantify bridge-specific inputs and attributes based on bottom-up data collection efforts

Data Analysis

Inputs

- **Environmental Inputs** → Freeze-thaw cycles, hot-dry cycles, temperature range, temperature gradients precipitation, etc.
- **Live Load** → ADTT, available traffic studies, trucking information, WIM, etc.
- **Preservation & Maintenance** → Number of snow falls greater than 1 in, available records (legacy data collection), common state practices, etc.

Attributes

- **Design, Structural Characteristics** → Number of modes below 5 Hz, damping levels, actual distribution factors, global stiffness, design details (legacy data collection)
- **Construction Quality** → Available records (legacy data collection), variation of cover, variation of concrete modulus, deviations from design/specification, etc.

Step 4 – Closing the loop – Explanation for observed over- or under-performance

Bridge-Specific Inputs and Attributes

- Environmental Inputs
- Live Load
- Preservation & Maintenance
- Design, Structural Characteristics
- Construction Quality

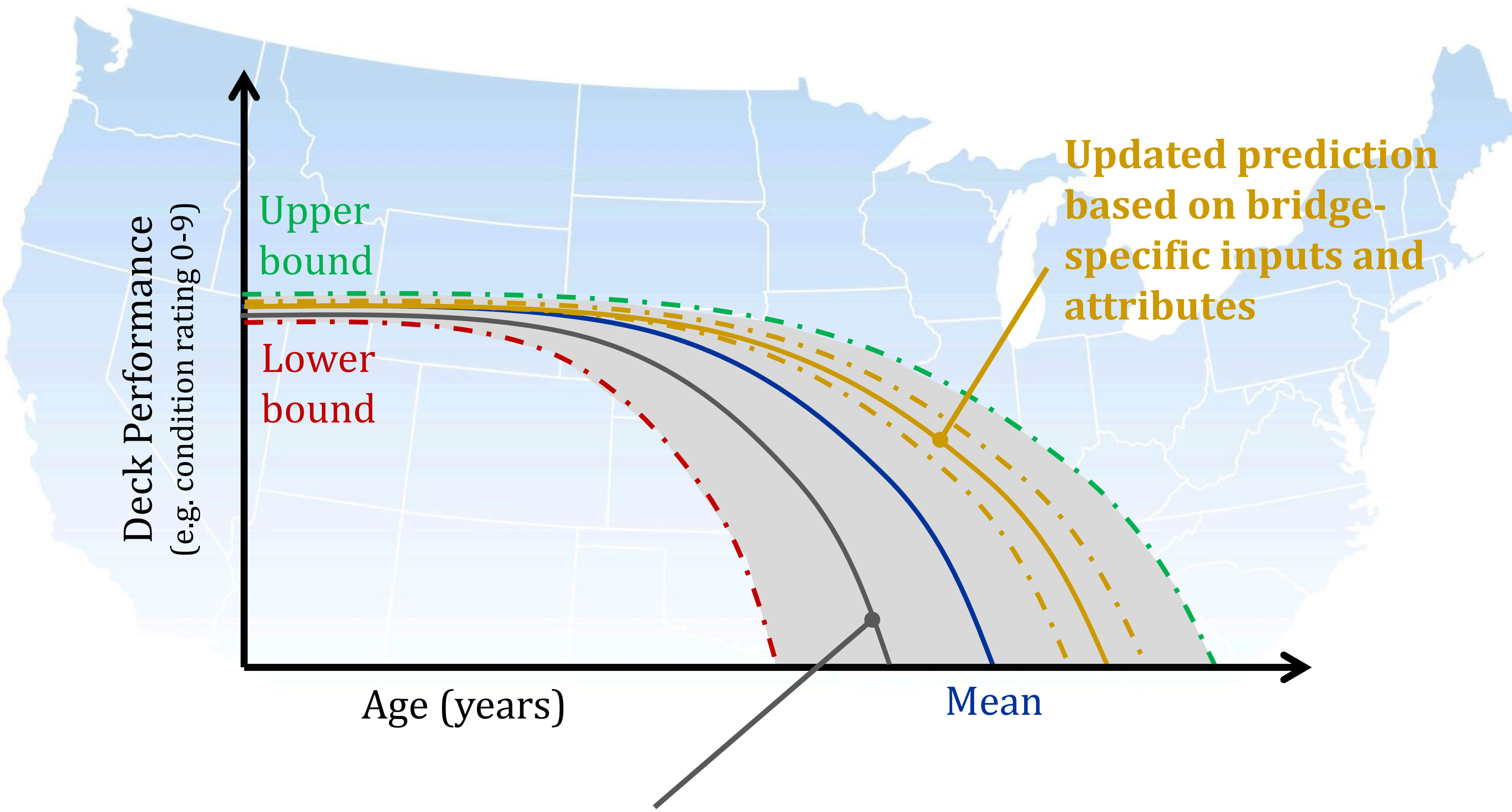
Quantified level of Over- or Under Performance

Identify correlations between Inputs/ Attributes and Over/ Under-Performance

As more bottom-up data become available…

- Update, refine, validate key assumptions
- Quantify and model the influence of various inputs and attributes
- Ongoing model refinement and validation
- Updating of data collection approaches

Outcome – Enhanced Predictive Capabilities



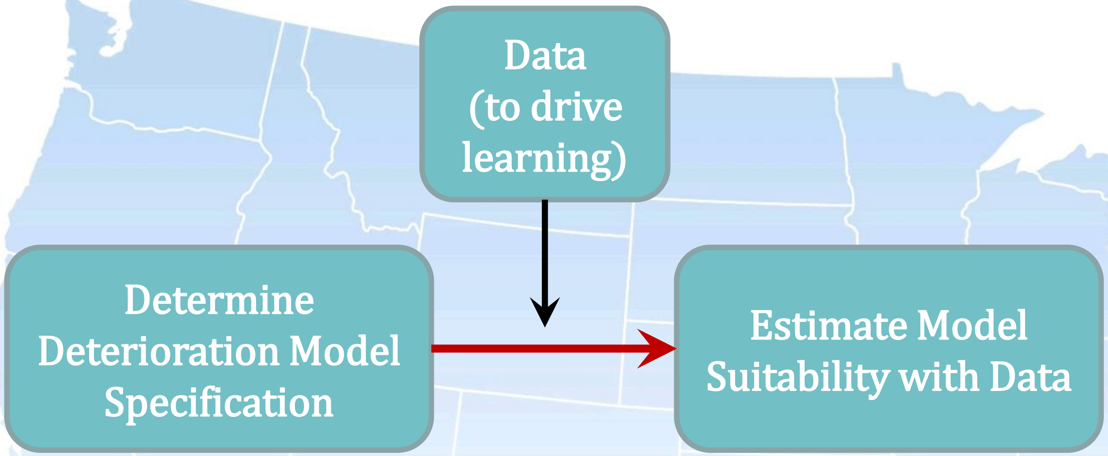
BEAST – Provides full life-cycle data for improved model refinement and validation

Long-Term Bridge Performance Program

LTBP Data-Driven Deterioration Modeling Methodology (D^3M^2)

A modified top down approach to "*learning*"

Traditional Deterioration Learning Approach



ISSUE: Data should determine model specification, not subjective judgments

Inherently assume that the chosen model specification best describes deterioration. → *Problematic*

Only very poor fit would motivate new choice of model specifications. → *Compromised Accuracy*

Only one model specification can be considered every time. → *Inability to Incorporate Different Opinions*

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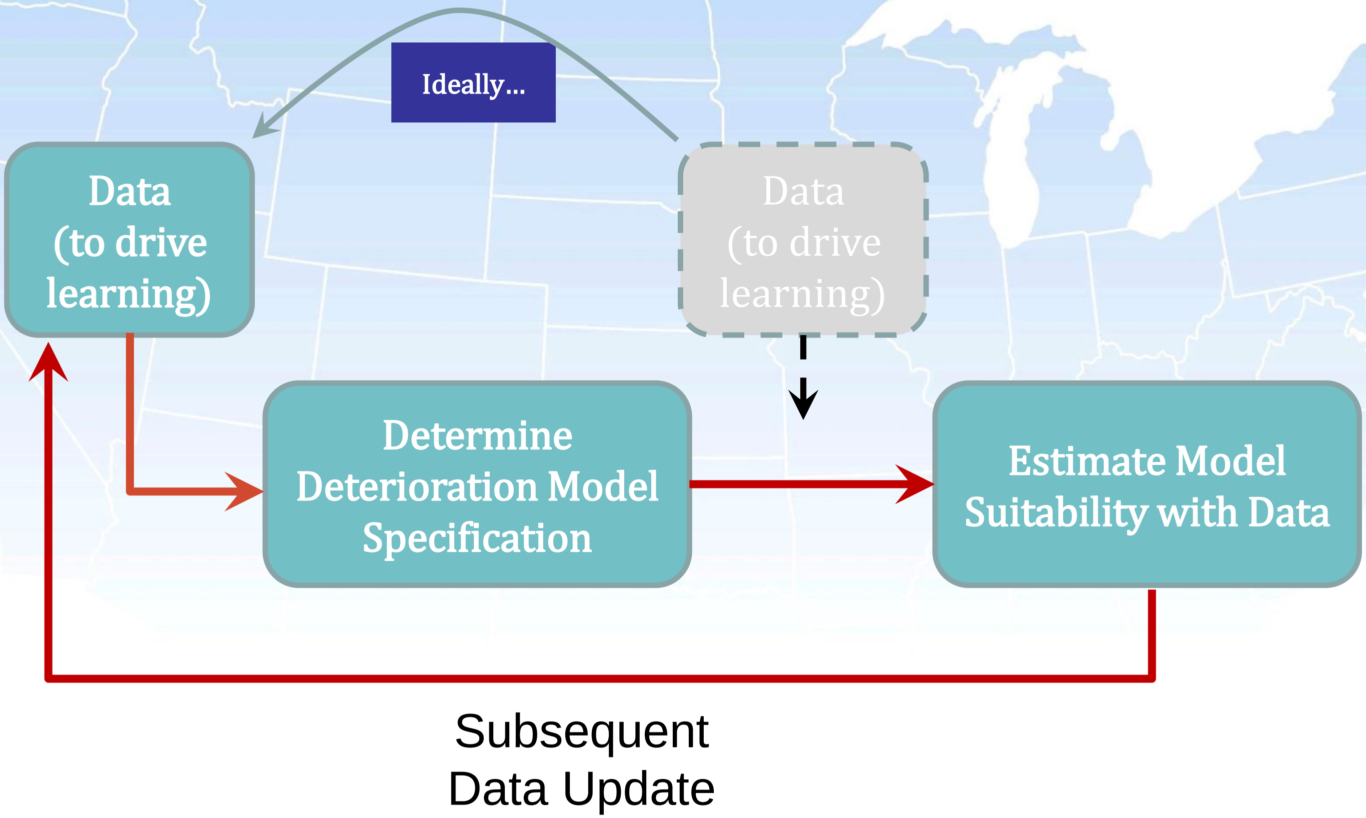
Traditional Deterioration Learning Approach - Modified



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LTBP Data-Driven Deterioration Modeling Methodology (D^3M^2)

Incorporate the *"Learning of Model Specification"*

- Propose multiple models of different types
- Allow different opinions to be simultaneously considered

- Model Type 1
  - Model 1
  - Model 2
  - Model 3
- Model Type 2
  - Model 1
  - Model 2
  - Model 3

Long-Term Bridge Performance Program

LTBP Data-Driven Deterioration Modeling Methodology (D^3M^2)

Assign Weights to Proposed Models

Initial weights are assumed – consider weights as ***prior probabilities*** of each model being the true model

Research Community			Practitioner Experience		
Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
20%	20%	20%	10%	15%	15%

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LTBP Data-Driven Deterioration Modeling Methodology (D^3M^2)

The Learning Process

- Learning is in the form of updating weights of each model using data
- Evaluate the probability of observing new/next data set given each candidate model
  - Alternatively, how much each candidate model agrees with data
- Update the weights of the models based on the probabilities
  - Models with greater likelihoods (higher probability of observance) gain more weight -- they agree more closely with the data

Long-Term Bridge Performance Program

LTBP Data-Driven Deterioration Modeling Methodology (D^3M^2)

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Long-Term Bridge Performance Program

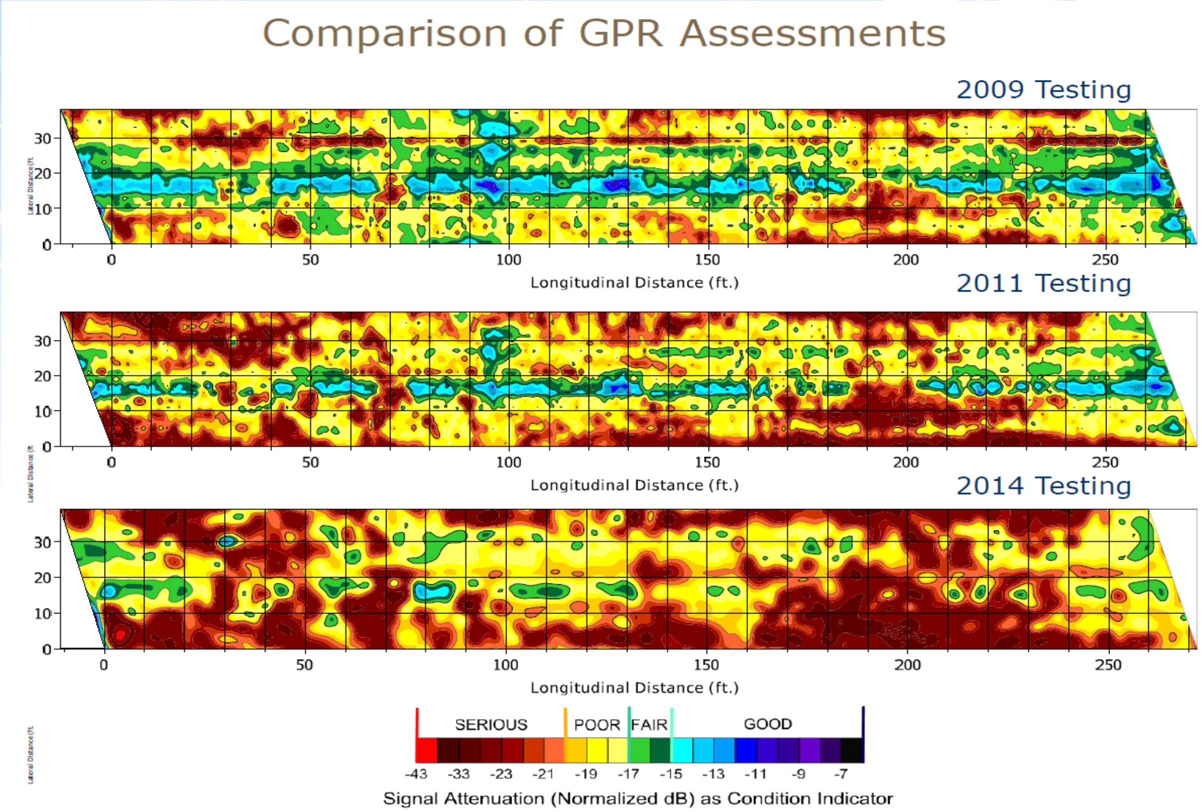
LTBP Data-Driven Deterioration Modeling Methodology (D^3M^2)

VA Pilot Bridge – Haymarket VA

- Constructed in 1979
- Single Index Learning – One Data Source - Ground Penetrating Radar (GPR) Data on VA Pilot Bridge
- Three measurements: Sep 2009, Aug 2011 and Oct 2014

Long-Term Bridge Performance Program

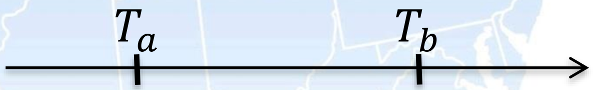
Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

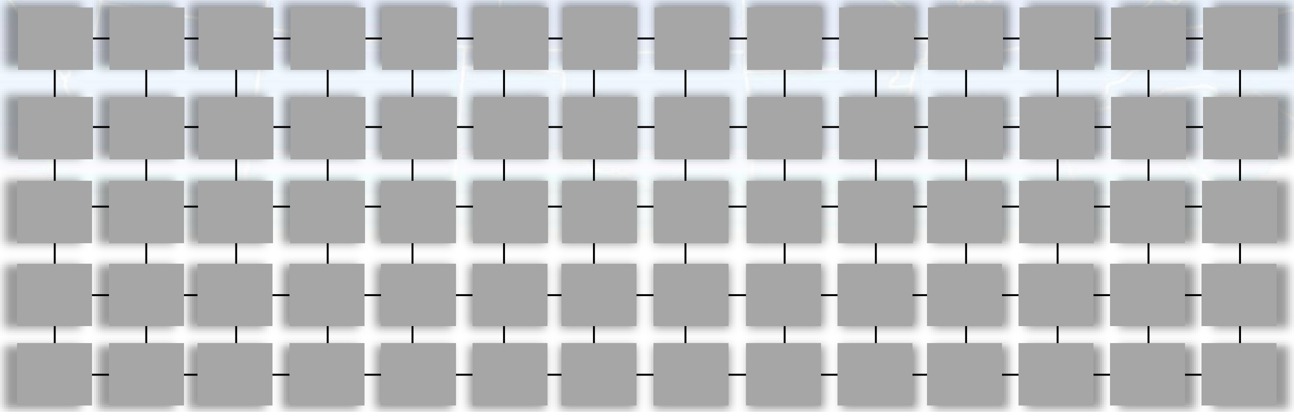


Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Modeling

- Accountable variables: ***AGE***
- ***GPR*** at T_a vs. GPR at T_b





Long-Term Bridge Performance Program

Demonstration of the D³M² Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Propose Candidate Models

Model Type 1: $GPR_{T_b} =$

$$GPR_{T_a} \cdot \exp(\alpha + \beta_T \cdot (T_b - T_a) + \varepsilon)$$

$$\varepsilon \sim N(0, (T_b - T_a)^2 \cdot \sigma^2)$$

Model Type 2: $GPR_{T_b} =$

$$\mu + GPR_{T_a} \cdot \beta_{GPR} \cdot (T_b - T_a) + \delta$$

$$\delta \sim N(0, (T_b - T_a)^2 \cdot \varphi^2)$$

$\alpha = -0.30$
$\beta_T = 0.20$
$\sigma^2 = 0.08^2$

$\alpha = -0.30$
$\beta_T = 0.25$
$\sigma^2 = 0.07^2$

$\alpha = -0.35$
$\beta_T = 0.25$
$\sigma^2 = 0.04^2$

$\mu = -10$
$\beta_{GPR} = 0.25$
$\varphi^2 = 5^2$

$\mu = -8$
$\beta_{GPR} = 0.50$
$\varphi^2 = 5^2$

$\mu = -8$
$\beta_{GPR} = 0.25$
$\varphi^2 = 6^2$

All Greek Letters are Coefficients

Long-Term Bridge Performance Program

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Data Analysis

LTBP Program

Assumed Initial Weights

Model Type 1: $GPR_{T_b} =$

$$GPR_{T_a} \cdot \exp(\alpha + \beta_T \cdot (T_b - T_a) + \varepsilon)$$

$$\varepsilon \sim N(0, (T_b - T_a)^2 \cdot \sigma^2)$$

Model Type 2: $GPR_{T_b} =$

$$\mu + GPR_{T_a} \cdot \beta_{GPR} \cdot (T_b - T_a) + \delta$$

$$\delta \sim N(0, (T_b - T_a)^2 \cdot \varphi^2)$$

Model Type 1			Model Type 2		
$\alpha = -0.30$ $\beta_T = 0.20$ $\sigma^2 = 0.08^2$	$\alpha = -0.30$ $\beta_T = 0.25$ $\sigma^2 = 0.07^2$	$\alpha = -0.35$ $\beta_T = 0.25$ $\sigma^2 = 0.04^2$	$\mu = -10$ $\beta_{GPR} = 0.25$ $\varphi^2 = 5^2$	$\mu = -8$ $\beta_{GPR} = 0.50$ $\varphi^2 = 5^2$	$\mu = -8$ $\beta_{GPR} = 0.25$ $\varphi^2 = 6^2$
20%	20%	20%	10%	15%	15%

All Greek Letters are Coefficients

Demonstration of the D^{3}M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Learning with 2009 – 2011 data (*updating weights*)

Model Type 1: $GPR_{T_b} =$

$$GPR_{T_a} \cdot \exp(\alpha + \beta_T \cdot (T_b - T_a) + \varepsilon)$$

$$\varepsilon \sim N(0, (T_b - T_a)^2 \cdot \sigma^2)$$

Model Type 2: $GPR_{T_b} =$

$$\mu + GPR_{T_a} \cdot \beta_{GPR} \cdot (T_b - T_a) + \delta$$

$$\delta \sim N(0, (T_b - T_a)^2 \cdot \varphi^2)$$

Model Type 1	Model Type 1	Model Type 1	Model Type 2	Model Type 2	Model Type 2
$\alpha = -0.30$, $\beta_T = 0.20$, $\sigma^2 = 0.08^2$	$\alpha = -0.30$, $\beta_T = 0.25$, $\sigma^2 = 0.07^2$	$\alpha = -0.35$, $\beta_T = 0.25$, $\sigma^2 = 0.04^2$	$\mu = -10$, $\beta_{GPR} = 0.25$, $\varphi^2 = 5^2$	$\mu = -8$, $\beta_{GPR} = 0.50$, $\varphi^2 = 5^2$	$\mu = -8$, $\beta_{GPR} = 0.25$, $\varphi^2 = 6^2$
0%	100%	0%	0%	0%	0%

All Greek Letters are Coefficients

Long-Term Bridge Performance Program

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Distinct Results

- Confidence ~100%
- Agency might not trust learning results
- Readjust the weights

0%	100%	0%	0%	0%	0%

Long-Term Bridge Performance Program

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Distinct Results

- Confidence ~100%
- Agency might not trust learning results
- Readjust the weights

2%	90%	2%	2%	2%	2%

Long-Term Bridge Performance Program

Demonstration of the D³M² Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Data Analysis

LTBP Program

Learning with *2011 – 2014* data (*updating weights*)

Model Type 1: $GPR_{T_b} =$

$$GPR_{T_a} \cdot \exp(\alpha + \beta_T \cdot (T_b - T_a) + \varepsilon)$$

$$\varepsilon \sim N(0, (T_b - T_a)^2 \cdot \sigma^2)$$

Model Type 2: $GPR_{T_b} =$

$$\mu + GPR_{T_a} \cdot \beta_{GPR} \cdot (T_b - T_a) + \delta$$

$$\delta \sim N(0, (T_b - T_a)^2 \cdot \varphi^2)$$

Model Type 1			Model Type 2		
$\alpha = -0.30$, $\beta_T = 0.20$, $\sigma^2 = 0.08^2$	$\alpha = -0.30$, $\beta_T = 0.25$, $\sigma^2 = 0.07^2$	$\alpha = -0.35$, $\beta_T = 0.25$, $\sigma^2 = 0.04^2$	$\mu = -10$, $\beta_{GPR} = 0.25$, $\varphi^2 = 5^2$	$\mu = -8$, $\beta_{GPR} = 0.50$, $\varphi^2 = 5^2$	$\mu = -8$, $\beta_{GPR} = 0.25$, $\varphi^2 = 6^2$
0%	100%	0%	0%	0%	0%

All Greek Letters are Coefficients

Long-Term Bridge Performance Program

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Learning is flexible and can be corrected any time

Models can be added or removed any time

No.	1	2	3	4	5	6	7
Weight	45%	15%	10%	15%	10%	5%	

80%

X 80%

36%	12%	8%	12%	8%	4%	20%

Demonstration of the D³M² Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Remove Candidate Models with 0% Weights

Model Type 1: $GPR_{T_b} =$

$$GPR_{T_a} \cdot \exp(\alpha + \beta_T \cdot (T_b - T_a) + \varepsilon)$$

$$\varepsilon \sim N(0, (T_b - T_a)^2 \cdot \sigma^2)$$

Model Type 2: $GPR_{T_b} =$

$$\mu + GPR_{T_a} \cdot \beta_{GPR} \cdot (T_b - T_a) + \delta$$

$$\delta \sim N(0, (T_b - T_a)^2 \cdot \varphi^2)$$

Model Type 1			Model Type 2		
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0%	100%	0%	0%	0%	0%

All Greek Letters are Coefficients

Long-Term Bridge Performance Program

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Remove Candidate Models with 0% Weights

Model Type 1: $GPR_{T_b} =$

$$GPR_{T_a} \cdot \exp(\alpha + \beta_T \cdot (T_b - T_a) + \varepsilon)$$

$$\varepsilon \sim N(0, (T_b - T_a)^2 \cdot \sigma^2)$$

$\alpha = -0.30$

$\beta_T = 0.25$

$\sigma^2 = 0.07^2$

100%

All Greek Letters are Coefficients

Data Analysis

LTBP Program

Long-Term Bridge Performance Program

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Add New Candidate Models → Refined Learning

Model Type 1: $GPR_{T_b} =$

$$GPR_{T_a} \cdot \exp(\alpha + \beta_T \cdot (T_b - T_a) + \varepsilon)$$

$$\varepsilon \sim N(0, (T_b - T_a)^2 \cdot \sigma^2)$$

$\alpha = -0.31$	$\alpha = -0.30$	$\alpha = -0.30$	$\alpha = -0.31$
$\beta_T = 0.25$	$\beta_T = 0.25$	$\beta_T = 0.26$	$\beta_T = 0.26$
$\sigma^2 = 0.07^2$	$\sigma^2 = 0.07^2$	$\sigma^2 = 0.07^2$	$\sigma^2 = 0.07^2$
	100%		

Equal Weights

All Greek Letters are Coefficients

Long-Term Bridge Performance Program

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Add New Candidate Models → Refined Learning

Model Type 1: $GPR_{T_b} =$

$$GPR_{T_a} \cdot \exp(\alpha + \beta_T \cdot (T_b - T_a) + \varepsilon)$$

$$\varepsilon \sim N(0, (T_b - T_a)^2 \cdot \sigma^2)$$

$\alpha = -0.31$ $\beta_T = 0.25$ $\sigma^2 = 0.07^2$	$\alpha = -0.30$ $\beta_T = 0.25$ $\sigma^2 = 0.07^2$	$\alpha = -0.30$ $\beta_T = 0.26$ $\sigma^2 = 0.07^2$	$\alpha = -0.31$ $\beta_T = 0.26$ $\sigma^2 = 0.07^2$	**Equal Weights**
25%	25%	25%	25%	

All Greek Letters are Coefficients

Long-Term Bridge Performance Program

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Learning with 2009 – 2011 data (*updating weights*)

Model Type 1: $GPR_{T_b} =$

$$GPR_{T_a} \cdot \exp(\alpha + \beta_T \cdot (T_b - T_a) + \varepsilon)$$

$$\varepsilon \sim N(0, (T_b - T_a)^2 \cdot \sigma^2)$$

$\alpha = -0.31$ $\beta_T = 0.25$ $\sigma^2 = 0.07^2$	$\alpha = -0.30$ $\beta_T = 0.25$ $\sigma^2 = 0.07^2$	$\alpha = -0.30$ $\beta_T = 0.26$ $\sigma^2 = 0.07^2$	$\alpha = -0.31$ $\beta_T = 0.26$ $\sigma^2 = 0.07^2$
87.49%	11.84%	0.08%	0.59%

All Greek Letters are Coefficients

Long-Term Bridge Performance Program

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

Learning with *2011 – 2014* data (*updating weights*)

Model Type 1: $GPR_{T_b} =$

$$GPR_{T_a} \cdot \exp(\alpha + \beta_T \cdot (T_b - T_a) + \varepsilon)$$

$$\varepsilon \sim N(0, (T_b - T_a)^2 \cdot \sigma^2)$$

$\alpha = -0.31$ $\beta_T = 0.25$ $\sigma^2 = 0.07^2$	$\alpha = -0.30$ $\beta_T = 0.25$ $\sigma^2 = 0.07^2$	$\alpha = -0.30$ $\beta_T = 0.26$ $\sigma^2 = 0.07^2$	$\alpha = -0.31$ $\beta_T = 0.26$ $\sigma^2 = 0.07^2$
95.25%	4.74%	0.00%	0.00%

All Greek Letters are Coefficients

Long-Term Bridge Performance Program

Demonstration of the D^3M^2 Concept Using Data Collected from the LTBP Program VA Pilot Bridge

- Multi-Index Learning
  - Indices reflect the condition of the same element: *inevitably correlated*
  - Essential for D^3M^2 to simultaneously learn multiple indices
  - E.g. GPR & Half-Cell Potential (HCP)

All Greek Letters are Coefficients

Model Type Example

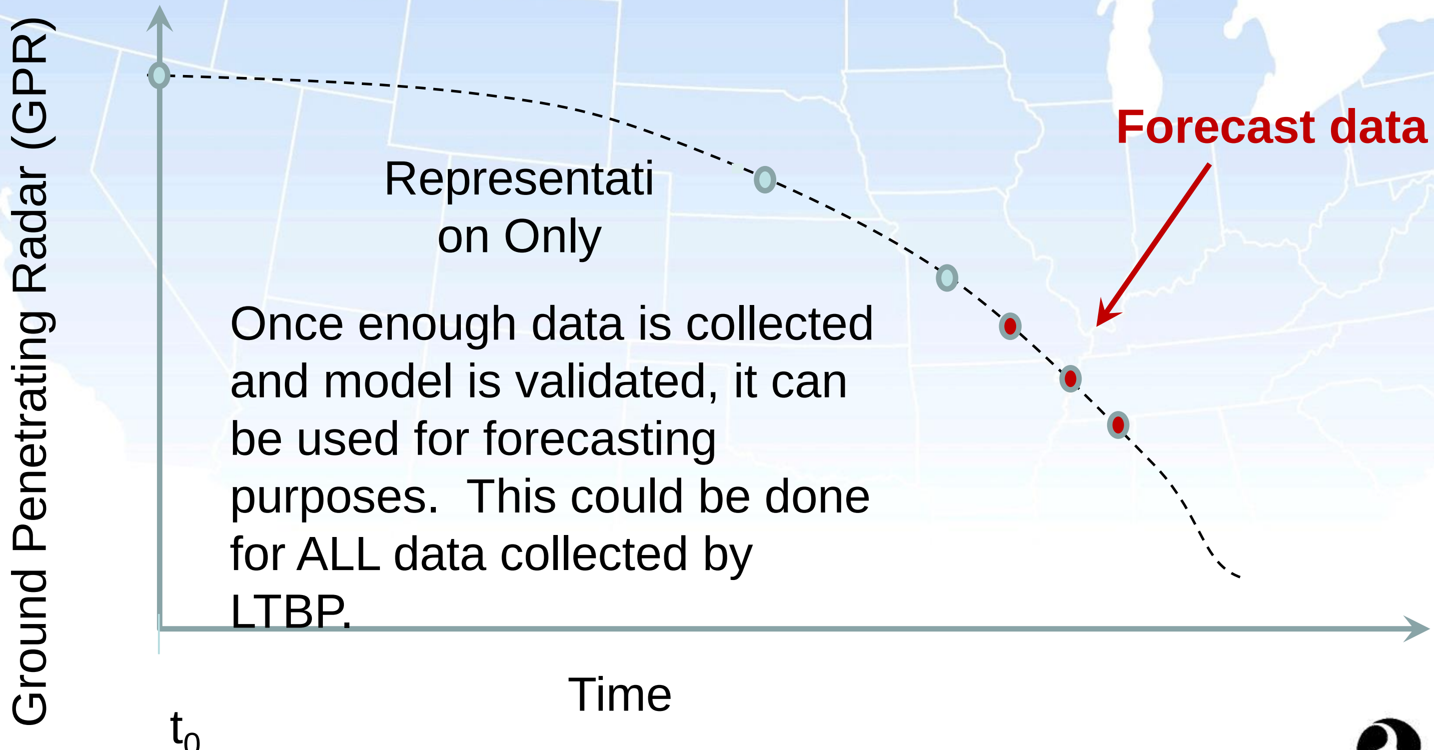
$$GPR_{T_b} = GPR_{T_a} \cdot \exp(\alpha + \beta_{GPR} \cdot (T_b - T_a) + \varepsilon)$$

$$HCP_{T_b} = \omega \cdot \mathrm{HCP}_{T_a} + \beta_{HCP} \cdot (T_b - T_a) + \delta$$

The ability to model and forecast individual indices allows us to forecast bridge conditions, and accordingly make optimal repair decisions

What are the Implications of Proposed Data-Driven Modeling Approach ?

Forecasting Ground Penetrating Radar Results (Bridge Decks)

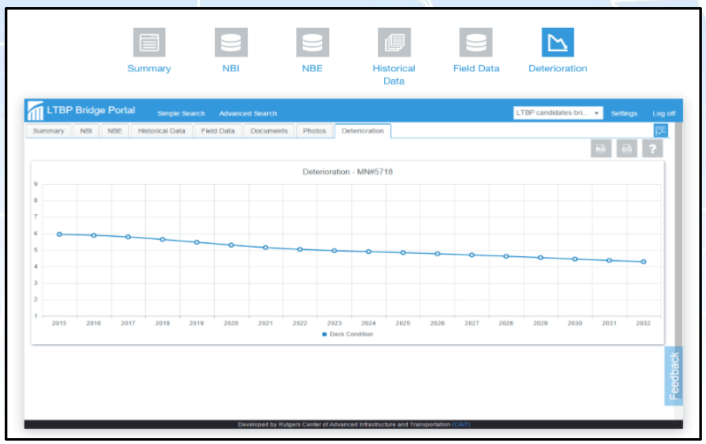


Once enough data is collected and model is validated, it can be used for forecasting purposes. This could be done for ALL data collected by LTBP.

Long-Term Bridge Performance Program

Where Are We Now?

A Beta Version of Deterioration Modeling Application has been developed for NBI and NDE data and incorporated into the Bridge Portal



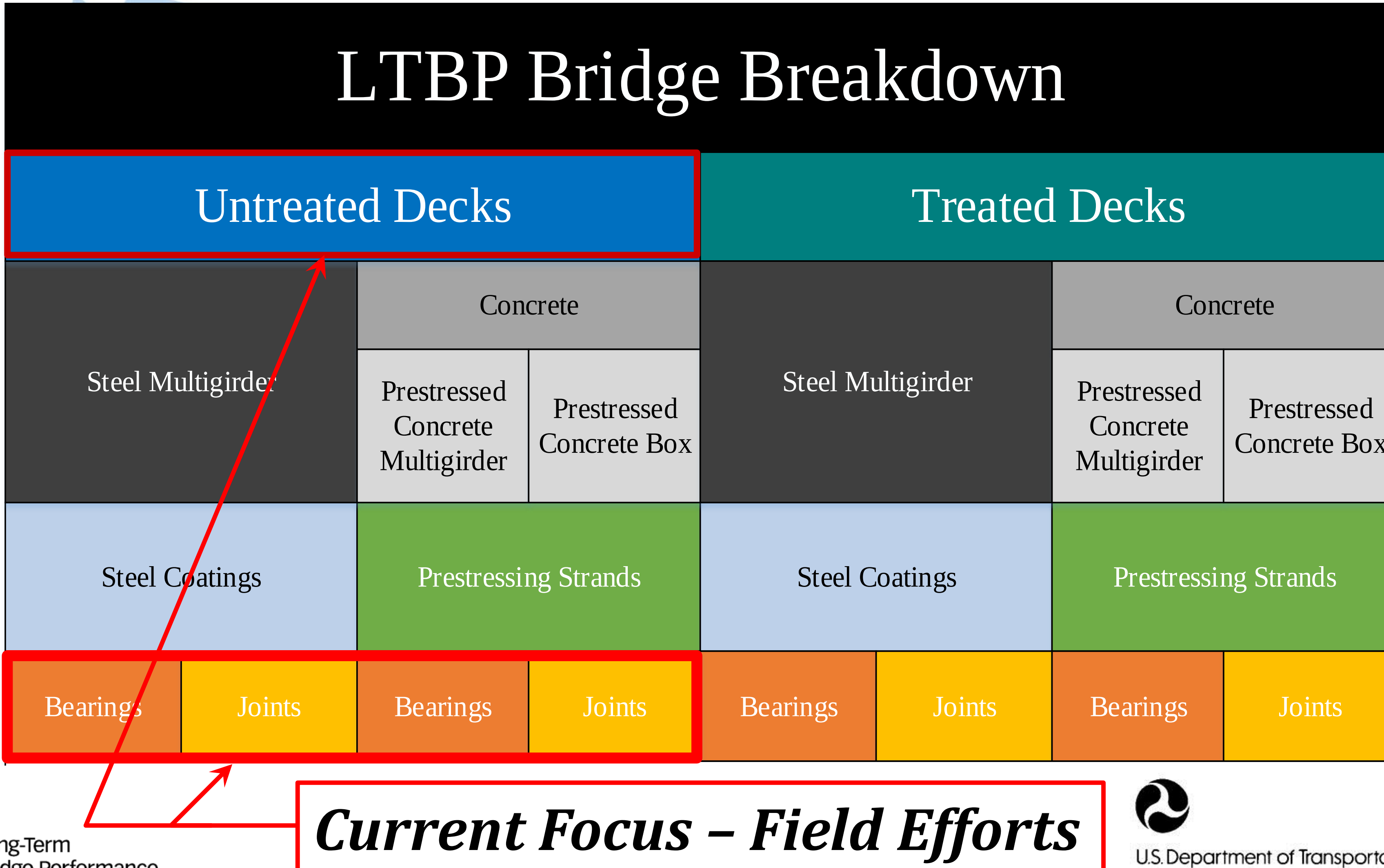
Conversations with Pilot States (NY, NJ, etc.) on validating the Deterioration Modeling Application

<u>We Need Historical Data – Core Elements OK !!</u>

Long-Term Bridge Performance Program

- LTBP Data Collection
- Data Management
- LTBP Analysis
- Moving Forward

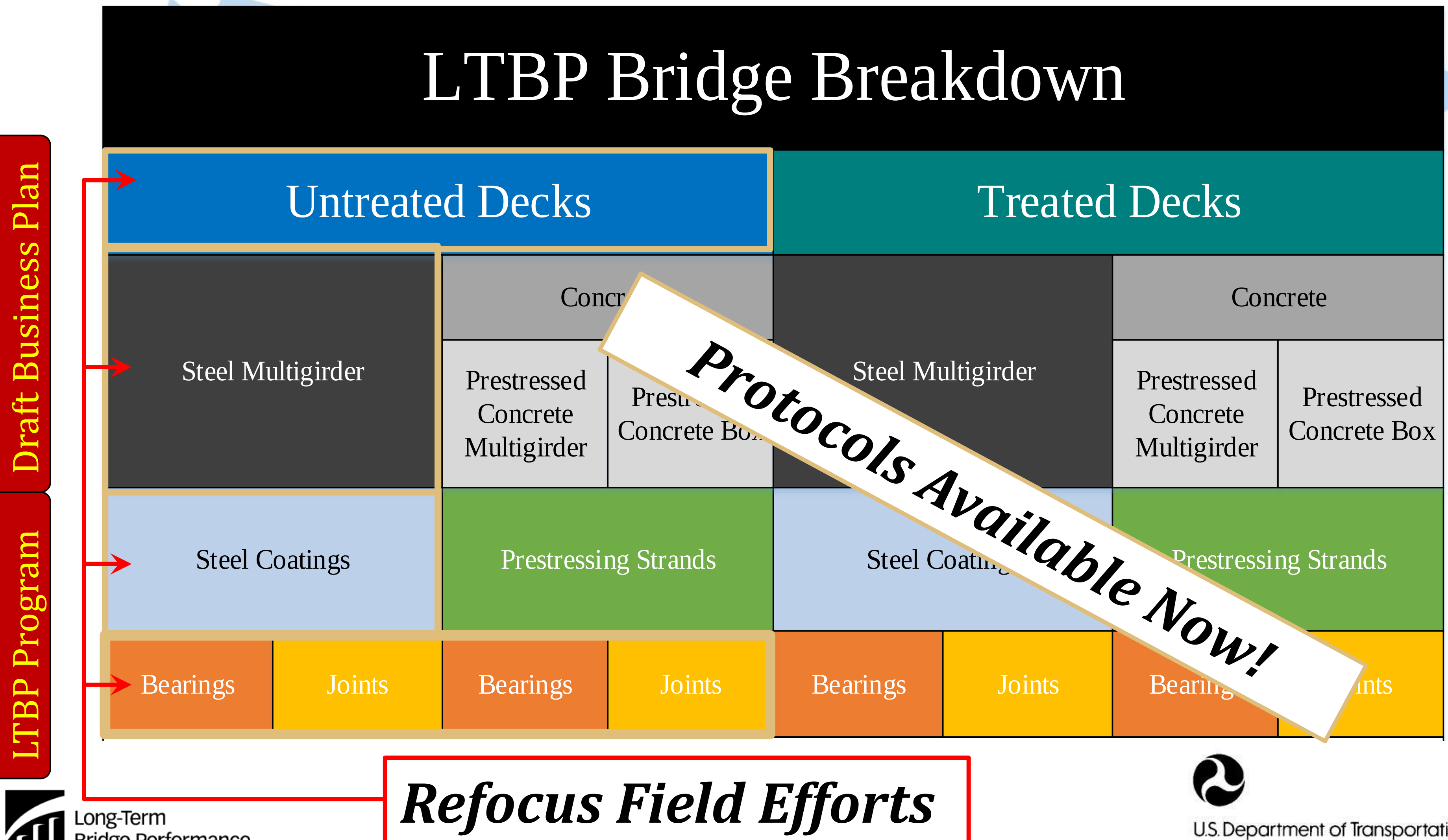
Long-Term Bridge Performance Program



Schematic Schedule

LTBP Program

Long-Term Bridge Performance Program



Long-Term Bridge Performance Program

LTBP Bridge Breakdown

Untreated Decks

Treated Decks

Steel Multigirder

Concrete

Prestressed Concrete Multigi

Prest

Concrete

Prestressed Concrete Multigirder

Prestressed Concrete Box

Stee

nds

Steel Coatings

Prestressing Strands

Bearings | Joints | Bearings | Joints | Bearings | Joints | Bearings | Joints

Studies for Development of Protocols in Progress

Draft Business Plan

LTBP Program

Long-Term Bridge Performance Program

Draft Business Plan

LTBP Program

LTBP Bridge Breakdown

Untreated Decks				Treated Decks			
Steel Multigirder		Concrete		Steel Multigirder		Concrete	
		Prestressed Concrete Multigirder	Prestressed Concrete Box			Prestressed Concrete Multigirder	Prestressed Concrete Box
Steel Coatings		Prestressing Strands		Steel Coatings		Prestressing Strands	
Bearings	Joints	Bearings	Joints	Bearings	Joints	Bearings	Joints

Realign Field Efforts

Long-Term Bridge Performance Program

Status Update

2016 Midwest Bridge Prese … Partnership

Octo…

Questions ?

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LTBP Program Coordinator

Long-Term Bridge Performance Program

Federal Highway Administration