AI Applications in Pavement Management

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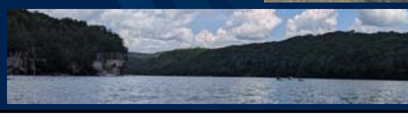

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Outline

- Ongoing work
  - Performance modeling
- Upcoming tasks
  - Applications for WV PMS
- High impact potential for AI applications
  - Brainstorming with FHWA

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What is AI?

- …any technology or machine that can perform complex tasks typically associated with human intelligence, such as problem-solving, planning, reasoning, and decision-making.

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Categories of AI

- Machine learning
  - learn from data and improve system performance without being explicitly programmed
- Deep learning
  - Multi-layered NNs
    - Natural language processing
    - Computer vision

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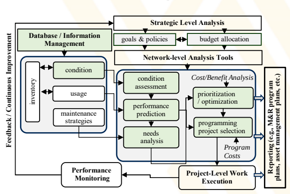
Pavement Management



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Ongoing work…

Performance Modeling and Unrecorded Maintenance

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FHWA Project Objective

Development of approaches and proof-testing of **adaptive project specific pavement performance models for PMS from "family" models** for developing prioritization projects.

Leverage information from pavement segment and family to predict future segment condition

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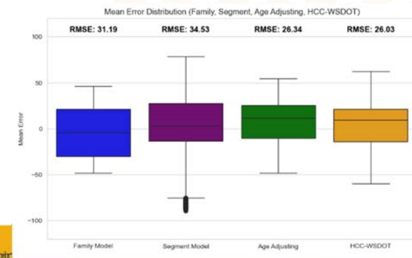
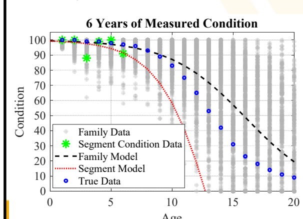
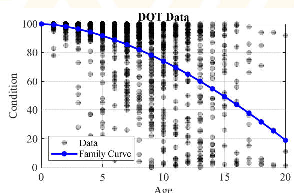
Why not model segment data?



Data used in project

- Synthetic Data
- State DOT Data





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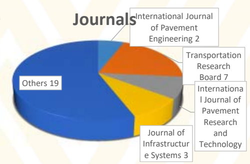
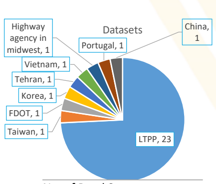
Literature Review

- Articles were extracted between (2016-2024)
- Keywords:
  - 'Pavement performance prediction'
  - 'Machine Learning'
  - 'Neural networks'
  - 'IRI'
  - 'Performance index'
- 34 most relevant articles were studied in detail

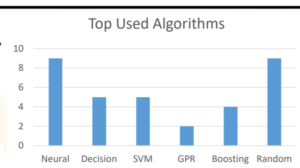


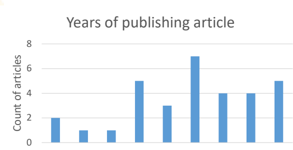
ScienceDirect Taylor & Francis ASCE Sage MDPI SPRINGER NATURE

Literature Review



No. of Road Segments	
Min	26
Max	7615
Avg	1078.7
Median	118
Std Dev	2363.066





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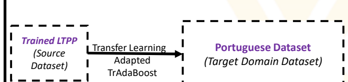
Transfer learning for pavement performance prediction

Pedro Marcelino[a]*, Maria de Lurdes Antunes[a], Eduardo Fortunato[a], Marta Castilho Gomes[b]



Dataset	Size	Model Type
LTPP to Portuguese	2807-83	Adapted TrAdaBoost

Features [5]	Target [1]
Ann Δ_{avg}, AADT, Pavement Thickness, SN, AA Precipitation	IRI

Highlights

- Two stages: IRI from IRI0 and IRI from features.
- Transfer learning perform quite well in case of few data and at long-term forecasts.
- Boosting doesn't require same distribution and can perform well where available data is scarce.

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Synthetic Measurement Data

mm (actual PCI measurements)

	Y1	Y2	Y3	Y4	Y29	Y30
R1	100	80	60	40	20	0
R2	100	90	70	50	30	10
R3	100	80	70	50	40	20
R4	100	70	50	20	5	0
R5	100	90	80	60	50	30

mm2 (PCI measurements+errors)

	Y1	Y2	Y3	Y4	Y29	Y30
R1	100	82	42	58	18	3
R2	98	89	68	54	29	12
R3	99	83	58	69	41	27
R4	99	76	52	28	7	1
R5	99	94	82	63	48	36

- '**mm**' is generated measurements of 500 segments for 30 years.
- '**mm2**' we added errors to it
- '**mm3**' we hid some measurements.

mm3 (PCI measurements + errors + NaNs)

	Y1	Y2	Y3	Y4	Y29	Y30
R1	100	82	42	58	18	3
R2	98					
R3	99	83	58	69		
R4	99	76	52			
R5	99	94	82	63	48	36

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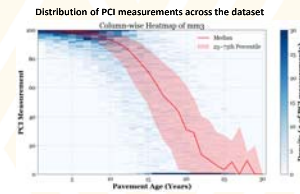
DATA ANALYSIS



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The challenge…

- ML methods are not traditionally designed to deal with missing data, so how to select features?

Imputation algorithm + ANN or LSTM

Train ANN on features of the data

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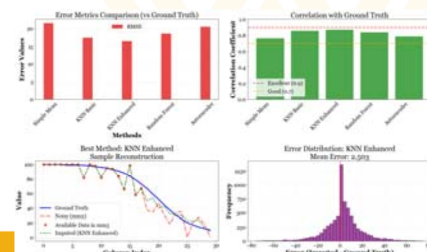
Imputation (NOT PREDICTION) results



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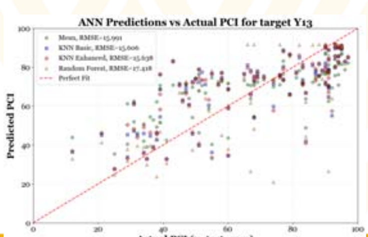
Prediction Model FROM IMPUTED DATA

Features: Y6,Y7,Y8,Y9,Y10
Target: Y13



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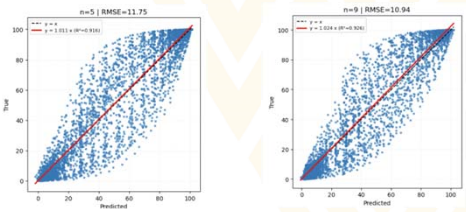
Example Feature definitions (20+)

Denoised segment statistics

Feature	Definition / How it's calculated	Role
seg_mean	mean(y_den) where y_den is Huber-smoothed fit on (t_seg, y_meas[t_seg])	Central level of observed history (noise-reduced).
slope_first	Local slope between first two points: Δy/Δt.	Early-rate indicator.
slope_last	Local slope between last two points: Δy/Δt.	Recent-rate indicator.
slope_mid_theilsen	Median of all pairwise slopes on (t_seg, y_den) (Theil–Sen).	Robust overall trend.
last_age	Latest observed age in t_seg.	Defines window end

Low-noise synthetic data



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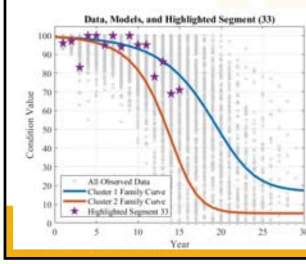
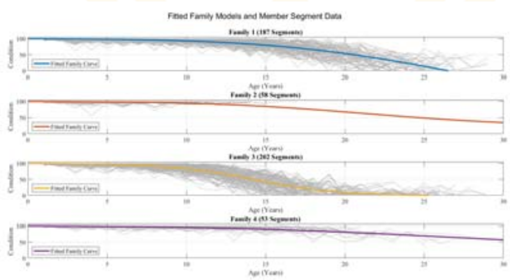
Clustering?

Article
Deep Time-Series Clustering: A Review
Ali Alqahtani [1,2,3,*], Mohammed Ali [2,3], Xianghua Xie [3] and Mark W. Jones [3]



$$L_{ik} = \prod_{t \in S_i} \mathcal{L}(x_i(t) \mid \Theta_k).$$

$$u_{ik}^{\text{lik}} = \frac{L_{ik}}{\sum_{j=1}^{K} L_{ij}} \quad \text{with} \quad \sum_{k=1}^{K} u_{ik}^{\text{lik}} = 1.$$



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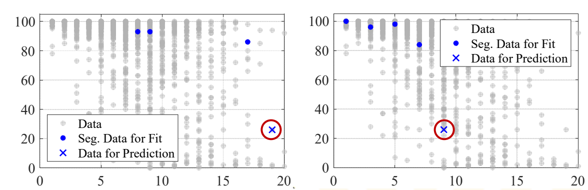
Challenge moving to DOT Data …How to Select Target???



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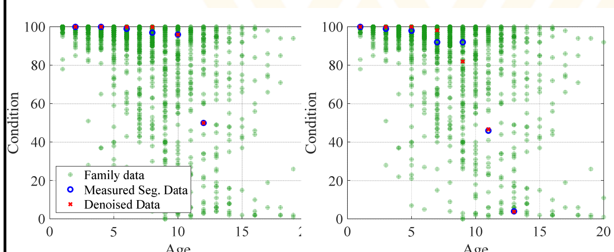
Huber Loss to Denoise?



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Metric to evaluate quality of fit?

Three criteria:

- How well does predicted data fit with measured segment data from prior years in model
$$\mathcal{M} = \log \mathcal{L}(x \mid \mathcal{F}(x, age))$$
- How likely is the predicted data to be observed in the family? $\mathcal{P}(y|\phi)$, where y is predicted data and ϕ is the distribution from the family model
- How likely is predicted data to be part of segment given the measured data? $\mathcal{P}(y|y_{meas})$

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Upcoming…

Applications of AI in WV PMS

Objectives and Tasks

- **Objective** – identify areas of pavement management that can be enhanced by AI and build prototype tools to demonstrate their benefits for a subset of those areas.
  1. Comprehensively map the pavement management process in WV and identify key areas that AI can be integrated.
  2. Gather data & models for those areas where AI will be investigated.
  3. Build prototype AI models and evaluate their performance compared to traditional pavement management processes
  4. Develop a final report and user guides
  5. Implementation Support.

Holistic Asset Management and Accurate Cost Estimation

- Network-level cost estimates for paving projects are often inaccurate
  - neglect the condition of ancillary assets like guardrails, signage, or drainage, which are only assessed during costly site visits.

Computer Vision to Evaluate Existing Images + Deep Learning to Categorize Condition & Cost

generate a comprehensive project scope and a more accurate, all-inclusive cost estimate

Promising applications…

Brainstorming with FHWA & other colleagues

Physics-Informed Language Models (PILM) for Advanced Mechanistic-Empirical (ME) Prediction

- **The Challenge:** Current ME models are constrained by pre-defined transfer functions that limit the complexity of the inputs they can consider from mechanistic models (e.g., only peak strain).
- **The Solution:** move beyond traditional PINNs to **Physics-Informed Language Models**. Instead of just replacing a transfer function with a neural network, use LLM's ability to process complex sequences and relationships. The model could take the *entire distribution of stresses and strains* from a mechanistic simulation, along with material properties and environmental data, as a complex input sequence.

Are we losing information?

PM

Condition Images

Distresses

Condition Index

Performance Model

Needs Assessment

Generative AI for Multi-Modal Pavement Analysis and Data Augmentation

- **The Challenge:** Pavement management involves a significant *loss of information*. Rich visual data from images is condensed into simplified distress codes (e.g., "medium severity alligator cracking"), which are then further abstracted into a single condition index. This process loses critical context about the *causes* of deterioration and the relationships between different distress types.
- **The LLM Solution: Multi-Modal Large Language Models**. These models can process and understand diverse data types—images, sensor readings (e.g., GPR), historical maintenance text logs, and structured data—simultaneously. Instead of reducing images to codes, an LLM can generate rich, descriptive text summaries of pavement condition.

Conclusions…

Under development.

Questions and Discussion?

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