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A STRUCTURALIZED LINK-BASED **CRACK DENSITY INDICATOR** BASED ON A CRACK VECTOR MODEL (CVM)

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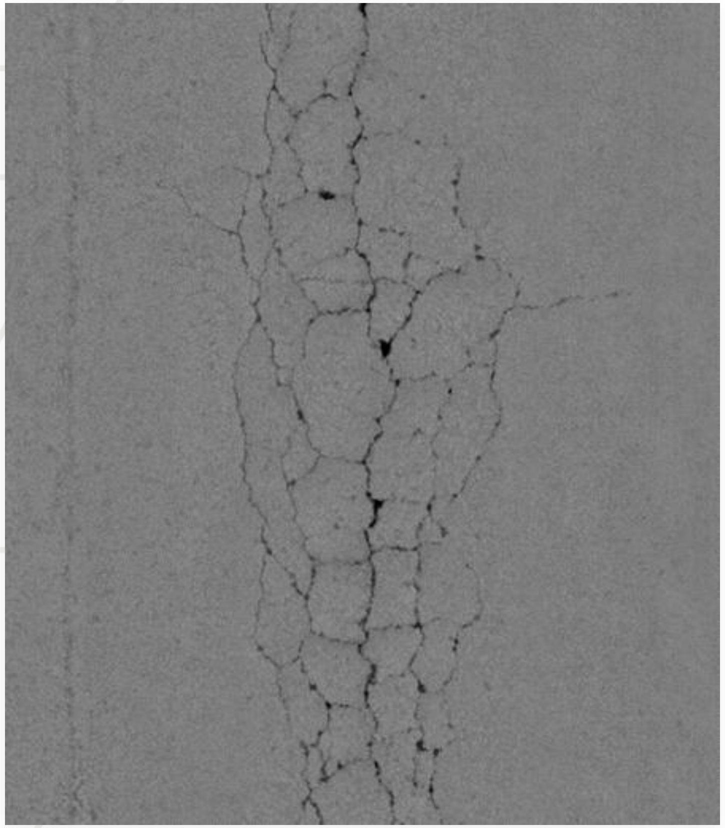
OUTLINE

- Needs for Crack Density Indicator
- Crack Vector Model (CVM) as Foundation
- Proposed Crack Density Indicator
- Optimal Parameter Design
- How the Density Indicator Helps

Why Do We Need Density?

Crack density offers a potential means to identify and classify alligator/pattern cracks using quantifiable criteria.



Example of alligator/pattern cracking

Length, width, and orientation aren't enough

These crack attributes cannot support the alligator/pattern crack classification.

It's about the pattern, not the pieces

Alligator/pattern cracking is defined by how cracks interconnect; it's defined as a network, not individual cracks.

Agencies need one consistent number

ASTM E3303 already treats density as key, but its grid-based methods need further refinement.

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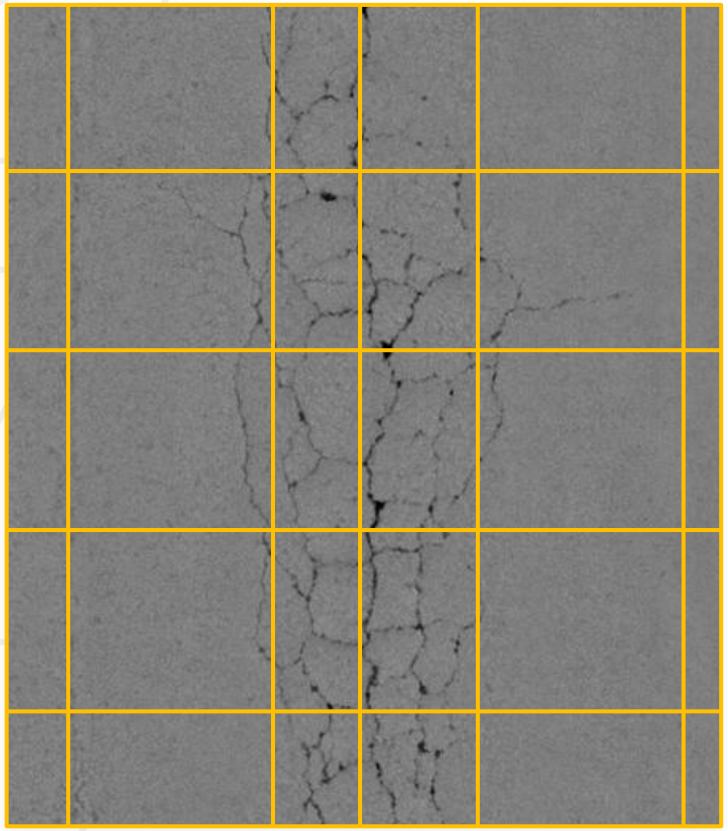
How the Density is Measured Now?

The common approach is to overlay grids and measure cracks in each one.



Predefined grid
density = crack length ÷ cell area
(e.g., ASTM E3303)

Grid setting is a judgment call

Different grid sizes and positionings give different answers for the same pavement.

Cracks get split by grid lines

Arbitrary partitioning hides the shape of the crack network and loses track of individual crack structures.

Results might be inconsistent

Same set of cracks may result in different density values under different grid settings.

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What Density Method Is Really Needed?

A density number that is objective, repeatable, and speaks the practitioner's language.

Objective

No subjective judgment needed, objective procedure and results.

Repeatable

Same evaluation section, same result every time.

Interpretable

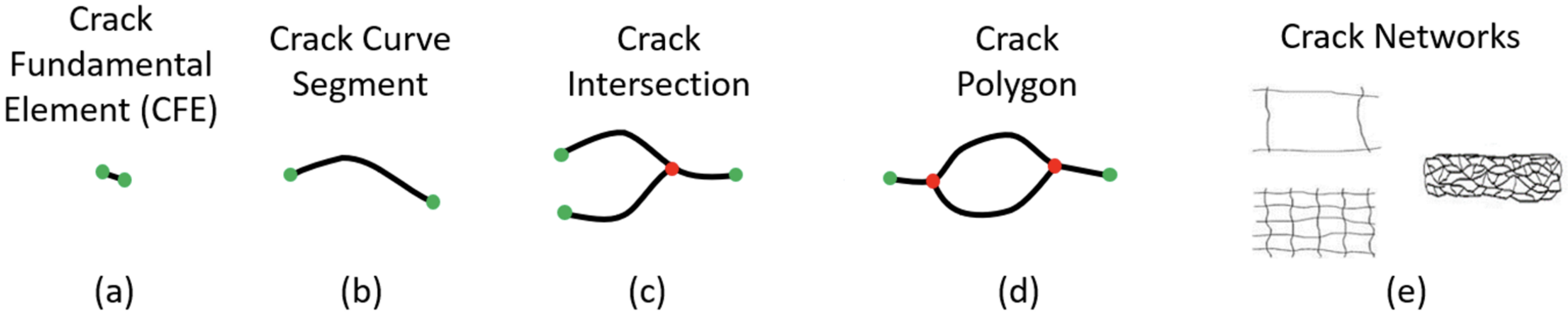
An interpretable calculation procedure: consider each individual crack and its neighborhood.

Customizable

Agencies set their own parameters to align with the alligator/patter cracking definition and decision-making.

Crack Fundamental Element

- The concept of the crack fundamental element (CFE) was originally proposed in 2014:
  1. Using fundamental geometry of node and link, to represent crack.
  2. Similar to roadway networks, existing GIS knowledge is leveraged.
- CFE serves as the basis of the digital twin of cracking data to perform the measurement and reporting in a digitized format.



Crack Fundamental Element

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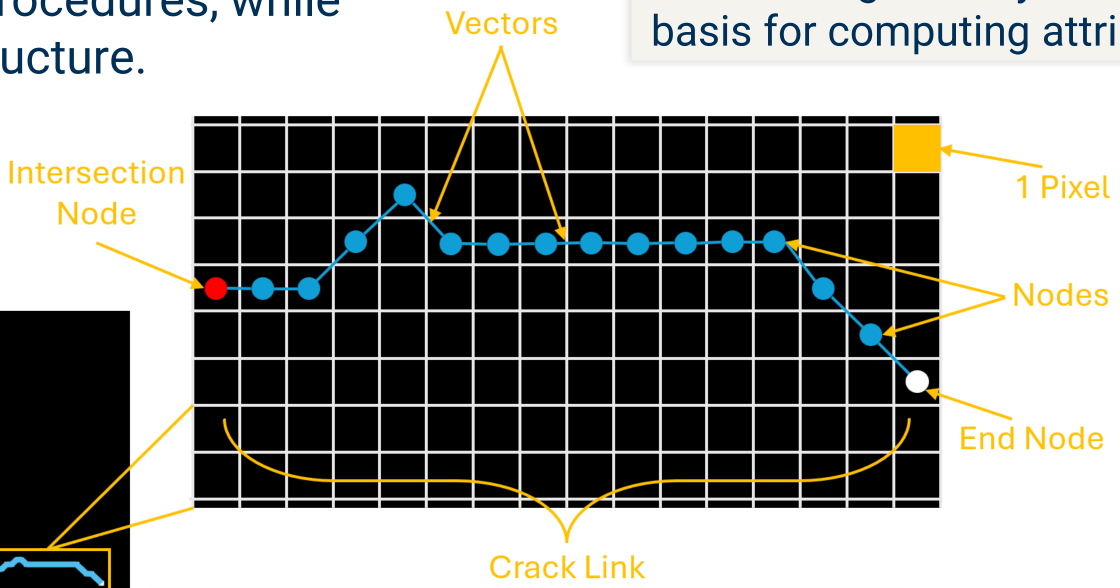
Tsai, Y., Jiang, C., Huang, Y. (2014) “A Multi-scale Crack Fundamental Element Model for Real World Pavement Crack Classification”, ASCE Journal of Computing in Civil Engineering, vol. 28, no. 4, 2014

Crack Vector Model (CVM) as Fundamental Data Layer

Introduced **CVM** (Yang, 2024), developed on the concept of the **crack fundamental element** (Tsai, 2014), to provide the most fundamental crack information with executable procedures, while preserving individual crack structure.

Crack Vector

Straight-line segment between two adjacent nodes. Vectors collectively define link geometry and serve as a basis for computing attributes.



Crack Node

Discrete digitized point describing geometry. Includes start, end, and intermediate nodes capturing curvature. Default spacing: 1 pixel.

Crack Link

Continuous segment bounded by start/end nodes. Consists of ordered crack nodes connected by vectors. The fundamental analytical unit.

Yang, Z. (2024). Crack propagation analysis using pavement image registration and crack vector model for predictive and precision pavement maintenance, Georgia Institute of Technology.

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Why CVM Unlocks Density

Because every crack link is a separate crack element, we can measure **density** for each one individually and assign it as an attribute, such as length and width.

Without CVM

Cracks are just pixels.

- ✖ Must impose a grid to count anything
- ✖ Cracks get cut arbitrarily by grid borders
- ✖ Difficult to trace back which cracks are dense

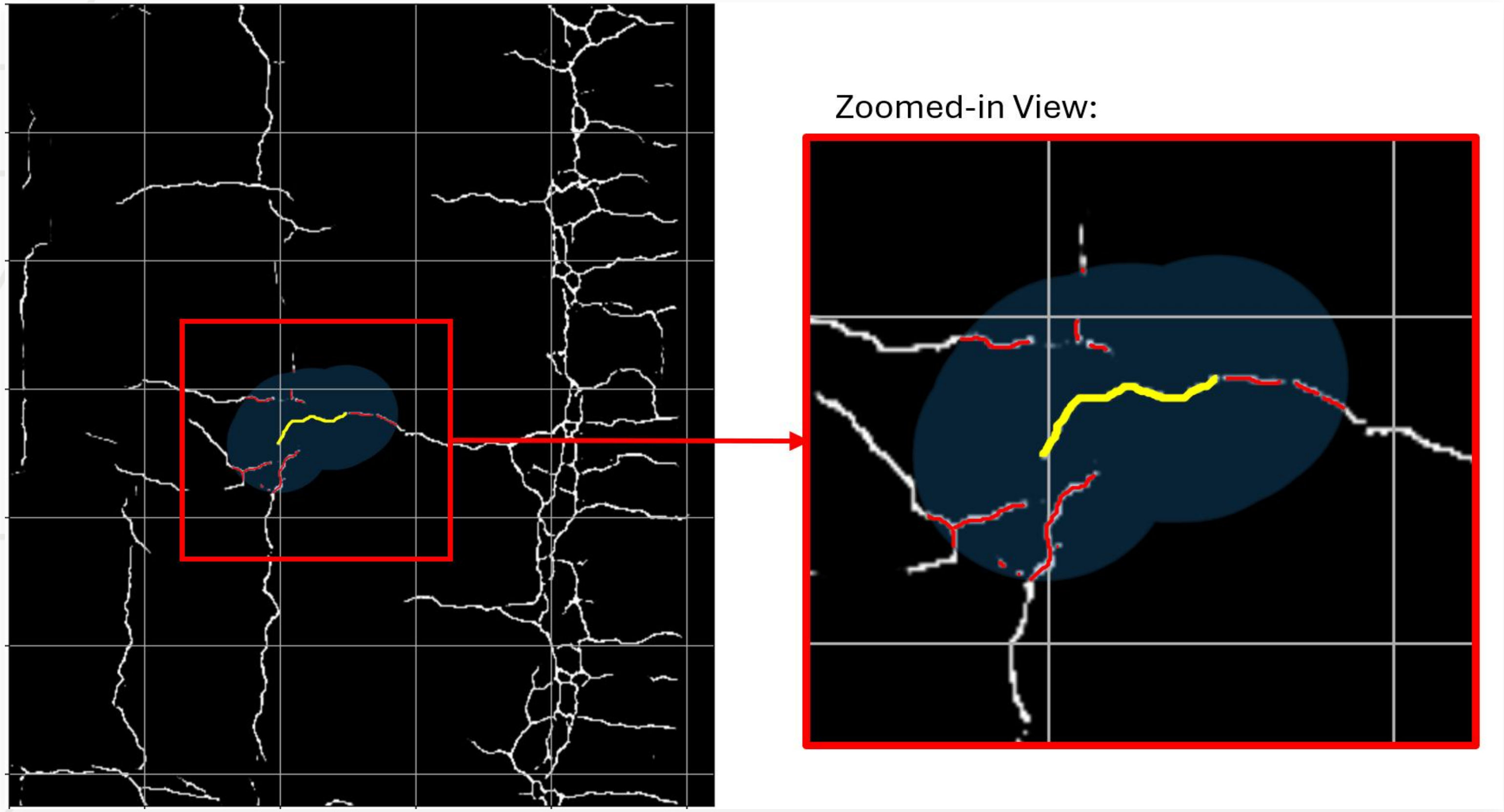
With CVM

Cracks are objects.

- ✔ Each crack link has its own identity and attribute
- ✔ Draw a buffer around it and consider its neighbors
- ✔ No grids, no arbitrary cuts, no guesswork

Proposed Link-based Density

For every single crack link, draw a circular buffer around it and measure the crack length within it.



Yellow: the crack link for calculation.
Blue circle: its buffer.
Red: nearby crack length measured.

Three steps

1. **Pick a crack link**
   Go through all the crack links from the CVM.
2. **Draw its buffer**
   Create a circular buffer of radius *r* around the link centerline.
3. **Compute density**
   Length of included neighbor cracks ÷ buffer area.

Classify Alligator/Pattern Cracks in One Step

If density exceeds the threshold, it's alligator cracking.

If $D_i \geq T \rightarrow$ **Alligator crack**

D_i = *measured density at crack link i*

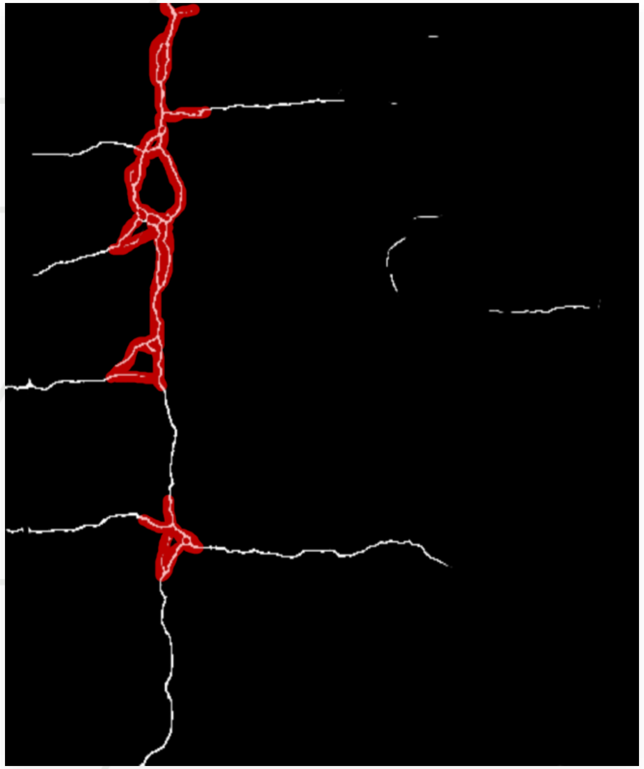
T = *density threshold*

Two parameters need to be designed:

- ***Buffer Radius r***
- ***Density Threshold T***

Design Parameters Using Ground Truth

Two experts independently marked alligator regions on 24 pavement images.



Annotation Example (red overlay)

24	pavement images covering alligator, longitudinal, transverse, and block cracking
4,809	crack links labeled (3,920 alligator + 889 non-alligator)
0.83	IoU score between expert annotations, indicating strong consensus
Both	only cracks where both experts agreed were kept for training

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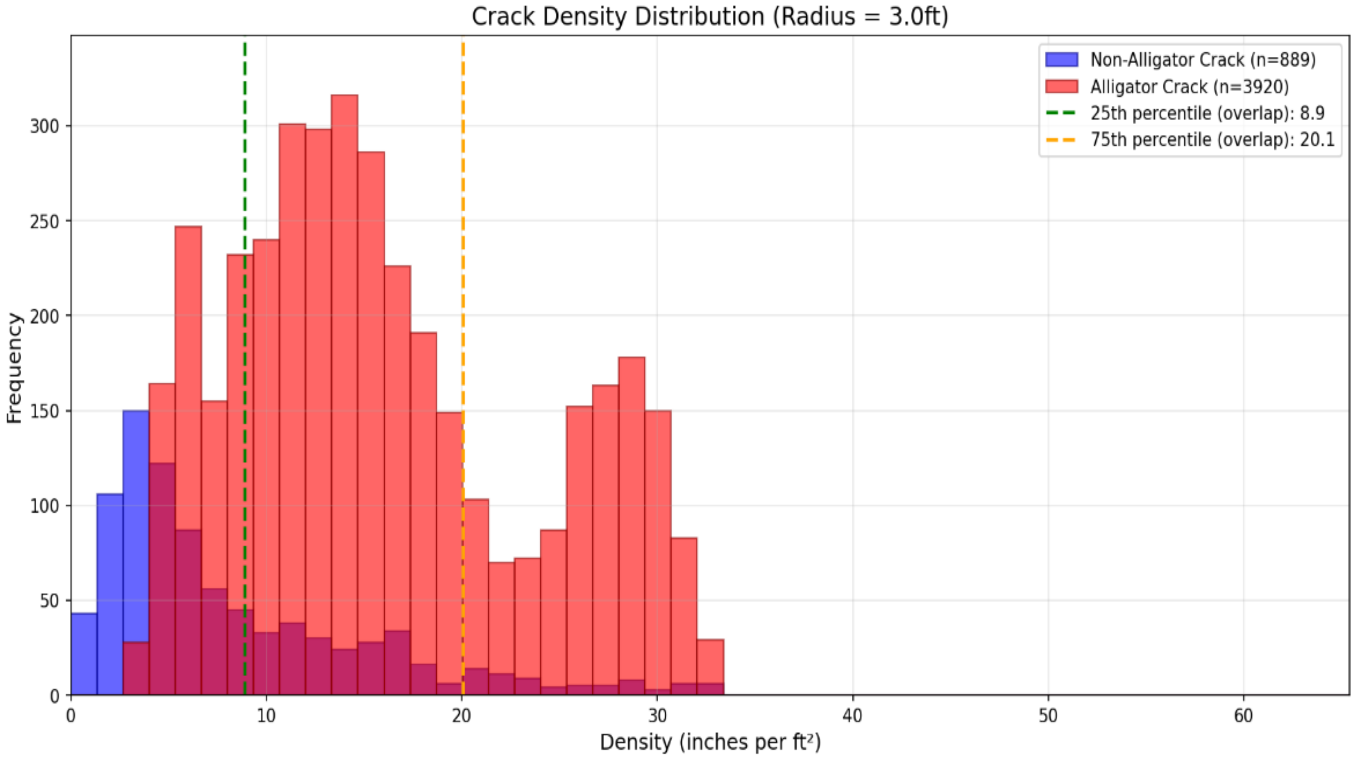
Density Can Separate Alligator/Pattern Cracks

Density values for alligator vs. non-alligator cracks barely overlap, so a threshold can split them.



Buffer = [illegible] ft

Non-alligator cracks (blue) cluster at low density. Alligator cracks (red) spread out at a higher density. As the buffer grows, numbers and differences shrink, so the threshold has to be well-determined.

Sensitivity Study

We tested 6 buffer sizes × 26 thresholds to determine which combination works best.

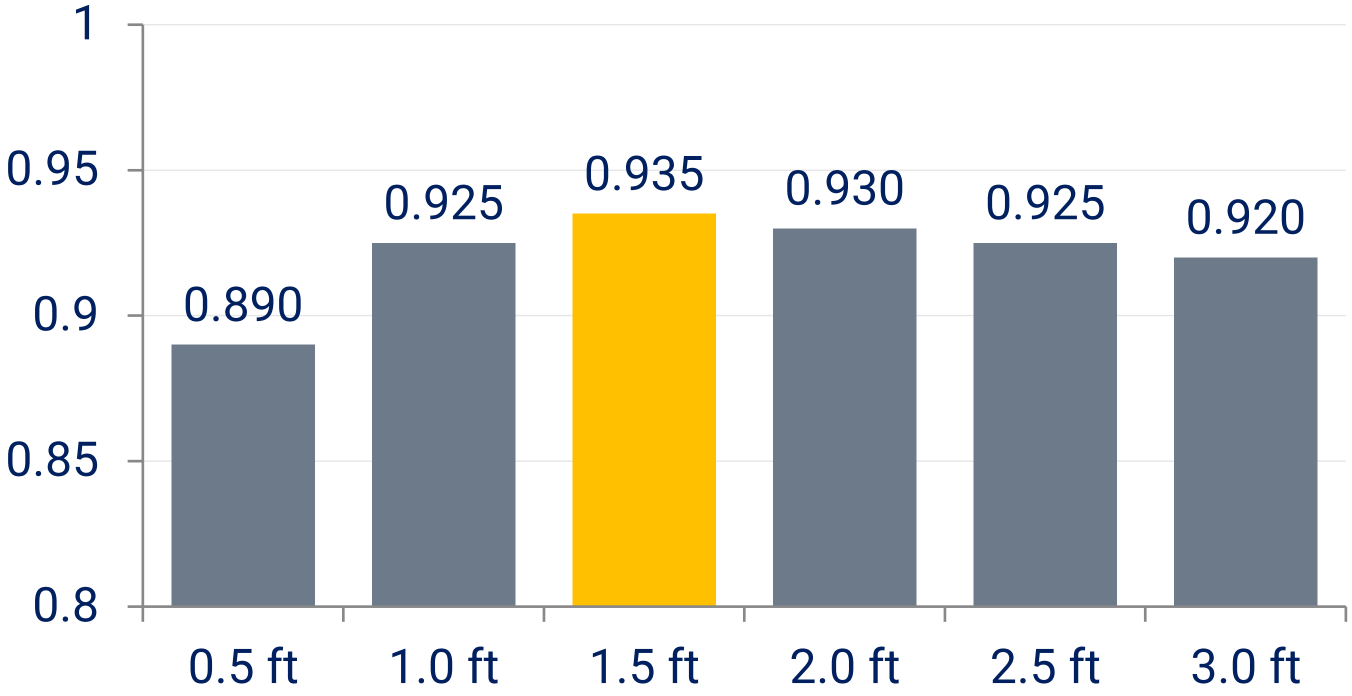
The grid search

Buffer radius (r)
0.5 – 3.0 ft
6 values, 0.5 ft steps

Density threshold (T)
5 – 30 in/ft²
26 values from overlap zone

Scored by
F1-score
balances precision and recall

Peak F1-score by buffer radius



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The Optimal Combination

Buffer radius of 1.5 ft, threshold of 6 in/ft² (0.5 ft/ft²).

OPTIMAL BUFFER RADIUS

1.5 ft

Aligns ASTM D6433: individual alligator pieces are typically under 1.5 ft.

OPTIMAL THRESHOLD

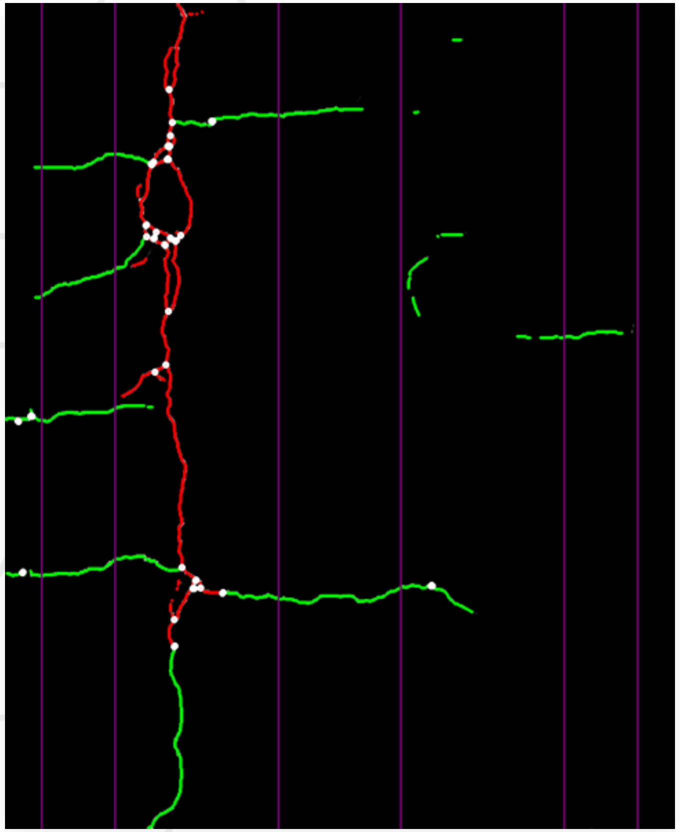
6 in/ft² (0.5 ft/ft²)

Density values above this reliably represent alligator patterns.

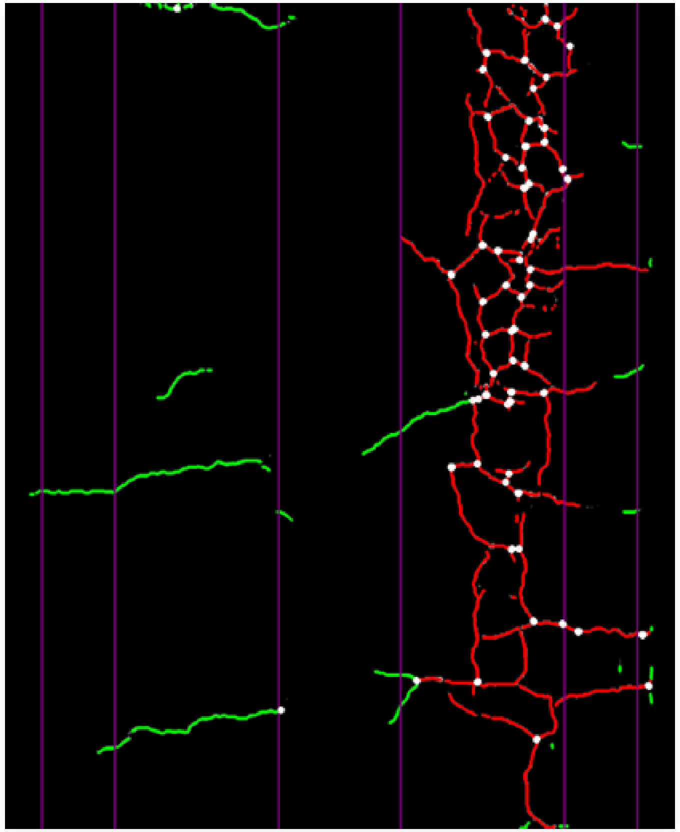
Performance at the optimal settings

0.935	0.977	0.897	0.867
F1-score	Recall	Precision	Accuracy

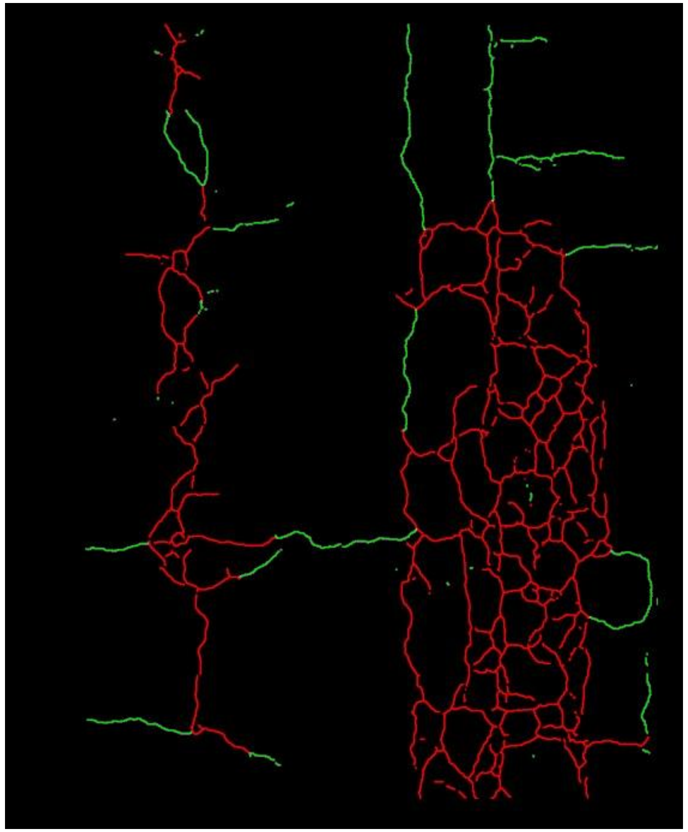
Results in Real Cases



Localized cluster detected



One major band



Two major regions

- Classified as alligator
- Classified as non-alligator

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How Can This Help Agencies

One indicator, plugged into the tools that current frames are already using.

Objective Alligator Crack Classifier

Classify alligator/pattern cracking in an objective, repeatable way, while maintaining each individual crack's structure.

Customizable to tune to different protocols

Same ground reference-based procedure can be used to customize the parameter setting for **different agencies' definitions for alligator/pattern cracks**.

No model retraining needed

Once the setting is done, no retraining on the new data is needed.

Key Takeaways

Structurally-defined link-based density is the missing dimension

Crack length or width alone can't tell the interconnections a crack network has, but density can.

CVM makes it measurable

Treating each crack as an element, not a pixel, unlocks a repeatable definition of density.

1.5 ft buffer, 6 in/ft² threshold

These are designed through expert-labeled data.

Agencies keep control

Parameter setting customizable, no retraining, aligned with ASTM D6433 and LTPP practice.

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THANK YOU!

QUESTIONS?

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