Next-Generation Pavement Condition Diagnosis and Maintenance Optimization using 3D Laser and AI Technologies: **Opportunities and Challenges**

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Outline

- Needs for automatic pavement condition evaluation and optimized pavement asset Management
- Emerging 3D laser technology
  - Opportunities & Challenges
- Use of **Crack Fundamental Element (CFE) to leverage the** newly extracted pavement distresses with high granularity
- Cases for optimized pavement asset management (3R: right time, right treatment, right location) using the automatically extracted pavement distress data:
  - Case 1: Automatic crack detection and classification
  - Case 2: Automatic detection and classification of OGFC loss of aggregates
- Summary

Needs for Automatic Pavement Condition Evaluation and Optimized Pavement M&R and Asset Management

Transportation Assets in U.S.

(Challenges: a great need of maintenance and rehabilitation)

> $1,750,000,000,000

Local Governments (Counties and Cities):

- Own more than 75% of nation's 4 billion miles of roadway
- Own more than half of nation's 600,000 bridges

Infrastructure

- Pavement
- Bridge
- Tunnel
- Hardware
  - Sign
  - Guardrail
  - Lighting
  - …

Others

- Equipment
- Vehicle
- Real Estate
- Human Resource
- …

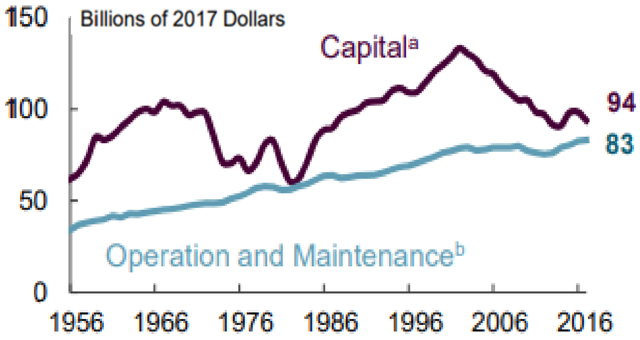
Pavement M&R Needs in U.S.

- US Highways (all public road and street) by end of 2017
  - More than **4.2 million centerline miles**
  - Valued more than **$ 3.4 trillion**

- US highway operation, maintenance and rehabilitation (M&R) cost
  - **$ 83 billion** annually in 2017
  - M&R expenditure will increase further in the future

- If we can save 1% of **$ 83 billion** annual M&R spending, which is **$ 830,000,000** saving every year.

US Spending of Highways Infrastructure

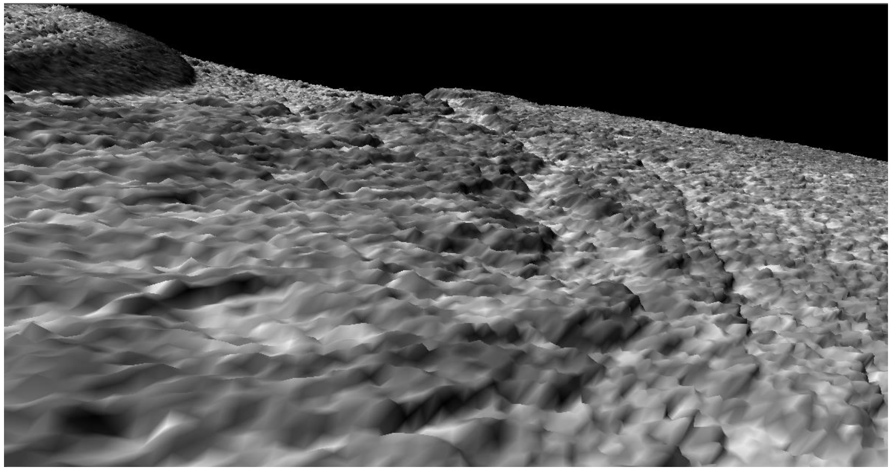


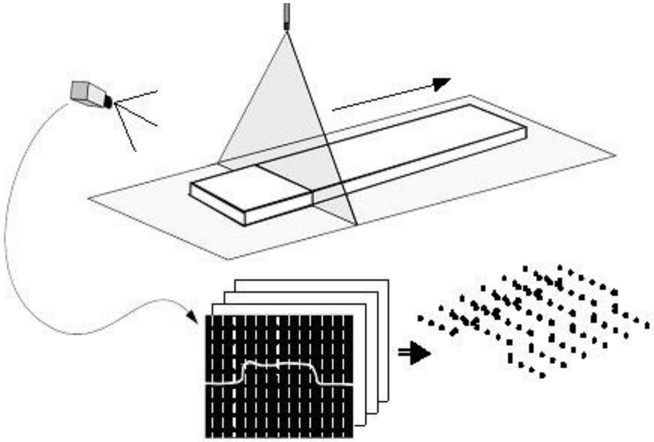
https://www.cbo.gov/system/files/2018-10/54539-Infrastructure.pdf

- Our research goal is to develop **enhanced methodologies and methods** to better determine the **right time, right treatment at right location** (3R) for optimizing our annual M&R spending.

Emerging 3D Laser Technology

2D/3D Pavement Surface Data Collected with 3D Laser Technology (Transverse Pavement Profiler)





- Resolution
  - Driving direction: 1 – 5 mm
  - Transverse direction: 1 mm
  - Elevation: 0.5 mm
  - Data points collected per second and width covered
    - 2 (lasers) * 2048 (points/profile/laser) * 5600 HZ = 22,937,600 points/second

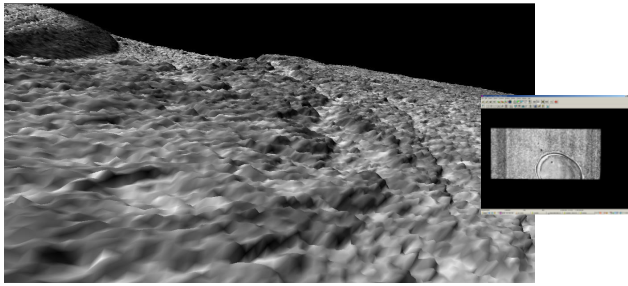
(Laurent, et. al., 2008)

(Operated at highway speed, 100 km/hr)

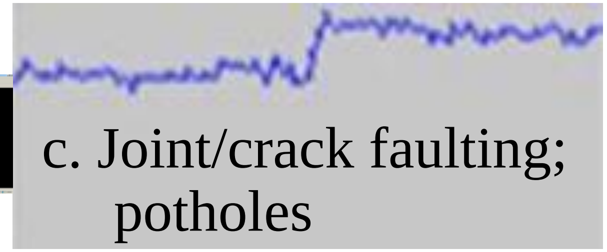
Opportunities

- Automated pavement condition evaluation using ML
- New Pavement Performance Indicators
- Pavement Preservation Quantity Estimation
- Optimized Pavement MR&R
- Predictive Performance Models
- Pavement Construction Quality Control
- Pavement Construction Automation
- Road Safety Support
- Safe navigation of CV/AV

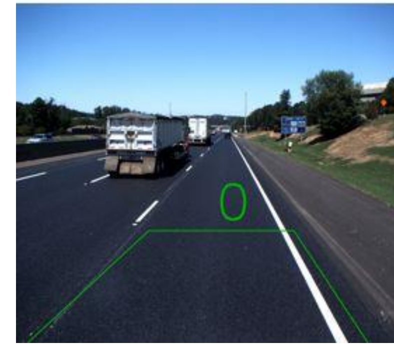
3D pavement data and its applications



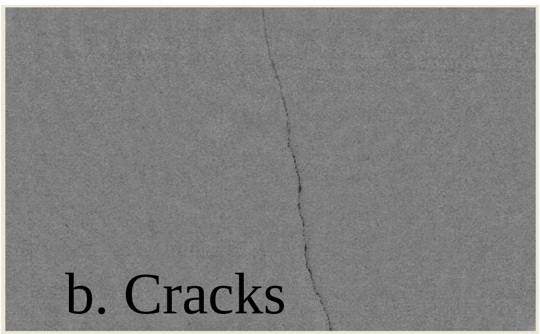
a. Texture (IRI; MPD; RVD)



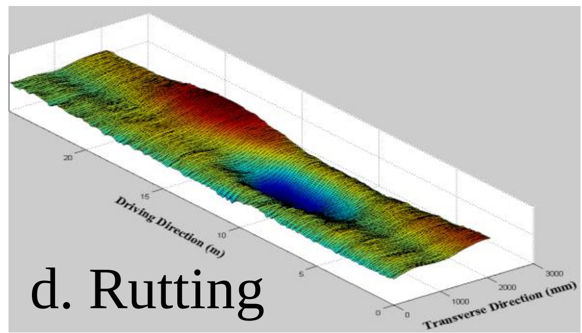
c. Joint/crack faulting; potholes



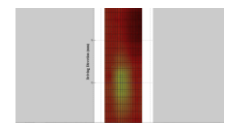
e. Raveling



b. Cracks



d. Rutting



1.Hsieh, Y., Tsai, Y. (2021). "Automated **Asphalt Pavement Raveling Detection and Classification** using Convolutional Neural Network and Macrotexture Analysis". *Transportation Research Record*. 2021;2675(9):984-994.

3.Hsieh, Y., Tsai, Y. (2020) "**Machine Learning for Crack Detection**: review and model performance comparison", ASCE Journal of Computing in Civil Engineering, 34 (5), 04020038.

4.Tsai, Y., Chatterjee*, A, (2017) "**Pothole** Detection and Classification Using 3D Technology and Watershed Method", ASCE Journal of Computing in Civil Engineering, 32(2), 04017078

5.Tsai, Y., Li*****, F. (2012) "Detecting Asphalt **Pavement Cracks** under Different Lighting and Low Intensity Contrast Conditions Using Emerging 3D Laser Technology", ASCE Journal of Transportation Engineering, 138(5), 649–656

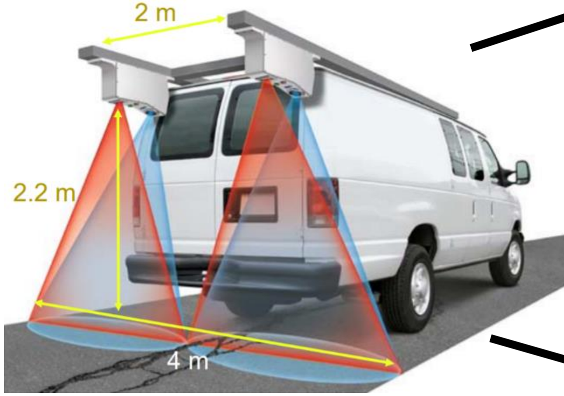
6. Tsai, Y., Wu, Y., Lai, J., Geary, G. (2012) Characterizing Micro-milled **Pavement Textures Using RVD** for Super-thin Resurfacing on I-95 Using A Road Profiler, Journal of The Transportation Research Record, No.2306, pp.144-150.

7. Tsai, Y., Wu, Y., Ai, C., Pitts, E. (2012) "Feasibility Study of Measuring **Concrete Joint Faulting** Using 3D Continuous Pavement Profile Data," ASCE Journal of Transportation Engineering,138(11),1291-1296.

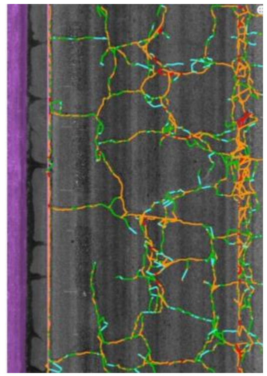
8. Tsai, Y., Li, F., Wu, Y. (2013) "**Rutting Condition** Assessment Using Emerging 3D Line-Laser Imaging and GPS/GIS Technologies", the International Conference on Road and Airfield Pavement Technology, Taipei, Taiwan, July 14, 2013.

Data Science in Transportation/CEE (*Infrastructure)*

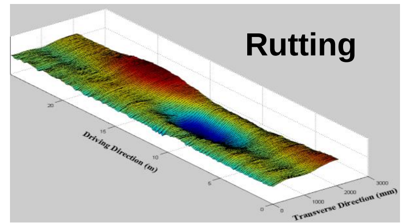
3D Technology



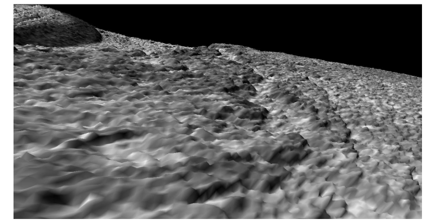
1.Automated and intelligent Infrastructure health condition Evaluation



Cracking



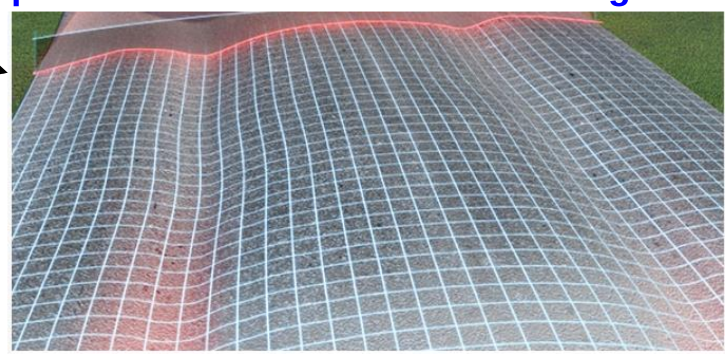
Rutting



Texture (IRI; MPD; RVD)

Other infrastructure <u>characteristics and distresses</u>

2. Optimize the high-resolution 3D digital terrain and pavement distresses for safe navigation of CAV



Proposed high-resolution digital terrain model with the extracted pavement distresses and properties, like rutting and texture

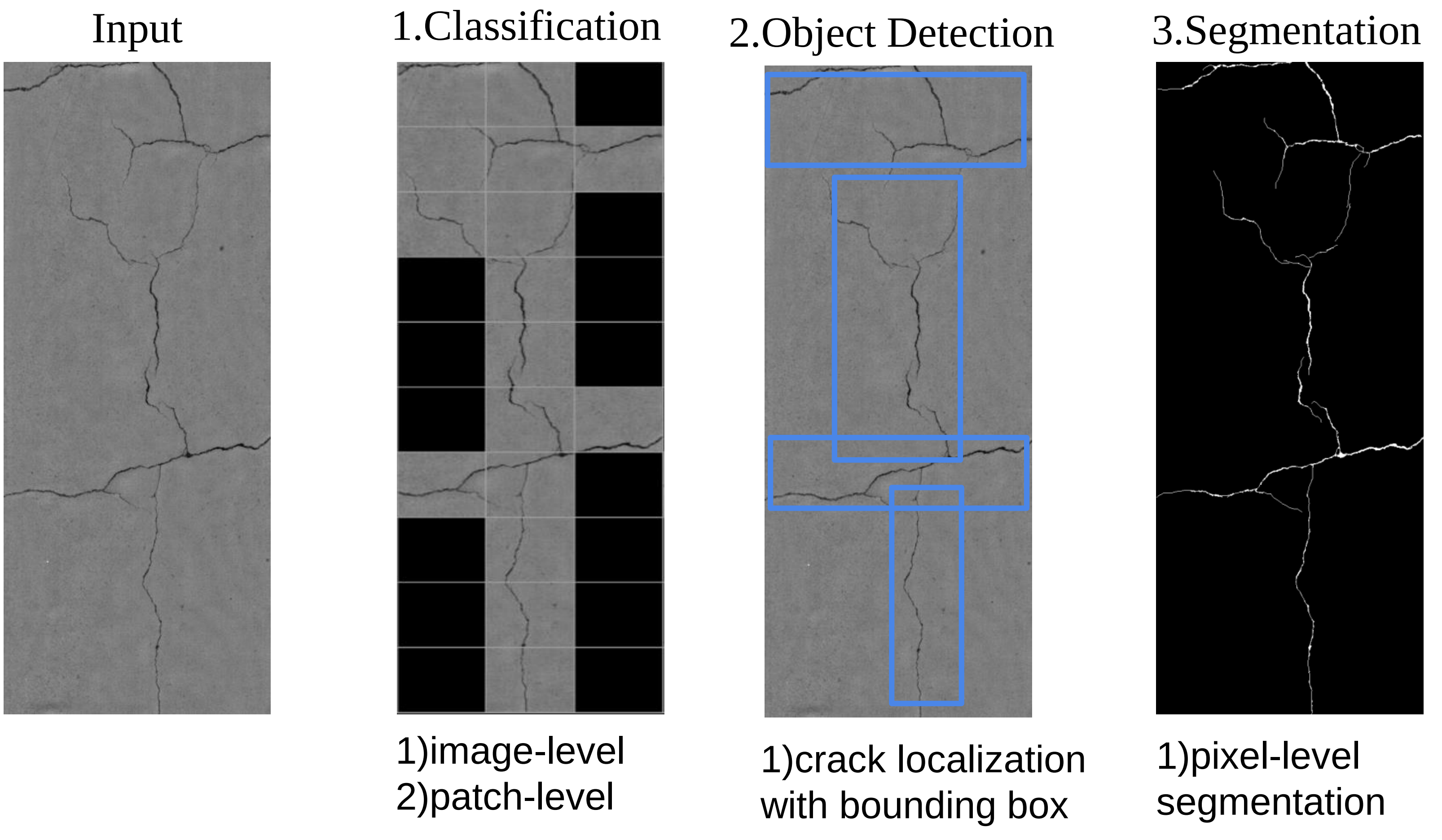
Automated Crack Detection and Classification Using ML/DL

Critically Review of Development Trends of Automated Crack Detection

- Totally 67 papers were reviewed
- Literature Categories
  - Traditional ML-based methods
  - Deep learning (DL)-based methods

Hsieh, Y., Tsai, Y. (2020) "Machine Learning for Crack Detection: review and model performance comparison", ASCE Journal of Computing in Civil Engineering, 34 (5), 04020038.

DL-based Crack Detection Applications and Problem Formulations



Note: It is important to **specify adequate crack detection outcomes** **for your pavement preservation & management** so you can **formulate adequate ML problems and applications**.

1.DL - Classification

- Determine whether an image/image patch contains cracks
  - Image-level
  - Patch-level
- Consider as a binary classification task: Lightweight CNNs with less than 10 layers are usually used

1.DL - Image-level Classification

- Using the whole acquired images as input
- No localization information is involved

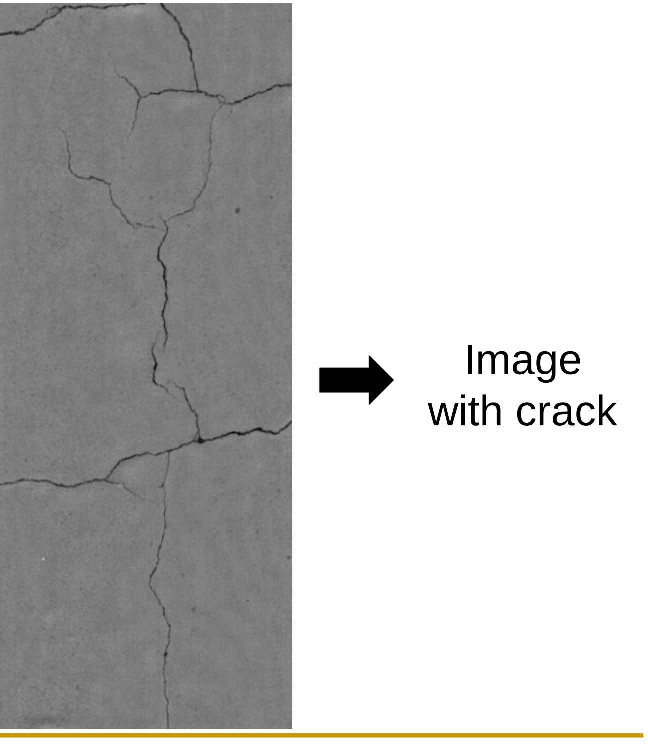
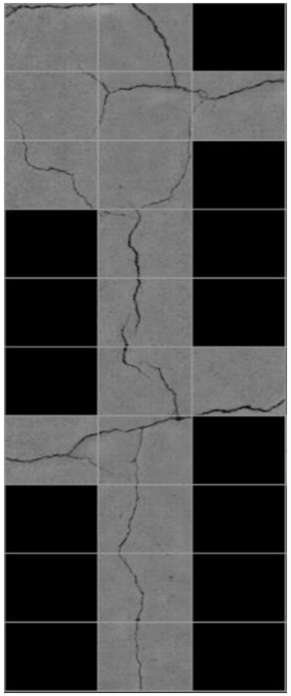


Image-level classification

1.DL - Patch-level Classification

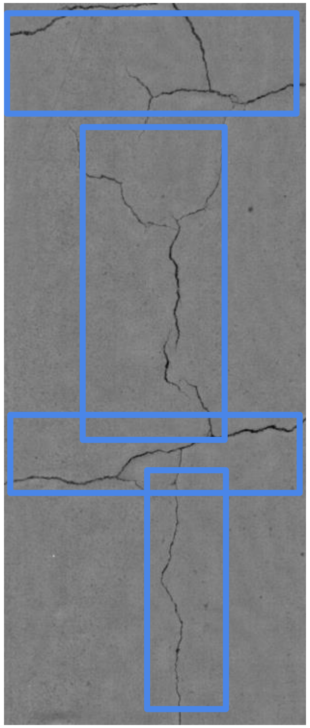
- Benefits of using image patches:
  - Generate more dataset
  - Able to generate crack localization information in original images
- Results can further be used in crack types classification
- Generate coarse and blocky prediction of cracks which cannot be used to estimate crack features such as crack width, length, and branches



Patch-level classification

2.DL - Object Detection

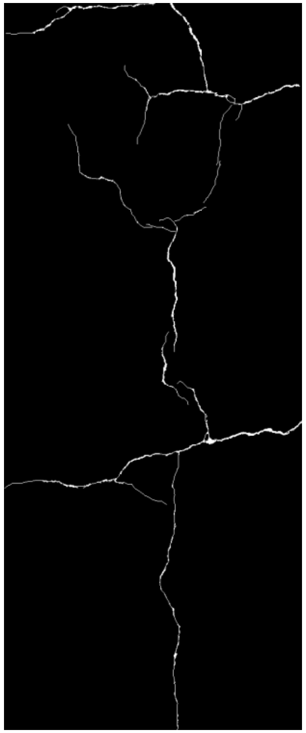
- Generate bounding boxes around the areas that contain cracks
- Usually, crack type classification is also performed to label the crack type for each generated bounding box
- Utilize or modify existing object detection model (e.g. Faster-RCNN [1], SSD [2])



Object Detection

3.DL - Segmentation

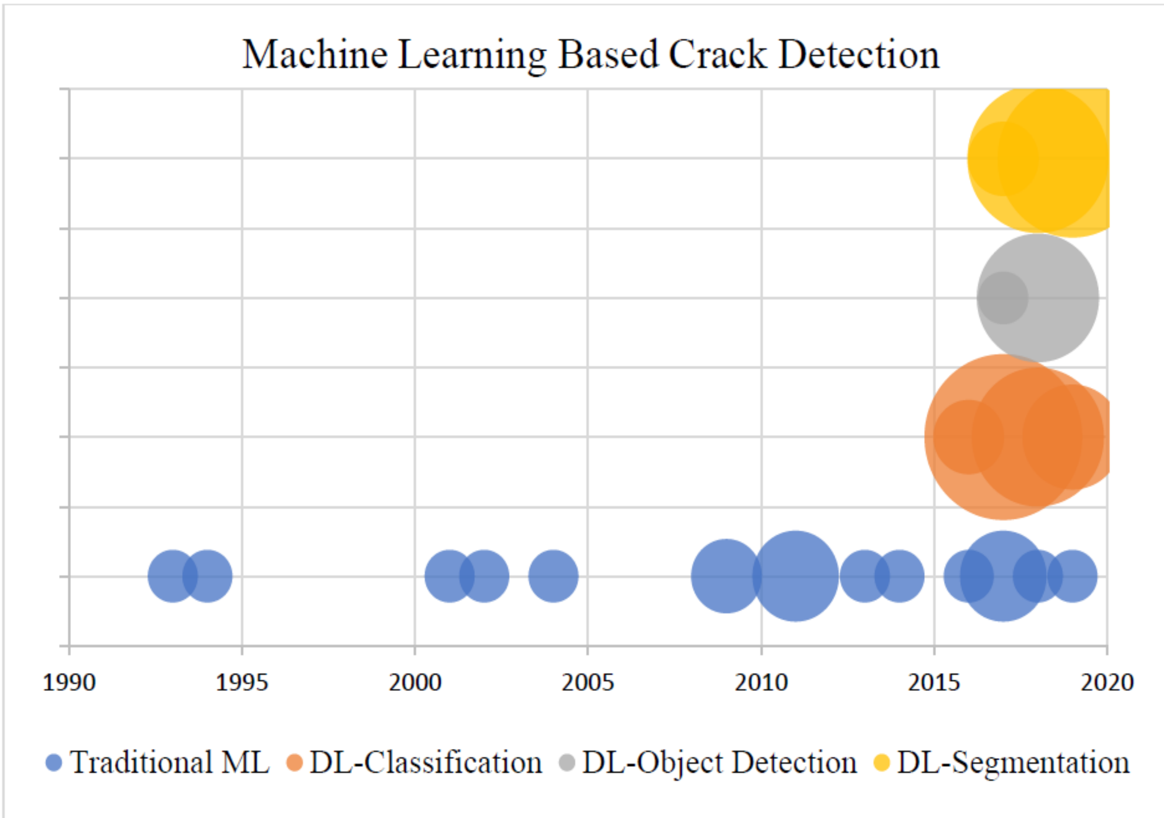
- Pixel-wise prediction (segmentation) of cracks
  - Precise crack location
  - Precise crack structure
- The current trend of utilizing DL on crack detection:
  - Pixel-wise segmentation can be used in both crack types classification and obtaining important crack features
  - With the advances of sensing technologies, 2D and 3D data with higher resolution can be obtained



Segmentation

ML-based Crack Detection Trend

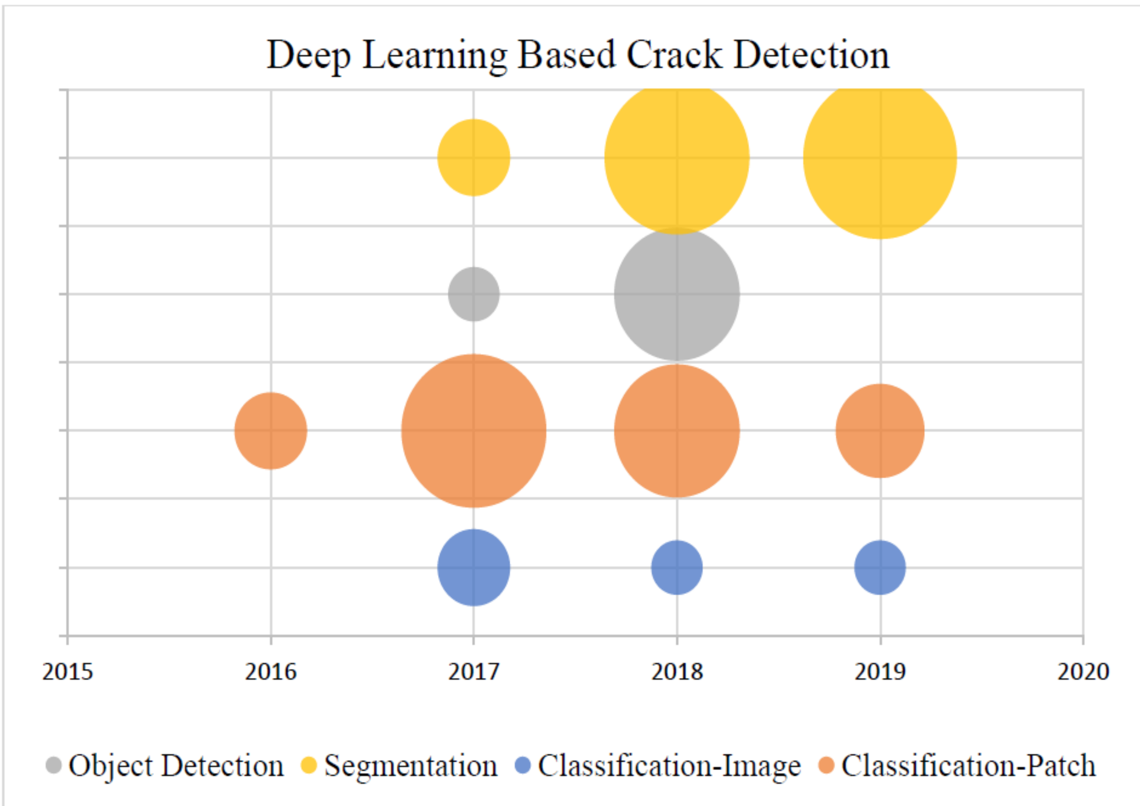
The number of publications on DL-based methods has grown rapidly since 2016, this shows that DL-based methods have proven their effectiveness



Hsieh, Y., Tsai, Y. (2020) “Machine Learning for Crack Detection: review and model performance comparison”, ASCE Journal of Computing in Civil Engineering, 34 (5), 04020038.

ML-based Crack Detection Trend

Patch-level classification received most of the attention in 2016 and 2017, then segmentation quickly replaced it with the number of research still increasing



Hsieh, Y., Tsai, Y. (2020) "Machine Learning for Crack Detection: review and model performance comparison", ASCE Journal of Computing in Civil Engineering, 34 (5), 04020038.

Challenges

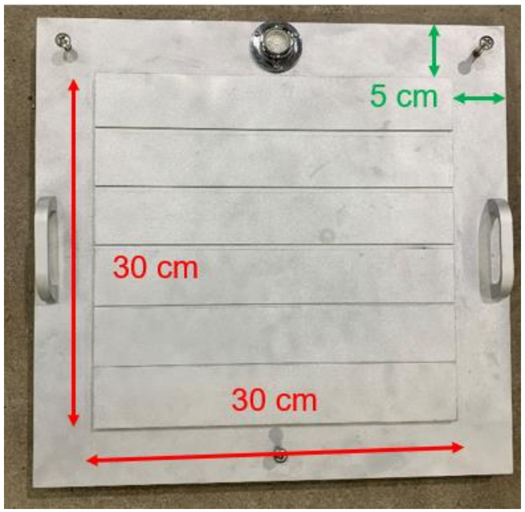
- Data Quality Management
- Utilization of 3D pavement Data
- Transitioning from Manual to Automated Pavement Condition Assessment
  - Pavement Rating System
  - Forecasting and Treatment Selection
  - *Matching New Data to Legacy Pavement Condition Data*
- Data Collection Considerations
  - Surveying Multi-lane Roads
  - Surveying Local Roads
- Switching to a Different Imaging System (legacy data)

Challenges: Data Quality Management (1/2)

System Data and Image Quality Assessment

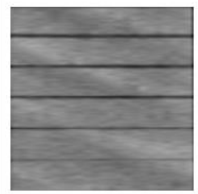
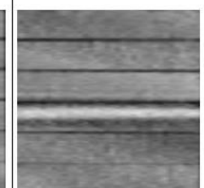
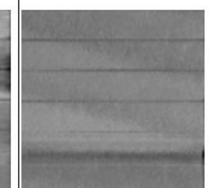
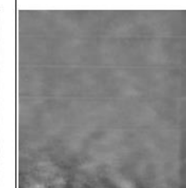
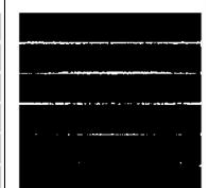
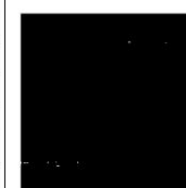
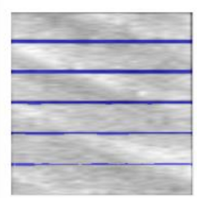
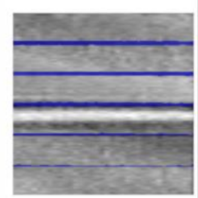
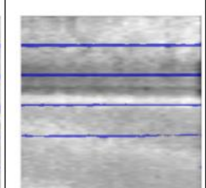
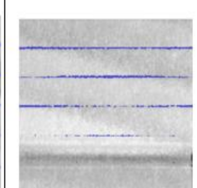
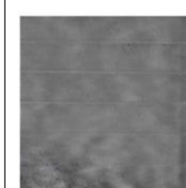
- **Some systematic errors can arise during data collection**
- **Periodic data quality verification**
- **Many efforts are currently underway to standardize practices for calibration, certification, and verification of 3D pavement imaging systems**
  - **Transportation Pooled Fund, TPF-5(299)**, which aims to improve the quality of pavement surface distress and transverse profile data collection and analysis.
  - **Altmann and Ferris (2020)** have published a study with proposed AASHTO standards for calibration, certification, and verification of transverse pavement profile measurements.
    - Focus: Rutting, Cross slope, and Edge drop-off
  - **Ongoing: NCHRP 01-60 research project** aims to develop methods for measuring the characteristics of pavement surface images used for pavement evaluation and analysis, in addition to developing standard practices for the calibration, certification, and verification of imaging systems for consideration and adoption by AASHTO.
    - Focus: Cracking and Macrotexture

Data Quality Assessment – Gap Board Analysis



Gap Board

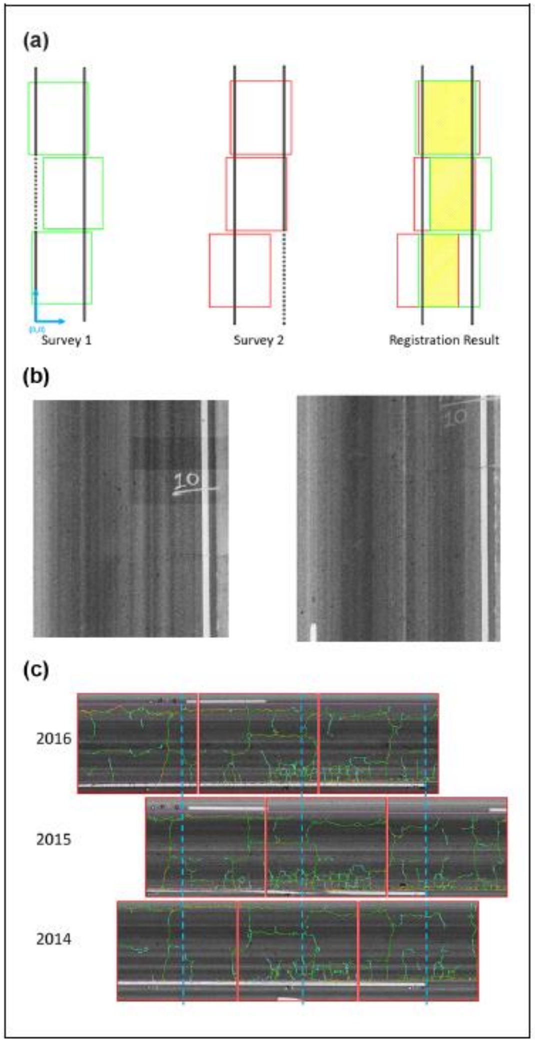
Consists of five gaps of widths: 1mm, 2mm, 3mm, 4mm, and 5mm

Sample Image ID	1	2	3	4	5
Range Image					
Binary Image of Segmented Gaps					
Segmentation Overlay on Range Image					

Challenges: Data Quality Management (2/2)

Pavement Trend Checking

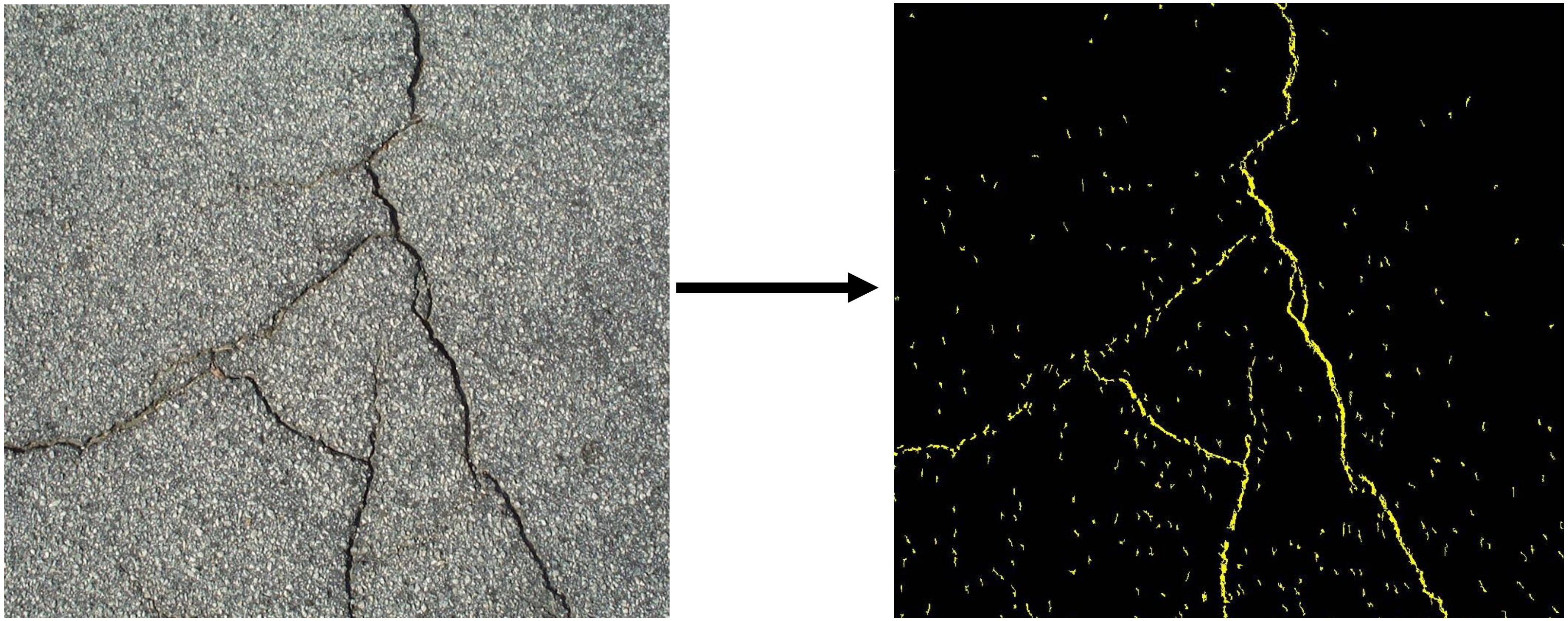
- Multi-year pavement condition trend checking is crucial
  - Pavement condition should not improve without any applied treatment or deteriorate significantly without any valid reason.
- **Multiple-timestamp 3D pavement data registration** is essential to guarantee the **same pavement region of interest is being collected over the years**
  - In the transverse road direction: Vehicle wandering may result in a difference in the coverage area between different surveys
- **Consistent segments based on linear referencing system**
  - Properly match the pavement condition extracted from the collected images with the linear referencing system consistently over the years.
  - Maintain consistent reporting segment termini over the years to properly track deterioration behavior

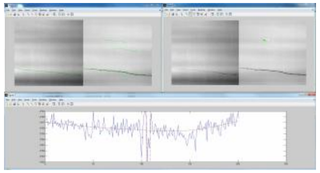


Tsai, Y., and Yang, Z. (2020). "New pavement performance indicators using crack fundamental elements and 3D pavement surface data with multiple-timestamp registration for crack deterioration analysis and optimal treatment determination.", *Transportation Research Record*, 2674(7), 115–126.

Case 1: Automated Crack Detection & Classification

Automatic Crack Detection



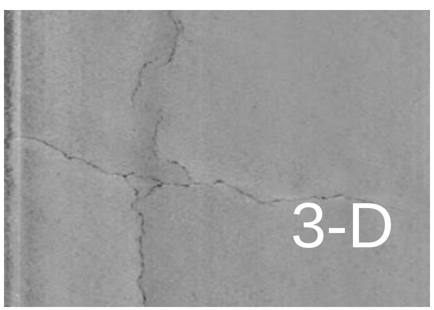


Kaul*, V., Yezzi, A., Tsai, Y. (2012) “Detecting Curves with Unknown Endpoints and Arbitrary Topology Using Minimal Paths”, IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 34, No. 10, pp. 1952-1965

Tsai, Y., Kaul*, V., Yezzi, A (2013) “Automating the Crack Map Detection Process for Machine Operated Crack Sealer”, Automation in Construction, Vol. 31, 10-18.

Key Components of Existing Automated Crack Evaluation (Detection and Classification)

Stage 1:
Data Acquisition

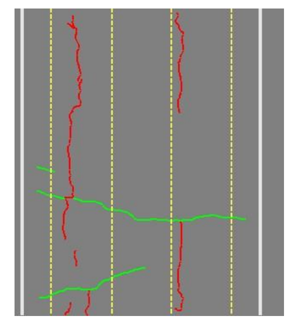


Raw Data

Stage 2:
Crack Detection

Crack Map

Stage 3:
Crack Classification and Quantification



Left Wheelpath
LC Level 1 14.1

Right Wheelpath
LC Level 1 10.1

Non Wheelpath
BT Level 1 17.4

1. Type
2. Severity Level
3. Extent

Jiang*, C. and Tsai, Y. (2015) "Enhanced Crack Segmentation Algorithm Using 3D Pavement Data", ASCE Journal of Computing in Civil Engineering.

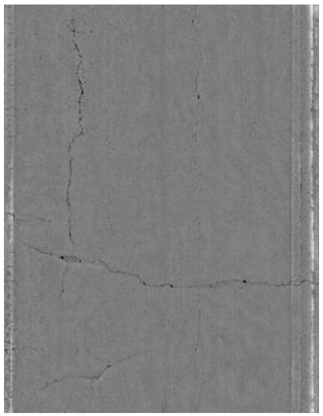
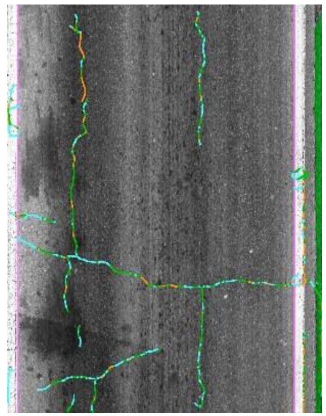
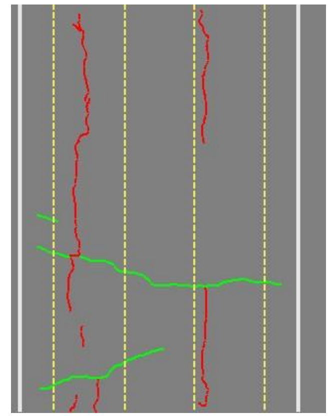
Asphalt Pavement Load Cracking

Level 1	Level 2
Level 3	Level 4

Asphalt Pavement Block Cracking

Level 1	Level 2
Level 3	

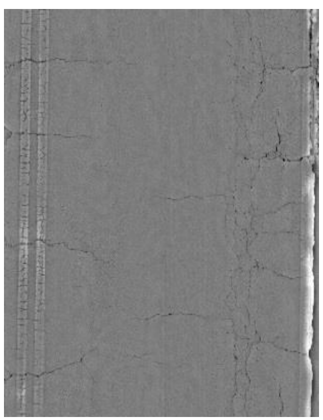
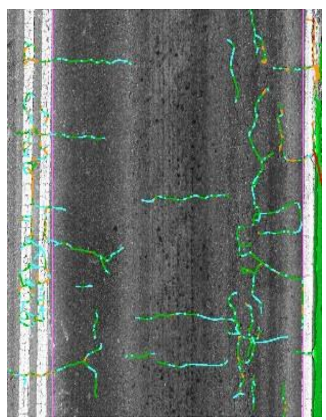
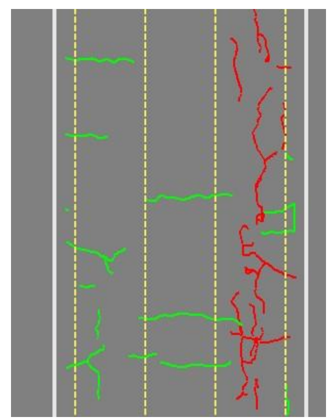
Load Cracking Classification Results (Severity Level 1-2)

Left Wheelpath
LC Level 1 14.1

Right Wheelpath
LC Level 1 10.1

Non Wheelpath
BT Level 1 17.4

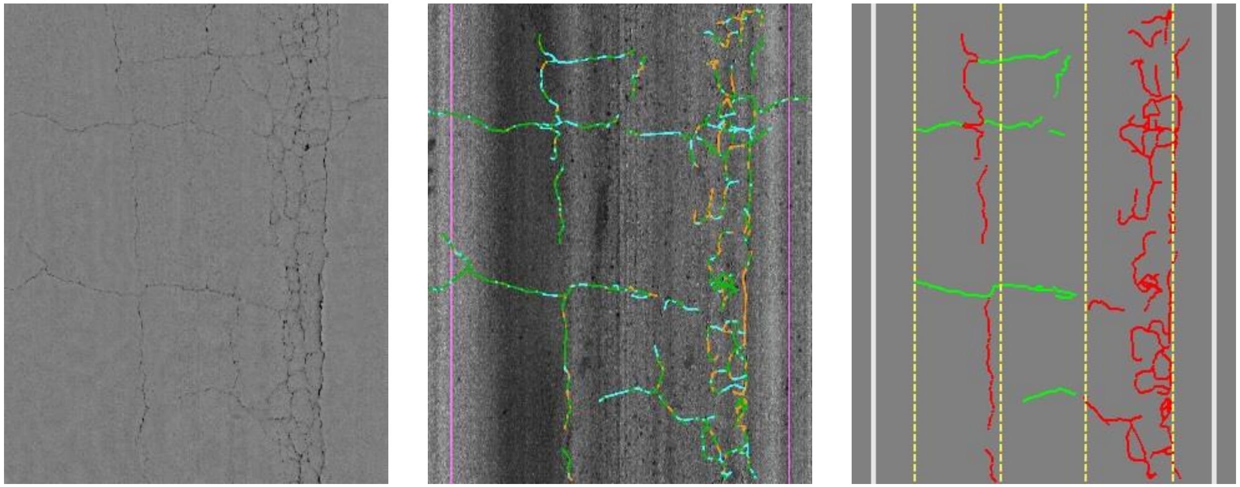
Left Wheelpath
None 0

Right Wheelpath
LC Level 2 16.0

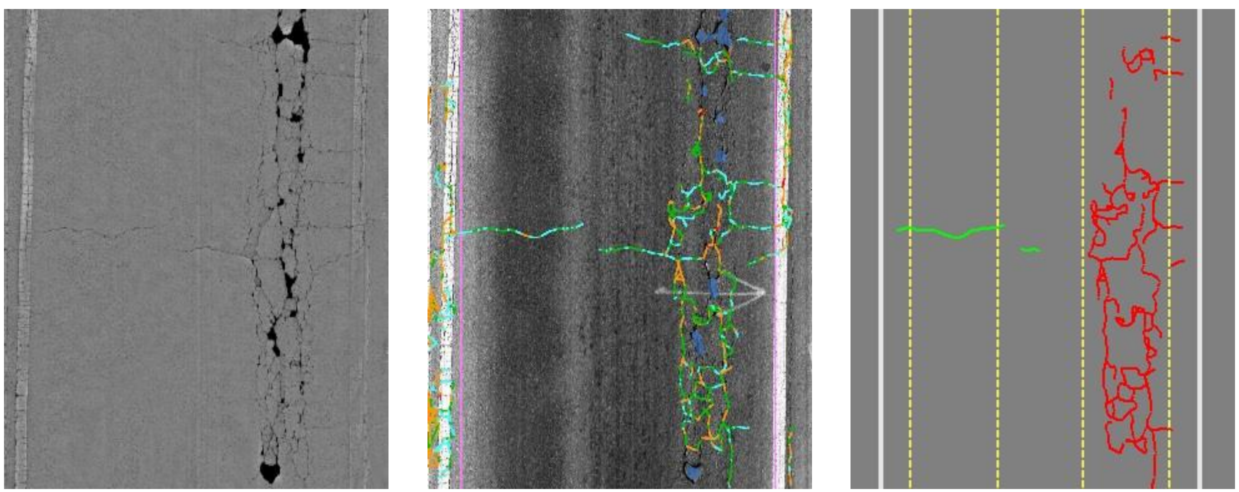
Non Wheelpath
BT Level 1 32.7

Measurement Unit: Foot

Load Cracking Classification Results (Severity Level 3-4)



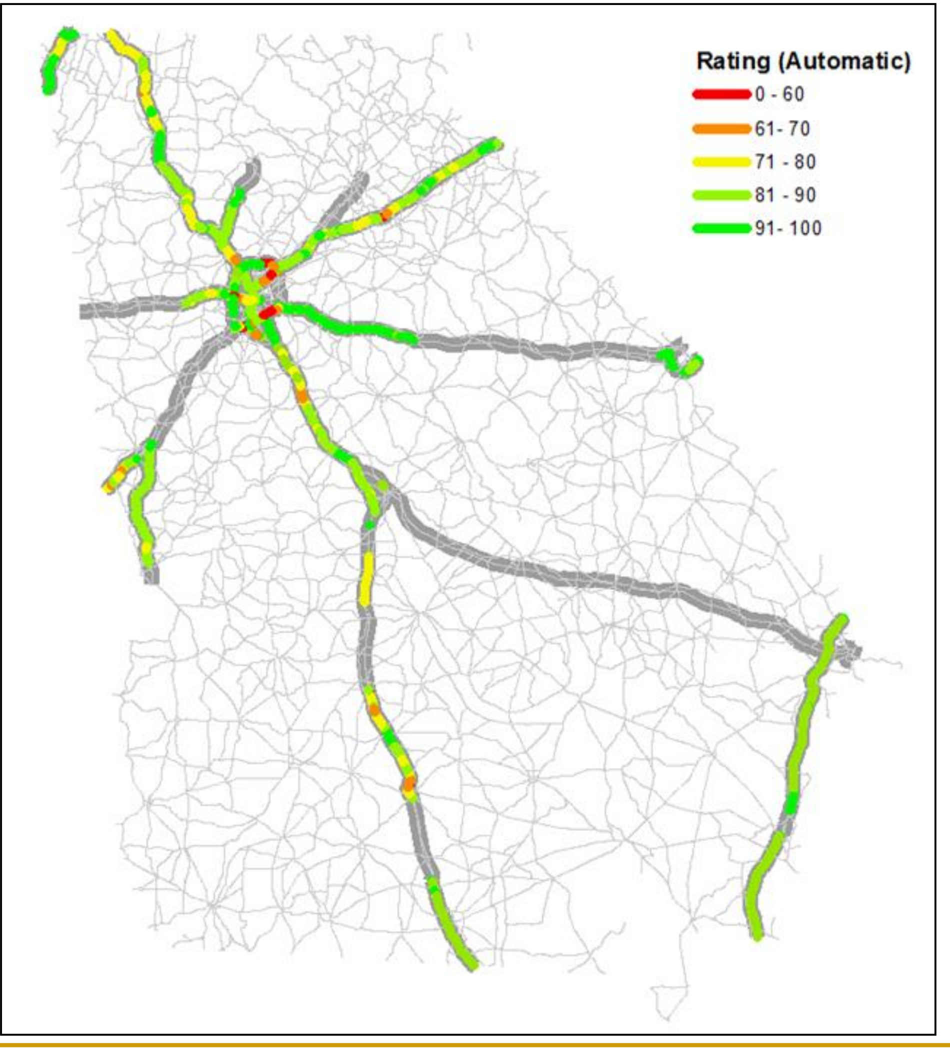
Left Wheelpath	
LC Level 1	12.6
Right Wheelpath	
LC Level 1	15.9
Non Wheelpath	
BT Level 1	18.8



Left Wheelpath	
None	0
Right Wheelpath	
LC Level 2	14.7
Non Wheelpath	
BT Level 1	4.1

Measurement Unit: Foot

Pavement Condition (COPACES) on Georgia's Interstate Highways



Tsai, Y., Wang, Z., Ai, C. (2017) "Implementation of Automatic Sign Inventory and Pavement Condition Evaluation on Georgia's Interstate Highways", Final Report, Georgia Department of Transportation.

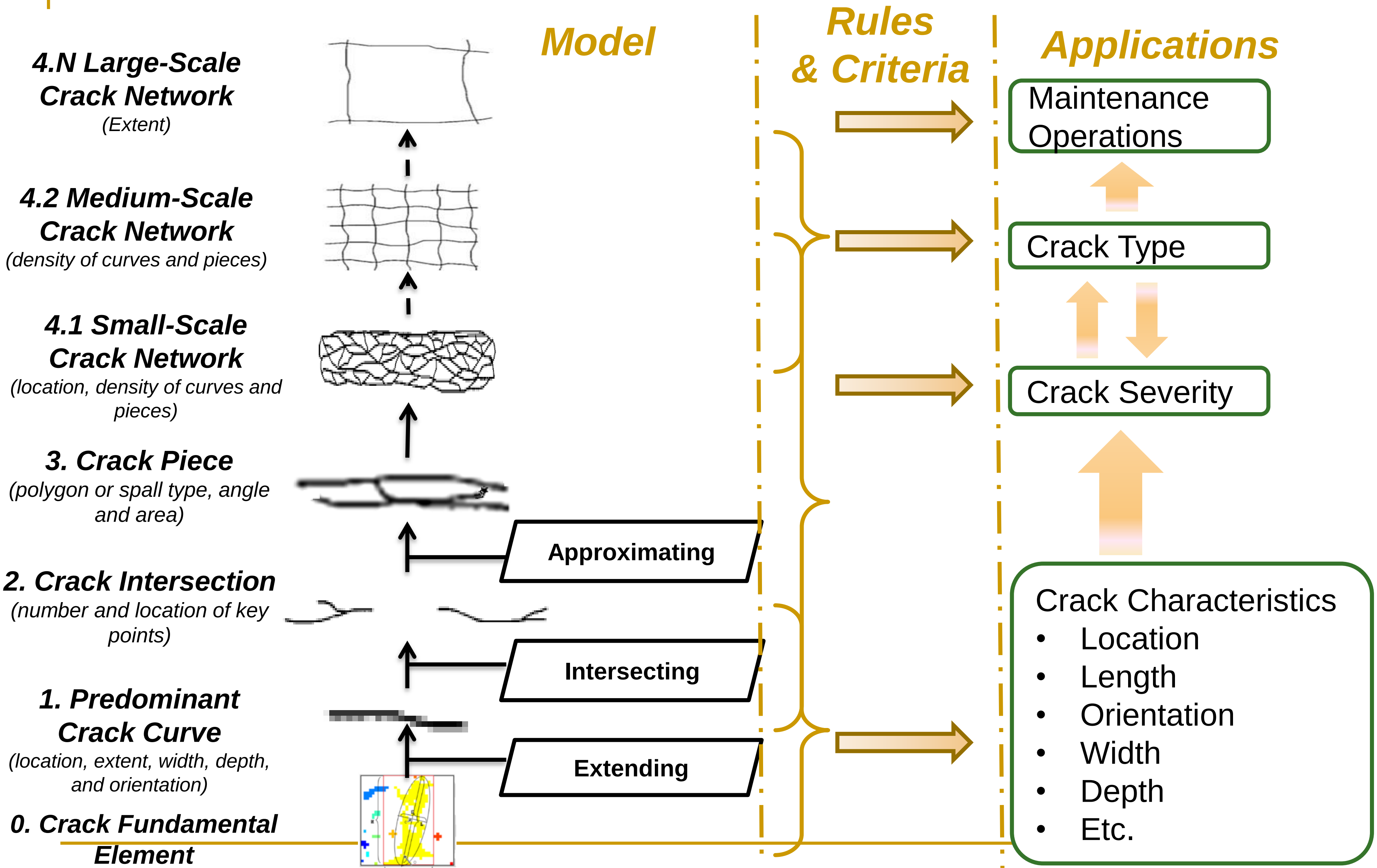
Successful Implementation of 3D Laser Technology and Automatic Detection and Classification to Georgia's Interstate Highway System

(2017 AASHTO High Research Value Award, Sweet 16)

Tsai, Y., Wang, Z., Ai, C. (2017) "Implementation of Automatic Sign Inventory and Pavement Condition Evaluation on Georgia's Interstate Highways", Final Report, Georgia Department of Transportation.

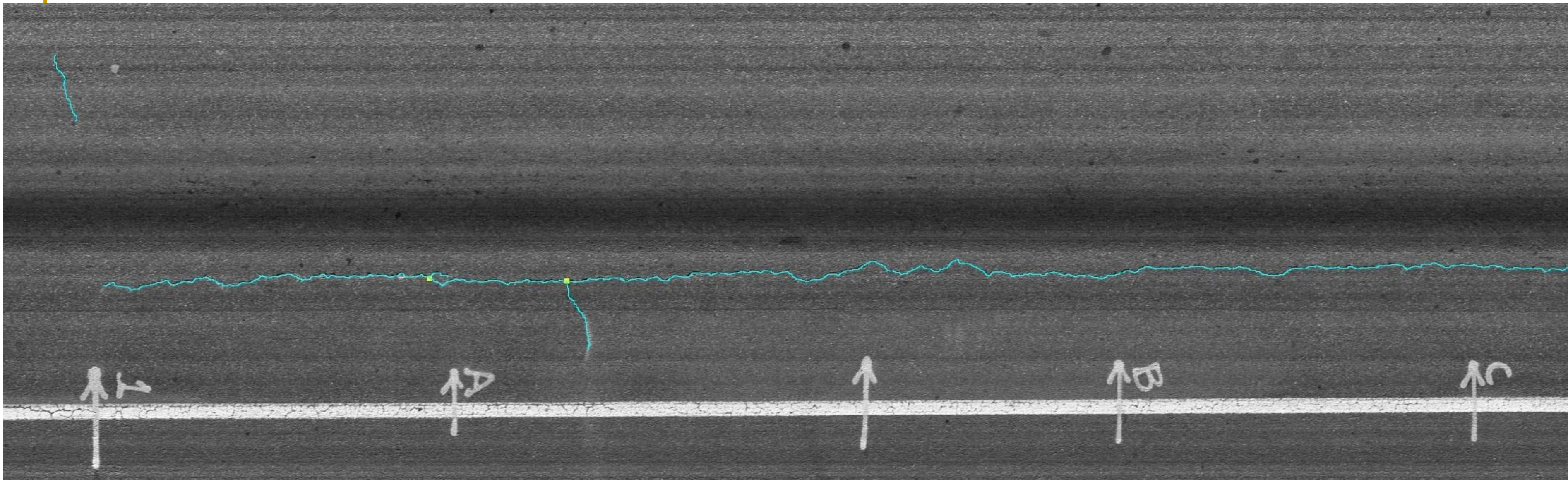
Revolutionize Infrastructure Management:
Fundamental Crack Element (CFE) with Topology Representation

Multi-scale crack fundamental element model

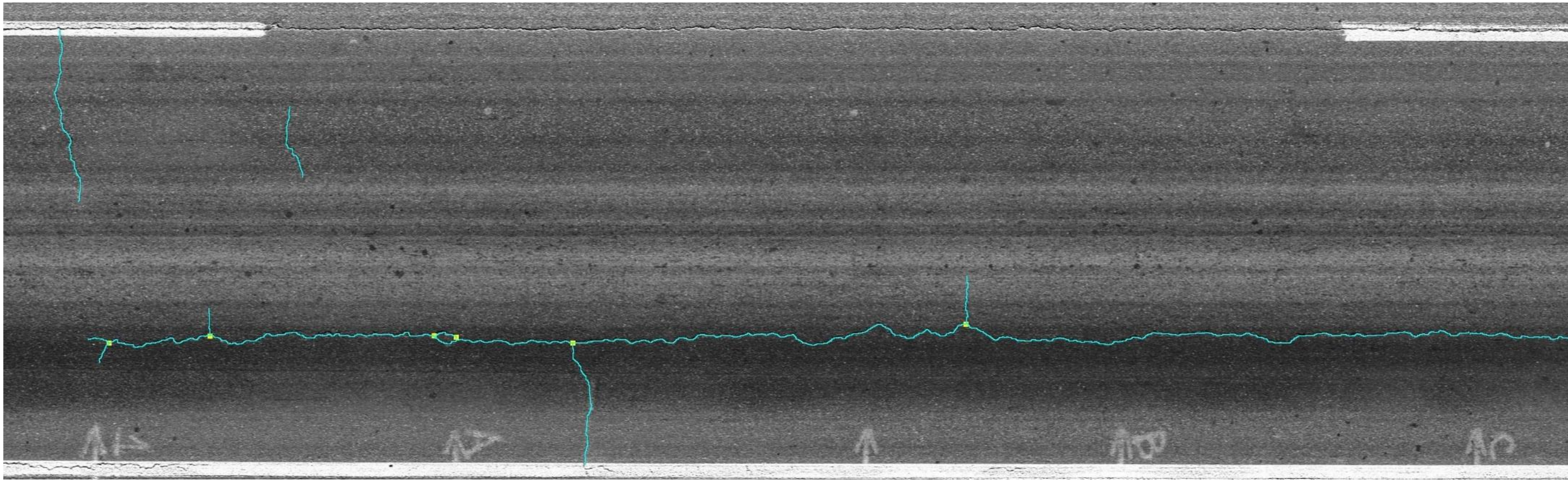


Tsai, Y., Jiang, C., Huang, Y. (2014) "A Multi-scale Crack Fundamental Element Model for Real World Pavement Crack Classification", ASCE Journal of Computing in Civil Engineering.

Detailed crack propagation

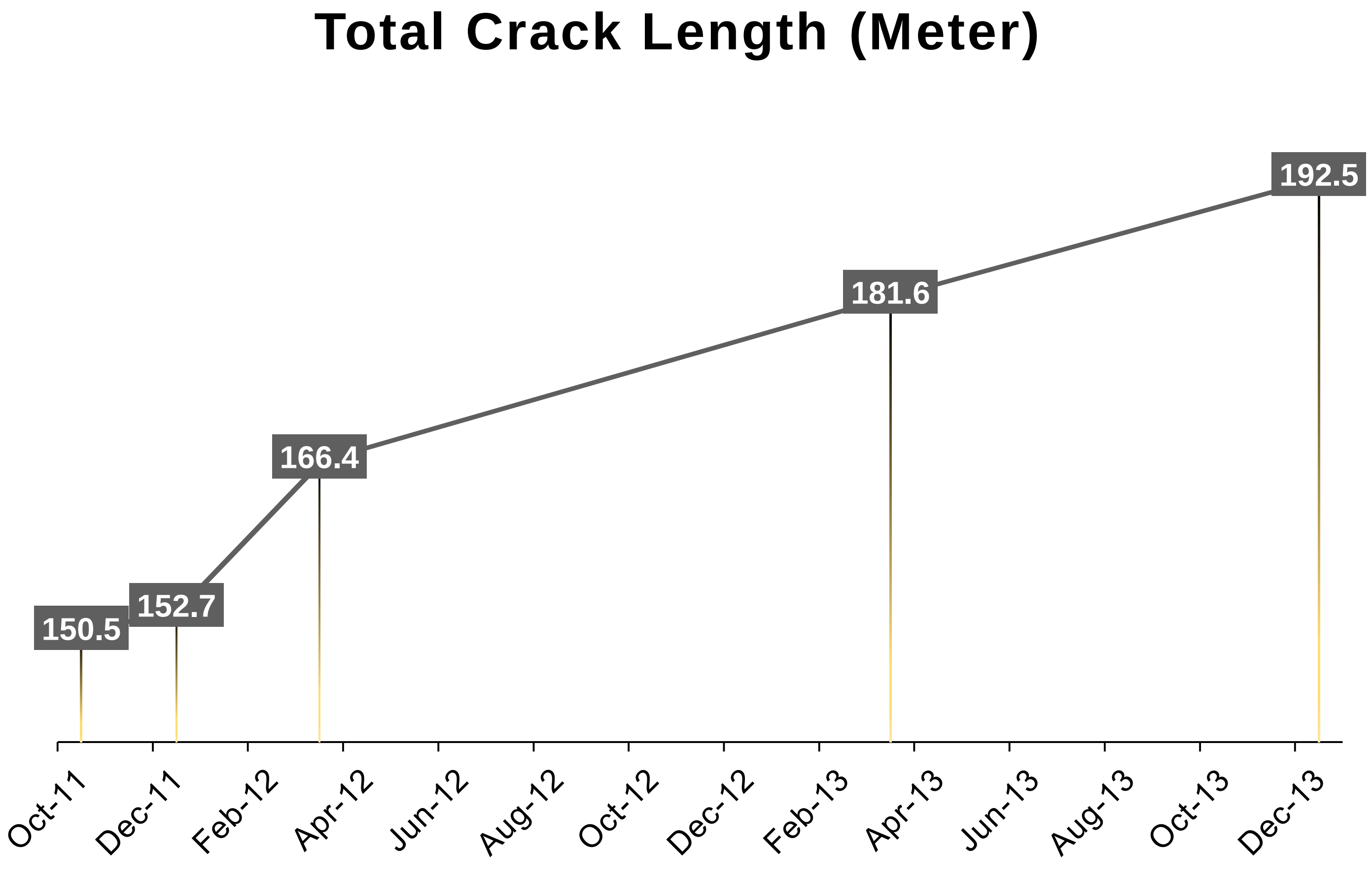


Oct. 15, 2011



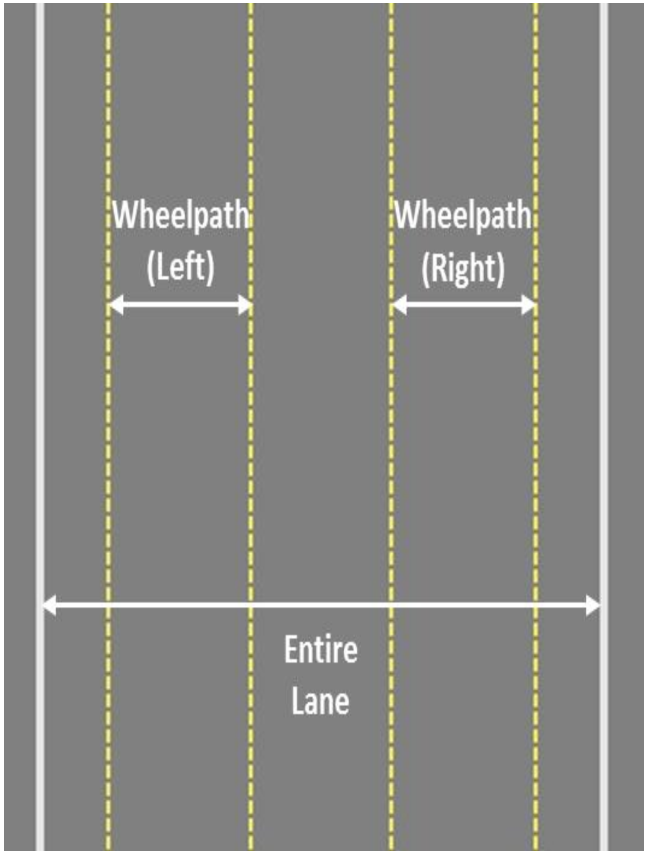
Dec. 07, 2013

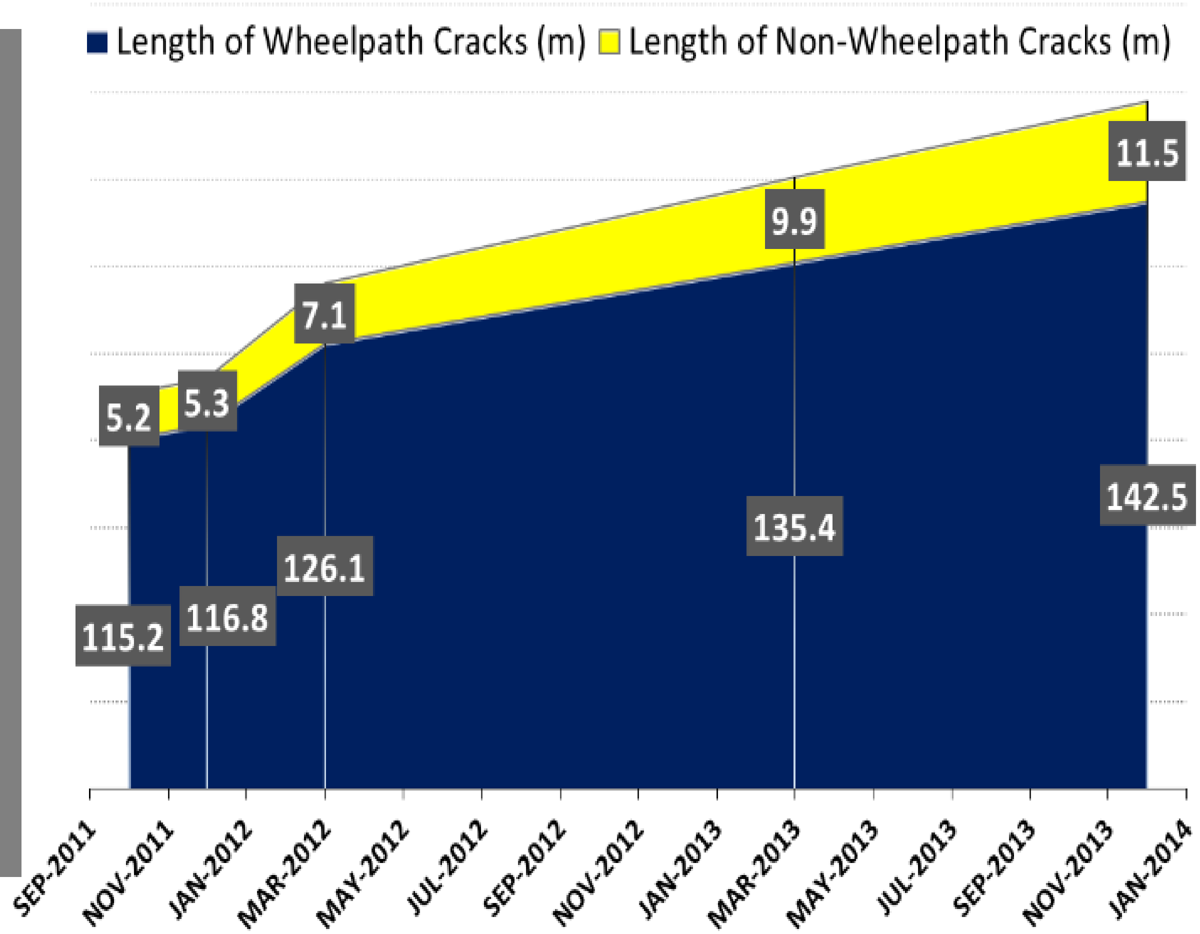
Property: Crack Length



The following slides will show that the propagation on transverse direction is more significant than on longitudinal direction.

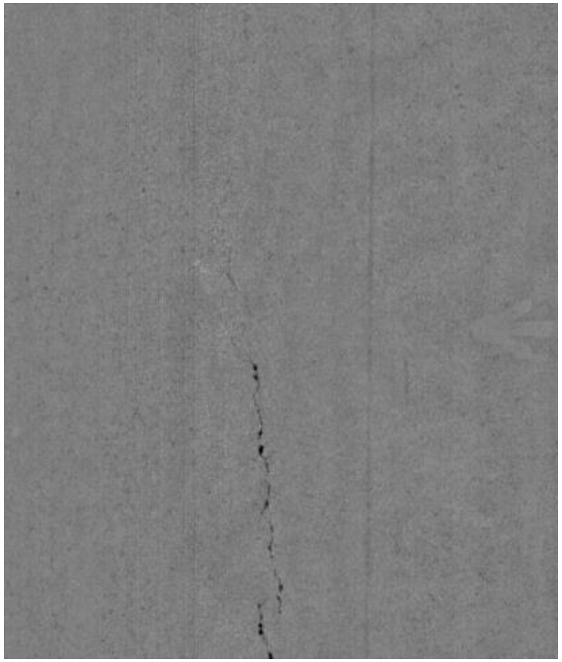
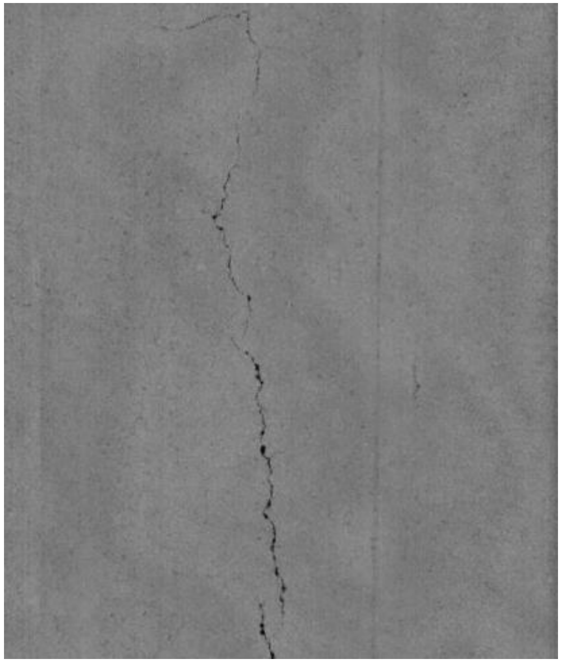
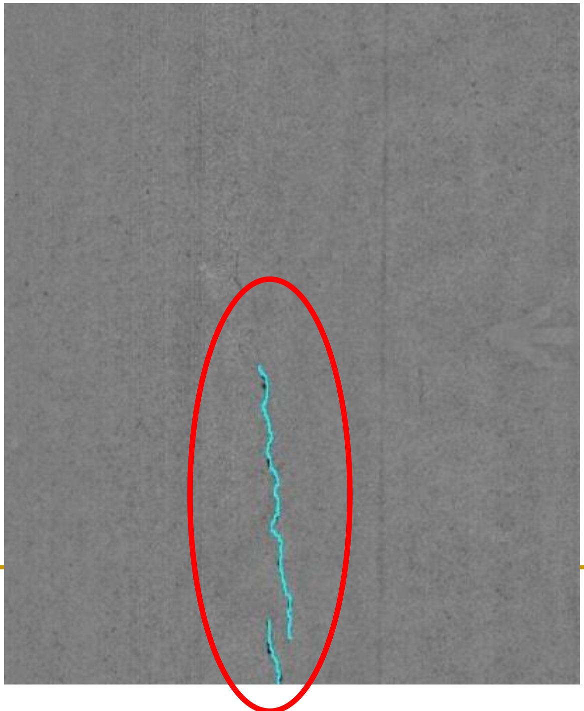
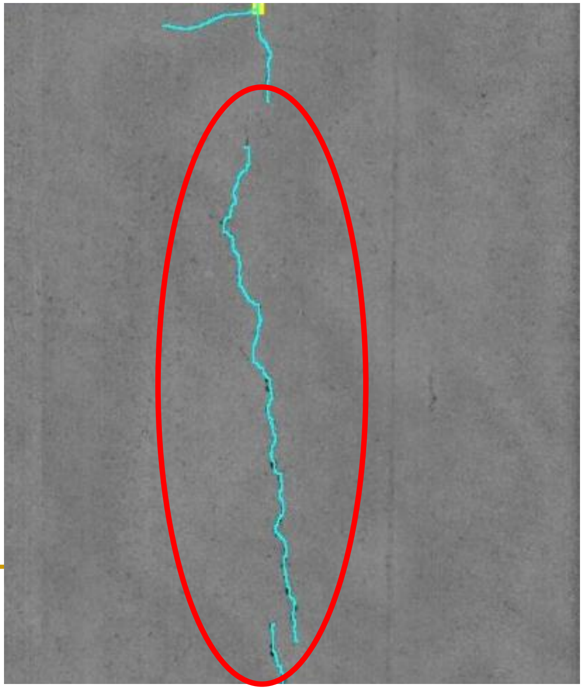
Comparison between crack propagation inside and outside the wheelpaths





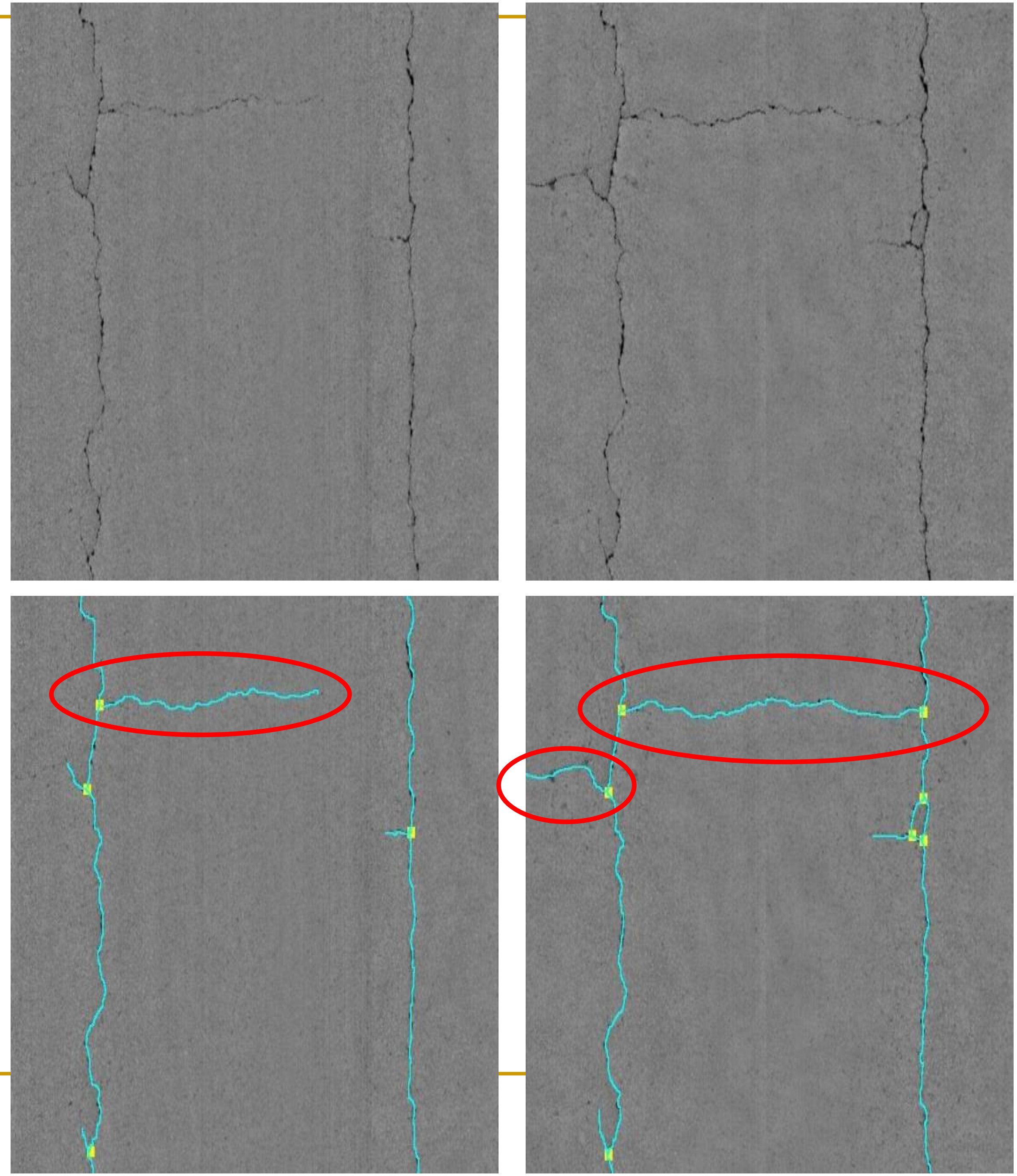
Example of Longitudinal Propagation

Oct. 2011 Range Image	Dec. 2013 Range Image
Oct. 2011 Crack Map	Dec. 2013 Crack Map

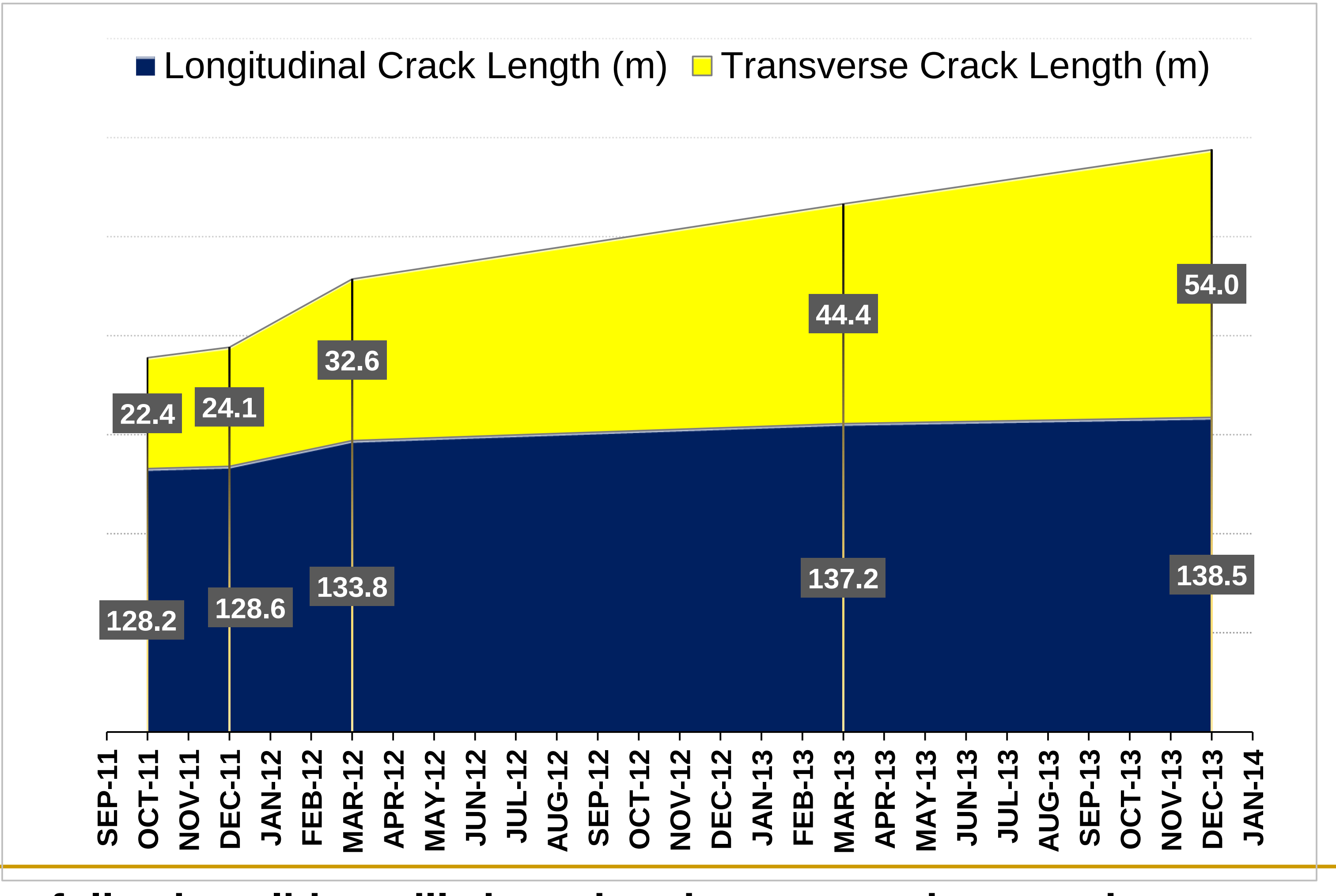





Example of Transverse Propagation

Oct. 2011 Range Image	Dec. 2013 Range Image
Oct. 2011 Crack Map	Dec. 2013 Crack Map



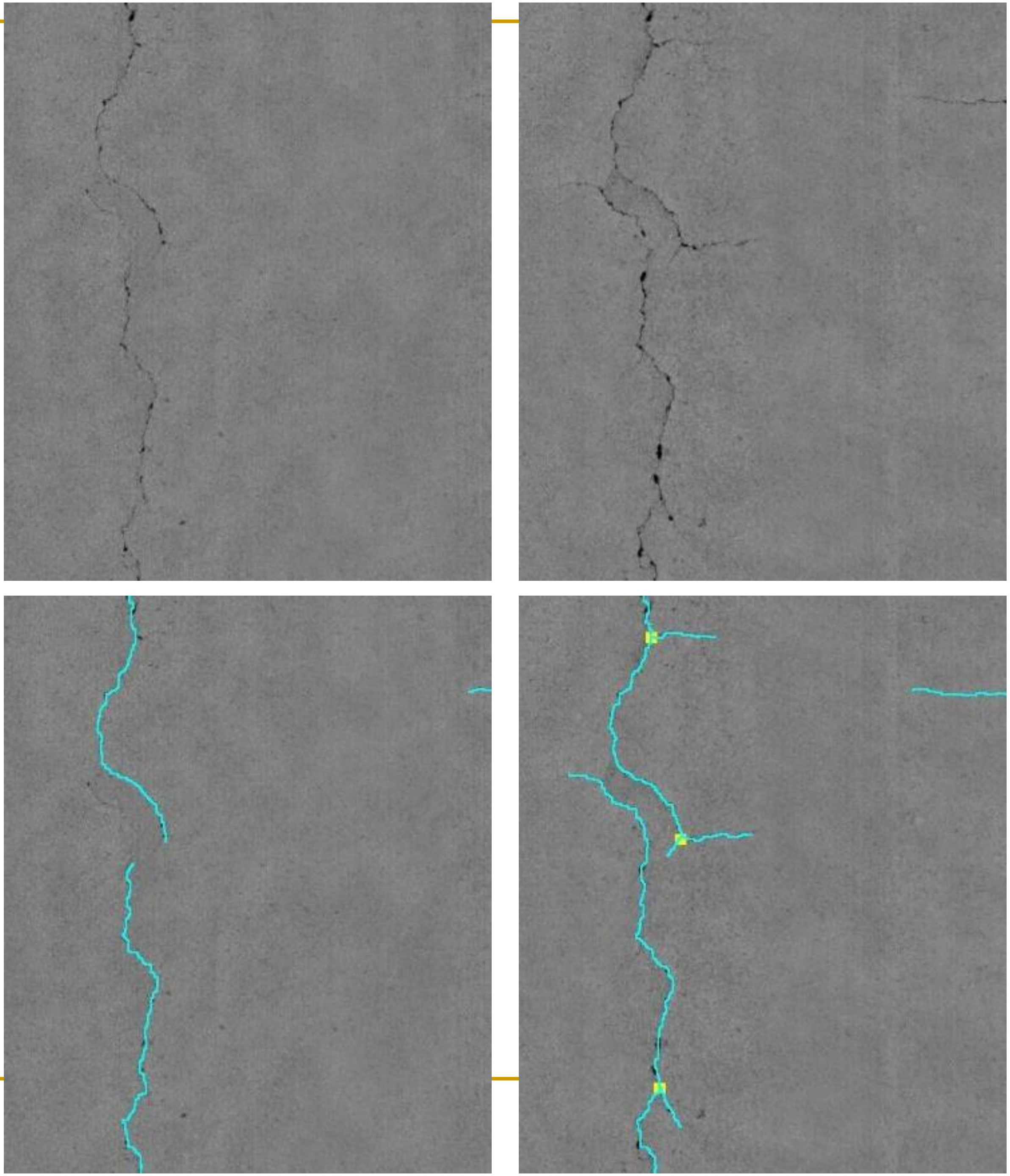
Comparison between crack propagation along longitudinal and other directions



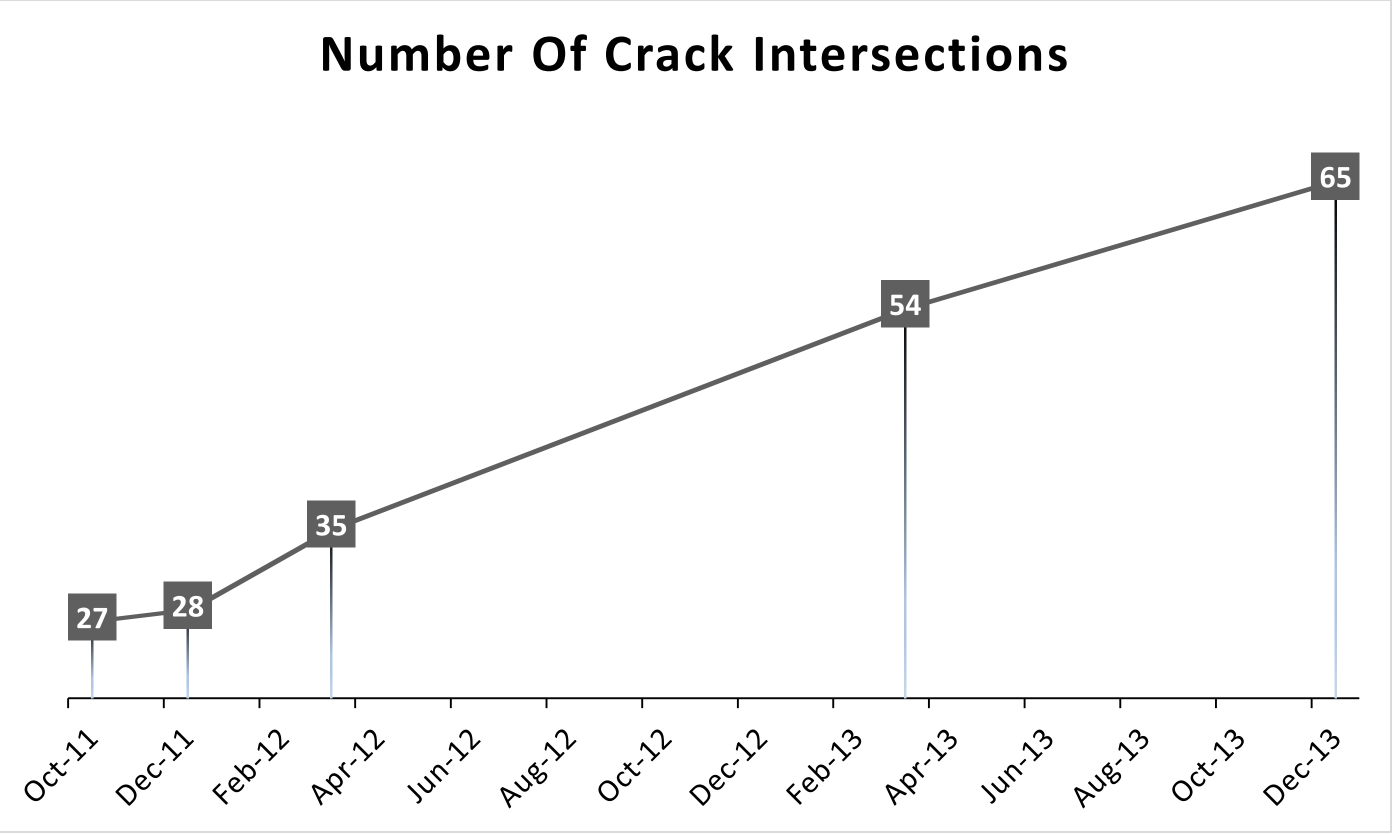
The following slides will show that the propagation on other directions is more significant than on longitudinal direction.

Example of Branching Out (Crack Intersection Points)

Dec. 2011 Range Image	Dec. 2013 Range Image
Dec. 2011 Crack Map	Dec. 2013 Crack Map

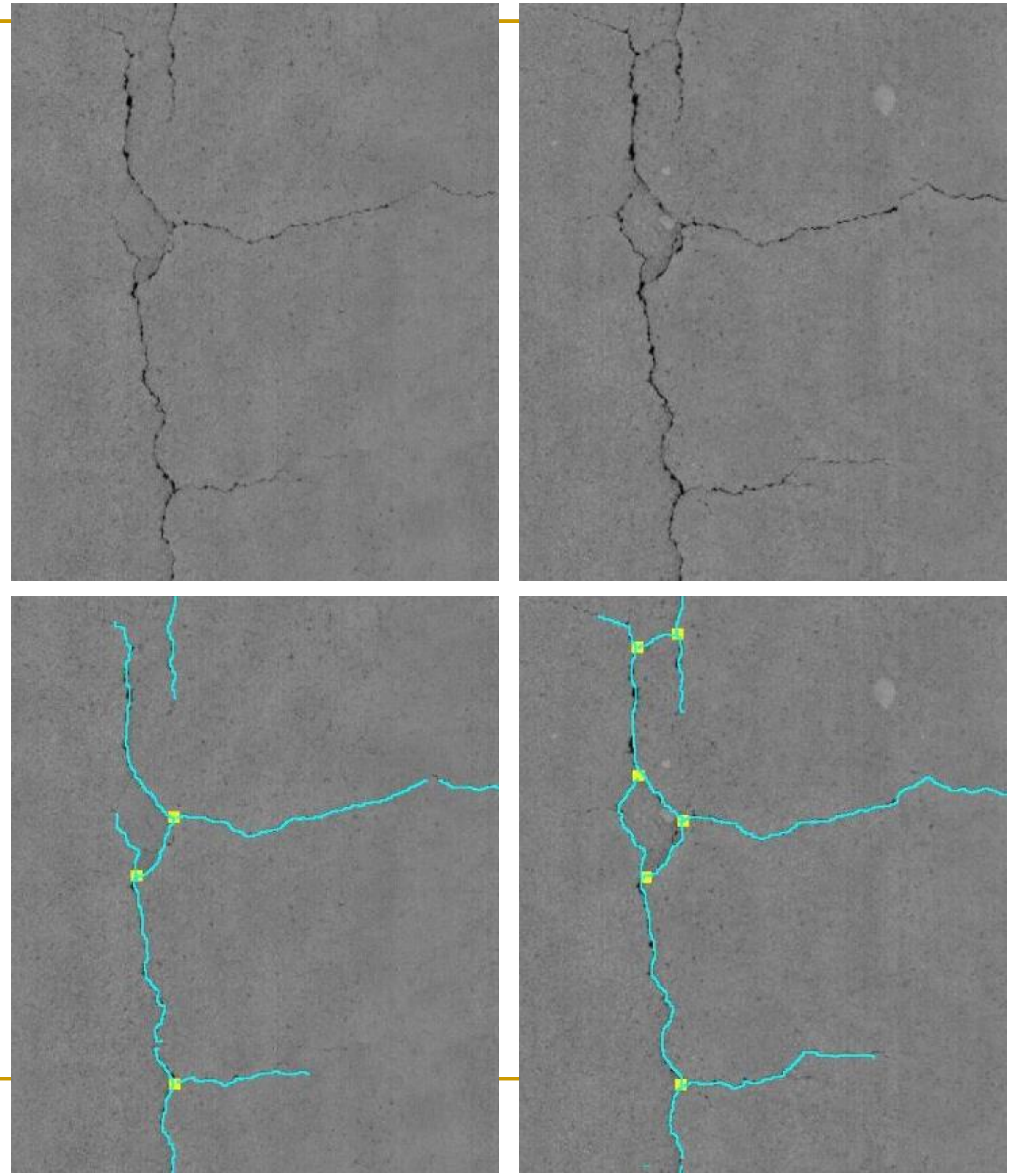


Property: Crack Intersection Points

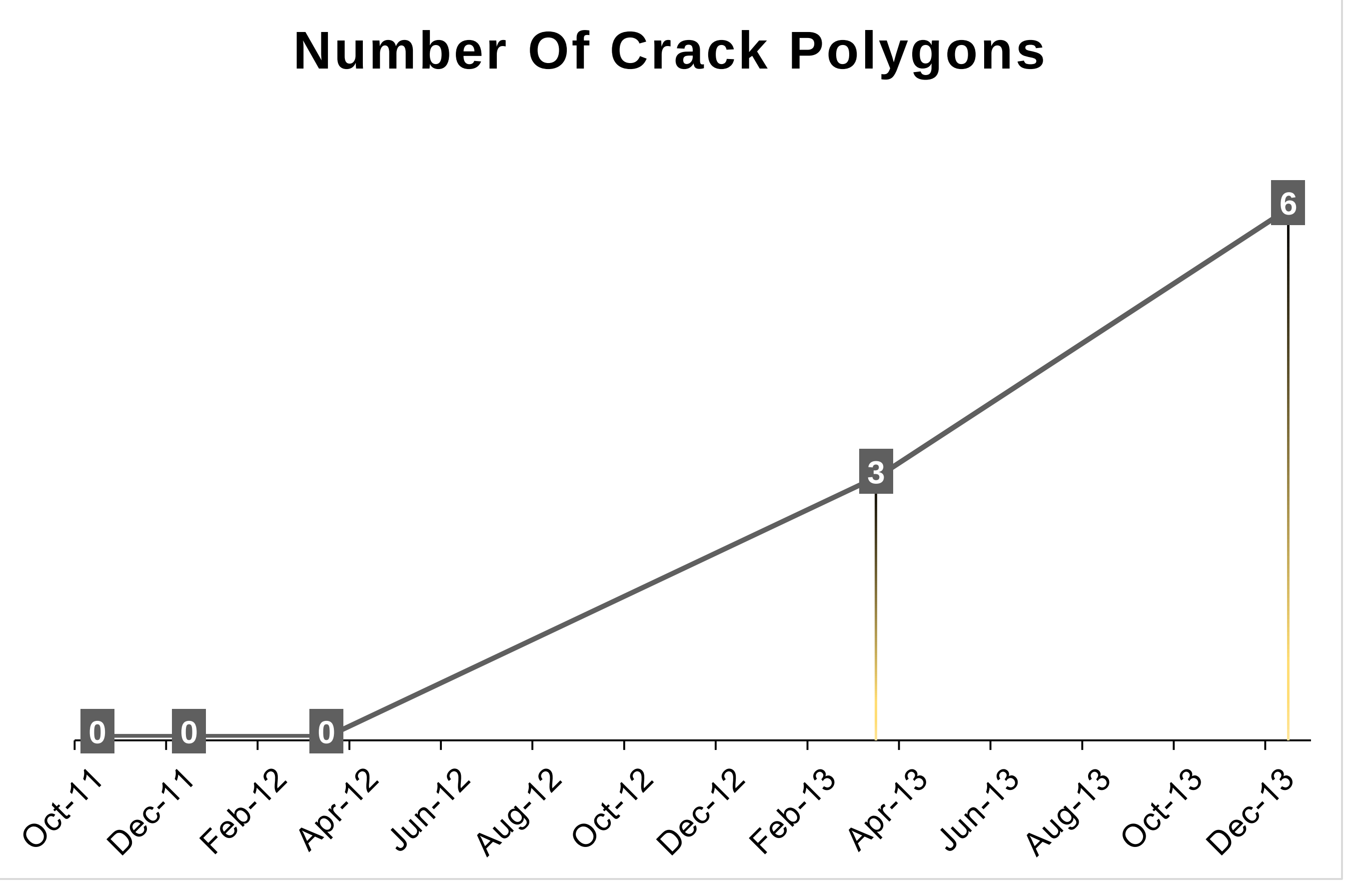


Example of Forming Polygons (Crack Polygons)

Dec. 2011 Range Image	Dec. 2013 Range Image
Dec. 2011 Crack Map	Dec. 2013 Crack Map



Property: Crack Polygons



Case 2: Automated Detection and Classification of Open-graded Friction Course Pavements (OGFC) Loss of Aggregates

Background

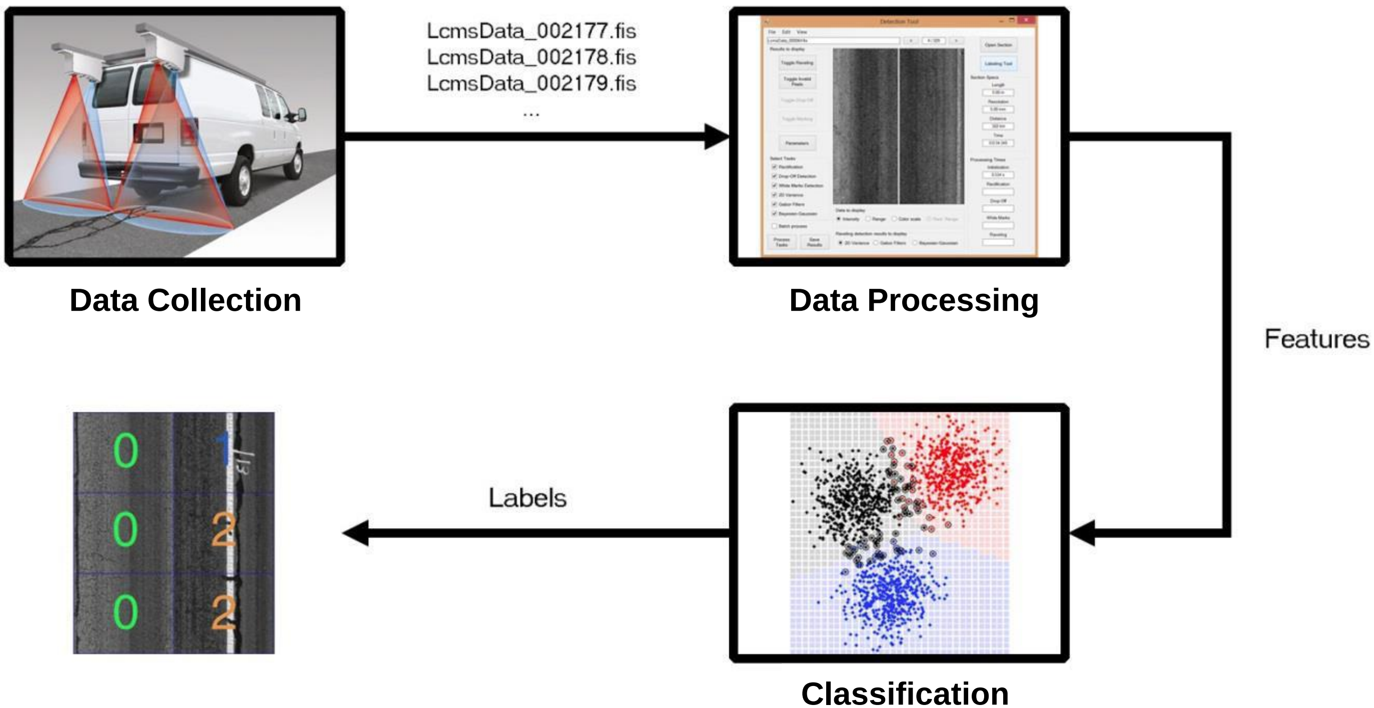
- **What is the importance of loss of aggregates detection and classification?**
  - Loss of aggregates (raveling) is the predominating distress to Open Grade Friction Course (OGFC) pavements.
    - OGFC is a porous surface type that is designed to reduce surface standing water in rainy weather conditions. Georgia's entire asphalt interstate pavement use OGFC to improve safety in rainy condition.
    - Due to the porous nature, OGFC aggregates have less contact/binding surface to each other.
    - Prone to raveling distress, and once raveling occurs, it typically develops very rapidly.
  - OGFC reduces water spraying in wet conditions

Raveling Survey Practices

- Classified into 3 severity levels
  - Level 1: Loss of substantial number of stones. Could be rejuvenated with fog seal.
  - Level 2: Loss of most surface. Too many stones lost to rejuvenate the surface and not enough to repave the road.
  - Level 3: Loss of substantial portion of surface layer (>1/2 depth). Surface must be removed and repaved.
- Currently reported by visual inspection
  - Predominant level in % length per mile
- For convenience, in this study, pavements without raveling were labeled as severity level 0.

Automatic Raveling Detection and Classification Using Machine Learning

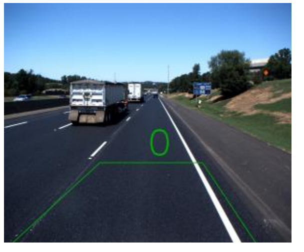
- Procedures
  - Data collection (3D line laser imaging data)
  - Data processing (pre-processing and feature generation)
  - Classification using machine learning, including SVM and Random Forest (output raveling severity levels; classifier needs to be trained first)



Tsai, Y. and Wang Z. (2015) "Development of an Asphalt Pavement Raveling Detection Algorithm Using Emerging 3D Laser Technology and Macrotexture Analysis", National Academy of Science NCHRP IDEA-163 Final Report.

Automatic Raveling Detection and Classification Methods Using 3D Technology and Macro-texture Analysis

(NCHRP IDEA 163)



Tsai, Y. and Wang Z. (2015) “Development of an Asphalt Pavement Raveling Detection Algorithm Using Emerging 3D Laser Technology and Macrotexture Analysis”, National Academy of Science NCHRP IDEA-163 Final Report.

Significant Saving Can be Generated if Pavement Loss of Aggregates Section with Micro-milling and Thin Overlay Treatment Potential Can be Applied.

- Besides improving the accuracy and productivity of current data collection, **using 3D pavement technology with ML can also help achieve savings on maintenance & rehabilitation:**
- **An estimated saving is $17 million,** assuming there are 100 lane-miles of raveling (loss of aggregates) on open-graded friction course (OGFC) that can be identified accurately for micro-milling and thin overlay treatment.
  - A conventional mill and resurfacing of a four-lane open-graded FC-5 friction course pavement is approximately $310,000 per lane mile based on Long-Range Estimating costs from the FDOT State Estimates Office.
  - A resurfacing replacing only the FC-5 due to raveling can usually be done for around $140,000 per lane mile, if done in a timely manner.
  - The difference and saving is approximately $170,000 per lane-mile.

Summary (1/2)

- 3D laser technology has become a mainstream technology to collect simultaneously 2D intensity and 3D range pavement image data in the US for automatic pavement condition evaluation with image processing and machine learning.
- Machine Learning/Deep Leaning is the future trend for automated crack detection. Fast, robust, and accurate data acquiring and ground-truth labeling methods should be further developed.
- New US national standards have been developed on 1) PSI open format 2D/3D pavement surface data, and 2) 2D/3D pavement surface data quality measures
- Automatically extracted pavement distresses and characteristics data have high spatial resolution and distress granularity.
- Great opportunities to use automatically extracted pavement distresses with high granularity and spatial resolution to optimize pavement asset management in terms right treatment at right time and right location.

Summary (2/2)

- **High-resolution 3D pavement data with enhanced automated pavement distress detection** provide great opportunities and challenges for advancing the **reliable pavement performance models development**:
  - **New, valuable performance indicators** need to be devised to characterize the detailed pavement distresses, like intersections and polygons defined in the crack fundamental element (CFE).
  - Linkage needs to be established between **new indicators** and the commonly used composite rating, as well as the **optimal treatment method and timing**.
  - Small-scale, localized treatments (homogeneous pavement performance section) can be planned cost effectively in a pavement management system using the detailed pavement distress data and the corresponding deterioration models
  - Need for developing the **accurate and reliable pavement performance and forecasting models using existing and new indicators**.
  - Need for developing **new quantitative measures**, like loss of aggregate percentage (rather than H, M, L severity levels) for raveling evaluation and forecasting for optimal timing of fog seal treatment.

Thanks

&

Q/A