Durability of sustainable porous asphalt wearing courses: Top-Down Cracking assessment and modelling

07 SEPTEMBER .22

Università di Napoli Parthenope

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UNIVERSITÀ POLITECNICA DELLE MARCHE

Outline

1. Introduction
2. TDC in asphalt pavements
3. TDC survey of the Italian motorway network
4. TDC prediction model

1. Introduction

Porous Asphalt Mixtures

Why using porous asphalt mixtures as surface layers?

Porous Asphalt Mixtures

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- ❑ Increase traffic noise absorption

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- ❑ Reduce the splash & spray during wet weather

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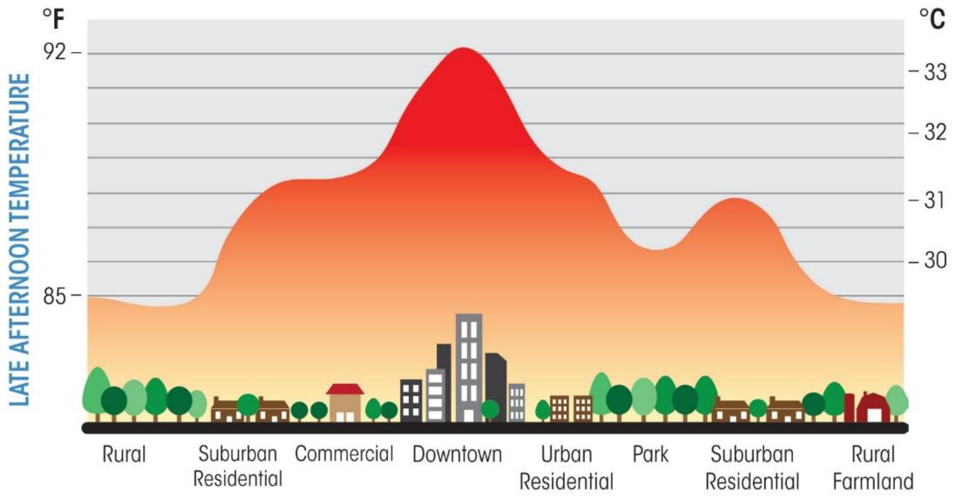
Porous Asphalt Mixtures

Why using porous asphalt mixtures as surface layers?

- ❑ Increase traffic noise absorption
- ❑ Reduce the splash & spray during wet weather
- ❑ Prevent the risk of hydroplaning
- ❑ Limit the Urban Heat-Island effects (?)



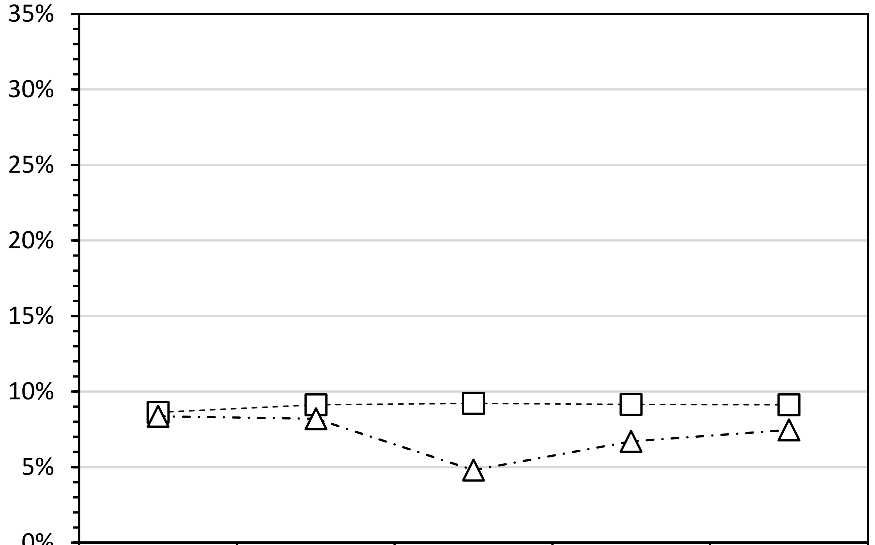
Porous Asphalt Mixtures

In Italy, more than 85% of motorway surface layers are made with PA mixtures!!

Porous Asphalt Mixtures

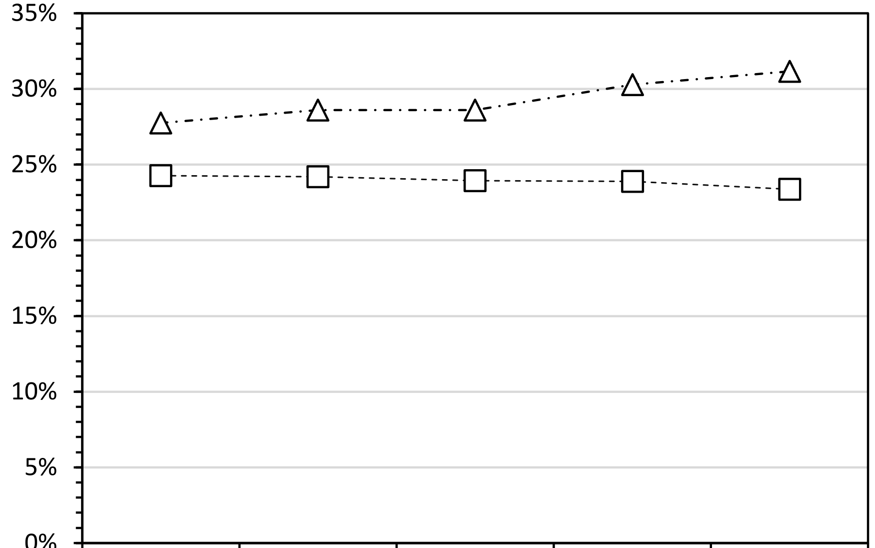
Safety issues

% Fatalities Motorways - ISTAT



	2014	2015	2016	2017	2018
---□--- Wet	8,6%	9,1%	9,2%	9,1%	9,1%
-·-△-·· Wet	8,4%	8,2%	4,8%	6,7%	7,5%

% Fatalities Secondary roads - ISTAT

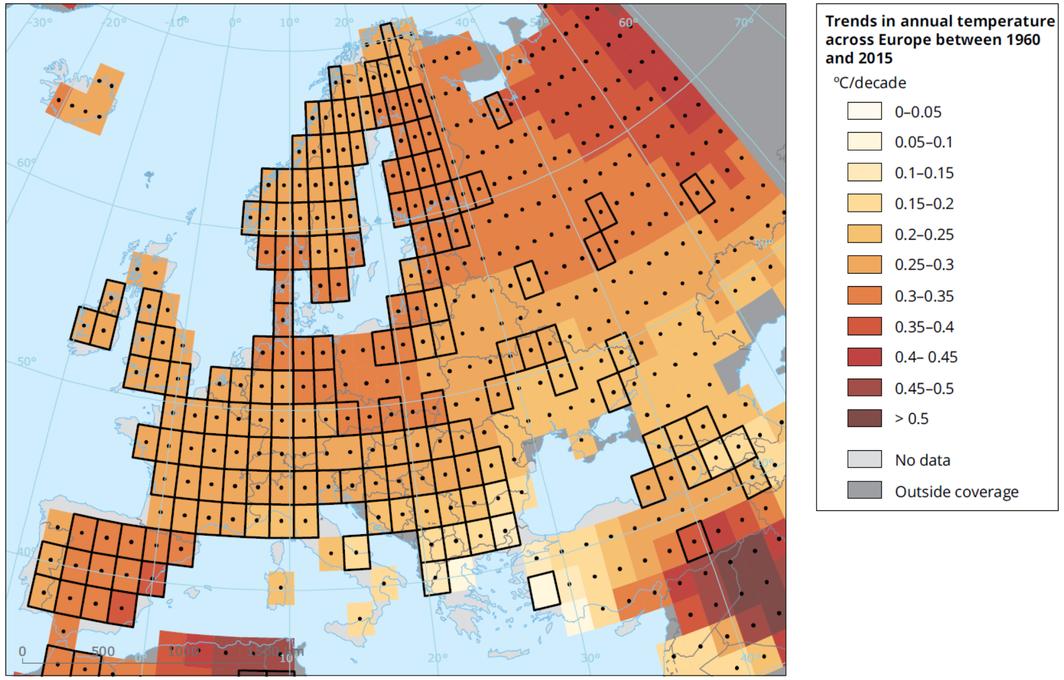


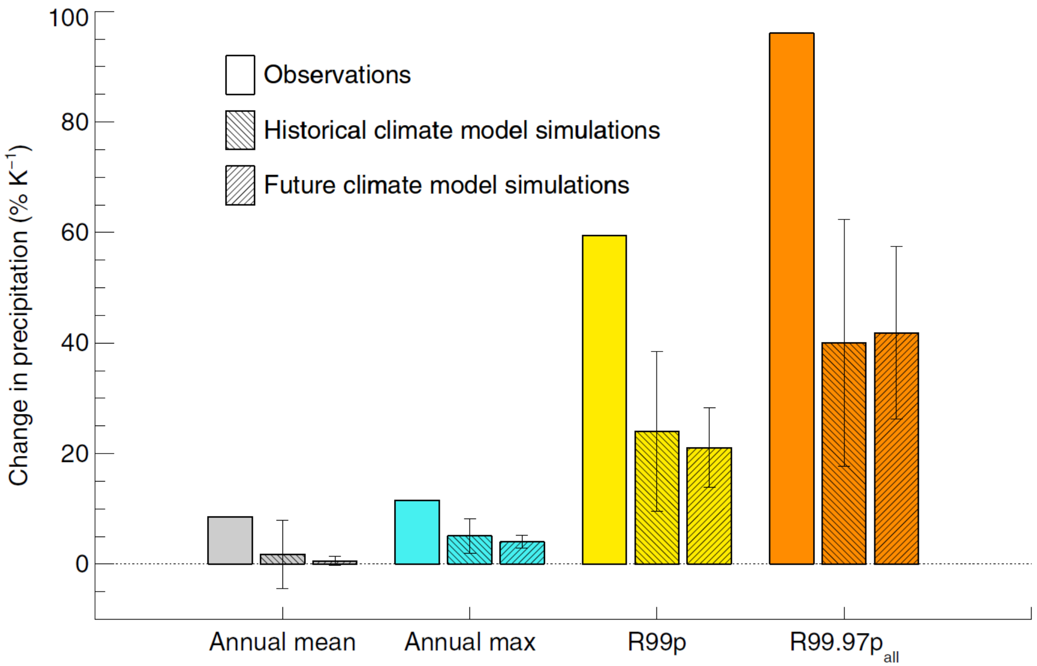
	2014	2015	2016	2017	2018
---□--- Dry	24,3%	24,2%	23,9%	23,9%	23,4%
-·-△-·· Wet	27,8%	28,6%	28,6%	30,3%	31,2%

- Reduced % of total fatalities on Motorway wet pavements

Porous Asphalt Mixtures

Safety issues





- Increasing precipitations due to Global Warming
- Increasing *extreme sub-daily precipitation events*

→ Greater demand for Porous Asphalt Mixtures

SG. Myhre, K. Alterskjær, C.W. Stjern et al., "*Frequency of extreme precipitation increases extensively with event rareness under global warming*", Nature Scientific Reports 9, 16063, 2019.

Porous Asphalt Mixtures

Safety issues

Drainability Reduction ⟷ Clogging of voids of porous surface layers

International recommendations:

- High Air Voids content (AV ≥ 20%)
- Air voids dimension strictly linked to maximum aggregate size (Dmax ≥ 11 mm)

H. Bendtsen, J. Raaberg, Clogging of Porous Pavements - International Experiences, Danish Road Institute, 2007
C. B. Nielsen, Clogging of Porous Pavements - Assessment of Test Sections, Danish Road Institute, 2007

Porous Asphalt Mixtures

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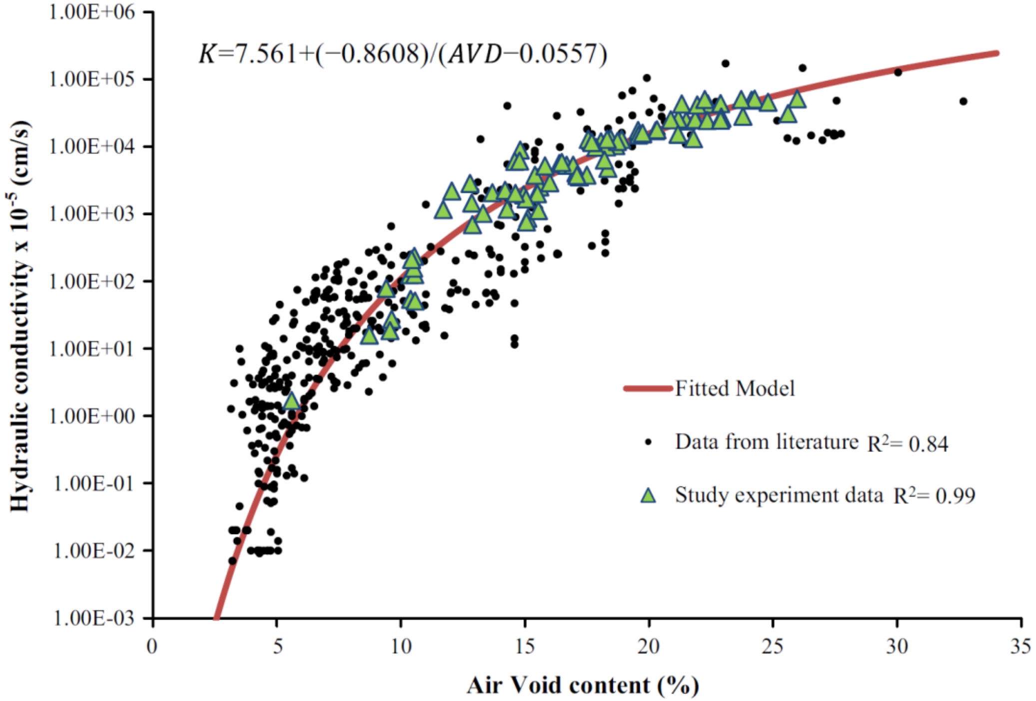

M. Aboufoul, A. Garcia, Factors affecting hydraulic conductivity of asphalt mixture, Materials and Structures 2017

Porous Asphalt Mixtures

Safety issues

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International recommendations:

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- Air voids dimension strictly linked to maximum aggregate size (Dmax ≥ 11 mm)
- Clogging is prevented along the wheel path at high traffic speeds

Colwill D.M., Hydraulic conductivity of porous asphalt, European conference on porous asphalt, Madrid, 1997.

Alvarez, A. E., A. E. Martin, C. K. Estakhri, J. W. Button, C. J. Glover, S. H. Jung, Synthesis of Current Practice on the Design, Construction, and Maintenance of Porous Friction Courses, Texas Transportation Institute, 2006.

Porous Asphalt Mixtures

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Drainability Reduction ⟷ Clogging of voids of porous surface layers

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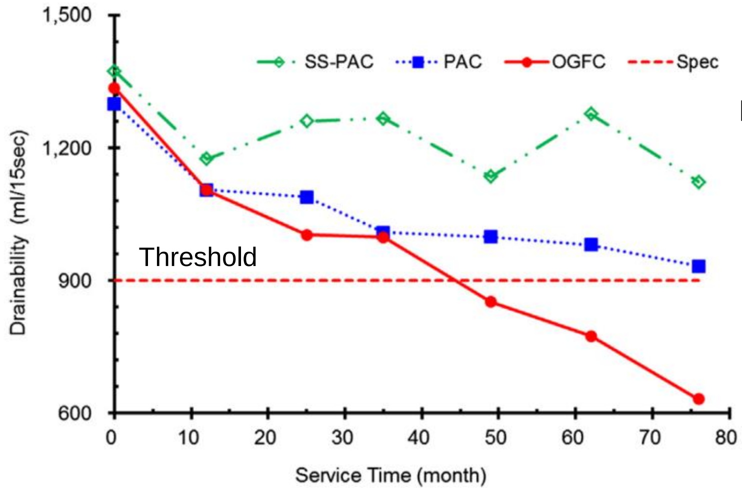
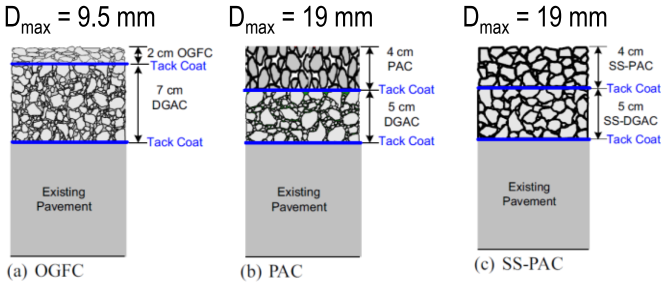
- High Air Voids content (AV ≥ 20%)
- Air voids dimension strictly linked to maximum aggregate size (Dmax ≥ 11 mm)
- Clogging is prevented along the wheel path at high traffic speeds due to the tire action (pumping and suction)





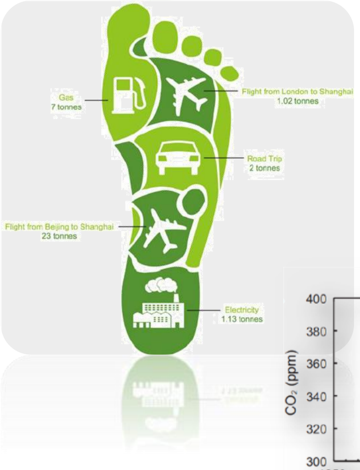
J. S. Chen, C. H. Yang, C. T. Lee, Field evaluation of porous asphalt course for life-cycle cost analysis, Construction and Building Materials, 2019.

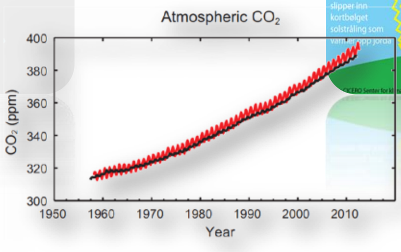
Porous Asphalt Mixtures

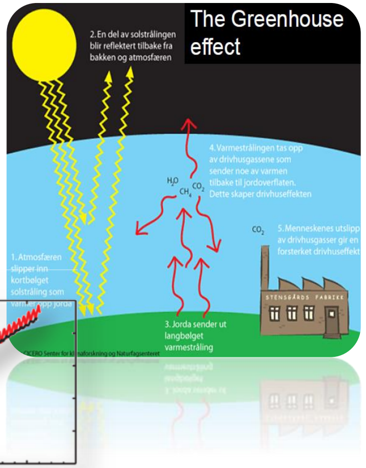
Sustainability issues

“Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004”

“The transportation sector (road traffic, civilian aviation, shipping, railways, and other mobile sources) is today responsible for the most GHG emissions in Europe”







Porous Asphalt Mixtures

Sustainability issues

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CAN ROAD PAVEMENTS MAKE THE DIFFERENCE?

SUSTAINABLE PAVING MIXTURES

Porous Asphalt Mixtures

Sustainability issues

RAP Recycling + **WMA tech**

Warm Recycling

… Need of specific laboratory and in field studies to find out “*What we still do not know*”…

Porous Asphalt Mixtures

Sustainability issues

Research Project

www.extremerecyclingofasphalt.com

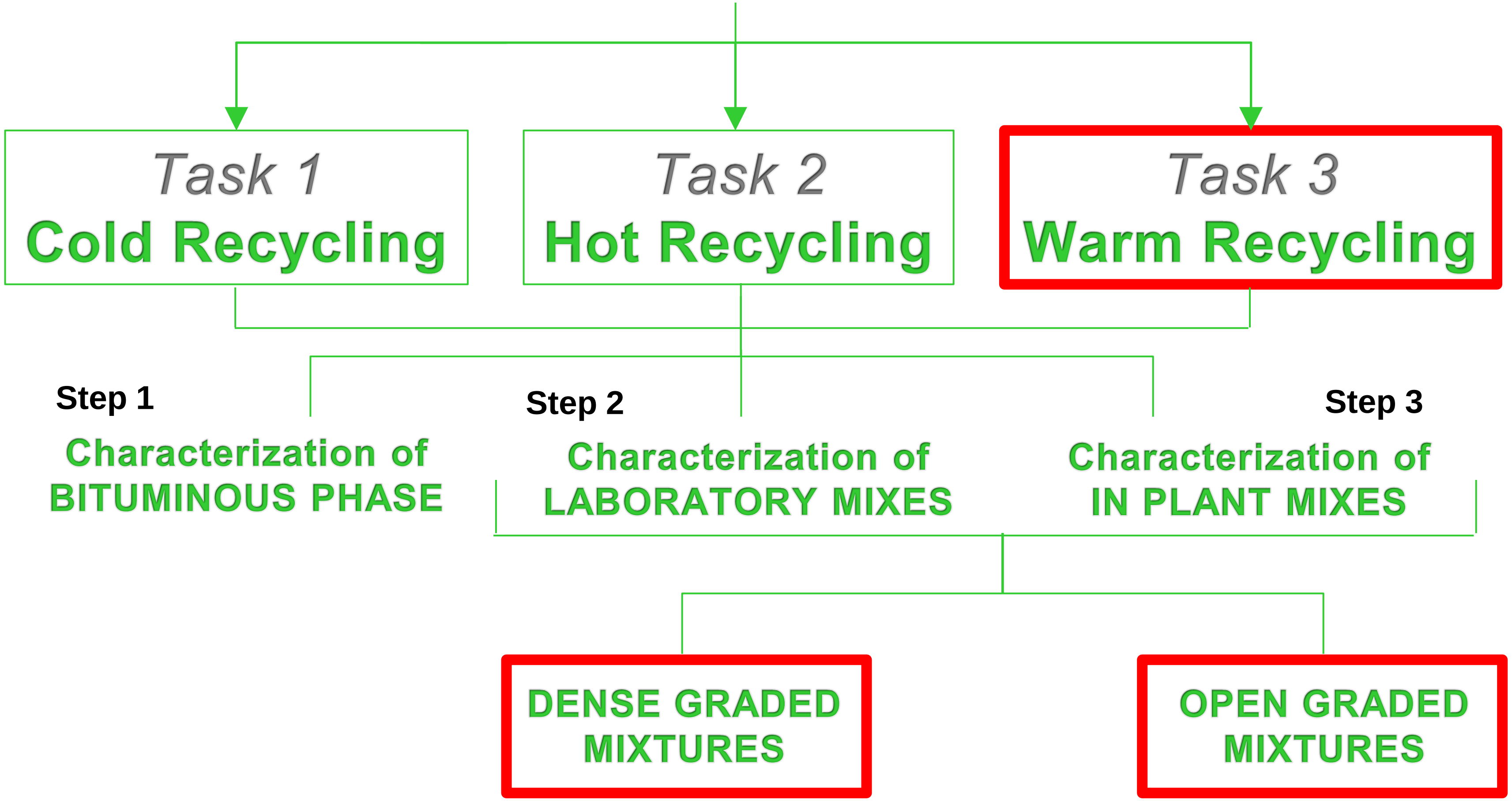
Extreme Recycling of Asphalt

A new ERA for recycling bituminous mixtures

Task 1	Task 2	Task 3
Cold Recycling	**Hot Recycling**	**Warm Recycling**

Porous Asphalt Mixtures

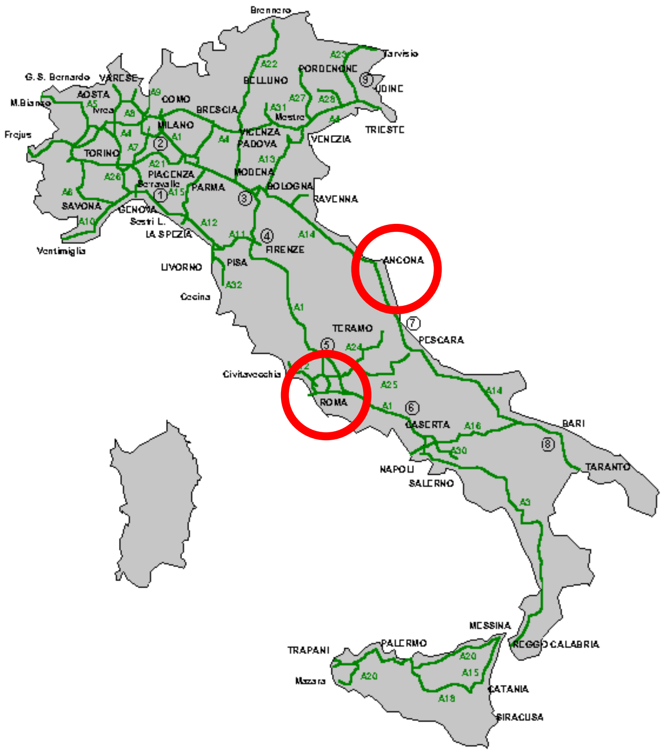
Sustainability issues



Porous Asphalt Mixtures

Sustainability issues

Full-scale trial project – Analysis of asphalt plant mixtures



- In-plant production for rehabilitation works
- In-service heavy traffic motorways **A14** and **A1**
- Full-scale trial sections including both **OG SURFACE** and **DG BASE-BINDER** courses

  WMA Sections → different chemical additives

  HMA Section → reference control section

Porous Asphalt Mixtures

Sustainability issues

Full-scale trial project – Analysis of asphalt plant mixtures

1. **OPEN-GRADED** mixtures
2. **RECYCLING →** 15% RAP
3. **WARM MIX ASPHALT**

ADHESION PROPERTIES
+
DURABILITY

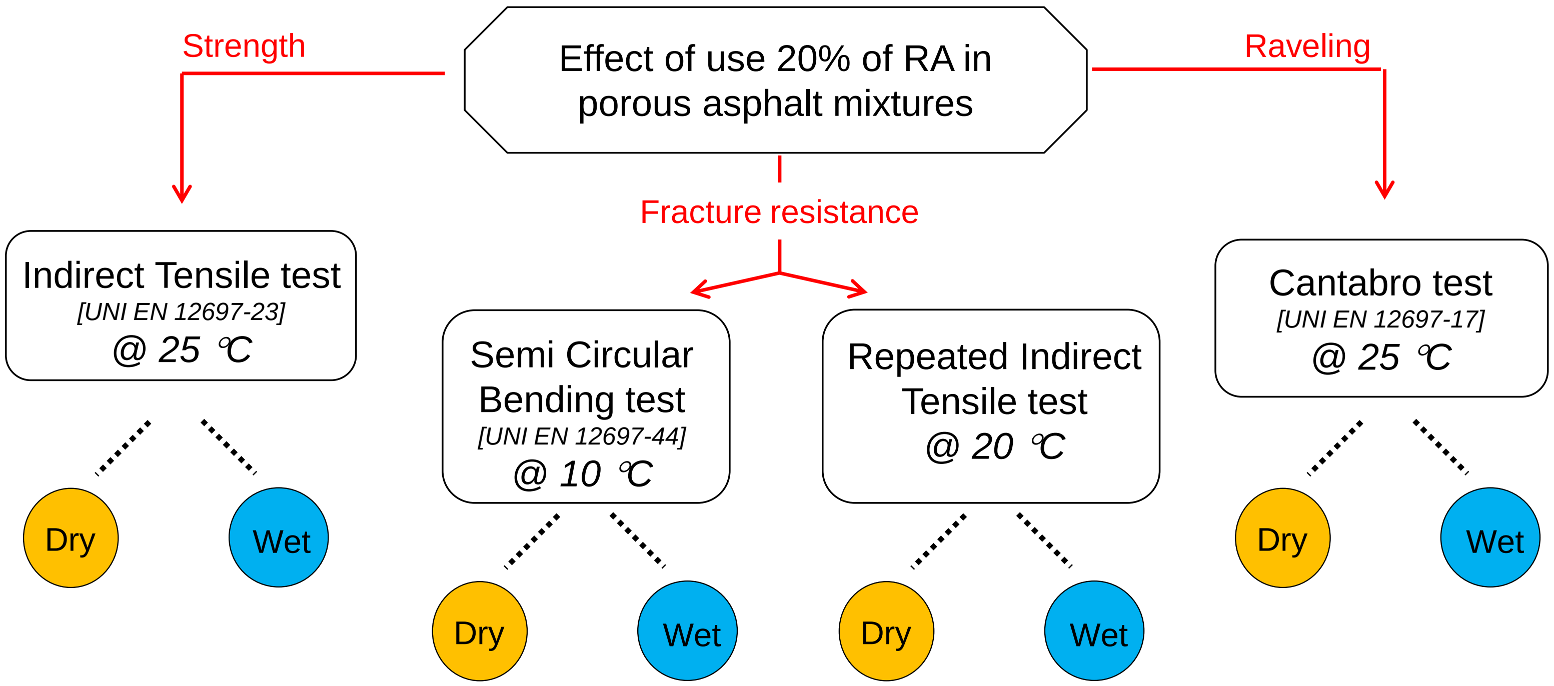
Porous Asphalt Mixtures

Sustainability issues

Full-scale trial project – Analysis of asphalt plant mixtures

Compactability evaluation **(CEI)**

+



*CONDITIONING MODE: **DRY – WET** (specimens kept in water at 40 °C for 72 h)

Porous Asphalt Mixtures

Sustainability issues

Full-scale trial project – Analysis of asphalt plant mixtures

Main Outcomes:

- OG-WMA mixtures ensured **very good workability**.
- OG-WMA mixtures satisfied acceptance requirements and international recommendations for mechanical properties and raveling resistance.
- **Excellent in-service behavour after more than 6 years**

Stimilli, F. Frigio, G. Ferrotti, S. Sciolette & F. Canestrari, "*In-plant production of warm recycled mixtures: a case study*", Intern. Conf. on Transport Infrastructure and Systems TIS2017, 2017.

A. Stimilli, A. Virgili, F. Canestrari, "*Warm recycling of flexible pavements: effectiveness of WMA additives on SBS modified bitumen and mixture performance*", Journal of Cleaner Production, vol. 156, 2017.

A. Stimilli, F. Frigio, F. Cardone, F. Canestrari, "*Performance of warm recycled open and dense graded mixtures in field trial sections*", 10th Intern. Conf. on the Bearing Capacity of Roads, Railways and Airfields (BCRRA), 2017.

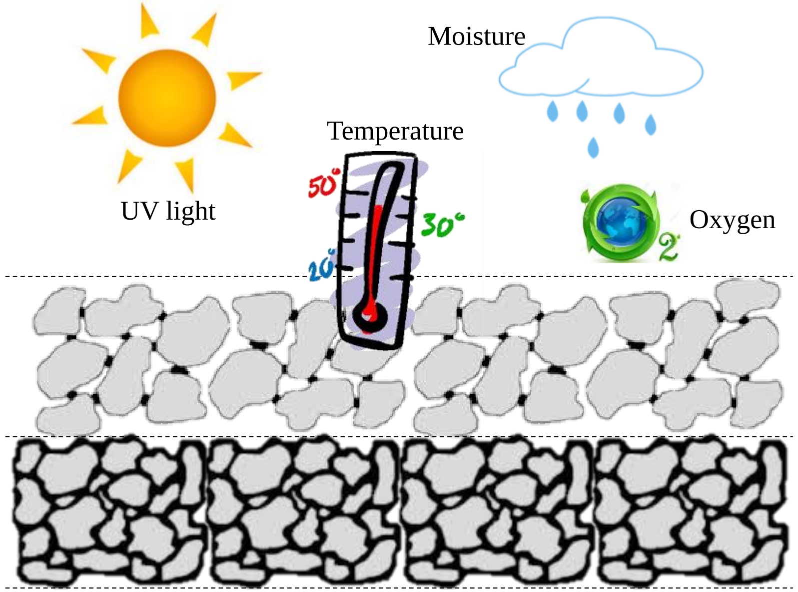
F. Frigio, A. Stimilli, A. Virgili, F. Canestrari, "*Performance Assessment of In-Plant-Produced Warm Recycled Mixtures for Open-Graded Wearing Courses*", Transportation Research Record: Journal of the Transportation Research Board, 2017.

F. Frigio, F. Canestrari, "*Characterization of warm recycled porous asphalt mixtures prepared with different WMA additives*", European Journal of Environmental and Civil Engineering, 2018.

Porous Asphalt Mixtures

Durability issues

Low durability of PA layers

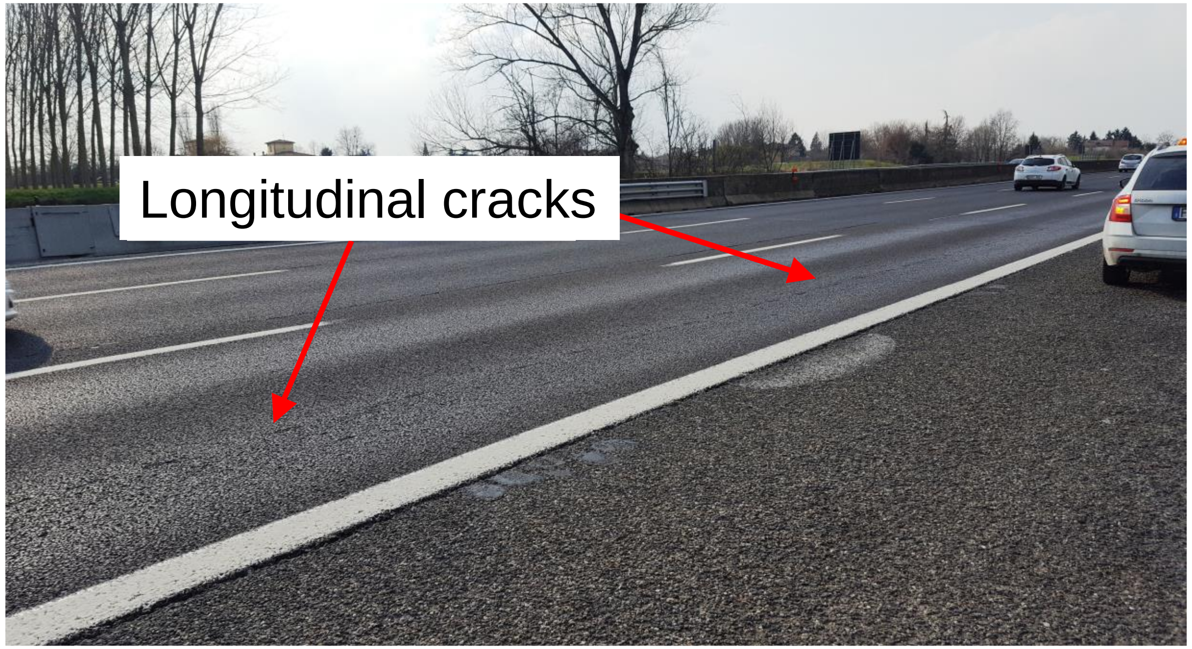


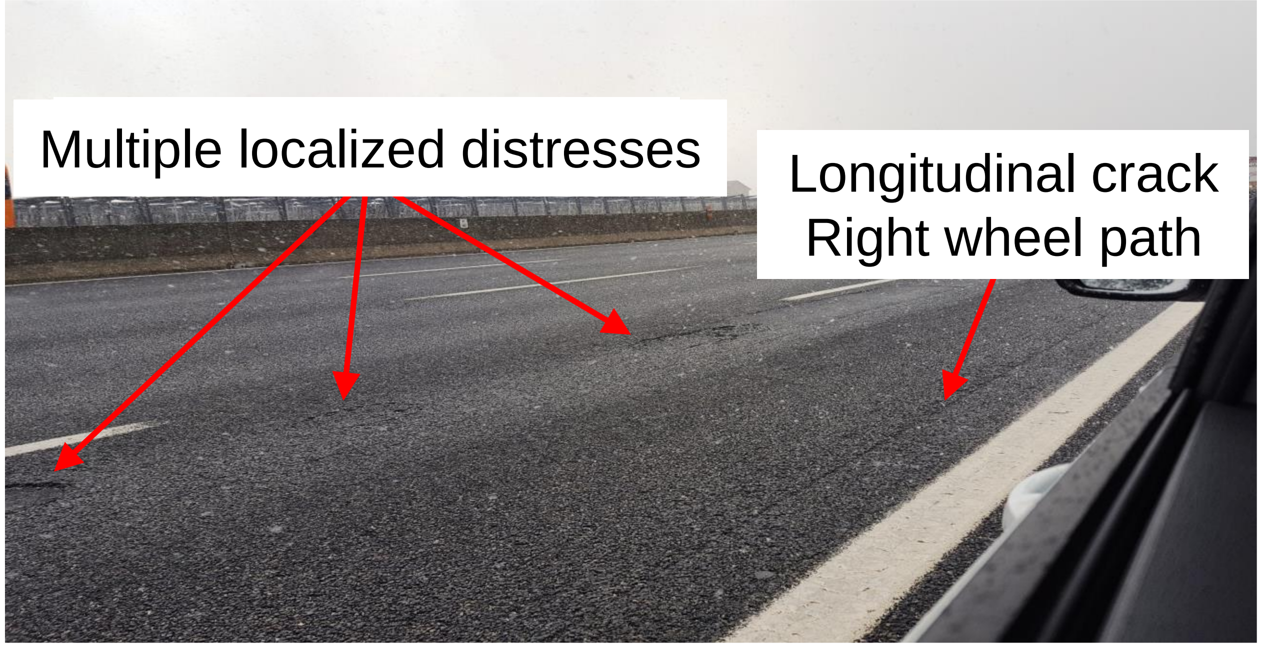
- ❑ High sensitivity of PA mixtures to traffic and climatic loading
- ❑ Premature aging of bitumen
- ❑ Exposure to water damage
- ❑ Ravelling distress

Other types of distresses?

Porous Asphalt Mixtures

Survey along Motorway A1 – February 2018





Porous Asphalt Mixtures

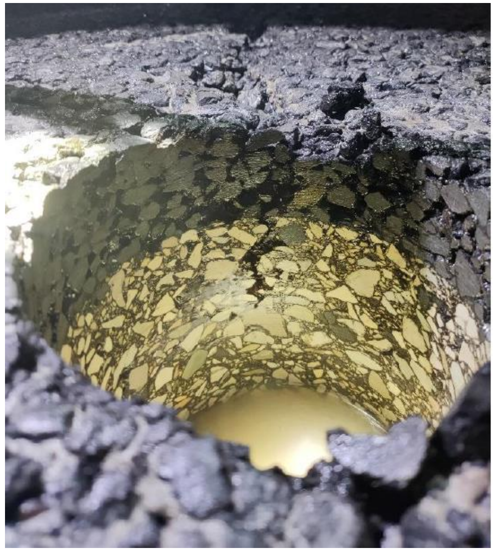
Survey along Motorway A14 – November 2018

2. Top-down cracking in asphalt pavements

Canestrari, F. & Ingrassia, L.P. (2020)
A review of top-down cracking in asphalt pavements: Causes, models, experimental tools and future challenges Journal of Traffic and Transportation Engineering (English Edition), 7(5), 541-572

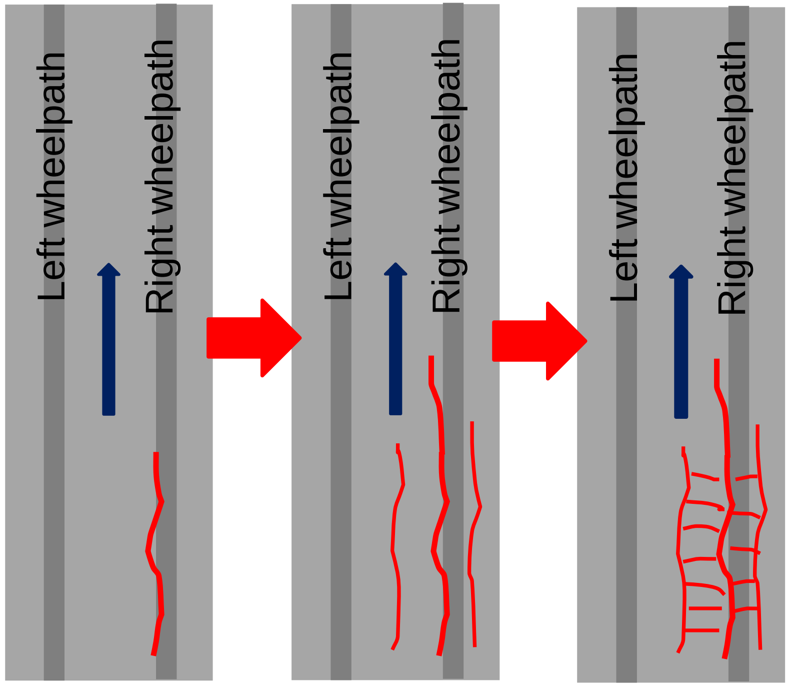
TDC problem statement

- **Longitudinal cracks** that **initiate** on the **pavement surface** and **propagate downwards**
- TDC and bottom-up cracking are both **fatigue distresses**
- TDC **often neglected in pavement design, management, maintenance**

TDC peculiarities

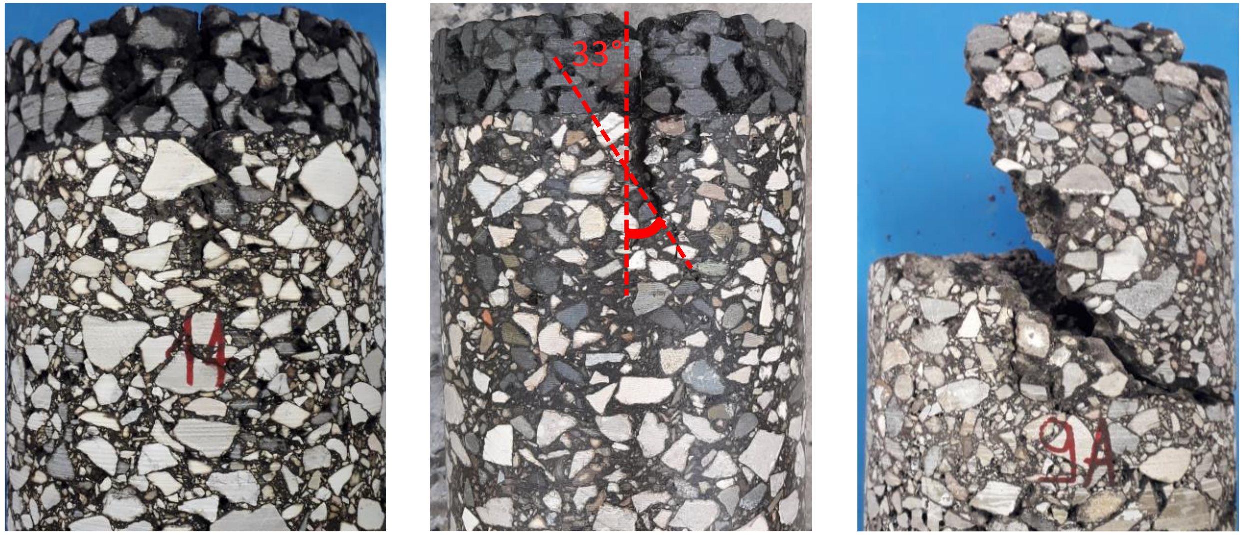
Evolution on the pavement surface



1. Isolated crack in the wheelpath area with length of 10-100 m order of magnitude
2. Formation of other longitudinal cracks parallel to the initial one at a distance of 0.3–1.0 m (***sister cracks***)
3. Formation of short transverse cracks → **alligator cracking pattern** in the wheelpath

TDC peculiarities

Evolution in depth



1. Vertical downward evolution
2. Deviation towards the center of the wheelpath → angles of 20°–40° with respect to the vertical plane
3. Sub-horizontal propagation and possible connection with other cracks → generalized failure in the upper part of the pavement

Main causes

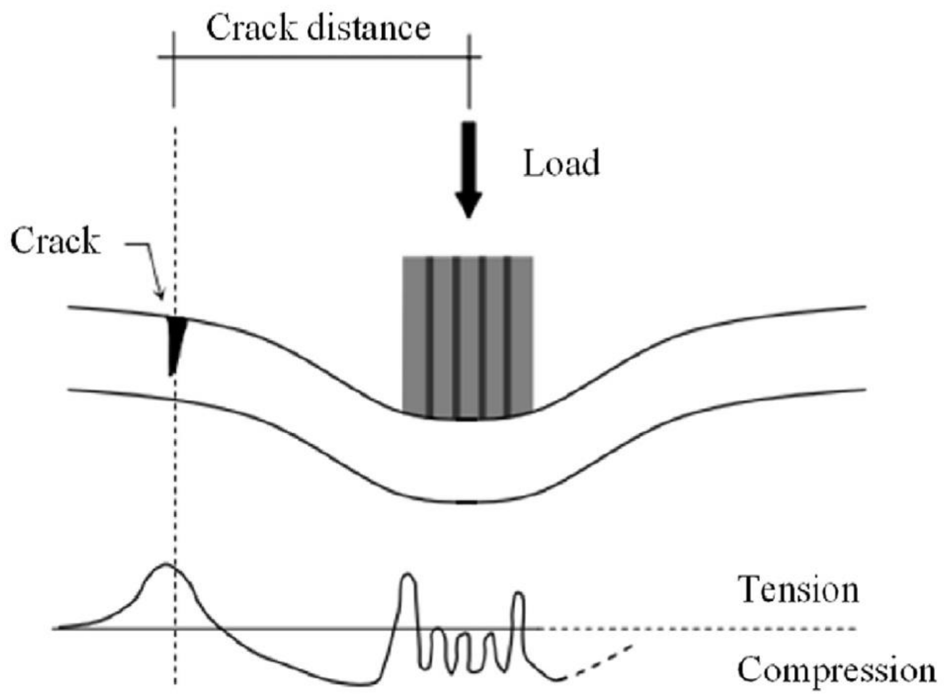
Traffic loadings and pavement structure

Thin asphalt pavements

Global flexural mechanism

TDC initiates at a certain distance from the wheelpath (maximum tensile strain)

Bottom-up cracking precedes TDC



Main causes

Traffic loadings and pavement structure

Thick asphalt pavements

Local tire-pavement contact stresses

↓

Tensile and shear stresses in the wheelpath area

↓

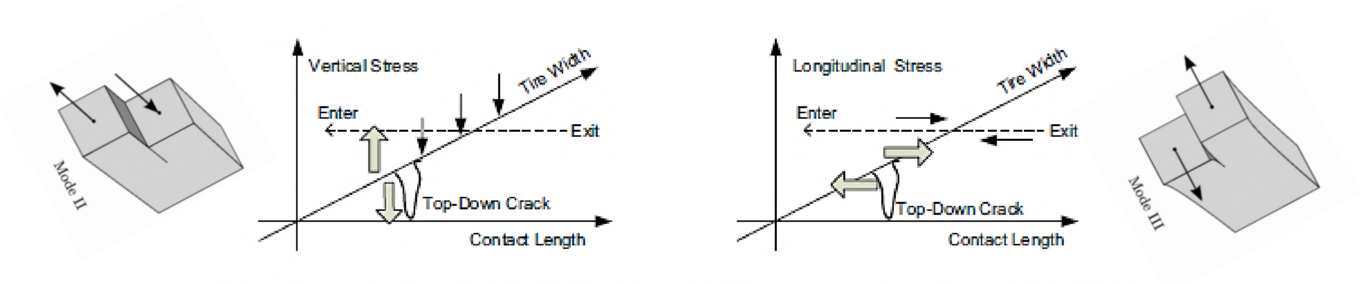
TDC precedes bottom-up cracking

Main causes

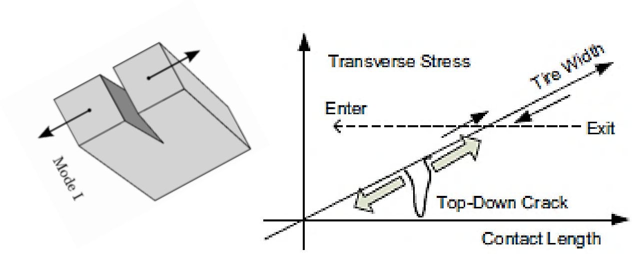
Traffic loadings and pavement structure

Thick asphalt pavements

Fracture modes associated with the contact stresses



(a) Mode II: Shearing under Vertical Stress (b) Mode III: Tearing under Longitudinal Stress

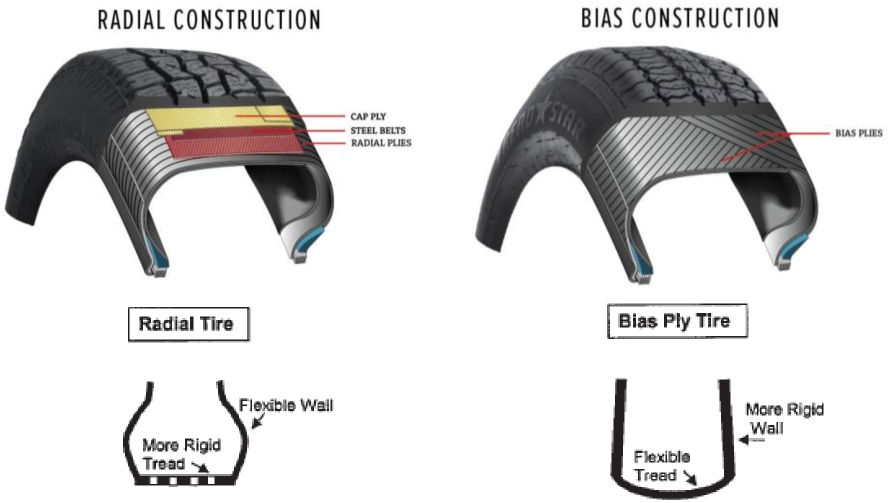


(c) Mode I: Opening under Transverse Stress

Main causes

Traffic loadings and pavement structure

Thick asphalt pavements



Influence of tire characteristics:

1. Progressive use of **radial tires** instead of bias ply tires
2. Increasing use of **wide single tires** («super-singles») instead of dual tires in heavy vehicles

Increase of tire-pavement contact stresses
For thick pavements the TDC stress level can be dominant

Main causes

Traffic loadings and pavement structure

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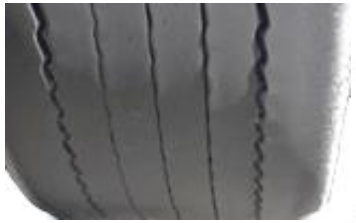

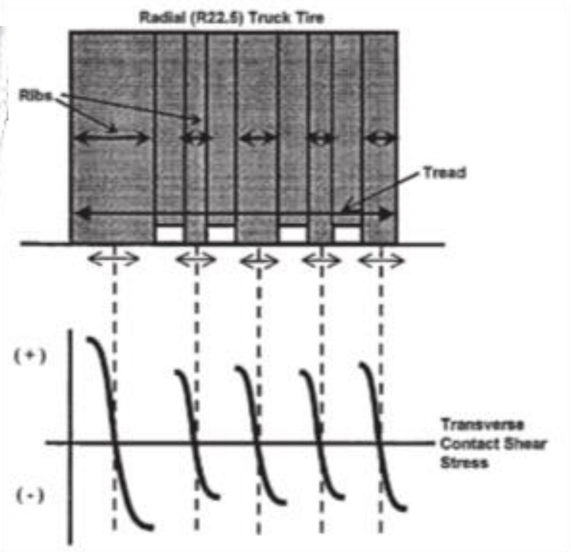

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Traffic loadings and pavement structure

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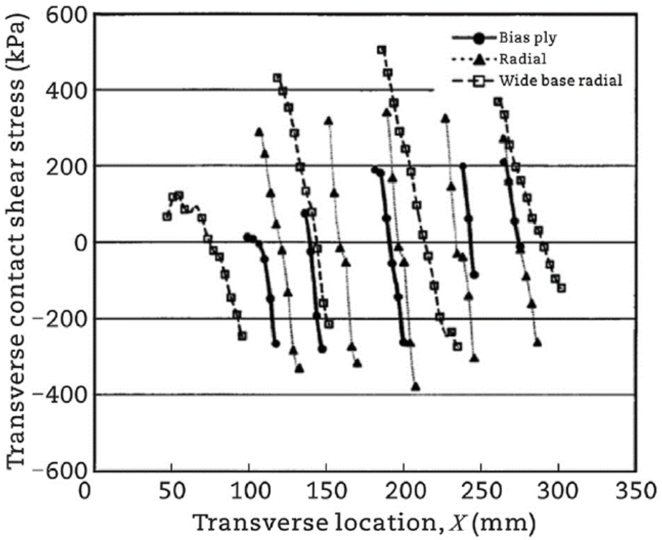


Increase of tire-pavement contact stresses

For thick pavements the TDC stress level can be dominant

Main causes

Properties of PA mixtures

Consequences of the high air void content (20–25%):

- **Accelerated aging** (greater exposure to oxygen, atmospheric agents and UV radiation)
- **Low fracture strength**
- Much **lower stiffness** as compared to the underlying layers
- The **air voids are flaws** in the material (initiation of micro-cracks)

The pavement tends to fail due to TDC rather than bottom-up cracking

Main causes

Stiffness Gradients

The **pavement surface is more exposed** to air, thermal variations, meteoric events, UV radiation

Stiffness variations limited to the upper part of the pavement due to **climatic conditions and aging**

Higher probability of crack initiation and **increased stresses** within the pavement **in the propagation phase**

Main causes

Construction Issues

Construction issues promote TDC:

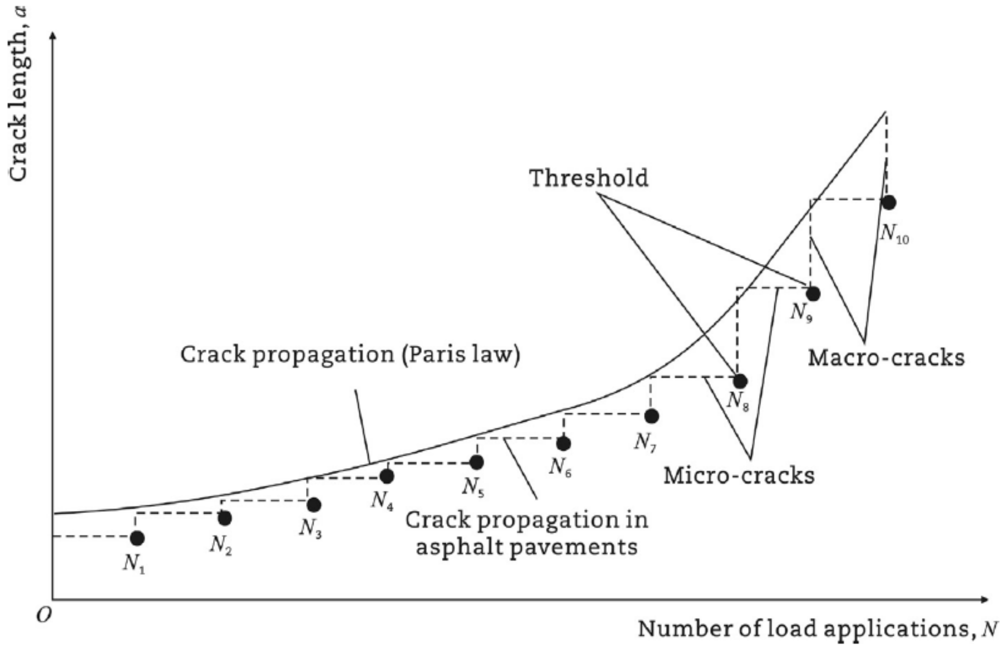
- **Mixture segregation** → pavement areas with prevalence of coarse aggregates → **low tensile strength + high air voids**
- **Poor compaction** → variability in the air void distribution → **stiffness gradients**

Initiation and Propagation Models

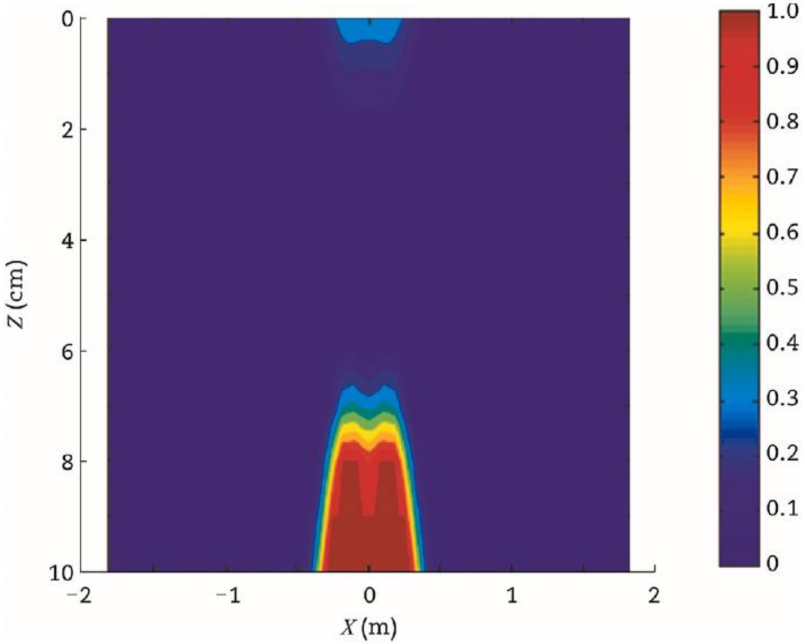
1. **Empirical models**
   - Mechanistic-Empirical Pavement Design Guide (MEPDG)
   - Wu & Muhunthan (2019)
   - **No rigorous description of the cracking process**
2. **Models based on fracture mechanics**
   - **Rigorous description of the propagation phase**
   - Paris Law model (Texas A&M University) → continuous propagation
   - HMA-FM model (University of Florida) → discontinuous propagation
3. **Models based on continuum damage mechanics**
   - **Rigorous description of the initiation phase**
   - VECD model (North Carolina State University)
4. **Models based on micro-mechanics**
   - Rigorous description of the initiation phase at a micro-scale
   - **Uncertain validity at a macro-scale**

Initiation and Propagation Models

Crack growth:
Paris Law vs HMA-FM model



VECD model:
damage distribution



Test Methods

- **No test method is universally acknowledged** as suitable for TDC
- Some **existing test methods** normally used to investigate the **cracking performance** or the **shear behaviour** have been proposed to study TDC
- Other **test methods specifically developed** for TDC (less consolidated)

Test Methods

Aspects to be considered:

- **Complexity**: specimen preparation, feasibility on field cores, specimen instrumentation
- **Practicality**: training time
- **Efficiency**: testing time and number of specimens
- **Equipment**: characteristics and cost
- **Result interpretation**: mechanics-based vs index parameters
- **Result analysis**: complexity in the analysis of the raw test results
- **Repeatability** (e.g. coefficient of variation, COV)
- **Sensitivity to the mixture properties**: aging, air voids, RAP, binder type and dosage
- **Correlation with field performance**

Test Methods

Table 3 – Evaluation of TDC test methods.

Test	Complexity			Practicality (training)	Efficiency	Equipment	Result interpretation	Result analysis
	Specimen preparation*	Core testing	Instrumentation					
ER method	None	Relatively easy	4 extensometers	Medium	1–2 h (3)**	Hydraulic machine (>€100,000)	Fracture mechanics	Relatively simple
Texas OT	Cutting, gluing to plates	Feasible	None	Medium	0.5–3 h (3)	Specific or AMPT accessory (€40,000)	Index parameter	Simple
NCAT OT	Cutting, gluing to plates	Feasible	None	Medium	0.5–3 h (3)	Specific or AMPT accessory (€40,000)	Index parameter	Simple
SCB	Cutting, notch	Not feasible for wearing courses	None	Minimum	30 min (12)	Any hydraulic or pneumatic machine (<€10,000)	Fracture mechanics	Simple
Illinois FI	Cutting, notch	Not feasible for wearing courses	None	Minimum	1 min (4)	Any hydraulic or pneumatic machine (<€10,000)	Index parameter	Simple
IDEAL-CT	None	Simple	None	Minimum	1 min (3)	Any hydraulic or pneumatic machine (<€10,000)	Fracture mechanics	Simple
RDT	Coring, cutting, gluing end plates	Not feasible for wearing courses	3 LVDTs	Relatively long	2 h (2)	Universal machine (€50,000 –€100,000)	Fracture mechanics	Simple with specific software
S_{app} method	Coring, cutting, gluing end plates	Feasible	3 LVDTs	Relatively long	1 h (3 + 3)	AMPT (>€50,000)	Continuum damage mechanics	Simple with FlexMAT
CSIC	Cutting, tack coat, gluing, hole, carbon fibers	Feasible	4 extensometers	Long	6–8 h (3)	Universal machine (€50,000 –€100,000)	Index parameter	Simple
Wu and Muhunthan (2019)	None	Simple	4 LVDTs	Minimum	1 min (3)	Any hydraulic or pneumatic machine (<€10,000)	Index parameter	Simple
Gu et al. (2019)	None	Simple	None	Minimum	1 min (3)	Any hydraulic or pneumatic machine (<€10,000)	Index parameter	Simple
UPT	None	Simple	None	Minimum	Several minutes (3)	Any hydraulic or pneumatic machine (<€10,000)	– (shear test)	Simple
URPT	None	Simple	None	Minimum	Several hours (3)	Hydraulic machine (>€100,000)	– (shear test)	Simple

Note: * Laboratory-prepared specimens. ** The number in parentheses indicates the minimum number of specimens to be tested.

Test Methods

Table 4 – TDC performance parameters: repeatability, sensitivity to mixture properties and correlation with field performance.

Parameter	Repeatability	Aging	Air void	Reclaimed asphalt	Binder type	Binder dosage	Correlation with field performance
ER	–	No [1,2]	Yes [1]	No [1]	No [1]	–	No [1,2]
$DCSE_f$	Fair (COV = 20%)	Yes [1]	No [1]	No [3] Yes [1]	No [1,3]	–	No [3] Yes [1]
TX-N_f	Low (COV = [30%, 50%])	Yes [1]	Yes [1]	Yes [1,3,4,5]	No [1,3] Yes [4,5]	Yes [5]	Yes [1,3]
TX-β	Fair (COV = 20%)	Yes [1]	No [1]	Yes [1,3]	No [1,3]	–	Yes [1,3]
TX-G_c	Good (COV < 10%)	No [1]	Yes [1]	No [1] Yes [3]	No [1] Yes [3]	–	No [3] Yes [1]
NCAT-N_f	Fair (COV < 30%)	Yes [1]	Yes [1]	Yes [1]	No [1]	–	Yes [1]
NCAT-β	–	Yes [1]	Yes [1]	Yes [1]	Yes [1]	–	Yes [1]
NCAT-G_c	–	Yes [1]	No [1]	No [1]	No [1]	–	Yes [1]
J_c	Fair (COV = 20%)	Yes [1]	No [1]	No [1], Yes [3] RAP: Yes, RAS: No [5]	No [1,3] Yes [5]	Yes [5]	No [1] Yes [3]
FI	Fair (COV = 20%)	Yes [1]	No [1]	Yes [1]	Yes [1]	–	Yes [1]
CT_{index}	Fair (COV < 25%)	Yes [1,6]	No [1,4,6]	Yes [1,4,6]	Yes [1,4,6]	Yes [6]	Yes [1,4,6]
n'	–	Yes [7,8]	Yes [7]	–	Yes [7]	–	–
S_{app}	–	Yes [11]	Yes [11]	Yes [11]	Yes [9,11]	Yes [9,11]	Yes [11]
ϵ_u	–	–	–	–	–	–	Yes [10]
CI	–	Yes [2]	–	–	–	–	Yes [2]

Note: [1] Chen (2020); [2] Gu et al. (2019); [3] Cao et al. (2019); [4] Im and Zhou (2017); [5] Zhou et al. (2017a); [6] Zhou et al. (2017b); [7] Luo et al. (2013a); [8] Gu et al. (2015); [9] Etheridge et al. (2019); [10] Wu et al. (2019); [11] Wang et al. (2020).

Test Methods

In summary:

- Test methods with a **mechanics-based background** can be considered more reliable, but they require more efforts → **Research purposes**
- Test methods that determine **index parameters** are simpler, faster, require minimum training and less expensive equipment, but their scientific soundness might be questionable → **Routine tests**

Implementation in a PMS

1. Correct identification of TDC

- **Not to be confused with other longitudinal cracks** repairable through sealings (e.g. scrapes caused by a heavy vehicle rim after tire blowout, construction joints)
- **Not to be treated like bottom-up cracking** → milling and reconstruction of few cm of pavement Vs full-depth rehabilitation

↓

Definition of reliable identification criteria

Implementation in a PMS

2. Definition of the optimal intervention time

- The **crack growth** rate **in depth** varies with the crack length
- The **longitudinal growth** follows a **sigmoidal law**

Timely maintenance allows to minimize pavement damage and costs

Implementation in a PMS

3. Assessment of the appropriate intervention depth

- Inaccurate estimation of TDC depth → **milling of intact asphalt concrete or non-removal of undesired cracks** (possible reflective cracking)
- Taking a statistically significant number of **cores** from the pavement is **expensive and destructive**

Correlation between TDC depth and traffic (monitoring of traffic)

UNIVPM-ASPI Research Project

Sustainability

Efficiency

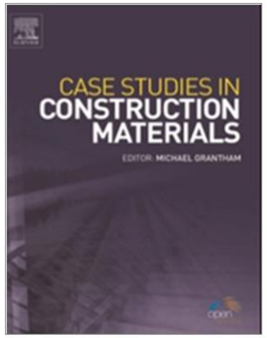
iPER Tech

Highway **P**avement **E**volutive **R**esearch

Innovation

Safety

3. TDC Survey of the Italian motorway network



Ingrassia, L.P., Spinelli, P., Paoloni, G., Canestrari, F. (2020)
Top-down cracking in Italian motorway pavements: A case study
Case Studies in Construction Materials, 13, e00442

Analysis of the trial network

- 4 motorway sections, both carriageways, slow lane → **400 km**
- Different **number of lanes per direction**, **traffic level**, **wearing course type** and **climate**
- **Non-automatic visual analysis of pavement ARAN images** (every 5 m)

Table 1
Characteristics of the trial network.

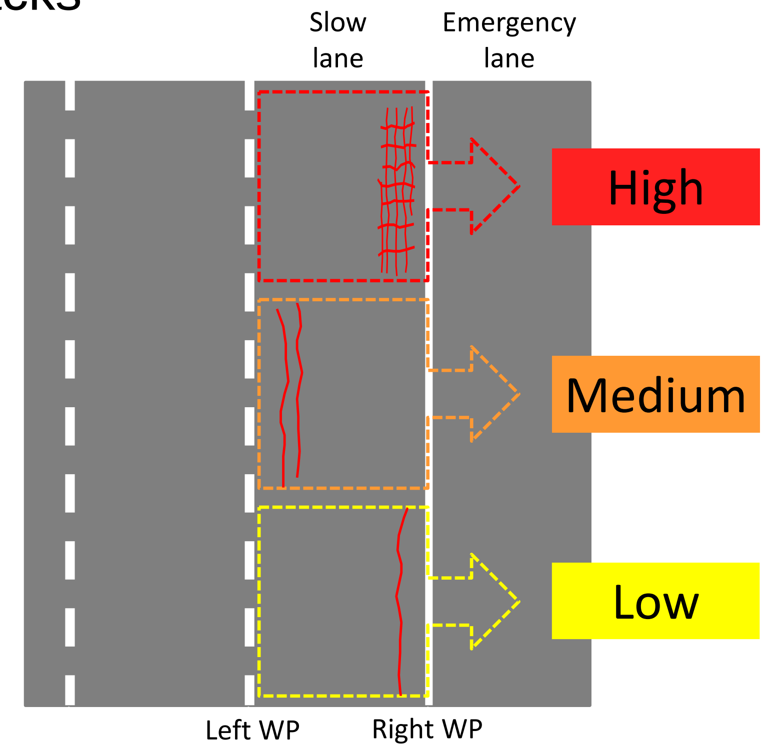
Section	S1	S2	S3	S4
Motorway	A1 MILANO-NAPOLI (DT3)	A14 BOLOGNA-TARANTO (DT3)	A14 DIRAMAZIONE RAVENNA (DT3)	A1 MILANO-NAPOLI (DT4)
Section	Ponte Fiume Enza - All. A14	All. Dir. Ravenna - A14	All. A14 - S.S. Romea	Sasso Marconi - All. Variante di Valico
From km	119 + 500	56 + 700	0 + 000	210 + 100
To km	188 + 900	143 + 900	29 + 800	220 + 000
Length [km]	69.4	87.2	29.8	9.9
Directions	North/South	North/South	East/West	North/South
N. lanes/ direction	3 (km 119 + 500–155 + 500) 4 (km 155 + 500–188 + 900)	3	2	3
Traffic level	High	Medium	Low	Medium
Wearing course	OGFC	OGFC	OGFC	Dense-graded
Climate	Mild	Mild	Mild	Cold winter

ARAN image

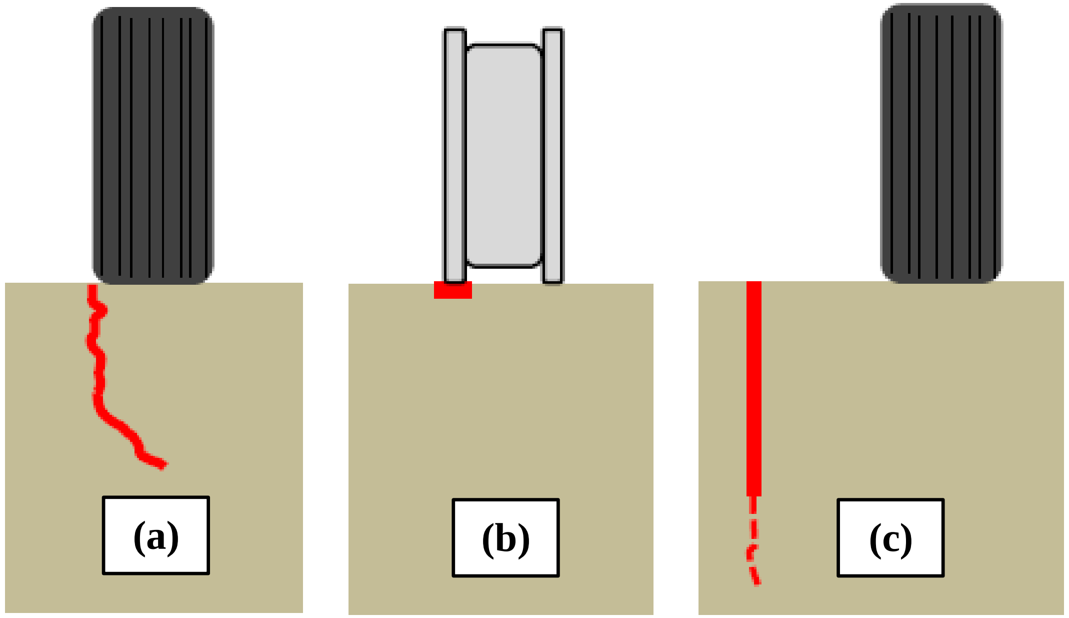
Analysis of the trial network

- **Identification criteria** to distinguish TDC and other longitudinal cracks (control cores)
- Calculation of the **length of the longitudinal cracks**
- Definition of **TDC severity**

1. **Low**: single longitudinal crack with limited width
2. **Medium**: single longitudinal crack with considerable width or presence of *sister cracks*
3. **High**: longitudinal cracks connected by transverse cracks



Types of longitudinal cracks



(a) **TDC**

(b) **Tire blowouts →** surface incisions due to the rim-pavement contact (truck drivers bad habit of keeping driving for some km after the tire blowout)

(c) **Construction joints**

Identification criteria: TDC

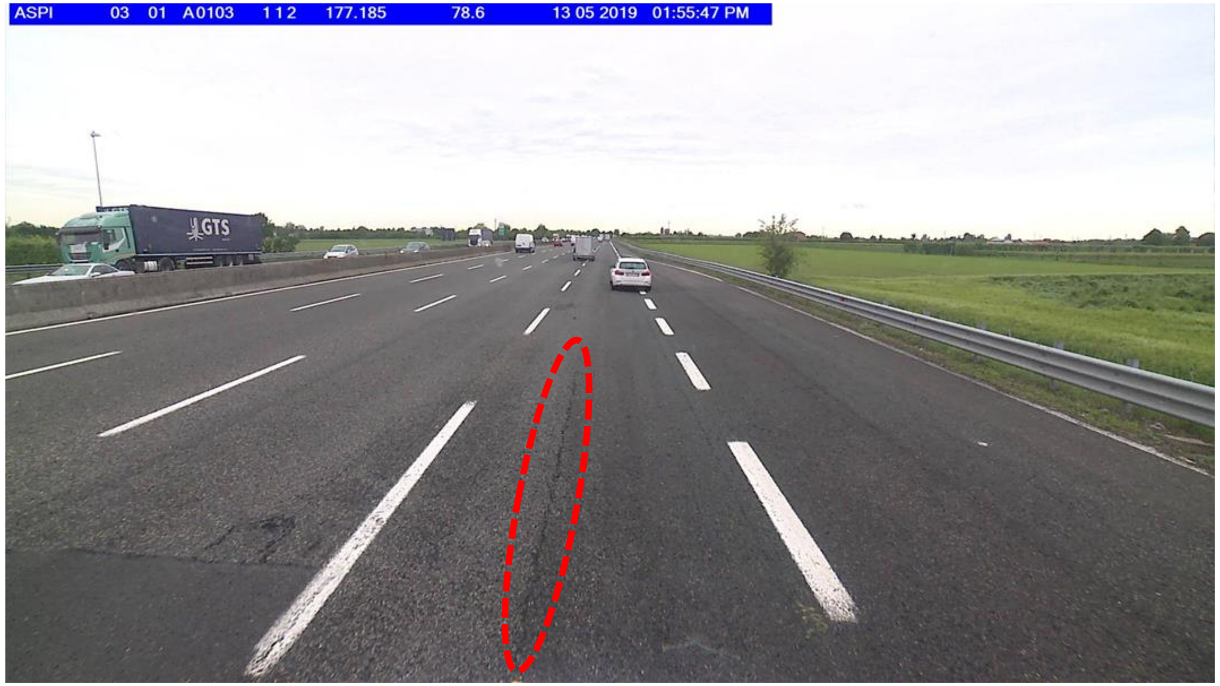
- Wheelpath area
- Rectlinear at global scale, irregular pattern at local scale
- Presence of *sister cracks*

Identification criteria: Tire blowouts

- Wheelpath area
- Typical deviation to the right (emergency lane, parking area,…)
- Discontinuous crack (discontinuous contact between rim and pavement)
- Straight incision (scratched aggregates)
- No global or local irregularity

Identification criteria: Joints

- In most cases, far from the wheelpath
- More regular pattern at local scale as compared to TDC



TDC calculation

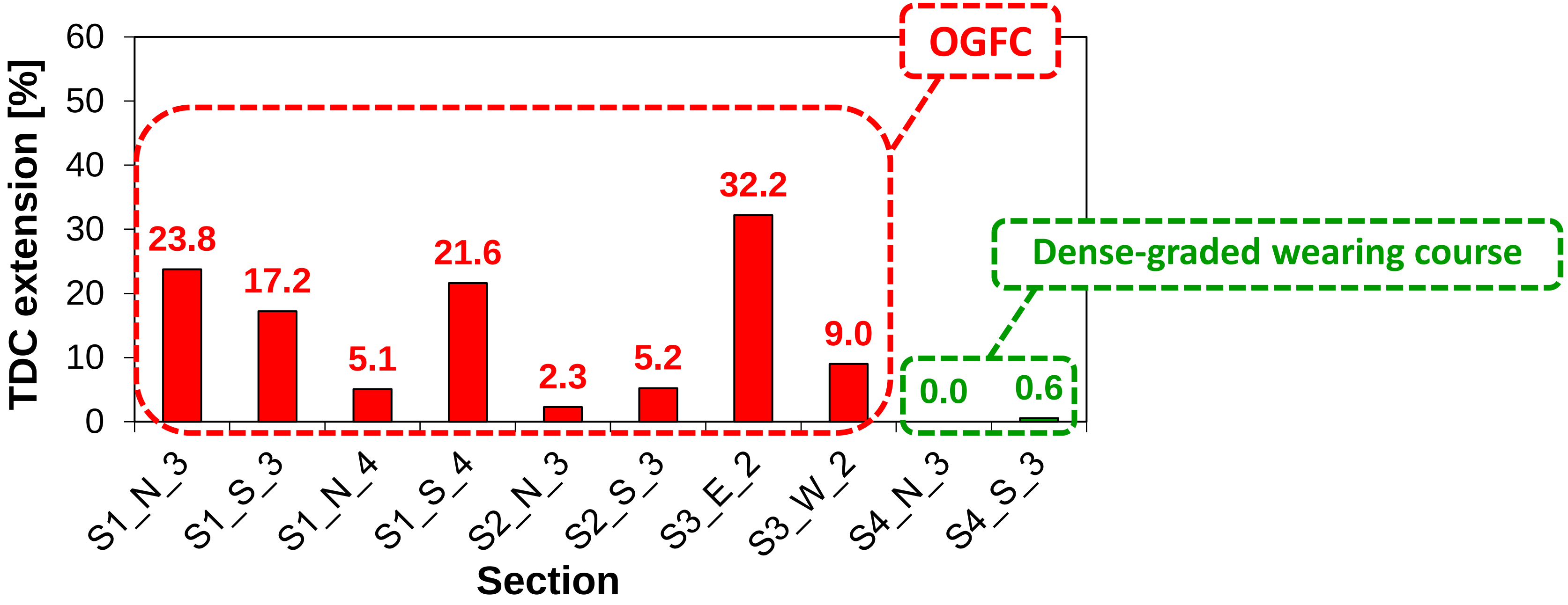
Total TDC

$$TDC\ (\%) = \frac{l_{TDC}}{l_0} \cdot 100$$

- $TDC\ (\%)$: total TDC percentage (either right or left wheelpath)
- l_{TDC} : TDC cumulated length (either right or left wheelpath)
- l_0 : length of the analysed section

TDC calculation

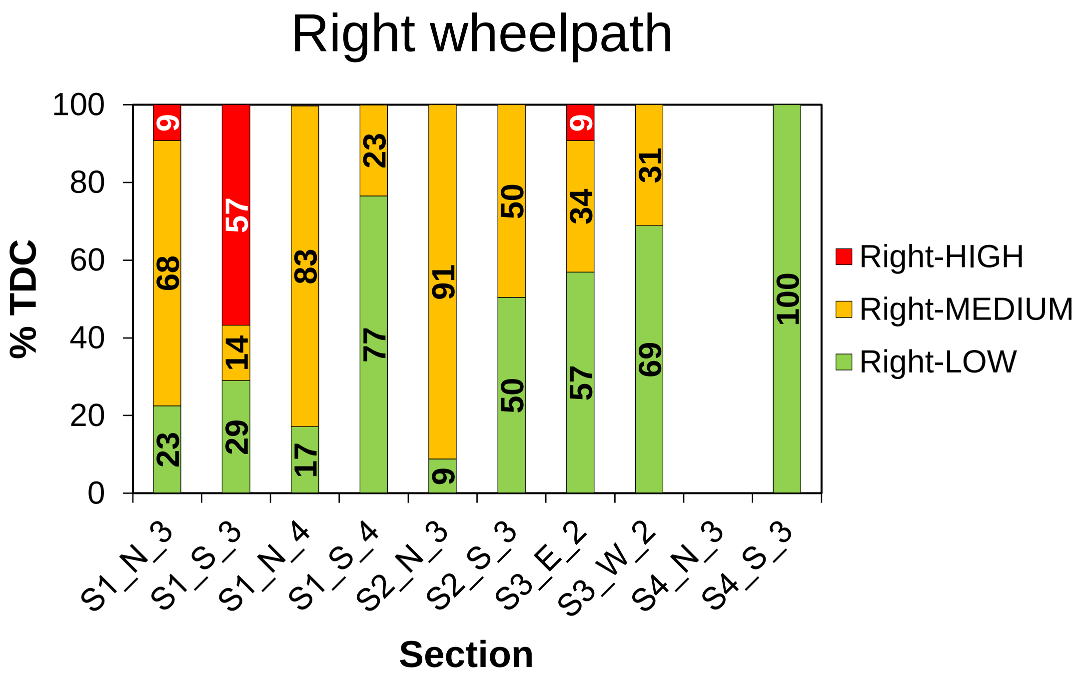
Total TDC

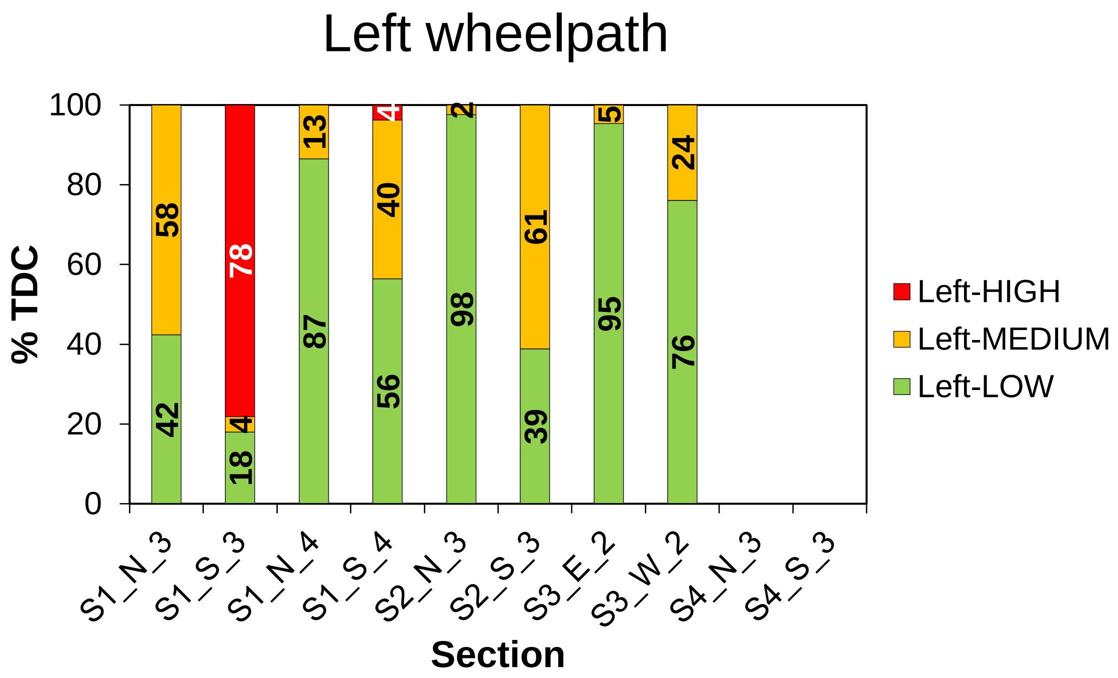


- **Up to 30% TDC with PA** (S1-S3)
- no TDC with dense-graded wearing course (S4)
- In general, **higher TDC for higher traffic level** (S1)

TDC calculation

TDC severity

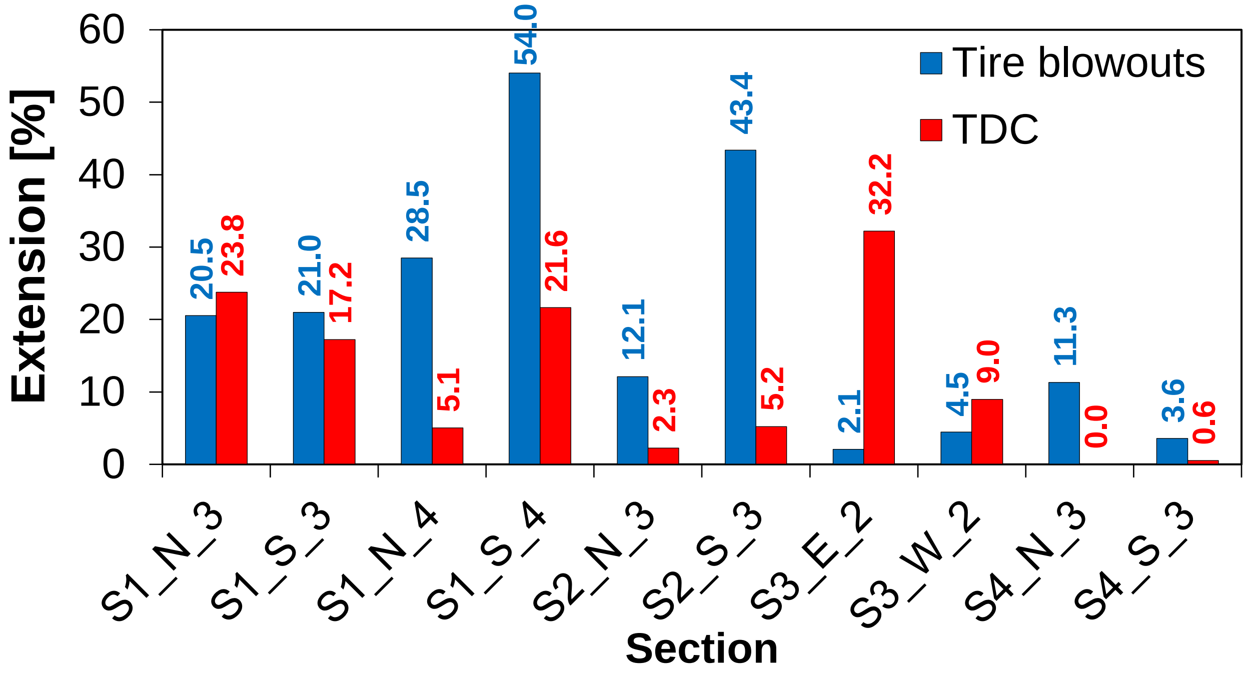




- In most cases, TDC severity is low or medium (frequent maintenance)
- High severity only for section S1 (high traffic level)

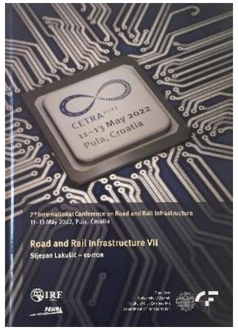
TDC calculation

TDC Vs Tire blowout



- The extension of tire blowouts is even higher than TDC!

Automatic detection of TDC

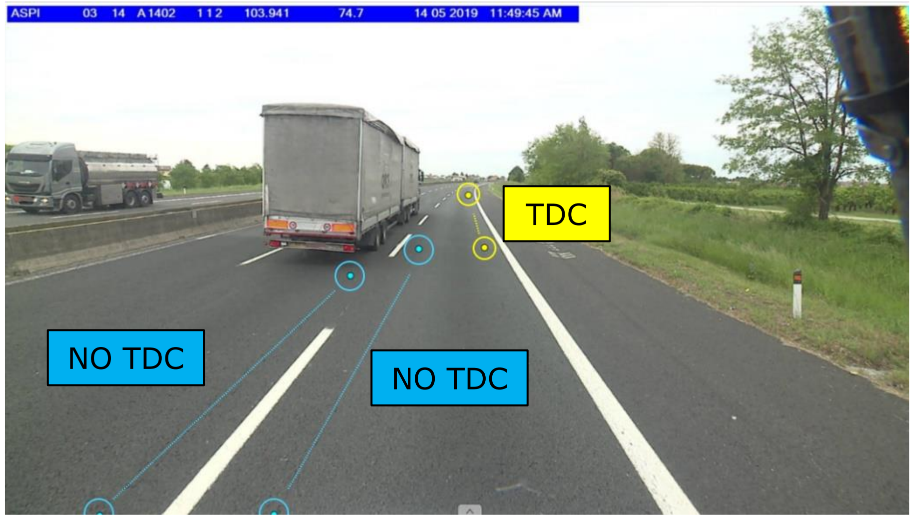


Chiola, D., Ingrassia, L.P., Salini, S., Canestrari, F. (2022),
Development of an automatic method for the recognition of top-down cracking on asphalt pavements
7th International Conference on Road and Rail Infrastructure (CETRA 2022), Pula, Croatia

Machine Learning (ML) algorithm

- **ML methods** often used for the **automatic detection of pavement distresses** (not specifically for TDC)
- High number of ARAN images available (1.2 million every 6 months)
- Procedure developed with Movyon (Hi-tech company):

1. Collection and pre-processing of the image
   - 900 images with longitudinal cracks
   - 900 images with intact pavement (no cracks)

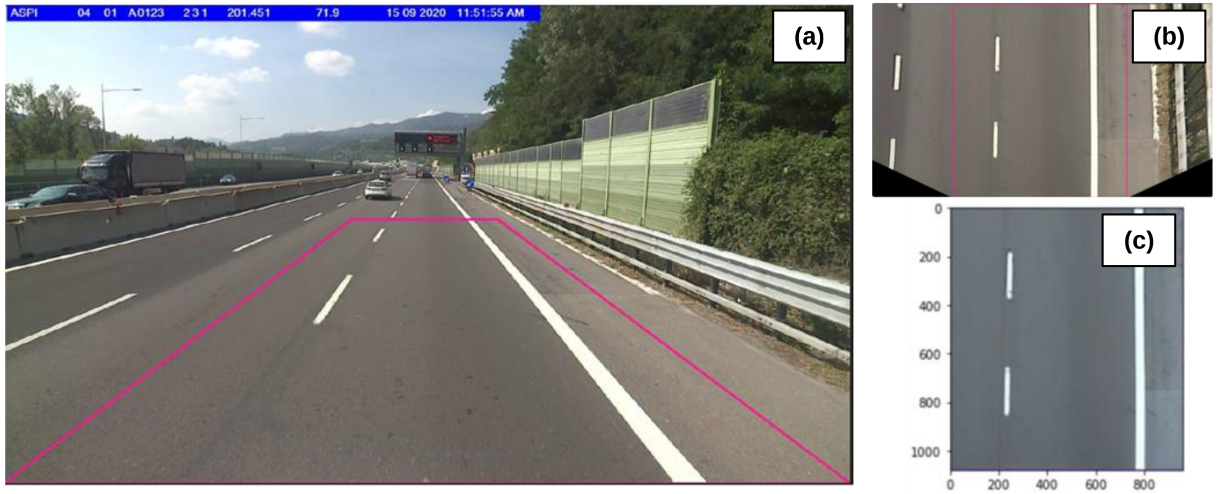


Labeled image

Machine Learning (ML) algorithm

- ML methods often used for the automatic detection of pavement distresses (not specifically for TDC)
- High number of ARAN images available (1.2 million every 6 months)
- Procedure developed with Movyon (Hi-tech company):

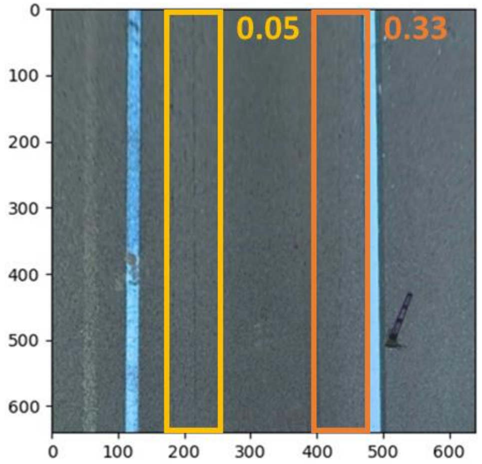
1. Collection and pre-processing of the image
    - From perspective view (a) to orthogonal projection (b) of the pavement surface
    - Final image (c) (dimensions in pixels)



Machine Learning (ML) algorithm

- ML methods often used for the automatic detection of pavement distresses (not specifically for TDC)
- High number of ARAN images available (1.2 million every 6 months)
- Procedure developed with Movyon (Hi-tech company):

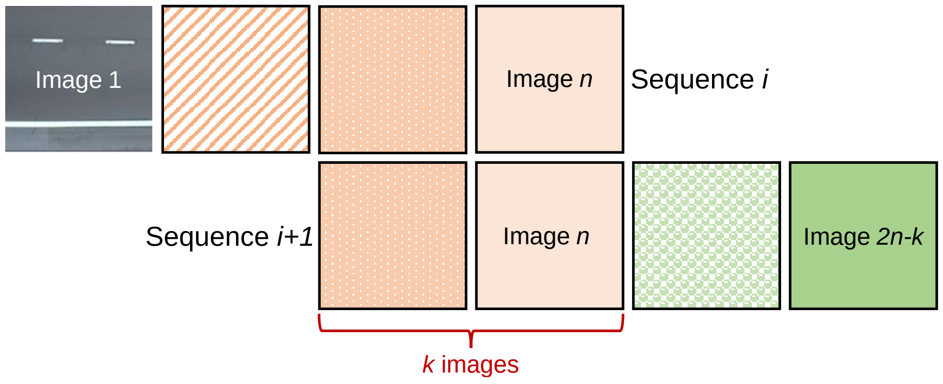
1. Collection and pre-processing of the images
2. Image analysis criteria – Single image
    - TDC **prediction confidence** from **0 (low)** to **1 (high)**
    - **Discard** the cracks within a certain distance from the horizontal markings delimiting the lane
    - **Merge** the longitudinal cracks with transverse distance less than a threshold value



Predicted TDC with related confidence

Machine Learning (ML) algorithm

- ML methods often used for the automatic detection of pavement distresses (not specifically for TDC)
- High number of ARAN images available (1.2 million every 6 months)
- Procedure developed with Movyon (Hi-tech company):
  1. Collection and pre-processing of the images
  2. Image analysis criteria – Single image
  3. Image analysis criteria –Sequence of images
     - **Sequences** of "n" images (algorithm free parameter, e.g. 10), with an **overlap** of "k" images
     - **Merge** the longitudinal cracks present in different images of the sequence with transverse distance less than a threshold value



Performance of the algorithm

- Different metrics:

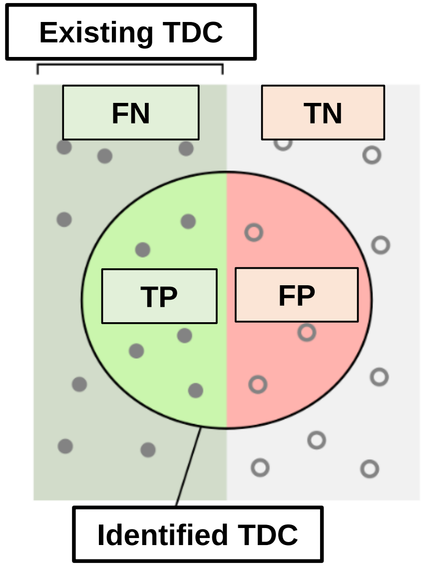
TP = number of True Positives FP = number of False Positives FN = number of False Negatives

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}$$

→ Measure of correctly identified TDC over the total **identified** TDC

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

→ Measure of correctly identified TDC over the total **existing** TDC



Maximization of Recall was preferred over Precision
(better to warn for a crack that is not TDC rather than skip a crack that is actually TDC)

Boolean_kpi → **= 1** if TDC is (is not) present and is (is not) detected
= 0 otherwise

Useful especially for **intact pavements** (TP=0)

Performance of the algorithm

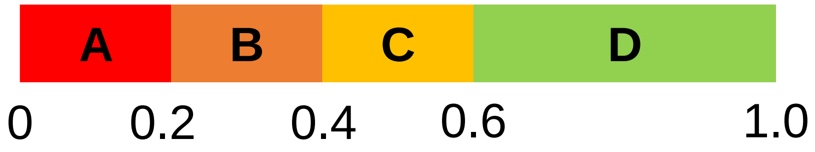
Cracked pavement				Intact pavement	
Stretch	Precision	Recall	Boolean_kpi	Stretch	Boolean_kpi
1	1	1	1	10	1
2	0.46	0.97	1	11	0.25
3	1	0.98	1	12	1
4	0.50	1	1	13	1
5	0.94	1	1	14	1
6	0.71	1	1	15	1
7	0.38	0.13	0.75	16	1
8	1	1	1	17	0.72
9	1	1	1	18	1
				19	1
				20	1
Average	**0.78**	**0.90**	**0.97**	**Average**	**0.91**

NOTE: values obtained considering all image sequences within the single stretch

- The algorithm overestimates the presence of TDC (Precision lower than Recall)
- Acceptable performance at the stretch level (global scale)

Validation through field cores

- 100 km trial section along the Italian motorway network
- Analysis with ML algorithm + sample check through a coring campaign
- Confidence classes:



Validation through field cores

Core	Confidence class	Distress
1	C	TDC
2	B	TDC
3	B	TDC
4	B	TDC
5	A	Tire blowout crack
6	A	Tire blowout crack
7	D	Reflective crack
8	C	Tire blowout crack
9	B	Reflective crack
10	B	Tire blowout crack
11	[illegible]	Tire blowout crack
12	[illegible]	Tire blowout crack
13	B	Tire blowout crack
14	C	Tire blowout crack

- Lowest confidence class (A) never associated to TDC, associated to other longitudinal cracks in 4 cases out of 10 (promising results)
- In general, no strong correlation between crack type and confidence class

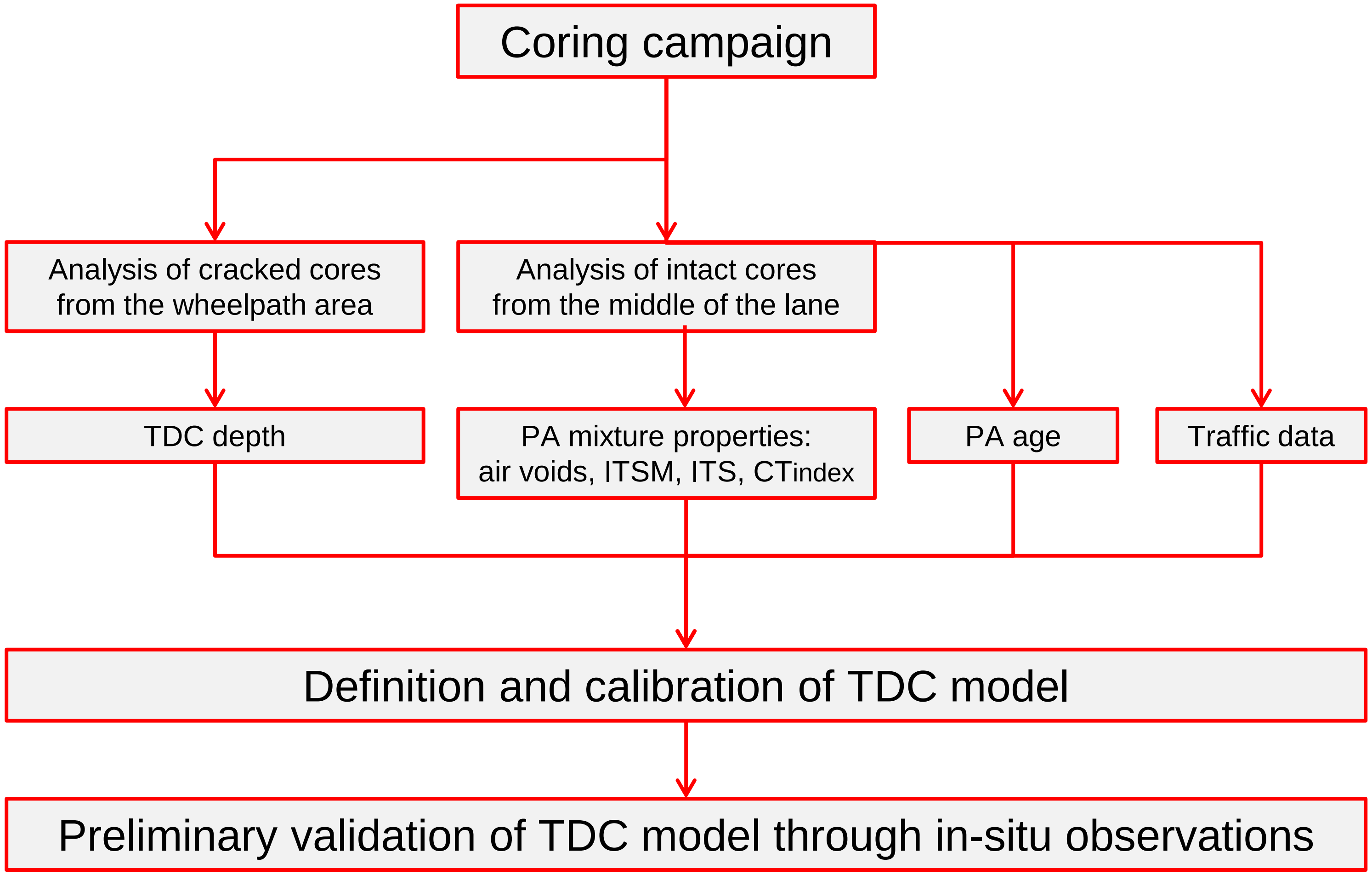
1. The algorithm is **not fully able to distinguish different types of longitudinal cracks**
2. The algorithm **works better at global scale rather than local scale**

Work in progress

4. TDC prediction model

Canestrari, F., Ingrassia, L.P., Virgili, A. (2022)
A semi-empirical model for top-down cracking depth evolution in thick asphalt pavements with open-graded friction courses
Journal of Traffic and Transportation Engineering (English Edition), 9(2), 244-260

Activities overview

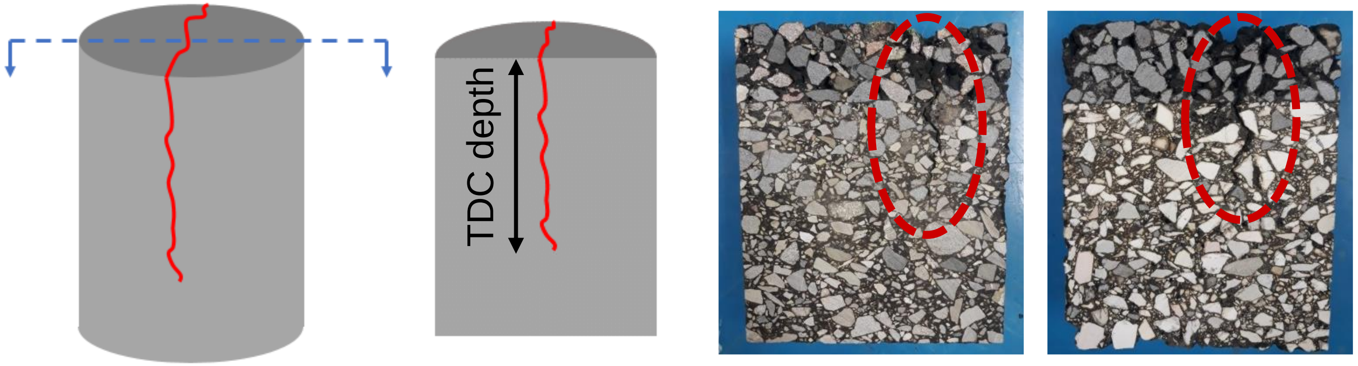


Coring campaign

- Slow lane, right wheelpath (carriageway narrowing)
- For each sampling point:

2 full-depth cores along the crack (10–20 m apart) + **1 PA intact core** (middle of the lane)

- Analysis of TDC cracked cores



Sampling point	Average TDC depth (mm)
1	80.0
2	100.0
3	11.0
4	0.0
5	0.0
6	35.0
7	78.5
8	120.0
9	140.0
10	112.5
11	122.5
12	190.0
13	66.5

Coring campaign

- Slow lane, right wheelpath (carriageway narrowing)
- For each sampling point:

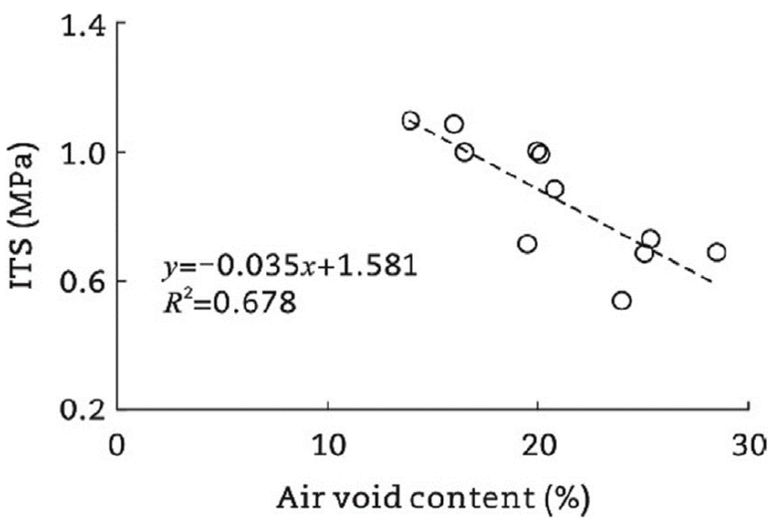
2 full-depth cores along the crack (10–20 m apart) + **1 PA intact core** (middle of the lane)

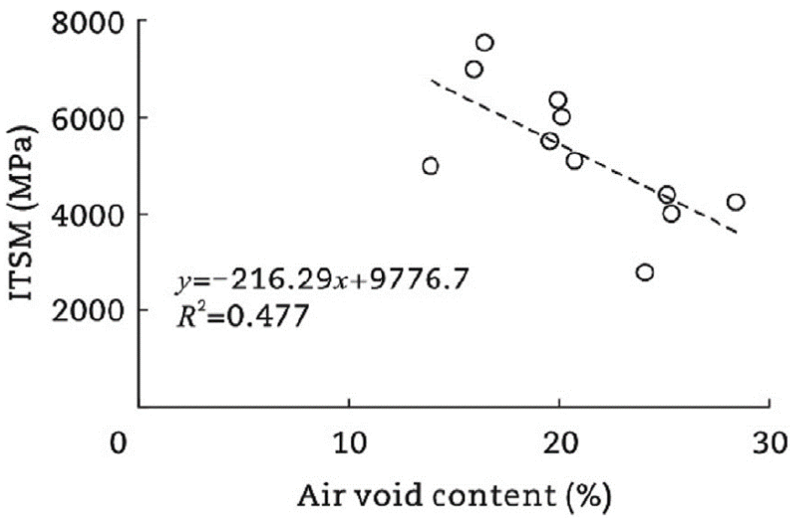
- Analysis of TDC cracked cores
- Properties of the PA mixture

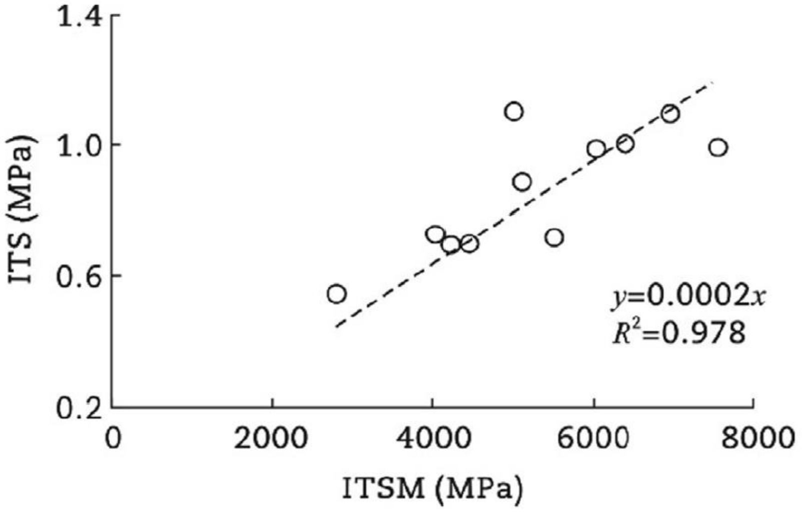
- Volumetric analysis (%Vv)
- ITSM @20°C (EN 12697-26)
- ITS @25°C (EN 12697-23)
- CTindex (from the ITS curve):

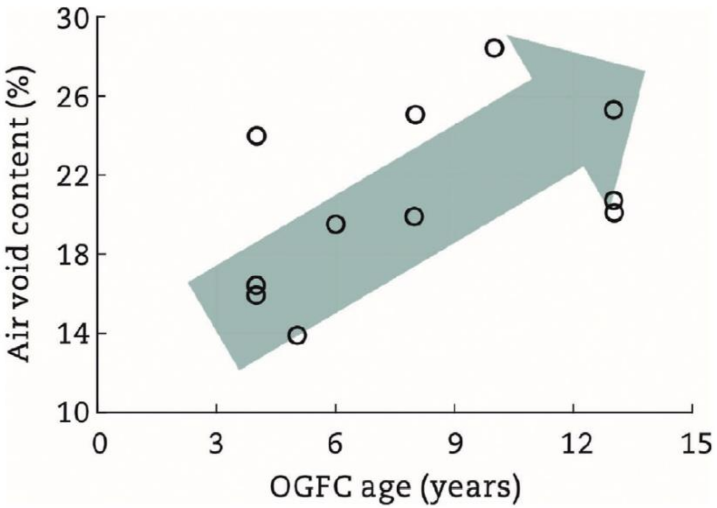
$$CT_{index} = \frac{H}{62} \cdot \frac{G_f}{|m_{75}|} \cdot \frac{l_{75}}{D}$$

Properties of the PA mixtures









- Air voids: from a minimum of 14% to a maximum of 28%
- ITS and ITSM decrease as the air voids increase (as expected)
- Reliable correlation between volumetric and mechanical properties
- Good correlation between ITS and ITSM

Hypotheses of the TDC model

- **Sigmoidal function** (sub-horizontal crack propagation at long term)
- **TDC_{max} = 150 mm** (field observations + binder-base interface)
- **Traffic loadings** expressed in terms of 12-ton fatigue ESALs
- **Properties of the PA mixture** expressed in terms of ITS (routine test + correlated with volumetrics and stiffness)
- **Effect of aging** → age of PA mixture

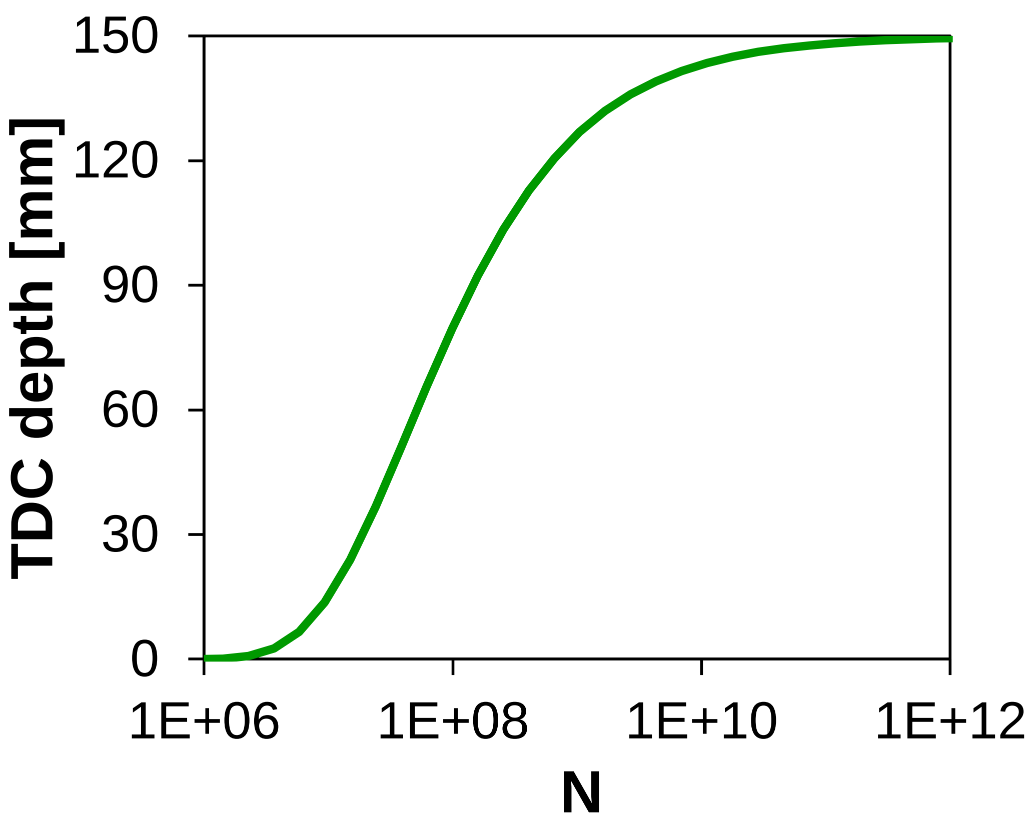
Definition of the TDC model

$$TDC = TDC_{max} e^{-\left(\frac{A}{N}\right)^{B}}$$

- *TDC*: predicted depth (mm)
- *TDCmax* = 150 mm
- *N*: cumulative 12-ton fatigue ESALs

$$A = [\alpha_1 - \alpha_2 \cdot (PA\ age)] \cdot 10^8$$
$$B = \beta_1 - \beta_2 \cdot ITS$$

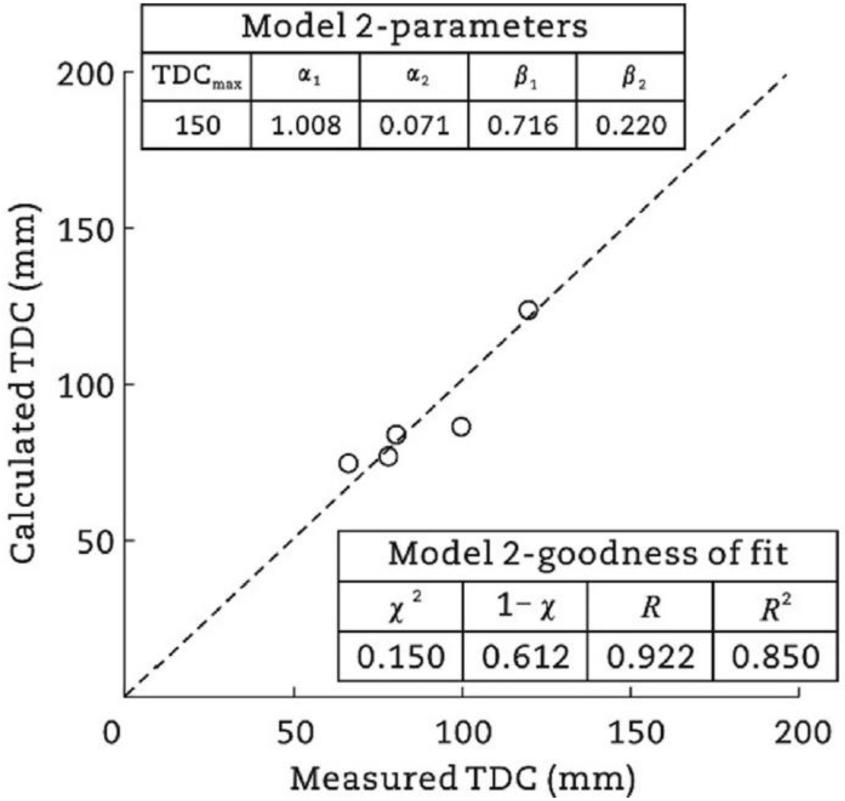
- *A*: **translation factor**
- *B*: **shape factor**
- *α1, α2, β1, β2*: model parameters

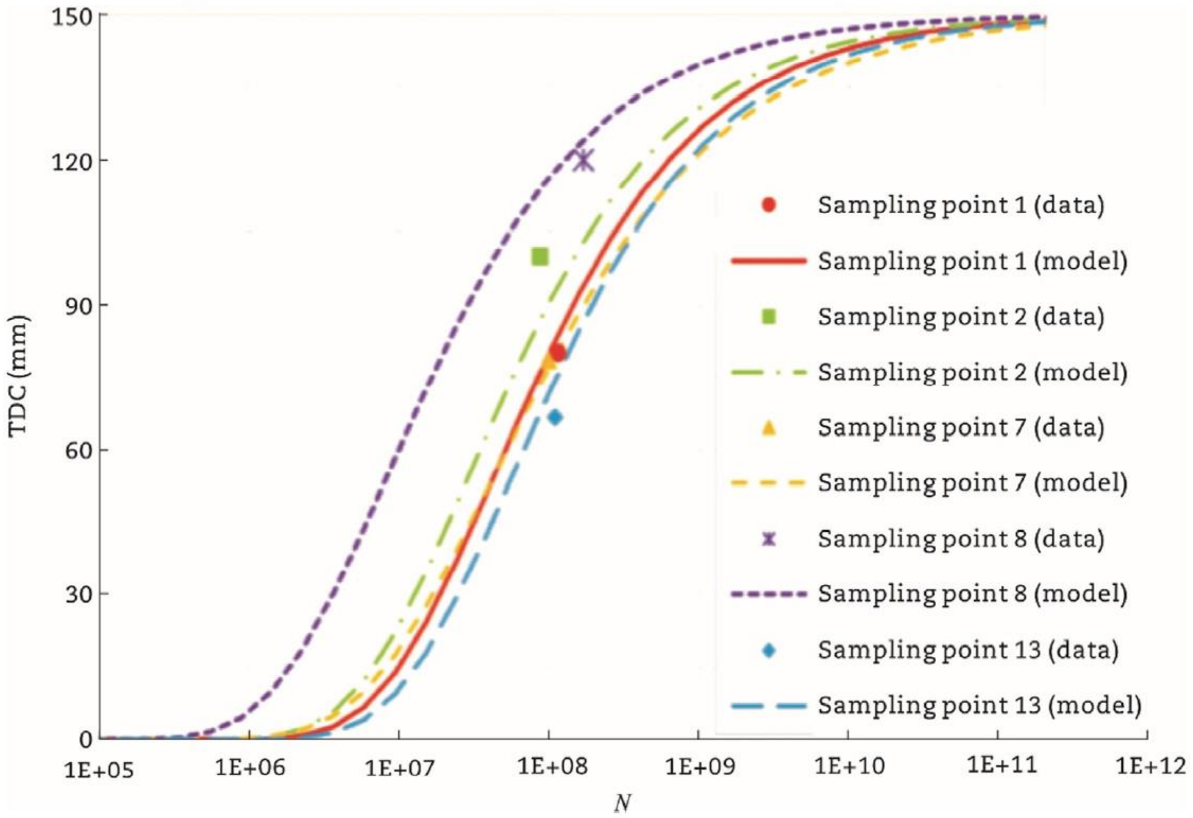


Calibration of the TDC model

$$A = [\mathbf{1.008} - \mathbf{0.071} \cdot (PA\ age)] \cdot 10^{8}$$

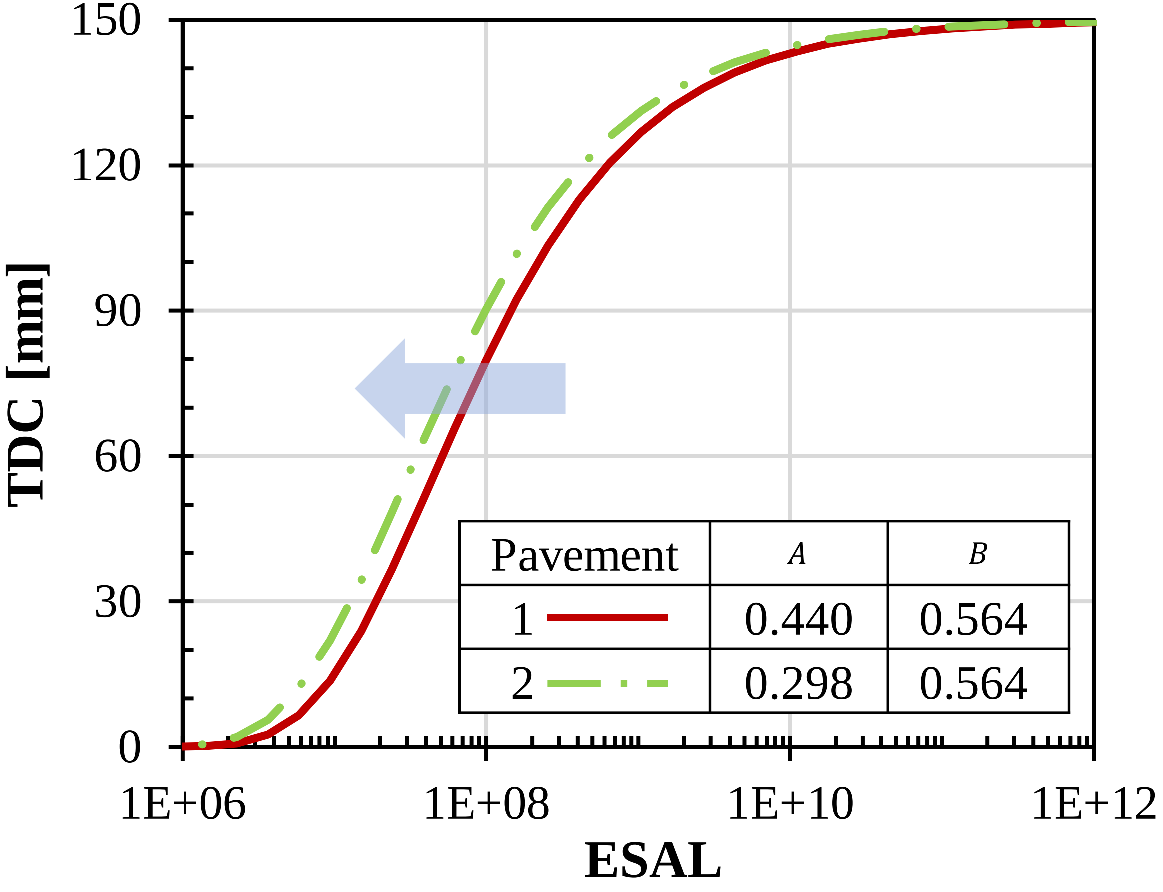
$$B = \mathbf{0.716} - \mathbf{0.220} \cdot ITS$$





Analysis of the TDC model

$$A = a \cdot 10^8 = [1.008 - 0.071 \cdot (PA\ age)] \cdot 10^8$$

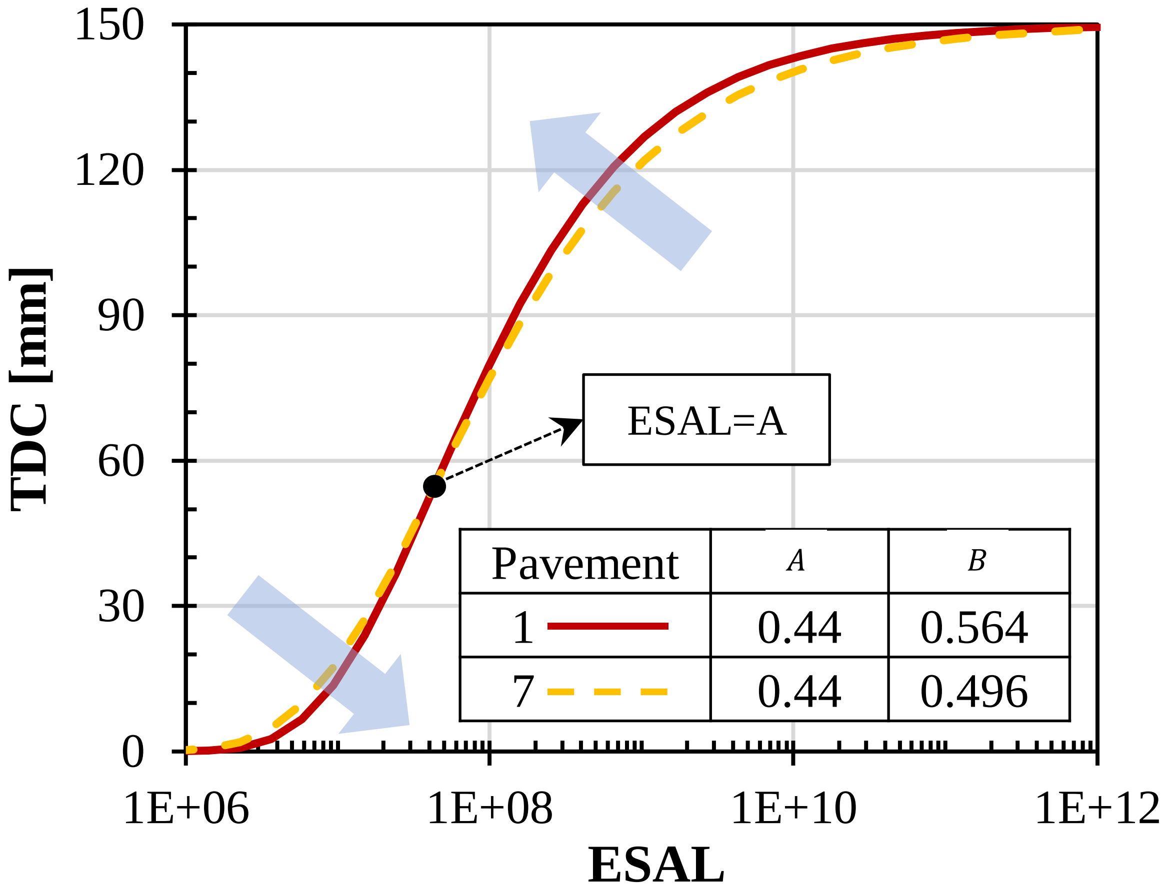


Pavement	*A*	*B*
1	0.440	0.564
2	0.298	0.564

- PA age increases → *A* decreases → translation to the left → **earlier crack initiation and propagation** (effect of aging)
- **Not applicable for PA age ≥ 14 years** → *A* = 0 → *TDC* = *TDCmax*

Analysis of the TDC model

$$B = 0.716 - 0.220 \cdot ITS$$



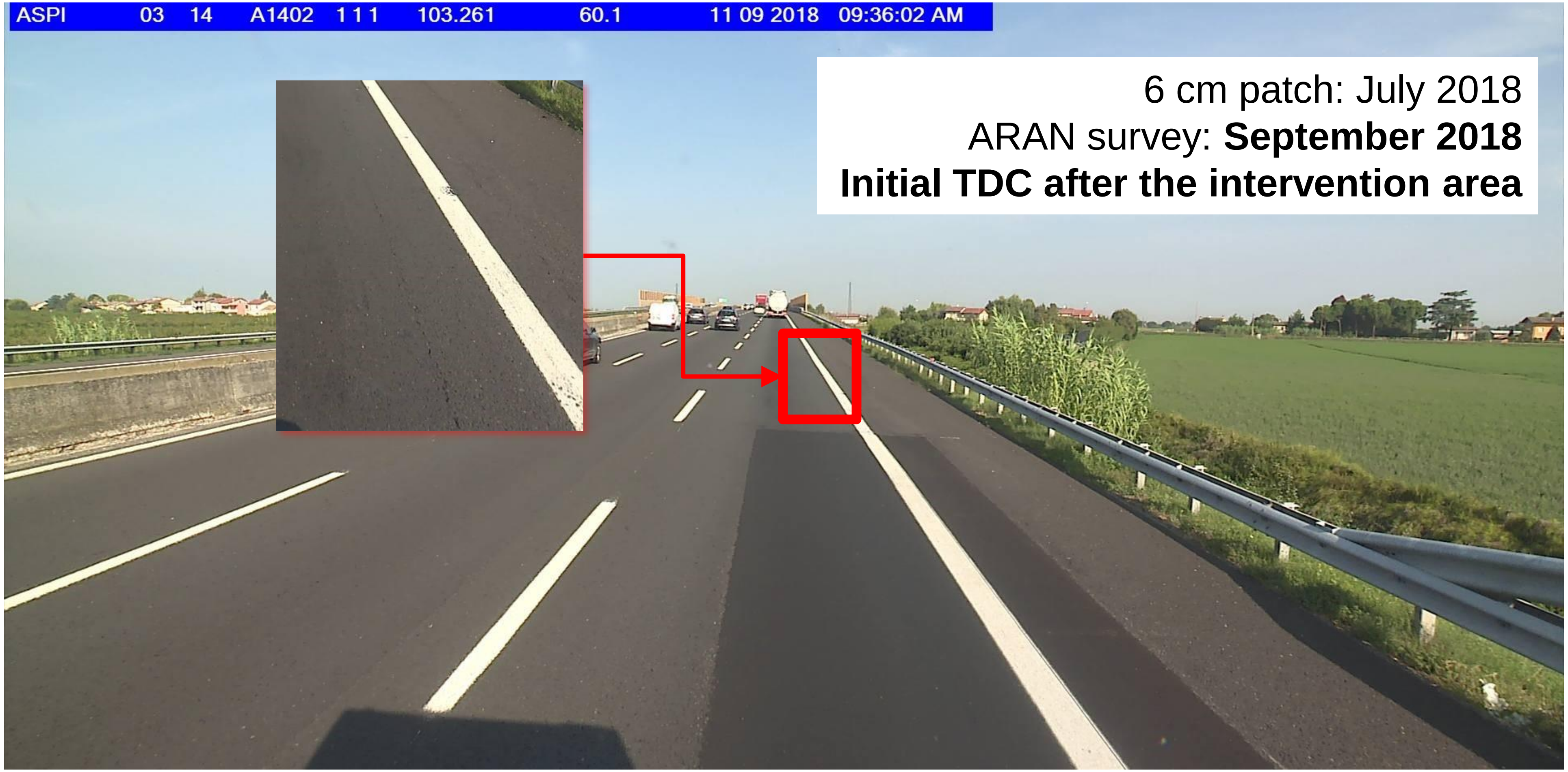
Pavement	*A*	*B*
1 (solid line)	0.44	0.564
7 (dashed line)	0.44	0.496

- ITS decreases → *B* increases → **anti-clockwise rotation → delayed crack initiation, faster crack propagation** (softer materials are less brittle)

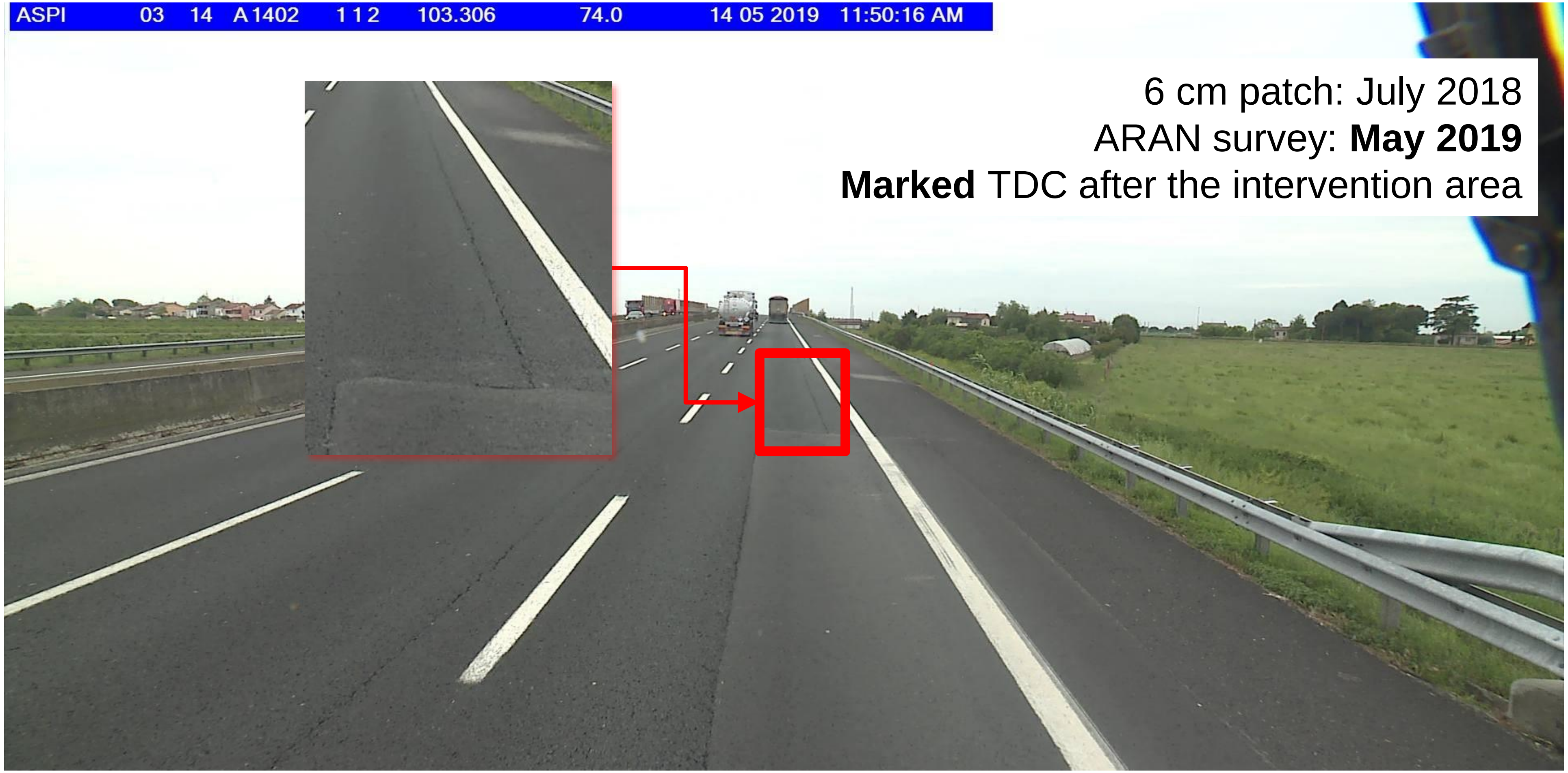
Preliminary validation of the TDC model

Preliminary validation of the TDC model

Preliminary validation of the TDC model

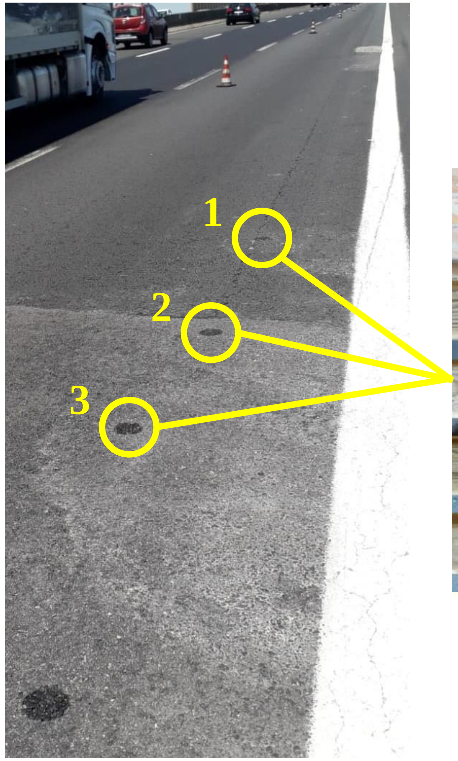


Preliminary validation of the TDC model

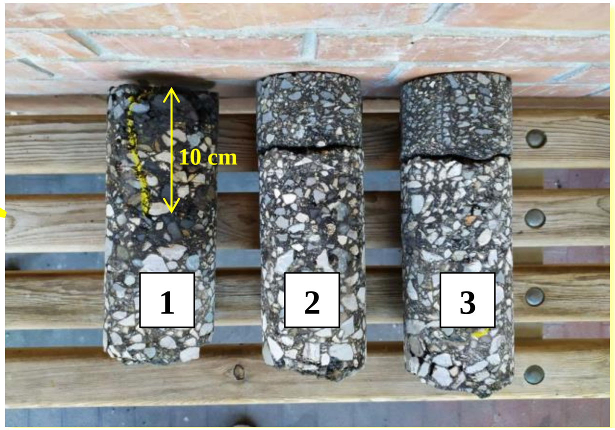


6 cm patch: July 2018
ARAN survey: **May 2019**
Marked TDC after the intervention area

Preliminary validation of the TDC model



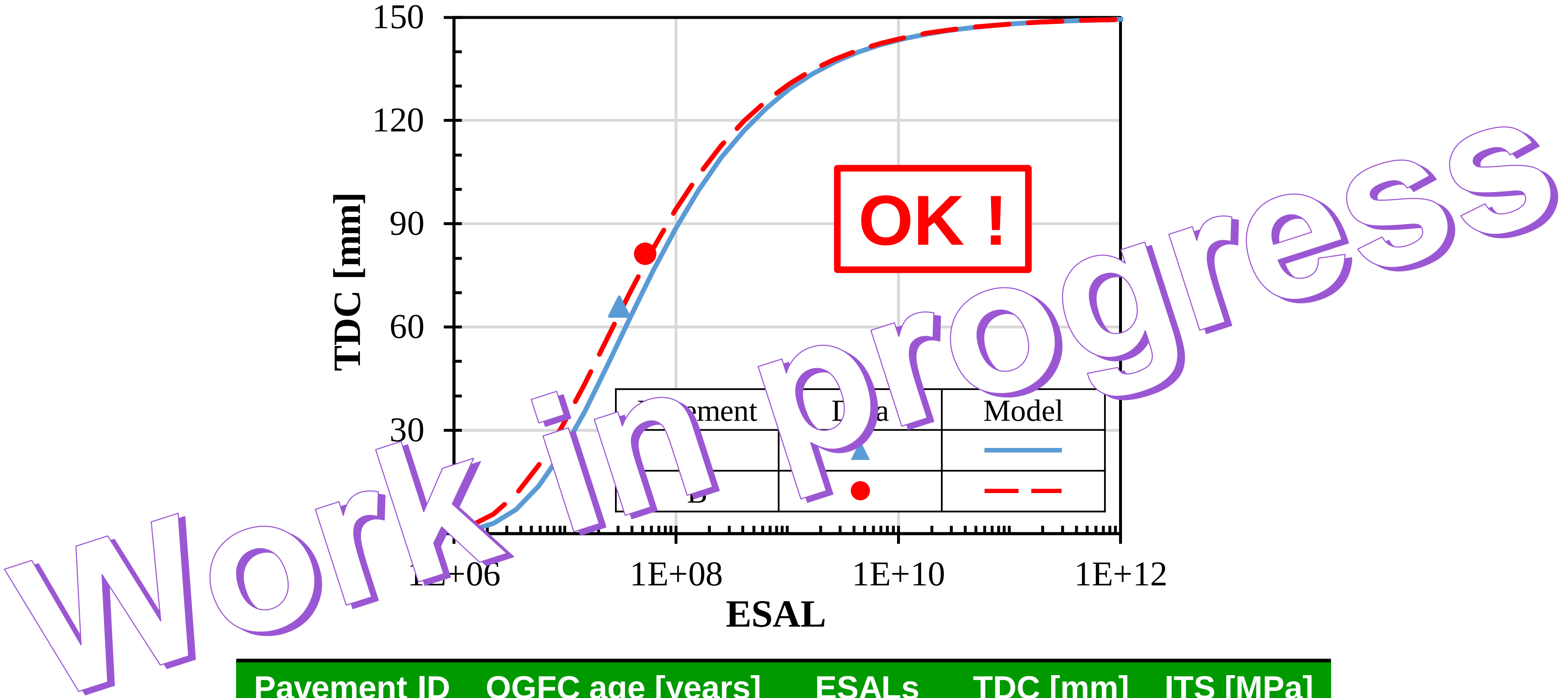
May 2020



July 2018: TDC ≤ 6 cm
May 2020: TDC = 10 cm

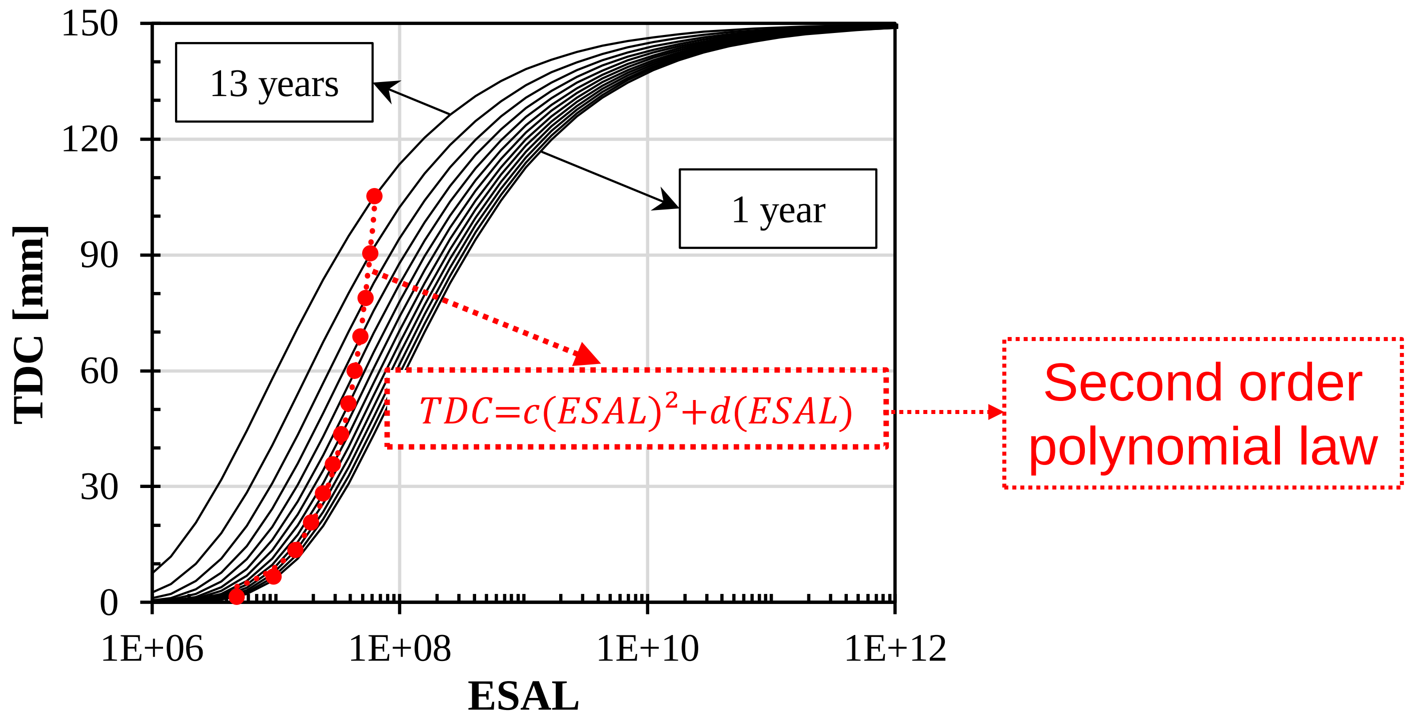
Strong acceleration of TDC in less than 2 years ⟷ Sigmoidal model

Further validation of the TDC model



Pavement ID	OGFC age [years]	ESALs	TDC [mm]	ITS [MPa]
A	10	3.10E+07	66	0.83
B	11	5.32E+07	81	0.90

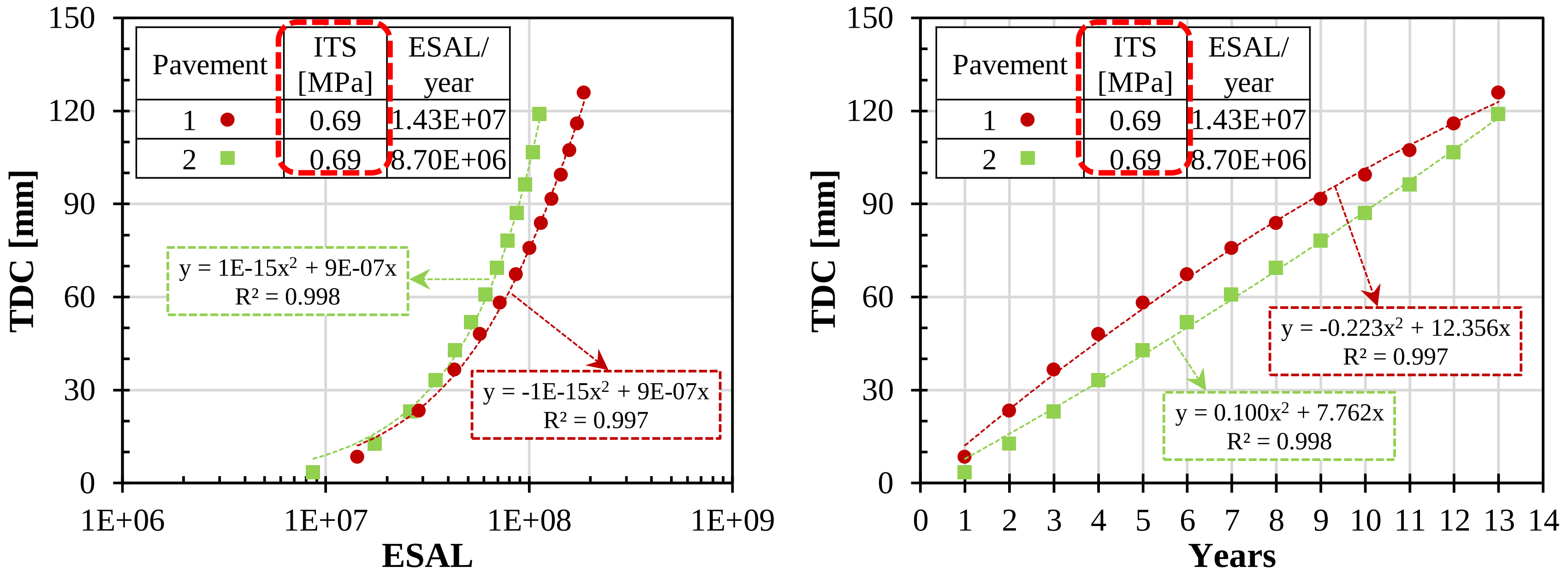
TDC evolution according to the model



- The correlation TDC-ESALs can be easily converted into a correlation TDC-YEARs
- It depends only on the **traffic level** and the **ITS** of the OGFC
- The correlation TDC-YEARS can be used in a PMS to compare different pavements and define the maintenance priorities of the network

TDC evolution according to the model

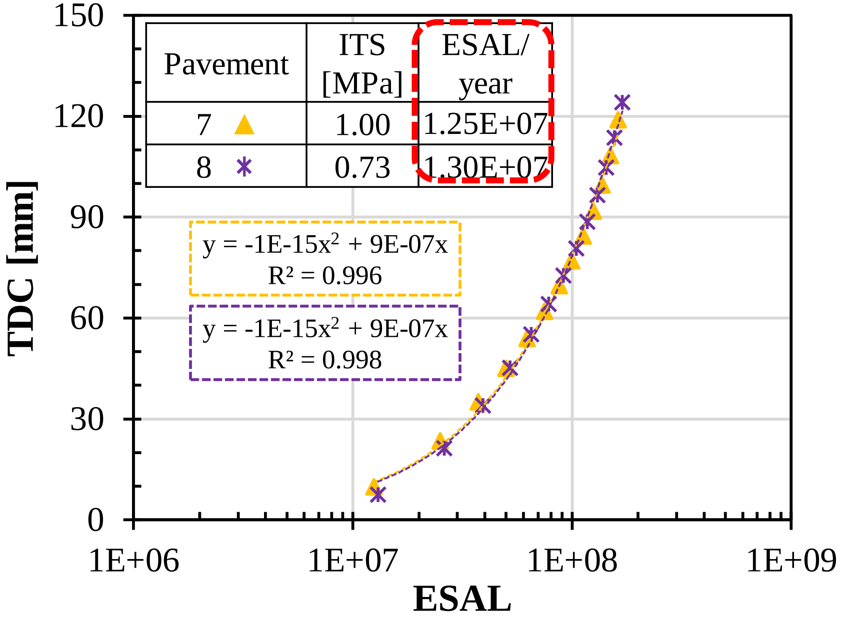
Effect of the traffic level

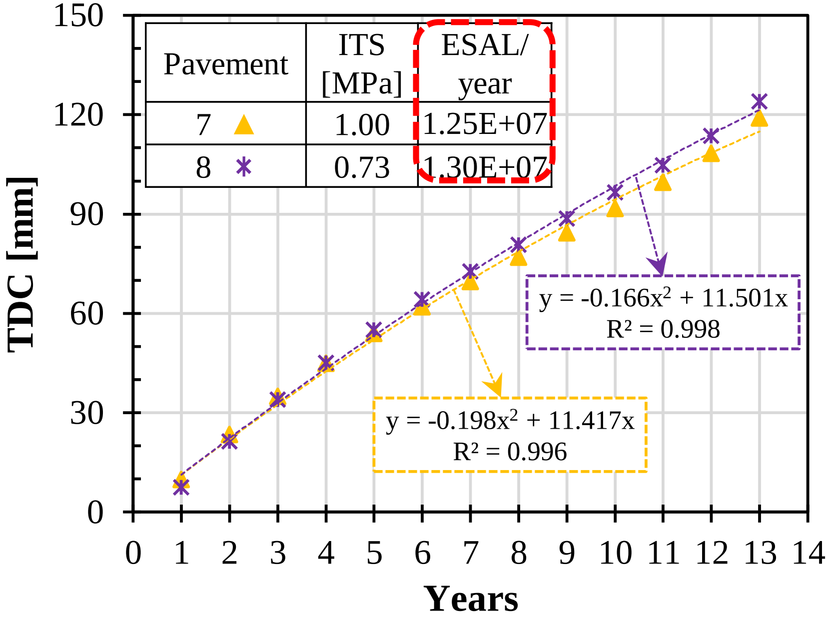


- Same ITS, the traffic level of Pavement 1 is almost the double
- TDC depth evolution as a function of ESALs is faster for the pavement with lower traffic (more prounanced aging effect)
- TDC depth over years is always greater for the pavement with the higher traffic level

TDC evolution according to the model

Effect of ITS





- Similar traffic level, different ITS values
- Comparable TDC depth → **the effect of traffic level is stronger**

Future work

- **Short term**: identification of pavements more likely affected by TDC and collection of additional data
- **Long term**: use in a PMS to plan timely surface TDC repair → minimization of pavement damage and maintenance costs

3rd SIIV International Winter School 2022

Pavement Assessment and management towards Smart and Safer mobility

December 18th-21st, 2022 – Moena, ITALY

Winter School 2022
Moena

Presentation and Preliminary Program

Following the success of the previous editions, SIIV and Università Politecnica delle Marche jointly organize the 3rd International Winter School, which will be held in Moena, Italy, on December 18th-21st, 2022.

The topic "*Pavement Assessment and management towards Smart and Safer mobility PASS*" of the Winter School focuses on the needs to promote a virtuous transition towards more sustainable and smart pavement networks.

The widening gap between the existing traditional infrastructure and the complex mobility systems d[illegible] rise of Cooperative, Connected and Au[illegible]ate[illegible] Mobi[illegible] (CCAM), and the emerg[illegible]ce of [illegible] pa[illegible]digm needs to be addressed. [illegible] co[illegible] behavior of innovative ma[illegible] ne[illegible] to be in[illegible]ated through reliable [illegible] by considering solid [illegible]re[illegible] [illegible]kground. At the same time, advanced pa[illegible] a[illegible]et management tools, including smart solu[illegible]ns ([illegible] non-destructive testing, image processing, [illegible]ensoring, artificial intelligence, digital twin technology), are necessary to ensure a safe and high-quality travel experience.

To this purpose, leading experts in the field have been invited as lecturers to promote and share up-to-date knowledge with the aim of fostering the sustainability and the digital modernization of the pavement network.

	Sunday December 18th
14.30-15.00	*Registration*
15.00-15.30	*Welcome* - Francesco Canestrari & Gaetano Bosurgi (SIIV President)
15.30-16.00	*Coffee Break*
16.00-18.30	*Round Table: Sustainable or Smart (SOS) pavements?*
	National Center Sustainable Mobility - Bifulco/Ottomanelli
	ANAS - Danish Road Director[illegible] MnDOT - MO[illegible]ON[illegible]
18.30-19.30	*Icebreaker Cocktail*
20.00-21.00	*Dinner*
	Monday December 19th
[illegible]5.00-16.0[illegible]	*[illegible]ecture* [illegible] Miha[illegible] [illegible]raste[illegible] Uni[illegible]ty of Minnesota
	& [illegible]b Ze[illegible] Mi[illegible]ota Department of Transportation
1[illegible]-17.0[illegible]	*[illegible]nd [illegible]re* [illegible]ard Y. Kim, North Carolina State University
1[illegible]-17.3[illegible]	*Coffee Break*
1[illegible]-18.3[illegible]	*[illegible]d [illegible]ture* - Andrea Graziani, Università Politecnica delle Marche
18.3[illegible]0	*4th Lecture* - Gordon Airey, University of Nottingham
[illegible]0-21.00	*Dinner*
	Tuesday December 20th
15.00-16.00	*5th Lecture* - Piotr Jaskula, Gdansk University of Technology
16.00-17.00	*6th Lecture - Andrea Benedetto, Università di Roma Tre*
17.00-17.30	*Coffee Break*
17.30-18.30	*7th Lecture -Arianna Stimilli, ANAS*
18.30-19.30	*8th Lecture* - Matteo Pettinari, Danish Road Directorate
20.00-21.00	*Dinner*
	Wednesday December 21st
15.00-16.00	*9th Lecture* - Nicolas Hautière, Université Gustave Eiffel
16.00-17.00	*10th Lecture* - Berardo Naticchia, Università Politecnica delle Marche
17.00-17.30	*Coffee Break*
17.30-18.30	*11th Lecture* - Expert CCAM
18.30-19.00	*Closing Session*
20.00-21.00	Dinner

Organized by Università Politecnica delle Marche (UNIVPM)
under the auspices of the Società Italiana Infrastrutture Viarie (SIIV)
Chairman: **Prof. Francesco Canestrari**

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Winter School 2022 SIIV Moena

The venue of the 3rd SIIV International Winter School is the *Hotel Arnika Wellness* on the San Pellegrino Pass (the town of Moena is 10 km away), a truly unique area, rich in traditions and history, culinary art and culture with a wonderful sight in the heart of the Dolomites, a Unesco World Heritage site.
The Hotel Arnika Wellness has a modern congress hall equipped with wireless internet connection, audio and video cameras, and comfortable seating. A new wellness spa as well as large indoor and outdoor spaces and natural surroundings are also available for all guests.

The official language of the SIIV International Winter School is English in order to attract the participation also of foreign PhD students and young researchers.
The number of admittable registrations is limited and for this reason an early expression of interest is recommended.

To this purpose, an email should be sent to the Chairman Francesco Canestrari **by September 30th, 2022** at the following email address: f.canestrari@univpm.it

Registration Fee .... 500 Euro

Which includes:
- 4 nights in double(*) room (in 18th, out 22nd).
- 4 dinners, 4 Coffee Breaks and 4 buffet breakfasts.
- Wellness center (spa, sauna, swimming pool).
- Covered parking for cars.
- SIIV Association fee and Certificate of Attendance.
- Presentations and materials.

(*) Additional charge for single room: 100 Euro