Norsk Asfaltforening

NADim-seminar 2023

Comparison of deflection measurements with RAPTOR / TSD / FWD

Arman Hamidi

Ph.D. Candidate, Norwegian University of Science and Technology (NTNU)

30. November 2023, Oslo

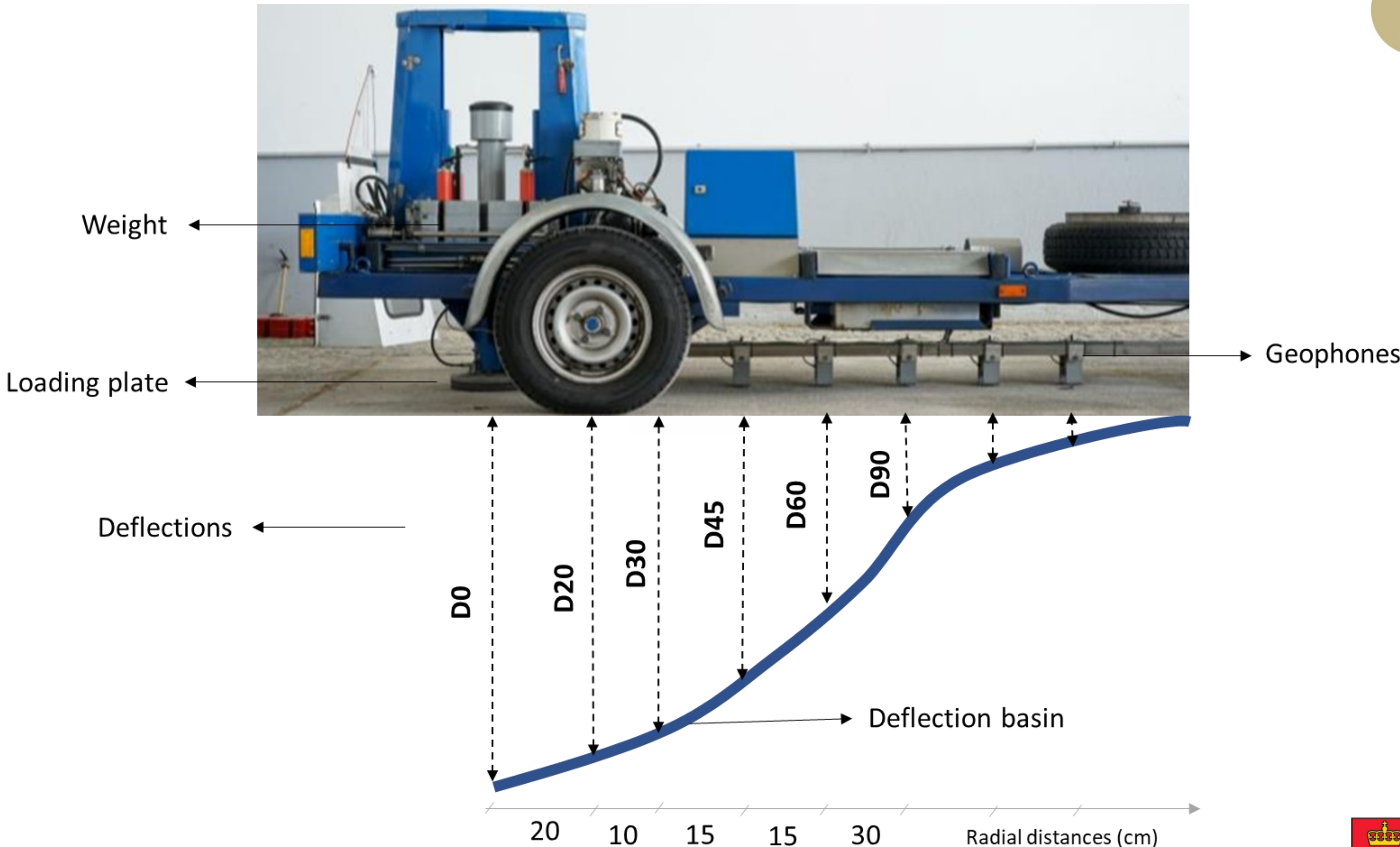
NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Pavement Management System

- Two Important questions:
  - WHEN are treatments needed?
  - WHICH treatments should be used?
- Maintenance timing
- Types of distresses
  - Functional
  - Structural

Falling Weight Deflectometer (FWD)



FWD versus TSDDs

- Disadvantages of using FWD
  - Discrete measurements
  - Lanes must be closed to traffic
  - Stationary dropping weight
  - Not suitable for network-level evaluations
- Traffic Speed Deflection Devices (TSDDs)
  - Two current types include **TSD** and **Raptor**
- Advantages of using TSDDs
  - Continuous measurements
  - Measuring at traffic speed
  - Resemble the service condition of roads
  - Suitable for network-level evaluations

Traffic Speed Deflectometer (TSD)

- Doppler laser sensors
- Measures deflection velocity
- Mathematical procedures are used to obtain deflections

Rapid Pavement Tester (Raptor)

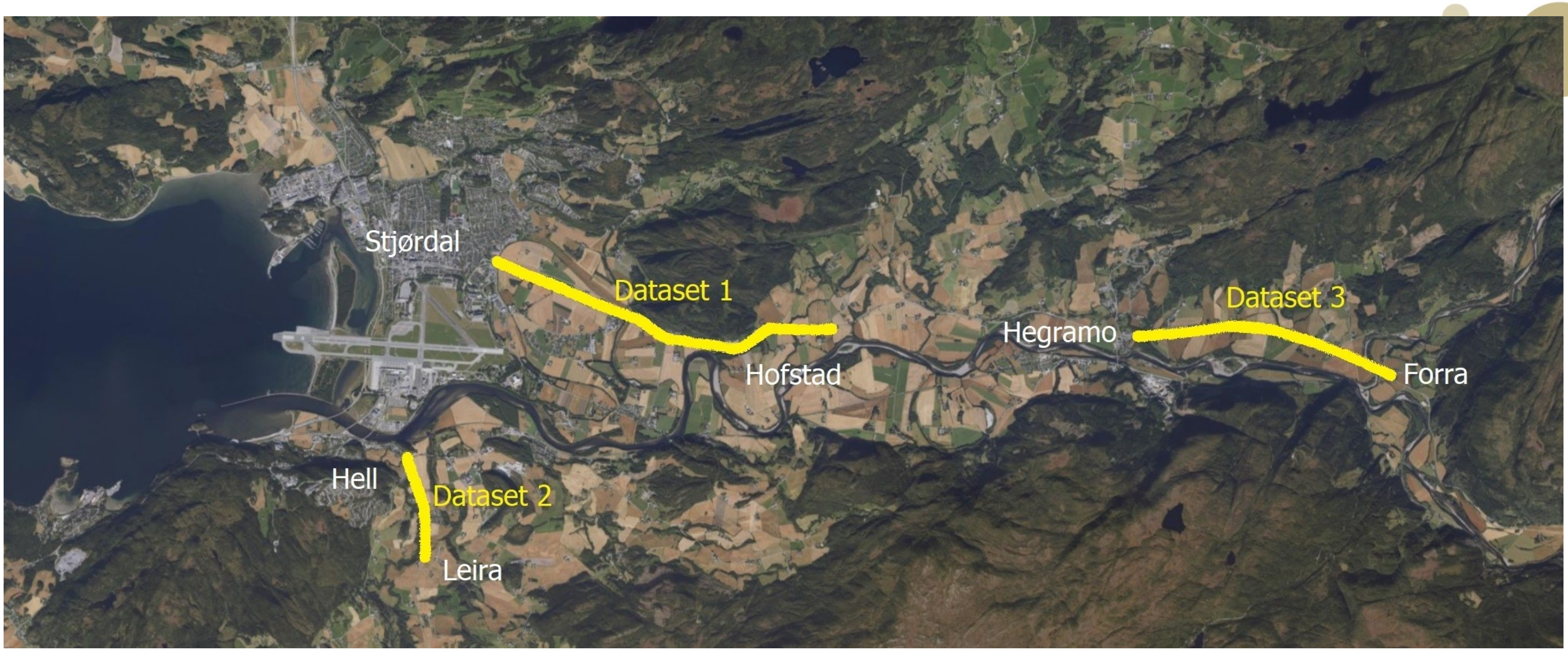
- Line laser sensors
- Image recognition techniques
- Raptor deflection indices (RDIs) are finally converted to equivalent FWD deflections

NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Is there any consistency between FWD and TSDDs?

Location of road sections

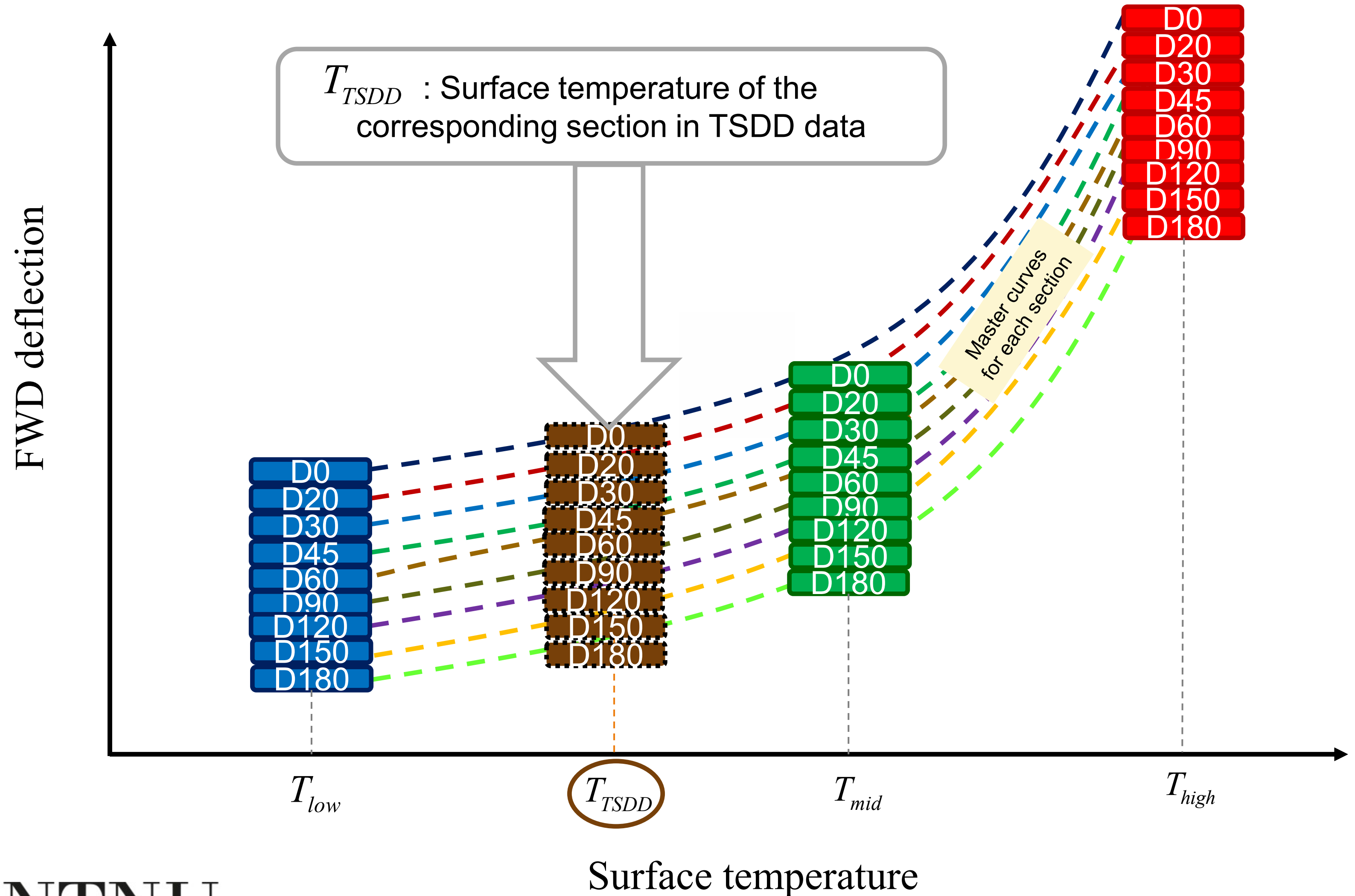


Dataset	Name	Location	Lane	FWD	Raptor	TSD	GPR
1	EV14 S2D1	Stjørdal-Hofstad	Right	✓	✓✓	✓✓	✓
2	FV705 S1D1	Hell-Leira	Right	✓	✓✓	✓	✓
3	EV14 S3D1	Hegramo-Forra	Right	✓	✓✓	✓	✓

NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

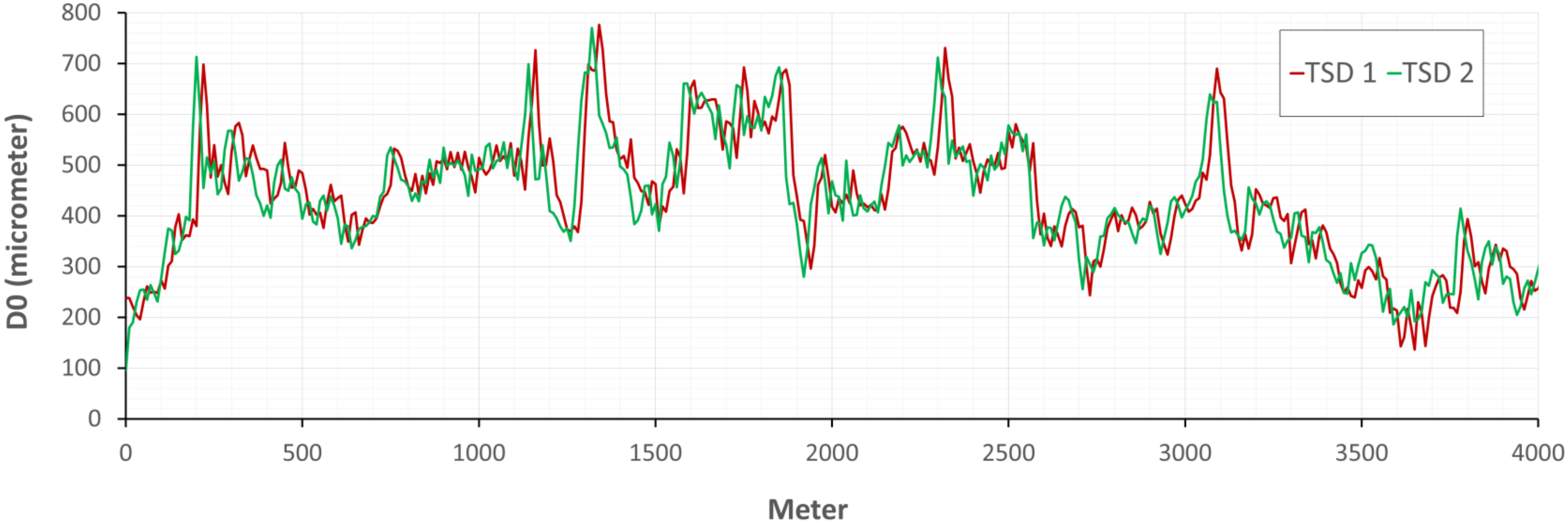
Temperature effect

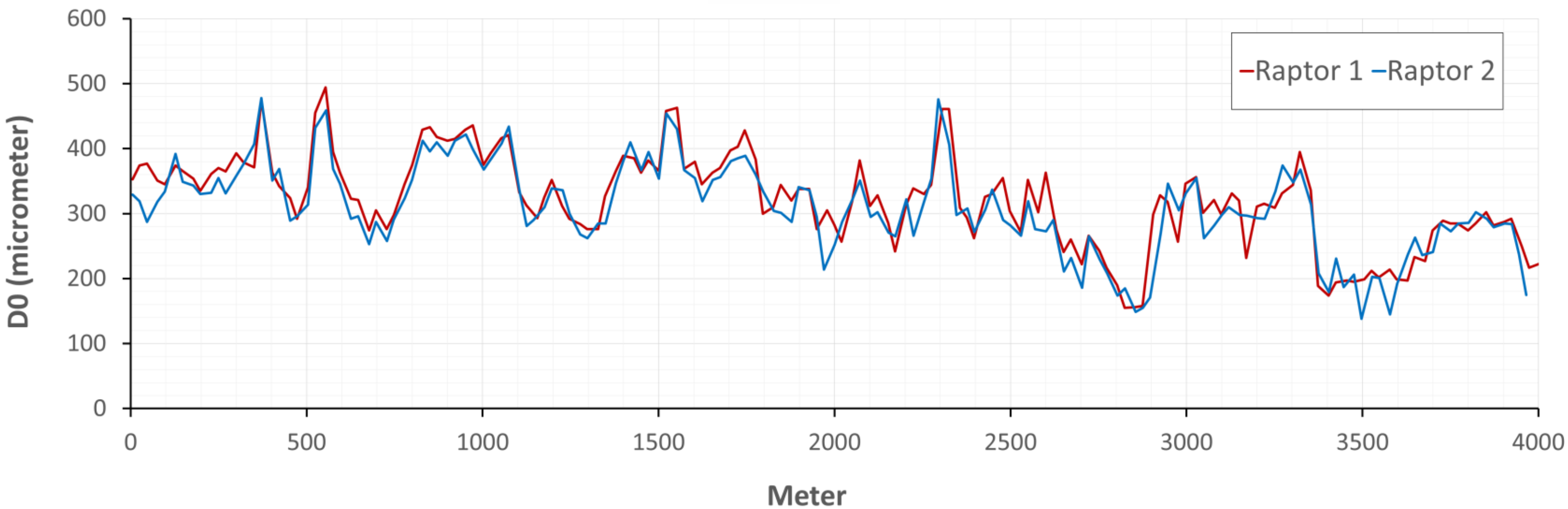


NTNU
Kunnskap for en bedre verden

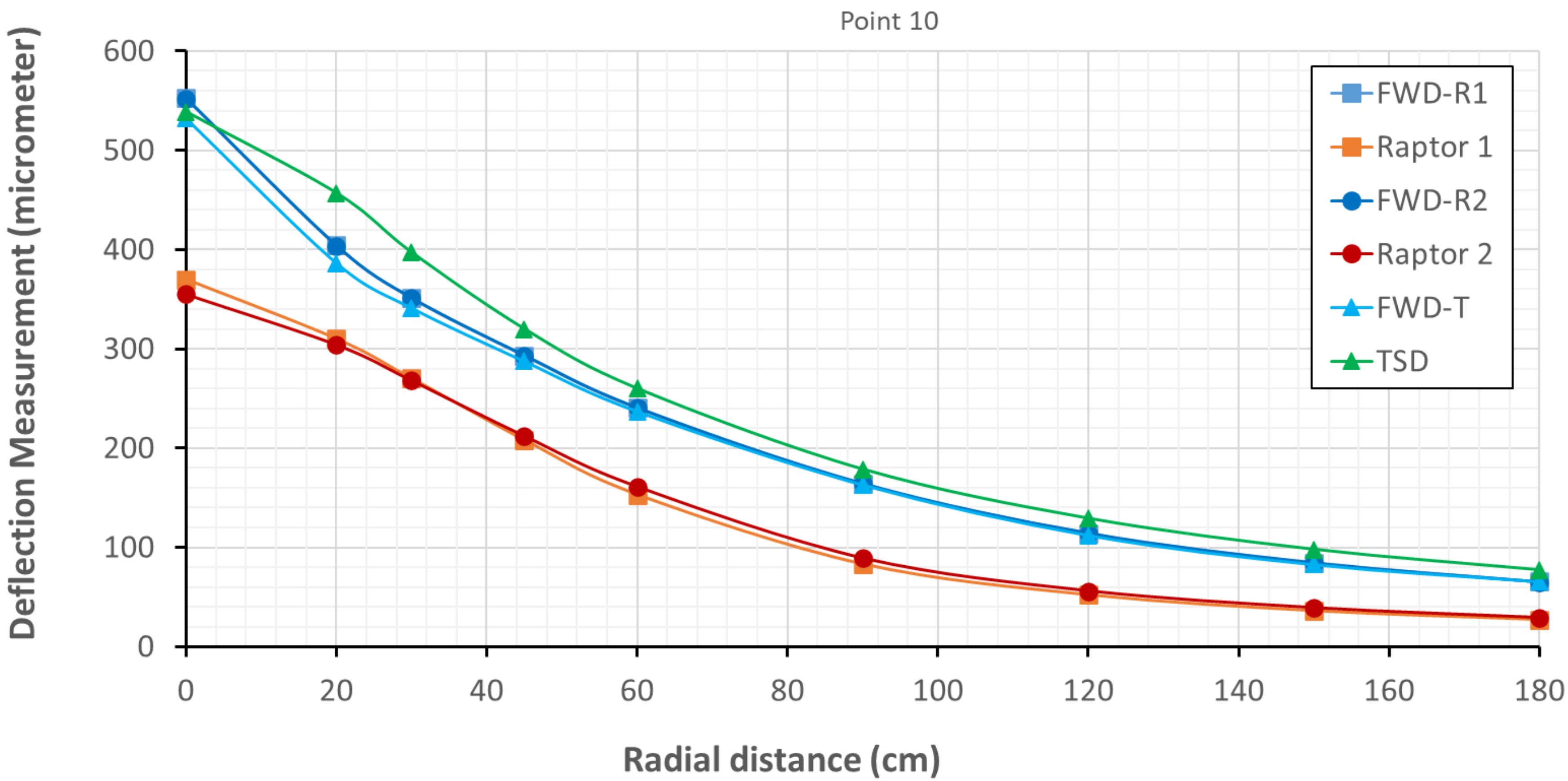
Statens vegvesen
Norwegian Public Roads Administration

Repeatability

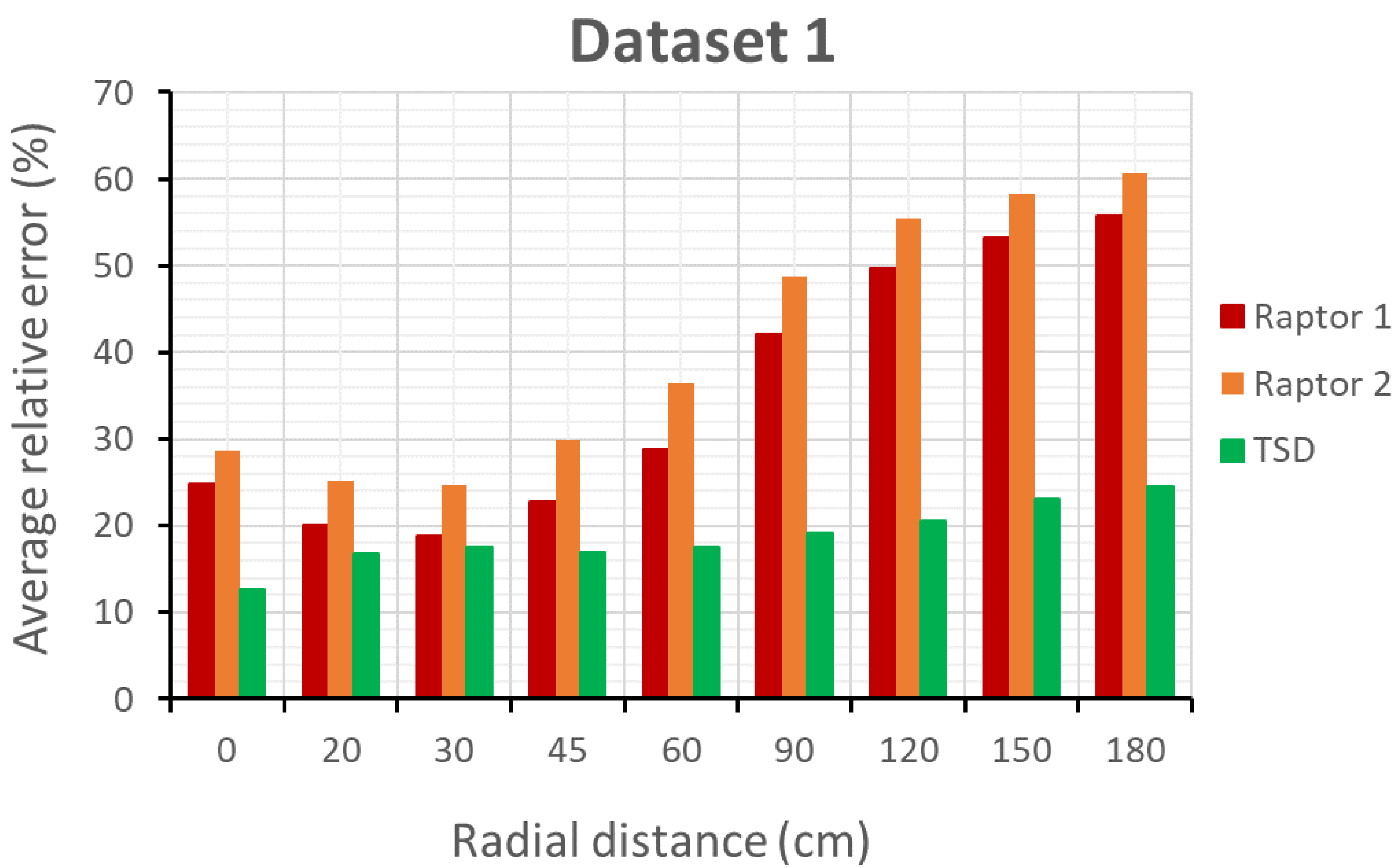




Graphical comparison



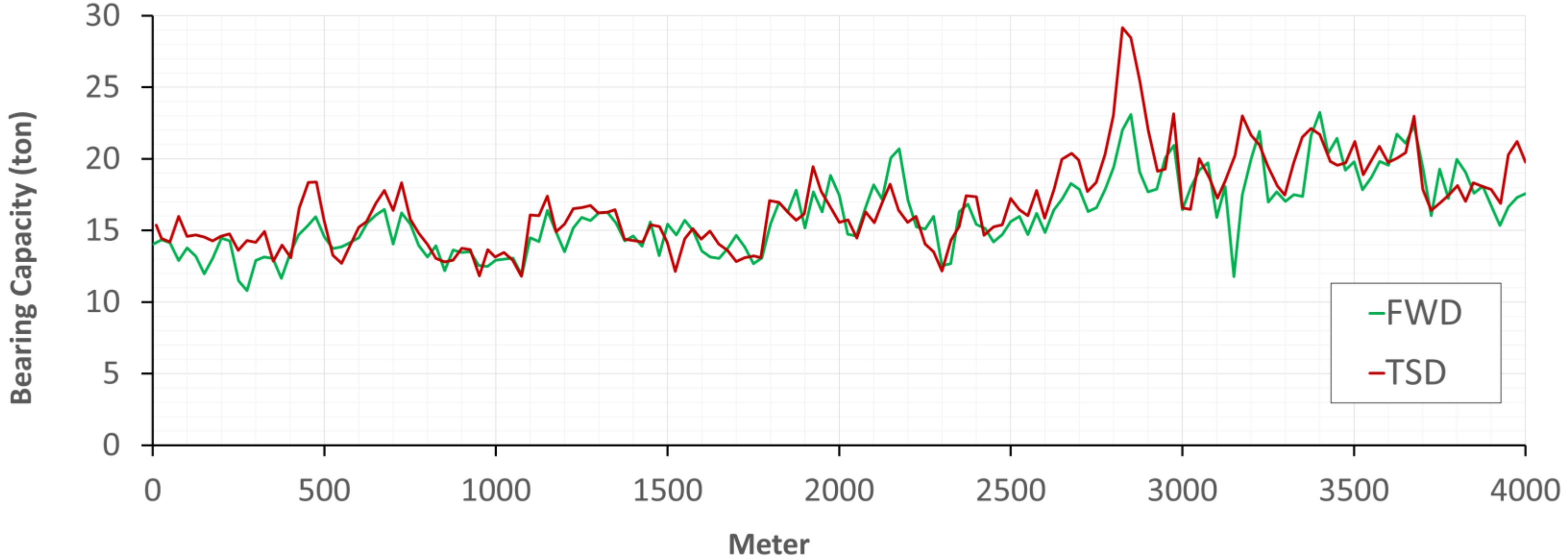
Statistical comparison

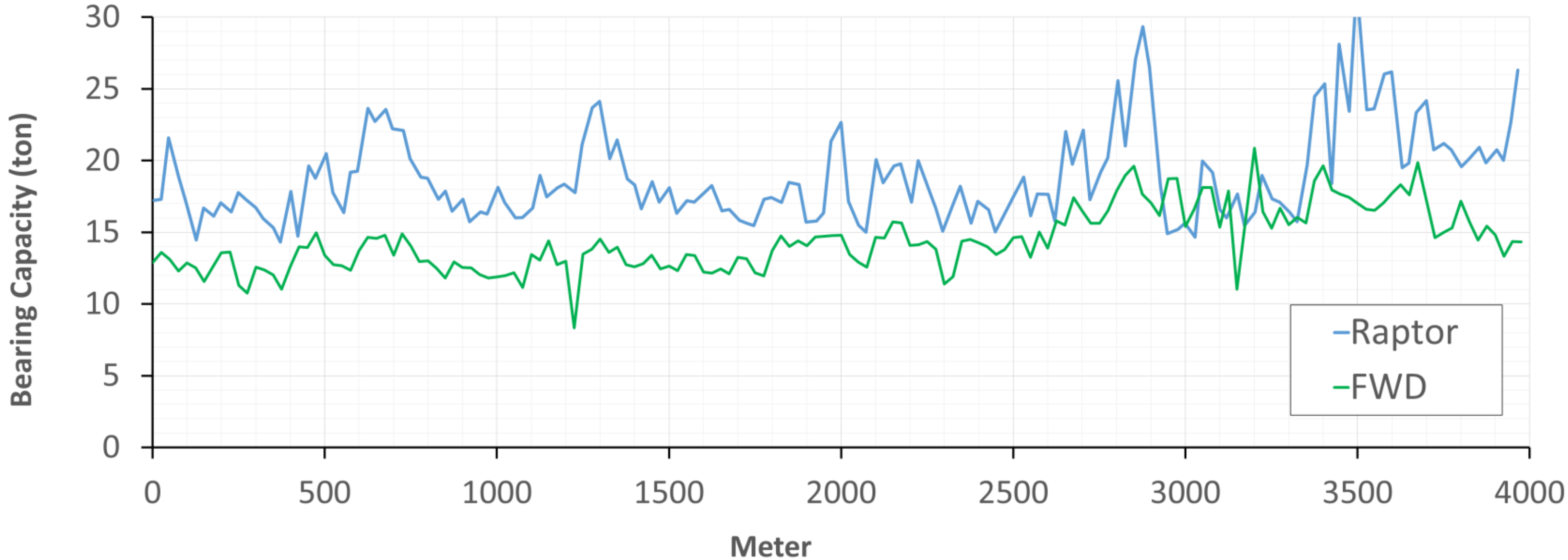


NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Structural comparison





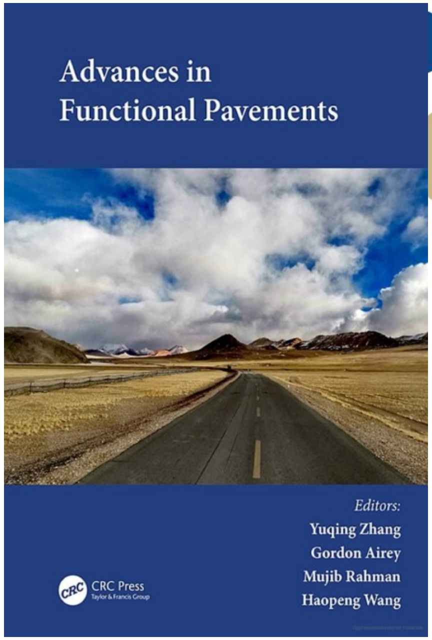
Kunı

vegvesen
Public Roads
stration

Research papres

- Revising the Norwegian formula for bearing capacity by applying a temperature correction factor

- Consistency between Traffic Speed Deflection Devices and Falling Weight Deflectometer



Taylor & Francis Group
an informa business

NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

How to use data from TSDDs in the Pavement Management System?

NTNU
Kunnskap for en bedre verden

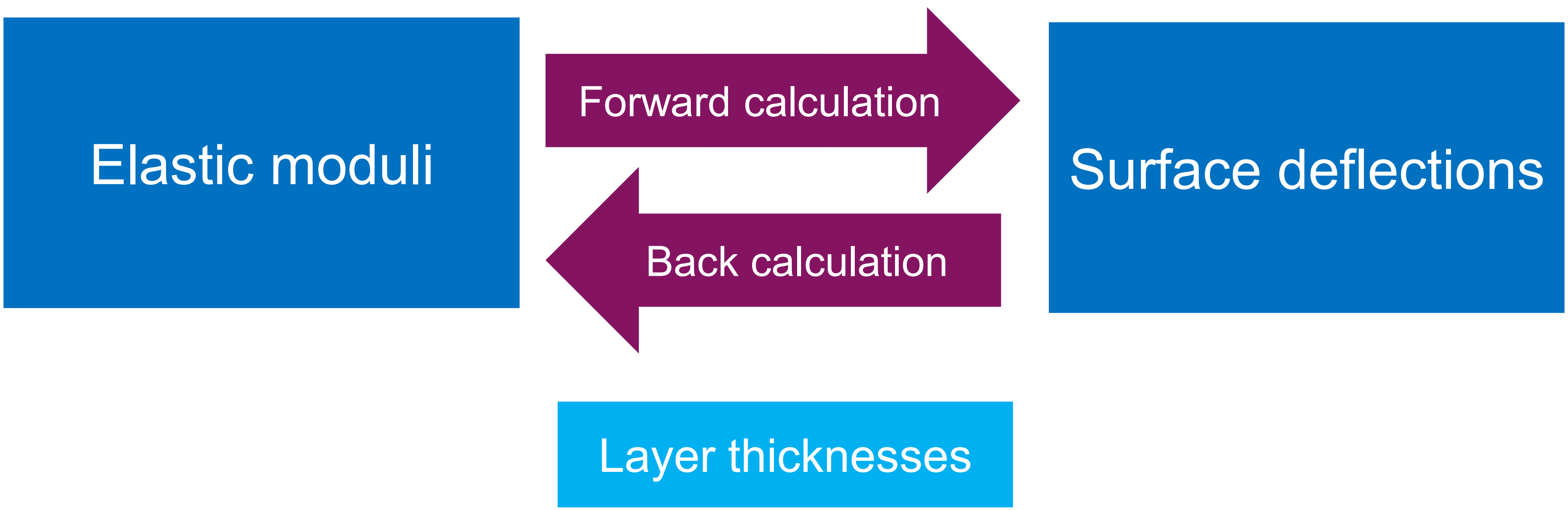
Statens vegvesen
Norwegian Public Roads Administration

Obtaining elastic moduli values

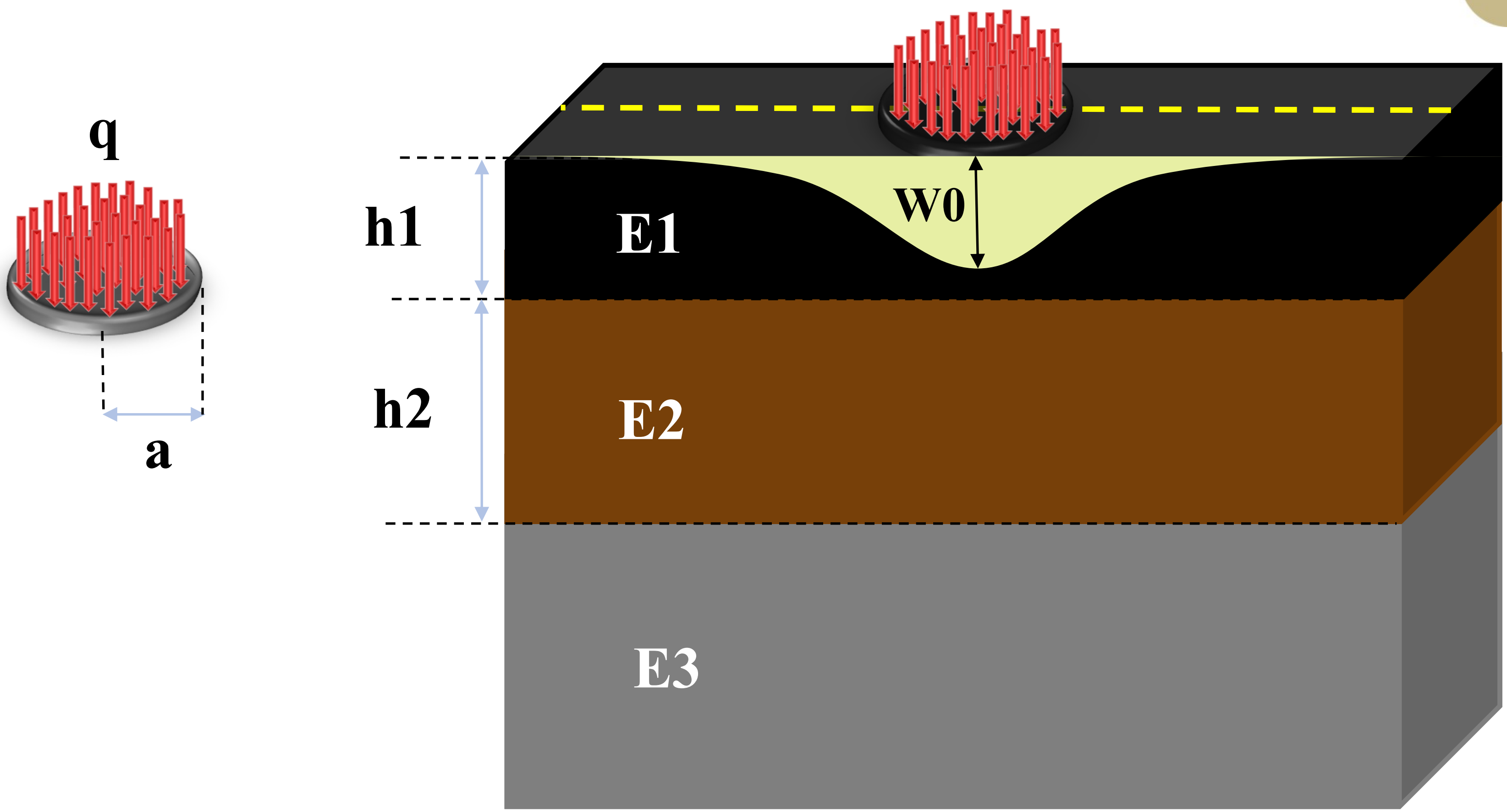
- **Method 1:** Directly using elastic back-calculation
  - ELMOD, BAKFAA, etc. can be used
  - A new elastic back-calculation procedure can be defined
- **Method 2:** Correcting data from TSDDs, then using elastic back-calculation
  - Compare TSDDs deflections with equivalent FWD deflections
  - Develop regression models for each radial distance
  - Use the corrected values in an elastic back-calculation process
- **Method 3:** Using viscoelastic back-calculation
  - Greenwood’s back-calculation procedure
  - Potential of defining a new viscoelastic back-calculation software

Forward- and back-calculation

- Deflections: Forward calculation
- Elastic moduli: Back calculation



Pavement structure: A 3-layer system

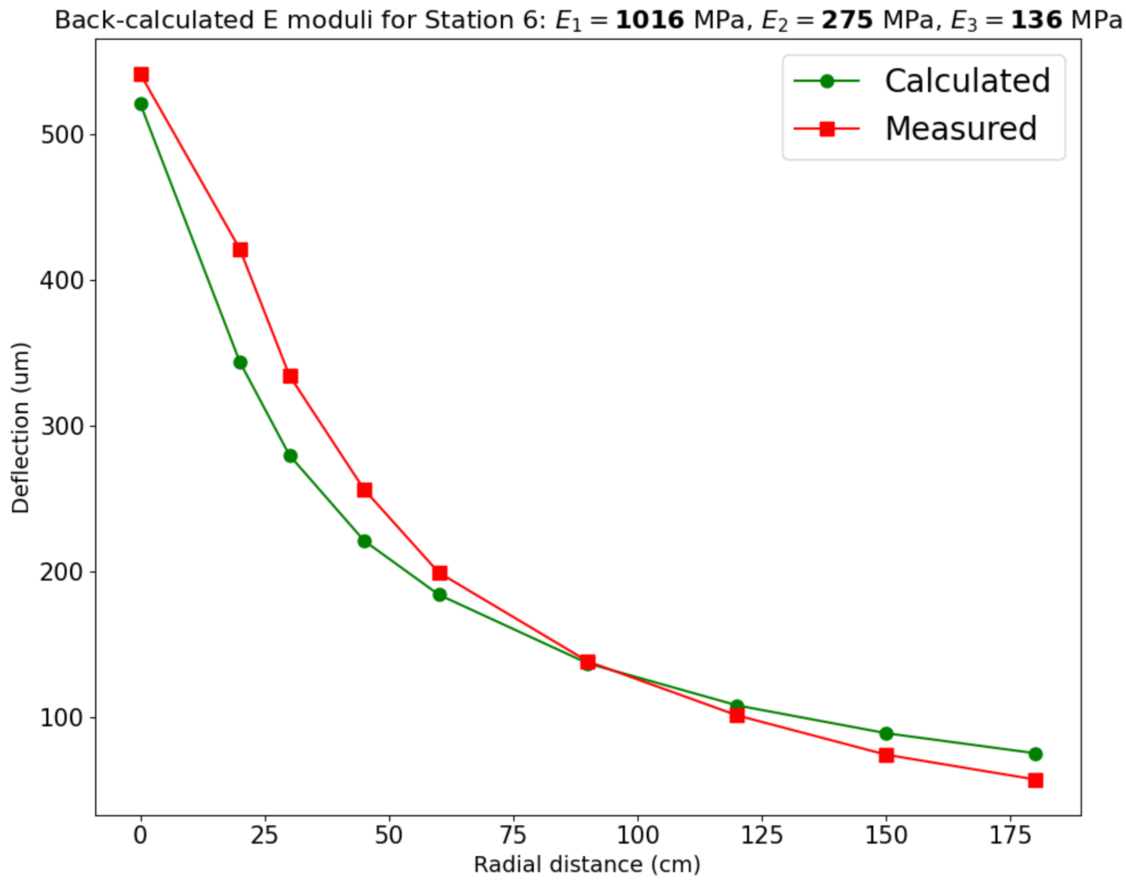


NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Elastic back-calculation

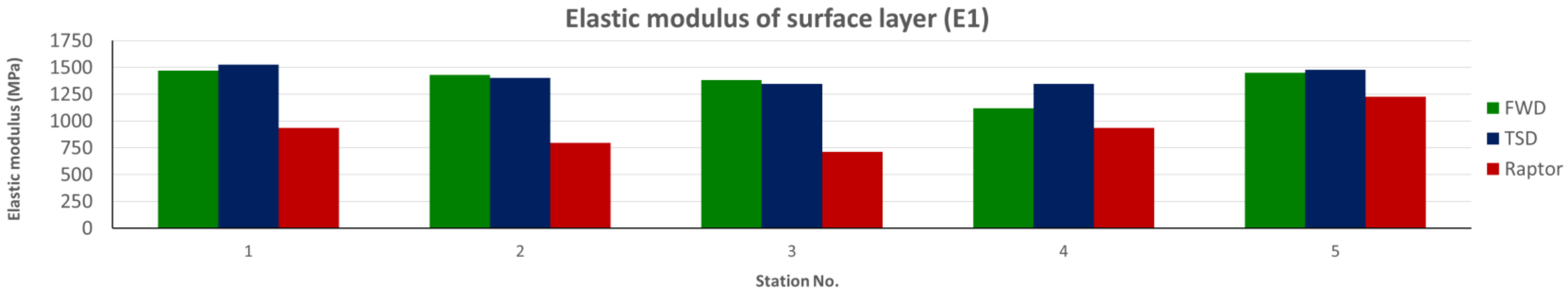
- A new back-calculation computer program

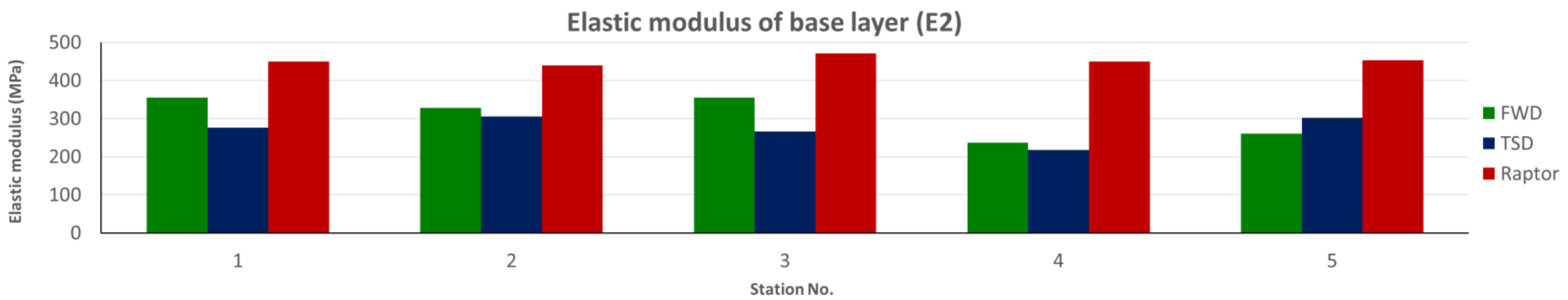


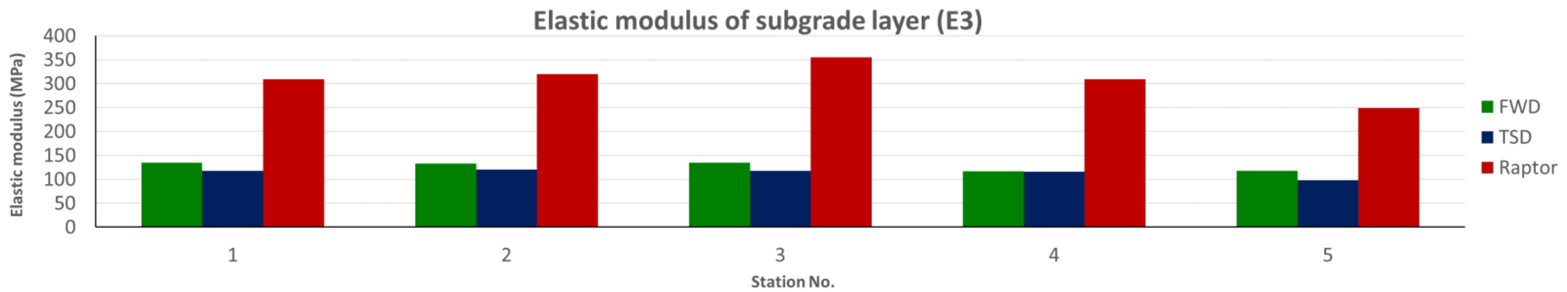
NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Method 1: Elastic moduli (without correction)



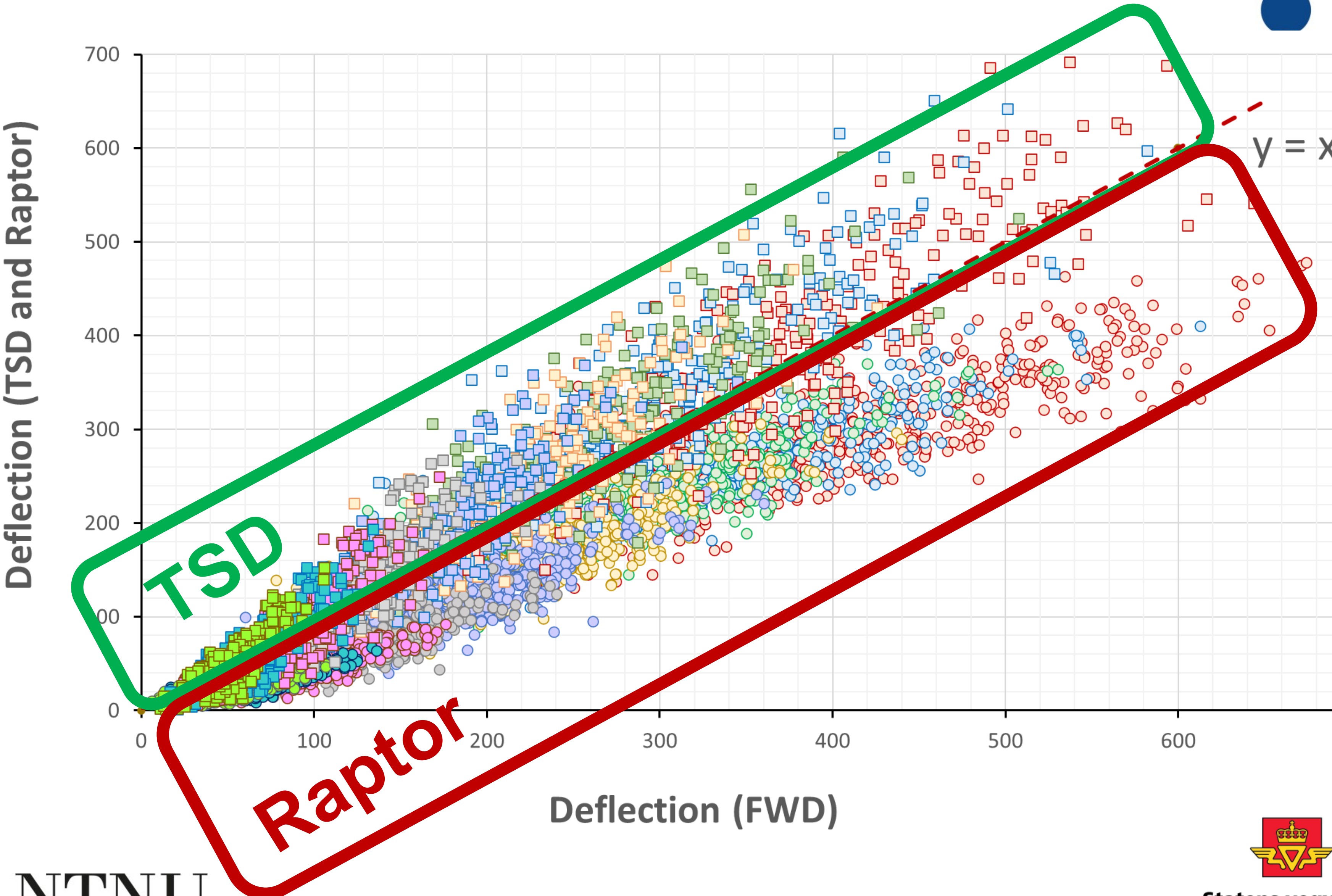




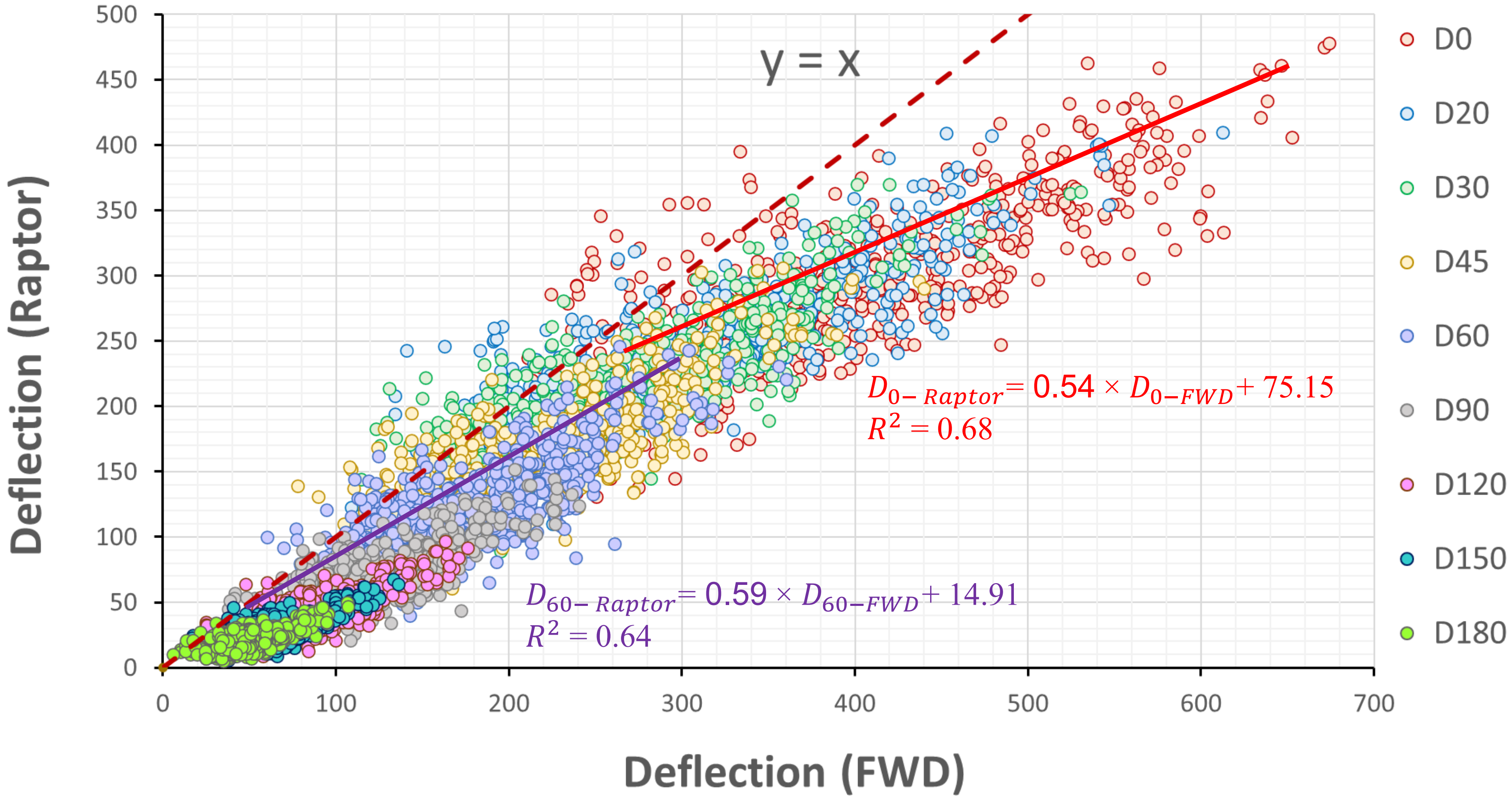
NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

TSD and Raptor versus FWD



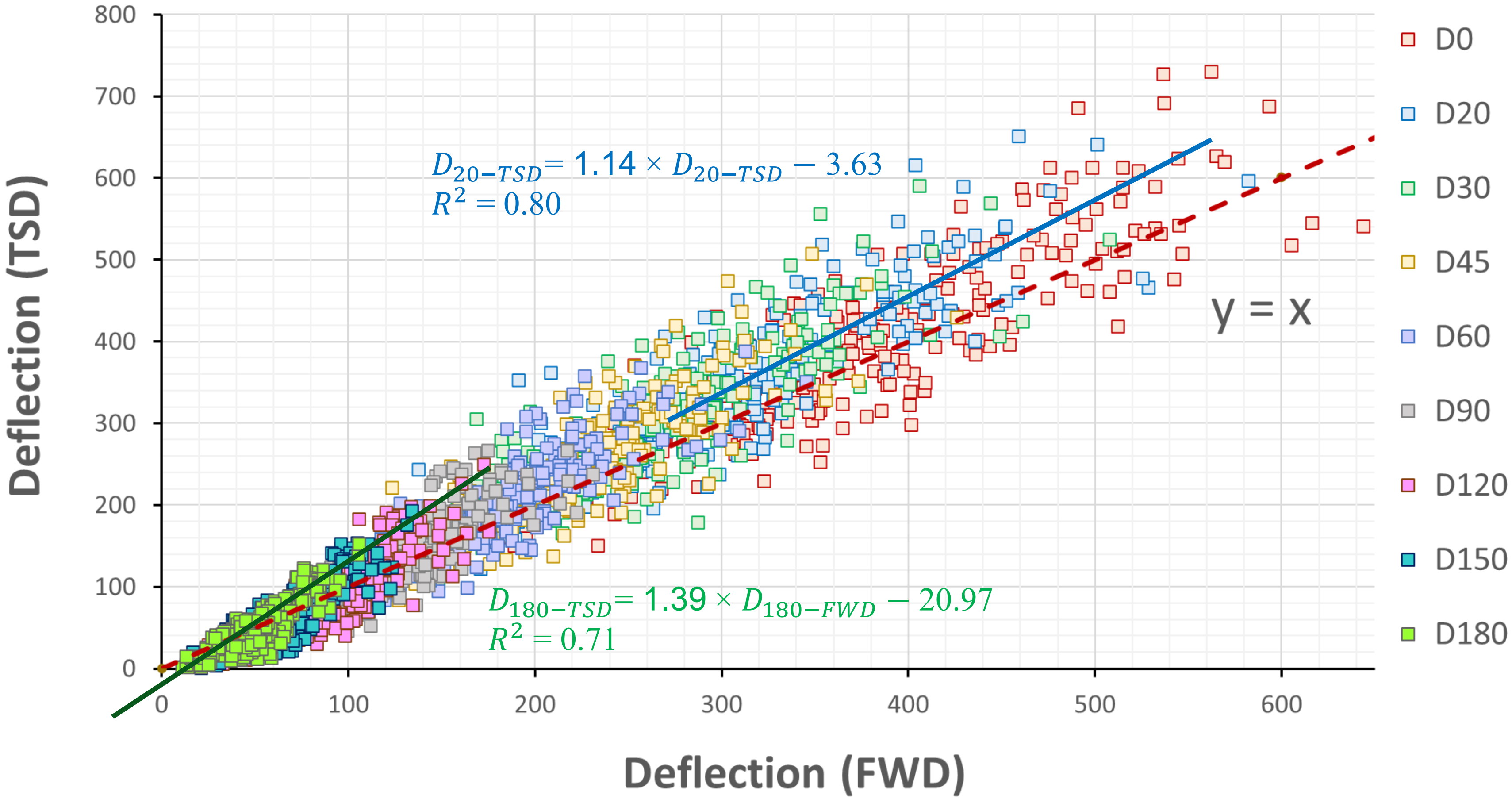
Raptor and FWD



NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

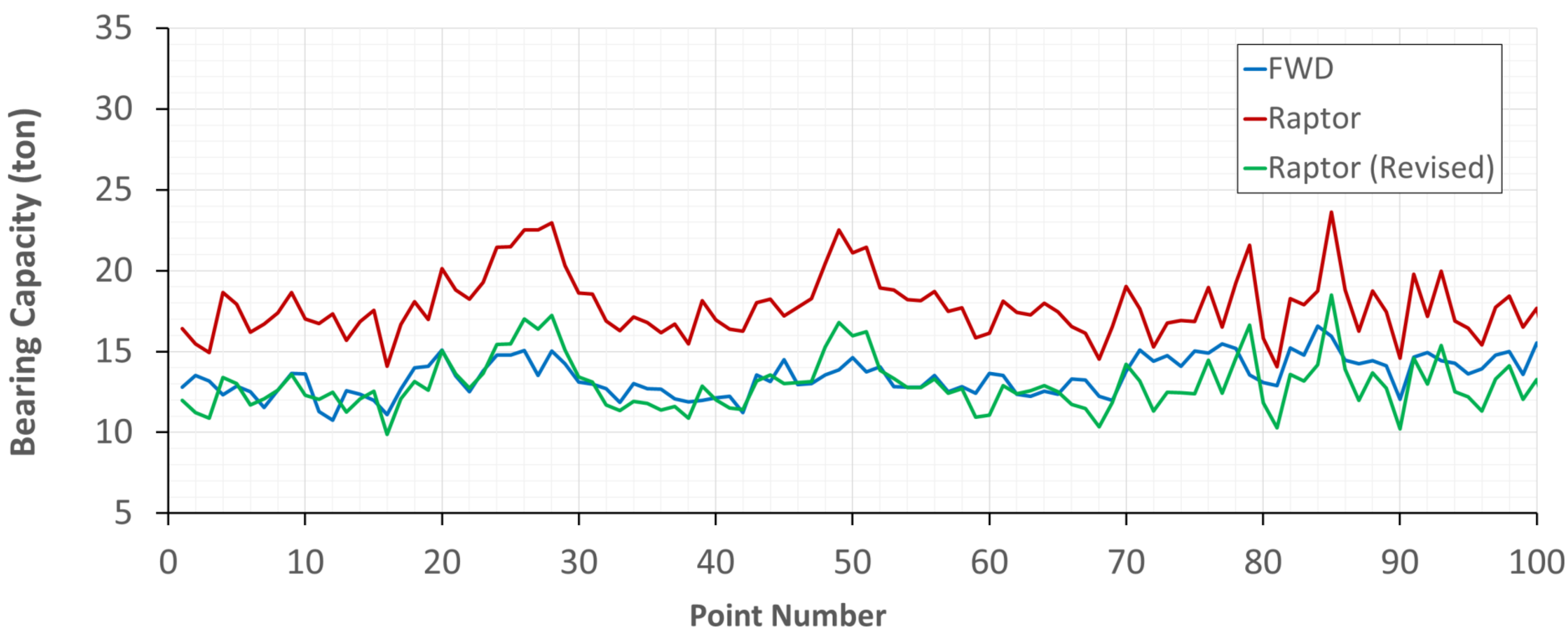
TSD and FWD



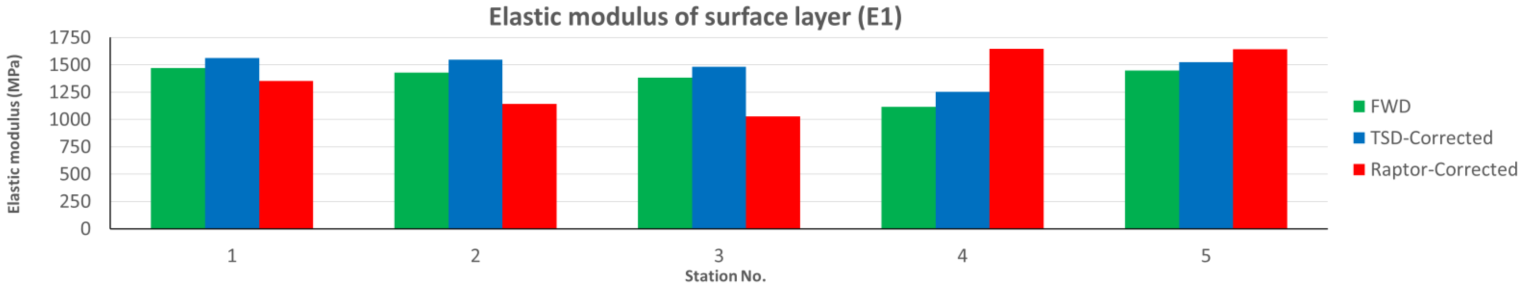
NTNU
Kunnskap for en bedre verden

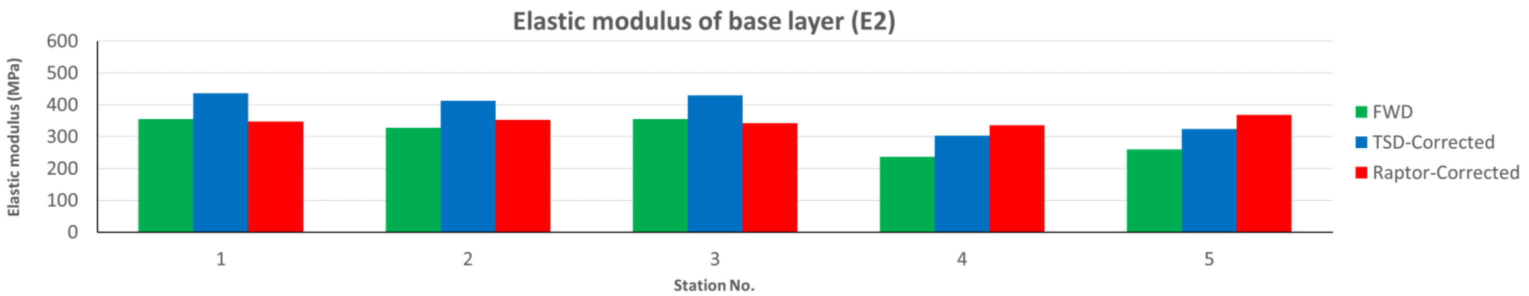
Statens vegvesen
Norwegian Public Roads Administration

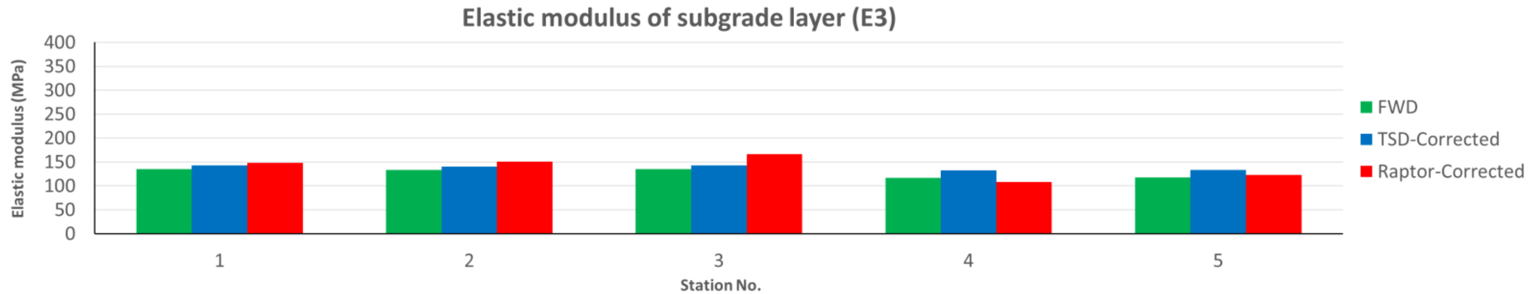
Bearing capacity after refinement



Method 2: Elastic moduli (after correction)







NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Elastic back-calculation: Challenges

- Asphalt layers are viscoelastic and not elastic
- Regression models between TSDDs and FWD can differ from road to road
- The effect of moving load is not reflected
- Driving speed might have effect on deflections
- Temperature difference is not reflected
- Mixture type might affect deflections
- Design frequency in dynamic modulus master curves

Viscoelastic Analysis

NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Viscoelastic characteristics

- Elastic behavior
- Viscoelastic behavior
  - Dynamic modulus test

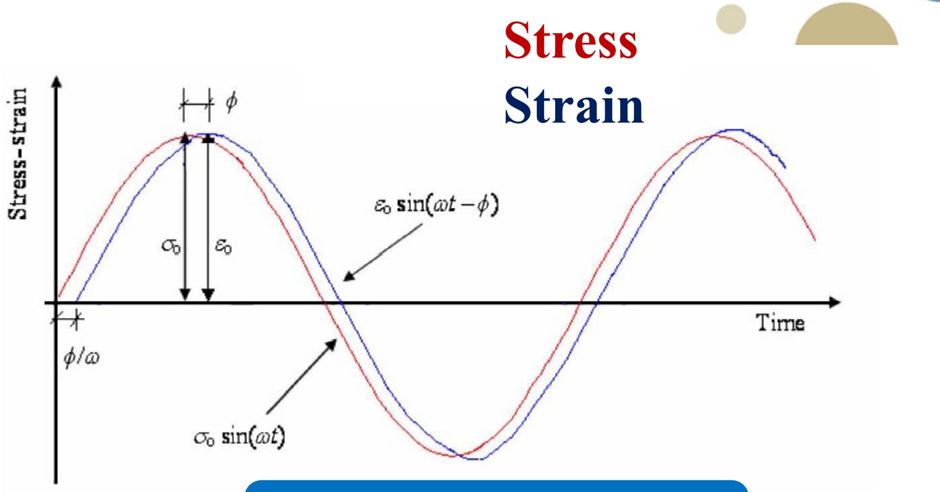
$$E^* = E' + iE''$$

E^* : Complex modulus

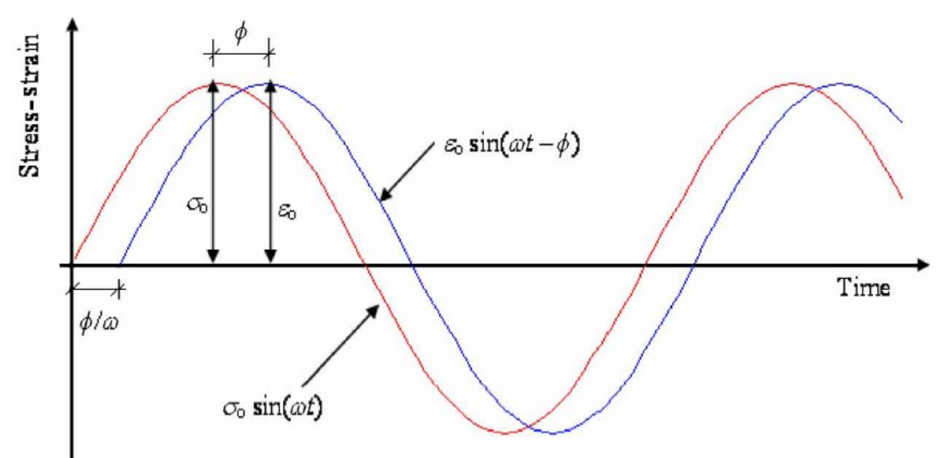
E' : Storage modulus

E'' : Loss modulus

$|E^*|$: Dynamic modulus



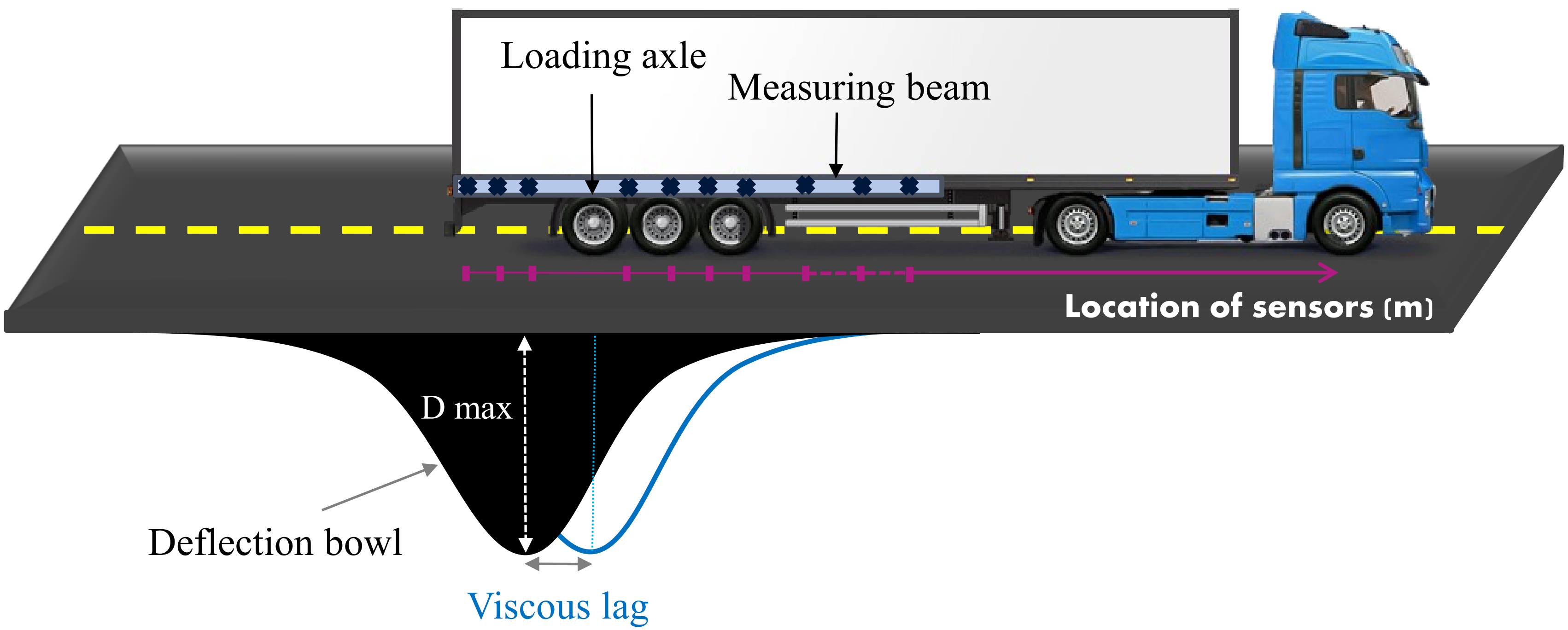
Elastic material



Viscoelastic material

TSD: Viscous lag

- Three sensors are behind the TSD’s loading axle
- A lag distance can be detected



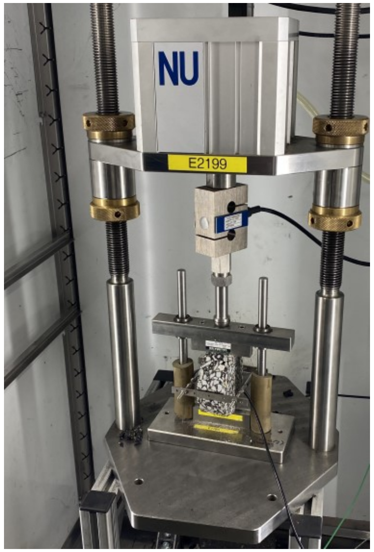
NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Considering viscoelasticity

ERAPave

Dynamic modulus master curves



Optimization techniques

Viscoelastic back-calculation

Viscoelastic forward-calculation

ViscoRoute software

Huet-Sayegh model parameters

NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Dynamic modulus test

$$E^* = |E^*|\cos\varphi + i|E^*|\sin\varphi$$

$$\log\left(|E^*|\right) = a + \frac{b}{1 + e^{c-d\left[\log(f_r)\right]}}$$

$$\log(a_T) = \frac{-C_1(T - T_r)}{C_2 + (T - T_r)}$$

$$\log(f_r) = \log(a_T) + \log(f)$$

$$\varphi = \frac{k_p . k_g{}^2}{\left[\log(f_r) - k_c\right]^2 + k_g{}^2}$$

$$\Rightarrow |E^*| = 10^{\left(a + \frac{b}{1+e^{c-d\left(\frac{-C_1(T-T_r)}{C_2+(T-T_r)} + \log(f)\right)}}\right)}$$

Huet-Sayegh model

$$E^* = E_0 + \frac{E_\infty - E_0}{1 + \delta\left[i\omega\tau(\theta)\right]^{-k} + \left[i\omega\tau(\theta)\right]^{-h}}$$

$$\tau(\theta) = \exp\left(A_0 + A_1\theta + A_2\theta^2\right)$$

$$M = \frac{1 + \delta\left[\omega\tau(\theta)\right]^{-k}\cos\frac{\pi k}{2} + \left[\omega\tau(\theta)\right]^{-h}\cos\frac{\pi h}{2}}{E_\infty - E_0}$$

$$N = \frac{\delta\left[\omega\tau(\theta)\right]^{-k}\sin\frac{\pi k}{2} + \left[\omega\tau(\theta)\right]^{-h}\sin\frac{\pi h}{2}}{E_\infty - E_0}$$

$$E^* = E' + iE'' = \left(E_0 + \frac{M}{M^2 + N^2}\right) + i \cdot \frac{N}{M^2 + N^2}$$

$$\Rightarrow \left|E^*\right| = \sqrt{\left(E_0 + \frac{M}{M^2 + N^2}\right)^2 + \left(\frac{N}{M^2 + N^2}\right)^2}$$

Finding model parameters

- Equate the two models:
  - Loss modulus $$\left|E^*\right|\cos\varphi = E_0 + \frac{M}{M^2+N^2}$$
  - Storage modulus $$\left|E^*\right|\sin\varphi = \frac{N}{M^2+N^2}$$
  - Dynamic modulus

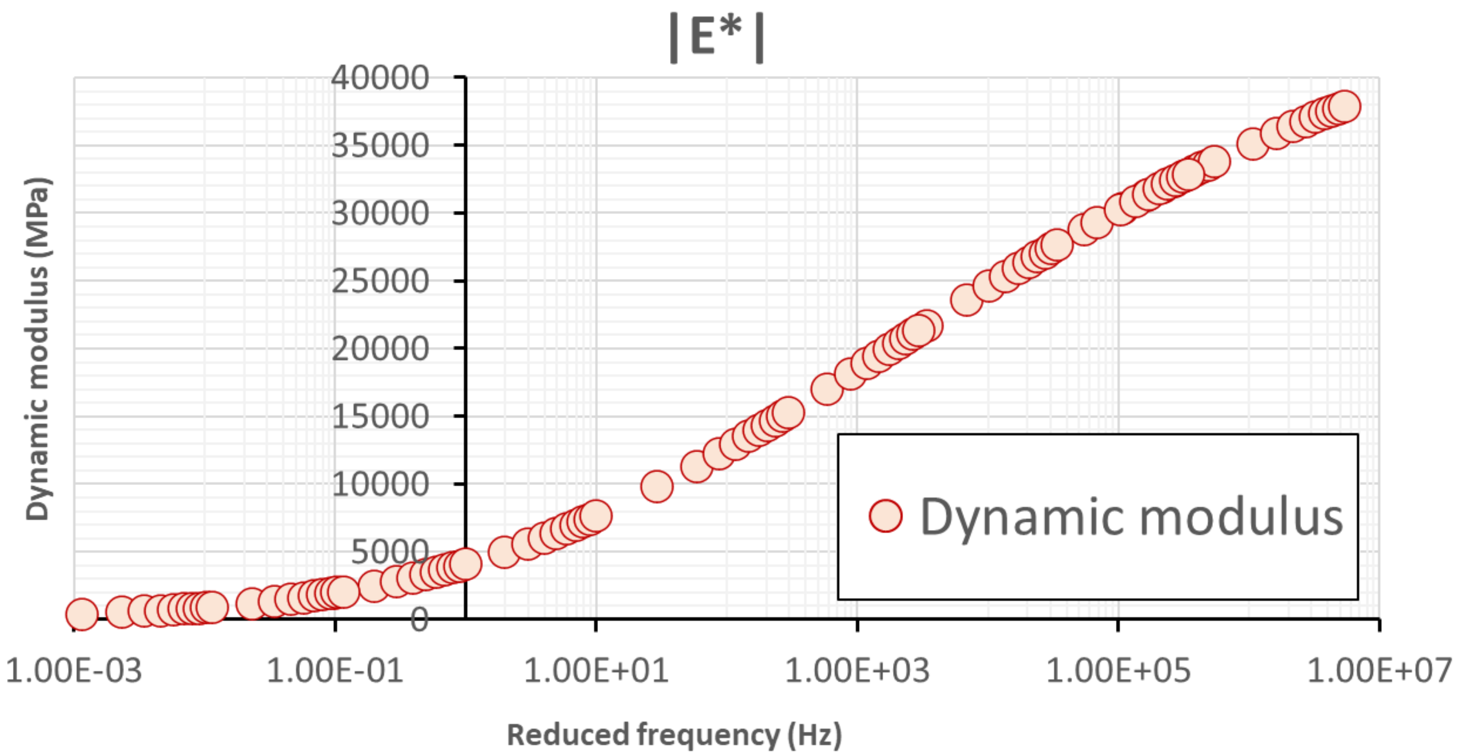
$$10^{\left(a+\frac{b}{1+e^{c-d\left(\frac{-C_1(T-T_r)}{C_2+(T-T_r)}+\log(f)\right)}}\right)} = \sqrt{\left(E_0+\frac{M}{M^2+N^2}\right)^2+\left(\frac{N}{M^2+N^2}\right)^2}$$

NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Dynamic modulus model parameters

- For each mixture type, dynamic modulus model parameters (a, b, c, d, C1, C2, kp, kg, kc) are known

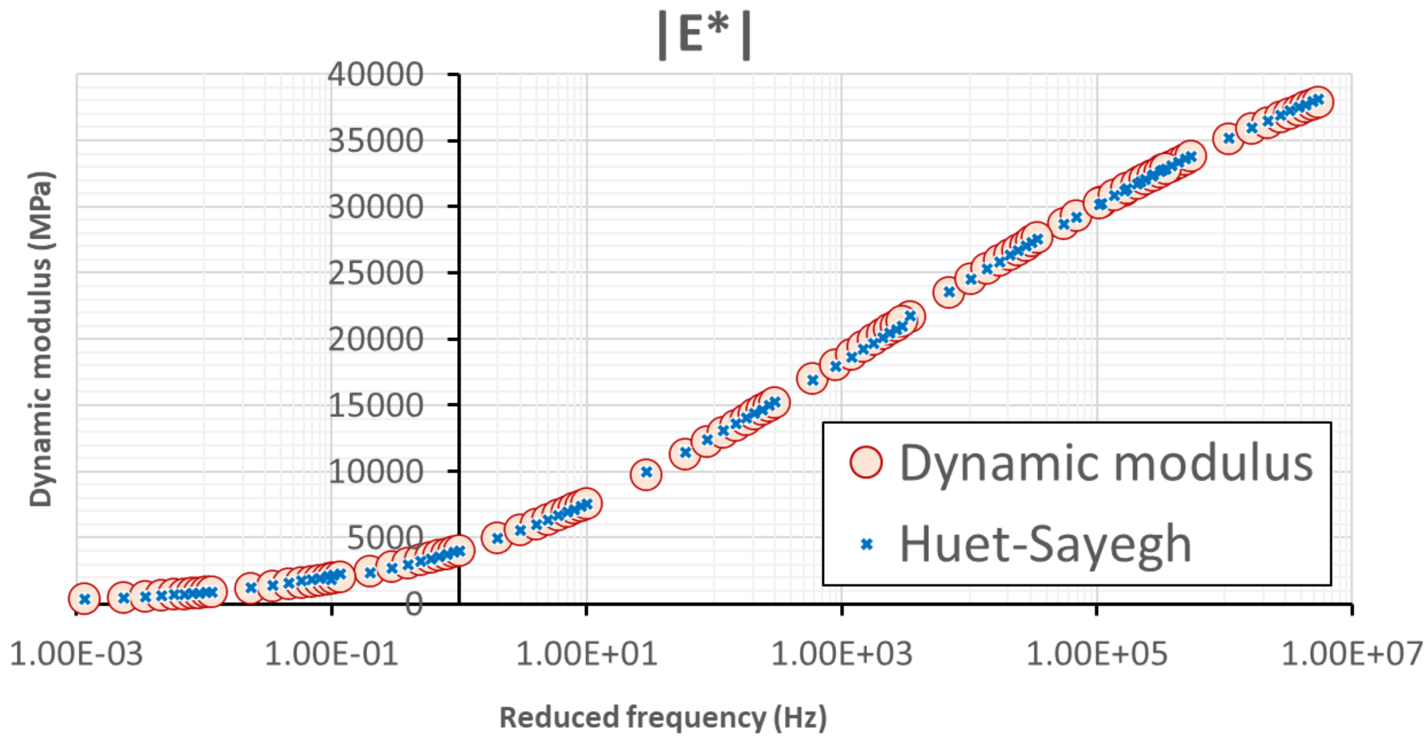


NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Huet-Sayegh model parameters

- For the same mixture, corresponding Huet-Sayegh model parameters (k, h, delta, A0, A1, A2, E0, Es) are obtained using optimization techniques

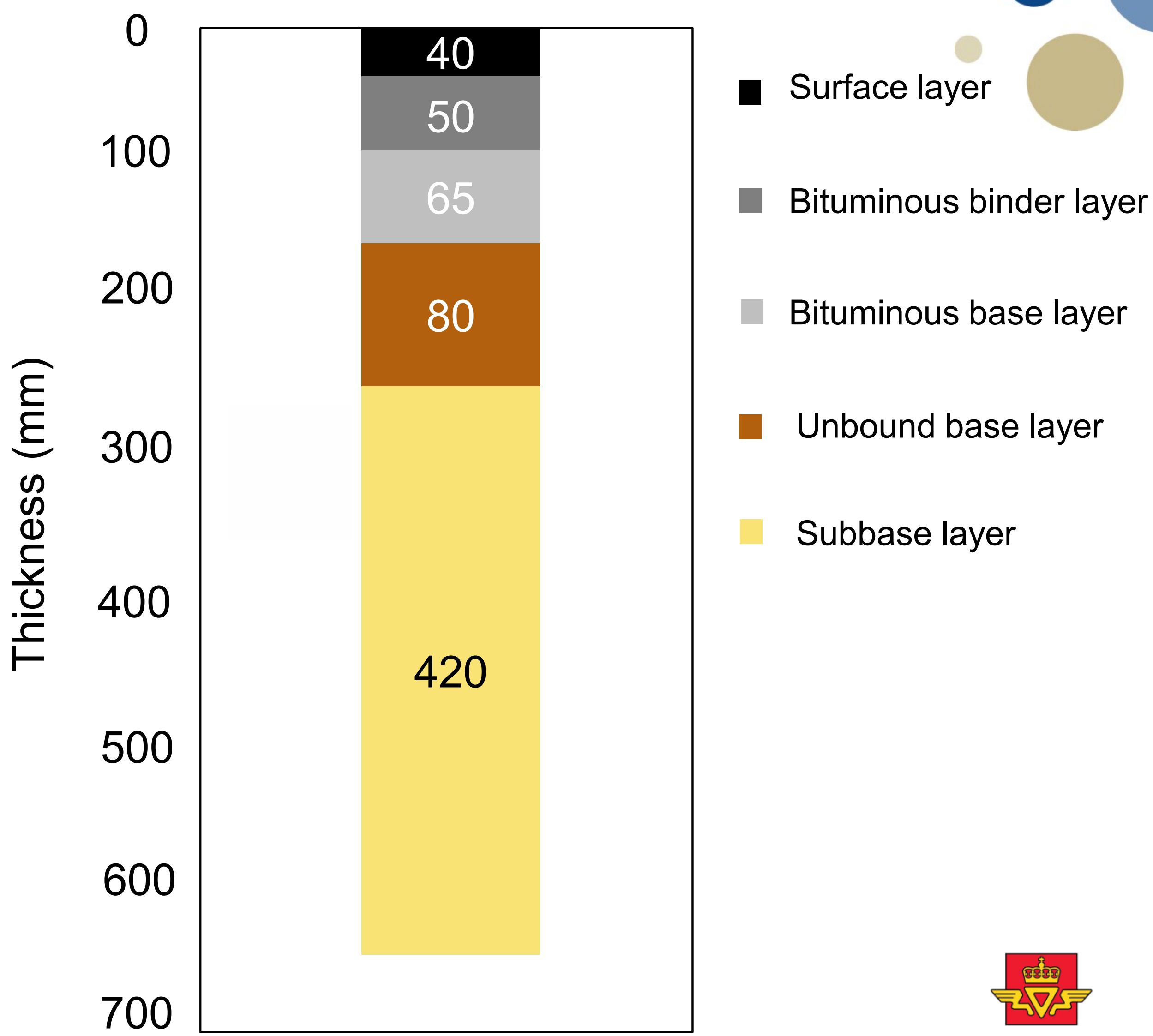


NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

A sample structure in ERAPave

- A sample structure
- Layer properties
  - SMA 11-70/100
  - AC 16-70/100
  - AC 16-160/220
  - Knust berg
  - Knust berg
  - Silt, cu<25

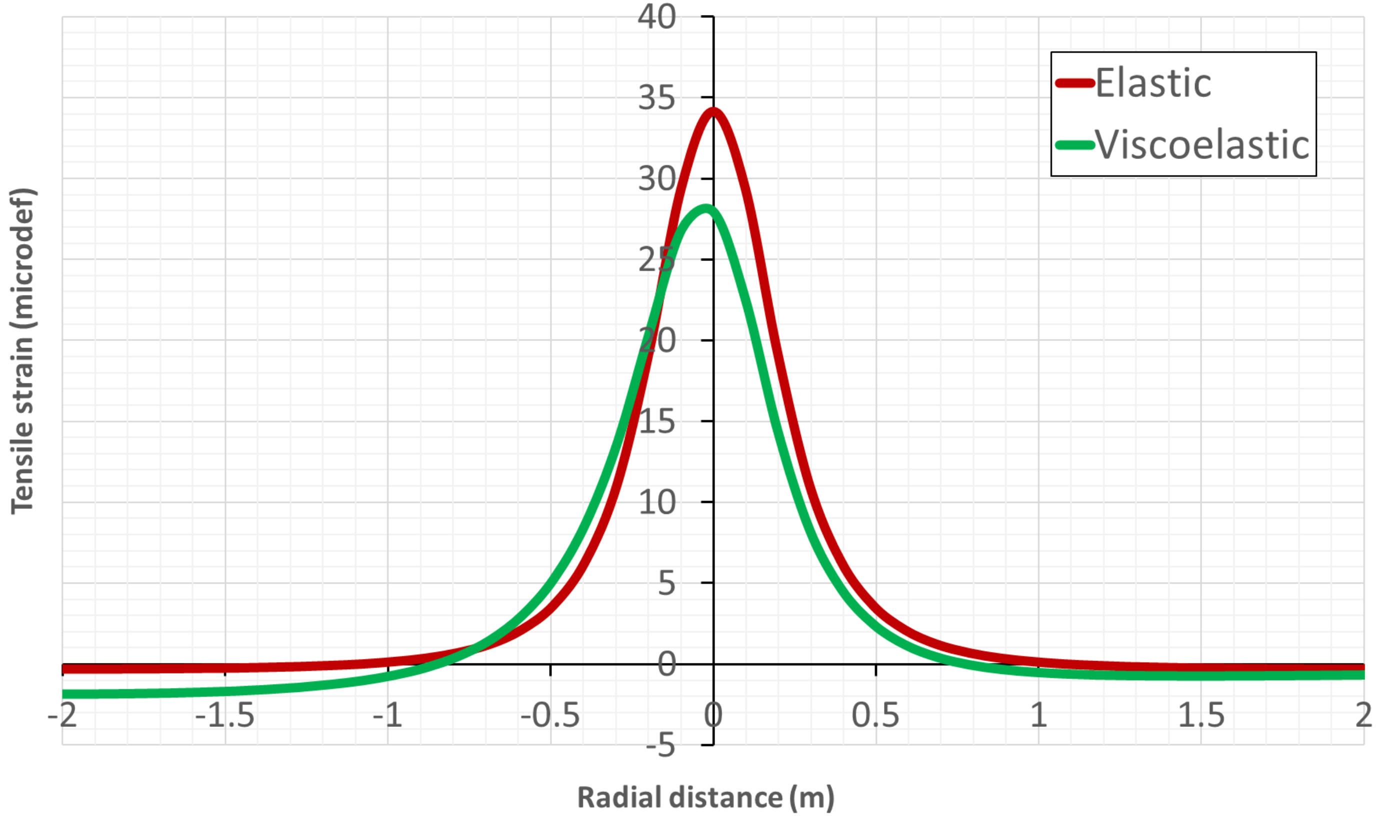


NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Fatigue model

- Tensile strain at the bottom of asphalt layers

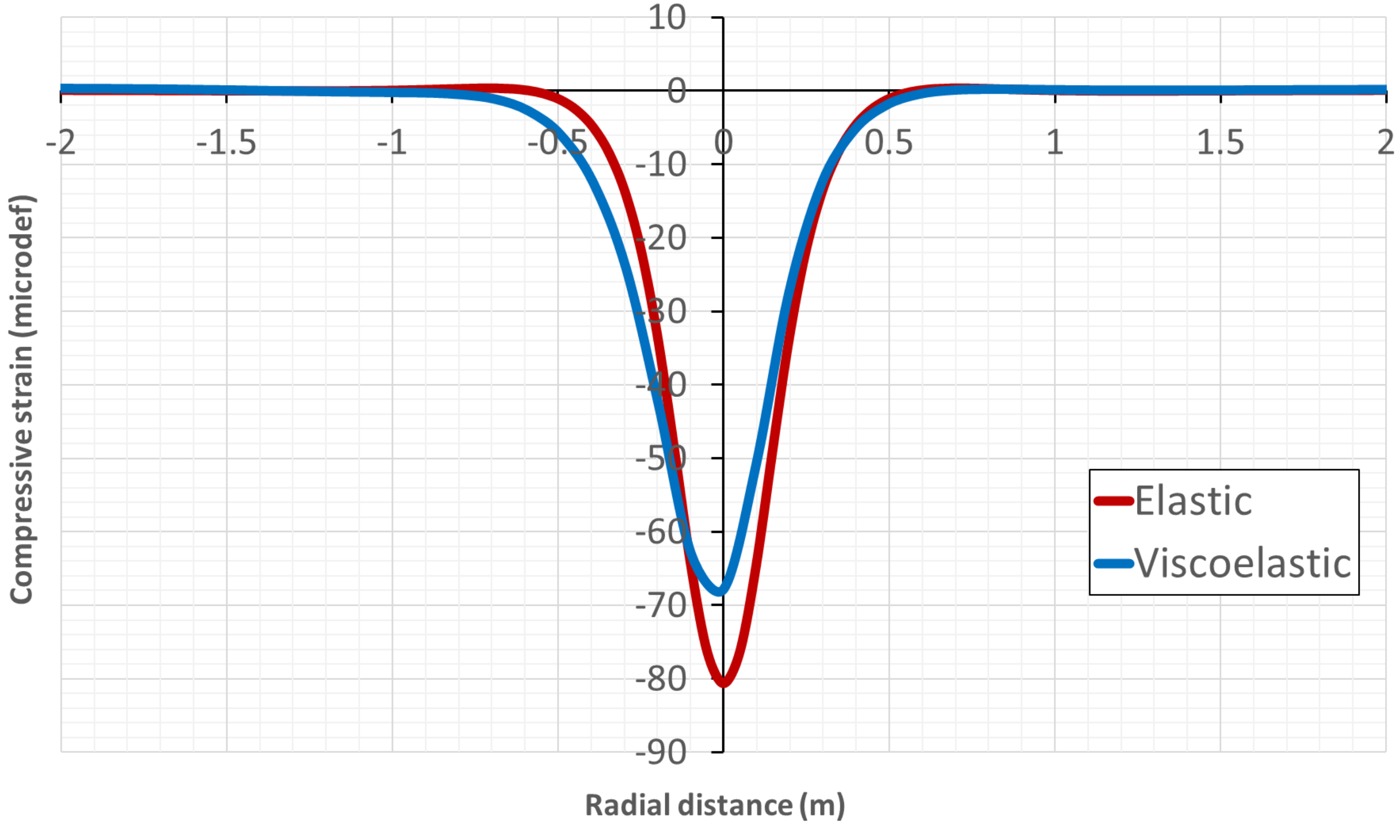


NTNU
Kunnskap for en bedre verden

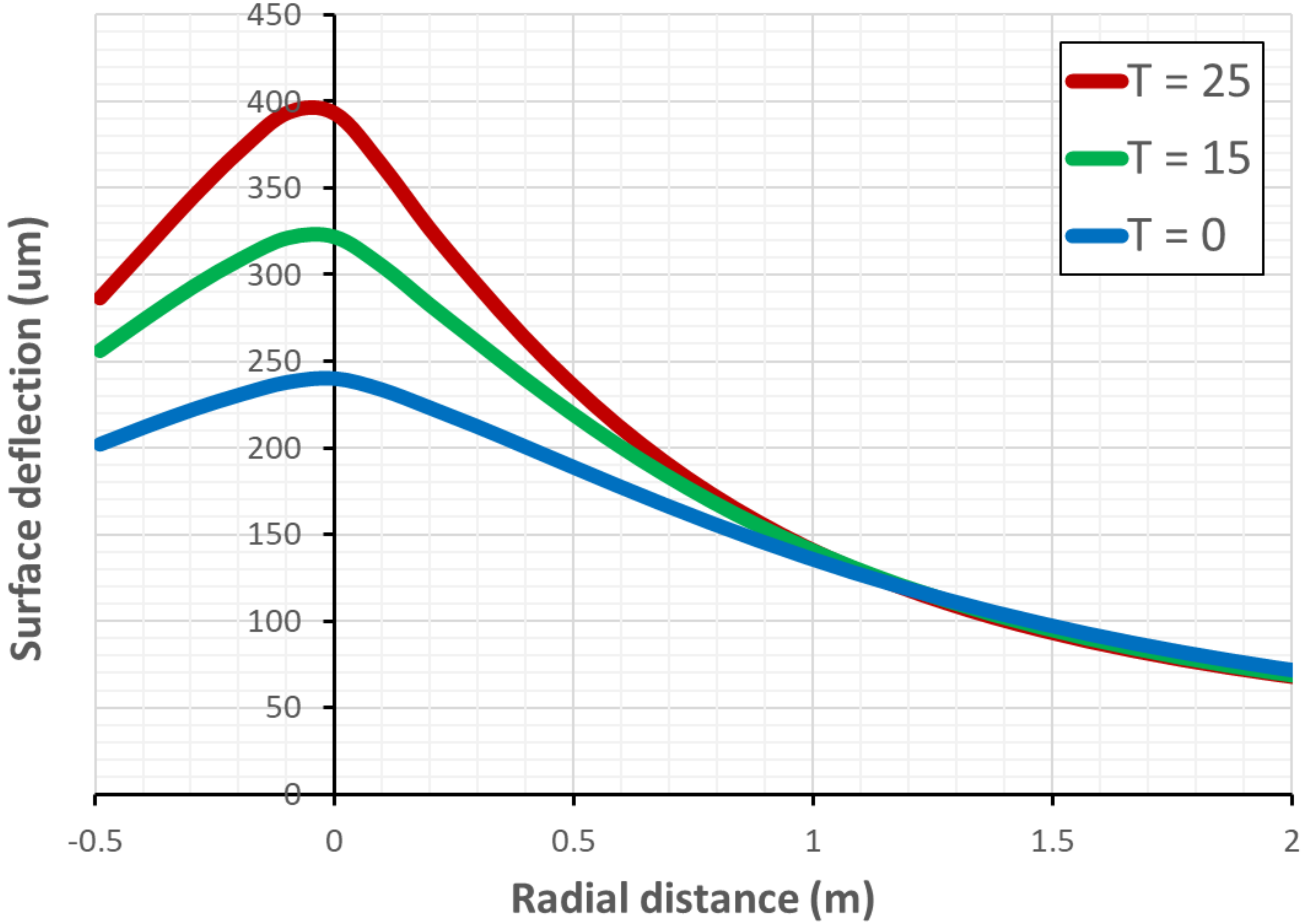
Statens vegvesen
Norwegian Public Roads Administration

Rutting model

- Compressive strain at the mid point of layer 4



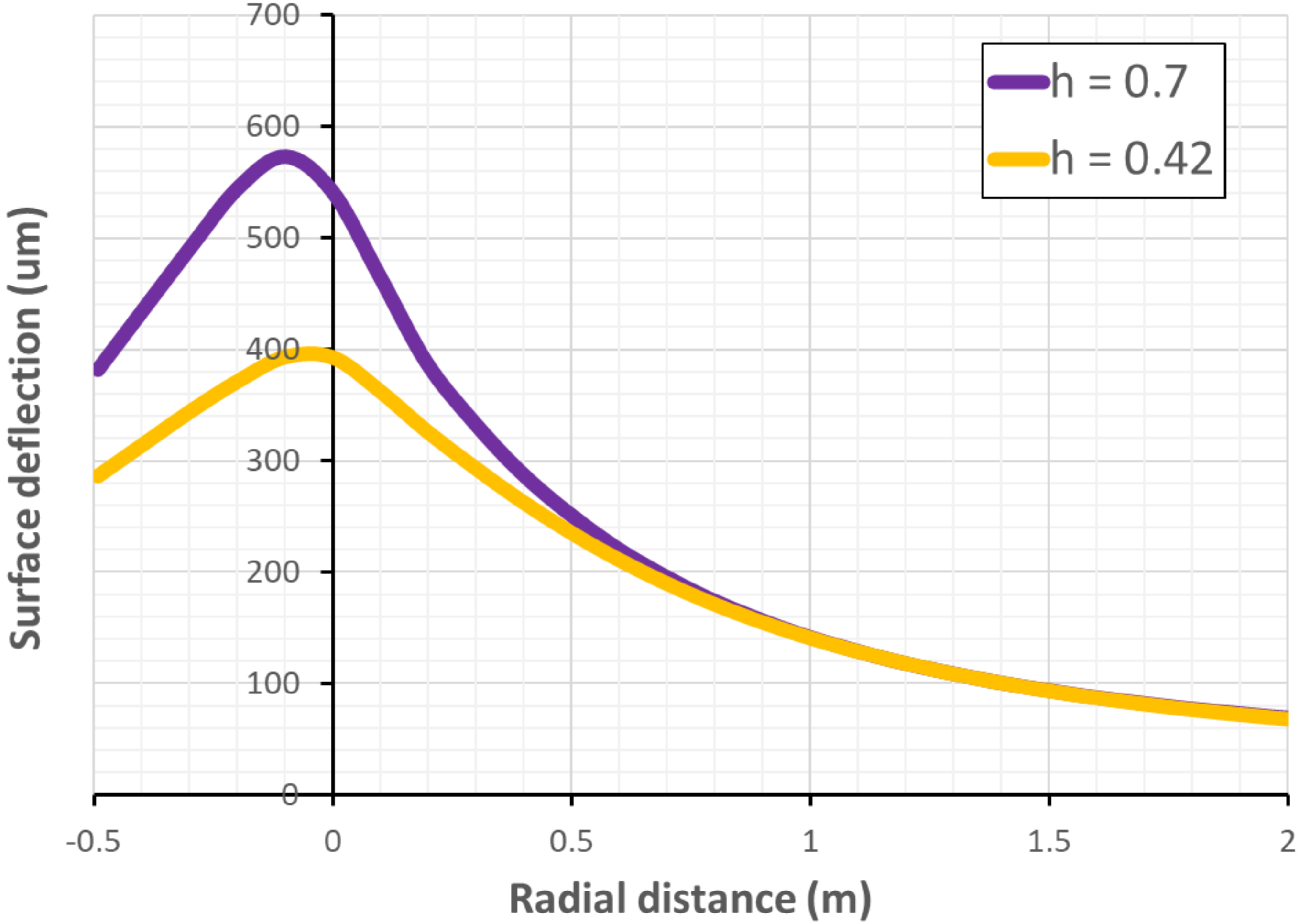
Temperature difference



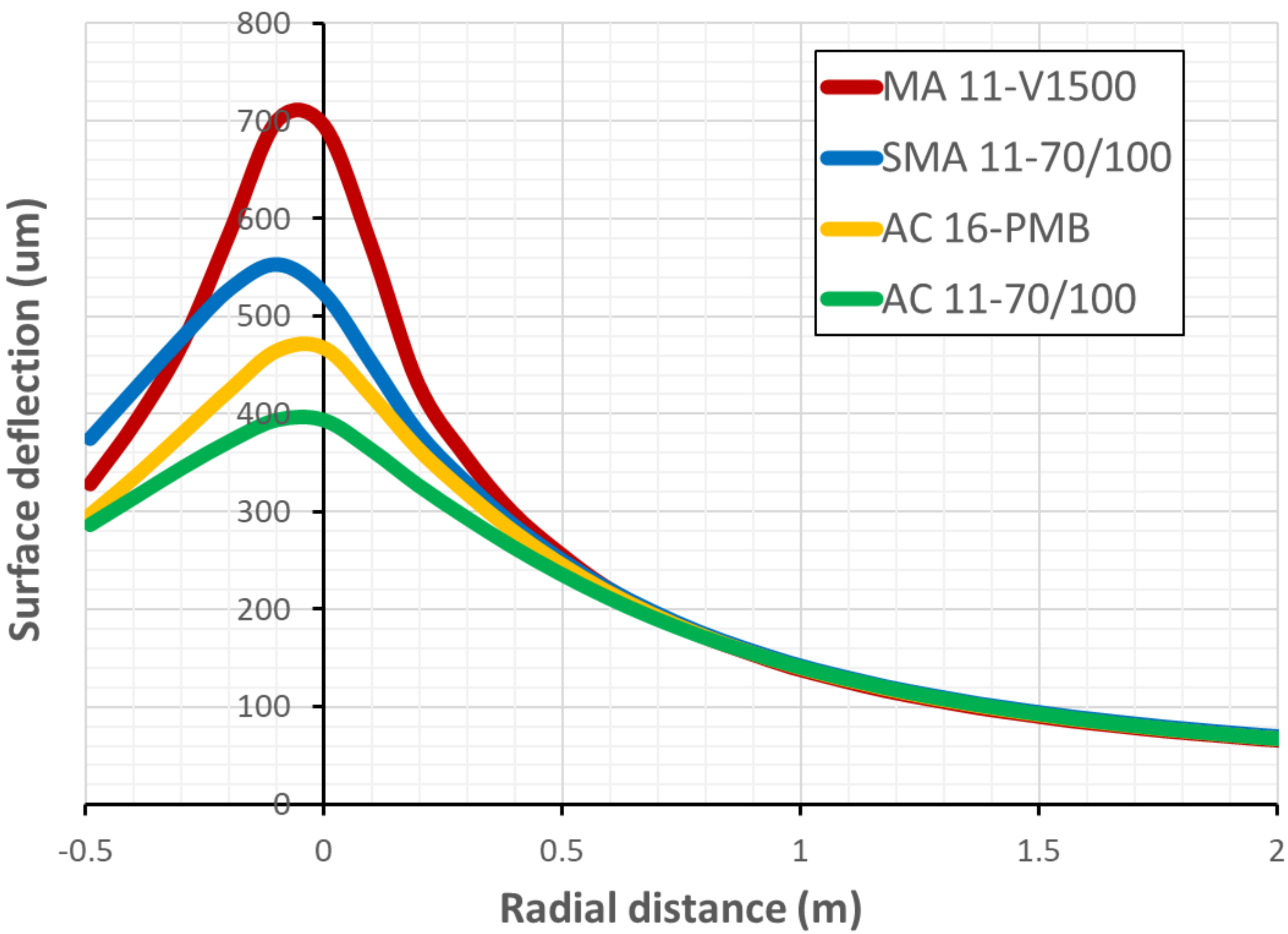
NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Model parameters



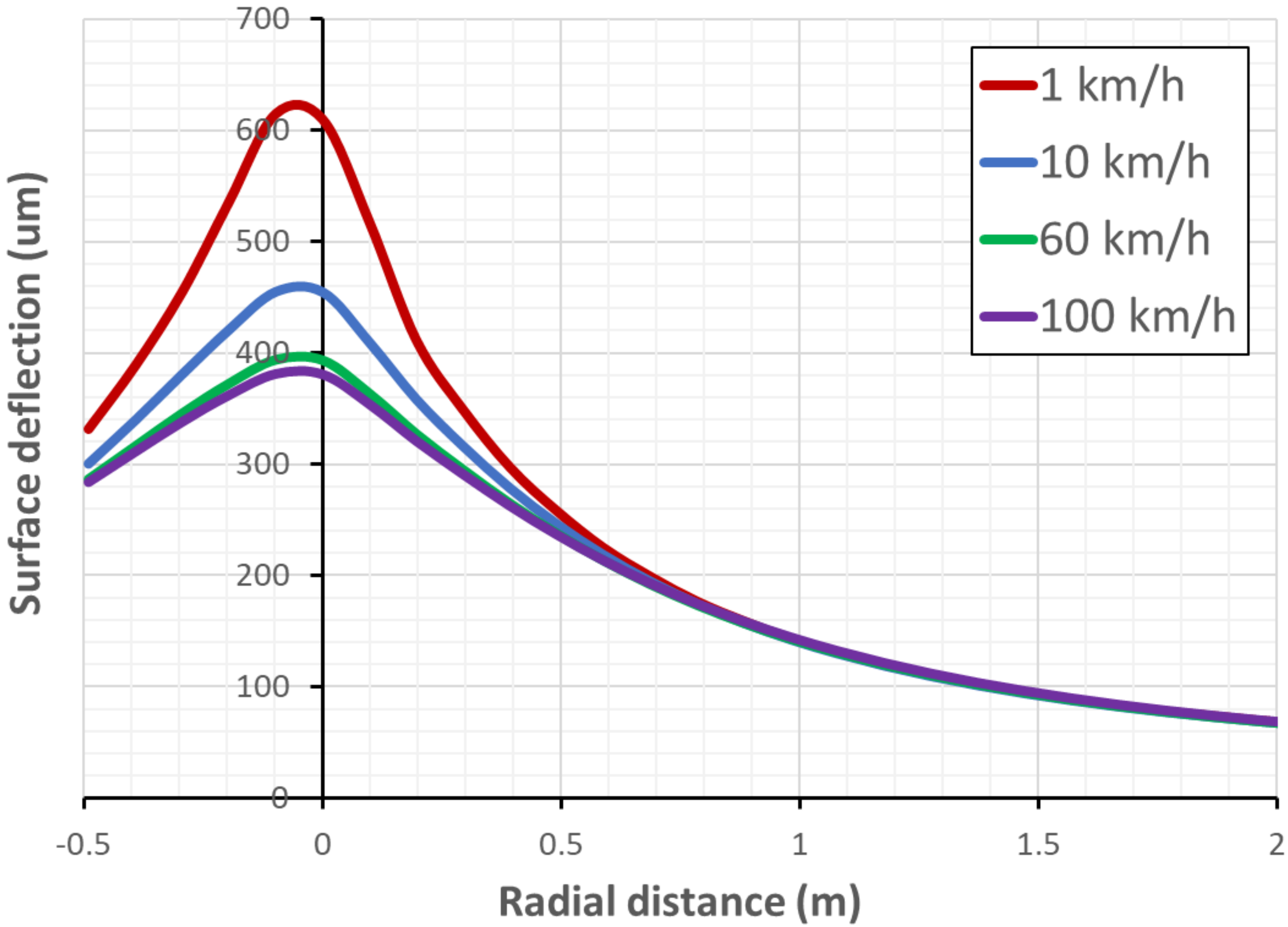
Mixture type



NTNU
Kunnskap for en bedre verden

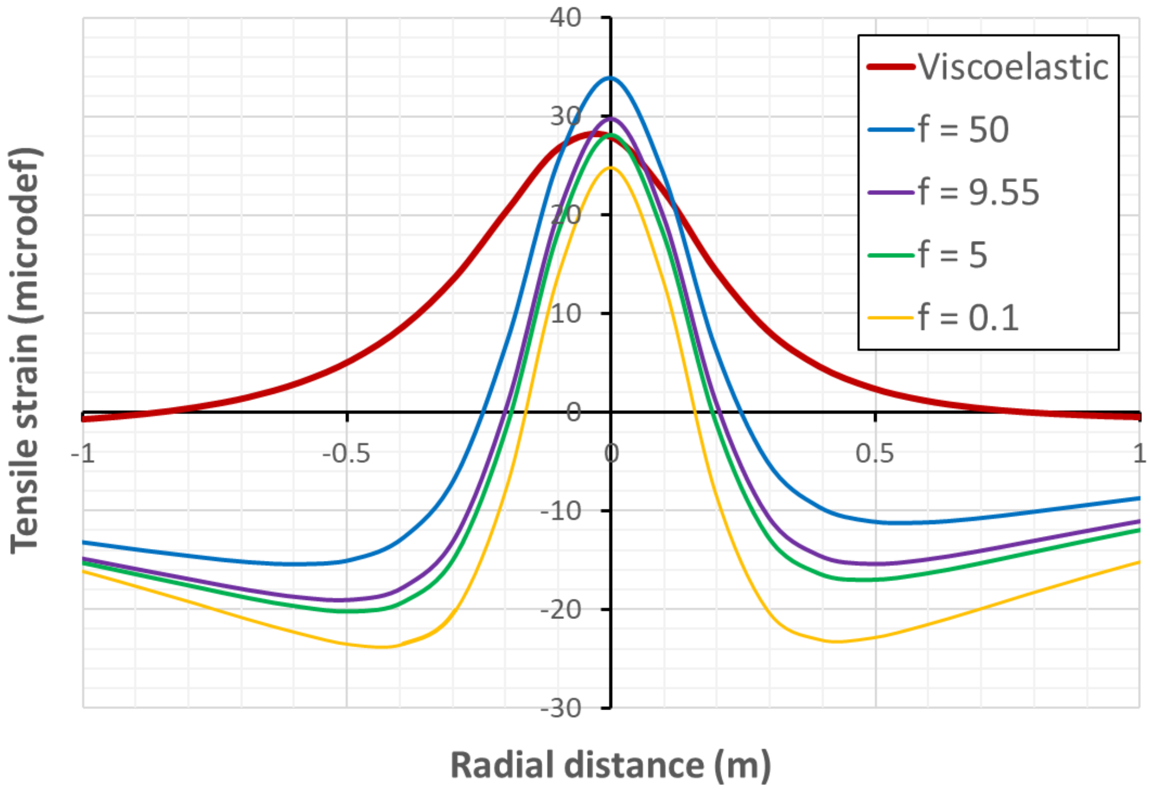
Statens vegvesen
Norwegian Public Roads Administration

Driving speed



Design frequency

- Tensile stress at the bottom of asphalt layers



NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration

Conclusion

- Repeatability of TSD and Raptor
- A good correlation between TSD and FWD
- Regression models between TSDDs and FWD can be defined
- Correcting Raptor data increases consistency with FWD in determining bearing capacity
- Raptor data should not be used in elastic back-calculation prior to refinement
- Regression correction models might not be unique
- Viscoelastic characteristics must be considered

Future studies

- Incorporating a viscoelastic analysis into ERAPave software
- Relationship between model parameters and deflection slopes of TSDDs should be established
- Determining deflection slopes from Raptor
- A more accurate procedure for obtaining deflections from deflection slopes should be obtained
- A temperature correction factor for TSDDs can be defined
- A speed correction factor for TSDDs can be obtained
- A more accurate formula for design frequency can be defined
- A new viscoelastic back-calculation procedure for obtaining pavement layers' moduli from TSDDs can be developed

Thank you

Email:
arman.hamidi@ntnu.no

Contact number:
(+47)92083152

Address:
Department of Civil and Environmental Engineering, NTNU, Trondheim, Norway

NTNU
Kunnskap for en bedre verden

Statens vegvesen
Norwegian Public Roads Administration