Quantitative Engineering Sustainability:
Integration of Mechanics-based Models and Life Cycle Environmental Footprint

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HPC day

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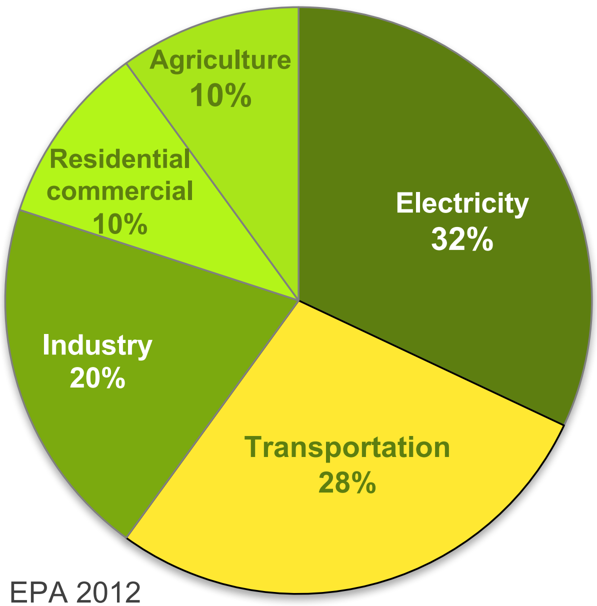
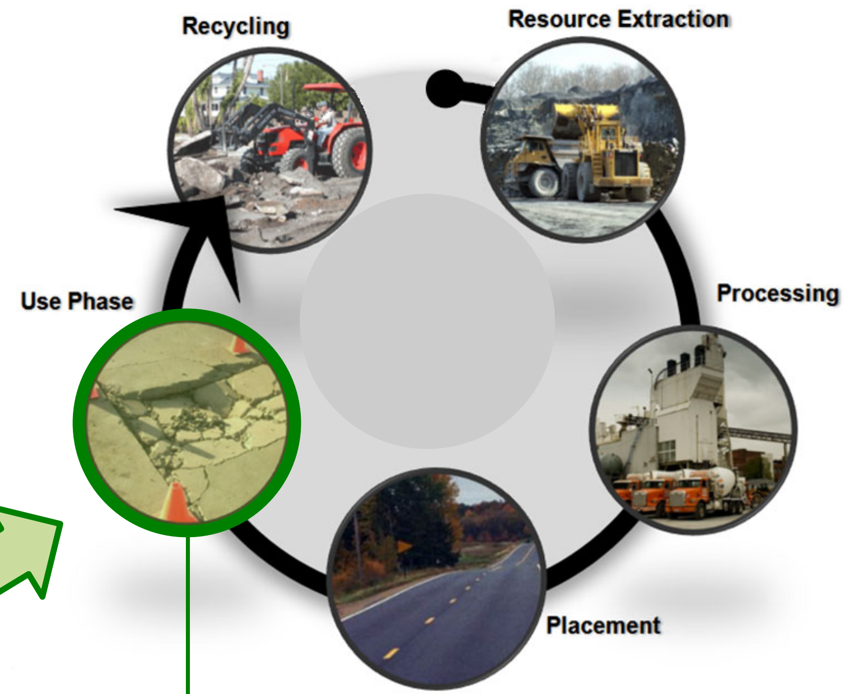
Path to sustainable roadway network



EPA 2012



Quantitative Engineering Sustainability

Pavement characteristics

MODEL

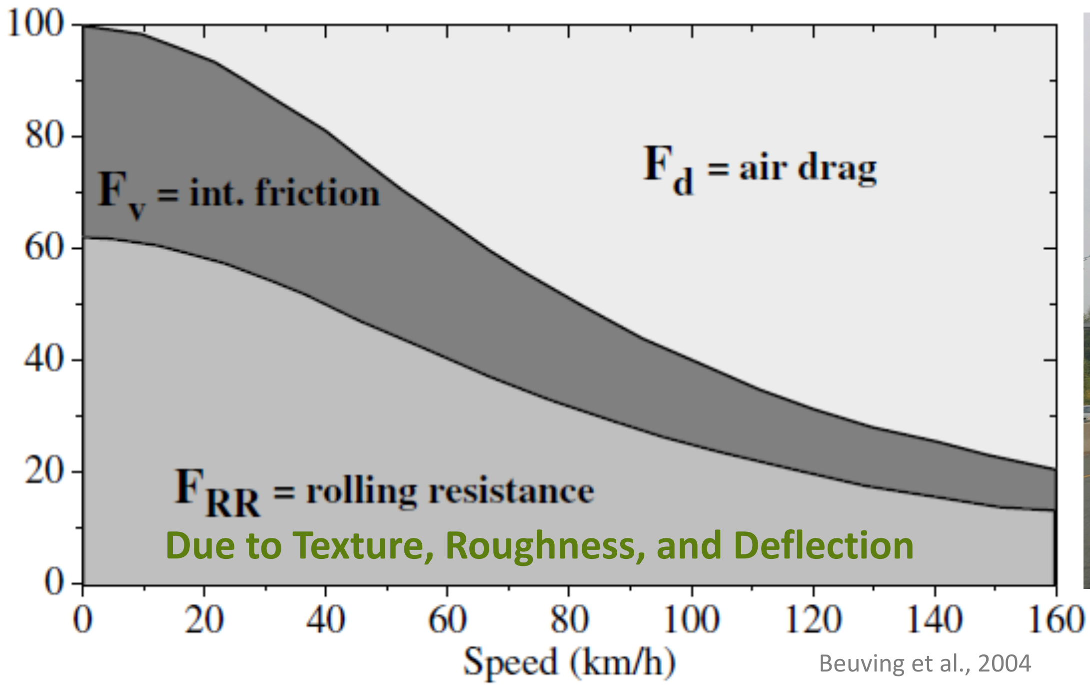
Environmental impact

Low use-phase impact via informed decision making:

- Optimal maintenance strategies
- Sustainable design of future structures

Dissipation mechanisms

Energy distribution in passenger car versus speed as a percentage of available power

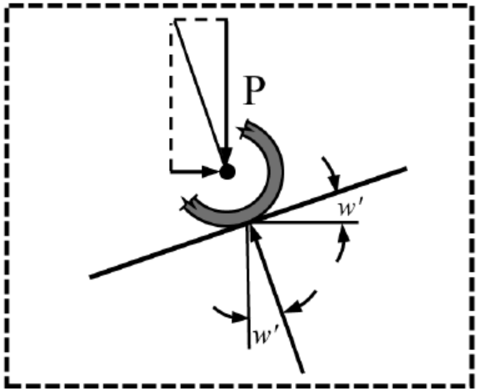


Beuving et al., 2004

http://www.en.wikipedia.org

Key drivers of rolling resistance

- Pavement deflection*:
  - Stiffness & thickness matter!
  - Speed & temperature (specifically for inner-city pavement systems)

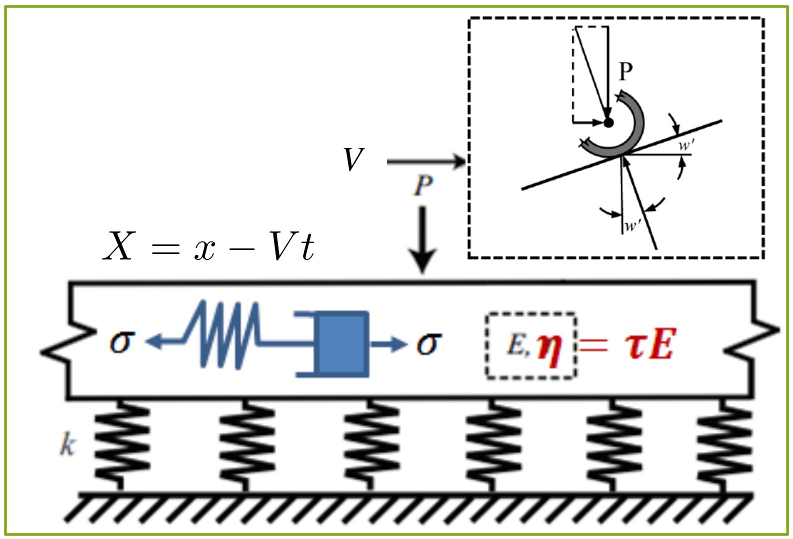


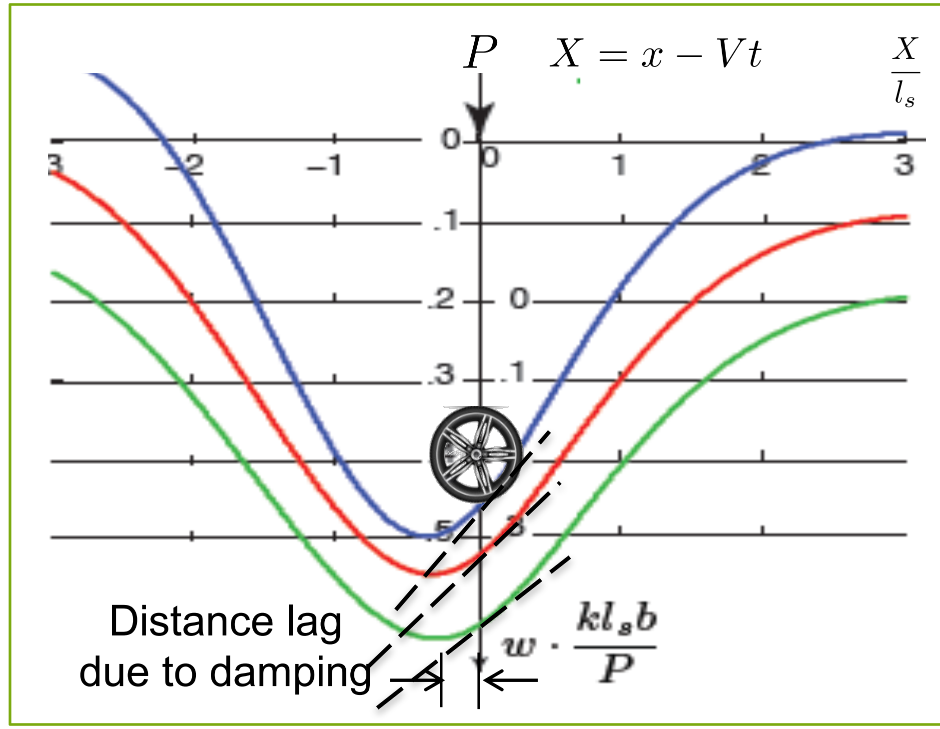
- Pavement roughness**:
  - Both road and vehicle dependent.
  - Evolution in time: material specific

- Pavement texture:
  - Tire-pavement contact area
  - Critical for safety

* Louhghalam A, *et al.*. Journal of Engineering Mechanics (2013)
**Louhghalam A, *et al.*. Journal of Engineering Mechanics (2015)

Deflection-induced PVI model





Max deflection behind the wheel; wheel on uphill

Clausius-Duhem inequality (2nd law of thermodynamics)

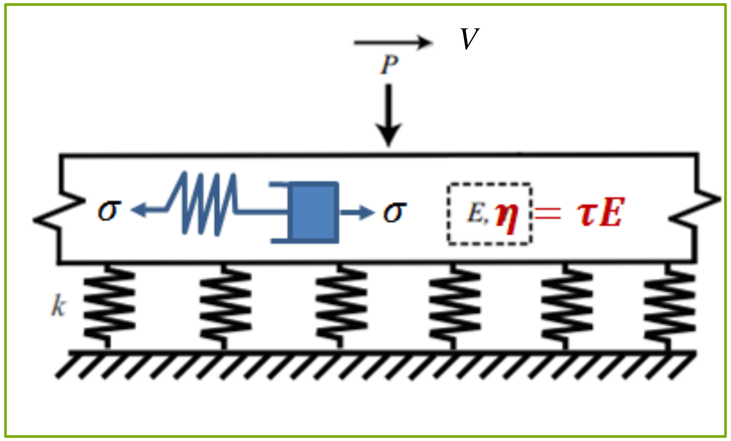
Dissipated energy $\delta\mathcal{E} = \frac{1}{V\tau}\int_{\ell}\frac{M^2(x,t)}{EI}dx$ **=** $\delta\mathcal{E} = -P\frac{dw}{dX}$

Deflection-induced PVI

Scaling relationship

$$\delta\mathcal{E} \propto (V\tau)^{-1}\, P^2\, E^{-1/4}\, h^{-3/4}\, k^{-1/4}$$

- P : Vehicle weight
- E : Pavement modulus
- h : Pavement thickness
- τ : Relaxation time
- k : Substrate stiffness
- T : Temperature
- V : Vehicle speed



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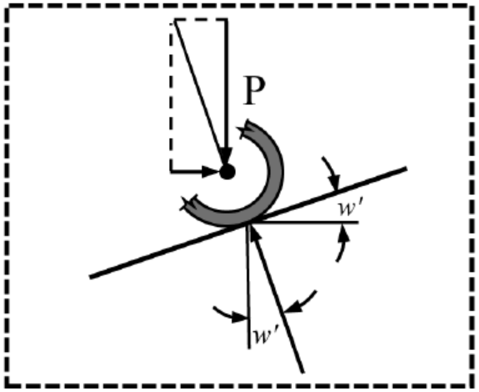

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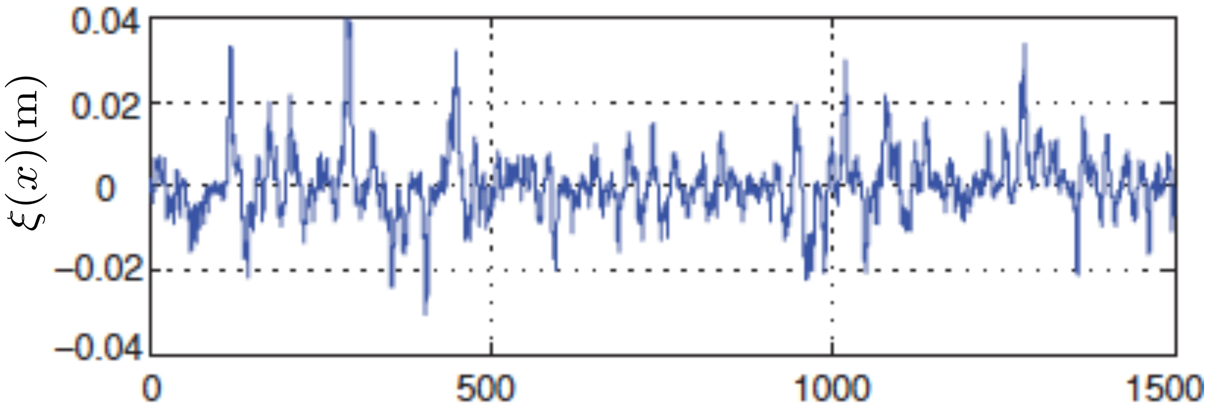
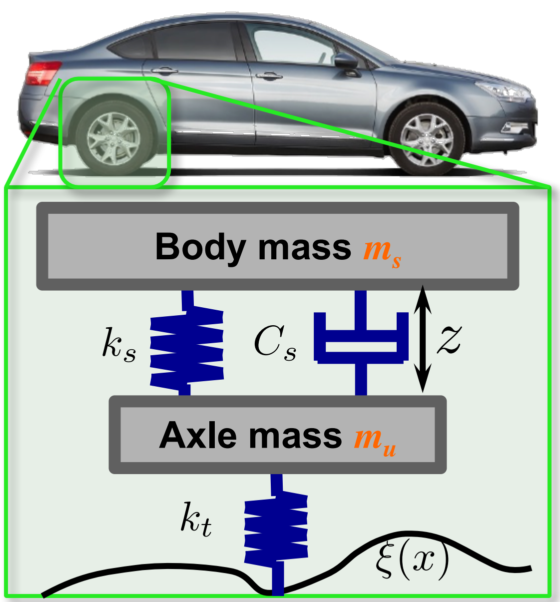
Roughness-induced PVI

Road roughness profile



Dissipated energy

$$\mathrm{E}\left[\delta\mathcal{E}\right] = \frac{C_s}{V}\mathrm{E}\left[\dot{z}^2\right]$$



- Roughness-induced dissipated energy in vehicle suspension must be compensated by the engine power to maintain a constant speed.

$$\mathrm{E}\left[\delta\mathcal{E}\right] = k_d^2 m_s \omega_s^{4-w} V^{w-2} \mathrm{E}\left[\mathrm{IRI}\right]^2 \mathcal{F}\left(\gamma, \beta, \xi, w\right)$$

Scaling relationship

$$\delta\mathcal{E} \propto \mathrm{IRI}^2 V^{w-2}$$

Up-scaling PVI emission to network-level environmental impact

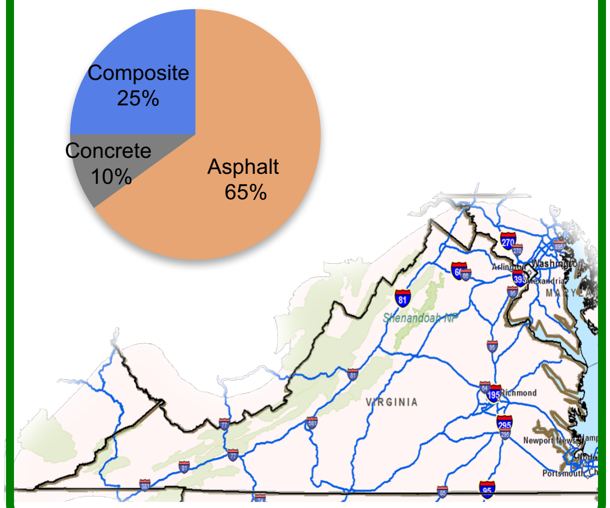
Mechanics-based models = platform for integrating big data

- Total network level environmental impact
- Scientifically-informed maintenance decisions

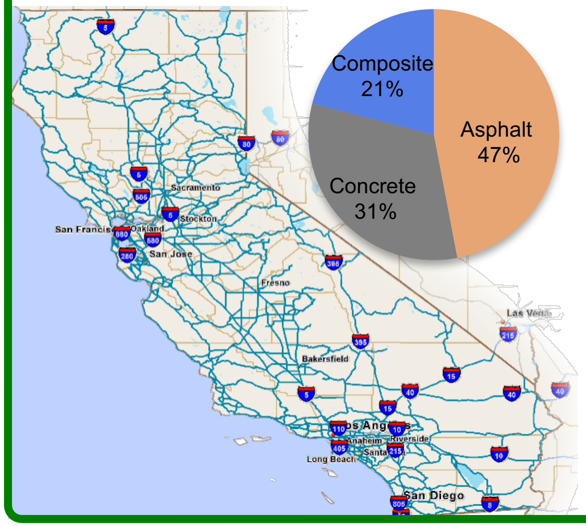
network scale

structural scale

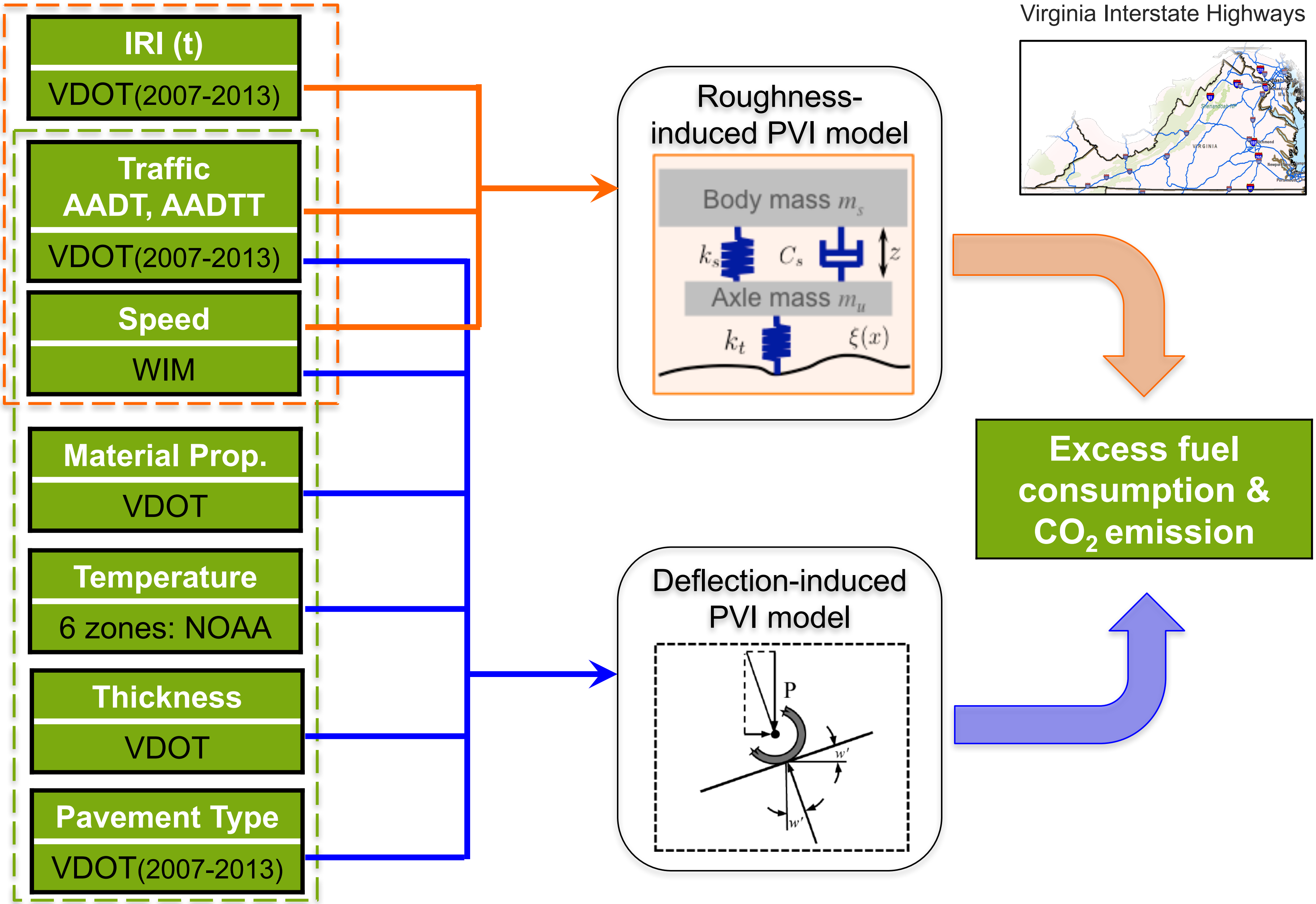
Virginia Interstate Highways



Caltrans roadway network

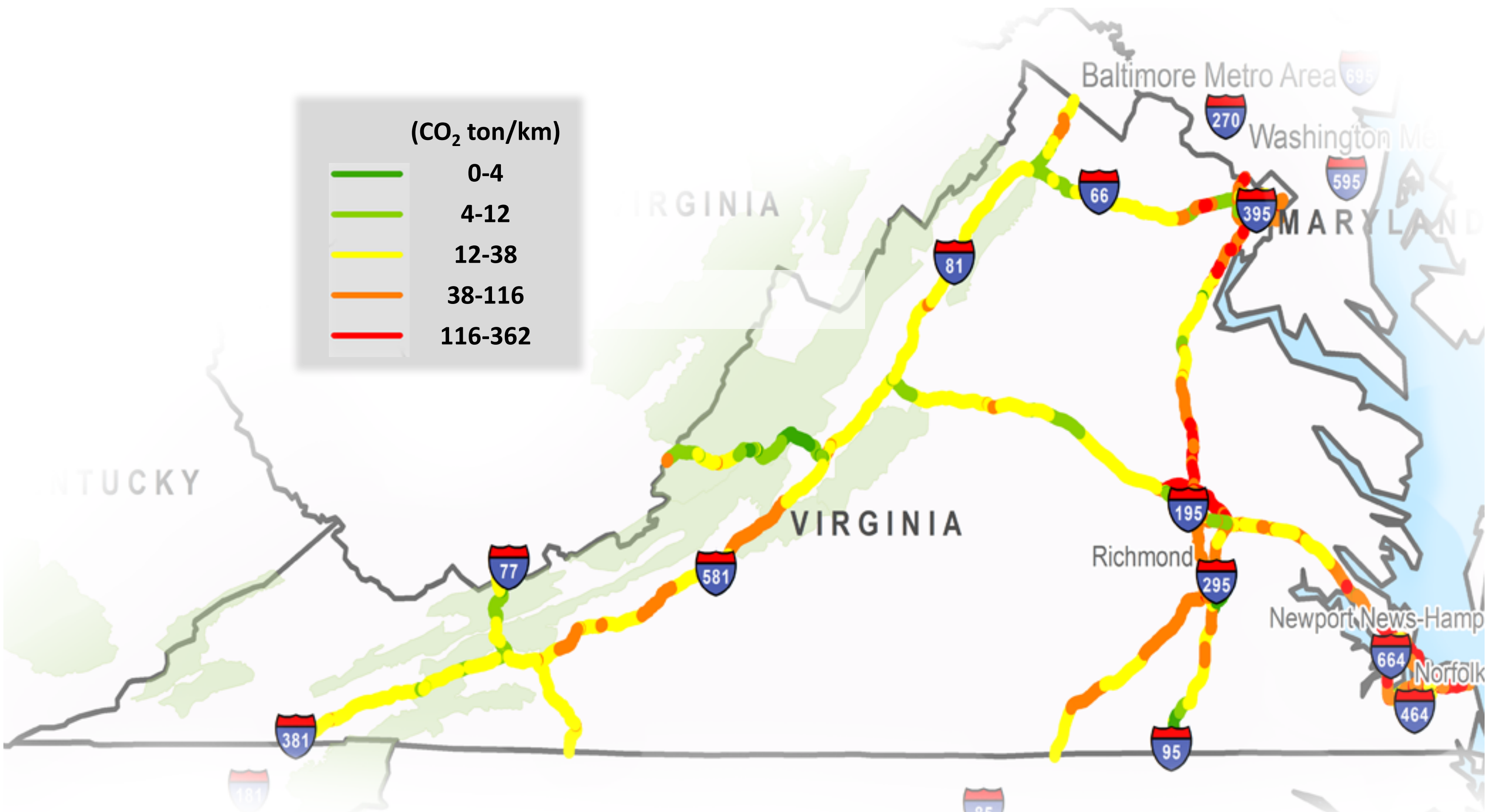


Blending big data into excess CO_2 emissions



Virginia interstate highways emissions

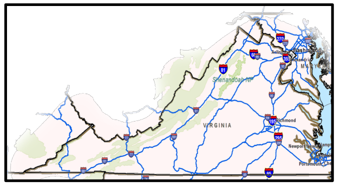
Annual CO_2 emissions (2013)

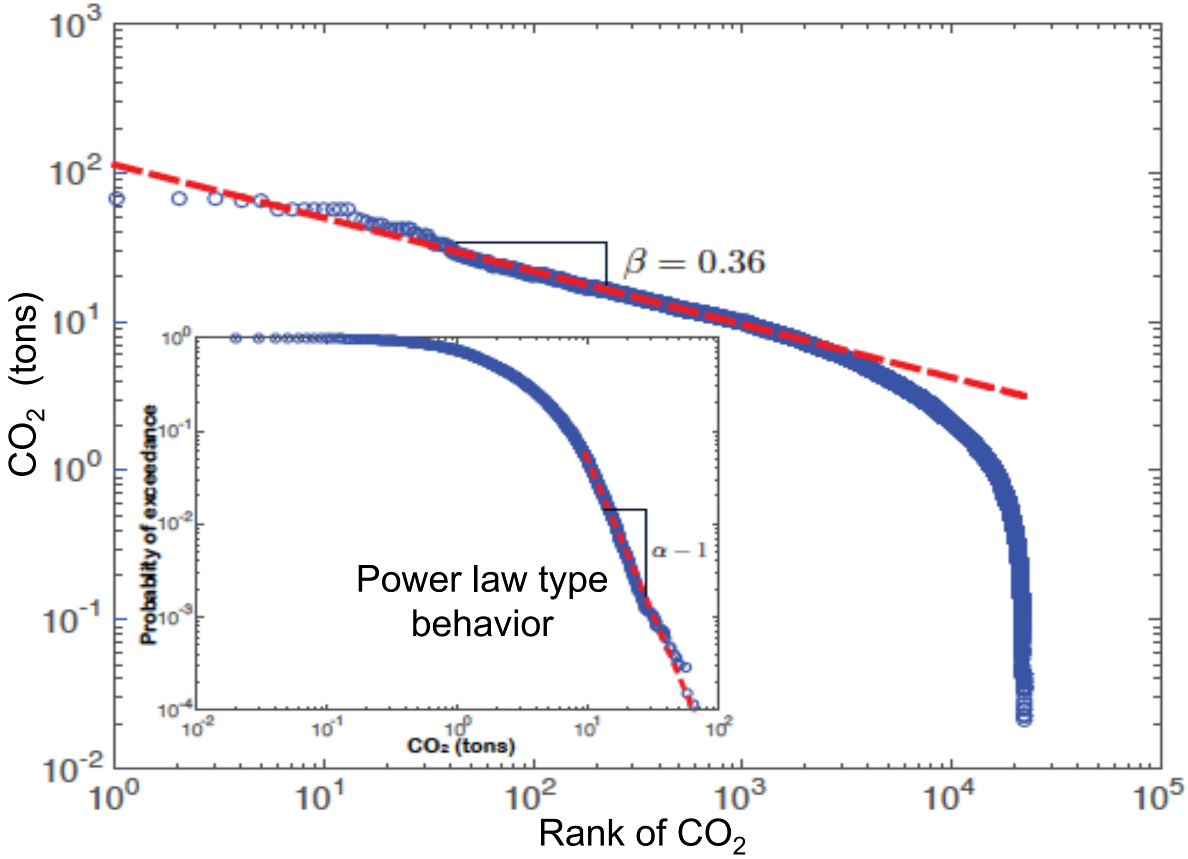


Total PVI impact (2013)

Carbon management via PVI

Strategies for pavement maintenance based on use-phase environmental impact ranking





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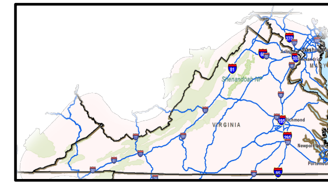
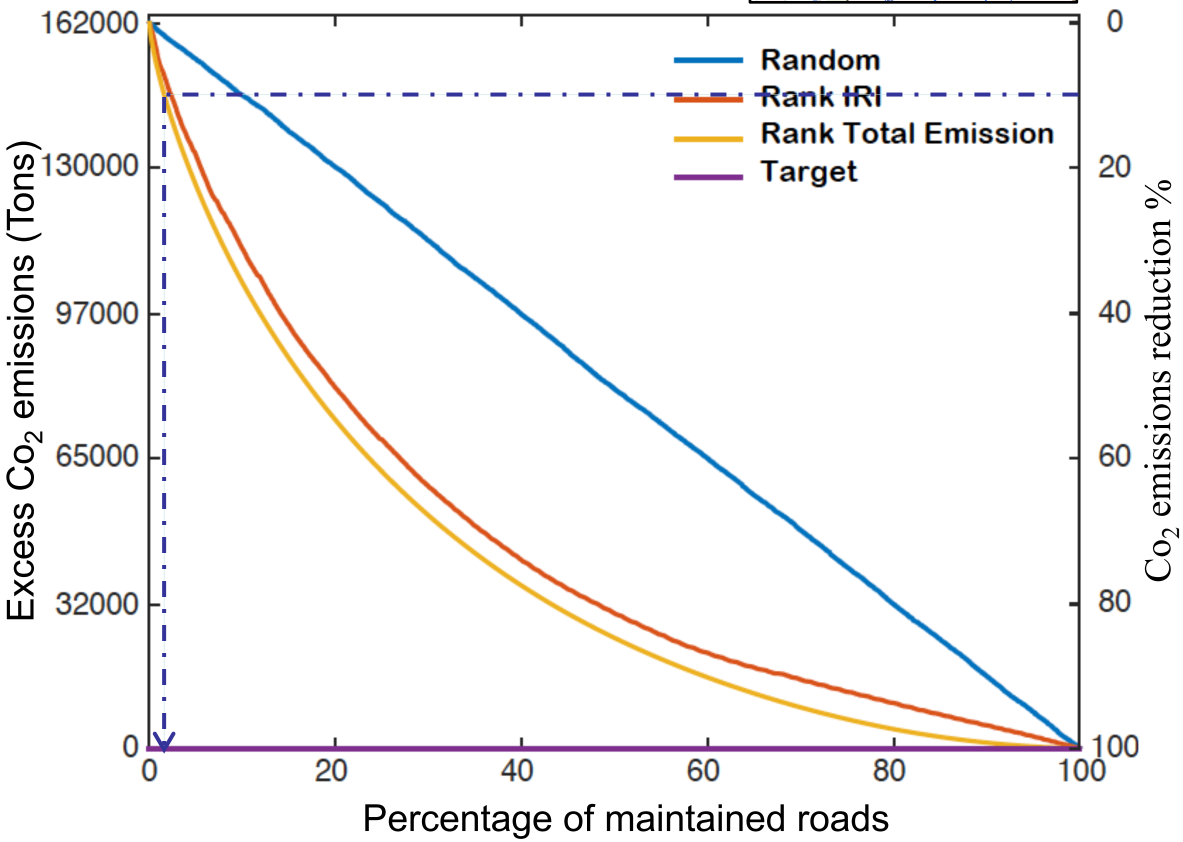


10% reduction in CO_2

Selection criteria	Maintained roads
Random	10%
IRI	2.5%
Excess CO_2	1.5%



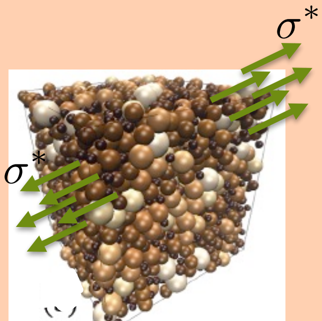
Top 10% contribution to excess CO_2 emission is due to **1.5%** of the analyzed roadway network

Future Outlook

Multi-scale time-dependent framework for sustainable/durable pavement infrastructure

Multi-scale time dependent framework

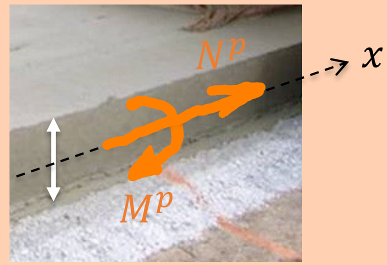
Material scale



[Masoero et al., PRL, 2012]

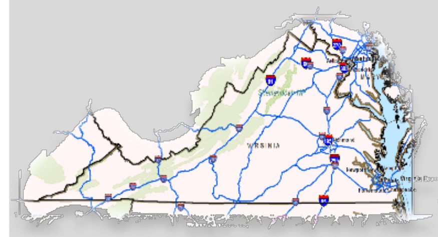
Mechanics
Thermodynamics

Structural scale



Big data
analytics

Network scale



Criteria

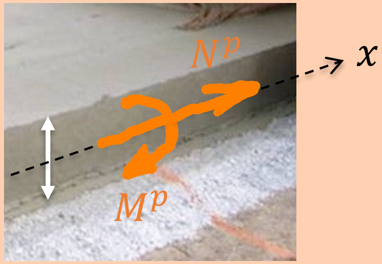
- Early age cracking
- Thermal gradient
- Drying
- Shrinkage
- Alkali silica reaction
- Freeze-thaw

- Damage mechanisms
- Evolution of road roughness
- Evolution of structural properties

Informed decision making

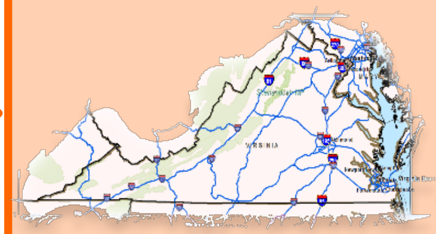
Multi-scale time-dependent framework

Structural scale



Big data analytics

Network scale



Criteria

Informed decision making

- Evolution of characteristics of structure over time

- Total environmental impact over full life-cycle

- Maintenance strategy
- Decision for building new structures
- Real-time decisions

Big data analytics & mechanistic modeling

- Real-time decision making
  - Avoiding routes with high environmental impact (fuel consumption)

- Predictive models for future development decisions
  - Truck lanes with specific pavement properties

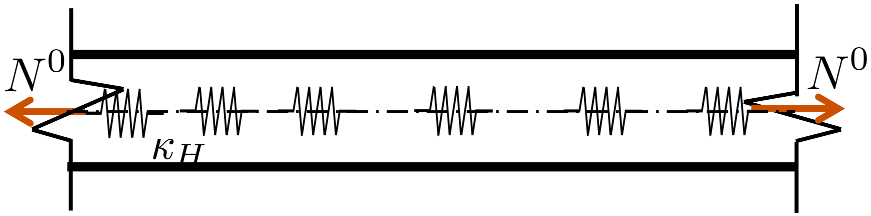
Nokia HERE

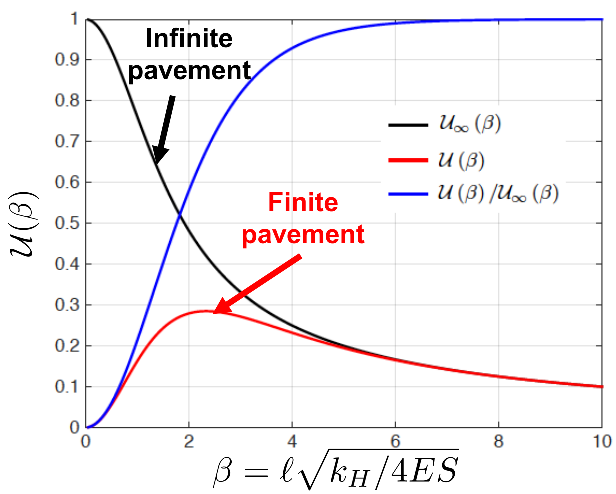
Measured accelerations
LIDAR
Environmental impact!?

company.nokia.com

Fracture mechanics based design

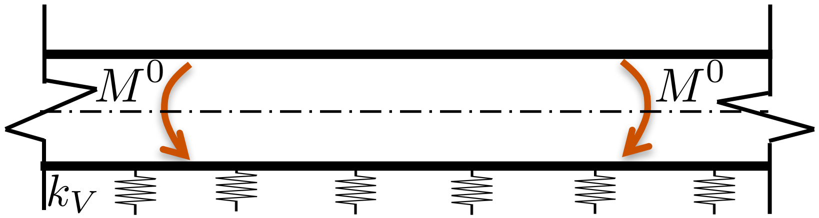
Axial Contribution

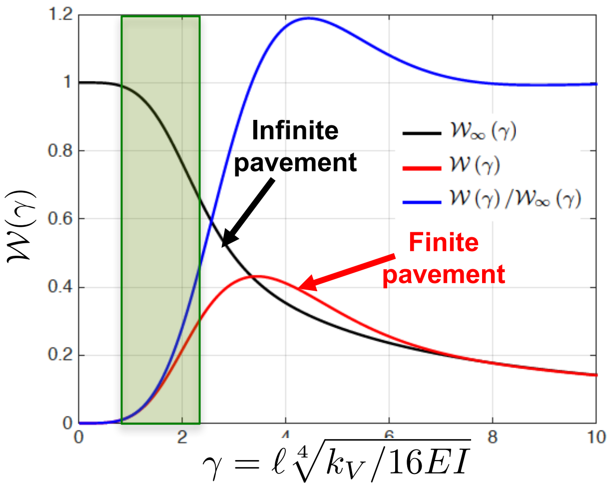




$$\mathcal{G}_{[[u]]} = \frac{1}{2E}\left(\langle N^0\rangle / S\right)^2 \ell \times \mathcal{U}_\infty(\beta)$$

Bending Contribution





$$\mathcal{G}_{[[\omega]]} = \frac{(M^0)^2}{2ESI}\ell \times \mathcal{W}_\infty(\gamma)$$

$$\mathcal{G}_{[[\omega]]} + \mathcal{G}_{[[u]]} < \mathcal{G}_c = \frac{\mathcal{K}_c^2}{E}$$

Fracture mechanics-based design

ASR-induced fracture

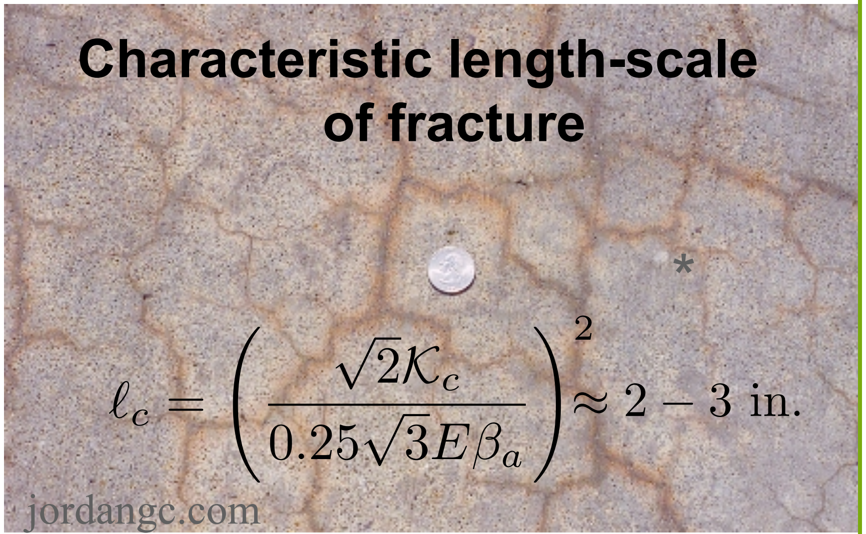
How much? Swelling

Compressive eigenstresses

$$\sigma^p = -E\beta_a\xi$$

When? ASR Kinetics of ASR

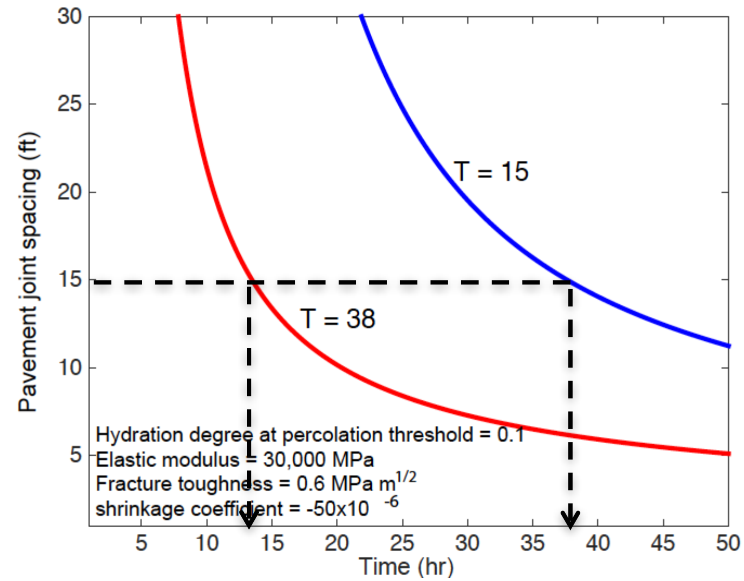
$$\xi(t) = \frac{1-\exp(-t/\tau_c)}{1+\exp(-t/\tau_c + \tau_L/\tau_c)}$$



Characteristic length-scale of fracture

$$\ell_c = \left(\frac{\sqrt{2}\mathcal{K}_c}{0.25\sqrt{3}E\beta_a}\right)^2 \approx 2-3 \text{ in.}$$

Shrinkage-induced fracture



– Critical time for cutting joints

on-site monitoring via hydration kinetics and by adapting to external temperature

$$\mathcal{K} = \langle \sigma^p(\xi) \rangle \sqrt{\frac{\ell}{2} \times \mathcal{U}_\infty(\beta)} \leq K_c(\xi)$$

$$t(T_{ext}) = t(T_0)\exp\left(\frac{E_a}{R}\left(\frac{1}{T_{ext}} - \frac{1}{T_0}\right)\right)$$