Monte Carlo modeling of asphalt surface wear under studded-tire traffic

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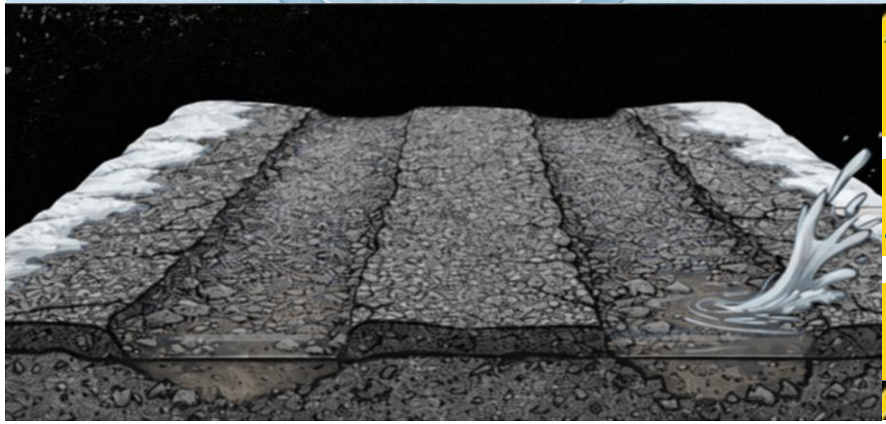
Context

23 % Braking distance on icy surfaces.
(P. Smith & Schönfeld, 1971)

42 % Accidents on snow- or ice-covered surfaces.
(Strandroth et al.,2012)

Québec **9,3 % ± 0,7 %.**
(*MTMD,2025)*



Reduced service life

Aquaplaning risk

Dust generation

Context

Studs

(Angerinos et al., 1999; Kossi and Raatikainen, 2019)

Materials

(Frith et al., 2004; Snilsberg et al., 2017; Keyser, 1970)

Traffic

(Lampinen, 1993)

Environment

(Kayser, 1973; Lind, K., 2015)

Materials and methods

Material sampling

PHASE 1

PHASE 2

Experimental program

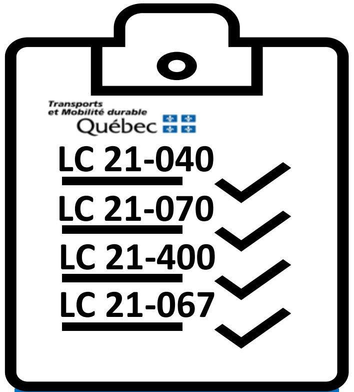
Material characterization

Laboratory traffic simulator

Wear rutting model

Monte Carlo simulation

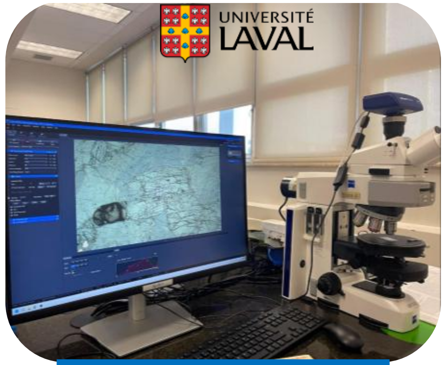
PHASE 3



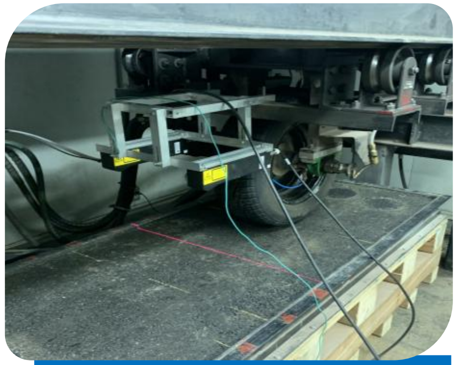
Micro-Deval

Nordic Ball Mill

Prall

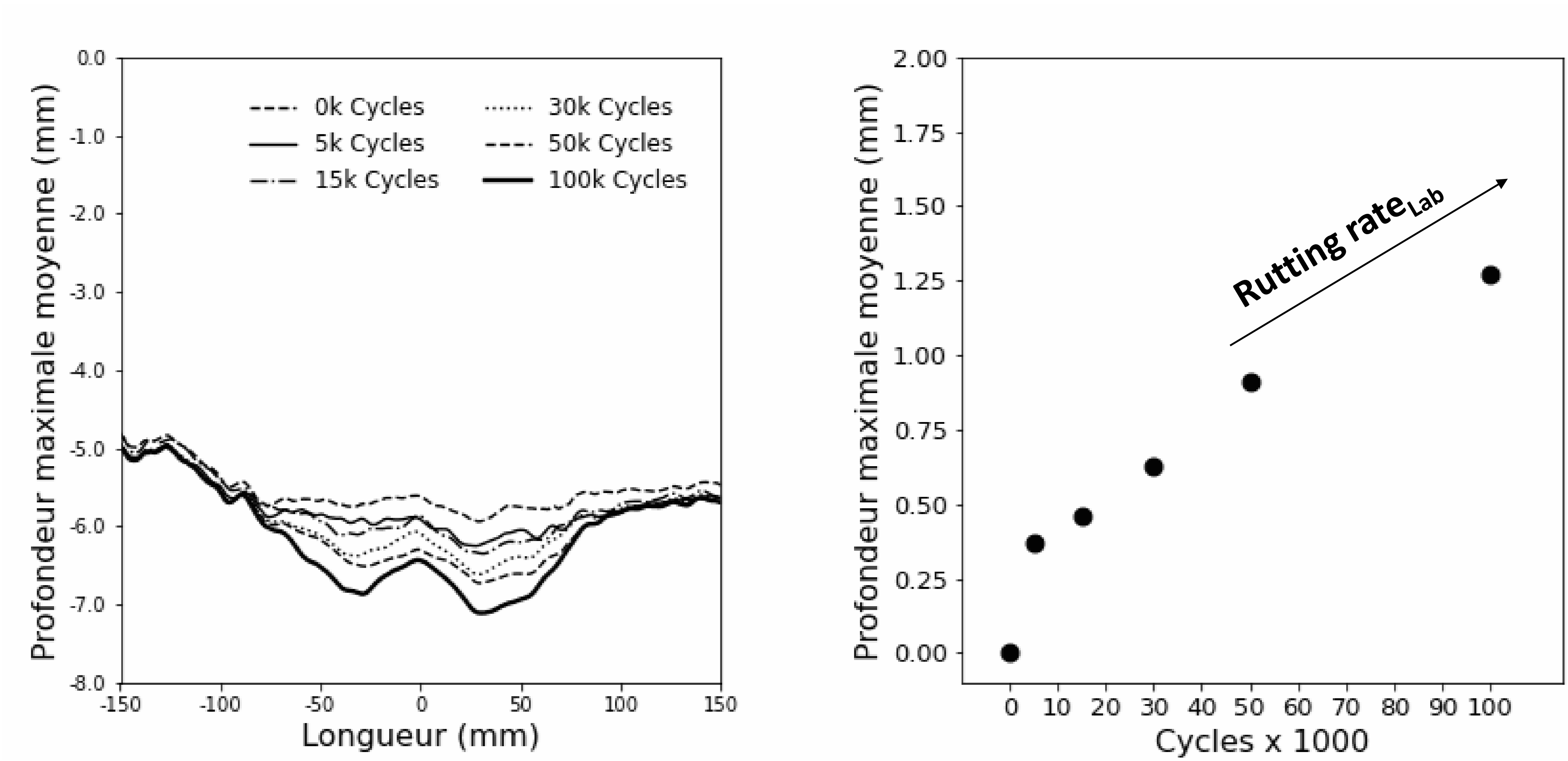


Pétrographie



Traffic simulator

Laboratory traffic simulator



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Model the tire motion using random numbers

Parameters:

R Tire radius
S Number of studs
L Length of the surface

L can be divided into segments of characteristic size *Δx*

Once one stud hits the surface:

$$\boxed{H_i \to H_i + 1}$$

(Riascos, 2019; Newman and Barkema,1999)

Convert surface hits into particle detachment

- **From the hits on each asphalt segment, particle detachment is decided RANDOMLY.**

- **Analogous to evaporation, asphalt particles "evaporate" due to stud impacts.**

Metropolis Algorithm

Given a current configuration $\mathcal{C}$, propose a new configuration $\mathcal{C}'$.

- Compute the energy change

$$\Delta E = E(\mathcal{C}') - E(\mathcal{C})$$

- Accept the move with probability

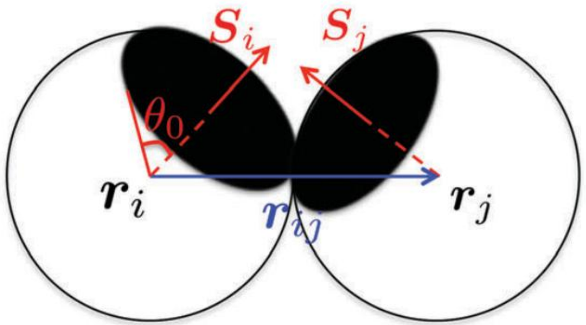
$$P_{\text{acc}} = \begin{cases} 1, & \Delta E \leq 0 \\ e^{-\frac{\Delta E}{kT}}, & \Delta E > 0 \end{cases}$$

- Otherwise, reject the move and keep the current configuration.

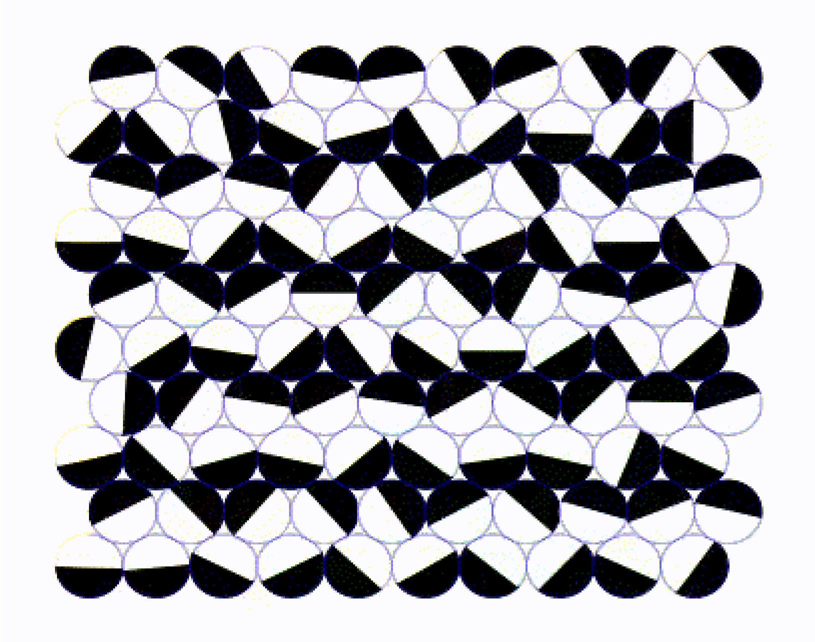
T: Temperature of the system modelled

(Newman, M. E. J. and Barkema, G. T. (1999). Monte Carlo methods in statistical physics. Clarendon Press, Oxford)

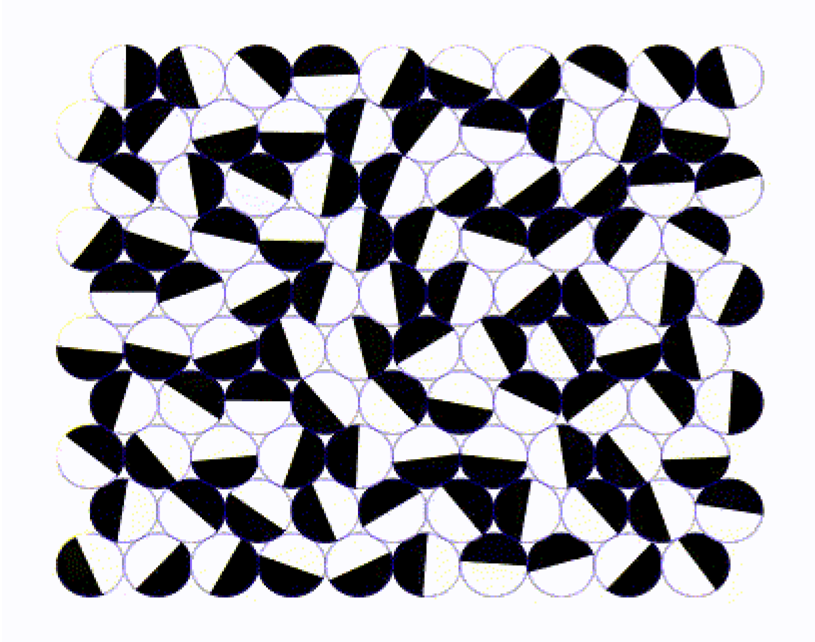
Example: Janus Particles



Janus particles
at temperature T



Janus particles
at higher temperature



(K. Mitsumotoa, H. Yoshino, Orientational ordering of closely packed Janus particles, Soft Matter, 2018,14, 3919-3928)

A model for asphalt surface wear

A quantity similar to the energy in the Metropolis Algorithm:

$$\varepsilon_i = E_0 \, \frac{1}{3} \left(H_{i-1}^{-\gamma} + H_i^{-\gamma} + H_{i+1}^{-\gamma} \right)$$

Stochastic particle detachment

If $\varepsilon_i > \nu E_0$

Particle release occurs with probability

$$p = \exp\left[-\frac{\varepsilon_i - \nu E_0}{(E_0 \Lambda)} \right]$$

γ Damage sensitivity

Controls the degradation rate under repeated impacts

- **Low: more resistant material**
- **High: faster degradation**

ν Detachment threshold

Energy threshold for particle release.

- Strength
- Stud–pavement interaction

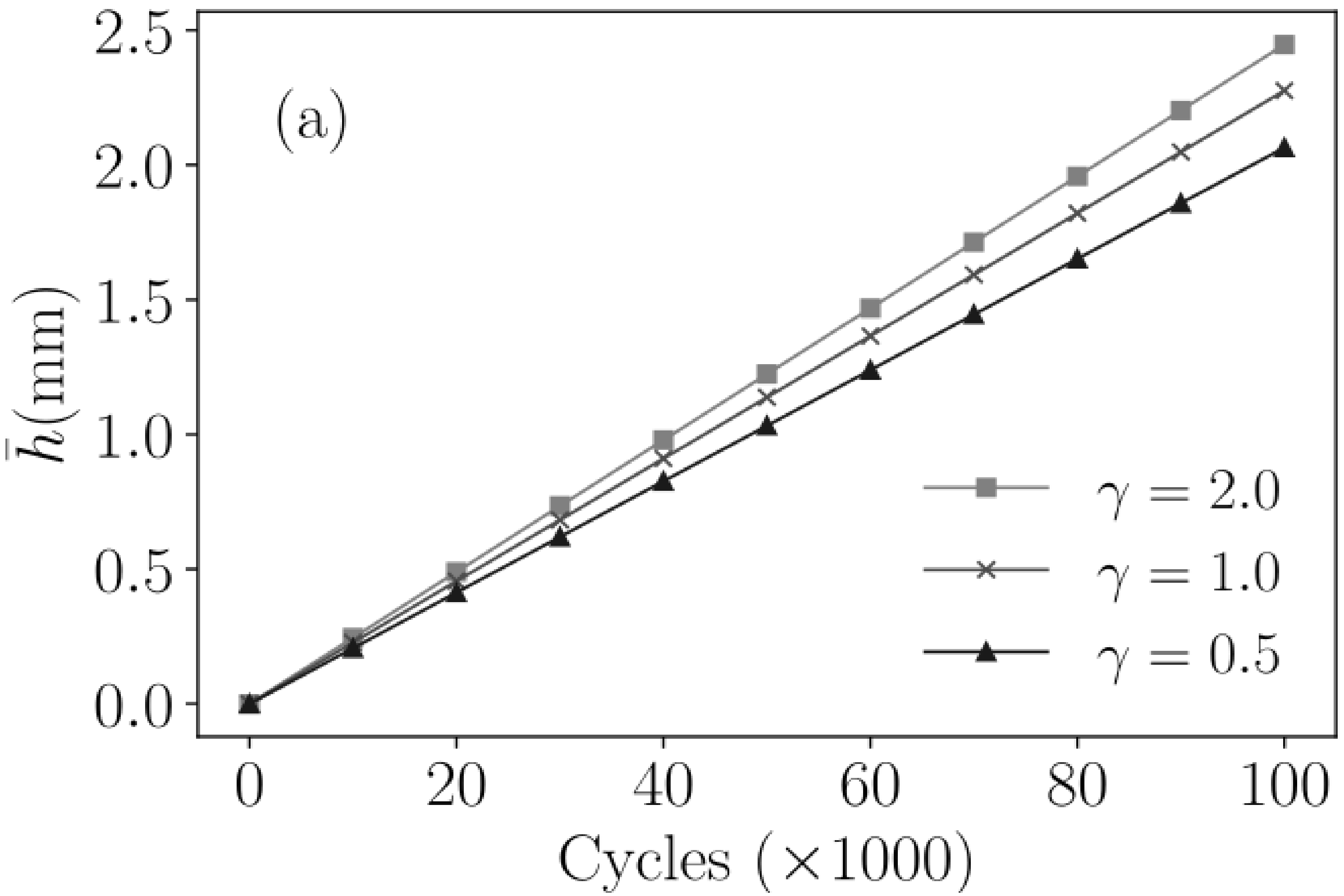
Λ Stochastic detachment factor

Controls spontaneous particle release probability.

- **Low: particles remain attached**
- **High: easier detachment**

(Aging in transport processes on networks with stochastic cumulative damage, A. P. Riascos, J. Wang-Michelitsch, and T. M. Michelitsch, Phys. Rev. E 100, 022312, 2019)

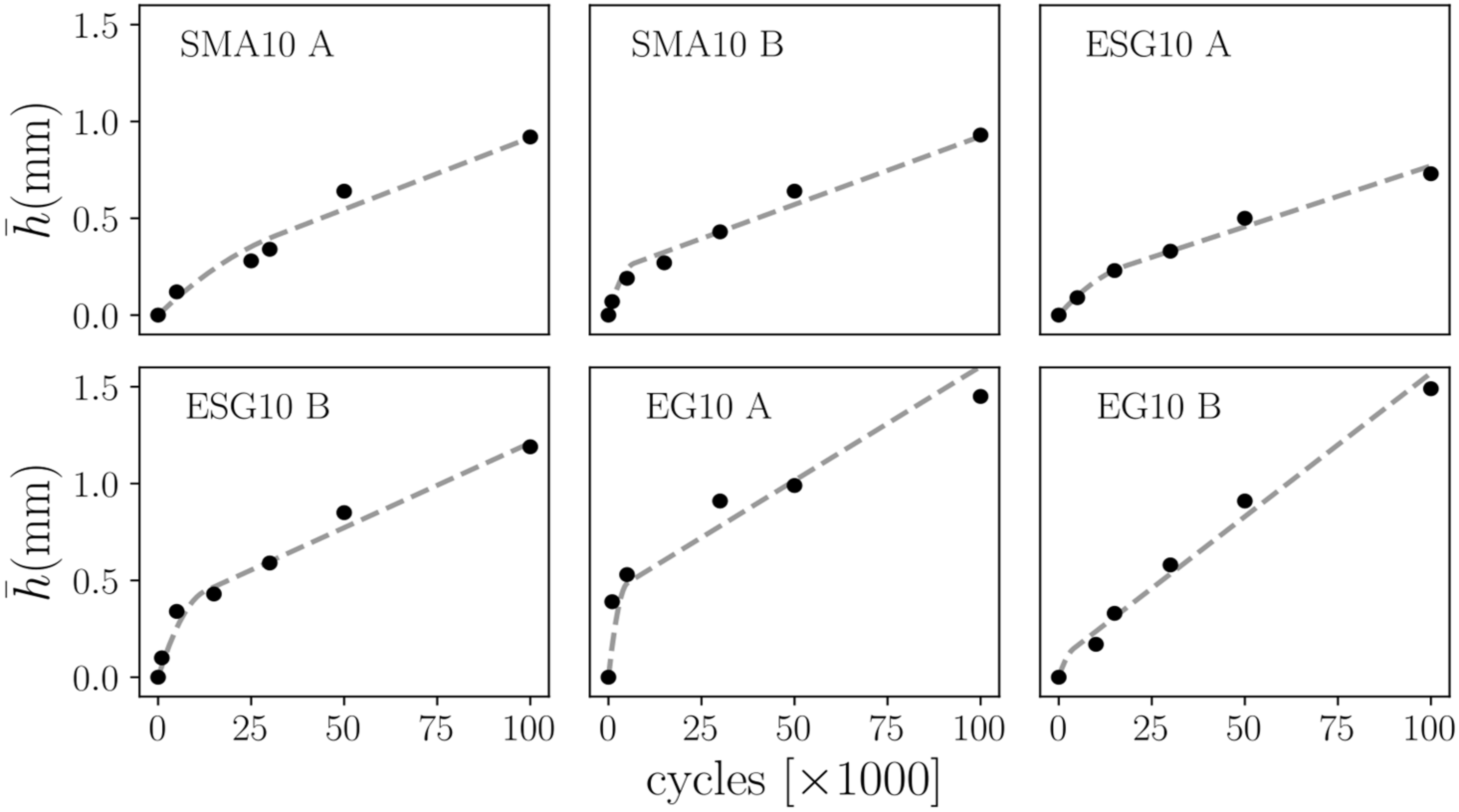
Numerical tests



Rutting rate

(Loaiza D, et al., Monte Carlo modeling of asphalt surface wear under studded-tire traffic, accepted for publication in the Journal of Cold Regions Engineering-2026)

Numerical tests + Laboratory test



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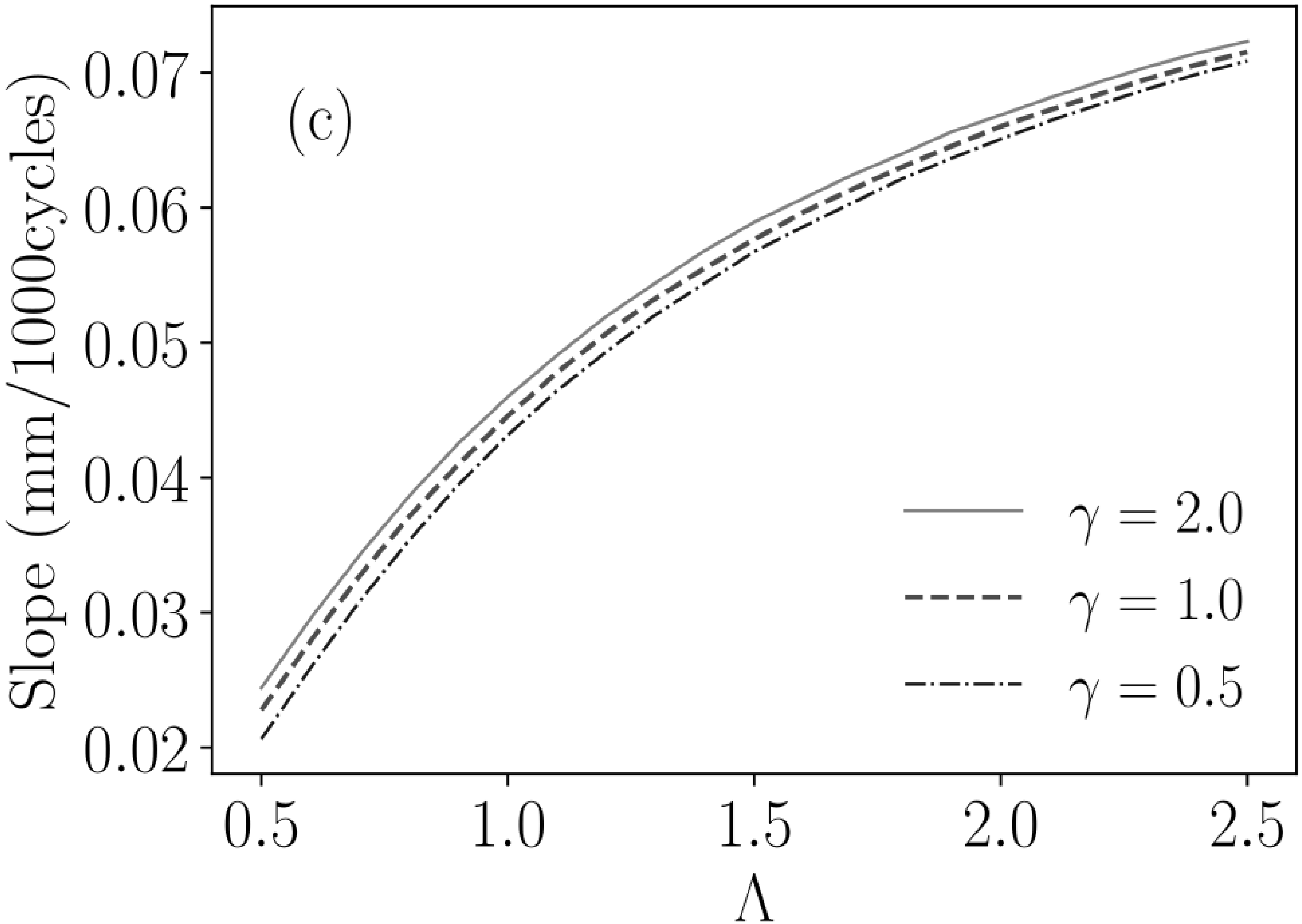
Numerical tests

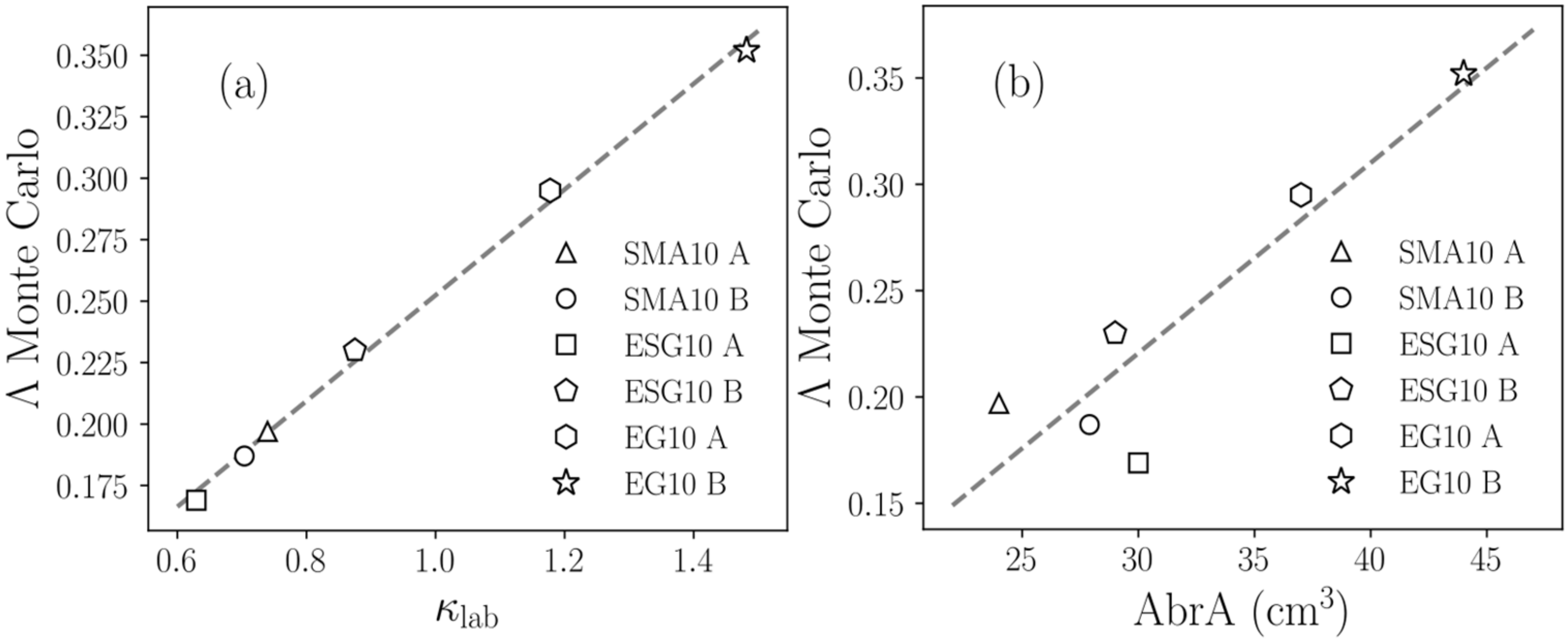


Λ

Stochastic detachment factor

(Loaiza D, et al., Monte Carlo modeling of asphalt surface wear under studded-tire traffic, accepted for publication in the Journal of Cold Regions Engineering-2026)

Numerical tests + Laboratory test



(Loaiza D, et al., Monte Carlo modeling of asphalt surface wear under studded-tire traffic, accepted for publication in the Journal of Cold Regions Engineering-2026)

Conclusions

- Monte Carlo framework captures the stochastic nature of stud impacts and particle detachment.
- Model reproduces transition from nonlinear to steady linear wear response.
- Λ strongly correlates with rutting rate in the lab.
- Lower Λ → higher-quality materials and improved wear resistance.
- Supports mixture design and long-term pavement performance in cold regions.

References

Abaza, O. A., & Dahms, D. (2021). Performance evaluation of studded tire ruts for asphalt mix designs in a cold region environment. Transportation Research Record: Journal of the Transportation Research Board, 2675(7), 32–44.

Angerinos, M. J., Mahoney, J. P., Moore, R., & O’Brien, A. (1999). A synthesis on studded tires. Washington State Department of Transportation.

Doré, G., & Zubeck, H. K. (2009). Cold regions pavement engineering. McGraw-Hill.

European Committee for Standardization. (2014). EN 1097-9:2014—Tests for mechanical and physical properties of aggregates—Part 9: Determination of the resistance to wear by abrasion from studded tyres—Nordic test.

European Committee for Standardization. (2016). EN 12697-16:2016—Bituminous mixtures—Test methods—Part 16: Abrasion by studded tyres

Frith, D. J., Morian, D. A., Stoffels, S. M., & Saboundjian, S. (2004). Hard aggregate resistance to studded tires: Alaskan experience. Transportation Research Record, 1874(1), 19–28.

Hjelle, H. M. (2007). A model for estimating road wear on in-service roads. International Journal of Pavement Engineering, 8(3), 237–244.

Jacobson, T., & Wågberg, L.-G. (2007). Utveckling och uppgradering av prognosmodell för beläggningsslitage från dubbade däck samt en kunskapsöversikt över inverkande faktorer: Version 3.2.03. VTI Notat 7-2007.

Keyser, J. H. (1970). Effect of studded tires on the durability of road surfacing. Proceedings of the 49th Annual Meeting of the Highway Research Board.

References

Kossi, H., & Raatikainen, J. (2019). Study on the effects that the decree on tyre studs has had on currently available studded tyres.

Liikennevirasto. (2018). Tierakenteen suunnittelu (No. 38/2018). Liikennevirasto.

MTMD. (2025a). Internal communication and unpublished data on studded-tire usage surveys (2015 and 2023) [Internal report / unpublished data]. Ministère des Transports et de la Mobilité durable du Québec.

Newman, M. E. J., & Barkema, G. T. (1999). Monte Carlo methods in statistical physics. Clarendon Press.

Riascos, A. P., Wang-Michelitsch, J., & Michelitsch, T. M. (2019). Aging in transport processes on networks with stochastic cumulative damage. Physical Review E, 100, 022312.

Roby, J. (2015). Effets sur la chaussée et impacts sur la sécurité des pneus à crampons (Avis technique N/Réf.: 834(031)13). Ministère des Transports et de la Mobilité durable.

Snilsberg, B., Saba, R. G., & Uthus, N. (2016). Asphalt pavement wear by studded tires: Effects of aggregate grading and amount of coarse aggregate. In Proceedings of the 6th Eurasphalt and Eurobitume Congress. Czech Technical University in Prague.

Strandroth, J., Rizzi, M., Olai, M., Lie, A., & Tingvall, C. (2012). The effects of studded tires on fatal crashes with passenger cars and the benefits of electronic stability control (ESC) in Swedish winter driving. Accident Analysis & Prevention, 45, 50–60.

Takagi, H., Onuma, H., & Shimojo, A. (1997). Effects of studded tire regulation on road environments and traffic conditions in Hokkaido. Hokkaido Development Bureau, Civil Engineering Research Institute, Japan

Thanks!

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