

Improving Winter Braking Safety for Heavy Vehicles

From Field Testing to Predictive Safety Systems (SafeTrucks)

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Executive Summary

Winter braking performance is one of the most critical safety challenges for heavy vehicles operating in Nordic and similar environments. Low-friction surfaces caused by snow and ice significantly increase stopping distances, particularly for heavy trucks and combinations where mass and braking system limitations amplify the problem.

This white paper presents results from controlled winter test campaigns conducted in Pudasjärvi, Finland, in 2025–2026. The findings confirm that braking performance is primarily friction-limited, with typical friction coefficients around $\mu \approx 0.11$. Heavy vehicles exhibit substantially longer stopping distances compared to passenger vehicles due to increased kinetic energy, brake system limitations under low friction, tyre load sensitivity, and reduced effectiveness of snow interaction mechanisms.

The study also shows that an additional braking contribution, referred to as the snow-plough effect, can appear on deformable snow surfaces but becomes negligible on hard polished snow. The results provide a validated physical foundation for the SafeTrucks concept, which integrates smart tyre sensing, environmental data, and digital analytics to enable predictive safety solutions for heavy-duty operation.

1. Background and Motivation

Braking performance in winter conditions depends on the interaction of multiple physical and system-level factors: tyre–road friction, vehicle mass and braking system capability, surface structure and snow properties, tyre design and materials, and ambient environmental conditions.

In classical vehicle dynamics, braking is treated as a friction-limited process. However, this simplified assumption does not fully capture winter conditions where snow can deform, leading to additional resistance mechanisms. On deformable snow surfaces, tyres can generate resistance not only through friction but also through snow compaction, material displacement, and wedge formation ahead of the tyre.

Understanding the relative importance of friction and snow interaction is essential both for improving heavy-vehicle safety and for developing digital systems that can identify changing risk conditions in real time. This white paper combines measured winter braking performance with a practical engineering interpretation and translates the results into the SafeTrucks system context.

2. Test Campaign Overview

The experiments were conducted at Pudasjärvi airfield in Finland under controlled winter testing conditions. The campaigns covered a representative range of light and heavy vehicles and combined braking measurements with smart tyre friction estimation, environmental sensing, and independent reference systems.

Vehicle classes

- Passenger car (~1.5 t)
- Van (~2.2 t)
- Medium-duty truck (~18 t)
- Electric semi-trailer (~40 t)
- Timber truck and trailer combination (~76 t)

Test speeds

- 50 km/h
- 80 km/h

Measurement systems

- Braking distance measurements
- University of Oulu reference systems
- FMI (Finnish Meteorological Institute) optical friction measurements
- Nokian Tyres Intuitu smart tyre friction estimation



Figure 1. Test track at Pudasjärvi Airfield, Finland



Figure 2 –Lappia truck with semi-trailer in braking (2026)

3. Surface Conditions

Two representative winter surface conditions were investigated, providing a practical contrast between deformable and non-deformable braking environments.

Year	Surface Type	Characteristics
2025	Loose snow on polished base	Deformable
2026	Hard polished snow	Non-deformable

Figure 3. Comparison of loose snow (deformable) and polished snow (non-deformable) surfaces.

4. Braking Performance Results

Measured stopping distances at approximately 80 km/h show a clear vehicle-class hierarchy, with heavy vehicles requiring substantially longer distances to come to a complete stop under the same winter surface conditions.

Vehicle	Stopping Distance (m)
Passenger car	110
Van	170
Truck (18 t)	195
Semi-trailer (40 t)	203
Combination (76 t)	207

Figure 4. Braking distance comparison across vehicle classes.

Key observation

Braking distance increases significantly with vehicle mass. Although theoretical friction-only models imply mass-independent stopping distance, practical braking behavior shows a clear mass effect due to system limitations and Tyre behavior under load.

5. Measured Friction Levels

Friction values measured using the Intuitu smart tyre system confirm that the polished snow surface represented a very low-friction operating environment typical of severe Nordic winter conditions.

$$0.107 \leq \mu \leq 0.112$$

$$\bar{\mu} \approx 0.110$$

Braking No	Start speed (km/h)	Measured CoF	Calculated braking distance (m)
#1	73,9	0,111	194
#2	74,1	0,108	210
#3	73,9	0,112	191
#4	74	0,107	201
#5	73,8	0,111	194
Av.	73,9	0,110	198

Figure 5. Measured friction coefficients with Intuitu Smart tyre System

6. Engineering Interpretation

A practical engineering interpretation of winter braking can be formed by combining a classical friction term with an additional snow-interaction term that becomes relevant on deformable surfaces.

6.1 Friction-limited component

$$F_{friction} = \mu \cdot m \cdot g$$

6.2 Snow interaction component

$$F_{snow} = k \cdot A \cdot \sigma$$

or, in a velocity-sensitive representation:

$$F_{snow} = c \cdot \rho \cdot A \cdot v^2$$

6.3 Combined braking model

$$a = \mu \cdot g + F_{\text{snow}} / m$$

$$d = v^2 / [2(\mu \cdot g + a_{\text{snow}})]$$

Interpretation

- Hard polished snow → braking dominated by friction
- Loose snow → braking consists of friction plus additional snow interaction

7. Snow-Plough Effect

The snow-plough effect results from snow compaction, material displacement, and wedge formation ahead of the tyre. When the surface contains a deformable or loose snow layer, this mechanism can add resistance and therefore contribute to braking deceleration.



Figure 6. Snow-plough effect observed during braking.

A key conclusion is that the snow-plough effect is surface-dependent and disappears on hard winter surfaces. Under hard polished snow conditions, braking depends almost entirely on available friction.

8. Heavy Vehicle Braking Behaviour

The increase in stopping distance with vehicle mass is explained by several interacting mechanisms rather than a single cause.

8.1 Kinetic energy scaling

$$E_k = 1/2 \cdot m \cdot v^2$$

Higher mass means proportionally more kinetic energy must be dissipated during braking.

8.2 Brake system limitations

- Limited braking force
- Thermal constraints
- Reduced efficiency under low-friction control conditions

8.3 Load sensitivity of friction

$$d\mu/dF_z < 0$$

Higher wheel load reduces effective friction, making heavy vehicles more sensitive to low-friction surfaces than lighter vehicles.

9. Detailed Tyre Performance Comparison

Tyre design directly determines braking performance because the available braking force depends on the effective friction coefficient μ . Tyre construction also influences how efficiently the tread interacts with deformable snow.

$$F_{friction} = \mu \cdot m \cdot g$$

9.1 Tyre categories

Winter tyres

- Soft compounds optimized for low temperatures
- High sipe density and aggressive tread patterns
- Strong snow interaction and highest effective friction
- Shortest braking distances under winter conditions

All-season tyres

- Compromise design between winter and non-winter use
- Moderate tread and medium stiffness compound
- Moderate friction and longer stopping distances than winter tyres

Energy-efficient tyres

- Harder compounds optimized for low rolling resistance
- Lower tread deformation and weaker snow interaction
- Lowest effective friction and longest winter braking distances

9.2 Snow interaction capability

Tyre Type	Snow Interaction	Snow-Plough Contribution
Winter	High	Strong
All-season	Moderate	Limited
Energy-efficient	Low	Negligible

Figure 7. Tyre tread comparison and snow interaction mechanisms.

9.3 Summary Table: Tyre Types and Braking Impact

Tyre Type	Compound	Friction (μ)	Snow Interaction	Braking Distance Impact	Typical Use Case
Winter tyre	Soft	High	Strong	Shortest	Nordic winter, ADR transport
All-season tyre	Medium	Medium	Moderate	+10–25%	Mixed climate operation
Energy-efficient tyre	Hard	Low	Weak	+25–50%	Fuel efficiency, non-winter focus

Key insight

Tyre selection is one of the most effective and immediate levers for improving winter braking safety, especially for heavy vehicles operating close to friction limits.

10. SafeTrucks System Concept

The SafeTrucks concept builds on measured winter braking physics and translates that understanding into a predictive safety system for fleets and heavy-duty applications.

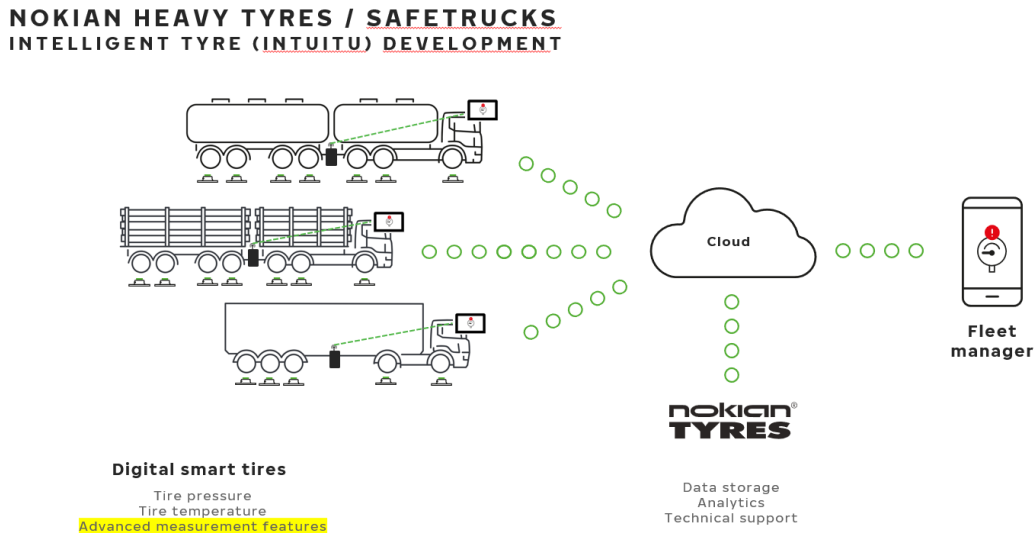


Figure 8. SafeTrucks system architecture.

System layers

- Physical layer: tyre sensing (Intuitu) and vehicle systems
- Digital layer: cloud analytics and FMI environmental data
- Business layer: fleet interface and deployment through service providers

Data flows

- Friction and tyre condition data → tyre sensing
- Vehicle data → onboard systems
- Environmental data → FMI
- Output → predictive insights and alerts

11. Ecosystem

SafeTrucks is enabled through a multi-partner ecosystem that combines tyre technology, environmental data, validation capability, field deployment, and international scaling.

Partner	Role
Nokian Heavy Tyres	Tyre technology and system integration
FMI	Weather services and environmental data
University of Oulu	Tyre measurement and modelling
Tyre service providers	“Total tyre care” for Fleets

12. SafeTrucks Xecs Project

SafeTrucks is developed under the Eureka Xecs framework, where the experimental results in this white paper provide the physical validation layer for a broader digital safety and commercialization concept.

- Real-time friction monitoring
- Predictive braking and safety algorithms
- System-level integration
- Nordic pilot deployment, including ADR trailer applications
- International scaling

13. Impact

Safety impact

- Reduced accident risk
- Better driver and fleet awareness
- Predictive safety alerts and decision support

Business impact

- Fleet safety services
- Digital platforms and analytics
- Scalable data-driven solutions

14. Conclusions

- Braking is primarily friction-limited under polished snow conditions.
- The snow-plough effect is secondary and surface-dependent.
- Heavy vehicles require significantly longer stopping distances than lighter vehicles.
- Tyre types strongly affect braking performance and safety.

Final statement

The integration of smart tyre sensing, environmental data, and analytics enables a new generation of predictive safety systems, forming the foundation of SafeTrucks.