

Determining coefficient of friction between combat vehicles and trailers according to NBN EN 12195-1

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Abstract

Belgian Defence transports combat vehicles using loading plans based on unvalidated coefficient of friction values of 10% and 30%. This study determines the practical coefficient of friction in accordance with European standards to optimise transport efficiency. A horizontal pull testing methodology utilising available military equipment registers traction forces. Pilot tests on concrete confirm setup reliability with a 57.43% dynamic coefficient of friction. Empirical trials with six combat vehicles on two trailer types reveal that actual friction significantly exceeds historical baselines. For trailer decks with gritted metal floors, the practical value ranges between 70.34% and 77.69%, while composite decks with wood and checker plates achieve up to 98.91%. Investigating external factors, including varying environmental conditions and tire pressure adjustments, establishes their practical effects on frictional stability. These data-driven results prove that current safety margins are excessively conservative, providing a scientific foundation to safely simplify lashing configurations and enhance operational safety.

1 Introduction

Belgian Defence frequently transports combat vehicles to training and deployment areas on specialised trailers. Currently, these transport operations rely on loading plans based on assumed coefficient of friction (COF) values, typically 10% for worst-case and 30% for best-case scenarios. However, these figures lack empirical validation, meaning current safety margins may be either dangerously insufficient or unnecessarily conservative, leading to over-engineered or inefficient lashing configurations.

The overall aim of this project is: How to determine the practical coefficient of friction between selected Belgian Defence combat vehicles and transport trailers in accordance with NBN EN 12195-1? To answer this question, four goals are set. The first goal is to analyse and define a testing methodology compliant with NBN EN 12195-1. The second goal is to design and validate a test setup adapted to available Belgian Defence equipment. The third goal is to investigate the impact of external factors such as trailer deck contamination and tire pressure on the COF. The fourth and final goal is to execute all selected tests, gather data and determine the practical COF for each configuration.

The method follows these four research goals systematically. First, standard NBN EN 12195-1 is analysed to determine a procedure that fits the project scope. Second, available equipment is mapped to design a fitting test setup for the requested vehicle and trailer combinations. Third, the impact of external factors is investigated to ensure a comprehensive understanding of their effect on the COF under various operational circumstances. Fourth, the tests are conducted using a dynamometer to measure longitudinal forces, applied by the winch of a tow truck. With the data gathered during these tests, the COF will be established for each specific test configuration.

It is expected that the COF is determined through the horizontal pull method across various combat vehicles and trailers. Since the theoretical COF for rubber on wood ranges between 70% and 95%, the hypothesis is that even under suboptimal circumstances, the practical COF is at least three to four times higher than the currently assumed 10% [1]. Consequently, the confirmed results will likely allow for the use of fewer or lighter lashings to secure vehicles safely and effectively.

2 Method

Belgian Defence currently relies on assumed COF values of 10% and 30% for the development of vehicle loading plans as a baseline for securing equipment [2]. This COF indicates the ratio of force required for sliding to occur compared to an object's weight [2]. It consists of two distinct versions: static friction, which is force needed to start movement, and dynamic friction, which is force needed to maintain it [2]. Currently, these figures serve as a baseline for securing combat vehicles, specifically armoured and unarmoured weapon systems designed for combat zones [3]. However, these values lack a foundation in empirical data, meaning existing lashing plans may be either dangerously insufficient or unnecessarily complex. By establishing a data-driven coefficient, the organisation aims to optimise transport safety and operational efficiency.

The first stage of the methodology focuses on detailed analysis of standard NBN EN 12195-1 to identify all the parameters required for an accurate testing procedure [4]. This involves downsizing extensive regulatory requirements to a focused set of criteria that suit the specific project scope. The goal is to develop a theoretical testing procedure that defines exactly how horizontal pull method should be applied to heavy combat equipment [4]. This method is selected because it replicates longitudinal forces experienced during transport more accurately than an inclined plane method for these specific vehicle-trailer combinations [5].

The second stage involves validating the procedure using available Belgian Defence equipment to ensure theoretical framework is practically feasible. This step maps out necessary resources, including specific vehicles, trailers, and measuring tools like dynamometers to measure pulling force applied by a tow truck winch. A pilot test is planned to verify if setup complies with NBN EN 12195-1 requirements. Based on need, procedure is adjusted and functional diagrams are created to ensure the test can be reproduced flawlessly. This phase ensures that innovation of a standardised testing setup improves resilience of transport infrastructure, directly linking the project to SDG 9 regarding industry, innovation, and infrastructure [6].

The third stage focuses on investigating the impact of external factors to ensure the empirical data remains reliable across diverse operational circumstances. Since transport occurs in varying environments, during this stage environmental

effects such as wet and mud-contaminated surfaces on the established baseline values are tested. Additionally, the effect of lowering tire pressure is analysed to determine how variations in contact area size influence frictional forces. By isolating these variables, the research aims to establish a comprehensive understanding of the safety margins required when baseline conditions are compromised. This investigative step ensures that the results are not only accurate in a controlled setting but also robust enough in an operational military environment.

The fourth and final stage involves execution of tests across all identified configurations to gather necessary empirical data. Each combination of vehicle and trailer is put through validated testing procedure while carefully documenting environmental parameters and surface conditions. Gathered data is interpreted to determine the actual coefficient for each configuration, leading to establishment of specific and general values for future loading plans. By optimising lashing requirements and preventing use of excessive materials, this research contributes to SDG 12 regarding responsible consumption and production by reducing unnecessary wear of equipment and securing materials [6].

3 Results

3.1 Analysis of standard NBN EN 12195-1 and parameter selection

The analysis of standard NBN EN 12195-1 was primarily focused on identifying the mandatory requirements for a standardised tensile test rig. This European standard prescribed four essential components for the horizontal pull method: a horizontal floor representing the loading platform, a tensile device registering force, a connection device to the loading unit and a PC-based evaluation system. Though the components seemed clearly specified, the use of Belgian Defence equipment meant that the rig would resemble the standard as much as possible.

Specific technical parameters regarding data acquisition were extracted from the standard to ensure the empirical validity of the results. This required a minimum sampling rate of 50 Hz and a test speed of 100 mm/min to accurately capture the friction profile. To meet the sampling specifications, a National Instruments USB-6211 data acquisition module was integrated with Dyna-Link MSI7200 dynamometers to achieve a sampling rate of 100 Hz, thereby exceeding the minimum requirement.

To satisfy the requirement for pulling at a low speed but with high force, all available recovery vehicles were tested for winch speed and capacity. Eventually the protected and combat recovery vehicles (PRV and CRV) were identified as the most suitable equipment. These vehicles provided the necessary hydraulic winching power at a speed of 2.5m/min, with integrated height adjustment to keep the pulling force horizontal. Because winches operated at higher speeds than the prescribed 100 mm per minute, the procedure was adapted by increasing the displacement distance of 50 to 85mm to 1.5 to 2.5m. This ensured that the duration of the traction remained consistent with the intent of the standard. Additionally, the PRV and CRV also had 230V power outlets, required for the PC-based logging systems in remote testing environments.

The final stage of the analysis focused on the environmental and safety factors that dictated the measurement of the practical friction factor. It was established that the standard required surfaces to be swept clean and free from impurities, with a mandatory limitation of the friction factor to 20% if these conditions were not met, in accordance with NBN EN12195-1. Furthermore, the standard required a sequence of three individual strokes with at least 30% force reduction between measurements to exclude the influence of material wear and stick-slip effects. These analytical findings provided the necessary criteria to initiate the validation of the selected hardware and measurement procedures.

3.2 Validation of test setup for COF determination

The transition from theoretical parameters to practical measurements required a rigorous validation phase to ensure the integrity of the data acquisition. This process focused on verifying the precision of the hardware components and the repeatability of the test procedure under controlled conditions. Before any operational tests were conducted on trailer platforms, the entire system was assembled and tested on a polished concrete surface. This preliminary phase allowed for the identification of potential systemic errors and ensured that the National Instruments data acquisition (DAQ) system correctly synchronised the signals from the dynamometers.

A primary concern during the validation phase was the linearity and accuracy of the Dyna-Link MSI7200 dynamometers. To verify these instruments, a series of static load tests were

performed where the sensor output was compared against a calibrated pallet scale. These measurements confirmed a linear response across the anticipated force range, ensuring that the analogue-to-digital conversion remained consistent during high-tension events. Furthermore, the sampling rate was monitored to confirm that the 100 Hz frequency was maintained without data loss, which was essential for capturing the peak static friction values prior to the sliding phase.

The physical setup of the measurement chain and the integration of the test vehicle can be seen in Figure 1. This became the standardised setup that was maintained throughout the entire research project. By capturing the horizontal alignment of the components in a controlled environment, the setup provided a benchmark for the subsequent field tests on mobile transport platforms.

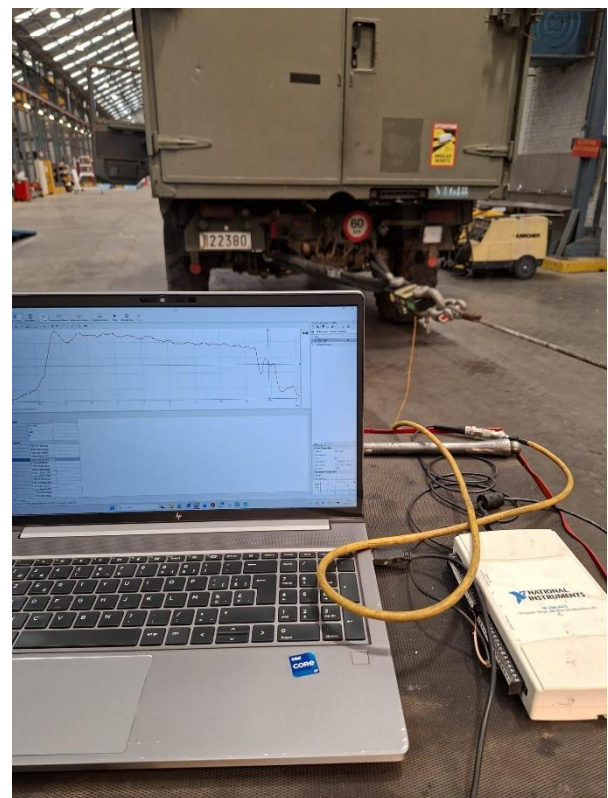


Figure 1 Test setup for tensile test

Figure 1 displays the Unimog test vehicle connected to the PRV's hydraulic winch via the Dyna-Link MSI7200 dynamometers. It illustrates the critical horizontal alignment of the setup, which prevented the introduction of vertical forces. Additionally, the National Instruments USB-6211 data hub is shown, recording the traction force in real-time between fixed distances.

Testing with this setup confirmed that the experimental rig was capable of isolating the horizontal friction force from other external influences. The successful execution of pilot tests on this concrete surface demonstrated that the static peak friction and dynamic friction were clearly detectable and that the measurements were reproducible over multiple iterations. The hydraulic winching system maintained a constant pulling speed, making it possible to plot the friction profile. This profile mapped the relationship between pulling force and time, providing the necessary scientific foundation for the subsequent operational phase.

The final stage of the validation process involved the establishment of the mathematical models used to calculate the COF under different braking conditions. Under standard testing circumstances, where all wheels of a vehicle were fully locked, the COF was calculated by dividing the total measured traction force by the total static weight of the vehicle. This was expressed by the formula (1), where F_{PULL} represented the measured horizontal force and F_N is the total weight of the vehicle. This method provided a baseline for the maximum friction potential when the entire contact surface was resisting the traction.

$$\mu = \frac{F_{PULL}}{F_N} \quad (1)$$

However, because the Unimog was tested using only the parking brake, which exclusively locked the rear wheels, a more complex calculation was required to obtain a reliable result. In this specific configuration, only the tires on the rear axle contributed to the frictional resistance, while the front wheels continued to rotate freely. This resulted in extra weight being pulled onto the rear axle while testing. To account for this, dynamic weight transferral had to be integrated into the equation to determine the actual weight acting on the rear axle during traction. This weight shift was calculated using formula (2) where h represented the height of the towing point and L the wheelbase of the vehicle.

$$\Delta W = \frac{F_{PULL} \times h}{L} \quad (2)$$

To determine the final practical COF for the Unimog, the weight shift was added to the static load of the rear axle, as the rearward traction caused a downward force on the rear of the

vehicle. The resulting formula (3) was defined, where $\Delta W + F_{N, rear}$ represented the combined static and dynamically transferred weight on the rear axle. By applying this specific model, it was ensured that the calculated friction values were not overestimated by incorrectly excluding the mass of the non-braking front axle. This mathematical approach ensured that the findings in the subsequent operational phase remained scientifically accurate and representative of the actual forces at play.

$$\mu = \frac{F_{PULL}}{F_{N, rear} + \Delta W} \quad (3)$$

The practical application of these mathematical models during the validation phase on polished concrete yielded highly consistent results. Initial measurements of the Unimog, prior to the weight transferral correction, showed a significant variance in the calculated friction values. However, once the dynamic weight shift was integrated, the results stabilised, resulting in a verified dynamic COF of 57.43% on the polished concrete surface. These values confirmed that the test setup functioned correctly, as they aligned with the prescribed rubber-on-concrete interactions according to NBN EN12195-1 [4]. This successful validation ensured that the measurement system was sufficiently robust to proceed with the operational tests on real trailer decks.

3.3 Testing impact of external factors on COF

Following the validation phase, the research focused on determining the influence of external factors on practical friction coefficients. To set a baseline, tensile tests were conducted with the same Unimog on a Broshuis trailer. This trailer featured a uniform trailer deck, consisting of a specialised gritted metal floor called Agrain. Each test from this point on was conducted ten times to gather sufficient data. The consistency of the data confirmed the reliability of the testing procedure.

In contrast to the conservative assumptions currently used by Belgian Defence, these measurements provided empirical evidence of a much higher friction potential. A graph of the fourth measurement can be seen in Figure 2 on the next page.

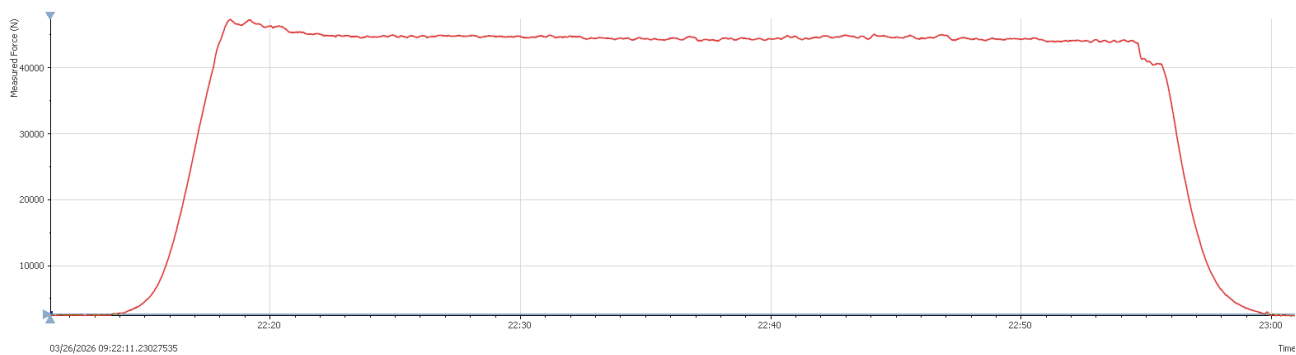


Figure 2 Tensile test of Unimog on Broshuis trailer

The traction force recorded during the standardised test on the Broshuis trailer was visualised in Figure 2. This graph represented the relationship between the measured horizontal pulling force and the elapsed time during the execution of one of three consecutive strokes. The graph displayed the fluctuations in traction force as the winch operated at a constant winding speed, showing a clear transition from the initial static resistance peak to a slightly lower, stable sliding phase. It served as the primary evidence for establishing the dynamic friction characteristics of the Broshuis Agrain surface by monitoring the force profile over a continuous interval.

Only a mathematical interpretation of the dynamic force measured in Figure 2 remained. Dynamic load transferral was not needed, as the friction caused by the Unimog required the footbrake to be used. The handbrake was not strong enough to withstand the pulling force, which caused the vehicle to roll instead of slide. Using formula (1), a dynamic COF of 74.38% was established based on the stabilised force levels recorded after the initial peak. The average dynamic force measured at 44610N, while the vehicle's weight was established at 59370N. This confirmed that the currently applied COF of 30% in military lashing plans was extremely conservative.

To analyse the influence of different trailer deck materials, ten subsequent measurements were performed on the Heavy Equipment Trailer (HET). Contrary to the uniform Agrain surface of the Broshuis trailer, the HET deck consists of a mix of wood and checker plate. The testing procedure resulted in a higher friction profile compared to the Broshuis. It was observed that the dynamic COF on the HET trailer reached values of 84.05% for full contact with wooden surface. When the Unimog was placed upon checker plate it even reached up to 98.91%. All measurements taken while the

Unimog was placed upon a mix of both wood and checker plate, resulted in values between those two. This confirmed that the material composition and surface condition of the deck were decisive factors. To obtain reliable results for a properly determined COF, tests needed to be carried out with different vehicles on both trailer types.

The impact of environmental contaminants was investigated next, by performing a series of tests under wet conditions. These tests were also conducted with the same Unimog on the Broshuis trailer, which allowed comparison between the results. Water was permanently sprayed on the trailer deck by using a fire hose. Unexpectedly, water did not reduce friction. In fact, a slight increase in frictional force was detected, which may be a result of the stick-slip effect [7]. Another explanation for this increase is the suction effect caused by the vacuum that is created as water is displaced from the contact patch between tire and trailer deck [8]. The COF in this case increased to 76.72%, which is a 2.34% increase compared to the baseline of 74.38% in dry circumstances. Due to the strangeness of the result a second series of ten measurements was conducted, confirming that there is no negative impact caused by wet conditions on this trailer deck.

Further trials were conducted to evaluate the influence of mud contamination, which presented a more significant challenge to frictional stability. These tests were performed in heavy terrain where the Unimog was driven through a puddle of mud between all measurements to simulate a worst-case scenario. This resulted in a considerably lower COF of 58.16%, which was 16.22% less than the baseline. In relative terms, the mud caused a 21.81% decrease in the friction coefficient. However, this test confirmed the hypothesis that the actual COF would remain significantly higher than the 10% currently used for worst-case scenarios, as the measured value remained nearly six times higher than the military standard.

Finally, the influence of tire pressure on the friction coefficient was analysed, as it directly affected the size of the contact surface area. Again, ten tests were conducted, this time with tire pressure at half of what the manufacturer subscribed for the Unimog. This series of tests demonstrated that reducing the tire pressure from a standard operating pressure to a reduced pressure resulted in an increase in the COF by 6.37%. It was observed that the larger footprint allowed for a more efficient distribution of the normal force, which stabilised the traction force during the sliding phase.

The comprehensive data regarding the impact of environmental and mechanical variables on the friction coefficient was systematically compiled in Table 1. This table illustrates the empirical findings derived from the multi-iteration testing cycles executed with the Unimog on the Broshuis trailer.

Table 1 Summary of environmental and mechanical influences on COF

External factor tested	Empirically proven COF	Difference with baseline
None (baseline)	74.38%	/
Water	76.72%	+ 2.34%
Mud	58.16%	- 16.22%
50% Tire pressure	80.75%	+ 6.37%

The values displayed in the table above indicated that while environmental contaminants and mechanical adjustments shifted the friction levels, the final outcomes remained remarkably robust. The baseline configuration achieved a dynamic COF of 74.38%, which increased to 76.72% under wet conditions and reached its peak at 80.75% when the tire pressure was halved. Conversely, the introduction of mud on the trailer deck generated the most severe degradation, causing a substantial absolute drop of 16.22% down to the lowest coefficient, being 58.16%.

The data contained in Table 1 confirmed that external factors did not compromise the safety of transport operations. Even under worst-case mud contamination, the resulting friction coefficient remained nearly six times higher than the traditionally applied 10% standard. This overview showed that the specialised trailer decks were resilient against severe operational and environmental changes, providing a justified foundation to advance toward wider, vehicle-specific testing configurations.

3.4 Determination of practical COF for selected test configurations

To conclude the empirical phase of the research, a series of traction tests was performed with different combat vehicles to determine the consistency of the friction coefficients across varied weight classes. The primary objective was to establish whether the high COF values recorded with the Unimog remained valid for other operational equipment under similar conditions. The results of these vehicle-specific trials, conducted on both the Broshuis trailer and HET, are summarised in Table 2 below.

Table 2 Summary of COF for different vehicle/trailer combinations

Vehicle type	Broshuis Agrain	HET Wood	HET Checker
Unimog	74.38%	84.05%	98.91%
DAF Light	77.69%	87.90%	98.00%
Fox	N/A ^(a)	80.78%	95.18%
Dingo	70.34%	72.60% ^(b)	102.62% ^(c)
Griffon	80.15%	85.44% ^(b)	85.44% ^(b)
Falcon	71.96%	84.07%	84.07% ^(d)

- (a) Vehicle's track width too small for Agrain friction surfaces
- (b) Vehicle's wheelbase prevented a distinct test on a specified wooden or checker plate surface. The result is an average of friction measured on a mix of both.
- (c) Due to non-horizontal pulling force, extra weight and friction might be added to test setup. Actual results will be lower.
- (d) Vehicle's wheelbase prevented a distinct test on the specified surface. Minimum measured amount of friction was used for safety measures.

The specific friction ranges for each platform were documented in Table 2. For the Broshuis trailer's Agrain deck, the dynamic coefficient of friction ranged between 70.34% and 77.69%, provided the vehicle's track width allowed full surface contact. On the HET's composite deck, the friction values depended entirely on the surface material. Measurements yielded ranges between 80.78% and 87.90% on wooden surfaces and between 95.18% and 98.91% on checker plates. Measurements taken on a mixed layout of both wood and checker plate consistently fell between these two distinct limits.

The data in Table 2 indicated that the practical friction potential significantly exceeded the historical baselines utilised by Belgian Defence. The empirically established coefficients proved to be substantially higher than the previously assumed 30% standard for optimal conditions. This large difference demonstrated that the physical grip characteristics of both trailer types remained highly resilient across all tested configurations. Consequently, these verified data points provided a robust and safe empirical foundation for the subsequent optimisation of military loading plans.

This verified friction data directly impacted the possibilities for adapting vehicle loading plans, although the practical application proved to be more complex than initially anticipated. In the lateral direction, it was determined that the empirically confirmed coefficient of friction could be utilised for stability calculations. Even with the integration of the mandatory 75% safety factor prescribed by standard NBN EN 12195-1, the friction potential remained theoretically high enough to absorb lateral forces without the necessity for additional tensioning straps during most transports [4]. Although operational transport regulations still mandated minimal securing measures, these results demonstrated that existing lashing plans could be significantly simplified.

The first option could be applied if the wheels of the braked axle effectively locked. The safest approach here was to account for various factors, namely the coefficient of friction between the wheel and the trailer deck, the number of braked axles, and the static axle load on these braked axles. The effective frictional force produced by the vehicle then became the sum of the products of axle load and COF, taking into account safety factors such as the prescribed 75% [4].

In cases where the wheels did not lock, it is recommended to perform additional tests on specific vehicle/trailer combinations. In this instance, it is not referred to as COF, but rather as rolling resistance since the vehicle's wheels rolled instead of slid. There was likely a causal link between the braking force of the parking brake and the rolling resistance of the vehicle, where drivetrain resistance and other factors also played a role. Using a COF in this case would therefore be discouraged.

The final option was the artificial locking of the wheels through the use of wheel chocks. This allowed the COF to be used for longitudinal calculations in the same way as for the transverse

direction. Using wheel chocks offered several advantages, such as universal applicability, lighter chains or straps and a perhaps even a reduction in number.

Beyond the technical optimisation of loading plans, the application of empirically proven COF values was found to offer significant environmental and economic advantages. A reduction in the required number of tensioning straps directly minimises the unavoidable wear and tear of synthetic materials, thereby decreasing the release of microplastics into the natural environment. Furthermore, the higher friction potential allows for the use of lighter securing equipment, such as straps and chains with smaller diameters or widths, which results in lower procurement costs. This reduction in equipment weight also decreases the overall mass of the trailer, leading to improved fuel efficiency for the towing vehicle and a subsequent reduction in CO₂ and fine particulate emissions. These implementations would help contribute to SDG 12, regarding responsible consumption and production by reducing unnecessary wear of equipment and reducing fuel consumption.

The final advantages identified in this research pertained to the ergonomics and operational safety of the user. By shifting the focus from heavy chains and numerous tensioning straps toward the use of wheel chocks, the physical strain on operators is significantly reduced, as there is less requirement for heavy lifting. Additionally, the reduction in the total amount of securing material enhances loading efficiency, which is of critical value for operators in combat zones. Since personnel are highly vulnerable during the loading process, faster securing procedures allow operators to return to the protection of their armoured cabins more quickly, thereby minimising their exposure to external threats and improving overall mission safety.

4 Conclusions

The primary aim of this research was to determine the practical coefficient of friction (COF) between selected Belgian Defence combat vehicles and transport trailers in accordance with the NBN EN 12195-1 standard. Historically, transport operations relied on assumed COF values of 10% and 30%, which lacked empirical validation. This study addressed the need for data-driven safety margins to optimise transport efficiency and operational safety.

In accordance with the first research goal, the NBN EN 12195-1 standard was analysed to define a standardised testing methodology. It was determined that the horizontal pull method was the most accurate procedure for replicating longitudinal forces. For the second goal, a test setup was designed and validated using available Belgian Defence equipment, including Dyna-Link MS17200 dynamometers and recovery vehicle winches. Pilot tests on a polished concrete surface confirmed the system's reliability, yielding a verified dynamic COF of 57.43%, which aligned with values prescribed by the standard.

The third goal involved investigating the impact of external factors on the COF. This was done by firstly identifying a baseline COF of 74.38% through use of the confirmed procedure, using a Unimog on a Broshuis trailer. It was then established that tire pressure and surface contamination significantly influenced the results. Lowering tire pressure resulted in a COF increase of 6.37% due to an enlarged contact patch. While mud contamination caused a significant decrease of 16.22% in the friction coefficient, resulting in a COF of 58.16%, the value remained nearly six times higher than the assumed 10% worst-case baseline. Unexpectedly, wet conditions did not have a negative impact on the Agrain trailer deck, even resulting in a slight COF increase to 76.72%.

Finally, the execution of tests across all identified configurations established the practical COF values for future loading plans. For the Broshuis Agrain deck, the COF was determined to range between 70.34% and 77.69%. On the HET composite deck, values ranged from 80.78% on wooden surfaces to 98.91% on checker plates. These findings demonstrated that the actual friction potential is consistently two to three times higher than the currently assumed military standards in best circumstances. Consequently, these results provided a scientific foundation for optimising lashing configurations, which could lead to

significant environmental, economic and ergonomic benefits.

Future research could be directed toward establishing a causal link between parking brake force and rolling resistance for vehicle configurations where the wheels do not effectively lock. Additionally, further investigation into the standardised use of wheel chocks as an alternative to heavy lashing materials is recommended to further enhance operational efficiency.

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