INTRODUCING A NOVEL ANALYSIS TOOL TO QUANTIFY THE IMPACT OF SUPERHEAVY LOAD VEHICLES ON PAVEMENTS


E. PÉREZ-GONZÁLEZ
Université Laval.
Professor of the Department of Civil and Water Engineering, specialized in studying the effect of dynamic loads on granular materials, dams, and pavements, with expertise in the impacts of superheavy vehicles on geostructures.

J-P. BILODEAU
Université Laval.
Professor of the Department of Civil and Water Engineering, specializing in pavement geotechnics and transportation infrastructure as an educator, researcher and consultant.

Abstract
Transporting loads exceeding regulatory limits offers economic and environmental benefits but raises concerns about potential damage to road infrastructure. Superheavy vehicles, characterized by higher load capacity and more axles, impose unique challenges. The mechanistic-empirical approach, widely used to analyze pavements, correlates mechanical responses with performance using damage laws. However, it often overlooks exceptionally high load amplitudes, leading to suboptimal decisions. To address this, Université Laval, under the NSERC Chair on heavy loads, climate, and pavements (i3C), developed a tool to quantify superheavy vehicle damage on Quebec's pavements. The project incorporated full-scale tests, lab experiments, and simulations, with instrumented pavement sections capturing responses under extreme loads, weather, and speeds. A performance model using plastic strain rate as a damage indicator was created, enabling a unified approach to evaluate maximum allowable loads, permanent deformation, and damage equivalency. This paper discusses the tool, its functionality, and analyses of three superheavy load transits.

Keywords: superheavy vehicles, pavements, materials, performance, tools.

1. Introduction

Transporting loads exceeding regulatory weight and dimensional limits offers economic and environmental benefits. However, such non-conventional vehicles raise concerns about potential pavement damage and other transport infrastructures. These superheavy vehicles differ from conventional traffic in load size and use of additional axles and wheels.

Superheavy load (SHL) transport is crucial in hydroelectricity, oil, and mining industries. The analysis of SHLs often relies on mechanistic-empirical (M-E) methods (Chen et al., 2013; Jooste & Fernando, 1995; Khanal et al., 2019), which provide a rational framework for studying pavement responses to various loading conditions. However, SHL loading typically involves unique conditions, including high loading rates, low traffic speeds, limited rest periods between consecutive axles, and three-dimensional stress variations (Hajj et al., 2018; Jooste & Fernando, 1995). These factors create stress states that conventional methods developed for standard traffic may struggle to predict accurately.

The M-E approach to SHL analysis uses structural models to simulate pavement responses—such as stresses, strains, and displacements—and correlates them with performance through damage laws. Figure 1 illustrates the SHL analysis process, where pavement behavior is assessed using models and criteria such as ultimate shear failure or deformation limits. However, this method often focuses solely on critical loading conditions, leading to overly conservative or suboptimal decision-making, particularly for extreme load amplitudes.

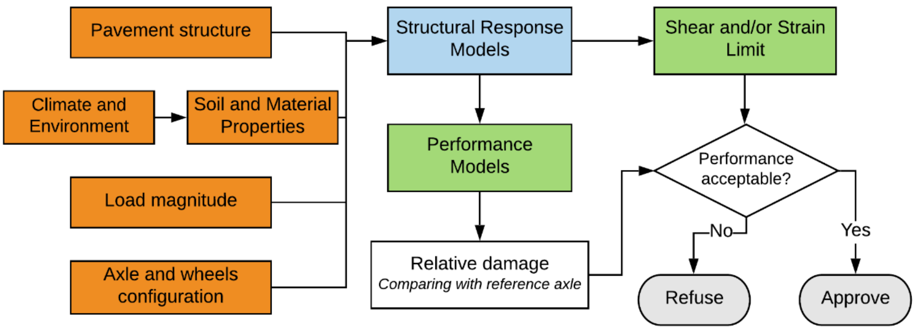

Figure 1. A simplified summary of the process of analysis of SHLs in pavements

2. Criteria in SHL Analysis

In analyzing the effects of SHL vehicles, three main criteria are commonly used: (i) the critical deformation criterion, (ii) the relative damage criterion, and (iii) the performance-based criterion.

The *critical deformation criterion* defines the maximum allowable strain values for specific pavement layers to ensure the structural integrity of the materials. This approach aligns with the principles of perpetual pavements, which aim to maintain stress levels below material strength limits (Khanal et al., 2016, 2019). For instance, Khanal et al. (2016) suggested a conservative threshold of 70 microstrains at the bottom of the asphalt concrete layer to prevent fatigue cracking under SHL loads. However, higher limits of up to 200 microstrains have also been reported (Prowell et al., 2010). Similarly, Willis and Tim (2009) proposed a limit of 200 microstrains for vertical deformation at the top of the subgrade to mitigate structural rutting. This criterion is straightforward to apply and is considered reliable due to its broad applicability to various materials.

The *relative damage criterion* quantifies the ratio of damage caused by an SHL vehicle compared to regular traffic. This method is widely adopted because it clearly measures the impact and costs associated with SHL traffic. However, its scope is limited, as it focuses primarily on deformation at the top of the subgrade, potentially leading to conservative estimates for permanent deformation behavior.

Calculating the relative damage between SHL and conventional vehicles helps quantify pavement life consumption caused by SHL vehicles, informing cost estimation. In M-E pavement analysis, damage is calculated using Miner's linear damage accumulation assumption (Miner, 1945), which defines damage (D) as the ratio of load applications (n) to the allowable applications (N_x):

$$D = \frac{n}{N_x} \tag{1}$$

Relative damage ($D_{relative}$) compares SHL vehicle damage to standard heavy traffic damage and is expressed as (E. L. Pérez-González et al., 2022b):

$$D_{relative} = \frac{D_{SHL}}{D_{std}} = \frac{n_{SHL}/N_{SHL}}{n_{std}/N_{std}} \tag{2}$$

Where the subindices, SHL refers to the condition defined by the SHL vehicle, and std refers to the standard or reference heavy traffic.

The *performance-based criterion*, introduced by Pérez-González (2021), evaluates the cumulative deformations across all pavement layers by comparing them to those caused by a reference heavy vehicle. This approach is based on the Pérez-Bilodeau-Doré model (E. L. Pérez-González et al., 2021) for granular and subgrade layers and incorporates the asphalt concrete deformation model from the MEPDG (ARA Inc, 2004, 2019). By calculating the relative deformation impact layer-by-layer for asphalt concrete, granular, and subgrade layers, this criterion comprehensively analyzes SHL vehicle effects on the entire pavement structure. The relative deformation impact for each layer is calculated as:

$$D_i = \frac{\delta_i^{SHL}}{\delta_i^{std}} \tag{3}$$

Where δ_i^{SHL} is the critical deformation caused by the SHL vehicle in layer i, and δ_i^{std} is the critical deformation caused by a reference truck in the same layer under identical conditions. The final damage is determined by summing the partial damage across all layers.

This criterion integrates all pavement layers, providing a rational and detailed approach for SHL analysis. However, its implementation requires precise material data for each layer, which may necessitate additional effort. While Shakedown theory provides a foundation for establishing load limits (Werkmeister, 2003), further research is required to refine maximum deformation thresholds and gain a deeper understanding of lateral deformation (rutting) and its influence across the pavement cross-section.

3. Practical Applicability of Performance-based criteria

The performance-based criteria offer a comprehensive framework for assessing the impact of SHL vehicles on pavement structures by accounting for cumulative deformations across all layers. This approach provides a more rational and accurate analysis than traditional methods, which often focus solely on critical conditions or individual layers. The proposed criteria focus on granular material and soil layers most susceptible to high loads.

The Pérez-Bilodeau-Doré model is an analytical tool designed to calculate deformations in granular materials and soils subjected to unconventional loads. Over time, the model has been updated to enhance its practicality and accuracy. The key modifications include:

a. A parameter was introduced to align field and laboratory conditions better, improving the model's applicability across different scenarios (E. Pérez-González et al., 2021).
b. Post-compaction parameters are now directly correlated with shakedown behavior (stability phase), reducing the model's complexity without compromising reliability (E. L. Pérez-González et al., 2022a).
c. A probabilistic framework has been incorporated to improve predictions of shakedown behavior based on the material’s stress history, increasing the model's robustness under varying conditions (E. L. Pérez-González et al., 2022a)

Figure 2 schematically summarizes the final model and criteria developed for SHL vehicle impact analysis.

Since the Pérez-Bilodeau-Doré model bases its predictions on deviatoric stresses (q) and confinement levels (σ_3), which vary significantly under SHL vehicles, using temporal segmentation of stress states (as illustrated in Figure 3) enhances deformation predictions. By defining a time differential (i.e., dt = 0.1s), this approach allows for detailed analysis of stress variations in both longitudinal and transverse directions. The deformation calculated for each combination of q and σ_3 within these temporal subsections is then aggregated, resulting in a more accurate and optimal estimate of the expected plastic deformation.

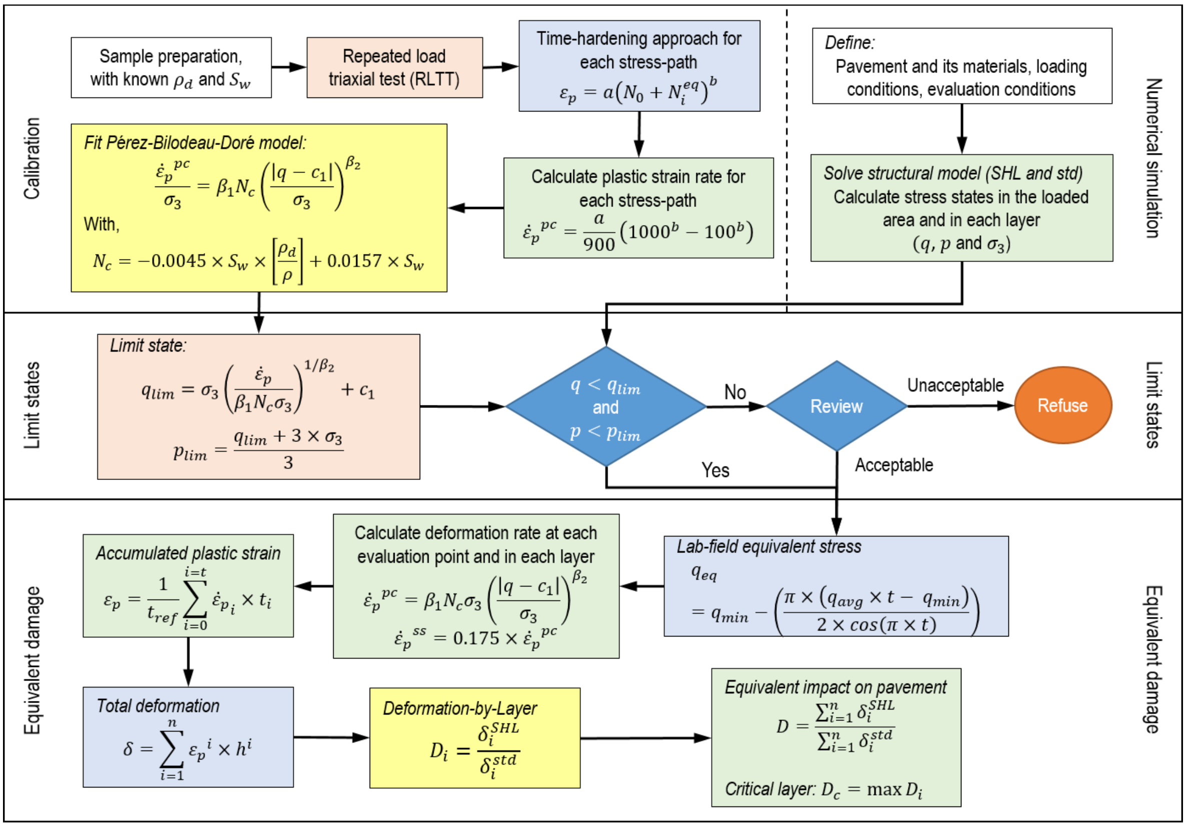

Figure 2. Flowchart of the performance-based criteria for SHL analysis

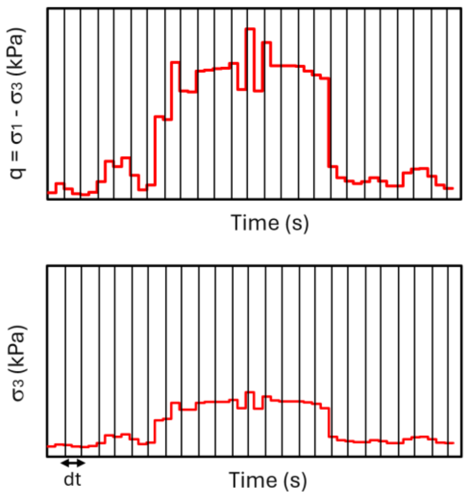

Figure 3. Schematic representation of subdivision of stress states in a temporal space.

4. i3C-SHL Software for SHL Vehicle Analysis

The PBD criteria outlined in Section 2 were operationalized by developing the i3C-SHL software. Built upon the structural calculation framework of the i3C-ME platform (Université Laval, 2019), which utilizes multi-layer elastic theory and accounts for stress-dependent material nonlinearity, this standalone tool extends functionality to superheavy load (SHL) vehicle analysis. The software evaluates atypical axle configurations using response surface methodology and integrates performance-based criteria, including critical strain thresholds and equivalent damage metrics, following the workflow defined in Figure 2. Designed for regional applicability, i3C-SHL incorporates material properties and climatic conditions specific to Quebec. It is freely accessible as part of the i3C software suite.

4.1 Features and Modules

The software architecture comprises four specialized modules:

a. General Module: Manages project metadata and user identification.
b. Vehicle Configuration Module: Defines SHL vehicle parameters, including axle count (≤24), tire specifications, axle spacing, load distribution, and traffic speed. Speed-dependent dynamic modulus adjustments for asphalt layers are derived from Quebec-specific temperature-frequency master curves.
c. Pavement Structure and Materials Module: Configures multi-layer pavement systems (≤10 layers) with user-defined precision levels (1–3). Asphalt layers are characterized by mix design and bitumen type, enabling Level 2 master curve parameterization. Granular and subgrade materials are similarly customizable, leveraging regionally calibrated property databases.
d. Analysis Parameters Module: This module specifies climatic conditions (e.g., seasonal freeze-thaw cycles, moisture variations) and mechanical criteria (fatigue, permanent deformation, asphalt base critical strain). Seasonal adjustments modulate material properties to reflect environmental effects.

4.2 Outputs

The software generates spatially resolved mechanical responses (stresses, strains, deflections) across depths and positions within the pavement structure (Figure 4). Users assess damage equivalence relative to reference vehicles (e.g., standard 10-wheel trucks under legal loads) through layer-specific and comparative analyses. Outputs include multi-indicator damage evaluations, enabling comprehensive impact assessments of SHL configurations on pavement performance.

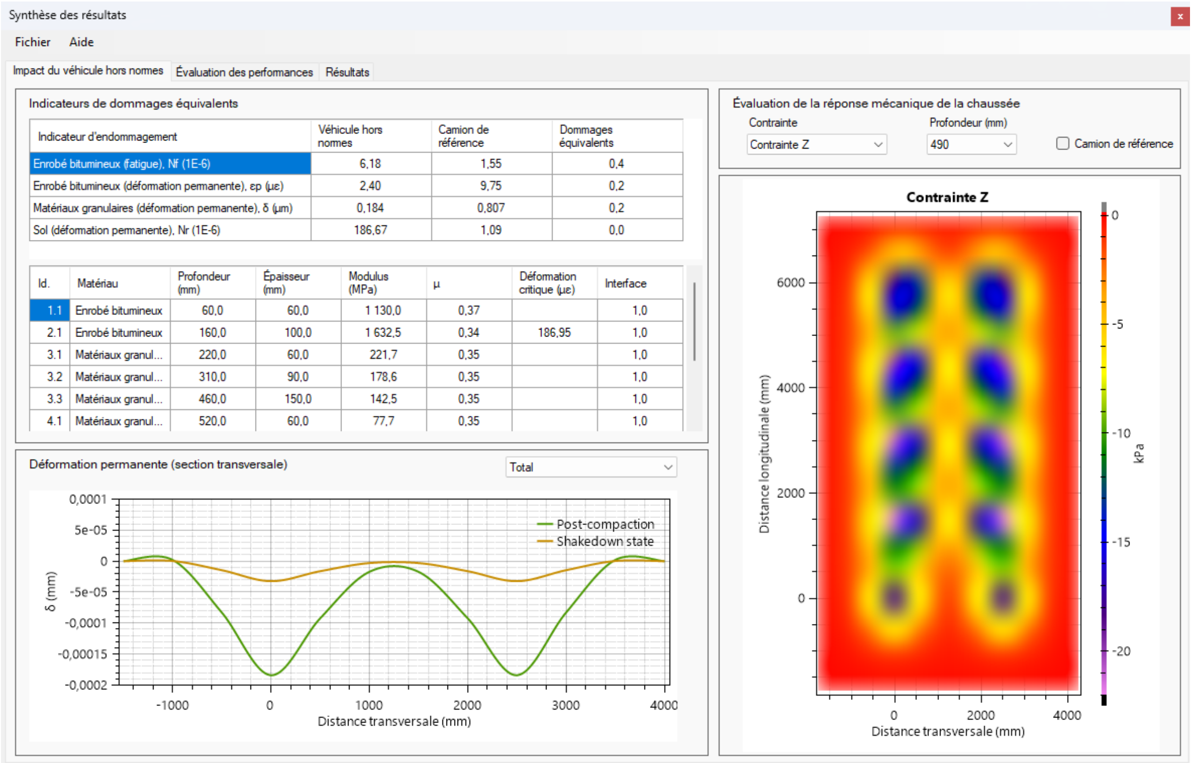

Figure 4. Modules available in the i3C-SHL software: Results

5. Criteria Applied to Cases in the Province of Quebec

The proposed criteria were adapted to materials and environmental conditions specific to Quebec, establishing the province as an optimal testing ground for initial validation. To evaluate the methodology, results from three 2020 superheavy load (SHL) vehicle permits (see Table 1) were compared against assessments generated using the Quebec Ministry of Transportation's (MTQ) existing framework.

The MTQ methodology, detailed in the « Guide d'évaluation de l'agressivité et des impacts des véhicules lourds » (Prophète, 2014), quantifies pavement damage through two metrics: (1) aggressiveness, expressed in equivalent single axle loads (ESALs), and (2) impact, defined as the number of standard vehicle passes equivalent to a single SHL traversal.

For comparative analysis, the three SHL configurations in Table 1 —selected randomly from vehicles operating on Quebec's Road network to ensure representativeness— were applied to pavement structures reflecting regional design practices. Structures incorporated granular material moduli typical of Quebec, with asphalt concrete (AC) layer thicknesses calibrated to road classifications: 100 mm (local roads), 130 mm (regional roads), 140 mm (national roads), and 200 mm (highways), summarized in Table 2, were analyzed to assess structural responses across varying load and thickness scenarios.

Table 1. Characteristics of SHL vehicles analyzed

Case	Number of axles	Wheels per axle	Declared axle load (kg)	Axle load (kN)	GVW (kN)
1	16	8	33375	327.3	5237
2	1	2	6700	65.7	1811
	2	4	12100	118.7	
	15	8	10250	100.5	
3	1	2	6500	63.7	3187
	2	4	14000	137.3	
	16	8	16000	156.9	
	1	2	6500	63.7	
	2	4	14000	137.3	

Table 2. Reference structure for the analysis

Layer	Thickness (mm)	Modulus (MPa)	Poisson ratio (μ)
AC layer	Variable[1]	3000	0.30
Base	200	200	0.35
Subbase	640	120	0.35
Subgrade	10000	60	0.40

[1]As a function of the road class.

To apply the layered deformation method in this study, certain assumptions were made:

a. Trucks were equipped with 11R22.5 tires traveling at 50 km/h.
b. Base, subbase, and subgrade materials were modeled using default parameters from the Pérez-Bilodeau-Doré (PBD) model included in the software i3C-SHL.

5.1 Comparison of Results

Table 3 compares equivalent damage predictions derived from the MTQ methodology and the criteria proposed by Pérez-Bilodeau-Doré (PBD). Case 2 shows the greatest alignment between methods, while discrepancies in other cases arise from the PBD model's sensitivity to material properties and its assessment of accumulated strain. Although the critical strain threshold (200 με) is partially met in selected scenarios, deviations occur when localized stress conditions diverge from the assumptions of traditional analyses.

The results were normalized using the local road condition as a reference to enable comparison between methods. This approach standardizes damage values by expressing them in relation to the impact of a reference vehicle, a common practice in pavement studies, to isolate the incremental effects of super-heavy loads (SHL) from conventional traffic. Standardization considers variations in load weight, axle configuration, and pavement performance, ensuring fair comparisons even with limited granular data.

Different trends are observed in the cases and road classes. In case 3, characterized by a moderate gross vehicle weight (GVW) and detailed axle configurations, the MTQ and PBD predictions agree closely, differing by less than 20% in all road classes. This indicates that conventional methods adequately capture impacts under moderate load conditions. In contrast, cases 1 and 2 show a significant divergence: PBD predictions exceed MTQ values

by factors of 5 to 7 for local roads (100 mm thick AC) and by factors of 2 to 3 for highways (200 mm thick AC). These differences arise because the PBD model incorporates the effects of accumulated deformation and superimposed stresses, which become more pronounced with different GVW and complex axle distributions.
The critical strains in the asphalt concrete (AC) layer exceed 200 με only in case 2 for local roads (263.5 με), which highlights the limitations of relying solely on strain-based criteria. Furthermore, subgrade deformations exceed critical thresholds in all cases, reinforcing the view that permanent deformation is the main failure mechanism. The sensitivity of the PBD model to the non-linearity of materials and to load distribution patterns underlines its value in scenarios where traditional methods may underestimate the progression of damage, especially in thicker pavements or under multi-axle loads.

Table 3. Comparison of results between applied methods

		Equivalent damage			Critical strain	
			Case 1			
AC-thickness (mm)	Road class	MTQ	PBD[1]	Fatigue[2]	AC	Subgrade
100	Local	7	46.4	0.0	66.0	1208.3
130	Regional	7	42.6	0.4	102.4	1059.4
140	National	9	54.7	0.6	106.3	1048.1
200	Highway	11	59.6	2.5	115.6	1091.3
			Case 2			
AC-thickness (mm)	Road class	MTQ	PBD[1]	Fatigue[2]	AC	Subgrade
100	Local	2	3.6	3.4	263.5	370.3
130	Regional	3	3.3	3.2	181.0	319.1
140	National	3	3.5	3.2	168.9	316.5
200	Highway	4	4.2	2.3	109.4	333.6
			Case 3			
AC-thickness (mm)	Road class	MTQ	PBD[1]	Fatigue[2]	AC	Subgrade
100	Local	9	17.7	7.7	263.5	370.3
130	Regional	9	18.4	10.3	242.2	724.1
140	National	10	20.7	10.8	228.8	717.4
200	Highway	12	23.4	11.1	165.4	757.0

[1]Pérez-Bilodeau-Doré model; [2]Asphalt Institute performance model.

5.2 Observations and Trends

Figure 5 presents the normalized results for the MTQ and PBD criteria. A key difference between the two methods is their approach to damage quantification. The MTQ criterion expresses damage in equivalent axle loads (ESAL), while the PBD model uses the proportionality of permanent deformation. To allow for direct comparison, all damage

estimates were normalized using the local road condition as a reference, dividing each prediction by the corresponding value for the same vehicle on a local road. An equality line in Figure 5 further highlights that the PBD criterion consistently predicts less damage than the MTQ approach, underlining the conservatism of the latter.
In the cases of highest and lowest load (Cases 1 and 2), the PBD predictions are consistently lower than the MTQ results. This discrepancy arises because the MTQ method, by focusing on critical stress conditions, tends to overestimate damage. At the same time, the PBD model considers the cumulative effects on the affected area. The consistency shown in case 3 can be associated with this specific case, and more information would be needed to conclude on the situations of equivalence between the two methods studied. By incorporating the progressive evolution of stress states and the spatial distribution of impacts, the PBD approach offers a more balanced assessment and serves as a valuable complement to traditional methodologies.

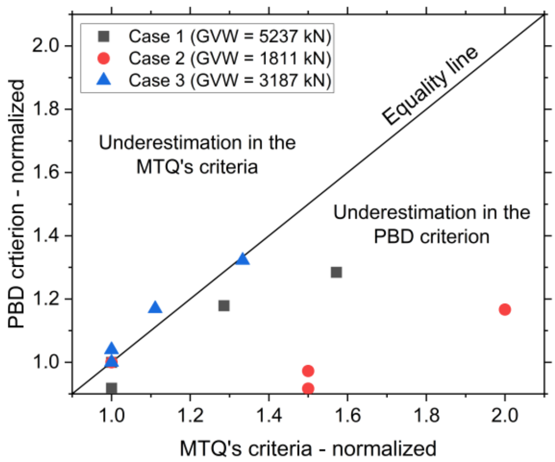

Figure 5. Comparison of results between MTQ criteria and the PBD criterion

Figure 6 illustrates the trends in critical strains and relative damage predictions. Figures 6a and 6c represent the critical strains in the asphalt concrete (AC) and subgrade layers, respectively, while figures 6b and 6d show the relative fatigue damage (Nf/Nref) and the damage derived from the PBD. The influence of the thickness of the AC layer is analyzed in all cases.
For a 100 mm AC layer, the critical deformations in the AC (Figure 6a) in cases 2 and 3 are comparable but significantly lower in case 1 despite its higher gross vehicle weight (GVW). This anomaly may be due to the effects of the axle configuration on stress distribution. The increase in the thickness of the CA raises the critical strains in case 1, probably due to the superposition of stresses, while the opposite trend occurs in cases 2 and 3. The maximum strain criterion (200 με) is only partially met in certain cases.
The relative fatigue damage (Figure 6b) reflects the same critical strain trends, as expected, given its dependence on strain-based calculations. The subgrade strains (Figure 6c) are highest in Case 1 (higher gross vehicle weight) and lowest in Case 2 (lower gross vehicle weight). The increase in the thickness of the cement-bound macadam slightly mitigates the

deformations of the subgrade in Cases 1 and 2, but amplifies them in Case 3, probably due to the superposition of stresses due to its greater number of axles.

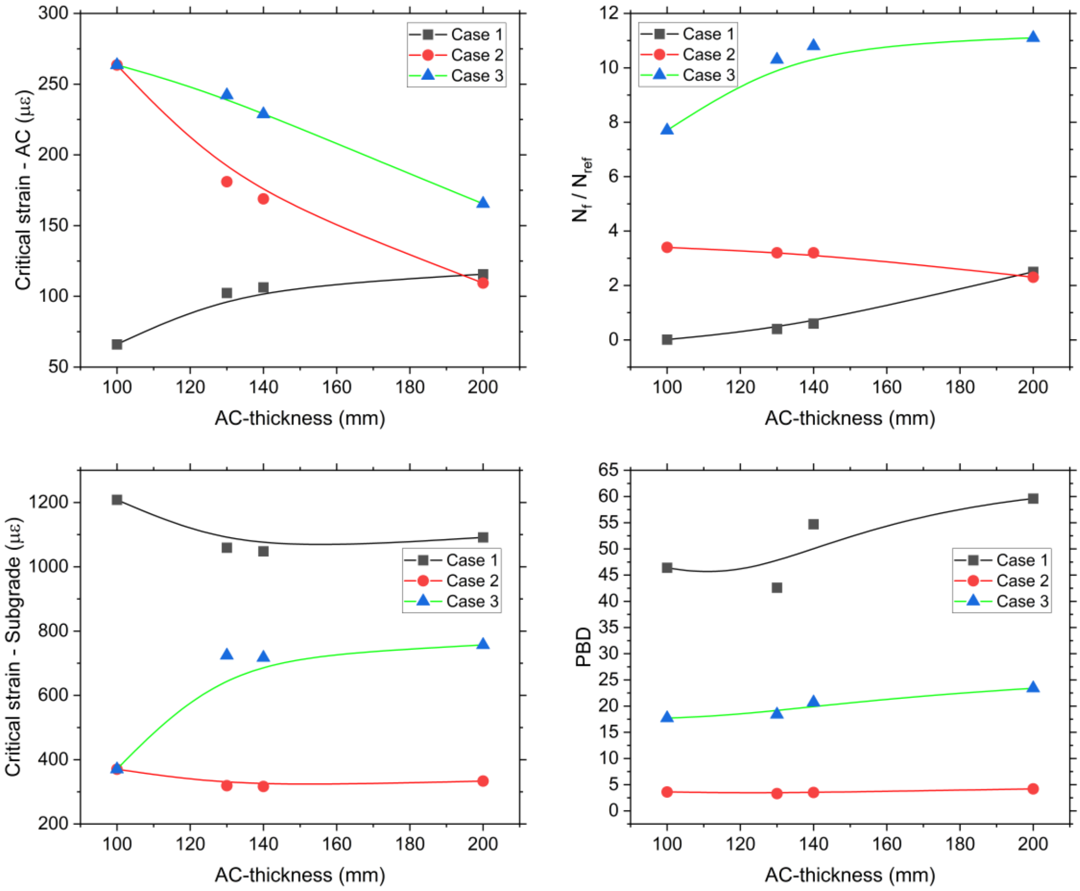

Figure 6. Comparative trends for (a) AC critical strains, (b) relative fatigue damage (N_f/N_{ref}), (c) subgrade critical strains, and (d) PBD relative damage.

In contrast, the PBD model (Figure 6d) shows damage trends based on permanent deformation that align with GVW magnitudes (Case 1 > Case 3 > Case 2). The accumulation of damage progressively increases with the thickness of the CA, especially with higher GVW. These results underline the importance of evaluating the effects of the whole vehicle and the limitations of relying solely on critical stress conditions for the evaluation of non-conventional vehicles.

6. Conclusions

This study presents a methodology for evaluating the impact of super-heavy load (SHL) vehicles on pavements, addressing the critical limitations of conventional approaches. By incorporating cumulative deformation, the evolution of stress state and spatial load distribution, the Pérez-Bilodeau-Doré (PBD) model reduces the overestimation inherent in traditional methods, focusing narrowly on critical stress conditions. Comparative analyses demonstrate that the PBD framework predicts systematically lower magnitudes of damage than the MTQ criteria, particularly in high-load scenarios. This divergence arises from the ability of the PBD model to account for progressive stress superposition and axle configuration effects, factors that govern actual pavement responses but are overlooked in conventional assessments, underscoring the importance of evaluating whole-vehicle impacts rather than isolated critical conditions.

Implementing these criteria in the i3C-SHL software improves practical applicability by integrating vehicle-specific parameters (e.g., axle distribution, gross vehicle weight), material properties, and climatic conditions. This tool provides a solid platform for optimizing pavement analysis, particularly for non-conventional vehicles, by aligning predictions with observed mechanical behavior.

The results highlight the need for region-specific adaptations, as local factors such as material properties, layer thickness, and climate significantly influence damage progression. Although the methodology is transferable to other regions, its accuracy depends on calibrating strain thresholds and validating assumptions with regional pavement performance data. Future work should prioritize the refinement of strain-based failure criteria, investigation of the effects of lateral stress distribution, and extension of model validation to various vehicle configurations and pavement types. Long-term monitoring of SHL impacts will improve predictive reliability, ensuring sustainable infrastructure management in the face of evolving freight transport demand.

7. References

ARA Inc. (2004). *Guide for the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (Final Report NCHRP 1-37A). Transportation Research Board of the National Academies.

ARA Inc. (2019). *AASHTOWare Pavement ME Design* (Version 2.5.5) [Computer software]. Applied Research Associates, Inc.

Chen, X., Lambert, J. R., Tsai, C., & Zhang, Z. (2013). Evaluation of superheavy load movement on flexible pavements. *International Journal of Pavement Engineering*, *14*(5), 440–448. https://doi.org/10.1080/10298436.2012.690519

Hajj, E., Siddharthan, R., Nabizadeh, H., Elfass, S., Nimeri, M., Kazemi, S., Batioja-Alvarez, D., & Piratheepan, M. (2018). *Analysis Procedures for Evaluating Superheavy Load Movement on Flexible Pavements, Volume I: Final Report* (Final Report FHWA-HRT-18-049; p. 122). U.S. Department of Transportation (USDOT). U.S. Department of Transportation (USDOT)

Jooste, F., & Fernando, E. (1995). *Development of a procedure for the structural evaluation of superheavy loads routes* (1335-3F; p. 258).

Khanal, S., Olidis, C., & Hein, D. (2016). *Modelling Pavement Response to Superheavy Load Movement*. 19.

Khanal, S., Zeigle, A., & Olidis, C. (2019). *Pavement Response to Superheavy Load Movement*. 2019 TAC-ITS Canada Joint Conference, Halifax, NS.

Miner, M. A. (1945). Cumulative Damage in Fatigue. *Transactions of the ASME*, *67*, A159–A164.

Pérez-González, E. (2021). *Development of an analysis tool to quantify the effect of superheavy load vehicles on pavements* [PhD thesis, Université Laval]. http://hdl.handle.net/20.500.11794/68410

Pérez-González, E., Bilodeau, J.-P., & Doré, G. (2021). Use of the permanent strain rate to analyze the effect of superheavy vehicles on pavements: Field validation. *Transportation Geotechnics*, *30*, 100603. https://doi.org/10.1016/j.trgeo.2021.100603

Pérez-González, E. L., Bilodeau, J.-P., & Doré, G. (2021). Analysis model for permanent deformation in granular materials under the action of superheavy vehicles. *Transportation Geotechnics*, *28*, 100536. https://doi.org/10.1016/j.trgeo.2021.100536

Pérez-González, E. L., Bilodeau, J.-P., & Doré, G. (2022a). A criterion to quantify the effect of superheavy vehicles on asphalt pavements based on layers deformation. *International Journal of Pavement Engineering*, *23*(12), 4410–4423. https://doi.org/10.1080/10298436.2021.1948045

Pérez-González, E. L., Bilodeau, J.-P., & Doré, G. (2022b). Analysis of the effect of superheavy load vehicles: A review of current criteria. *Canadian Journal of Civil Engineering*, *49*(4), 527–535. https://doi.org/10.1139/cjce-2020-0483

Prophète, F. (2014). *Guide d`évaluation d l`agressivité des impacts des véhicules lourds*. Ministère des Transports du Québec, Direction du laboratoire des chaussées, Service des matériaux d'infrastructures.

Prowell, B., Brown, E., Anderson, J., Von Quintus, S., Shen, S., Carpenter, S., Bhattacharjee, S., & Maghsoodlo, S. (2010). *Validating the Fatigue Endurance Limit for Hot Mix Asphalt* [NCHRP Report 646]. Transportation Research Board of the National Academies. https://doi.org/10.17226/14360

Université Laval. (2019). *Logiciel mécaniste-empirique de conception des chaussées souples: i3C-me* (Version 2) [Computer software]. Université Laval.

Werkmeister, S. (2003). *Permanent Deformation Behavior of Unbound Granular Materials* [PhD thesis, University of Technology Dresden Germany]. https://d-nb.info/968400930/34

Willis, J. R., & Timm, D. H. (2009). *Field-Based Strain Thresholds for Flexible Perpetual Pavement Design* [Report No. 09-09. National Center for Asphalt Technology]. Auburn University.