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Review

Structural Optimisation of Load-Bearing Structures of Freight Vehicles Subjected to Extreme Dynamic Loads: A Review

Vlad Imre Tent, Florin Bogdan Scurt *, Tiberiu Vesselenyi, Horia Beles, Bogdan Adrian Tolea and Madalin Florin Popa

Department of Mechanical Engineering and Automotive, University of Oradea, Universitatii Street No. 1, 410087 Oradea, Romania; tent_vlad@yahoo.com (V.I.T.); tvesselenyi@yahoo.co.uk (T.V.); horia.beles@uoradea.ro (H.B.); bogdan.tolea@uoradea.ro (B.A.T.); popa_madalinflorin@yahoo.com (M.F.P.)
* Correspondence: scurt.florinbogdan@didactic.uoradea.ro

Abstract

Trailers and semi-trailers for road freight operate under extreme dynamic loads that cause fatigue damage, deformation and structural failure. This review synthesises the literature on the structural optimisation of truck, trailer and semi-trailer structures under such loads, based on a targeted, iterative search of two databases and three publisher platforms, extended by citation chaining, that yielded 68 primary studies. The studies are grouped into three method families (topology, parametric and artificial intelligence (AI)-assisted optimisation) and compared by outcome, type of redesign and validation level. Same-material optimisations of complete frames and components save about 7–16% of mass, with or without tests; the largest values, 28% for steel longitudinal beams and a theoretical 67% for a fully composite trailer, come from beam shape optimisation and composite substitution in one numerical study. A coverage map of 56 scored studies shows that more than half do not consider time-varying loads, that fatigue, buckling and fail-safe criteria are rarely optimised together, and that optimised designs are seldom tested, while advanced formulations are demonstrated mostly on generic structures. The review proposes minimum safeguards for AI-assisted design, discusses manufacturability and economic feasibility, and outlines an integrated workflow linking measured load spectra, multi-criteria optimisation and staged experimental validation.

Keywords: freight transport; trucks; structural optimisation; topology optimisation; extreme dynamic loads; semi-trailers; lightweight design; finite element method; experimental validation; digital twin

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1. Introduction

Freight transport represents a fundamental pillar of the global economy, facilitating the movement of products and materials indispensable to various industries. The load-bearing structures of road freight vehicles are exposed to complex dynamic loads, such as sudden accelerations, impacts, vibrations and other extreme loads. These conditions can cause premature structural deterioration, leading to considerable economic losses, major risks to road safety, and negative effects on the environment.

According to the statistical pocketbook of the European Commission [1], more than three-quarters (77.4%) of the freight transported within the European Union (EU) is carried by road.

Because freight transport does not take place solely on public roads, it is characterised by extreme loading, caused partly by overloading and partly by poor road conditions.

To partially address the problems caused by vehicle overloading, several directives and online platforms have been introduced. Directive 96/53/EC [2], for example, sets the maximum authorised weights and dimensions of road vehicles and vehicle combinations, including trailers.

In addition, the Romanian Ministry of Environment, Waters and Forests has developed the SUMAL 2.0 (Forest Inspector) online platform [3], to which all timber transport permits are uploaded. The platform is used mainly to verify, in real time, the quantity of timber transported by each vehicle; because this quantity is declared on each transport permit, the platform can also be used to check whether a vehicle is overloaded.

In Romania, compliance with the maximum authorised masses and dimensions is also controlled by the State Inspectorate for Road Transport Control (ISCTR) [4], in accordance with Regulation (EC) No 1071/2009 [5]. Annex IV of this regulation, which lists the most serious infringements for the purposes of Article 6(2)(a) [5], includes under point 7: "Carrying goods exceeding the maximum permissible laden mass by 20% or more for vehicles the permissible laden weight of which exceeds 12 tonnes, and by 25% or more for vehicles the permissible laden weight of which does not exceed 12 tonnes".

Despite these regulations and the institutions that penalise overloading, operators want their vehicles to carry as large a payload as possible, and increasing the payload has become a priority in modern vehicle engineering.

Optimising structures to withstand these extreme dynamic loads requires the use of advanced design and simulation methods, which can ensure not only increased structural strength and reliability but also reduced costs associated with materials and maintenance. At the same time, current requirements call for the adoption of sustainable solutions that minimise environmental impact without compromising performance.

The choice of material is part of the same problem. Around 1960, "engineering materials" effectively meant metals, whereas, from the late 1980s, high-modulus fibre composites and materials tailored to functional requirements widened the options available to designers [6]; their use in freight-vehicle structures is discussed in Section 3.5.2.

This review does not develop new optimisation methods or analyse new structures. Instead, it synthesises and critically compares the optimisation approaches reported for the load-bearing structures of trucks, trailers and semi-trailers subjected to extreme dynamic loads, assesses how robustly their reported benefits have been validated, and maps where the published evidence is dense or sparse.

The main objectives of this review are as follows:

- To synthesise the literature on the behaviour of road-freight structures under extreme dynamic loads;
- To compare topology, parametric and artificial intelligence (AI)-assisted optimisation in terms of reported mass reduction, stiffness, natural frequency and validation level;
- To identify gaps in load-spectrum modelling, multi-criteria integration and experimental validation;
- To outline research directions for lightweight, safe and sustainable trailer structures.

2. Materials and Methods

2.1. Literature Search Strategy

The literature underlying this review was identified through a targeted, iterative search rather than a single pre-registered systematic protocol. An initial set of keyword searches—combining terms such as "truck chassis," "trailer frame," "semi-trailer," "topology optimization," "structural optimization," "lightweight design," "finite element analysis," and "dynamic/extreme loads"—was carried out in two bibliographic databases (Scopus and Web of Science), supplemented by three publisher platforms (ScienceDirect, Springer-

Link and MDPI). Starting from this initial set, the search was expanded through citation chaining—examining the reference lists of key papers, as well as more recent papers citing them—until no further studies meeting the scope of the review were identified.

Priority was given to peer-reviewed studies addressing the structural analysis, optimisation, or lightweight design of trucks, trailers, or semi-trailers under dynamic or extreme loading conditions, spanning publications from 2010 to 2026, with particular emphasis on the past five years. A small number of studies on closely related structural components (e.g., truck cabs and gearbox housings) were retained where directly relevant to the optimisation methods discussed. Studies addressing vehicle types outside road-freight transport, or addressing only non-structural aspects (logistics, emissions and routing), were excluded unless they offered a structural-optimisation method explicitly noted as transferable.

Because the search was iterative, the numbers of records retrieved, screened and excluded at each step were not recorded systematically; the selection process is therefore described qualitatively in Figure 1, and this limitation is acknowledged later in this section. The final body of literature cited in this review comprises 68 primary studies, which form the basis of the synthesis and 56 of which are scored in the coverage map of Section 4.7, and seven background sources (a statistical report, two legislative documents, two institutional websites, a textbook and a review of topology optimisation), which are cited for context in the Introduction and in Section 2.2.2 and are not counted as included studies.

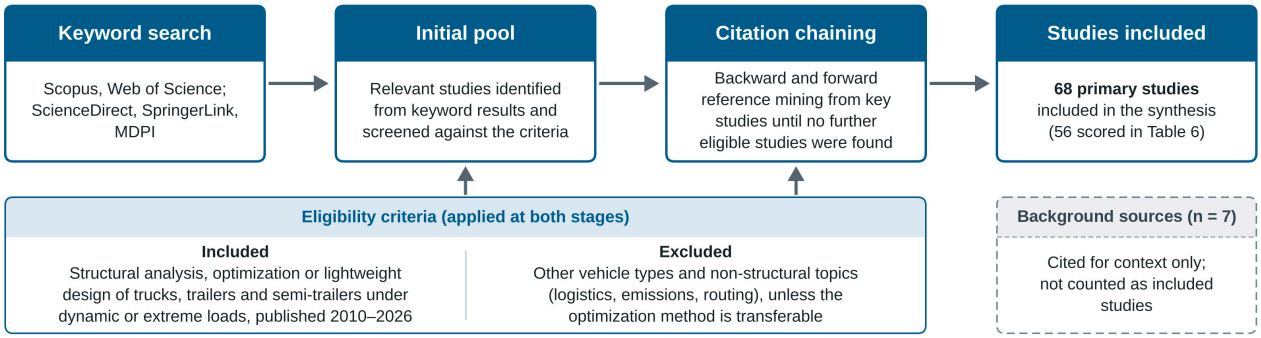


Figure 1. Literature search and selection process. Background sources cited for context (n = 7) are shown separately and are not counted as included studies.

The search and selection steps are summarised in Figure 1.

This search strategy has limitations. Without a pre-registered systematic protocol such as PRISMA, the selection may be biased towards frequently cited, English-language studies and towards research groups that are well connected through citations, and industrial reports and other grey literature, in which part of the industrial design practice is documented, are under-represented. Searching two bibliographic databases and three publisher platforms, together with backward and forward citation chaining, was intended to limit this bias, but the review should be read as a critical synthesis of a representative body of studies rather than as an exhaustive census of the field. Accordingly, the counts in the coverage map (Section 4.7) describe the reviewed sample and indicate relative rather than absolute research density.

2.2. Modelling and Optimisation Methods

This section summarises the modelling and optimisation methods used in the studies reviewed in Section 3: finite element and multibody analysis (Section 2.2.1), topology optimisation (Section 2.2.2), parametric optimisation (Section 2.2.3), experimental validation (Section 2.2.4), and surrogate models and machine learning (Section 2.2.5).

2.2.1. Finite Element and Multibody Analysis

Finite element analysis (FEA) uses a detailed finite element (FE) model of the trailer structure to evaluate stress distributions, deformations and critical points under dynamic loads [7–11].

Multibody dynamics (MBD) simulation reproduces the dynamic behaviour of the vehicle–trailer combination, including the interaction of the suspension, chassis and road, and is used to generate realistic load spectra [8,11–14].

Combining FEA with MBD-derived loads provides a more complete picture of the structural response and durability under operating conditions [8,10].

2.2.2. Principles of Topology Optimisation

Topology optimisation, including bidirectional evolutionary methods, has been extended to nonlinear structures subjected to dynamic loads, maximising stiffness while minimising mass [15–17].

Dynamic-response constraints and fail-safe criteria can also be integrated, the latter to ensure resistance to partial damage [16,17].

The main steps of the process—definition of the design domain, the loads and boundary conditions and the objective and constraints, iterative finite-element-based redistribution of material, and interpretation of the result for manufacture—are illustrated in Figure 2, as described in [18].

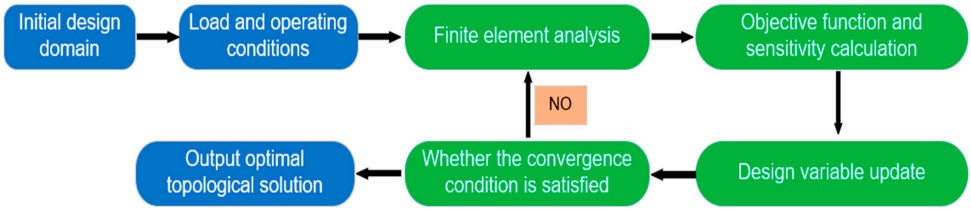


Figure 2. Illustrative diagram of the main steps in the topological optimisation process. Reproduced from [18], distributed under the terms of the Creative Commons Attribution (CC BY) license.

The review by Tang et al. [18] also synthesises the linear-elastic theoretical framework of topology optimisation (sensitivity analysis, optimisation criteria and smoothing of the topological solution) and the nonlinear phenomena relevant to real structures, namely stress constraints and geometric, material and contact nonlinearities.

2.2.3. Parametric Optimisation

Parametric (size and shape) optimisation varies a limited set of design variables, such as plate and wall thicknesses, cross-section dimensions and shapes, stiffener spacing, material grades and the positions of structural members, and evaluates their effect on the structural response, usually through a parametric finite element model coupled with an optimisation algorithm such as response-surface methodology or a genetic algorithm. The load cases considered for trailer structures typically include vertical shocks from road irregularities, vibrations on degraded roads, braking and cornering manoeuvres, local impacts during loading and unloading, and concentrated loads from heavy equipment; multibody simulations show that speed changes markedly increase the longitudinal loads at the fifth wheel and suspensions, whereas cornering adds large lateral loads and uneven left–right axle loads [13]. The parametric optimisations reviewed in Section 3.2 report mass reductions of about 7–16% for complete frames and components that keep their original material and 28% for the shape optimisation of the steel longitudinal beams of a trailer, relative to the mass of the beams alone; the higher value of 67% refers to a purely numerical scenario for a fully composite trailer structure.

2.2.4. Experimental Validation

Optimised prototypes can be validated on road-simulation rigs, where cycles of dynamic loading are applied to verify durability and in-service behaviour [9]. Physical measurements are also used to validate the numerical models, for example by verifying finite-element stresses against physical tests for the suspension arm of an aircraft-recovery trailer (airport ground-support equipment, i.e., a non-freight demonstrator) and by comparing multibody-simulated axle loads of a semi-trailer with existing field-test data [10,13].

2.2.5. Surrogate Models and Machine Learning

Machine learning techniques (e.g., linear regression and neural networks) are used to accelerate the prediction of structural behaviour based on simulation results, facilitating multi-objective optimisation; for example, regression models trained on multibody-simulation data have been used to predict the peak axle loads of a semi-trailer from vehicle speed and pothole dimensions, and a multilayer-perceptron surrogate combined with a genetic algorithm has been used to reduce the computation time of structural optimisation under transient impact loads [13,19].

Table 1 maps each method to its main applications and to representative studies reviewed in this paper:

Table 1. Key methods and applications.

Method/Modelling	Main Application	Citations
FEA + MBD	Dynamic analysis, fatigue, structural validation	[7–9,11,12,14]
Topological optimisation	Optimal material distribution, fail-safe	[15–17]
Experimental testing	Physical testing of optimised prototypes; validation of FE models	[9,10,20–22]
Surrogate models/machine learning	Rapid prediction, multi-objective optimisation	[10,13,19,22,23]

In practice, these methods are combined rather than used in isolation; how often each combination has been validated experimentally is assessed in Section 4.7.

3. Results

This section synthesises the reviewed studies by optimisation family (Figure 3). Sections 3.1–3.3 discuss, in turn, topology optimisation, parametric (size and shape) optimisation and AI-assisted optimisation; Section 3.4 compares the outcomes reported across the three families together with their validation level; and Section 3.5 reviews the enabling technologies on which the three families depend: vehicle-level innovations, materials and hybrid structures, manufacturing and joining, and load characterisation, validation and digital twins.

3.1. Topology Optimisation

Topology optimisation has been applied both to complete truck chassis and to individual load-bearing components, in most cases under a small set of quasi-static load cases. In one study, topological optimisation is applied to a truck chassis, taking into account several loading conditions (weight, braking, and centrifugal forces). A mass reduction of ~14% is achieved without exceeding the stress limit [24]. Another study evaluates the lightweighting potential of a ladder-type chassis structure for commercial road vehicles, using simplified static loading cases, predominantly for structural sizing. The conclusion is that "material-independent" topological optimisation offers greater mass-reduction po-

tential than simply changing the material [25]. A further study reduces the mass of a heavy-truck chassis by about 6% by removing low-stress material in successive iterations, without a formal optimisation algorithm, and tests a 1:10 scale model of the modified chassis in compression [26].

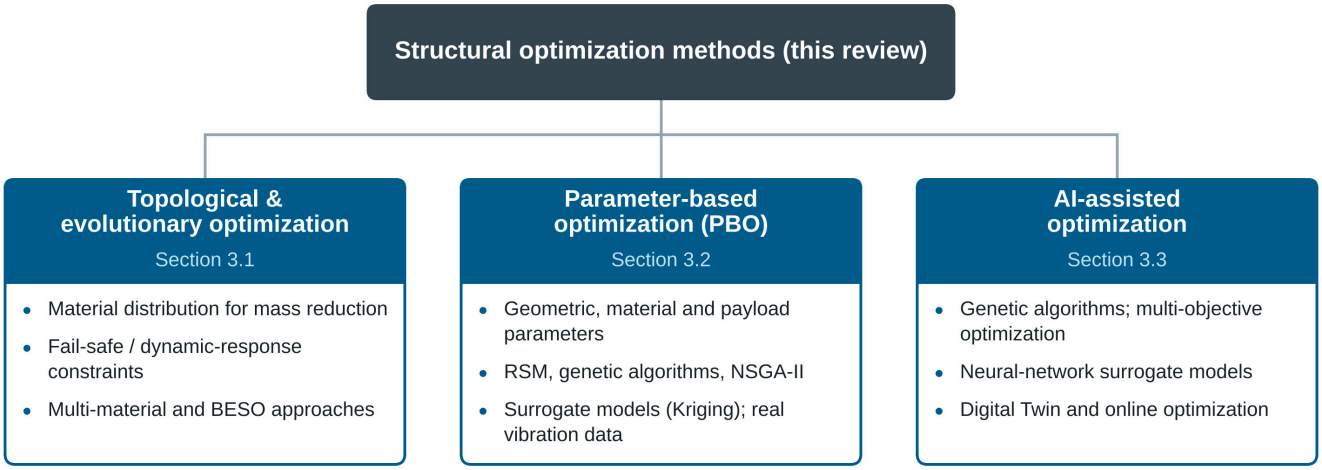


Figure 3. The three families of structural-optimisation methods examined in this review.

Recent frame-level studies combine topology optimisation with size optimisation or multi-objective formulations. For a hydrogen-fuelled truck frame [27], a multi-objective topology optimisation maximising static stiffness under multiple load cases and the lowest natural frequency reduced the maximum stress by about 35.6% and the mass by about 7.8% and raised the first natural frequency by 1.9 Hz; the authors state that the improvement was verified by modal testing, without specifying which frame was tested. For an electric mixer truck frame [23], six working conditions (for example, tank lifting and climbing a slope) were analysed; a Kriging surrogate combined with a multi-objective genetic algorithm and the analytic hierarchy process (AHP) was used to size the structure so as to minimise both its mass and its maximum stress, and topology optimisation was additionally applied, reducing the frame mass by 11.96% in simulation. For a mobile pump truck frame [28], topology optimisation was combined with a multi-objective genetic algorithm under four typical working conditions (full-load bending, torsion, emergency turning and emergency braking), reducing the frame mass by 87.88 kg (10.89%); a modal analysis, supplemented by a harmonic response analysis (0–70 Hz), showed that resonance with road- and engine-induced vibrations was avoided. By contrast, for a heavy-duty truck frame [29], a simpler redesign without a formal optimisation algorithm, replacing the frame material with a higher-strength one and removing cross-members, reduced the mass by 58 kg (4.6%) while meeting the strength requirements under four static working conditions, with a modal analysis to avoid resonance.

At the component level, the leaf-spring brackets of truck suspensions [30] have been optimised through topology to reduce mass while maintaining strength, as has the gearbox housing of an agricultural tractor [31] (a non-road-freight application), a load-bearing part of the vehicle structure that was optimised under several static load cases for lower mass and higher stiffness and strength (−8.44% mass).

A fundamental approach to the lightweight design of flatbed trailers is presented in one study [32]. The two-stage design process (topological optimisation followed by thickness optimisation) led to a frame configuration completely different from traditional ladder-type structures, with high bending stiffness and a higher torsional natural frequency. Extending this approach, a further study [33] proposes a method based on ground beam structures for

optimising the flatbed-trailer frame, offering a systematic alternative to classical topological-optimisation methods for generating optimal geometric configurations of the longitudinal beams.

One crash-box study [34] addresses the frontal-impact crashworthiness of heavy passenger coaches, i.e., a non-freight demonstrator; nevertheless, topological optimisation under dynamic (crash) conditions is highly relevant to the design of energy-absorbing elements in trailers (cross-members, rear underrun protection devices and anchoring points). The authors integrate a topology algorithm with nonlinear impact simulations and show how optimised components can improve energy-absorption profiles without significant mass increases (a method transferable to trailer chassis elements).

Topology optimisation methods for dynamic loads, including multi-material, density-based and equivalent-static formulations, have so far been demonstrated on generic structures rather than on trailer frames [35–37].

Methodological studies, mostly demonstrated on generic structures, have refined topology optimisation for efficiency and manufacturability. One study [38] improves the efficiency and precision of proportional topology optimisation; a second study [39] projects the optimised layout onto standard structural profiles, addressing the manufacturability of organic shapes; a third study [40] uses a voxel-based evolutionary scheme to control natural frequencies; a fourth study [41] defines part boundaries more sharply through an immersed finite-element level-set formulation; and a specific approach for sheet-metal parts is presented in a fifth study [42], which optimises material distribution and local thickness simultaneously for shell structures under stress constraints.

Where the formal optimisations reviewed in this subsection quantify the saving, the reported mass reductions lie between about 8% and 14% [23,24,27,28,31]; the two redesigns made without a formal optimisation algorithm saved 4.6% [29] and about 6% [26]. The evidence is almost entirely numerical and based mainly on quasi-static load cases. Physical tests are limited to the compression test of a 1:10 scale model of the modified chassis [26], the modal test reported for the hydrogen-fuelled frame, for which the tested frame is not specified [27], and the comparison of the crash-box model with prototype test data [34]; none of the optimised layouts were tested under road loading, and few studies explicitly address manufacturability, a notable exception being the projection of optimised layouts onto standard structural profiles [39].

3.2. Parametric (Size and Shape) Optimisation

Parametric (size and shape) optimisation keeps the layout of a structure fixed and adjusts its cross-sectional dimensions, wall thicknesses or profile shapes, which makes it a direct route from an existing frame design to a lighter one. The studies discussed below range from profile comparisons and cross-section sizing of complete frames to robust and multi-criteria design formulations.

One study [7] numerically analyses a truck ladder chassis, designated FH16 in the source and equipped with the components associated with the tractor unit (engine, transmission system, exhaust, suspension, and fuel tank). The analysis combines static stress analysis (ABAQUS), modal and harmonic analyses (ANSYS) and a vehicle-dynamics simulation (MATLAB/Simulink); no physical tests are reported. Two design variants of the main chassis members are compared: an open-profile chassis with "U" profiles and a closed-profile chassis with rectangular tubes.

Figures 4 and 5 show the finite-element model of the chassis, with its boundary conditions and loads, and the resulting von Mises stress distribution [7].

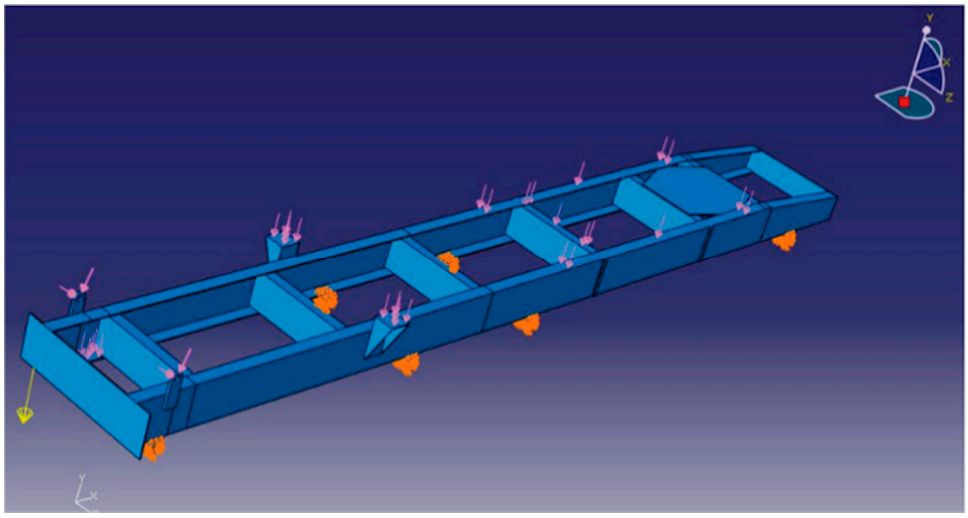


Figure 4. Finite-element model of the chassis with its boundary conditions and loads. Reproduced from [7], an open-access article distributed under the terms of the Creative Commons Attribution (CC BY) license.

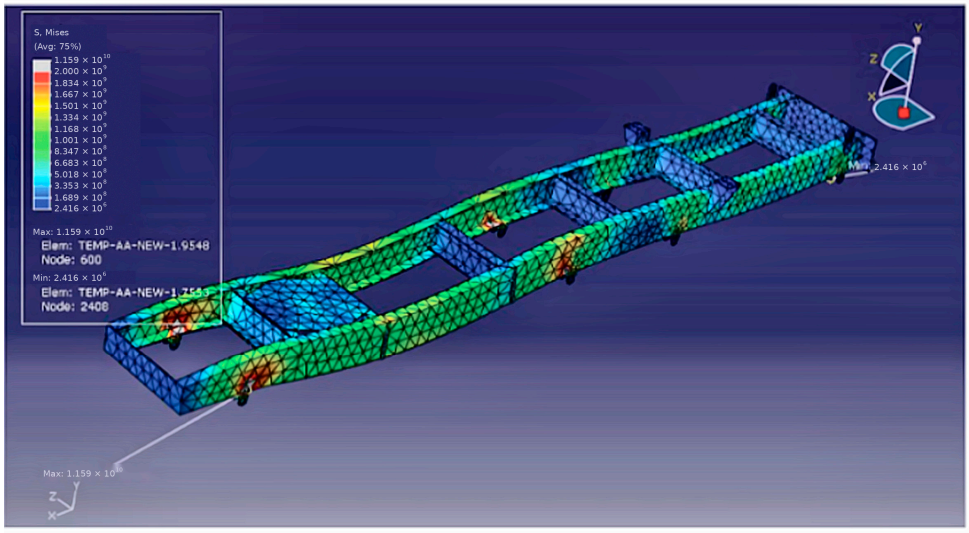


Figure 5. Von Mises stress distribution in the chassis. Adapted from [7] (numerical values rewritten in scientific notation), an open-access article distributed under the terms of the Creative Commons Attribution (CC BY) license.

The analysis shows that the open "U" profile and the closed rectangular-tube profile have comparable, but not identical, safety factors (1.92–2.54 vs. 1.85–2.32), as illustrated in Table 2.

At these comparable safety levels, the reported totals make the chassis built from open "U" profiles 22.4% lighter than the one built from rectangular tubes (94.6 kg vs. 121.91 kg). This difference is uncertain, however, because the rectangular-tube masses are inconsistent (see the note to Table 2); recomputing segment B at 13.0 kg/m gives a total of 109.2 kg and a difference of 13.4%, whereas recomputing segment C at 16.1 kg/m gives 127.5 kg and 25.8%, so the published data support a difference of roughly 13–26%. Since [7] compares two alternative profiles rather than optimising a baseline design, its result is not included among the optimisation outcomes compared in Sections 3.4 and 4.1.

Table 2. Side-member segment masses and safety factors for the "U" profile and the rectangular tube, as reported in [7].

Section	Profile	Profile Dimensions (mm)	Mass (kg) [1]	Safety Factor
A (0–1250 mm)	U-shape	120/60 × 6	13.375	1.92
	Rectangular	120/60 × 6	16.25	2.03
B (1250–3300 mm)	U-shape	133/60 × 6.5	23.575	2.11
	Rectangular	133/60 × 6.5	33.01	1.85
C (3300–4200 mm)	U-shape	133/60 × 6.5	10.35	2.54
	Rectangular	133/60 × 6.5	11.7	2.32
Total chassis weight	U-shape	-	94.6 kg	-
Total chassis weight	Rectangular	-	121.91 kg	-

[1] Labelled "kg/m" in the source; the values are, however, consistent with the masses of the side-member segments A, B and C: for the U-profile, segments B and C, which share the 133/60 × 6.5 profile, both correspond to 11.5 kg/m (23.575 kg/2.05 m and 10.35 kg/0.90 m). The total chassis weight equals twice the sum of the segment masses, i.e., two side members (2 × 47.3 = 94.6 kg; 2 × 60.96 = 121.92 kg, reported as 121.91 kg). For the rectangular tube, segments B and C correspond to 16.1 and 13.0 kg/m despite the identical nominal profile, and segment A, with the smaller 120/60 × 6 profile, also corresponds to 13.0 kg/m; these inconsistencies are present in the source and cannot be resolved from the published data.

One study [20] presents a complete workflow (CAD modelling, parametric FEA, optimization and prototyping) for a 1:6-scale low-bed semi-trailer chassis. Weak points were first identified under bending, after which nine cross-sectional dimensions of the I- and box-sections were optimised to minimise mass under a maximum-stress constraint, reducing the chassis mass from 77.93 kg to 65.79 kg (−15.6%) and the maximum combined stress by 18.7%. The optimised chassis was then manufactured and subjected to two experimental load cases, which confirmed the finite-element predictions to within 7.75–10.24% of the measured stress levels. This is one of the few reviewed studies in which the optimised structure itself was physically tested.

Two further optimisations concern vehicles outside road-freight transport. For the suspension arm of an aircraft-recovery trailer, design of experiments, response surfaces and the NSGA-II algorithm reduced the mass by 13.7% (from 146.81 to 126.69 kg) and the maximum stress by 8.6%, using a finite-element model whose stresses had been verified against physical tests [10]. A missile-transporter semi-trailer, a military application, was optimised for minimum mass under a stress constraint and became 12.6% lighter and 10.1% stiffer in bending; no tests are reported [43].

Another study [44] investigates trailer weight reduction by combining material selection with parametric structural optimisation. For a 13.5 m European trailer, the authors define critical load cases and build a parametric FE model; shape optimisation alone reduces the mass of the existing steel longitudinal I-beams by 28% (140 kg), whereas combined shape and material optimisation of a fully composite trailer structure yields savings of up to 67% (1326 kg). Both results are purely numerical, and the 67% value defines a theoretical limit of the design space rather than a validated product. A related parametric study on an automotive chassis [45] combined metal-matrix-composite materials with weight optimisation based on static structural analysis, Latin hypercube sampling and response surfaces.

An applied study [46] presents parametric-FEA evaluations of ways to reduce the mass of a semi-trailer frame (lightening holes and dimensional changes) while maintaining the required strength and gives practical recommendations for its longitudinal members; no tests are reported.

The optimisation of the main longitudinal beam's cross-section is exemplified by one study [47], which applies the response-surface method to the lightweight design of the longitudinal-beam structure of a mobile pump truck. Compared with the original finite-element model, the height, width and thickness of the beam section were reduced by 10 mm, 11 mm and 0.8 mm, respectively, reducing the mass of the entire frame by 35.8 kg with minimal changes in displacement and stress across the four motion scenarios analysed; optimising the cross-sectional geometry can thus produce significant mass reductions without compromising structural performance. Likewise, a recent approach to cross-sectional optimisation is offered by one study [22], which proposes a multi-level optimisation methodology for the cross-sections of the thin-walled frame beams of a tri-axle unmanned forestry vehicle (an off-road transport vehicle rated for a 3 t load, i.e., not a road-freight vehicle). Key design variables were selected by sensitivity analysis, response surfaces were built using least-squares regression and radial-basis-function networks, and a multi-objective genetic algorithm balanced mass, modal frequency, and bending and torsional stresses. The frame mass was reduced by 10.1 kg (7.44%) without loss of static or dynamic performance, and the finite-element model was verified experimentally, with differences of, at most, 5.4% in static strain-gauge tests and 3.3% in modal tests.

Robust and multi-criteria formulations address conflicting design requirements. A robust multi-objective size optimisation of a truck cab [48] balanced mass against fatigue life under cyclic torsion while keeping the design insensitive to small manufacturing variations; its baseline cab was validated by modal and full-scale fatigue tests. Two further studies propose general methods for handling multiple objectives [49] and multiple constraints [50], and another formalises the choice of the final design through multi-criteria decision-making (MCDM) and robust decision-making methods [51].

Excluding the profile comparison of [7], the parametric optimisations above report mass savings of about 7–16% for complete frames and components that keep their original material [10,20,22,43], 28% for the shape optimisation of the steel longitudinal beams alone and up to a theoretical 67% for a fully composite redesign [44]. Only one study tested the optimised structure itself, a 1:6 scale chassis [20], while three others validated their finite-element models or baseline designs experimentally, by physical tests of the suspension arm [10], by strain-gauge and modal tests [22] or by modal and full-scale fatigue tests of the baseline cab [48]. The remaining results are numerical, and only three studies consider time-varying loading through a vehicle-dynamics simulation [7], a dynamic model of the trailer [10] and cyclic torsion for fatigue life [48].

3.3. AI-Assisted Optimisation

In this review, AI-assisted optimisation denotes studies in which a data-driven or bio-inspired component—an evolutionary search algorithm, a machine-learning surrogate model, a generative design tool or a digital twin—drives or accelerates the structural optimisation. The evidence for such methods applied specifically to trailer structures is still limited, and most of the studies discussed below are numerical.

Among these methods, a multi-objective genetic algorithm combined with response surfaces reduced the mass of a trailer axle by 10.7% (10.2 kg); bench tests of the optimised prototype confirmed that its stiffness, strength and fatigue life met the requirements of the applicable trailer-axle standard [21]. Neural-network surrogate models approximate the structural response and accelerate optimisation under complex dynamic loads; combining a multilayer perceptron (MLP) with a genetic algorithm reduced the computation time of structural optimisation under transient impact loads compared with FEA-based optimisation, without compromising the accuracy of the response prediction [19]. Digital twins

allow the structural optimisation to be updated online from monitored data, a concept demonstrated so far on a structure outside freight transport [52].

Table 3 summarises the outcomes reported by these studies and their validation level.

Table 3. Outcomes reported by the AI-assisted studies and their validation level. Changes are given relative to the baseline design of each study; negative values denote reductions.

AI Method/Optimisation	Result/Main Benefit	Citations
Multi-objective genetic algorithm + response surfaces	−10.7% mass (−10.2 kg); stiffness, strength and fatigue life met the trailer-axle standard JT/T 475-2002 in bench tests	[21]
Neural-network (MLP) surrogate + genetic algorithm	Shorter computation time than FEA-based optimisation, at comparable prediction accuracy (numerical study)	[19]
Digital Twin + optimisation	Optimisation updated online from monitored data (non-freight demonstrator)	[52]

Taken together, these studies show clear computational benefits of AI-assisted methods—surrogate models reduce the cost of evaluating design variants [19], and digital twins enable optimisation driven by monitored data [52]—but their evidence base for trailer structures remains thin. Of the AI-assisted studies discussed in this section, only [21] reports bench validation of an optimised trailer component; ref. [19] is a numerical study and [52] uses a non-freight demonstrator. None of the reviewed studies provides a like-for-like comparison showing that AI-assisted methods outperform conventional optimisation for trailer frames, and the comparative study discussed below shows that a purely generative design can be structurally unsafe without engineering refinement. AI-assisted methods should therefore be regarded as accelerators of conventional, validated design workflows rather than as substitutes for them, consistent with the coverage map in Section 4.7.

A critical evaluation of generative-AI-assisted design is offered by one study [53], which compares three design approaches—manual, AI-generative, and hybrid—for a truck wheel-mounting aid frame, a workshop device used when mounting truck wheels (i.e., equipment rather than a load-bearing vehicle structure), using finite-element analysis under a static load of 2500 N.

The results show significant performance differences: the manual design produced a maximum stress of 106.58 MPa and a safety factor of 2.02; the design generated exclusively by AI produced a maximum stress of 1818.2 MPa and a safety factor of only 0.118, indicating structural failure; while the hybrid design (combining AI generation with engineering refinement) achieved the best performance, with a safety factor of 2.11. This study shows that optimisation based exclusively on generative AI, without engineering validation and adjustment, can produce structurally unsafe solutions, underscoring the need for a hybrid human–AI approach.

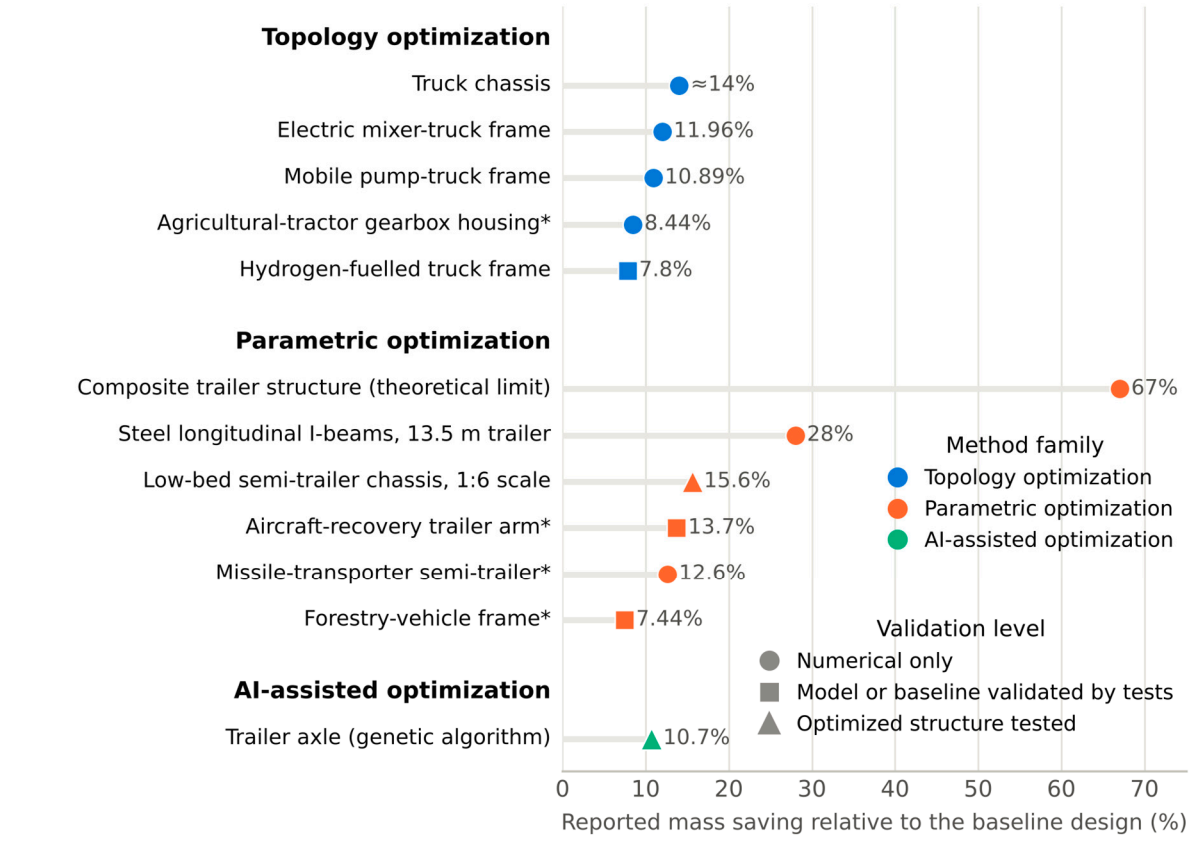
3.4. Cross-Family Comparison of Reported Outcomes

Table 4 lists every formal optimisation reviewed in Sections 3.1–3.3 whose mass saving is reported as a percentage, and Figure 6 plots the same results.

Table 4. Mass- and stress-reduction outcomes of the formal optimisations reviewed in Sections 3.1–3.3, as plotted in Figure 6. Changes are given relative to the baseline design reported in each study; negative values denote reductions.

Reference	Component	Method	Reported Outcome	Validation
[10]	Suspension arm, aircraft-recovery trailer (non-road-freight)	Design of experiments + response surfaces + NSGA-II	−13.7% mass (146.81 → 126.69 kg); −8.6% max. stress	Numerical; FE model validated by physical tests
[20]	Low-bed semi-trailer chassis, 1:6 scale	Parametric sizing (response surfaces)	−15.6% mass (77.93 → 65.79 kg); −18.7% max. stress	Experimental (optimised prototype, two load cases; FE–test difference 7.75–10.24%)
[21]	Trailer axle	Genetic algorithm	−10.7% (10.2 kg)	Experimental (bench test)
[22]	Frame, unmanned forestry vehicle (non-road-freight)	Cross-section optimisation (response surfaces + multi-objective genetic algorithm)	−7.44% mass (10.1 kg)	Numerical; FE model validated by strain-gauge and modal tests
[23]	Electric mixer-truck frame	Size optimisation (Kriging + multi-objective genetic algorithm) + topological optimization	−11.96% mass	Numerical
[24]	Truck chassis	Topological optimisation	≈−14% mass	Numerical
[27]	Hydrogen-fuelled truck frame	Multi-objective topological optimisation	−7.8% mass; −35.6% max. stress	Numerical; modal test reported, tested frame not specified
[28]	Mobile pump-truck frame	Topological optimisation + multi-objective genetic algorithm	−10.89% mass (87.88 kg)	Numerical
[31]	Gearbox housing, agricultural tractor (non-road-freight)	Topological optimisation	−8.44% mass	Numerical
[43]	Missile-transporter semi-trailer (military, non-road-freight)	Mass minimised under a stress constraint	−12.6% mass; +10.1% bending stiffness	Numerical
[44]	Trailer longitudinal beams (13.5 m)	Shape optimisation	−28% (140 kg)	Numerical
[44]	Trailer structure, composite	Shape + material optimisation	up to −67% (1326 kg)	Numerical

In Figure 6, the optimisations that keep the material of a complete frame or component lie between about 7% and 16%, whether they are purely numerical or supported by tests, whereas the two highest values, 28% and 67%, come from the beam shape optimisation and composite substitution of a single numerical study [44]. Only two of the optimised structures, the 1:6 scale chassis [20] and the trailer axle [21], were tested physically; Section 4.1 compares the results by type of redesign.



* Non-road-freight application.

Figure 6. Percentage mass savings listed in Table 4, by study and component, grouped by method family; the marker shape indicates the validation level. From top to bottom, the results are from [23,24,27,28,31] (topology optimisation), [44] (two results), [10,20,22,43] (parametric optimisation) and [21] (AI-assisted optimisation). The profile comparison [7] and the redesigns without a formal optimisation algorithm [26,29] are not shown; the modal test reported for [27] is shown as model or baseline validation because the tested frame is not specified, and the 67% value is a theoretical limit of the design space [44].

Taken together, the three families support different kinds of redesign rather than a single line of progress: topology optimisation changes the layout of a frame or component, parametric optimisation resizes or reshapes a given layout, and AI-assisted methods mainly accelerate either process. Where several objectives are optimised, they combine mass with stiffness, natural frequency, stress or fatigue life; cost is quantified in only one study [54], and manufacturability is rarely treated as a design requirement (Sections 4.5 and 4.6). The comparative study [53] shows that generative AI outputs are only as reliable as the engineering judgement applied to validate them, reinforcing the view that even the most advanced optimisation pipelines still require a human-in-the-loop verification step before results can be trusted for structural components subjected to extreme dynamic loads.

3.5. Enabling Technologies

The studies reviewed in this section address the vehicle-level solutions, materials, manufacturing processes and load-characterisation and validation tools on which the three optimisation families depend. Section 3.5.1 covers vehicle-level innovations, Section 3.5.2 materials and hybrid structures, Section 3.5.3 manufacturing and joining technologies, and Section 3.5.4 load characterisation, validation and digital twins.

3.5.1. Vehicle-Level Innovations in Freight Transport

Besides the topology, multi-material and shape-and-material optimisations discussed in Sections 3.1 and 3.2, several vehicle-level solutions aim to increase capacity, reduce tare mass or improve safety. Changes in structural configuration can also save mass: reducing the number of supports of an aluminium tank mounted on a four-axle road tanker from five to two lowered the tank tare mass by 9.6% in a numerical study [55]. At the level of the running gear, theoretical models and optimisation algorithms for the hydraulic suspensions of modular trailers aim to improve stability and load distribution across configurations and road conditions [56]. Finally, in a pilot study conducted in Spain, a semi-trailer was extended from 13.6 m to 18 m to increase the cargo volume carried per trip; the extension increased the tare mass by about 1800 kg, reducing the payload accordingly, and the dynamic behaviour of the combination was assessed by simulation against OECD reference data [57].

Taken together, these solutions show that mass reduction, material selection, suspension behaviour and structural configuration interact rather than act separately: a lighter frame changes the dynamic response that the suspension must accommodate, and a longer or modular platform changes the load paths that the frame and its joints must carry.

Table 5 presents the technologies and advanced structural solutions used in optimising trailer structures subjected to extreme dynamic loads.

Table 5. Advanced technologies and structural solutions.

Innovation/Technology	Main Benefit	Citations
Multi-material topological optimisation	Reduced mass, increased resistance to dynamic loading	[35]
Material selection + shape optimisation	−28% (140 kg) for steel longitudinal I-beams; up to −67% (1326 kg) for a fully composite trailer structure (numerical)	[44]
Reduced number of tank supports	−9.6% tank tare mass (numerical)	[55]
Optimised hydraulic suspension	Stability and safety for special transport	[56]
Longer (18 m) semi-trailer	Higher cargo volume per trip; tare mass +1800 kg (pilot study)	[57]

The gains summarised in Table 5 should therefore be read as potential rather than demonstrated in service; they are numerical, theoretical or pilot-study results, and none of the studies reports a physical test of an optimised structure.

3.5.2. Materials and Hybrid Structures

Reducing vehicle mass (lightweighting) without compromising safety remains a major priority. Research is therefore examining the transition from conventional steels towards hybrid and composite solutions.

Using a single material, even an advanced steel such as ASTM A148 [58] or an advanced high-strength steel (AHSS), is becoming insufficient to satisfy mass-reduction and impact-safety requirements simultaneously. The clear trend is towards multi-material solutions, in which base steel structures are locally reinforced with aluminium or composite materials. However, integrating these materials raises joining and fatigue-behaviour issues that require dedicated optimisation strategies.

Although new materials are gaining ground, steel remains dominant in heavy-duty applications. A comparative study [58] analyses the load behaviour of a high-strength

cast steel in order to identify the section geometry (I, C, and rectangular) that minimises internal stresses.

For welded structures subjected to dynamic loads, one study [59] addresses the problem of heat-affected-zone embrittlement in AHSS, proposing solutions to extend fatigue life.

The application of composite materials to heavy-truck structures is documented in one study [60], which evaluates replacing the high-strength low-alloy (HSLA) steel in the ladder-type chassis of a heavy truck with advanced composite materials—carbon fibre (CFRP) and basalt fibre (BFRP). The structural and modal analyses (carried out in ANSYS on CAD models from SolidWorks) compared von Mises stress, strain energy, and natural frequencies under loading representative of payload and running gear. The results show that CFRP significantly reduces total deformation and increases natural frequencies, offering stiffness and dynamic-stability advantages, while BFRP offers higher strain energy and damping, beneficial for impact-energy absorption, albeit with greater static deformation and lower modal frequencies. The authors recommend using CFRP for load-bearing elements where stiffness is critical, BFRP for secondary areas exposed to impact, and exploring hybrid CFRP/BFRP/metal solutions for an optimal cost–performance balance.

Despite these promising results, the adoption of composite materials in heavy-duty freight structures remains considerably more limited than in aerospace or motor-sport applications, where design cycles and cost tolerances differ substantially. The joining techniques required to integrate CFRP or BFRP elements into predominantly steel chassis—adhesive bonding, mechanical fastening, or hybrid riveted-bonded joints—still lack the standardised fatigue-life data available for all-metal structures, which slows their broader industrial uptake in trailer and truck-frame design.

3.5.3. Manufacturing and Joining Technologies

The manufacturing process imposes severe constraints on design; accordingly, the recent literature focuses on the digitalisation of welding processes and on the freedom offered by additive manufacturing.

As discussed in Section 3.1, topology optimisation can generate non-intuitive, organic layouts, for example, with voxel-based or level-set formulations but, for freight vehicles, such shapes still have to be translated into manufacturable parts, either by projecting them onto standard structural profiles or by casting or additive manufacturing.

Joint quality is equally critical; one study [61] identifies stochastic fatigue models of welded joints from structural experiments, accounting for the inherent variability of the welding process. Artificial intelligence is increasingly used for weld quality control: machine-learning models can predict resistance-spot-weld quality from process parameters as an alternative to destructive testing [62], generalisable models can be transferred between robots and parts [63], and a digital twin of the spot-welding process has been built to predict weld quality [64]. To limit welding distortion, the welding sequence has been optimised with a neural-network model combined with a chaotic whale optimisation algorithm, a bio-inspired method [65].

Additive manufacturing widens the design space at the conceptual stage, as shown for an automotive FlexBody chassis structure [66], but the anisotropy induced by the build direction must then be accounted for in the optimisation itself [67].

For trailer frames, which are mostly welded from standard profiles, these studies point to two practical routes: constraining the optimised layout to standard structural members, as in the geometry-projection method discussed in Section 3.1, and controlling weld quality and distortion through data-driven process models. Additive manufacturing, by contrast, mainly widens the options available at the concept stage.

3.5.4. Load Characterisation, Validation and Digital Twins

Realistic load cases and validation data link structural optimisation to service conditions; the studies in this subsection obtain them from measurements, vehicle-suspension models, reduced-order models and digital twins. One study [68] reports acceleration measurements on a light single-axle trailer (category O2; maximum payload 980 kg) towed by a passenger car over artificial road obstacles 25 mm and 50 mm high, at 20 and 30 km/h and with loads of 0–300 kg. No simulation or optimisation is performed and the vehicle is not a heavy freight trailer; nevertheless, the measured responses, including the higher risk of wheel–road contact loss for an empty trailer at low speed, illustrate the transient events that realistic load cases for chassis and cargo-securing points should capture. Another study [69] evaluates how much an air suspension system reduces the dynamic loads transmitted to a semi-trailer's axles. The results provide quantified data (reduction in dynamic peaks) and recommendations on suspension tuning parameters that can be incorporated into parametric chassis optimisations to achieve better structural performance under real conditions, thereby linking structural optimisation to suspension-parameter optimisation.

Reduced-order models make repeated structural simulations cheaper: one study [70] proposes a model-reduction method for the time-domain structural mechanical response. Fast models of this kind are also needed for digital twins, whose role in predictive-maintenance strategies for commercial vehicles is discussed in one study [71]. The authors analyse how integrating digital twins with artificial-intelligence methods enables the shift from reactive/scheduled maintenance to predictive maintenance in the operation of commercial-vehicle fleets, through continuous monitoring of structural condition and early prediction of failures.

Simulation realism must also be balanced against cost: one study shows how nonlinear behaviour affects vibration-fatigue simulations of automotive components [72], while another [73] predicts the noise, vibration and harshness (NVH) performance of a heavy truck at the full-assembly level with a methodology based on frequency-response functions (FRFs) and multi-level frequency-based sub-structuring (FBS), applied to truck subsystems (cab, cab suspension, chassis and chassis suspension). Compared with full FE modelling, the FBS approach significantly reduces computation time while maintaining good correlation with the results of the detailed model—an important practical advantage for the rapid evaluation of design changes on NVH performance.

These studies provide the realistic load cases and efficient models that the optimisation methods of Sections 3.1–3.3 require, but none of them feed its measurements or models back into the optimisation of a trailer structure; closing this loop is one of the gaps discussed in Section 4.

4. Discussion

This section interprets the evidence reviewed in Section 3. It first examines how reliable the reported mass reductions are (Section 4.1), which design criteria the optimizations consider (Section 4.2) and how extreme dynamic loads are represented (Section 4.3). It then discusses the limits of AI-assisted optimisation (Section 4.4), the manufacturability of optimised geometries (Section 4.5) and their economic feasibility (Section 4.6), summarises the coverage of the reviewed literature (Section 4.7) and outlines an integrated design workflow (Section 4.8).

4.1. Reliability of the Reported Mass Reductions

The reported mass reductions depend mainly on the type of redesign (Figure 7). Optimisations that keep the material of a complete frame or component and change its layout or cross-sections report savings of about 7–16%: 7.8–14% for the topology optimisations

of truck frames and of an agricultural-tractor gearbox housing [23,24,27,28,31], 7.4–15.6% for the parametric optimisations of chassis, frames and a suspension arm [10,20,22,43] and 10.7% for the genetic-algorithm optimisation of a trailer axle [21]. The two largest values come from a single numerical study and from redesigns of a different scope: shape optimisation of the steel longitudinal I-beams of a 13.5 m trailer reduced the mass of these beams by 28% and combined shape and material optimisation of a fully composite trailer structure defines a theoretical limit of 67% [44].

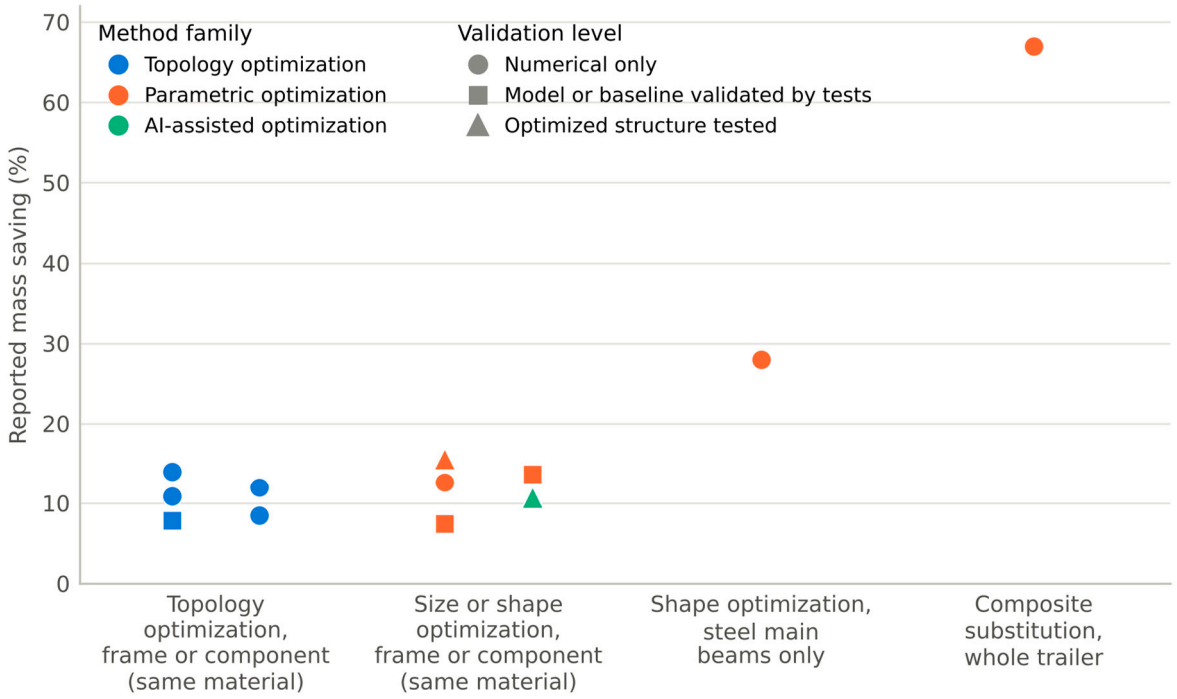


Figure 7. Reported mass savings of the results in Figure 6, grouped by type of redesign: topology optimisation of a frame or component [23,24,27,28,31], size or shape optimisation of a frame or component [10,20–22,43], shape optimisation of the steel main beams [44] and composite substitution for the whole trailer [44]. The colour indicates the method family and the marker shape the validation level.

Validation level does not explain this difference. The purely numerical results among these same-material optimisations, 8.4–14% [23,24,28,31] and 12.6% [43], lie within the range of those supported by tests, 7.4–15.6% [10,20–22,27], and a test can show whether a lighter design is adequate but not whether a reported percentage is overstated. Only two optimised structures were tested physically: the 1:6 scale low-bed semi-trailer chassis, whose measured responses agreed with the predictions to within 7.75–10.24% [20], and the trailer axle, which met the stiffness, strength and fatigue-life requirements of the applicable standard in bench tests [21]. In the other three cases, the tests concerned the finite-element model or an unspecified frame: the suspension arm of an aircraft-recovery trailer, a non-road-freight application [10], the frame of a forestry vehicle, an off-road application [22], and the hydrogen-fuelled truck frame, for which a modal test is reported without stating which frame was tested [27].

What the data do show is narrower: the savings above 16% come from one numerical study [44], in which the shape of the main beams or the material of the whole trailer was changed. They should therefore not be generalised to redesigns of complete frames that keep their material, and the adequacy of such lighter designs remains to be shown by tests, preferably under service-representative loading. The close agreement between measured and predicted responses in the tested cases, within about 3–10%, also indicates that calibrated finite-element models are reliable for static and modal behaviour; the main uncertainty

lies less in the solvers than in the load cases, which are discussed in Section 4.3. A staged validation sequence, from scale-model or component tests to bench tests of the optimised structure and, finally, instrumented road tests, would allow the remaining numerically optimised designs to be checked at proportionate cost.

4.2. Design Criteria: Mass, Fatigue and Fail-Safe Behaviour

Most of the reviewed optimisations minimise mass subject to stress or stiffness limits or trade mass against stiffness and natural frequency, while fatigue, buckling and damage criteria are rarely part of the optimisation; the missile-transporter semi-trailer [43], a military application outside road-freight transport, for example, was optimised for mass under a stress constraint (12.6% lighter; 10.1% stiffer in bending), and buckling appears mainly in generic formulations such as a multiscale method with stress and buckling constraints [74].

Fatigue enters the optimisation explicitly in only two of the reviewed studies, as an objective balanced against mass for a truck cab [48] and as a constraint for a trailer axle [21]. Fail-safe design is the least covered theme: a damage-tolerance assessment of truck trailers combines driving-scenario load spectra with crack-growth analysis [11], and a fail-safe topology optimisation method treats dynamic loads through equivalent static loads [17], but neither is combined with multi-criteria optimisation or experimental validation (Section 4.7). No reviewed study optimises mass, fatigue durability and fail-safe behaviour simultaneously. The review therefore cannot point to a validated unified methodology; Section 4.8 instead outlines how these criteria could be combined in a single design workflow.

4.3. Representation of Extreme Dynamic Loads

Most optimisations in the reviewed literature replace the dynamic service loads by a small set of static load cases, often scaled by acceleration factors for braking, cornering or vertical loading [20,23–25,29,47]. Such amplified static loads can bound peak stresses for strength checks, but they carry no information on the number of cycles, the frequency content or the sequence of loads that govern fatigue damage. A structure lightened against static load cases can therefore be adequate, or even overdesigned, for strength and still fail prematurely in fatigue, particularly at welded joints [59] and at the stress concentrations that topology and size optimisation tend to create; conversely, overly conservative factors consume part of the mass saving that the optimisation seeks.

Studies that represent the loads more realistically follow three routes: multibody simulations of road excitation feeding transient finite-element and fatigue analyses [8,12,14], durability tests on road simulators or field measurements [9,13,68], and load spectra derived from driving scenarios for damage-tolerance assessment [11]. Equivalent-static-load formulations make dynamic topology optimisation tractable [17,37] but represent the transient response only at selected instants, and surrogate models trained on transient simulations have been proposed as an alternative [19].

The interaction between suspension and structure is particularly under-represented: measurements show that an empty light trailer can lose wheel–road contact over obstacles at low speed [68], air suspensions reduce the dynamic loads transmitted to semi-trailer axles [69], and a dynamic road stress factor has been used to select the air-suspension pressure of a tractor semi-trailer that minimises the dynamic tyre forces on the road [75]. Degraded roads, variable speeds, uneven or excessive loading and suspension behaviour are rarely considered together, an exception being the driving-scenario load spectra used in [11], and none of these effects are yet fed into frame optimisation. Optimised designs should therefore be checked against measured or simulated load spectra before their mass savings are accepted.

4.4. AI-Assisted Optimisation: Limits and Safeguards

Dynamic and multi-constraint topology optimisation remains computationally expensive [74], which is the main motivation for the evolutionary algorithms, surrogate models and digital twins reviewed in Section 3.3. The evidence shows both their potential and their risks: a surrogate-based optimisation under transient impact loads reduced computation time at comparable accuracy [19], and a genetic-algorithm design of a trailer axle passed bench tests against the applicable standard [21], whereas a purely generative design of a workshop frame reached a safety factor of only 0.118, compared with 2.02 for the manual design and 2.11 for a hybrid design refined by engineers [53].

These results support the use of AI tools as accelerators within an engineering workflow rather than as autonomous designers. On the basis of the reviewed studies, five minimum safeguards are proposed for chassis and trailer design: (i) all safety-relevant requirements, including static strength, fatigue, buckling, manufacturing and type-approval constraints, should be encoded explicitly in the optimisation rather than checked afterwards; (ii) surrogate models should be used only within the range of their training data, and their prediction errors should be reported; (iii) every AI-generated or surrogate-optimised design should be re-analysed with an independent high-fidelity finite-element model under the full set of load cases, including dynamic and fatigue checks; (iv) a qualified engineer should review and refine the design, as in the hybrid approach of [53]; and (v) the final structure should be validated physically, as in the bench tests of [21], before it is used on the road. None of the reviewed studies proposes or tests such a framework, which therefore remains a recommendation of this review.

4.5. Manufacturability of Optimised Geometries

Topology optimisation tends to produce organic layouts that conventional trailer manufacturing, based on welded standard profiles and sheet metal, cannot reproduce directly. The reviewed studies suggest three practical ways of bridging this gap. The first restricts the design space to manufacturable members from the outset by projecting the layout onto standard structural profiles [39], by optimising beam-based ground structures [33] or by coupling topology with plate-thickness optimisation [32,42]. The second keeps a conventional ladder or beam layout and sizes the cross-sections of its standard I- or box-section members [20,22,47], possibly combined with topology optimisation, as in [23]. The third reserves casting for compact, highly loaded components such as brackets and housings, for which topology optimisation has been demonstrated [30,31], while additive manufacturing has so far been explored mainly at the concept stage [66] and requires the anisotropy of printed material to be included in the optimisation [67]. In all cases, welded joints remain fatigue-critical details [59], so weld quality and distortion control [61,65] belong to the design problem rather than only to production.

4.6. Economic Feasibility

A systematically omitted aspect in the literature analysed is the explicit evaluation of the economic feasibility of the proposed optimisation solutions. Most studies report mass reductions and structural performance improvements but rarely quantify the initial investment required (material changes and retooling of manufacturing processes) relative to the long-term economic benefits (fuel savings and increased payload capacity). A notable exception is the study [54], which, in addition to the structural optimisation of a tipping-silo semi-trailer made of composite materials (a mass reduction of about 28%, i.e., approximately 1800 kg for the complete semi-trailer, distinct from the 28% (140 kg) reported in [44] for the steel longitudinal beams alone) includes an explicit estimate of the investment payback period (about 3–4 years, depending on the annual mileage) and of the resulting fuel savings.

The general absence of such an economic analysis in the rest of the literature represents a real barrier to the industrial adoption of advanced optimisation solutions, regardless of their technical merits.

This gap is all the more relevant given that AI-based methods—although promising in terms of computational speed—themselves entail additional costs (software licences, specialised expertise, and computing infrastructure) that are rarely discussed in the studies analysed. A holistic evaluation of trailer structure optimisation should therefore integrate not only technical criteria (mass, stiffness, and safety) but also the economic criteria of industrial implementation—a research direction that is currently insufficiently explored. Until such evaluations are available, the commercial viability of composite structures and AI-based design workflows cannot be established from the reviewed literature, and the mass savings reported in Section 3 should not be read as evidence of economic benefit.

4.7. Coverage of the Reviewed Literature

Table 6 summarises how the 56 scored studies cover the three criteria discussed in this section (real dynamic loads, multi-criteria optimisation and experimental validation, the last divided into validation of a model or baseline design and tests of the optimised design) across four groups of methods, and Figure 8 presents the same information as a shaded grid.

Table 6. Coverage map of the reviewed literature: coverage score and, in brackets, the number of studies meeting each criterion.

Subject/Approach	Real Dynamic Loads	Multi-Criteria Optimisation	Model or Baseline Validated	Optimised Design Tested
Simplified numerical modelling (n = 33)	3 (15)	3 (6)	2 (5)	2 (4)
Advanced formulations (n = 18)	3 (7)	2 (5)	2 (3)	0 (0)
AI-assisted optimisation (n = 3)	1 (1)	0 (0)	0 (0)	0 (0)
Fail-safe and partial damage (n = 2)	1 (2)	0 (0)	0 (0)	0 (0)

Legend, Table 6: Each cell gives a coverage score followed, in brackets, by the number of studies in that row that meet the criterion; n is the number of studies assigned to the row, and each of the 56 scored studies is assigned to one row only. Model or baseline validated: physical tests or field measurements that validate a numerical model or characterise a baseline structure, joint or vehicle; optimised design tested: the optimised design itself was tested physically, at full or reduced scale. Score: 0 = no study; 1 = 1–2 studies; 2 = 3–5 studies; 3 = 6 or more studies.

Four patterns emerge from these counts. First, the simplified-numerical-modelling row is the largest and the most frequently tested: 9 of its 33 studies report physical tests or field measurements and 4 of them tested the optimised design itself, namely a semi-trailer prototype on a road simulator [9], the 1:6 scale low-bed semi-trailer chassis [20], the trailer axle [21] and a 1:10 scale model of a modified truck chassis [26]; most studies in this row concern road-freight trucks, trailers and semi-trailers. Second, the advanced-formulations row describes the methods literature more than freight structures. Only 3 of its 18 studies concern truck or trailer structures, namely the hydrogen-truck frame [27], the flatbed-trailer frame [33] and the truck cab [48]; the others are method studies demonstrated on

generic benchmark structures [15,16,35–42,49,50,74], an automotive design-decision framework [51] and a coach crash box [34]. Only one of the seven real-dynamic-load credits in this row, the cab [48], concerns a freight-vehicle structure, and none of its three test credits concerns an optimised design: the hydrogen-truck frame reports a modal test of an unspecified frame [27], the crash-box model was compared with prototype data [34] and the cab was tested in its baseline form [48]. The scarcity of tests in this row therefore partly reflects the fact that method studies seldom include physical tests. Third, none of the three AI-assisted studies concerns a freight vehicle: they are demonstrated on a generic structure [19], a structure outside freight transport [52] and workshop equipment [53]. Fourth, the fail-safe and partial-damage row contains only two studies, one on truck trailers [11] and one generic method [17], both purely numerical, which makes it the least-covered and least-validated area identified in this review.

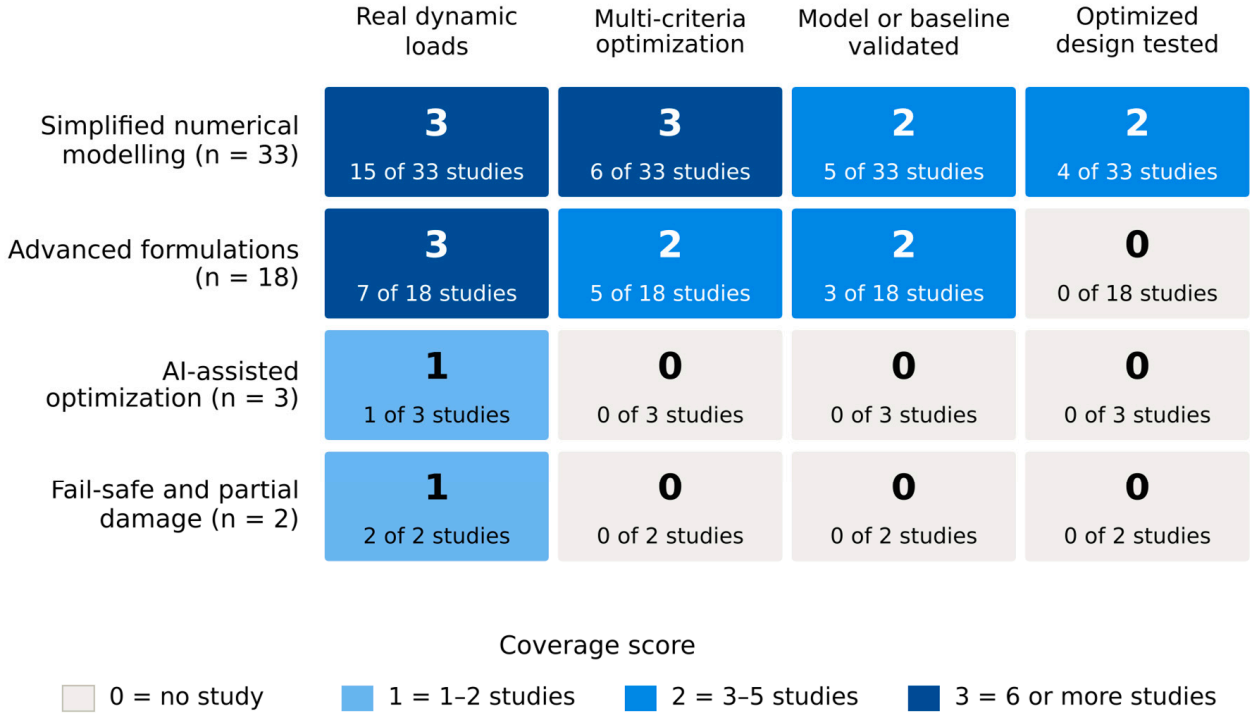


Figure 8. Coverage map of Table 6 shown as a shaded grid. Each cell gives the coverage score (0–3) and the number of studies in the row that meet the criterion.

The classification underlying Table 6 reflects the specific methodological focus and reported outcomes of each reviewed study, rather than a single overall judgement. Studies grouped under simplified numerical modelling—which analyse a given structure or load case with deterministic finite-element or multibody models or by measurement, and, where they optimise, use size, shape, material or single-objective topology optimisation, including response-surface and genetic-algorithm searches with one or several objectives—include [7–10,12–14,20–26,28–32,43–47,54,58–60,68–70,72,73]. Studies grouped under advanced formulations—whose main contribution is a new or improved formulation, mostly of topology optimisation (under dynamic, stress, buckling, frequency or crash requirements, or with multi-material, multiscale, voxel-based, level-set, geometry-projection, ground-structure or multi-objective schemes), together with robust and multi-criteria design frameworks—include [15,16,27,33–42,48–51,74]. Studies grouped under AI-assisted optimisation, whose main contribution is the data-driven component itself, namely a neural-network surrogate, a digital twin or a generative-design tool, include [19,52,53]; studies that use genetic algorithms, response surfaces or other surrogates only as search tools within a

size or topology optimisation, such as the trailer axle [21] discussed in Section 3.3, are scored with that optimisation. Studies grouped under fail-safe and partial damage, which explicitly target resistance to partial structural failure as a primary design objective, include [11,17]. Each of the 56 scored studies was assigned to one row only, even when, like the two fail-safe studies, it is cited under several themes in the review; a study meeting more than one definition was assigned to the more specific one (fail-safe before AI-assisted, AI-assisted before advanced, advanced before simplified), so that no study is counted twice. The remaining 12 primary studies, on vehicle-level configurations [55,57], suspensions [56,75], welding [61–65], additive manufacturing [66,67] and predictive maintenance [71], provide context for Sections 3.5 and 4.3 and are not scored. Within its row, a study was credited with real dynamic loads only where time-varying loading (road or manoeuvre excitation, transient, impact or crash loading, harmonic or random vibration) or fatigue under cyclic loading was analysed, whereas static or quasi-static load cases, including braking or cornering accelerations applied as static loads, and modal analysis alone were not counted; the mobile pump-truck frame [28], for example, is credited for its harmonic response analysis. A study was credited with multi-criteria optimisation only where two or more distinct performance criteria (for example, mass, stiffness, natural frequency or fatigue life) were optimised simultaneously as objectives, rather than a single objective under constraints. Experimental validation was credited only where physical tests (laboratory, bench, scale-model, modal or road tests) or field measurements were reported and is divided into tests that validate a model or characterise a baseline structure, joint or vehicle and tests of the optimised design itself; the modal test reported for [27] is counted in the first group because the source does not state that the optimised frame was tested. The studies counted in each cell are as follows. Real dynamic loads: [7–10,12–14,21,28,59,68–70,72,73] in the first row, [15,16,34–37,48] in the second, [19] in the third and [11,17] in the fourth. Multi-criteria optimisation: [10,21–23,28,47] in the first row and [27,33,48,49,51] in the second. Model or baseline validated: [10,13,22,59,68] in the first row and [27,34,48] in the second. Optimised design tested: [9,20,21,26] in the first row. No AI-assisted or fail-safe study was credited with multi-criteria optimisation or experimental validation.

4.8. Towards an Integrated Design Workflow

Combining the findings of Sections 4.1–4.7, an integrated workflow for trailer structures under extreme dynamic loads would link six steps (Figure 9): (1) load definition from measured or multibody-simulated road and manoeuvre spectra rather than amplified static cases; (2) concept topology optimisation with stress, fatigue and frequency constraints and with damage scenarios in which individual members are removed, so that fail-safe load paths are built in; (3) translation of the layout into standard profiles, sheet parts or cast nodes; (4) multi-objective size and shape optimisation of mass, fatigue life and residual strength after damage, accelerated by surrogate models used within their validity range; (5) independent high-fidelity verification, including weld fatigue and crash or partial-failure cases; and (6) physical validation on scale models, components and the complete structure, with service measurements and digital twins feeding updated load data back into the first step. The reviewed studies address most of these steps individually, but none cover the complete chain. Closing this gap, through validated multi-criteria optimisation of complete trailer structures under measured dynamic loads that includes fail-safe, manufacturing and cost requirements, is the main research agenda that emerges from this review.

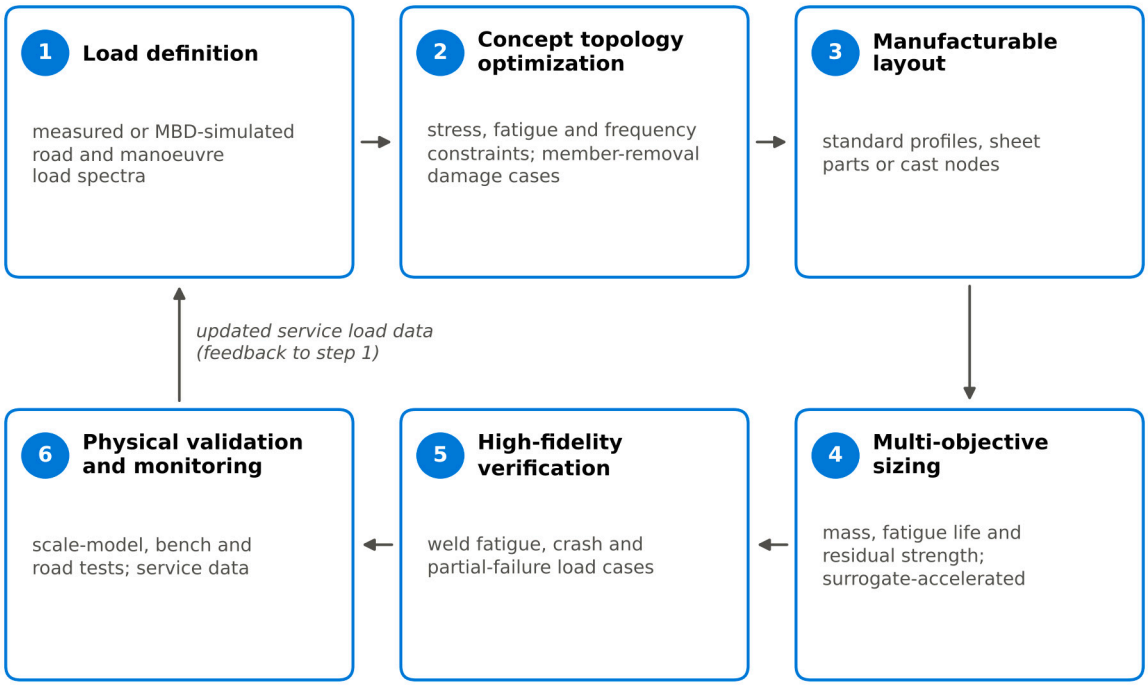


Figure 9. Integrated design workflow proposed in this review for trailer structures under extreme dynamic loads. Examples of reviewed studies that address individual steps are [9,13,68] (step 1), [16,17,27] (step 2), [33,39] (step 3), [19,22,48] (step 4), [34,59,72] (step 5) and [20,21,71] (step 6); none covers the complete chain.

5. Conclusions

The critical analysis of the specialised literature presented in the previous sections shows that the field of structural optimisation for road freight vehicles is undergoing a significant transformation. The design paradigm is evolving from conventional static sizing, based on generous safety factors, towards dynamic, multi-criteria and AI-assisted approaches, although these remain unevenly developed and rarely validated experimentally (Table 6). Five main conclusions follow from the review.

First, the reported mass savings depend mainly on the type of redesign. Optimisations that keep the material of a complete frame or component report about 7–16%, whether or not they were tested, whereas the largest values, 28% for the steel longitudinal beams alone and a theoretical 67% for a fully composite trailer, come from beam shape optimisation and composite substitution in a single numerical study. Only two of the optimised structures behind these figures were tested physically, and the tests showed that the lighter designs met their requirements rather than confirming the size of the saving (Section 4.1, Figure 7).

Second, more than half of the scored studies do not consider time-varying loads; static or quasi-static load cases can bound peak stresses but not fatigue damage, and measured or simulated load spectra, including suspension–structure interaction, are rarely fed into the optimisation (Section 4.3).

Third, machine learning and digital twins are promising but still weakly evidenced for freight-vehicle structures: surrogate models can substantially reduce computation time [19] and digital twins allow structural parameters to be updated from monitored data [52,71], yet physical validation of AI-optimised designs remains rare—the trailer-axle study [21] is the clearest example—and a purely generative design proved structurally unsafe without engineering refinement [53]. Their application to fail-safe scenarios for freight trailers is still at an early stage, and AI tools should therefore be used as accelerators within a verified engineering workflow, subject to the safeguards proposed in Section 4.4.

Fourth, no reviewed study optimises mass, fatigue durability and fail-safe behaviour simultaneously: fatigue enters the optimisation in only two studies and fail-safe design, addressed by two numerical studies, is the least covered and least validated theme (Sections 4.2 and 4.7).

Fifth, industrial uptake depends on manufacturability and cost, which are rarely evaluated: organic topologies must still be translated into standard profiles, sheet parts or cast nodes and only one study quantifies the payback period of a lighter design [54] (Sections 4.5 and 4.6).

These findings define the research agenda summarised by the integrated workflow of Section 4.8 (Figure 9): validated multi-criteria optimisation of complete trailer structures under measured dynamic loads, with fatigue, fail-safe, manufacturing and cost requirements treated together and with the optimised structures tested under service-representative conditions.

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