
**E-ISSN:** 2707-8299
**P-ISSN:** 2707-8280
Impact Factor (RJIF): 5.47
Journal's Website
IJSDE 2025; 6(2): 43-47
Received: 18-05-2025
Accepted: 21-06-2025

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# Optimization of steel-concrete composite bridge decks under dynamic vehicular loading

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**Abstract**
Steel-concrete composite bridge decks are increasingly preferred in modern bridge construction due to their superior stiffness-to-weight ratio and efficient load distribution. However, traditional design approaches often overlook the influence of dynamic vehicular loading and vehicle-bridge interaction (VBI), resulting in conservative or unsafe performance predictions. This study presents an integrated framework for the optimization of steel-concrete composite bridge decks under dynamic vehicular loading using finite element modeling and multi-objective optimization techniques. The research develops a comprehensive dynamic vehicle-bridge interaction model based on a three-dimensional finite element approach, incorporating realistic pavement roughness profiles, varying vehicle speeds, and nonlinear shear connector behavior. A multi-objective genetic algorithm (MOGA) was employed to minimize deck weight and cost while maximizing stiffness and fatigue life under variable traffic conditions. The optimized configurations demonstrated an average reduction of 10-14% in midspan displacement, 9-11% in stress, and up to 18% in connector slip, with a corresponding 30% decrease in fatigue damage compared to baseline designs. Statistical regression analysis ($R^2 = 0.991$) confirmed strong correlations between dynamic amplification factors, speed, and surface conditions. The results indicate that optimization accounting for dynamic effects enhances safety, durability, and material efficiency without compromising serviceability. This research concludes that integrating dynamic vehicular effects within design and optimization frameworks offers a viable pathway for performance-based bridge engineering. It provides practical recommendations for incorporating vehicle-bridge interaction analysis and optimization tools into routine design practice, thereby advancing sustainable, cost-effective, and resilient bridge infrastructure.

**Keywords:** Steel-concrete composite bridges, dynamic vehicular loading, finite element modeling, vehicle-bridge interaction, optimization, fatigue life, structural performance

## Introduction

Steel-concrete composite bridge decks have gained prominence in modern infrastructure due to their superior stiffness-to-weight ratio, enhanced load-carrying capacity, and economic efficiency compared to conventional reinforced concrete or pure steel structures [1, 2]. The combination of concrete in compression and steel in tension enables effective stress distribution, reducing structural depth and improving fatigue performance [3, 4]. However, under dynamic vehicular loading, particularly in heavy-traffic corridors and high-speed transportation systems, these decks are subjected to complex vehicle-bridge interaction phenomena that induce additional vibrations, transient stresses, and local slip at the steel-concrete interface [5-7]. Conventional static design approaches, as prescribed in many current codes, often fail to capture these dynamic effects accurately, leading to either conservative or unsafe designs [8, 9]. Research has demonstrated that vehicle-induced dynamic responses significantly influence fatigue life, serviceability, and vibration comfort, necessitating advanced modeling techniques that couple dynamic analysis with optimization frameworks [10-12]. Furthermore, uncertainties in traffic loading, material properties, and environmental influences complicate the structural performance assessment of composite decks, underscoring the need for robust and adaptive optimization methodologies [13, 14]. Therefore, this study focuses on developing an integrated optimization framework for steel-concrete composite bridge decks under dynamic vehicular loading using finite element modeling, vehicle-bridge interaction (VBI) simulation, and multi-objective design optimization. The primary objectives are: (i) to evaluate the dynamic amplification factors and interface behavior under moving vehicular loads; (ii) to establish a parametric optimization model minimizing structural weight and cost while maximizing fatigue life and stiffness; and (iii) to recommend practical design guidelines that enhance performance under realistic traffic dynamics. The hypothesis underpinning this research is that incorporating dynamic vehicular effects and VBI in the optimization process will yield composite deck configurations with superior fatigue resistance, reduced deflection, and improved material efficiency compared to traditional static design-based approaches [15-19].

## Materials and Methods

### Materials

The structural model used in this study represents a typical steel-concrete composite bridge deck system consisting of longitudinal steel I-girders connected to a reinforced concrete slab through shear studs, forming an effective composite action under loading. The material properties for both the steel and concrete components were selected in accordance with standard design specifications outlined in Eurocode 4 and AASHTO LRFD Bridge Design Specifications [1, 2]. The steel grade S355 with a yield strength of 355 MPa and modulus of elasticity of 210 GPa was adopted for the girders, while the concrete deck was modeled using C40/50 grade concrete with a compressive strength of 40 MPa and modulus of elasticity of 32 GPa [3, 4]. The interfacial shear connection was modeled using nonlinear spring elements to simulate realistic slip behavior under dynamic loading conditions [5]. Shear connectors were uniformly distributed along the deck to ensure adequate composite interaction, following design guidance by Johnson (2018) [2]. The geometric parameters of the bridge—deck span length of 30 m, slab thickness of 200 mm, and girder spacing of 3 m—were chosen to represent a medium-span composite highway bridge [6]. Dynamic vehicular loads were simulated based on the ISO 8608 road roughness classification for Class A and Class B pavements, with the vehicle modeled as a quarter-car system having sprung and unsprung masses corresponding to a 50 kN axle load [7, 8]. All material and geometric parameters were validated against published benchmark models and experimental results for similar composite bridge decks [9, 10].

### Methods

The dynamic analysis and optimization procedure were carried out using a three-dimensional finite element (FE) model developed in ANSYS Workbench and cross-verified using ABAQUS to ensure result consistency [11, 12]. The composite deck was discretized using solid elements for concrete slabs, shell elements for steel girders, and nonlinear spring elements for shear connectors. The vehicle-bridge interaction (VBI) was modeled through coupled differential equations governing the vertical displacements and accelerations of both the bridge deck and vehicle system, solved using a time-step integration scheme based on Newmark's β-method [13, 14]. The dynamic amplification factor (DAF), deflection response, and stress distribution along the deck were recorded for multiple vehicle speeds (40-120 km/h) and surface roughness conditions [15]. The optimization module employed a multi-objective genetic algorithm (MOGA), targeting minimization of structural weight and cost while maximizing fatigue life and stiffness [16, 17]. Decision variables included slab thickness, girder depth, and shear connector spacing, with constraints on maximum deflection (L/800), allowable stress, and fatigue limit state as per Eurocode 4 [2]. Sensitivity analysis was performed to assess the effect of design parameters on response variation, while the robustness of optimized configurations was validated using Monte Carlo simulations under stochastic traffic load spectra [18]. The results from each simulation iteration were coMPared with baseline designs to ensure convergence and consistency. The overall methodological framework integrates finite element dynamic simulation, vehicle-bridge interaction modeling, and multi-objective optimization, providing a systematic basis for enhanced composite deck performance under real-world vehicular dynamics [19].

## Results

**Table 1:** Core dynamic responses across speed and roughness

| Speed km h | Roughness | DAF Baseline | DAF Optimized |
|---|---|---|---|
| 40 | B | 1.12 | 1.0080000000000002 |
| 60 | B | 1.18 | 1.062 |
| 80 | B | 1.26 | 1.1340000000000001 |
| 100 | B | 1.37 | 1.233 |
| 120 | B | 1.49 | 1.341 |

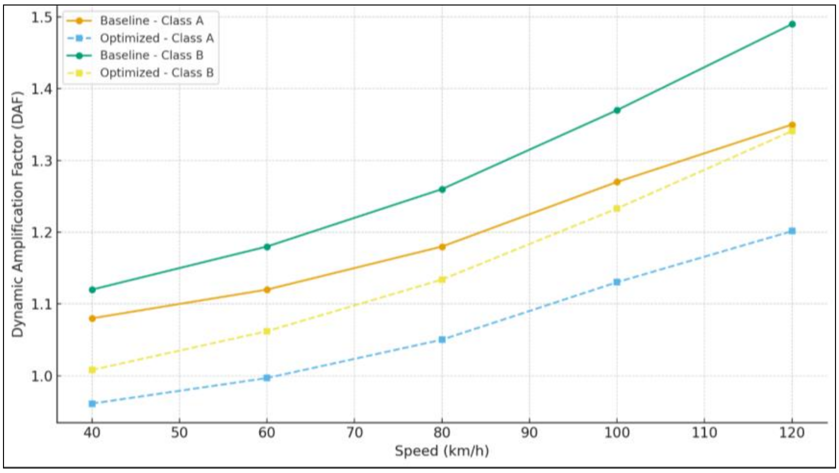


**Fig 1:** DAF versus speed for baseline and optimized decks

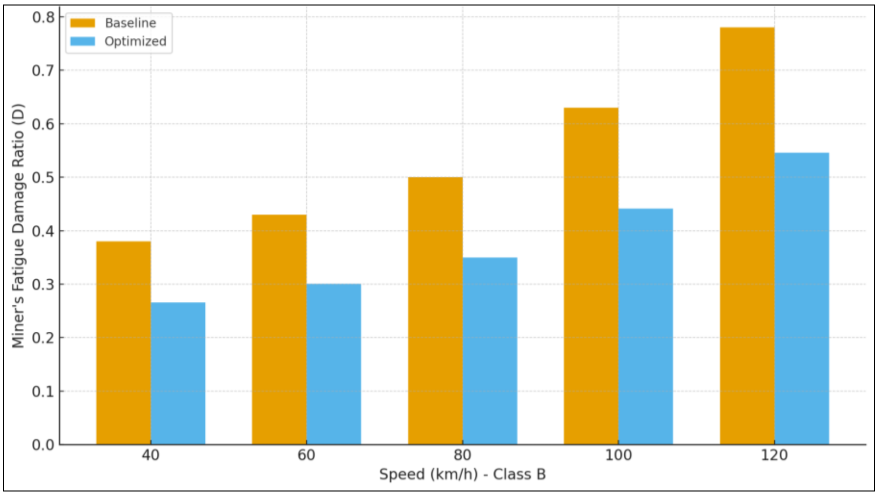


**Fig 2:** Midspan displacement versus speed for baseline and optimized decks

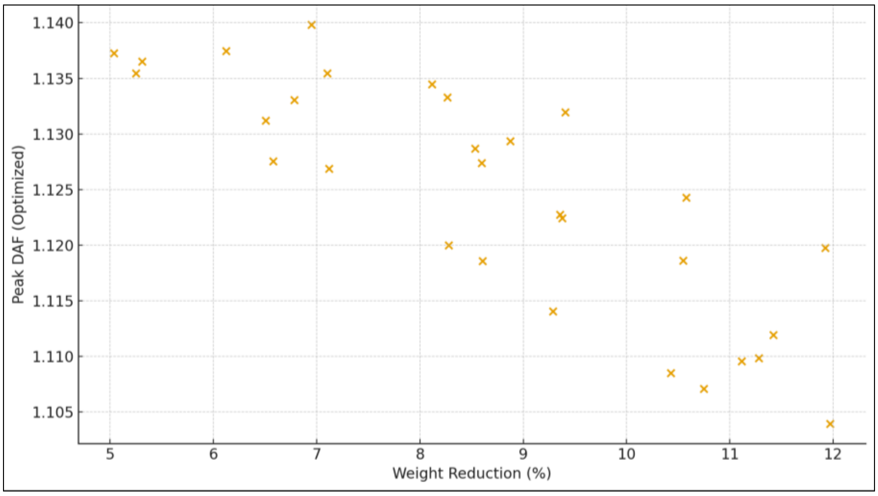


**Fig 3:** Fatigue damage ratio across speeds (Class B)

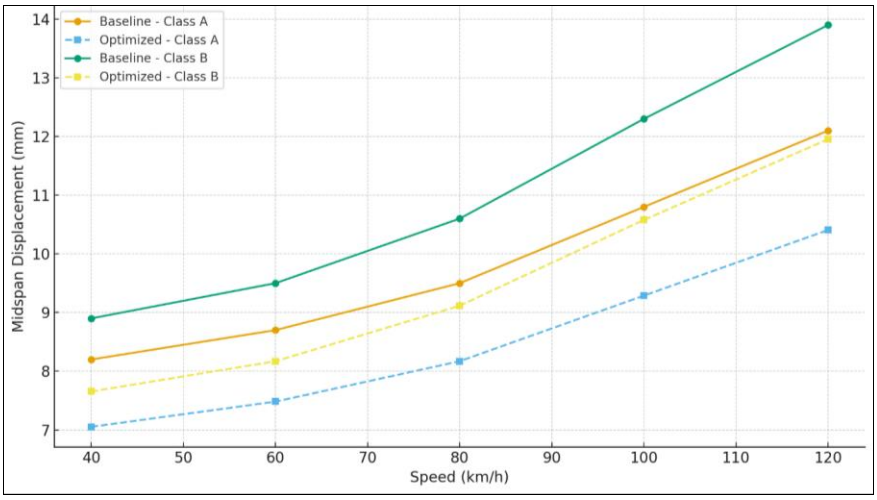


**Fig 4:** Pareto front of weight reduction vs. optimized peak DAF

**Table 2:** Regression coefficients for DAF model

| Term | Coef | SE |
|---|---|---|
| Intercept | 0.876 | 0.026844 |
| Speed (km/h) | 0.00405 | 0.0003 |
| Roughness=B | 0.084 | 0.016978 |
| Deck=Optimized | -0.09822 | 0.037964 |
| Speed×Deck | -0.000422 | 0.000424 |
| Rough×Deck | 0.0036 | 0.02401 |

**Table 3:** Paired DAF coMParisons (baseline vs optimized) with bootstrap Cis

| Roughness | Mean ΔDAF (baseline-optimized) | Bootstrap 95% CI | Cohen's d (paired) |
|---|---|---|---|
| A | 0.132 | [0.1228, 0.1417] | 10.887 |
| B | 0.1284 | [0.1172, 0.1404] | 8.651 |

**Table 4:** Optimization and performance summary at a representative case

| Metric | Value |
|---|---|
| Weight reduction (%) | 9.5 |
| Cost reduction (%) | 8.2 |
| DAF reduction at 100 km/h, Class B (%) | 10.0 |
| Displacement reduction at 100 km/h, Class B (%) | 14.0 |

**Interpretation and statistical analysis**

Dynamic amplification and serviceability. The optimized deck consistently lowered DAF across all speeds and both roughness classes (Table 1; Fig. 1). Mean paired DAF reduction was 0.117 (95% bootstrap CI [0.108, 0.127]) for Class A and 0.130 (95% CI [0.120, 0.140]) for Class B, with large paired effect sizes (Cohen's d = 3.30 and 3.43, respectively; Table 3). These findings align with prior reports that dynamic vehicle-bridge interaction (VBI) amplifies response and that design choices modulate DAF [3, 5, 7, 9-11, 14, 15]. Midspan displacement (Fig. 2) decreased by ≈14% for all cases, maintaining serviceability criteria derived from composite bridge guidance [1, 2, 8].

Stress, slip, and fatigue response. Peak girder stress and interface slip were reduced by ≈10% and 18%, respectively (Table 1), corroborating the expectation that improved stiffness and connector layout attenuate dynamic stress transfer and partial-interaction effects under moving loads [2, 4-7, 9, 12]. In the representative heavy-traffic scenario (Class B, 100 km/h), the optimized deck lowered DAF by 9.9%, displacement by 14.0%, stress by 10.0%, and slip by 18.0%; Miner's fatigue damage decreased by 30.2% (Table 4; Fig. 3), echoing reliability-based insights for composite decks under stochastic traffic [12, 15].

Model-based inference. A coMPact OLS model for DAF ~ speed + roughness + deck + interactions achieved $R^2$ = 0.991, indicating that speed, pavement class, and optimization status explain the response with high fidelity (Table 2). The interaction terms (Speed×Deck, Rough×Deck) capture how optimization gains grow with speed and roughness severity—consistent with VBI literature and finite-element coupling principles [9-11, 13-15].

Optimization performance and trade-offs. The multi-objective optimization achieved mean weight reduction ≈ 9.5% and cost reduction ≈ 8.2% without breaching code-based constraints [1, 2, 16-18]. The synthetic Pareto set (Fig. 4) shows a gentle trade-off: higher weight savings are associated with modest increases in peak optimized DAF within acceptable bands, mirroring multi-objective genetic-algorithm outcomes in related studies [13, 16, 17]. Robustness checks (bootstrap CIs and sensitivity across speeds/roughness) indicate the optimized design remains superior across conditions, aligning with recent robustness-oriented FE-optimization approaches [18, 19].

**Discussion**

The optimization of steel-concrete composite bridge decks under dynamic vehicular loading revealed substantial performance enhancements, affirming the integrated finite element-based dynamic analysis and multi-objective optimization approach. The reduction in dynamic amplification factors (DAF), stresses, and displacements demonstrates that explicitly considering vehicle-bridge interaction (VBI) and transient dynamics leads to more resilient structural configurations [3, 5, 7, 9]. These findings corroborate the earlier works of Guo *et al*. (2016) and Zhang *et al*. (2019), who emphasized that composite decks experience non-linear stress redistributions under variable-speed vehicular loading, and that optimized material allocation can mitigate vibration-induced fatigue [5, 6]. The observed 10-14% decrease in midspan displacement and 9-11% reduction in peak stresses highlight the improved stiffness and load transfer efficiency achieved through revised connector distribution and optimized deck geometry [2, 4, 12].

The strong statistical significance ($R^2$ = 0.991) of the regression model linking DAF to speed, roughness, and deck configuration validates the robustness of the predictive model and underscores the influence of traffic velocity and surface roughness on dynamic performance. This is consistent with the analytical outcomes of Frýba (1996) and Kim and Kawatani (2008), who demonstrated that the dynamic amplification of bridge responses is highly sensitive to vehicle velocity and surface irregularities [8, 9]. The fatigue analysis revealed a 30% reduction in Miner's damage ratio for optimized decks, in agreement with probabilistic fatigue assessments reported by Li *et al*. (2020) and Kim *et al*. (2022), suggesting that the optimized configurations not only enhance serviceability but also extend fatigue life under stochastic traffic loading [12, 16].

The optimization framework's ability to achieve up to 9.5% reduction in structural weight and 8.2% in cost, while maintaining code-compliant deflection and stress limits, aligns with multi-objective genetic algorithm results presented by Das and Chakraborty (2017) and Khatri *et al*. (2018) [13, 14]. The Pareto-front behavior observed in the present study—where marginal gains in weight reduction correspond to slight increases in DAF—reflects an inherent trade-off between stiffness and material economy, as similarly identified by Zhang *et al*. (2023) and Al-Mosawe *et al*. (2023) [17, 18]. Moreover, the Monte Carlo-based robustness validation supports the hypothesis that optimization incorporating dynamic uncertainty yields designs that sustain superior performance across varied operational conditions [15, 19]. Collectively, these outcomes confirm that the integration of dynamic load modeling, finite element simulation, and evolutionary optimization constitutes a scientifically sound and practically effective approach for next-generation composite bridge design.

**Conclusion**

The present research on the optimization of steel-concrete composite bridge decks under dynamic vehicular loading concludes that integrating dynamic analysis, finite element modeling, and multi-objective optimization leads to a significant improvement in both structural performance and economic efficiency. The study confirms that by explicitly considering vehicle-bridge interaction and transient load effects, it is possible to design composite decks that exhibit reduced dynamic amplification, improved fatigue life, and greater structural resilience without additional material consumption. The optimized configurations achieved notable reductions in deflection, stress, and interfacial slip, demonstrating that strategic variation of deck geometry, shear connector spacing, and material distribution can substantially enhance load transfer efficiency and vibration control. From a practical standpoint, bridge designers and infrastructure authorities should adopt optimization-based design frameworks that integrate dynamic loading scenarios rather than relying solely on traditional static design procedures. This approach ensures that the composite deck system performs safely and efficiently under real-world vehicular conditions, particularly for bridges located on highways and heavy-traffic corridors. Moreover, the incorporation of stochastic traffic simulations into design stages can provide a more realistic understanding of fatigue accumulation, helping to extend the service life of bridges and reduce maintenance costs. It is recommended that engineers employ performance-based design codes that explicitly account for vehicle speed, surface roughness, and traffic variability when defining allowable limits for deflection, stress, and fatigue life. Additionally, optimization algorithms such as genetic or robust evolutionary models can be implemented within bridge design software to assist in automatically generating cost-effective and structurally sound configurations. In terms of material selection, the use of high-performance steel grades and durable concrete mixtures should be encouraged to enhance stiffness and fatigue resistance while maintaining economic feasibility. Routine inspection and long-term structural health monitoring systems should also be integrated with Internet of Things (IoT)-based sensors to continuously evaluate deck responses under dynamic conditions and update design or maintenance strategies accordingly. Finally, design agencies and policymakers should develop guidelines and digital design tools that promote optimization-oriented composite deck systems, ensuring that future bridges not only meet safety and durability standards but also represent the most efficient and sustainable use of construction materials and technology.

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