Research on Vehicle Model Simplification Strategies and Their Applicability for the Vibration Analysis of Suspension Bridges

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ABSTRACT

To investigate the influence of different simplified vehicle models on the dynamic response of long-span suspension bridges, this paper takes a suspension bridge as a case study and establishes its spatial finite element model using bar elements. Various simplified vehicle models, including a single moving constant force, dual moving constant forces, a moving mass, a moving sprung mass, a quarter-car model, and a half-car model, are adopted to conduct vehicle-bridge coupled vibration analysis based on ANSYS software. The dynamic displacement responses of the bridge under different vehicle models are compared. The results indicate that all vehicle models can reflect the fundamental laws of vehicle-bridge coupled vibration under moving loads. The influence of the vehicle model on the displacement response of the suspension bridge is generally minor; however, it becomes increasingly significant as the vehicle-to-bridge mass ratio increases.

***Keywords**—simplified; vehicle models; long-span suspension bridges; Vibration Analysis*

I. INTRODUCTION

Vehicle-bridge coupled vibration is a critical dynamic issue that must be considered in the design, operation, and maintenance of long-span suspension bridges. With the continuous increase in bridge spans and the growing trend towards heavier vehicle loads, the dynamic interaction between vehicles and bridges becomes increasingly complex. Accurately evaluating the vehicle-induced vibration response of bridges is of great significance for ensuring structural safety, guiding fatigue design, and enhancing ride comfort.

In the numerical simulation of vehicle-bridge coupled vibration analysis, the establishment of a vehicle model is one of the core aspects. To balance computational efficiency and accuracy, researchers have developed various vehicle analysis models, ranging from highly simplified to highly refined ones. Highly simplified models, such as the moving force model and the moving mass model, have been widely used in early theoretical analyses due to their simple formulation and low computational cost. As research progressed, spring-mass models (e.g., quarter-car and half-car models) that can account for vehicle suspension characteristics have gradually become mainstream. These models can more realistically reflect the dynamic characteristics of the vehicle itself and its coupling effect with the bridge.

Extensive numerical simulation studies have been conducted to investigate the influence of simplified vehicle models on vehicle-bridge coupled vibration. Gui [1] performed a comparative analysis between moving force and moving mass models. Wang [2] and Xiao [3] further conducted numerical solutions for vehicle-induced vibration using moving mass (moving sprung mass), quarter-car, and half-car models. Their findings indicate that although certain discrepancies exist among the results obtained from different models, all can reasonably reflect the general patterns of vehicle-bridge coupled vibration responses. However, these comparative studies were all based on simply supported beams. Taking a concrete continuous rigid-frame bridge as the research object, Xue [4] investigated the influence of vehicle dynamic characteristic parameters (such as suspension stiffness, damping, and tire stiffness) on bridge dynamic responses, concluding that bridge deflection is insensitive to these vehicle parameters. It is worth noting that the aforementioned studies have focused predominantly on medium- and small-span bridges, while relevant comparative investigations on kilometer-scale long-span suspension bridges remain unreported. Theoretically, it is generally accepted that the dynamic characteristics of vehicles can be neglected when the vehicle mass is far smaller than the bridge mass [5, 6]. However, this conclusion still lacks quantitative validation through numerical calculations specifically for long-span suspension bridges.

II. EVOLUTION OF SIMPLIFIED VEHICLE MODELS

This paper focuses on the displacement behavior of suspension bridges subjected to vehicle loads, while temporarily excluding the investigation of internal forces, stress responses, as well as vehicle vibration states and ride comfort issues. Based on these research objectives, the suspension bridge is discretized using a spatial bar system finite element model. The vehicle models adopt a series of simplified models from classical theory, ranging from highly simplified representations such as moving force, moving mass, and moving sprung mass, to relatively simplified single/multi rigid body mass-spring-damper systems. Figure 1 illustrates the evolution of typical vehicle models, which can be categorized into two main types: moving load models (Fig. 1(b)-(d)) and spring-damper-mass systems (Fig. 1(e)-(g)). Among these, the moving constant force model considers only the self-weight of the vehicle; the moving harmonic force model further incorporates the unbalanced inertial force from the engine; the moving mass model simultaneously accounts for both gravitational and inertial effects of the vehicle. In contrast, the mass-spring-damper system considers both the inertial effects and the inherent vibration characteristics of the vehicle. The moving sprung mass model serves as a "bridge" connecting the simple moving mass model and complex multi-body models, providing a transition for increasing model complexity. The quarter-car model, a two-degree-of-freedom system, captures the pitching motion of the vehicle body, while the half-car model, a four-degree-of-freedom system, can further simulate the more complex vertical and pitch coupled vibration characteristics between the front and rear axles or the vehicle body.

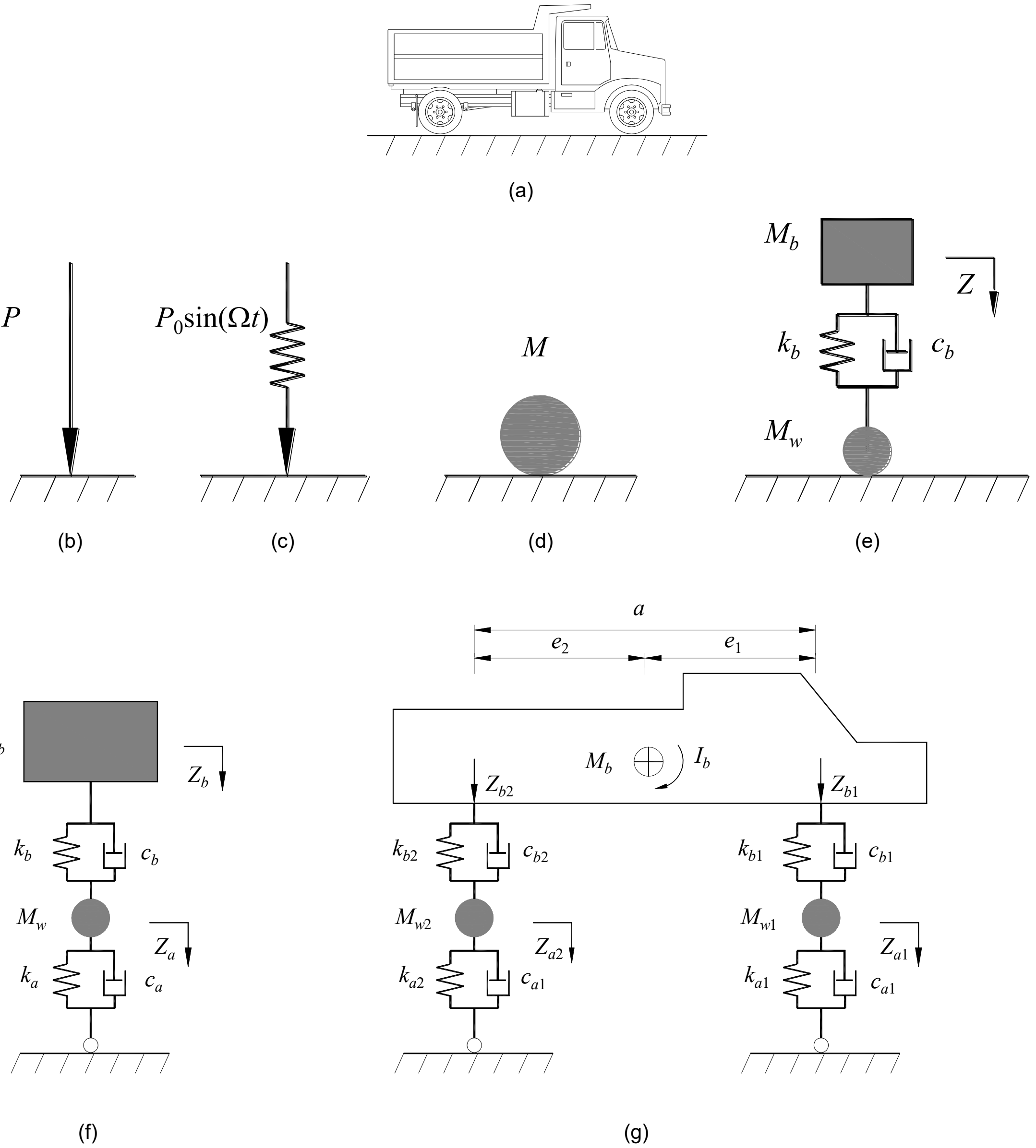


Fig. 1. simplified vehicle models:(a) Schematic Diagram of a Two-Axle Vehicle Model (b) Moving constant force (c) Moving harmonic force (d) Moving mass (e) Sprung mass (f) a quarter-car model (g) a half-car model

III. NUMERICAL EXAMPLE ANALYSIS

A. *Equivalent Models Under Moving Loads*

To clarify the influence of different simplified vehicle models on the vehicle-induced vibration response of suspension bridges, this paper takes the Aizhai Suspension Bridge as the engineering background (bridge overview available in Ref. [8]), and selects two Steyr two-axle trucks as the vehicle models (as shown in Fig. 1(a)). Based on the ANSYS platform, the separated iteration method is employed to solve the vehicle-bridge coupled equations of motion, conducting vibration response analysis of the suspension bridge under moving loads. In the analysis, the Aizhai Suspension Bridge is discretized into a spatial bar system model (as shown in Fig. 2); the vehicles are simplified into six forms, namely moving constant force, dual moving constant forces, moving mass, moving sprung mass, quarter-car model, and half-car model. The calculation parameters for each vehicle model are detailed in Table 1.

TABLE I. CALCULATION PARAMETERS OF VEHICLE MODELS

Model Type	Parameter Symbol	Parameter Description	Value	Unit
Moving constant force	P	Single axle weight of vehicle	328	kN
Moving mass	M	Total vehicle mass	33450	kg
Moving sprung mass	M_b	Sprung mass	32025	kg
	M_w	Unsprung mass	1425	kg
	k_b	Suspension stiffness	6.5×10^5	N/m
	c_b	Suspension damping coefficien	2.1×10^4	N·s/m
Quarter-car model	M_b	Sprung mass	32025	kg
	M_w	Unsprung mass	1425	kg
	k_b	Suspension stiffness	6.5×10^5	N/m
	k_a	Tire stiffness	2.85×10^6	N/m
	c_b	Suspension damping coefficient	2.1×10^4	N·s/m
	c_a	Tire damping coefficient	0	N·s/m
Half-car model	M_b	Sprung mass	32025	kg
	I_b	Pitch mass moment of inertia	82615.67	kg·m2
	M_{w1}	Unsprung mass of front axle	480	kg
	M_{w2}	Unsprung mass of rear axle	945	kg
	k_{b1}	Front suspension stiffness	1.7×10^5	N/m
	k_{b2}	Rear suspension stiffness	4.8×10^5	N/m
	k_{a1}	Front tire stiffness	9.5×10^5	N/m
	k_{a2}	Rear tire stiffness	1.9×10^6	N/m
	c_{b1}	Front suspension damping coefficient	0.7×10^4	N·s/m
	c_{b2}	Rear suspension damping coefficient	1.4×10^4	N·s/m
	c_{a1}	Front tire damping coefficient	0	N·s/m
	c_{a2}	Rear tire damping coefficient	0	N·s/m
	e_1	Distance from CG to front axle	2.6524	m
	e_2	Distance from CG to rear axle	0.9726	m

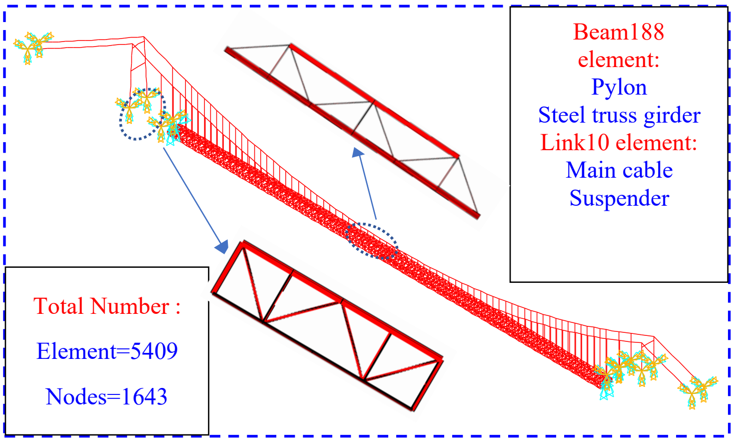
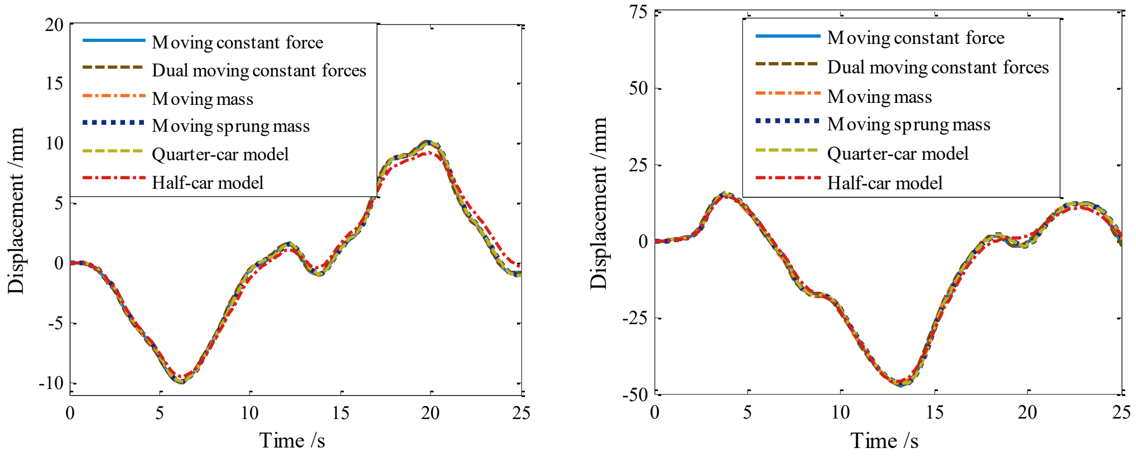


Fig. 2. FE model of the Aizhai Bridge[8].

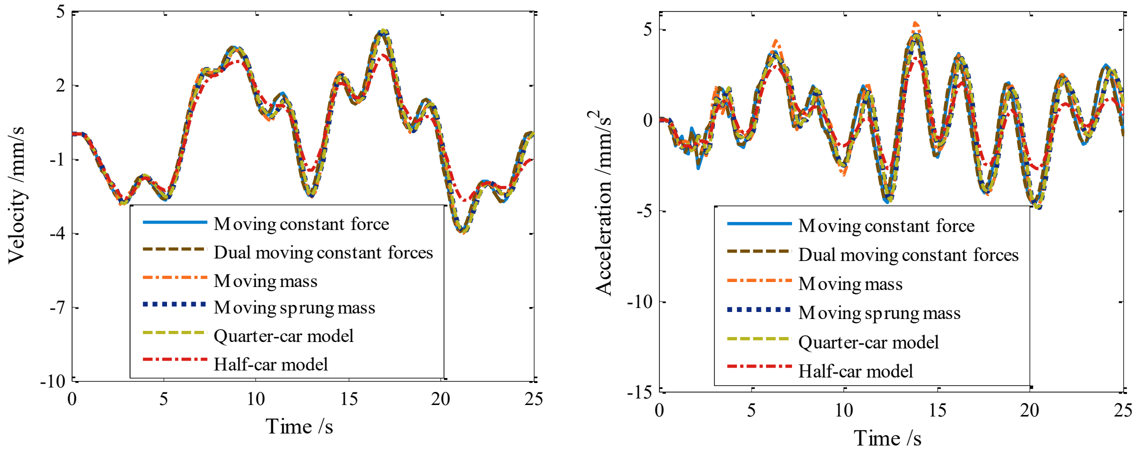
B. *Comparative Analysis of Numerical Results*

Fig. 3 presents the time-history curves of the dynamic response of the suspension bridge when different vehicle models cross the bridge at a speed of 40 m/s. It can be observed that the time-history curves of the longitudinal displacement at the girder end and the vertical displacement at the mid-span, calculated using different vehicle models, are in excellent agreement, whereas certain differences exist in the velocity and acceleration response curves at the girder end.



(a) Longitudinal displacement at the girder end

(b) Vertical displacement at the mid-span

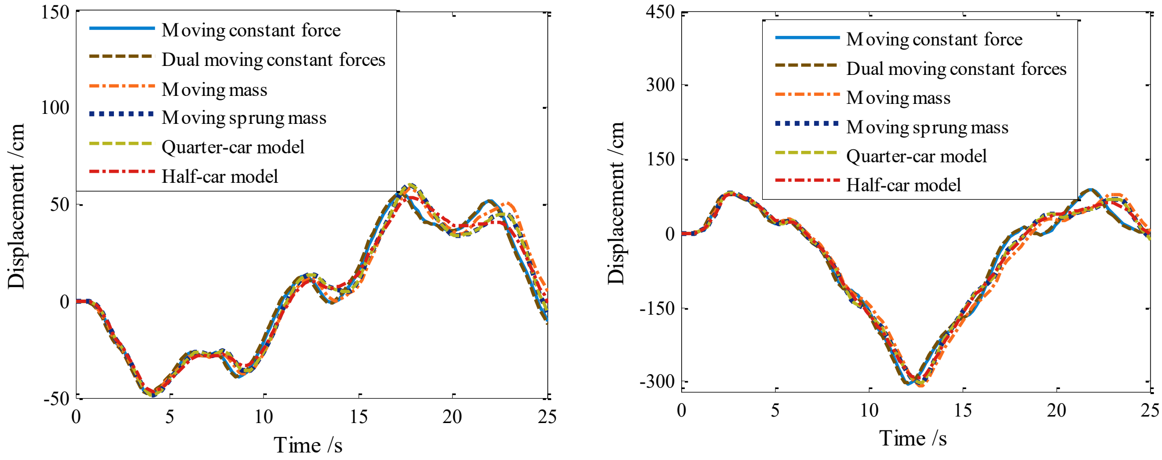


(c) Velocity at the girder end

(d) Acceleration at the girder end

Fig. 3. Dynamic responses under different simplified vehicle models

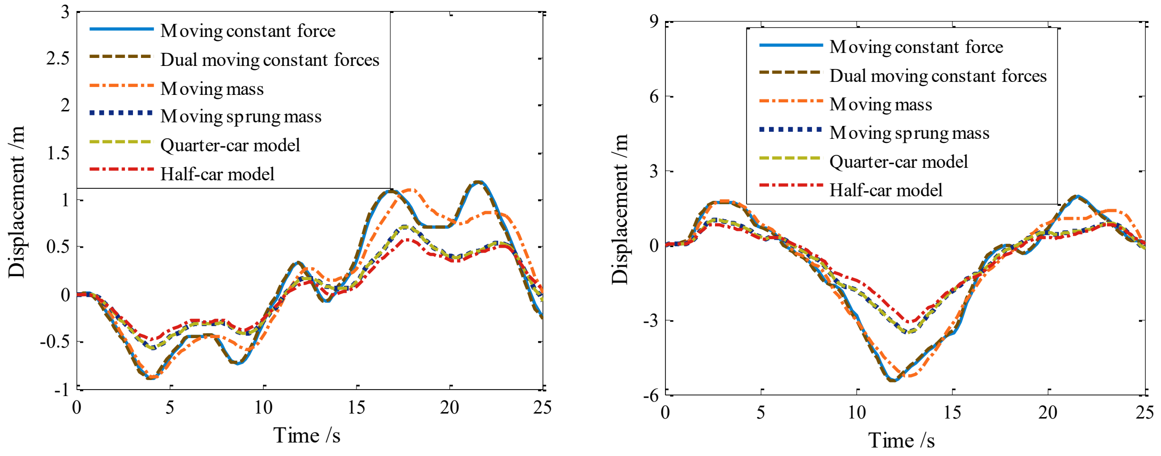
To evaluate the influence of vehicle mass and dynamic characteristics on the displacement response of the suspension bridge, vehicle-induced vibration analyses were conducted by magnifying the vehicle parameters in Table 1 by factors of 50 and 100, respectively. The corresponding time-history curves of displacement responses are presented in Fig. 4 and Fig. 5. It can be observed that when the vehicle parameters are magnified by a factor of 50, the displacement responses under different vehicle models exhibit slight differences. However, when the magnification factor reaches 100, the influence of the vehicle model on the structural displacement response becomes remarkably significant. Among the models, the displacement responses obtained from the sprung mass, quarter-car, and half-car models are relatively close to each other. Furthermore, as the vehicle model transitions from the moving force model to the more refined half-car model, the displacement response of the bridge gradually decreases. This indicates that in vehicle-bridge vibration analysis, the use of the simplified moving force model tends to overestimate the bridge response due to the neglect of the vehicle's dynamic characteristics, yielding results on the conservative side.



(a) Longitudinal displacement at the girder end

(b) Vertical displacement at the mid-span

Fig. 4. Dynamic responses under different simplified vehicle models（Vehicle parameters magnified by a factor of 50）



(a) Longitudinal displacement at the girder end

(b) Vertical displacement at the mid-span

Fig. 5. Dynamic responses under different simplified vehicle models（Vehicle parameters magnified by a factor of 100）

IV. CONCLUSIONS

Based on the numerical simulation analysis of vehicle-bridge coupled vibration presented above, the following conclusions can be drawn:

(1) For long-span bridges, such as kilometer-scale suspension bridges, the mass of the stiffening girder can reach tens of thousands of tons, which is far greater than the mass of conventional highway vehicles (typically tens of tons), and the vehicle dimensions are much smaller than the bridge span. Under such conditions, the influence of the vehicle's dynamic characteristics and wheelbase on the vehicle-induced displacement response of the bridge is negligible. A highly simplified moving concentrated load model can provide reliable solutions for the displacement response.

(2) As the vehicle-to-bridge mass ratio increases, the influence of vehicle dynamic characteristics gradually becomes more significant. For medium- and small-span bridges, it is necessary to adopt relatively refined vehicle models in the simulation to obtain more accurate vibration responses.

(3) The above conclusions are derived from comparative analyses focusing on the vehicle-induced displacement response of long-span suspension bridges. For other types of responses, such as local structural vibrations, internal force responses, and stress responses of concern in fatigue problems, the influence patterns of different vehicle models remain unclear and require further in-depth comparative investigation.

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