Optimization of the Traffic Load Model for Suspenders of a Super-Long-Span Suspension Bridge Considering Influence Line Geometry and Extreme Load Effect Scenarios

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Abstract: The reasonable expression of live load and its accuracy are important to the safety and design rationality of highway bridge structures. In this study, the optimization issue of the traffic load model for the suspenders of large-scale suspension bridges is studied. Taking a 2300-m main span suspension bridge as an example, a method for suspender classification based on the geometric feature of the influence lines is proposed, and the extreme traffic load effect scenarios are analyzed and used as an optimization reference. Multi-objective optimization based on a genetic algorithm is used to explore the improvement of the traffic load model of the suspender. The traffic load model of the suspender is optimized with three objectives, i.e., accuracy, convenience, and improvement, and the optimization results regarding the load value and loading length are obtained. The value of the uniformly distributed load of the optimized model ranges from 6.4 kN/m to 8.9 kN/m, and the maximum value of the concentrated force could reach 1433 kN. By comparing the obtained optimized model with the current specification model and the extreme load effect scenario model, the improved applicability of the optimized model in the analysis of the load effect of the suspender can be verified. The optimized method and relevant conclusions can provide useful references for the improved design and operation management of similar bridge structures.

Keywords: traffic load model; multi-objective optimization; super-long-span suspension bridge; suspender; influence line; extreme load effect scenario

1. Introduction

In recent years, with the rapid development of urbanization and transportation networks, long-span suspension bridges have become an important choice to address the traffic bottleneck problems in the road network. In particular, those suspension bridges whose main span reaches 2000 m are often faced with the dual challenges of technological innovation and construction costs. As a key engineering structure, suspension bridges require the continuous improvement of their design. In order to meet the growing traffic demand and optimize the performance and economic benefits of suspension bridges, the development of a technical standard needs ongoing innovation and effective progress. With the in-depth study of structural performance and traffic load, the need to adjust the traffic load standard according to the design characteristics of bridges to meet the needs of structural performance and traffic network function has become a consensus. This initiative not only helps to improve the safety and reliability of the suspension bridge, but also provides strong support for the development of transportation infrastructure.

Being one of the main load-bearing components of a suspension bridge, the mechanical performance of a suspender is crucial to the structural integrity and service safety of the bridge. By connecting the main cable and the deck, the suspender converts the tension
of the main cable into the supporting force for the bridge deck, ensuring the stability and safety of the whole structure. Compared with the mechanical characteristics of the main cable, main beam, main tower, and other components, the load response of the suspender is localized, that is, the suspender is most sensitive to the load action within a certain range nearby, while the load action outside of this range will hardly have any obvious impact on it. In addition, through the investigation of existing studies, it has been found that, under the same level of traffic load, the load effect level of a suspender is higher than that of the other main components, and the effect beyond the limit value is more likely to occur [1,2], resulting in the elevated overall stress of the suspender and the bridge. Therefore, it is urgent and of practical significance to study the extreme effect of traffic loads on suspenders and to establish a corresponding load model. At present, the research on the modeling of traffic load mainly focuses on common issues, including the statistical analysis of load parameters, load modes and their values, load combinations, and partial safety factors, etc., [3–8]; however, there are still few studies of particular issues related to traffic load, such as the extreme load effect scenarios, differences among the responses of the main components to traffic load, and the reasonable traffic load determination for super-long-span suspension bridges. The uncertainty of traffic load and its effect is mainly caused by its complex temporal and spatial distribution. If the most unfavorable traffic load effect of the components cannot be calculated accurately, it will be difficult for the bridge design, management, and maintenance parties to obtain specific operational decision-making guidance, which is harmful to the safe service of the components and the overall structure. Therefore, based on the above shortcomings in the analysis of the suspender load effect and the construction of the traffic load model, it is necessary to optimize and improve the existing traffic load model.

To optimize the traffic load model of a suspender, it is important to determine an appropriate optimization objective and select a suitable optimization algorithm. In the engineering field, several aspects regarding the traffic load model are of great concern, including the accuracy of the load effect analysis, the complexity of the calculation process, and the rationality of the calculation scheme. The application of optimization algorithms in the field of bridge engineering can solve design problems with room for improvement, thus significantly increasing the accuracy of the analysis, helping engineers to better understand and predict the behavior of bridges, and improving the efficiency and safety of bridge design and maintenance [9–11]. Commonly used optimization algorithms include the genetic algorithm, the particle swarm optimization algorithm, the simulated annealing algorithm, and so on [12,13]. The genetic algorithm is a computational model used to search for the optimal solution by simulating the natural evolution process and has good robustness and global search ability when solving multi-objective optimization problems [14,15]. In terms of the load and responses of bridges, the application of the genetic algorithm mainly includes load model calibration, damage identification, and reliability prediction. By calibrating the structural model through the genetic algorithm based on measured data, the static and dynamic characteristics of the model can be closer to the characteristics of the actual structure [16]. By using the genetic algorithm together with other methods to capture the change in structural properties or responses to load, the damage of bridge structures can be identified, and the optimal design parameters can be obtained [17–19]. The reliability analysis based on the genetic algorithm can skillfully identify the critical failure modes of the bridge components or the whole structure and estimate the probability of failure in an effective and accurate way, which offers the decision maker an important reference for making practical solutions [20–23]. In addition, the improved genetic algorithm can also be used to optimize the arrangement of the measurement points of bridge monitoring sensors, layout of tendons for prestressed concrete, or realize the mathematical optimization course of cable force, so as to improve the working efficiency and reduce the cost [24–26].

The purpose of this paper is to study the traffic load effect and traffic load model optimization of the suspenders of the super-long-span suspension bridge by theoretical analysis and numerical simulation. In Section 2, taking a suspension bridge with a main
span of 2300 m as an example, the traffic load effects of the main components are analyzed. In Section 3, a classification method of a suspender based on the geometric feature analysis of the influence line is proposed, and the extreme load effect scenario and load level of the bridge under the action of heavy vehicles are analyzed. On this basis, three optimization objectives of accuracy, convenience, and improvement are proposed in Section 4. Multi-objective optimization based on the genetic algorithm is adopted to optimize the traffic load models of the different types of suspenders of the bridge, and finally the optimized traffic load models for the different types of suspenders are obtained. In Section 5, the optimization results are analyzed and discussed, and conclusions are drawn in Section 6. The research results and conclusions can provide a useful reference for the precise design, operation management, and maintenance of similar long-span suspension bridges.

2. Analysis of Traffic Load Effect of a Super-Long-Span Suspension Bridge

In this study, a super-long-span suspension bridge with a main span of 2300 m is selected as the main background project, and the relevant problems regarding traffic load are studied. The Zhang-Jing-Gao Yangtze River Bridge is located in the lower reaches of the Yangtze River in China, connecting Suzhou, Taizhou, and Nantong. The South Passage Bridge (hereafter referred to as the “ZG Bridge”) is a two-span continuous suspension bridge with a main span of 2300 m, as shown in Figure 1. The cable layout is 660 m + 2300 m + 1220 m, and the beam layout is 2300 m + 717 m. The bridge adopts an integral steel box girder, and the bridge deck is equipped with eight two-way lanes. The Chinese specification (General Specifications for Design of Highway Bridges and Culverts, JTG D60) is chosen to decide the loading criteria on the background project, considering the location of the bridge and the optimization potential of the traffic load model.

![Figure 1](image_url)

**Figure 1.** The layout of the Zhang-Jing-Gao Yangtze River Bridge. (a) The front elevation of the bridge (unit: m); (b) The layout of the standard main beam section (unit: mm).

The mechanism of the suspension bridge has obvious geometric nonlinear characteristics, however, for traffic load, the difference between the effects considering geometric nonlinearity and not considering is acceptable, and the effect without considering geometric nonlinearity is higher, which is conservative [27,28]. Therefore, the traffic load effect of the suspension bridge components can be obtained according to the principle of linear superposition. To be specific, the calculation of the traffic load effect of the bridge...
components is mainly based on the loading of the effect influence line, and there are two commonly used loading methods, which are as follows:

1. Loading the specification load model on influence lines. The uniformly distributed load of the lane load is fully arranged on the influence line range with the same sign that causes the most adverse effect on the structure, and the concentrated force is imposed on the peak value of the influence line. When there are vehicles in multiple lanes, the multilane reduction factor should be considered, and the longitudinal reduction in the traffic load on the long-span bridge should also be considered.

2. Loading the random traffic flow on influence lines. The effect under this type of loading is calculated at every fixed time interval. In each calculation, the coordinates of the points on the influence line with an axle load are multiplied by the value of the corresponding axle load. The quantity of the traffic load effect at a certain time is the sum of all axle loads multiplying corresponding coordinates of the influence line. When random traffic flow loading is used to obtain the load effect, considering that the duration of the traffic flow simulation is obviously shorter than the service time of the bridge, the calculated effect value must be extrapolated in order to obtain the extreme value of the load effect corresponding to the service time of the structure.

The effects of the main components obtained by the above two loading methods are defined as the specification value \( E_{\text{CODE}} \) and the extreme load effect \( E_{\text{EV}} \), respectively. In existing studies, the ratio of the two \( \frac{E_{\text{EV}}}{E_{\text{CODE}}} \) is commonly used as the evaluation index of the actual effect level of the component or the applicability of the specification load model [29,30]. Specification load model loading and random traffic flow loading are carried out on the ZG Bridge. The selected effect influence lines and the calculated effects are shown in Table 1.

**Table 1. Traffic load effect of main components.**

<table>
<thead>
<tr>
<th>Influence line</th>
<th>Mid-span Displacement of Main Beam (m)</th>
<th>Axial Force of Main Cable at Saddle (N)</th>
<th>Axial Force of Suspender at L/4 * (N)</th>
<th>Axial Force of Suspender at L/2 * (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CODE</td>
<td>-3.23</td>
<td>5.05 \times 10^7</td>
<td>3.94 \times 10^3</td>
<td>4.31 \times 10^3</td>
</tr>
<tr>
<td>EV</td>
<td>-2.11</td>
<td>3.10 \times 10^7</td>
<td>4.94 \times 10^3</td>
<td>5.19 \times 10^3</td>
</tr>
<tr>
<td>EV/CODE</td>
<td>65.36%</td>
<td>61.31%</td>
<td>125.42%</td>
<td>120.49%</td>
</tr>
</tbody>
</table>

* \( L \) is the length of the middle span.

According to the loading results, the extreme load effects of the mid-span displacement of the main beam and the axial force of the main cable at the saddle are both less than that of the corresponding specification value, while the axial force of the suspenders is greater than their specification value, indicating that the specification load provides a sufficient safety reserve for the main beam and the main cable. However, for the suspender, when the actual traffic load level is high, the limit set by specification may be exceeded. The further analyzing the source of this difference, we can see from the shape of the influence lines of each effect in Table 1 that the performance of the main beam and main cable is related to the overall structural system, and it is less affected by the action of the local vehicles, and the influence lines are spread over the whole span and are relatively gentle. Because the suspender is directly connected to the bridge deck under traffic load, its influence line of axial force has a prominent peak and steep distribution, with non-negligible coordinate values only in a limited range. The result of the difference in the shape of the influence lines is that, for the main beam and the main cable, the effect is mainly affected by the uniformly distributed load, which is loaded along the whole bridge span, while the suspender is mainly affected by the heavy vehicles acting nearby. Therefore,
the suspender is a component with a higher degree of sensitivity to a heavy concentrated force.

At the same time, for the super-long-span suspension bridge, the number of suspenders is large, and the position and length of the suspender and other factors lead to differences in the load response to vehicles. Under the action of the same traffic flow, some suspenders can be safe, while the other suspenders are faced with an insufficient safety reserve. Therefore, it is necessary to classify this large number of suspenders before studying its traffic load effect and applicable load model.

3. Analysis of Classification and Extreme Load Effect Scenario of Suspenders

3.1. Classification of Suspenders Based on Geometric Feature Analysis of Influence Lines

The three-dimensional finite element model of the ZG Bridge is built in ANSYS, in which the main cable and suspenders are simulated with LINK10 ELEMENT, and the main beam and main tower are simulated with BEAM44 ELEMENT. The connections and constraints of the components are imposed according to the structural design scheme. A total of 184 influence lines of axial force of all of the suspenders in the middle span and side span of the bridge are extracted by conducting a structural analysis, as shown in Figure 2.

![Figure 2. Influence line of axial force of all suspenders.](image)

Using the local extreme value identification method in signal analysis, the geometric features of all of the suspender influence lines are analyzed, including the properties of the extreme points (maximum and minimum) and the number of extreme points. Considering the loading pattern of the traffic load and the basic geometry feature of the influence lines of the suspenders, the number of maximum points is set to be no more than two, as well as the number of minimum points. The main judging conditions are as follows:

**Judging condition 1 (extreme point judgement)**

A data sample is determined to be a local extreme point when it is either greater (less) than the two adjacent samples or equal to the supremum (infimum).

\[
\text{if } s_i \geq s_{adj} \text{ or } s_i = s_{sup} \\
\text{then } s_i \text{ is a extreme point (maximum point)} \\
\text{else} \\
\text{else } s_i \text{ is non extreme point} \\
\text{end}
\]
if $s_i \leq s_{adj}$ or $s_i = s_{inf}$
  $s_i$ is a extreme point (minimum point)
else
  $s_i$ is non extreme point
end

where $s_i$ is the value of a data sample; $s_{adj}$ is the value of two adjacent samples of $s_i$; and $s_{sup}$ and $s_{inf}$ are the supremum and infimum of the data sample set, respectively.

**Judging condition 2 (Single extreme point retention judgement)**

When there is a maximum point whose value is 100 times greater than the other maximum points, only this extreme point is retained.

if $s_{imax} \geq 100s_{othmax}$
  $s_{imax}$ is the only extreme point
else
  a further judgement is needed (in judging condition 3)
end

where $s_{imax}$ is the value of a maximum point and $s_{othmax}$ is the value of any maximum point other than $s_{imax}$. When this judging condition is true, it means that the value of this maximum point is much larger than the value of the other maximum points.

**Judging condition 3 (extreme point sign and retention judgement)**

When the absolute value of the minimum value in the minimum points is less than 0.1 times that of the maximum value in the maximum points, only the maximum points are retained. Otherwise, both of the maximum points and the minimum points are retained.

if $|\min(s_{imins})| \leq 0.1\max(s_{imaxs})$
  $s_{imaxs}$ are retained
else
  $s_{imaxs}$ and $s_{imins}$ are retained
end

where $s_{imins}$ are the values of the minimum points; $|\min(\cdot)|$ is the absolute value of the minimum of multiple values; $s_{imaxs}$ are the values of maximum points; and $\max(\cdot)$ is the maximum of multiple values. When this judging condition is true, it means that the values of the minimum points are not of the same order of magnitude as the values of the maximum points, thus, they have little influence on the traffic load effect.

According to the above criteria, all of the axial force influence lines of the suspenders can be divided into three categories, and named, respectively, according to their shapes as an Inverted icicle type, an Angle iron type, and a W-shape type, as shown in Figure 3. Compared with all of the suspender influence lines shown in Figure 2, it can be seen that the influence lines near both ends of the bridge are mostly of the Angle iron type, while those near the mid-span position are mostly of the Inverted icicle type. The W-shape influence lines only appear in two- or multi-span continuous suspension bridges near the conjunction of adjacent spans, and the coordinate value of the influence line is zero at the intersection of bridge spans and has sign changes. There are only two types of suspender influence line of a single-span simply supported suspension bridge, i.e., the Angle iron type and the Inverted icicle type.
Influence line of a single-span simply supported suspension bridge, i.e., the Angle iron type, Inverted icicle type, and W-shape type.

Figure 3. Classification of influence line based on geometric features.

3.2. Extreme Load Effect Scenario Analysis of Suspender

The extreme effects of super-long-span suspension bridges are often obtained under the scenario of heavy vehicles gathering in different degrees, in which case the local load concentration of the bridge will increase significantly, which is especially unfavorable to the performance of the components near the heavy vehicles’ gathering area. Therefore, a load effect assessment is necessary for the design and evaluation of suspension bridges. By analyzing the load level and effect characteristics in the extreme load effect scenario, the bearing capacity of the bridge can be determined, and corresponding measures can be taken to ensure the safe operation of the bridge. By evaluating the load effect of the components in extreme load effect scenarios, the safety margin can be determined, and possible risks can be identified, which is helpful to formulate appropriate maintenance measures and safety management strategies.

In the traffic load effect analysis of bridges, the definition of a heavy vehicle usually refers to vehicles with a large load-carrying capacity. The specific definition of a heavy vehicle may vary depending on different countries, regions, or design specifications. In general, heavy vehicles can include trucks, large trucks, trailers, heavy machinery, and equipment transport vehicles. These vehicles usually have a large weight and carrying capacity, and, therefore, inflict a heavy load on the bridge structure. The definition of a heavy vehicle can be defined according to the weight of the vehicle, the number of axles, the size, and other parameters. In practical engineering, the specific definition of a heavy vehicle is usually determined according to the requirements of the design specifications and the design objectives of bridges. For example, some design specifications may define a vehicle with a certain load capacity or axle load limit as heavy. In this study, vehicles weighing more than 10 t are defined as heavy vehicles, and only the distribution of vehicles weighing more than 10 t on the bridge deck is considered in the analysis of an extreme load effect scenario [31,32].
Based on the design traffic volume of the bridge, a representative random traffic flow is generated to act as a database for an extreme load effect scenario extraction. The generated traffic flow can simulate and reflect the spatial–temporal distribution and evolution of vehicles on the bridge deck. Extreme load effect scenarios and their effects are analyzed based on random traffic flow loading. In order to facilitate the calculation, the bridge deck is divided into grids, and the mesh size is determined according to the size of the heavy vehicles. In this study, the grid length is set at 20 m, and each lane could be divided into 151 grids, with a total of 151 grids × 8 lanes = 1208 grids for the whole bridge. The vehicle distribution and load information on the bridge deck are obtained at a certain sampling interval, and the effect calculation is carried out to obtain the extreme value of the effect in a certain period of time. Due to the limited duration of the random traffic flow (in this study, 7 days), in order to ensure a sufficient sample size, the sampling interval of 1 s is used to obtain the hourly extreme load effect scenarios of the whole bridge, and each suspender could obtain 24 × 7 = 168 extreme load effect scenarios. Taking the suspender at the midpoint in the middle span as an example, some representatives of the extreme load effect scenarios extracted are shown in Figure 4.

Figure 4. Cont.
Figure 4. Hourly extreme load effect scenario of the suspender.

According to the vehicle distribution and vehicle weight information contained in the extreme load effect scenarios, the corresponding traffic load effect can be calculated, and the corresponding traffic load level can be obtained. An extreme load effect model is established to act as the reference load in the subsequent optimization process. In order to facilitate the comparison with the current specification load model, the calculation scheme of “uniformly distributed load + concentrated force” is adopted, and the load values are determined accordingly.

\[
\left( q_{\text{ref}} \cdot \omega_{l} + P_{\text{ref}} \cdot v_{l} \right) \cdot n_{\text{lane}} = \alpha E_{es}, \tag{1}
\]

\[
\alpha = f(E_{EV}, E_{CODE}, E_{es}), \tag{2}
\]

\[
E_{es} = \sum_{j=1}^{n} P_{j} v_{j}, \tag{3}
\]

where \( E_{es} \) is the load effect calculated according to the vehicle distribution in extreme load effect scenarios; \( \alpha \) is the effect adjustment coefficient obtained by a comprehensive consideration of the extreme load effect, specification value, and extreme scenario-induced effect; \( E_{EV} \) is the extreme value of the effect corresponding to the 100-year design reference period obtained by extrapolation; \( q_{\text{ref}} \) is the value of the reference uniformly distributed load obtained from the analysis of the extreme load effect scenarios; \( \omega_{l} \) is the influence line area; \( v_{l} \) is the peak value of the influence line; \( P_{\text{ref}} \) is the value of the reference concentrated force obtained from the analysis of the extreme load effect scenarios; \( P_{j} \) is the gross weight of a heavy vehicle in the extreme load effect scenario; \( v_{j} \) is the coordinate of the influence line where the heavy vehicle \( P_{j} \) acts; and \( n_{\text{lane}} \) is the total number of heavy vehicles on the bridge deck.
of the influence line where the heavy vehicle \( P_j \) acts; and \( n \) is the total number of heavy vehicles on the bridge deck.

4. Multi-Objective Optimization of the Traffic Load Model of Suspenders Based on the Genetic Algorithm

4.1. Selection of Optimization Variables

The optimization of the traffic load model mainly involves two aspects, load form (calculation scheme) and load value. In order to facilitate the designers’ selection, this study establishes the optimized load model by introducing several coefficients to the traffic load model specified in the design specification. Taking the Chinese specification [33] as an example, the traffic load (that is, the lane load) used for the calculation of the overall structural effect is composed of the uniformly distributed load and the concentrated force. The load value can be adjusted by setting proportional coefficients, and the loading length (range) of the uniformly distributed load can be adjusted by setting the proportional coefficient of the influence line area. In addition, the contribution ratio of the uniformly distributed load and the concentrated force to the total traffic load effect can be adjusted by setting the effect adjustment coefficient. Based on the above considerations and the aforementioned research on the traffic load effect, geometric characteristics, and extreme load effect scenarios of the suspender, five optimization variables are adopted in the subsequent multi-objective optimization process of this study, which are shown in Table 2. It should be noted that the selection of the optimization variables and optimization objectives in this study also takes into account the computational cost. The limited number of optimization variables and optimization objectives are determined to minimize the calculation cost and shorten the solving time without sacrificing the optimization effect.

Table 2. Summary of optimization variables.

<table>
<thead>
<tr>
<th>Optimization Variables</th>
<th>Description</th>
<th>Example *</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_1 )</td>
<td>Adjustment coefficient of effect induced by uniformly distributed load</td>
<td>( E_{q,\text{kom}} = x_1 \cdot E_q )</td>
</tr>
<tr>
<td>( x_2 )</td>
<td>Adjustment coefficient of effect induced by concentrated force</td>
<td>( E_{P,\text{kom}} = x_2 \cdot E_P )</td>
</tr>
<tr>
<td>( x_3 )</td>
<td>Proportional coefficient of influence line area</td>
<td>( \omega_{\text{om}} = x_3 \cdot \omega_0 )</td>
</tr>
<tr>
<td>( x_4 )</td>
<td>Proportional coefficient of uniformly distributed load valuing</td>
<td>( q_{\text{kom}} = x_4 \cdot q_{\text{code}} )</td>
</tr>
<tr>
<td>( x_5 )</td>
<td>Proportional coefficient of concentrated force valuing</td>
<td>( P_{\text{kom}} = x_5 \cdot P_{\text{code}} )</td>
</tr>
</tbody>
</table>

* Notations with the subscript “om” correspond to parameters in the optimized model; \( E_q \) and \( E_P \) are the load effects induced by the uniformly distributed load \( q_{\text{kom}} \) and concentrated force \( P_{\text{kom}} \); \( \omega_0 \) is the real area of the influence line; \( q_{\text{code}} \) and \( P_{\text{code}} \) are the uniformly distributed load and concentrated force specified in the specification.

4.2. Establishment of Optimization Objective Function

As can be seen from the comparison of the effect influence line and the extreme effect of the main components of the ZG Bridge in Table 1, the influence lines of the suspenders have an obvious peak and local characteristics. Compared with the peak value of the influence line and its vicinity, the influence line coordinate among most loading ranges is very small. In addition, the extreme value of the axial force obtained by extrapolation exceeds the code value, indicating that the traffic load model in the current specification is not applicable to the evaluation of the axial force of the suspender, and this problem has not been found in the analysis results of the traffic load effect of the other components. Furthermore, differences exist among the different suspenders in terms of the relationship between their real traffic load effects and the corresponding code values, which needs to be properly considered in the process of load model optimization. Based on the above considerations, this study proposed three objectives for the optimization of the traffic load model of the suspenders of super-long-span suspension bridges, namely accuracy, convenience, and improvement.
4.2.1. Optimization Objective 1—Accuracy

The comparison between the code value of the component and the extrapolated extreme effect of the random traffic flow loading in Table 1 shows that the effect level of the component under the actual traffic load is different from that represented by the specification model. Moreover, for the two representative suspenders, the specification model is not safe. However, for suspension bridges with a large number of suspenders, suspenders at the quarter span and suspenders at the midspan are representatives of large load effects, so they are often selected for effect analysis to obtain the unfavorable load effects. This indicates that, for other suspenders, the specification model may be unsafe or conservative. Therefore, when optimizing the traffic load model of suspenders, it is necessary to consider the relationship between the load effects derived from different load values and loading methods and take it as the benchmark or start point to optimize the load model. In addition, the dependency of one suspender on the adjacent suspenders should also be considered. In this study, the possible adverse influence of the adjacent suspenders is taken into account by setting a suitable and matched safety margin in the final optimized model. The accuracy optimization function is constructed according to the aforementioned optimization demand as follows:

\[ f_1(x) = f_{11}(x) + f_{12}(x) + f_{13}(x), \]  
\[ f_{11}(x) = \omega_{11}\left( x_1 \cdot x_3 \cdot q_{\text{code}} \cdot \frac{n_{\text{lane}} \cdot \eta_1 \cdot \eta_{\text{ml}}}{E \cdot V} - 1 \right), \]
\[ f_{12}(x) = \omega_{12}\left( x_4 \cdot q_{\text{code}} - q_{\text{kref}} \right), \]
\[ f_{13}(x) = \omega_{13}\left( x_5 \cdot P_{\text{code}} - P_{\text{kref}} \right), \]

where \( \omega_{1i} \) is the weight of the three component functions that make up the optimization objective function 1, where \( i = 1, 2, 3, \sum \omega_{1i} = 1; il_{\text{area}} \) is the area of the influence line of the selected suspender; \( il_{\text{peak}} \) is the peak value of the influence line of the selected suspender; \( q_{\text{code}} \) is the uniformly distributed load value specified in the specification model (in the Chinese specification, this is 10.5 kN/m); \( P_{\text{code}} \) is the concentrated force value specified in the specification model (in the Chinese specification, this is 360 kN); \( n_{\text{lane}} \) is the number of lanes (in this study, this is 8); \( \eta_1 \) is the longitudinal reduction factor (in the Chinese specification, this is 0.93); and \( \eta_{\text{ml}} \) is the multilane reduction factor (in the Chinese specification, this is 0.5).

4.2.2. Optimization Objective 2—Convenience

The convenience of the traffic load model is closely related to the loading length of the uniformly distributed load. To solve this problem, the characteristics of the influence lines are analyzed. The axial force influence lines of all of the suspenders of four suspension bridges (the ZG Bridge and another three bridges, numbered as B1, B2, and B3) with different main spans are extracted. The basic information of the four bridges is shown in Table 3. After fitting the trend of the relationship between the influence line area and its peak value, it has been found that there is an obvious “platform” in the fitted curve. As can be seen from Figure 5, the area of the influence line initially increases with the increase in the peak value and soon reaches the platform. After that, the area of the influence line does not increase with the increase in the peak value of the influence line, and the area of the influence line remains in a relatively stable numerical range.
Table 3. Basic information on bridges.

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Main Span</th>
<th>Number of Lanes</th>
<th>Main Beam</th>
<th>Number of Suspenders</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZG</td>
<td>2300 m</td>
<td>8</td>
<td>Steel box girder</td>
<td>184</td>
</tr>
<tr>
<td>B1</td>
<td>1490 m</td>
<td>6</td>
<td>Steel box girder</td>
<td>90</td>
</tr>
<tr>
<td>B2</td>
<td>1208 m</td>
<td>8</td>
<td>Steel box girder</td>
<td>74</td>
</tr>
<tr>
<td>B3</td>
<td>700 m</td>
<td>4</td>
<td>Steel box girder</td>
<td>57</td>
</tr>
</tbody>
</table>

Figure 5. Trend fitting of influence line area and peak value.

The ratio of the influence line area $S$ of the suspender to the peak value $V_p$ of the influence line is defined as the length of the sensitive effect zone $SL$ (referred to simply as the influence line length in Figure 6), that is, $SL = S / V_p$. The $SL$ of the four suspension bridges is statistically analyzed, as shown in Figure 6. The results show that the mean $\mu$ and the standard deviation $\sigma$ of $SL$ both increase with the increase in span, which indicates that the length of the sensitive effect area of the suspender increases and the difference between the suspenders at different positions also increases. Therefore, the sensitive effect area of the suspenders of a super-long-span suspension bridge with main span exceeding 2000 m is larger, and there are more scenarios that may cause the extreme load effect. The problem of the traffic load effect is more complicated, and further analysis is needed.

Based on the foregoing analysis, we select the proportional coefficient of the influence line area as the convenience optimization objective for the load model. The loading length of the uniformly distributed load can be obtained according to the value of $x_3$ after the completion of the optimization process, and the degree of convenience of the optimized model can be evaluated accordingly.

$$f_2(x) = x_3,$$  \hspace{1cm} (8)

where $x_3$ is the proportional coefficient of the influence line area, i.e., the ratio of the optimized loading area of the influence line to the real area of the influence line.
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4.2.3. Optimization Objective 3—Improvement

A conclusion that can be drawn from the study in Section 2 is that the traffic load model in the current specification is not applicable enough to the calculation of the axial force of suspenders, and it is reflected that the code value may not envelope the extreme load effect under the action of the actual traffic flow. The main reason for this problem is that the mechanical characteristics of the suspender are not considered adequately. Combined with the analysis of the axial force influence line of the suspenders, it can be seen that significant load effects of a suspender will be induced under the action of heavy loads (mainly manifested as heavy axial loads) within a limited range of its position. While for the action of uniformly distributed load, even if it is arranged over the full span of a bridge (due to the limited magnitude of the area of the influence line), it is difficult to cause obviously adverse effects. In addition, for long-span bridges, this study shows that the uniformly distributed load is smaller than that of small to medium span bridges [34]. Therefore, in

Figure 6. Statistics of influence line length of suspenders from bridges with different main spans.
the optimization of the traffic load model for the suspender, the role of concentrated force should be considered specially, and the contribution of uniformly distributed load should be appropriately reduced. Two indicators are selected to represent the improvement of the above problems in the optimized model. One of these is $x_4$, that is, the proportional coefficient of the valuing of the uniformly distributed load, and the other is the ratio of $x_4$ to $x_5$. Searching the minima of function $f_3(x)$ means reducing the value of the uniformly distributed load and relatively improving the value of the concentrated force at the same time.

$$f_3(x) = f_{31}(x) + f_{32}(x),$$

$$f_{31}(x) = \omega_{31} \cdot x_4,$$

$$f_{32}(x) = \omega_{32} \cdot (x_4 / x_5),$$

where $\omega_{3j}$ is the weight of the two component functions that make up the optimization objective function 3, $j = 1, 2, \sum \omega_{3j} = 1$.

5. Results and Discussion

5.1. Settings of Optimization

Representative suspenders are selected for each of the three types of suspenders classified in Section 3.1, which are the suspender at the midpoint of the middle span (named HMM, representing the Inverted icicle type), the longest suspender of the side span (named HSL, representing the W-shape type), and the shortest suspender of the side span (named HSS, representing the Angle iron type). The multi-objective optimization method based on the genetic algorithm is adopted for the iterative optimization of the three optimization objectives of accuracy, convenience, and improvement, as specified in Section 4.2. The reference value or constants involved in the optimization process are shown in Table 4, and the optimization flow chart is shown in Figure 7.

Table 4. Reference value/constant for optimization.

<table>
<thead>
<tr>
<th>Suspender</th>
<th>$h_{area}$</th>
<th>$h_{peak}$</th>
<th>$E_{LV}$(N)</th>
<th>$E_{CODE}$(N)</th>
<th>$q_{kref}$(kN/m)</th>
<th>$P_{kref}$(kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMM</td>
<td>8.3</td>
<td>0.08</td>
<td>519,000</td>
<td>431,334</td>
<td>4.5</td>
<td>1277</td>
</tr>
<tr>
<td>HSL</td>
<td>8.6</td>
<td>0.02</td>
<td>182,335</td>
<td>362,700</td>
<td>3.0</td>
<td>1161</td>
</tr>
<tr>
<td>HSS</td>
<td>10.6</td>
<td>0.07</td>
<td>642,620</td>
<td>507,780</td>
<td>7.0</td>
<td>1408</td>
</tr>
</tbody>
</table>

Figure 7. Optimization flow chart.

5.2. Results of Optimization

The Pareto fronts made of 60 optimal solutions for each representative suspender after the multi-objective optimization process are shown in Figure 8. As conflicts usually exist among the objectives of a multi-objective optimization issue, the improvement of one objective may cause a performance reduction in another or several objectives. Therefore, it is necessary to coordinate and compromise among them to achieve the optimization of each objective as much as possible. In this study, the accuracy objective is given priority to be met, and the optimal solutions of the convenience objective and the improvement objective are determined accordingly. According to the obtained optimized value of $x_1$～$x_5$, 

$$f_3(x) = \omega_{31} \cdot f_31(x) + \omega_{32} \cdot f_32(x),$$

where $\omega_{3j}$ is the weight of the two component functions that make up the optimization objective function 3, $j = 1, 2, \sum \omega_{3j} = 1$. 

5.1. Settings of Optimization

Representative suspenders are selected for each of the three types of suspenders classified in Section 3.1, which are the suspender at the midpoint of the middle span (named HMM, representing the Inverted icicle type), the longest suspender of the side span (named HSL, representing the W-shape type), and the shortest suspender of the side span (named HSS, representing the Angle iron type). The multi-objective optimization method based on the genetic algorithm is adopted for the iterative optimization of the three optimization objectives of accuracy, convenience, and improvement, as specified in Section 4.2. The reference value or constants involved in the optimization process are shown in Table 4, and the optimization flow chart is shown in Figure 7.
an improved traffic load model (hereafter referred to as “optimized model”) for the selected representative suspenders can be built. The specific results are shown in Table 5.

Figure 8. Optimization results of selected suspenders. (a) Pareto front of suspender HMM; (b) Pareto front of suspender HSL; (c) Pareto front of suspender HSS.
Table 5. Optimization results of traffic load model for suspenders.

<table>
<thead>
<tr>
<th>Suspender</th>
<th>Calculation Scheme</th>
<th>Uniformly Distributed Load (kN/m)</th>
<th>Concentrated Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMM</td>
<td>( \hat{q}_1 )</td>
<td>6.4</td>
<td>1433</td>
</tr>
<tr>
<td>HSL</td>
<td>( q_2 )</td>
<td>8.9</td>
<td>1314</td>
</tr>
<tr>
<td>HSS</td>
<td>( q_3 )</td>
<td>7.7</td>
<td>1426</td>
</tr>
</tbody>
</table>

5.3. Comparison and Discussion

5.3.1. Comparison between Suspenders

According to the optimization results, the optimized values of five optimization variables are shown in Table 6. The table shows that the proportional coefficients of uniformly distributed load valuing \( x_4 \) of the optimized models are all less than one, in line with the optimization requirements of decreasing uniformly distributed load. The proportional coefficients of concentrated force valuing \( x_5 \) are all greater than 3.5, and the \( x_5 \) of the HMM is close to 4, verifying that the function of the concentrated force should be emphasized when establishing traffic load model of suspenders in order to reflect the actual load effect level more reasonably. The optimization results of the adjustment coefficients of effect \( x_1 \) and \( x_2 \) basically reflect a similar situation, which reduces the uniformly distributed load's contribution to the total effect, while increasing the proportion of concentrated force in the total effect. The optimization results of the proportional coefficient of influence line area \( x_3 \) are all 0.9, and the corresponding loading lengths of the uniformly distributed load of each representative suspender are 224 m for the HMM, 1244 m for the HSL, and 1463 m for the HSS, respectively. These results verify the feasibility of optimizing the loading length of the uniformly distributed load for the load effect calculation of suspenders on the basis of keeping the rationality of the load effect analysis. Although the final optimized values of \( x_3 \) for the different suspenders are the same, it is actually the result of balancing several optimization objectives. The length of the sensitive effect zone (SL) does have an influence on the proposed optimized model, and this can be confirmed from the different value ranges of the optimal solutions of optimization objective 2 for the three representative suspenders, as shown in Figure 8. The optimization effect is most obvious for the HMM, which belongs to the Inverted icicle type, verifying the correctness of the geometric feature analysis of the influence line in Section 4.2.2.

Table 6. Optimized values of optimization variables.

<table>
<thead>
<tr>
<th>Suspender</th>
<th>( x_1 )</th>
<th>( x_2 )</th>
<th>( x_3 )</th>
<th>( x_4 )</th>
<th>( x_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMM</td>
<td>0.98</td>
<td>1.02</td>
<td>0.90</td>
<td>0.61</td>
<td>3.98</td>
</tr>
<tr>
<td>HSL</td>
<td>0.50</td>
<td>0.60</td>
<td>0.90</td>
<td>0.85</td>
<td>3.65</td>
</tr>
<tr>
<td>HSS</td>
<td>0.90</td>
<td>1.30</td>
<td>0.90</td>
<td>0.73</td>
<td>3.96</td>
</tr>
</tbody>
</table>

5.3.2. Comparison between Load Models/Effects

The load value of the optimized model is compared with the specification model and the extreme load effect scenario model, as shown in Table 7. It can be seen from the table that, compared with the specification model, the value of the uniformly distributed load in the optimized model of the three representative suspenders is reduced, and the decrease is from 1.6 kN/m to 4.1 kN/m. The value of concentrated force is significantly increased, which can reach four times that of the value of the specification model. Compared with the extreme load effect scenario model, in terms of the uniformly distributed load, the load value of the optimized model has increased to a different extent. In terms of the concentrated force, the load value has been relatively close to that of the extreme load effect scenario model, indicating that the effect of the concentrated force has been reasonably considered in the extreme load effect scenario model. To explain the results further, the increase in the value of the uniformly distributed load in the optimized model is mainly an adjustment to ensure that the optimized model has a reasonable safety margin for the
extreme load effect of the suspender after considering the role of the adjustment coefficient of effect comprehensively.

Table 7. Comparison of load model values.

<table>
<thead>
<tr>
<th>Suspender</th>
<th>Uniformly Distributed Load (kN/m)</th>
<th>Concentrated Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimized Model</td>
<td>Extreme Load Effect Scenario Model</td>
</tr>
<tr>
<td>HMM</td>
<td>6.4</td>
<td>4.5</td>
</tr>
<tr>
<td>HSL</td>
<td>8.9</td>
<td>3.0</td>
</tr>
<tr>
<td>HSS</td>
<td>7.7</td>
<td>7.0</td>
</tr>
</tbody>
</table>

The effect under the action of the optimized model is calculated and compared with the extreme load effect ($E_{EV}$) obtained by the extrapolation method, and the growth rate of effect corresponding to each optimal solution is shown in Figure 9. As can be seen from the figure, the growth rate is positive, indicating that the optimized model can well contain the adverse effects that may occur during the design reference period of the suspenders. Among them, the growth rate of the HMM is between 6.4% and 27.4%, the growth rate of the HSS is between 8.8% and 17.0%, and the growth rate of the HSL is no more than 5.9%. The load effect level and safety margin for the extreme load effect of the optimized model are in accordance with the mechanical characteristics of each representative suspender, which is a result with a reasonable optimization effect and practical applicability.

Figure 9. Comparison of traffic load effect of suspenders—growth rate (%).

6. Conclusions

Aiming at the optimization of the traffic load model of super-long-span suspension bridges, this paper carried out related studies specific to suspenders of a suspension bridge with a main span of 2300 m, and the main conclusions are drawn as follows:

(1) There are a large number of suspenders of super-long-span suspension bridges, and the suspenders are mainly sensitive to the heavy concentrated forces acting in the vicinity of them. Different suspenders have different safety margins under the action of the same level of traffic load. When the actual traffic load is heavy, the other main components designed according to the specification can ensure reasonable service safety, but the load effect of some suspenders may exceed the limit.

(2) The influence lines of the axial force of suspenders can be classified according to their geometric features. According to the quantity and sign of extreme points, all of the influence lines of the axial force of suspenders were classified into three categories, namely the Inverted icicle type, the Angle iron type, and the W-shape type, and each type represents the different position information and mechanical characteristics of suspenders.

(3) By generating random traffic flow data and analyzing the contained vehicle distribution and vehicle weight information, scenarios that could induce an extreme traffic load effect were extracted, and a corresponding load model was built according to the
calculation results of the load effect. The load value of this model was used as a reference to establish an optimized traffic load model.

(4) Multi-objective optimization based on genetic algorithm was adopted to optimize the traffic load model of suspenders, and three representative suspenders were selected for case study. Taking accuracy, convenience, and improvement as the optimization objectives, the optimized traffic load models corresponding to each representative suspender were built. In terms of the load value, compared with the specification model, the uniformly distributed load of the optimized model decreased from 1.6 kN/m to 4.1 kN/m, and the concentrated force increased significantly, which could reach four times that of the specification model at most. In terms of load effects, the optimized model can well envelope the extreme load effects of suspenders that may occur during the design reference period, and the safety margin for the extreme load effect accords with the mechanical characteristics and load effect levels of each suspender, which proves that the optimized model has a reasonable optimization result.

Although the issue of the loading length of uniformly distributed load has been analyzed, the conclusions drawn in this paper are mainly focused on the valuing of the traffic load model and its reasonable safety margin. Possible changes to the calculation scheme and fineness of the load model can be further discussed in future studies. In addition to the static effect, the dynamic response induced by heavy vehicles is also of great significance for the resistance performance of suspension bridges. Since this study mainly discusses the optimization issue of the traffic load model for super-long-span suspension bridges, the applicability of the proposed optimized model to medium or shorter span bridges will be explored in subsequent relevant studies.

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