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Traffic control technologies without interruption for component replacement of long-span bridges using microsimulation and site-specific data

Junyong Zhou[1a], Xuefei Shi[*2], Liwen Zhang[1] and Zuo Sun[1]

[1]College of Civil Engineering, Guangzhou University, 230 West Waihuan Road, Guangzhou, Guangdong 510006, China
[2]Department of Bridge Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China

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Abstract. The replacement of damaged components is an important task for long-span bridges. Conventional strategy for component replacement is to close the bridge to traffic, so that the influence of the surrounding environment is reduced to a minimum extent. However, complete traffic interruption would bring substantial economic losses and negative social influence nowadays. This paper investigates traffic control technologies without interruption for component replacement of long-span bridges. A numerical procedure of traffic control technologies is proposed incorporating traffic microsimulation and site-specific data, which is then implemented through a case study of cable replacement of a long-span cable-stayed bridge. Results indicate traffic load effects on the bridge are lower than the design values under current low daily traffic volume, and therefore cable replacement could be conducted without traffic control. However, considering a possible medium or high level of daily traffic volume, traffic load effects of girder bending moment and cable force nearest to the replaced cable become larger than the design level. This indicates a potential risk of failure, and traffic control should be implemented. Parametric studies show that speed control does not decrease but increase the load effects, and flow control using lane closure is not effectual. However, weight control and gap control are very effective to mitigate traffic load effects, and it is recommended to employ a weight control with gross vehicle weight no more than 65 t or/and a gap control with minimum vehicle gap no less than 40 m for the cable replacement of the case bridge.

Keywords: long-span bridge; component replacement; traffic control; load effect; microsimulation; multi-axle single-cell cellular automaton (MSCA)

1. Introduction

A long-span bridge is generally a high-order statically indeterminate structure system, wherein, many components (e.g., suspender, stayed-cable, bearing) are designed with a lower life-span than the structure system considering the differences of material characteristics, manufacturing quality, control level, and intended use (Karbhari 2009, Frangopol *et al*. 2017). On the other hand, bridge components are suffering increasing diseases under severe environment and transportation conditions, which make the service lives of these components largely reduced. Therefore, the replacement of damaged bridge components is an important task to ensure structural safety and optimize life-cycle cost (Dekker *et al*. 1997, Kim and Kang 2016). The conventional strategy for component replacement is to close the bridge to traffic, such that the influence of the surrounding environment can be reduced to a minimum extent. However, since bridges are the lifeline nodes of transportation, complete traffic interruption for the bridge would bring substantial economic losses and negative social influence nowadays. Therefore, traffic control technologies without interruption for the replacement of bridge components would be an asset.

There are some practical cases from the literature that the bridge component was replaced without traffic interruption. The Rhine River Bridge was a busy gateway linking Germany and the Netherlands with a daily traffic volume of more than 75 000 vehicles. After having been in service for 30 years, stayed-cables of the bridge were replaced during which six-lane traffic was maintained successfully (Marzahn *et al*. 2009). In the replacement of stayed-cables of the Hale Boggs Bridge in Louisiana which carried four-lane traffic, the width of the work area was minimized to 3.73 m and so two-lane traffic was kept open in peak hours (Mehrabi *et al*. 2010). These studies showed bridge components could be replaced without traffic interruption. However, to the best knowledge of the authors, there were no evidential reports behind the use of traffic control measures for these bridges. Besides, few studies addressed the effects of different traffic control technologies on bridge safety. Notably, in the suspender replacement of the Tancarville Bridge which had been in service for almost 40 years, site-specific weigh-in-motion (WIM) data were collected to analyze the extreme traffic load effects on the bridge. It was found that the extrapolated forces of all the suspenders were smaller than the ultimate design ones. Therefore, the entire suspension system of the bridge was replaced without any interruption of the four-

∗Corresponding author, Professor
E-mail: shixf@tongji.edu.cn
[a]Ph.D. Lecturer
E-mail: jyzhou@gzhu.edu.cn

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lane bidirectional traffic (Lecroq *et al*. 2001, Cremona 2001).

Indeed, if realistic loading effects induced by running traffic during component replacement are below the design values (based on traffic load models from specifications), then the bridge safety could be guaranteed, and the replacement could be implemented without traffic interruption (Fu *et al*. 2013, Wang *et al*. 2012). With the advances of traffic measurements, site-specific load information provides a more realistic prediction of load effects over bridge remaining life. Hence, evaluation of traffic load effects on bridges based on site-specific data becomes the mainstream (Guo *et al*. 2012, Ruan *et al*. 2017a). For long-span bridges, the current measurements are unable to record load information and capture individual vehicle behaviors concurrently. Hence, traffic microsimulation based on site-specific statistical information is needed (Chen and Wu 2011, Caprani 2012, O'Brien *et al*. 2012, Ruan *et al*. 2017b, Zhou *et al*. 2019), which is a relatively new area of research.

Motivated by the strong requirement of less traffic disruption during bridge component replacement, this paper investigates the extreme load effects on long-span bridges considering different traffic control technologies. A numerical procedure of traffic control technologies without interruption is first proposed for bridge component replacement. Traffic microsimulation is then developed and programmed, incorporating site-specific data and different types of traffic control measures (i.e., speed control, weight control, vehicle gap control, and flow control). Finally, the numerical procedure and traffic microsimulation are implemented through a case study of cable replacement of a long-span cable-stayed bridge. Parametric studies on the effect of traffic control technologies under different traffic conditions are conducted to find feasible strategies. With the modern development of intelligent transportation system, traffic control technology based on microscopic simulation could provide more technical support for smart management of transportation infrastructure.

2. Numerical procedure

The numerical procedure of traffic control technologies without interruption for component replacement of long-span bridges is proposed as shown in Fig. 1. It includes three parts: the determination of adverse bridge state, the traffic microsimulation, and the selection of traffic control measures.

In the first, the most adverse bridge state during component replacement should be identified. This is also where the structural safety checking is based. The common known replaceable components in long-span bridges are bearings, suspenders, and stayed-cables. Besides, the adverse bridge state is closely related to the type of the replaced component. For example, the replacement of a suspender in tied arch bridges or suspension bridges is generally conducted based on the equivalent-force conversion principle (Sun *et al*. 2017, Feng *et al*. 2018). During the replacement, the force of the suspender is steadily transferred first from the target one to a temporary

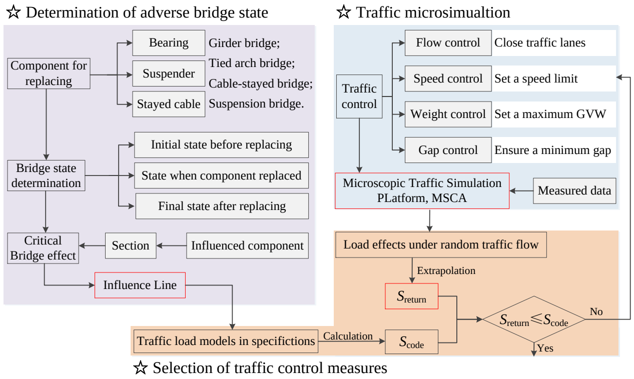

Fig. 1 Numerical procedure of traffic control technologies for component replacement

one, and then from the temporary one to the new one. Therefore, the bridge state is unchanged over the whole procedures, and the initial bridge state could be defined as the most adverse. However, in the replacement of stayed-cable of modern cable-stayed bridges, the target stayed-cable should be entirely removed before the installation and tension of the substitute (Sandberg and Hendy 2010). In this case, the bridge state without a stayed-cable is the most adverse. Since the replacement of components is always conducted steadily, the static influence lines (ILs) of these critical structural effects are extracted for the analysis of traffic control strategy. Note that these ILs are calculated considering the effect of geometrical nonlinearity of the dead load in the new equilibrium state.

Then, traffic microsimulation using site-specific traffic data is conducted to analyze the extreme load effects of bridges during component replacement, and to investigate whether traffic control is needed. Site-specific data provide realistic traffic information for the bridges, such as daily traffic volume, vehicle composition, gross vehicle weight, vehicle axle spacings, and vehicle speed. Traffic microsimulation uses car-following and lane-changing models to dynamically simulate microscopic behaviors of individual vehicles based on the input of traffic data. It can reproduce the traffic loading scenarios on bridges. In this paper, four different technologies including flow control, speed control, weight control, and vehicle gap control are studied.

Finally, bridge ILs from finite element analysis and vehicle load sequences from traffic microsimulation are combined to derive structural load effects. Provided that realistic load effects do not exceed the criterion (Herein, the design level is identified as the criterion, which will be discussed in the Conclusion section), the adopted traffic control technology is feasible, and the structural safety during the entire construction processes of component replacement can be ensured. With the sensitivity study of different traffic control technologies, the feasible traffic control strategy could be determined to minimize traffic interference and ensure bridge safety. In the numerical procedure, static traffic loading effects are investigated, and no dynamic load allowance is involved.

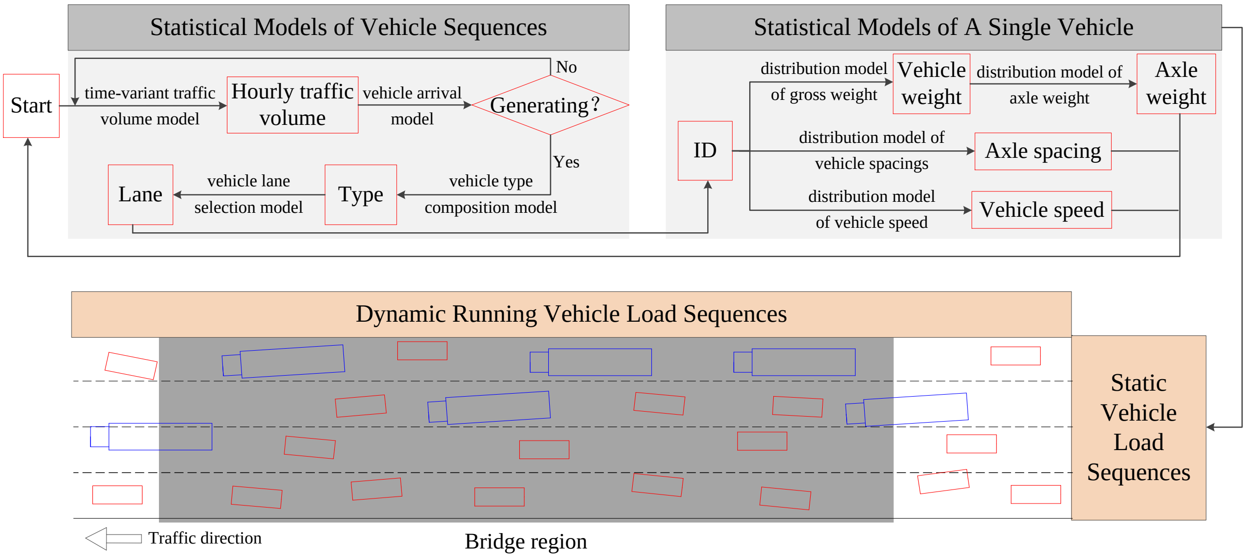

Fig. 2 Flowcharts of traffic microsimulation based on site-specific data

3. Microsimulation considering traffic control measures

3.1 Traffic microsimulation

The use of microsimulation to study traffic loading effects on long-span bridges is a relatively new area of research. Caprani (2012) and O'Brien *et al*. (2012) used intelligent driver model, initially proposed by Triber *et al*. (2000), to simulate the running of the vehicle load sequences over long-span bridges. Chen and Wu (2011) introduced cellular automaton, initially proposed by Nagel and Schreckenberg (1992) to study traffic loading on long-span bridges. In their study, the modeling efficiency is impressive, but the loading accuracy is not as good since vehicle length, gap, and velocity are all integral times of the cell size. Ruan *et al.* (2017b) proposed an innovative multi-axle single-cell cellular automaton (MSCA) to precisely model vehicle axles loading and realistic vehicle gaps and vehicle lengths. In MSCA, ILs of bridge effects are embedded into the states of cells, and loading effects could be efficiently obtained through mathematical operation of these parameters in cells. Furthermore, MSCA is validated and calibrated based on the measured weigh in motion (WIM) data, and is used in many complex traffic scenarios modeling for long span bridges (Zhou *et al.* 2019).

Fig. 2 summarizes the processes of traffic microsimulation using site-specific data. First, following statistical models of vehicle sequence (including hourly traffic volume, vehicle arrival, vehicle composition, and vehicle lane-choice), the generation of a single vehicle is determined. Then, vehicle configuration data (including gross vehicle weight, axle weight, axle spacing, and speed) are assigned to the target vehicle based on the relevant statistical models of a single vehicle. Next, cycle the above two steps, and static vehicle sequences are generated at the start of the road. The vehicle sequences run along the road following microscopic traffic rules such as acceleration, deceleration, lane-changing, and overtaking. Finally, vehicle sequences are loaded over the bridge ILs, and history of bridge load effects is obtained.

In the paper, traffic microsimulation is performed using MSCA, and the simulation processes are similar as indicated in Fig. 2. It is noted MSCA is proposed for free traffic condition (Ruan *et al.* 2017b), while the relevant traffic rules need improvement where there is traffic control. Considering traffic control technologies including speed control, weight control, vehicle gap control, and flow control, simulation rules in MSCA are modified and improved in the following.

3.2 Improved MSCA

MSCA has four fundamental parts, i.e., lattice, cell's states, neighborhoods, and transition rules (Ruan *et al.* 2017b). Speed and weight control is the regulation of traffic parameters of individual vehicles, which are determined by cell's states. Vehicle gap control is the restriction on vehicle behavior when following each other, and is belong to the scope of car-following and lane-changing rules. Flow control is to reduce the number of passing vehicles on the bridge through closing traffic lanes, which is determined by lane-changing rules. In the following, MSCA is improved such that various traffic control technologies could be considered in microsimulation.

Speed control is implemented by setting a maximum velocity in restrictive regions. Considering the randomness that drivers comply with the standard of the speed limit, the maximum velocity in MSCA is set to obey a normal distribution with a mean value of the speed limit, v_m, and a coefficient of variation being 0.1.

Weight control is to limit gross vehicle weight or vehicle axle weight. In design standards for roadways and bridges, weight limits are defined both on gross vehicle weight and vehicle axle weight. However, for bridges in service, weight restriction on gross vehicle weight is widely employed due to its convenient implementation in reality. The weight limit is defined to be a constant value, G_m, to ensure that the gross weight of any vehicle is below the standard for bridge safety.

Gap control is to ensure a minimum car-following gap between vehicles to avoid potential traffic conflict and severe loading on infrastructures. Conventional vehicle gap control is conducted by setting caution sign of gap limit before the bridge. Whereas, future advanced implementation is that the real-time distances between vehicles could be automatically displayed through intelligent transportation system (Lipari *et al.* 2017), reminding drivers of keeping the minimum gap. On vehicle gap control regions in MSCA, the minimum vehicle gap, gap_m, should be ensured, and the rules of vehicle acceleration and deceleration defined in MSCA are modified. Furthermore, vehicle gap control should also be applied to the lane-changing rule of MSCA, and the pristine gap_i^t should be amended to $\mathrm{gap}_i^t + \mathrm{gap}_m$ to ensure that the minimum vehicle gap, gap_m, is always guaranteed.

$$v_i^{t+1} = \min\{v_i^t + a\Delta t, v_{\max}\};\, if\ \mathrm{gap}_i^t > (v_i^t + a\Delta t)\Delta t + \mathrm{gap}_m,\quad \Delta t = \max\{1s, \Delta t\} \tag{1}$$

$$v_i^{t+1} = \max\left\{\frac{\mathrm{gap}_i^t - \mathrm{gap}_m}{\Delta t} - b\Delta t, 0\right\};\, if\ \mathrm{gap}_i^t \le (v_i^t + a\Delta t)\Delta t,\quad \Delta t = \max\{1s, \Delta t\} \tag{2}$$

Where v_i^{t+1} and v_i^t are the velocities of vehicle i at t+1 and t moments, respectively. $v_{\max}$ is the speed limit. Δt is the simulation time step. a and b are the unit acceleration and deceleration defined for the transformation, respectively. gap_i^t is the vehicle gap from the front axle of vehicle i to the rear axle of vehicle i+1.

Flow control considered in the paper is to restrict the number of vehicles on the bridge but ensure daily traffic volume on the road. The common practice is the lane closure. On a roadway with lane closure, the lane-changing demands in various regions along the road are quite different. Generally, types of vehicle lane-changing behaviors could be classified into Discretionary Lane-Changing (DLC), Anticipatory Lane-Changing (ALC), and Mandatory Lane-Changing (MLC) (Bevrani and Chung 2012). For DLC, drivers change lane when vehicle velocities do not satisfy their subjective expectations. For MLC, drivers have to change lane to pass through due to environmental factors such as traffic accident and lane closure. ALC is the choice of early lane-changing before reaching the regions of MLC. Therefore, when vehicles are approaching the lane closure region, the lane-changing behaviors of vehicles can be referred to "DLC-ALC-MLC-DLC." An example layout of lane-changing behaviors on a two-lane roadway with one lane closure is shown in Fig. 3(a), and the lane-changing rules of MSCA are improved as follows:

• In regions of DLC, R_{DLC}, the original lane-changing rule of MSCA is applied. When the vehicle cannot accelerate in the current lane, but it can accelerate and does

Fig. 3 Modeling of vehicle lane-changing on a roadway with a partial lane closure: (a) zoning regions of lane-changing rules and (b) the developed visualization program

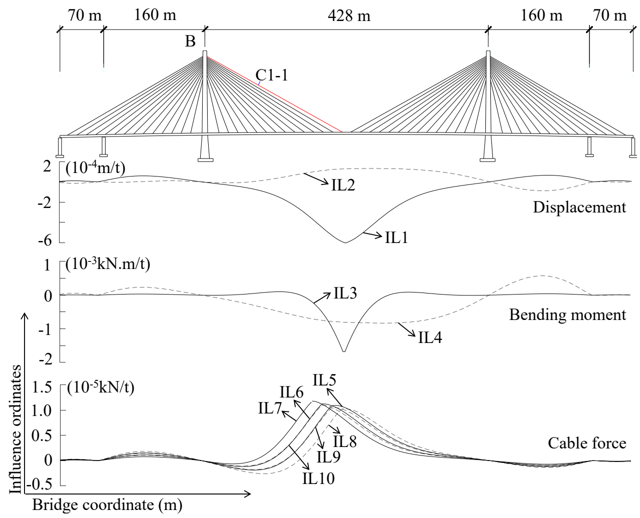

Fig. 4 The layout of the bridge and critical ILs for the replacement of cable C1-1

not collide with the following vehicle in the target lane, the vehicle changes to the target lane at the probability pb.

• In regions of ALC, R_{ALC}, if the vehicle can accelerate and does not collide with the following vehicle in the target lane (the open lane in the lane closure), the lane change occurs.

• In regions of MLC, R_{MLC}, if the vehicle does not collide with the following vehicle in the target lane (the open lane in the lane closure), the lane change occurs.

With these modifications and improvements in MSCA, the microsimulation program and its visualization are realized as shown in Fig. 3. Therefore, bridge loading effects under microscopic vehicle sequences could be dynamically modeled using MSCA considering different traffic control technologies.

4. Case study

A case study of traffic control for cable replacement of a long-span cable-stayed bridge is investigated in this section. The descriptions of the bridge and cable replacement are first introduced. Characteristic of measured traffic data on the bridge site is then analyzed. Traffic microsimulation considering different traffic control technologies and

Table 1 Overall statistical features of the traffic data

Items	Lane 1	Lane 2	Lane 3	Lane 4	Westbound	Lane 5	Lane 6	Lane 7	Lane 8	Eastbound
Average daily traffic volume (veh/d)	2458	3033	3997	3734	13222	3430	4087	3350	2563	13429
Truck Proportion (%)	92.61	73.60	13.82	1.97	38.83	1.10	18.48	74.70	88.60	41.45
Average vehicle gross weight (t)	34.60	19.84	3.73	2.02	12.68	2.00	4.56	24.93	34.53	17.70
Average vehicle speed (km/h)	55.56	70.37	94.58	99.86	82.90	100.12	98.73	81.27	68.97	89.15
No. of vehicles exceeding 55 t	122512	57424	496	11	180443	16	2504	123315	144735	270570
No. of vehicles exceeding 100 t	2114	559	2	0	2675	0	17	1209	6876	8102

various traffic conditions is conducted. Finally, the effects of different traffic control technologies on bridge loading effects are compared, and feasible traffic control strategies are recommended.

4.1 The description of the bridge and cable replacement

A double-pylon cable-stayed bridge is studied. The bridge uses flat steel box girder and concrete diamond pylon. The span arrangement of the bridge is 70+160+428+160+70 m, carrying eight-lane bidirectional traffic. Double cable-planes and total 112 stayed-cables are used. The general layout of the bridge is shown in Fig. 4.

The general scheme for cable replacing of a cable-stayed bridge is to remove each cable one-by-one (Fu *et al*. 2013), and is considered in the paper. The preliminary sensitive study indicates the removal of an outmost cable in the middle span is the most adverse scenario. Therefore, the most adverse bridge state assumed in the numerical procedure is the bridge condition without an outmost cable (e.g., cable C1-1) in the middle span. After the removal of the cable C1-1, it is essential to ensure bridge performance considering the load effects of the girder, pylons, and cables. Herein, several critical bridge effects are studied, and their ILs are shown in Fig. 4. In detail, they are: vertical displacement in the middle of the girder of the central span (IL1); longitudinal displacement in the top of the pylon in the work-side (IL2); longitudinal bending moment in the middle of the girder of the central span (IL3); longitudinal bending moment in the bottom of the pylon in the work-side (IL4); axial force of the three adjacent cables in the work-side (IL5, IL6, IL7); axial force of the three adjacent cables laterally opposite to the work-side (IL8, IL9, IL10).

4.2 Characteristic of traffic data

A WIM system was installed on the bridge site. Eight-lane traffic data from April 2016 to January 2017 were collected. After filtering some half-baked records and errors, total 200-day complete measurements were obtained.

Table 2 Main parameters in the simulation of MSCA

Item	Value
Road length, L	2000 m
Lane number, n	8
Cell size, Δl	5 m
Time step, Δs	0.5 s
Unit acceleration, a	[0-1] m/s2
Unit deceleration, b	[0-2] m/s2
Random deceleration factor, p	0.10
Lane-changing probability from an outer lane to an inner lane, pb_f	0.40
Lane-changing probability from an inner lane to an outer lane, pb_s	0.20

Table 3 Summary of traffic micro-simulation conditions for the bridge

Content	Simulation condition
Average daily traffic volume	26 651 veh/d, 60 000 veh/d, 90 000 veh/d
Speed limit, v_m	120 km/h, 100 km/h, 80 km/h, 60 km/h, 40 km/h
Weight limit, G_m	None, 100 t, 80 t, 65t, 55 t, 40 t
Minimum gap, gap_m	None, 20 m, 40 m, 60 m
Lane closure, lc	None, one-lane closure, two-lane closure

Table 1 gives the overall statistical features of the traffic data, where lanes 1 and 8 are the outmost lanes. The average daily traffic volume of the bridge is 26 651 veh/d, and the average truck proportion is 40%. It is shown that traffic volume, truck proportion, and average vehicle speed are mostly the same in the two traveling directions. However, the average vehicle weight and the number of heavy trucks in the eastbound direction are slightly larger than those in the westbound direction. It is noted there are 10 777 heavy trucks over 100 t, which are very significant to bridge loading. The results also reveal that traffic loads over lateral lanes are dramatically different. Heavy trucks tend to travel at lower speed in the outer lanes, and light vehicles mainly travel in the inner lanes at high speed. It complies with the traffic rule of traveling in divided-lane for different vehicle types.

4.3 Traffic microsimulation

Based on the statistical information from site-specific traffic data, eight-lane bidirectional traffic flow is modeled using MSCA. Main parameters defined in the simulation of MSCA are given in Table 2. The simulation road length is 2000 m, and the bridge starts 1000 m far away from the beginning of the road. The cell size is set to be 5 m, and the simulation time step is 0.5 s, which is accurate enough to capture adverse traffic loading on long-span bridges. The unit acceleration and deceleration are evenly sampled from the ranges of 0-1 m/s^2 and 0-2m/s^2 respectively. The random deceleration factor and lane-changing probabilities in MSCA are calibrated as presented in Table 2. The principle of calibration is to make the generated traffic flow

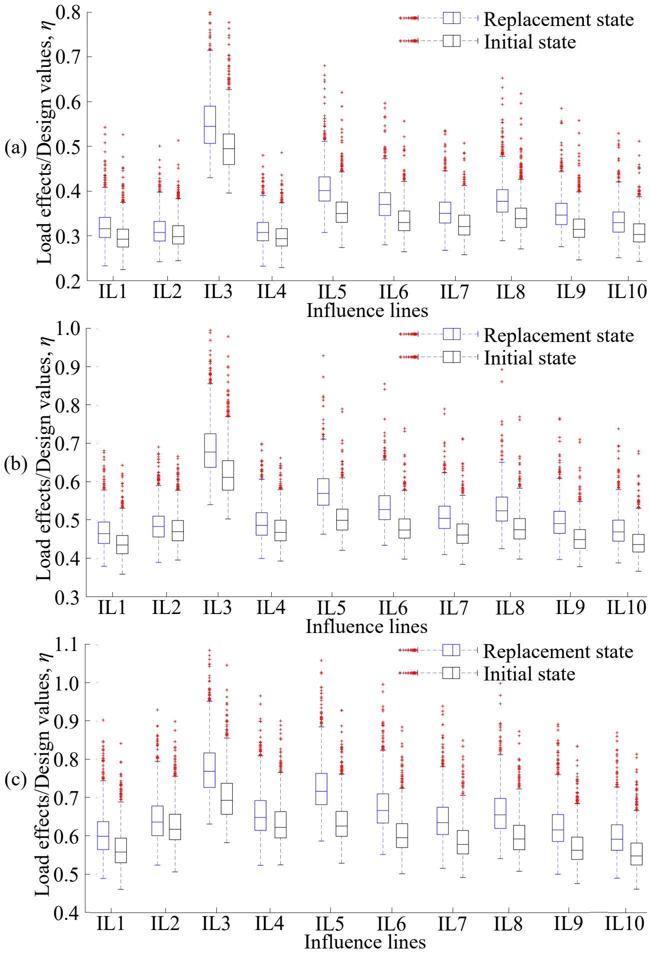

Fig. 5 Comparison of scale factors of daily maximum traffic load effects between initial and replacement bridge states under different daily traffic volumes: (a) 26 651 veh/d, (b) 60 000 veh/d, and (c) 90 000 veh/d

equivalent to the realistic traffic data in statistical level (Ruan *et al*. 2017b).

The average daily traffic volume of the bridge is 26 651 veh/d, which is far from the design level of an eight-lane highway. Hence, traffic conditions with a medium volume of 60 000 veh/d and a high volume of 90 000 veh/d are studied. It is noted the high volume is roughly determined based on highway traffic capacity of a four-lane freeway with a designed speed of 120 km/h and an average truck proportion of 40%. In the modeling of traffic flow with a daily traffic volume higher than the measurement, the statistical models such as vehicle composition are assumed to be the same as those from the measurement. That assumption of constant vehicle composition is conservative as truck proportion generally decreases with traffic volume growth. Traffic simulation on the measurement data is the reference condition, where the daily traffic volume is 26 651 veh/d; the speed limit is 120 km/h; no weight control and no gap control. To investigate the effect of various types of traffic control measures on bridge traffic loading, five kinds of speed limit, i.e., v_m={120 km/h, 100 km/h, 80 km/h, 60 km/h, 40 km/h}, six types of weight limit, i.e., G_m={none, 100 t, 80 t, 65 t, 55 t, 40 t}, four types of minimum gap, i.e., gap_m={none, 20 m, 40 m, 60 m}, and three types of lane closure, i.e., lc={0, 1, 2} are considered. The summary of traffic micro-simulation conditions for the bridge is listed in Table 3. Based on the principle of the control variate method, there are 15 cases for each traffic volume condition and totally 45 cases. On each simulation condition, 1 000-day traffic data is generated and loaded on the 10 bridge ILs with a single traffic control parameter only considered. In the modeling of flow control, the region of lane closure is taken to cover the whole bridge length. The regions of ALC and MLC are shown in Fig. 3, which are taken to be 400 m and 100 m respectively. In the modeling of weight control, if the vehicle is generated with gross weight larger than the weight limit, its gross weight is reset to the limit value. Furthermore, traffic control is only conducted in the traffic direction of cable replacement, and traffic in the other direction is normal as usual.

4.4 Results

Following the numerical procedure in section 2, a scale factor, $\eta = S_r / S_c$, is defined to represent the level of realistic bridge load effects. Where S_r is the realistic load effect induced by traffic flow, S_c is the standard load effect calculated by the traffic load model in the design code, D60 (MOT 2015). In the calculation of S_r for scale factors with and without cable removal, the ILs at the replacement state and initial state are used respectively. However, in the calculation of S_c, the ILs at the initial state should be used.

The scale factors of 1000 daily maximum traffic load effects between initial and replacement bridge states with different daily traffic volumes are compared as shown in Fig. 5 using box plot. The following conclusions could be drawn:

• Load effects of the same IL at the replacement state are all larger than those at the initial state, nearly 1.0~1.2 times in average, which indicates the bridge traffic load effects under cable replacement are more adverse and must be concerned;

• Realistic traffic load effects of various types of IL are all lower than the design values with low traffic volume even regarding outliers. However, when daily traffic volume grows to a medium or high level, there is a significant probability that realistic load effects may be larger than design values as can be seen from outliers exceeding η=1.0;

• The most adverse bridge effects for the cable replacement are the girder bending moment (IL3) and the stayed-cable force (IL5) nearest to the replaced cable. Their load effects are the most significant, and the differences between the replacement state and initial state are also the largest.

It is important to define the criterion that whether traffic control is needed to ensure component replacement. In this paper, the traffic load effect based on design load model is identified as the criterion, which is open to question and will be discussed in the Conclusion section. Nevertheless, if the design level is the criterion, then the return period of traffic loading effects during component replacement should be consistent with that of the design level. The return period of traffic load specified in the Chinese bridge design code-D60 (MOT 2015) is 1 950 years. It is known that the loading effects under traffic control for component replacement occur when replacement is needed. Suppose that the time interval for component replacement is n=20 years and the replacement takes m=5 days each time. There are 4 similar conditions for the replacement of cable C1-1, since the studied bridge is a double-pylon double-cable-plane symmetrical structure and the traffic flow in two directions is the same. The occurrence of traffic loading effects under cable replacement is (4m/n) times each year. Based on Extreme Value Theory, the cumulative distribution function of yearly maximum traffic load effects is

$$F_y(s) = [F(s)]^{4m/n} \tag{3}$$

Where, $F(s)$ is the cumulative distribution function of daily maximum traffic load effects at the cable replacement state.

Since the return period of traffic load specified in the design code is 1 950 years, the characteristic traffic load effects under cable replacement that is equivalent to the design level could be estimated by

$$F_y(s) = [F(s)]^{\frac{4m}{n}} = 1 - 1/T \tag{4}$$

Using Taylor expansion and ignoring second order small quantities, the characteristic traffic load effect could be calculated by

$$S_r^c = F^{-1}\left(1 - \frac{1}{4m(T/n)}\right) \tag{5}$$

Where, T is the return period of traffic load specified in the design code, T=1 950 y for D60; F(.) is the cumulative distribution function of daily maximum traffic load effects at the cable replacement state.

In Extreme Value Theory, if the underlying samples are independent and identically distributed, the limit distribution of local maxima from a given block size could be well approximated by the generalized extreme value (GEV) distribution given by

$$F(x) = \exp\left\{-\left(1 + \xi\frac{x-u}{\sigma}\right)^{-\frac{1}{\xi}}\right\}, 1 + \xi\frac{x-u}{\sigma} > 0 \tag{6}$$

Where, $u, \sigma,$ and ξ are the location, scale, and shape parameters, respectively.

Taking the example of daily traffic load effects under daily traffic volume of 26 651 veh/d at the replacement state, Fig. 6 shows how the characteristic values are derived. The scatter data of daily maximum scale factors are first fitted by GEV models, where the parameters in the GEV model are estimated by the maximum likelihood method. The fitted GEV model is then extended to the

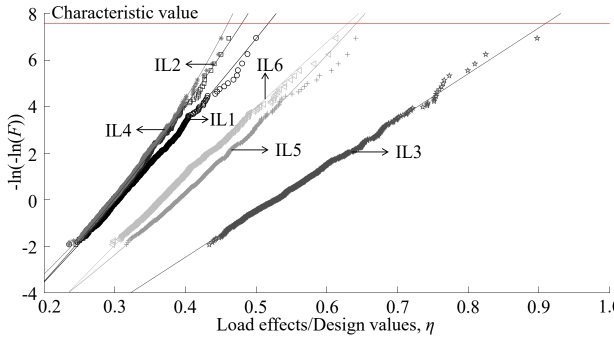

Fig. 6 The scatter data of scale factors, η and their GEV fitting model for various ILs in replacement state: An example of a daily traffic volume of 26 651 veh/d

Table 4 Characteristic scale factors, η_c for various ILs under different traffic conditions in replacement state

IL	Low traffic volume	Medium traffic volume	High traffic volume
IL1	0.52	0.69	0.92
IL2	0.48	0.72	0.94
IL3	0.91	**1.10**	**1.15**
IL4	0.46	0.72	0.96
IL5	0.64	0.85	**1.09**
IL6	0.58	0.78	**1.01**
IL7	0.56	0.75	0.96
IL8	0.63	0.79	0.99
IL9	0.58	0.73	0.94
IL10	0.52	0.70	0.90

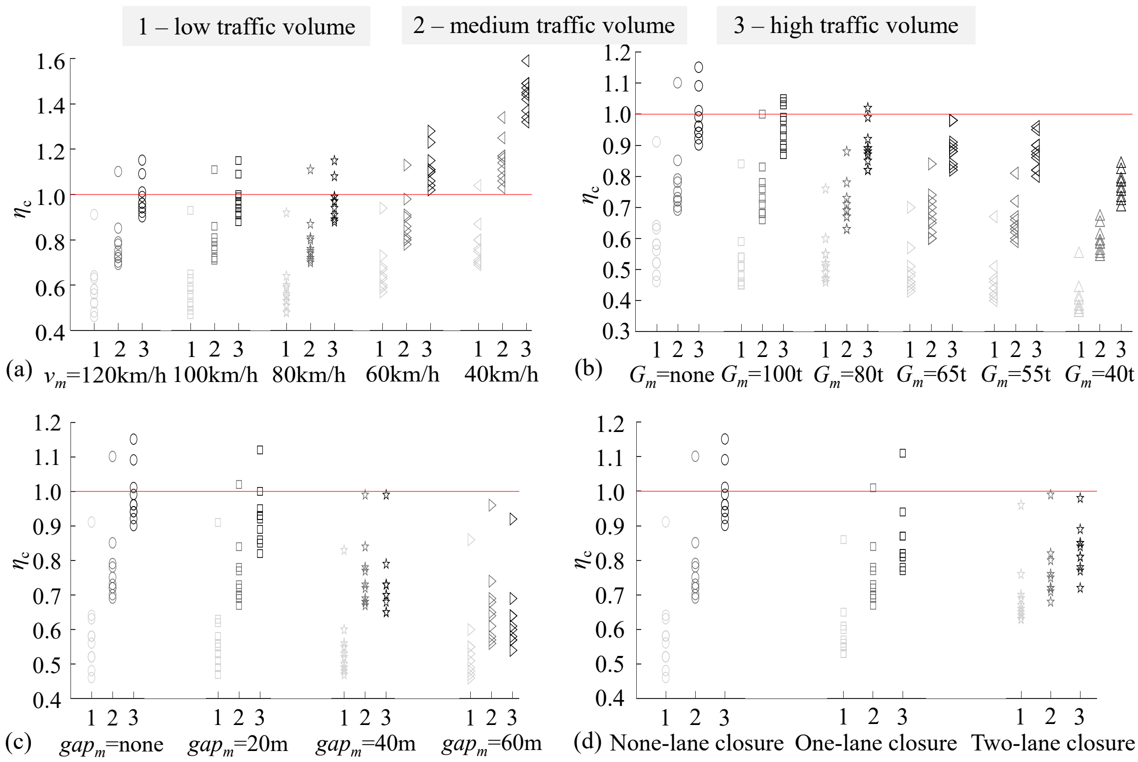

Fig. 7 Effect of traffic control measures on characteristic traffic load effects: (a) speed control; (b) weight control; (c) gap control; and (d) flow control

quantile value specified in Eq. (5), and a characteristic value is gained. It is noted the fitting is confident with calculated R^2 all larger than 0.995.

Table 4 gives the results of the characteristic scale factors, η_c, under different traffic conditions at the replacement state. Results indicate the characteristic scale factors for various ILs in current low volume condition with a daily traffic volume of 26 651 veh/d are all smaller than 1, which means traffic could be maintained without traffic control for cable replacement. Furthermore, the characteristic scale factor of IL3 exceeds 1 when traffic volume grows to a medium level of 60 000 veh/d. This indicates a potential risk of bending failure of the main girder. However, characteristic scale factors of other ILs are still all smaller than 1 ranging from 0.70 to 0.85. Moreover, when daily traffic volume comes to a high level of 90 000 veh/d, the characteristic scale factors of several bridge effects (e.g., IL3, IL 5 and IL6) exceed 1. Obviously, traffic control technologies should be implemented to mitigate the traffic load effects for bridge safety.

4.5 Effects of traffic control measures

4.5.1 Speed control

Speed control is an effective strategy to reduce bridge vibration and thus decrease structural dynamical responses. Speed control is easy to implement since velocities of individual vehicles are automatically displayed to drivers. With speed control, the work of component replacement could be steadily conducted. However, it should be noted from Fig. 7(a) that speed control increases traffic load effects on the bridge. That is because speed control reduces vehicle freedom and thus increases traffic density. Moreover, when the speed limit is over 80 km/h, the characteristic traffic load effects increase slightly. While, when the speed limit is lower than 40 km/h, traffic load effects significantly increased and are all greater than design values under the medium and high traffic volume conditions. It is recommended that the speed limit should be no less than 60 km/h under the low traffic volume condition. However, for medium and high traffic volume conditions, the single use of a speed limit is not recommended since it does not decrease but increase traffic load effects.

4.5.2 Weight control

Weight control directly reduces the loading effects of individual vehicles, and therefore mitigates bridge responses under random traffic flow. Fig. 7(b) gives the effects of weight control on characteristic traffic load effects. It is known that weight restriction reduces traffic load effects, particularly for girder bending moment (IL3). This is because the effective loading length of IL 3 is short. Its load effects are very sensitive to heavy trucks. Furthermore, the degree of reduction of traffic load effects from weight limit of none to 80 t is slight, but becomes apparent when weight limit is from 80 t to 40 t. Overall, a weight limit of 65 t could ensure that traffic load effects of all bridge ILs are below the design level under any traffic volume condition. Consequently, the limit of gross vehicle weight should be no more than 65 t during the component replacement.

4.5.3 Gap control

Gap control is an effective strategy to mitigate traffic load effects since vehicle intensity on the bridge is largely reduced. Fig. 7(c) shows the effects of gap control on characteristic traffic load effects. It is found load effects decrease slightly when the minimum gap is less than 20 m. However, when the minimum gap is greater than 40 m, traffic load effects of all bridge ILs are below the design level. Moreover, the implementation of gap control greatly influences all bridge effects other than girder bending moment (IL3). Again, girder bending moment has short effective loading length and thus is sensitive to heavy trucks. Gap control does not reduce heavy trucks, so it is reasonable. In short, gap control is recommended, and the minimum vehicle gap should be no less than 40 m.

4.5.4 Flow control

Flow control considered in the paper is implemented by lane closure. Fig. 7(d) gives the effects of flow control on characteristic traffic load effects. Results indicate traffic load effects under low traffic volume increase when the number of closed traffic lanes increases. This is because vehicles under low traffic volume condition generally have high speeds, and when reaching the lane closure region, their speeds should be reduced for safe pass-through. Thus, vehicle density on the bridge increases compared to the normal traffic condition without lane closure. Traffic load effects under medium traffic volume are basically the same no matter there is lane closure or not. However, traffic load effects under high traffic volume decrease when the number of closed traffic lanes increases. Because lane closure under high traffic volume reduces the number of vehicles crossing the bridge, the vehicle density on the bridge decreases. Overall, traffic load effects of all bridge ILs are below the design standard under two-lane closure, but this implementation will significantly reduce transportation efficiency.

4.5.5 Feasible strategy

Overall, the sole use of a speed limit does not decrease but increase traffic load effects, and it is not recommended in general condition. Weight restriction significantly decreases bridge load effects, especially for bridge ILs with short loading lengths, and a value of no more than 65 t is recommended. Gap control could limit traffic load effects of bridge ILs with long loading length, but not much effective for bridge ILs with short loading length. Flow control slightly reduces traffic load effects but significantly reduces transportation efficiency. Therefore, it is recommended to employ a weight control with gross vehicle weight no more than 65 t or/and a gap control with minimum vehicle gap no less than 40 m for the cable replacement of the case bridge.

5. Conclusions and discussions

5.1 Conclusions

This paper proposes a numerical procedure to determine traffic control technologies without interruption for component replacement of long-span bridges, which uses modern traffic microsimulation and site-specific data. A case study of cable replacement of a long-span cable-stayed bridge is illustrated. In detail, 3 kinds of daily traffic volume, 5 types of speed limit, 6 levels of weight limit, 4 types of minimum vehicle gap, and 3 kinds of lane closure are modeled to quantify the effect of traffic control technologies on extreme bridge traffic load effects during component replacement and show up the feasible traffic control strategy. Main findings are as follows:

(1) The case study shows traffic load effects on the bridge are all lower than the design values with a current daily traffic volume of 26 651 veh/d. Therefore, cable replacement could be conducted without traffic control. However, when daily traffic volume grows to a medium level of 60 000 veh/d or a high level of 90 000 veh/d, traffic load effects of girder bending moment and cable force which are near to the replaced cable exceed the design level, indicating a potential risk of failure. Traffic control should be implemented to mitigate traffic load effects.

(2) Parametric studies of traffic control technologies on bridge load effects give the quantitative relationship between traffic control measures and the resultant load effects. It contributes to the design of feasible traffic control strategies. Speed control by limiting the maximum velocity does not decrease but increase traffic load effects. Flow control using lane closure reduces load effects inconspicuously but decreases road capacity. However, weight control (by limiting the maximum gross vehicle weight) and gap control (by ensuring a minimum vehicle gap) could efficiently mitigate traffic load effects.

(3) Traffic loading effects under different levels of daily traffic volume should be all less than the design values so that bridge safety could be guaranteed. It is recommended to employ weight control with a gross vehicle weight no more than 65 t or/and gap control with a minimum vehicle gap no less than 40 m for the case bridge.

5.2 Discussions

The criterion of structural safety evaluation under component replacement is crucial to determine the use of traffic control. In the paper, the designed level of bridge traffic load effects is defined as the criterion due to little reference. By doing so, if characteristic traffic load effects during component replacement are below the design level (i.e., characteristic scale factor, η_c<1), the relevant traffic control measure is feasible. Notably, safety reserve during bridge component replacement should not be lower than that of the design level since it is not acceptable to the public that bridge damages during the event of component replacement rather than normal service condition. Consequently, the optimal criterion may be stricter than the used one (design level) in the paper. Whereas a stricter criterion demonstrates the significance of implementing traffic control technologies for bridge component replacement, and the determination of feasible traffic control measures using that criterion follows the same train of thought.

On the other hand, due to the lack of maintenance data, structural degradation is not involved in the case study.

However, provided that there is maintenance data, finite element model of the bridge could be updated, and the ILs of bridge effects could be obtained, and the analysis of traffic load effects and traffic control technologies follows the same train of thought in the case study. With the advance integration of intelligent transportation system and bridge structures, traffic control technologies studied in the paper could not only serve special issues such as component replacement, but also provide technical support for intelligent management of transportation infrastructures during normal service conditions.

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