Bridge damage detection by means of displacement based bridge weigh-in-motion

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Keywords: BWIM, Damage Detection, Displacement, Influence Line

Abstract. In order to develop an efficient and quantitative bridge inspection method using sensors, this study investigates feasibility of bridge damage detection using Bridge Weigh-In-Motion (BWIM) and deflection of the bridge. As deflection influence line changes due to damage in BWIM, a virtual axle is introduced to the vehicle and the process of axle weight identification so that the increase of identified wheel loads due to damage can be distributed to the virtual axle. Bridge damage thus can be detected by examining the wheel load on the virtual axle, which should theoretically be zero if the condition of the bridge has not changed from the reference state. Changes in the wheel load of the virtual axle due to damage in the bridge were observed from a laboratory experiment as well as simulations. The results also indicated that the wheel load of the virtual axle varied depending on the position of the virtual axle and the damage position. Observations demonstrated that the damage identification accuracy by means of the virtual axle can be improved by selecting the appropriate position of the virtual axle.

Introduction

How to efficiently inspect and maintain bridge structures has become a keen technical challenge worldwide. In Japan as an example, around 32% of bridges have reached their design life of 50 years in 2020 [1]. Although Japanese bridge inspection regulates visual inspections once every five years for highway bridges of longer than 2m since 2014, it is unclear whether the visual inspections can continue in this way due to a lack of experts and budgetary restrictions. For this reason, efficient and quantitative bridge inspection methods are needed. Structural health monitoring (SHM) thus has attracted attention as a technique to assist conventional visual inspections.

In monitoring bridges, displacement is an effective physical quantity that can assess changes in the structural performance of the bridge structure, however, a fixed point is required. Meanwhile, with the development of image processing technology and the increasing resolution of digital cameras, it is becoming possible to identify the bridge displacement by video image analysis [2]. Nevertheless, even if the displacement is identified, it is difficult to determine healthy or damage without information on external forces.

This study focuses on utilizing BWIM theory and bridge displacement for bridge damage detection, and aims to investigate the feasibility of a method to detect bridge damage by introducing the virtual axle to the vehicle, which does not exist in the original vehicle, and examining the weight distributed to the virtual axle in the process of identifying the axle weight of the BWIM using bridge displacement. The method using the virtual axle has the advantage that it does not require a driving test with a vehicle of known axle weight to obtain a new influence line, as long as a reference influence line has been obtained.

Damage detection theory in BWIM

When an $\boldsymbol{N}$-axle vehicle runs, the displacement response at the measurement point is expressed as a function of time as a superposition of the responses produced by each axle. The deflection influence line is obtained from the vehicle parameters such as the vehicle speed, the axle spacing, and each known axle weight $\boldsymbol{P_b}$. Using the deflection influence lines obtained here, we define the reference influence line matrix $\boldsymbol{I_b}$ as $\boldsymbol{I_{btk}}$, where $\boldsymbol{I_{btk}}$ denotes the influence line at the time t $(\boldsymbol{1 \leq t \leq K})$ for the $\boldsymbol{k}$th axle$(\boldsymbol{1 \leq k \leq N})$. Assuming no change in the deflection influence line, each axle weight and gross vehicle weight are identified by minimizing the error function $\boldsymbol{E}$ in Eq. 1 [3]. Eq. 1 indicates that the sum of the squares of the residuals of the assumed theoretical values and measured responses, i.e. the derivative by the axle weight is zero [3]. Each axle weight can be obtained in Eq. 2. The vehicle speed and each axle spacing are assumed to be known.

$$E = (\boldsymbol{D}_m - \boldsymbol{I}_b\boldsymbol{P})^T(\boldsymbol{D}_m - \boldsymbol{I}_b\boldsymbol{P}). \tag{1}$$

$$\boldsymbol{P} = \left(\boldsymbol{I}_b{}^T\boldsymbol{I}_b\right)^{-1}\boldsymbol{I}_b{}^T\boldsymbol{D}_m. \tag{2}$$

where $\boldsymbol{D_m}=\{\boldsymbol{D_m(1)},\cdots,\boldsymbol{D_m(K)}\}^{\boldsymbol{T}} \in \mathbb{R}^{\boldsymbol{K\times 1}}$ is the newly measured displacement response when this vehicle crosses the bridge, $\boldsymbol{P}=\{\boldsymbol{P_1},\cdots,\boldsymbol{P_N}\}^{\boldsymbol{T}} \in \mathbb{R}^{\boldsymbol{N\times 1}}$ is the identified axle weight in BWIM.

Problem of Original BWIM. The fundamental assumption of the BWIM theory is that the influence line (here, deflection influence line (DIL)) of the bridge does not change. In other words, it is assumed that $\boldsymbol{I_m} = \boldsymbol{I_b}$, where $\boldsymbol{I_m} \in \mathbb{R}^{\boldsymbol{K\times N}}$ is the deflection influence line obtained from the newly measured displacement response. However, the deflection influence line increases when the bridge stiffness decreases due to damage. The deflection influence line of the damaged bridge is denoted as $\boldsymbol{I_m} = \boldsymbol{I_b} + \Delta\boldsymbol{I}$, where $\Delta\boldsymbol{I}$ is the change in shape of the deflection influence line due to damage. When the BWIM method is applied without considering the change in the deflection influence line (*i.e.* $\boldsymbol{I_m} = \boldsymbol{I_b}$), the identified axle weight $\boldsymbol{P}$ is larger than the real axle weight $\boldsymbol{P_m}$. Thus, when the deflection influence line changes due to damage, the identified axle weight is identified as $\boldsymbol{P_m} + \Delta\boldsymbol{P}$. If the heavily identified axle weight $\Delta\boldsymbol{P}$ can be extracted somehow, it indicates the increase in the deflection influence line of the bridge due to damage. In order to

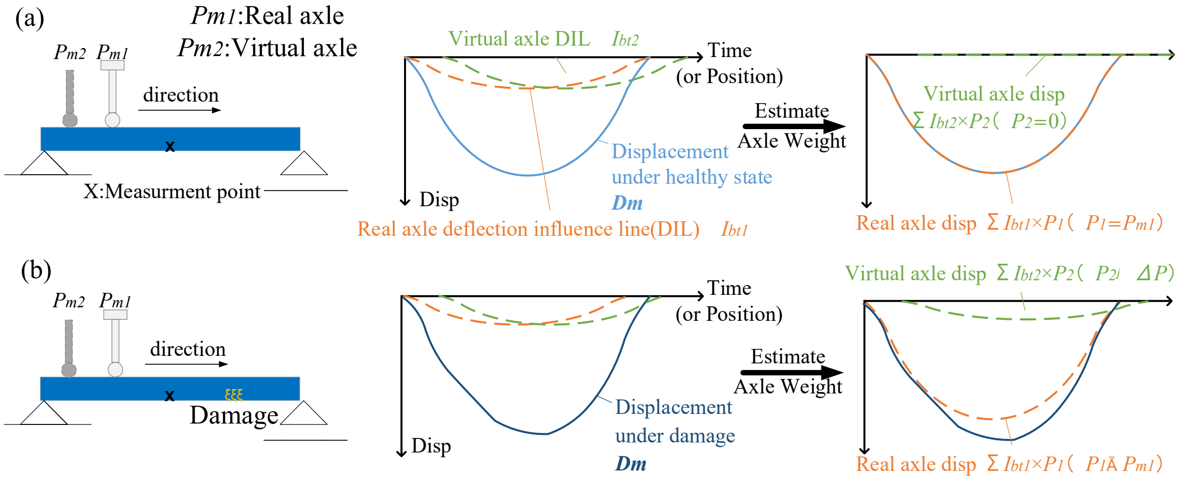


Fig. 1 Concept of virtual axle in BWIM

extract the heavily identified axle weight, the change in the influence line due to damage is identified as the weight of the virtual axle by adding the influence line of the virtual axle to the matrix $\boldsymbol{I_b}$ as shown in Eq. 3. This study investigates the possibility of damage detection based on this value of the virtual axle. Cantero et al. (2015) showed the weight of the virtual axle is calculated as 0kN theoretically if there have been no changes in the influence line [4].

$$\begin{bmatrix} I_{b11} & \cdots & I_{b1N} \\ \vdots & \ddots & \vdots \\ I_{bK1} & \cdots & I_{bKN} \end{bmatrix} \in \mathbb{R}^{K\times N} \rightarrow \begin{bmatrix} I_{b11} & \cdots & I_{b1N} & I_{b1N+1} \\ \vdots & \ddots & \vdots & \vdots \\ I_{bK1} & \cdots & I_{bKN} & I_{bKN+1} \end{bmatrix} \in \mathbb{R}^{K\times(N+1)}. \tag{3}$$

where $\boldsymbol{I_{bKN+1}}$ denotes the influence line for a virtual axle.

Concept of Virtual Axle. To simplify the explanation, assuming that a single axle vehicle including the virtual axle with known axle spacing passes through a bridge. When the virtual axle is placed behind the real axle, the influence line of the virtual axle is placed later on the time axis than the real axle, as shown in Fig. 1(a). When the virtual axle is placed forward, the influence line of the virtual axle is placed earlier on the time axis. In a healthy condition, when BWIM method is applied, the axle weight is distributed to the real axle and a value of almost zero is distributed to the virtual axle. However, in the damaged condition, as shown in Fig. 1(b), the damage is distributed to the influence line of the virtual axle. As described above, this study focuses on the fact that, in the process of axle weight identification in BWIM, the difference between the reference deflection influence line and the damaged deflection influence line is calculated as the weight of the virtual axle by introducing the virtual axle into the identification system matrix. Note that the real axle weight and the newly deflection influence line are essentially unknown, and only the measured displacement identifies each axle weight including the virtual axle.

Laboratory experiment

A moving vehicle experiment on a model bridge is conducted to verify validity of the damage detection by means of the BWIM method. The model bridge is a simply supported beam with span length of 5.4m, and width of 303mm, as shown in Fig. 2(a). The entrance side is pin-supported and the exit side is roller-supported. We introduced artificial damage into the model bridge. The

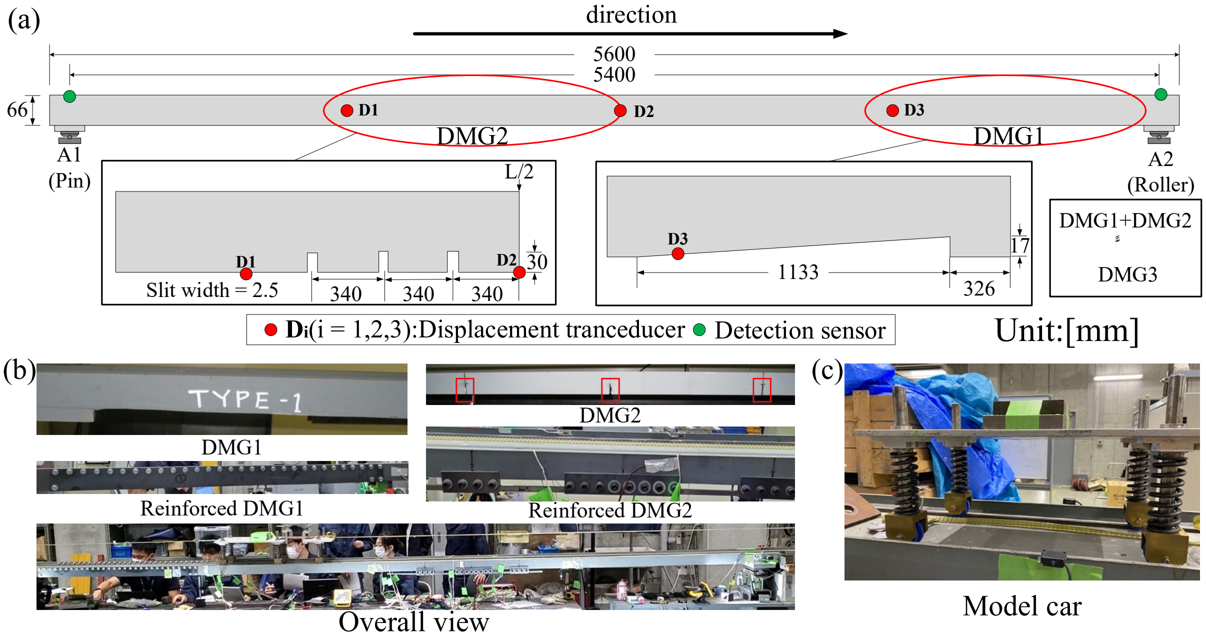
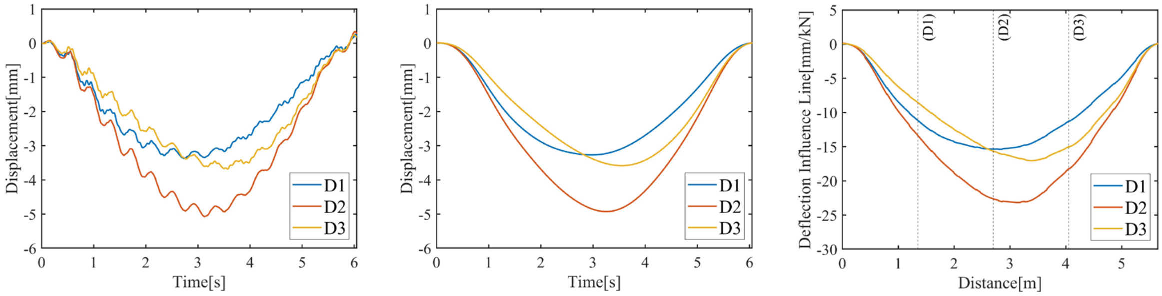


Fig. 2 Schematic diagram and photos of the model bridge and car.

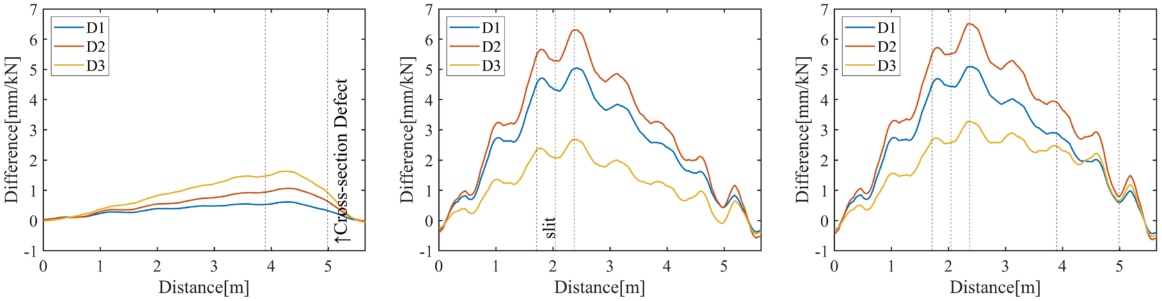
reinforced damaged section is regarded as the healthy condition (INT). The considered damage scenarios are shown in Fig. 2: DMG1 scenario models a local reduction in stiffness at the girder end near the exit support, DMG2 scenario models damage near the span center and DMG3 scenario considers both DMG1 and DMG2 scenarios. In DMG1 and DMG2, the damage areas other than the target damage area were reinforced by steel plates as shown in Fig. 2(b). For the moving vehicle experiment, a two-axle vehicle was used. Total weight of the vehicle was 0.215kN (0.107kN for both front and rear axles), and the axle spacing was 0.4m. The vehicle speed during the experiment was set to a constant velocity of 1.0497 m/s. Three measurement points (D1, D2, and D3) at quarter, center and three quarter span are considered. Laser sensors were installed at the entrance and exit to detect the entry and exit of vehicles. The sampling frequency was 200Hz. In each scenario (INT, DMG1, DMG2, and DMG3), the displacement for 10 times in a constant travel direction was measured. In the moving vehicle experiment, we applied a low-pass filter at 1Hz as a pre-processing step to smooth the displacement data to the extent that the waveform shape is not disturbed. The displacement responses from the sensors at the entrance and exit are measured and averaged. The measured and filtered displacement response at each measurement point for each scenario (INT, DMG1, DMG2, and DMG3) are shown in Figs. 3(a) and (b). The deflection influence line calculated at each measurement point of the model bridge is shown in Fig. 3(c).

Result. Fig. 4 shows the difference in the deflection influence lines for each scenario. The deflection influence lines at the measurement points near the damage show more significant changes with damage than at the other measurement points. Fig. 4 also shows that the effect of damage on the overall shape of the deflection influence line is greater when the damage is located near the center of the bridge than when the damage is located near the edges. Therefore, it is useful for estimating the position of the damage when a difference in trend can be identified, such that



(a) Original displacement (b) Filtered displacement (c) Influence line

Fig.3 Displacement responses and deflection influence lines.



(a) INT-DMG1 (b) INT-DMG2 (c) INT-DMG3

Fig. 4 Difference of deflection influence lines for each scenario.

Table 1 Axle weight estimation results using model bridge displacements
(True value: 0.107kN for both front and rear axles)

	INT		DMG1		DMG2		DMG3	
axle[kN]	front	rear	front	rear	front	rear	front	rear
D1	0.108	0.106	0.103	0.119	0.153	0.119	0.147	0.127
D2	0.107	0.107	0.101	0.122	0.164	0.098	0.156	0.110
D3	0.106	0.108	0.099	0.133	0.147	0.093	0.136	0.116

the weight of the virtual axle identified using the displacement at specific measurement point is more distributed than at other measurement points. In order to confirm the accuracy of the calculated deflection influence lines and the changes in the axle identification results due to damage, we identified each axle weight using the displacement responses at each measurement point in each scenario of the experiment with the reference deflection influence lines. The displacement responses for the INT condition were newly measured under the same conditions as the displacement responses for which the reference deflection influence lines were calculated. The identification results are presented in Table 1. We identified each axle weight with errors within ±1.1% at each measurement point in the INT condition. However, the error of the identified axle weights gets larger at each measurement point in the DMG condition and is particularly large at measurement points near the damage. This result also shows that the error also increases when the damage is spread over several positions.

Feasibility study

Using the theory described in the previous section, this study applied BWIM including the virtual axle to investigate the possibility of damage detection focusing on the values distributed to the virtual axle.

Simulation of Single Axle Vehicle and Virtual Axle Weight. In order to reduce errors caused by multiple axles and to clarify the effect of the damage on the virtual axle weight, this study considers a single axle vehicle where the noise and the dynamic effects have been neglected. A numerical simulation of a coupled vehicle-bridge interaction system is carried out to analyze the traffic vibration with a single axle vehicle [5].

A bridge and vehicle in the simulation are shown in Fig. 5. The virtual axle is placed in sequence within a range of -5.4m to 5.4m forward and backward from the real axle. In order to investigate how the damage position and the position of the virtual axle affect identification of the virtual axle weight, the simulation considered the local damage near the measurement points, which reflected the effects of the damage. A total of four scenarios were investigated: without damage (INT), with

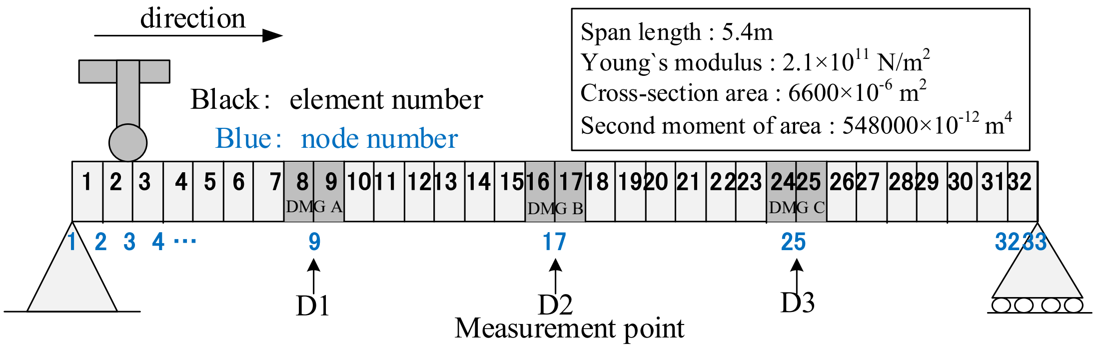
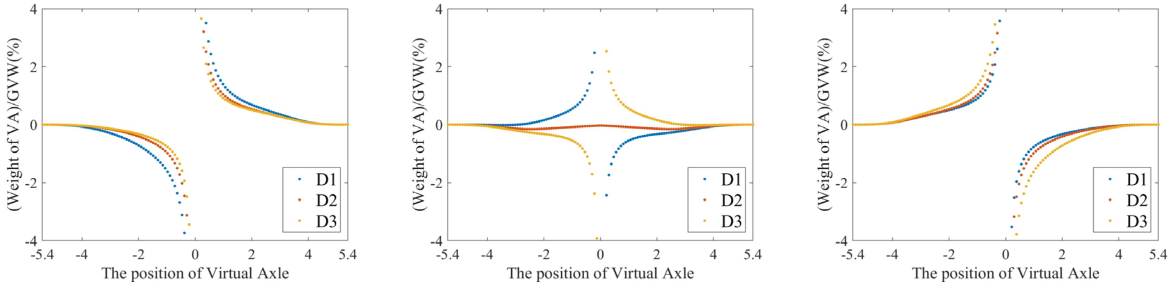


Fig.5 Bridge and vehicle models for simulation.

damage at quarter span near D1 (DMG A), with damage at half span near D2 (DMG B), and with damage at the three quarters span near D3 (DMG C). Damage scenarios simulated damage by reducing the bending stiffness of the specified element, assuming a reduction in stiffness due to corrosion or other damage.

The relationship between the position of the virtual axle and the identified virtual axle weight are shown in Fig. 6. The horizontal axis represents the position of the virtual axle (distance from the real axle) and the vertical axis represents the relative magnitude as a percentage of gross vehicle weight (GVW). A negative distance means that the virtual axle is placed behind the real axle. A positive distance means that the virtual axle is placed in front of the real axle. It should be noted that when the virtual axle is placed in front of the vehicle, the virtual axle weight showed a positive value when the damage is near the entrance (DMG A), whereas it showed a negative value when the damage is near the exit (DMG C). In contrast, the positive and negative values of the virtual axle weight are reversed when the virtual axle is placed at the behind of the vehicle. However, the



(a)DMG A (b) DMG B (c) DMG C

Fig. 6 Relationship between gross vehicle weight (GVW) and position of the virtual axle at each measurement point.

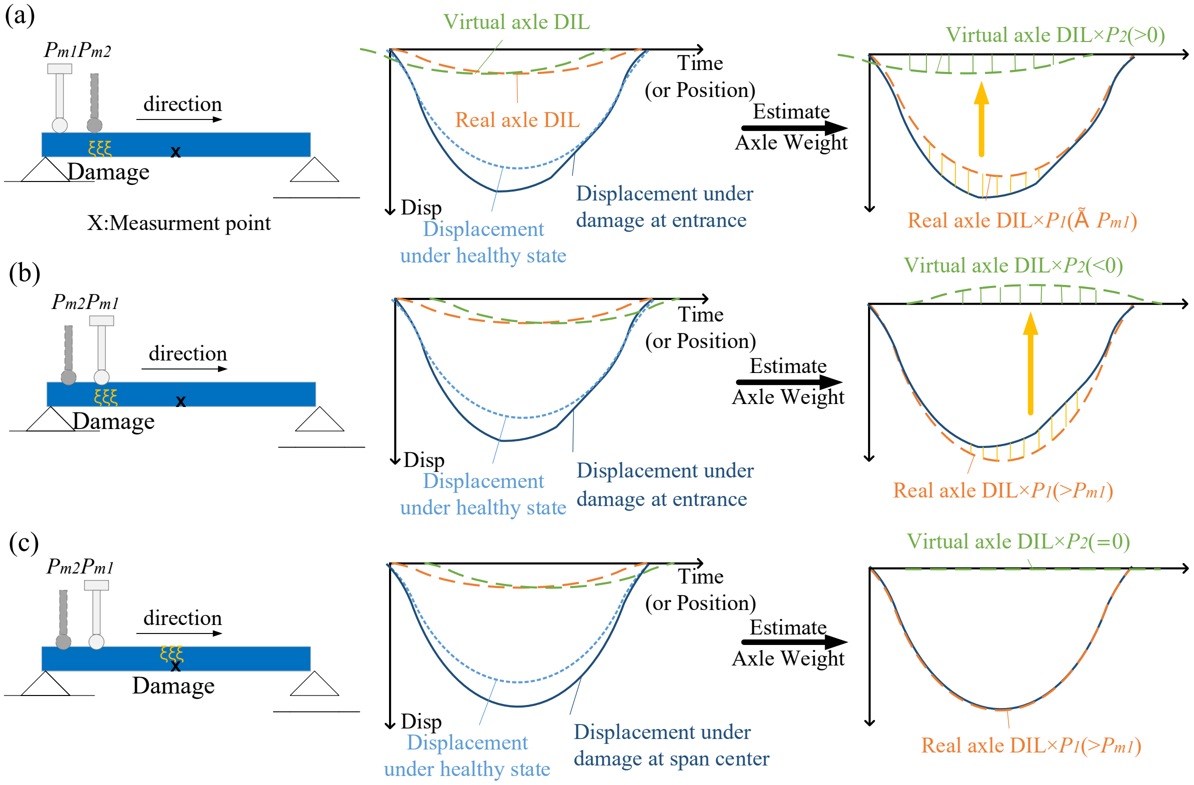


Fig. 7 Relationship between damage position and axle weight distribution.

virtual axle weight was less distributed for damage near the center (DMG B) than for other damage scenarios.

Relationship Between Damage Position and Virtual Axle Weight. This section discusses the relationship between the damage position and the virtual axle weight under different position of the virtual axle.

As shown in Fig. 7(a), when the virtual axle is placed in front of the vehicle (influence lines are placed earlier on the time axis), the virtual axle weight is identified as a positive value because the location where the displacement response changes due to damage is similar to the location of the deflection influence lines of the virtual axle. In contrast, when the virtual axle is placed behind the vehicle (placed later on the time axis), as shown in Fig. 7(b), the virtual axle weight is identified as a negative value because the displacement response changes due to damage are largely distributed to the real axle. The reason why the weight of the virtual axle is identified near 0kN in the central damage is that, as shown in Fig. 7(c), the damage at the span center greatly affects the overall shape of the displacement response. Therefore, the damage is distributed to the real axle, and not distributed to the virtual axle. Therefore, in damage detection using the identified virtual axle weight, the virtual axle should be placed in front of the vehicle when the damage is on the entrance side. On the other hand, the virtual axle should be placed behind the vehicle when the damage is on the exit side. In the next section, an optimal position of the virtual axle is examined so that changes in deflection of the bridge due to damage are well reflected to the virtual axle weight.

Optimal Position of Virtual Axle. Based on the discussion on relationship between damage position and virtual axle weight in the previous section, the optimal position of the virtual axle is investigated so as to provide a positive virtual weight due to damage. For this investigation experimental displacement responses are considered. Vehicle axle weights are identified by means of the BWIM method while changing the position of the virtual axle. We define the optimal position of the virtual axle as the position where the difference of the estimated GVW with virtual axle and without virtual axle is maximized. In each scenario, the virtual axle is placed in sequence within a range of -5.8m to 5.4m forward and backward from the real front axle, and the axle weights are identified.

The results are summarized in Table 2. In INT scenario, the weight of the virtual axle was identified as a maximum of 0.0002kN. Each axle weight was identified within a maximum error of ±0.1%. The reason why the virtual axle weight is not identified as the true value of 0kN is numerical errors in the process of solving the inverse problem. This study considers a pseudo-inverse matrix to solve the inverse problem, where the $\mathbb{R}^{K\times N}$ matrix changes to $\mathbb{R}^{K\times(N+1)}$ by

Table 2 Axle weight estimation results using model bridge displacements with virtual axle (True value: 0.107kN for both front and rear axles; optimal represents the optimal position of the virtual axle[m])

	INT				DMG1			
axle[kN]	front	rear	**virtual**	*optimal*	front	rear	**virtual**	*optimal*
D1	0.105	0.109	**0.000**	*-2.47*	0.103	0.118	**0.002**	*-2.18*
D2	0.104	0.110	**0.000**	*-2.30*	0.095	0.127	**0.001**	*2.61*
D3	0.103	0.111	**0.000**	*2.95*	0.094	0.138	**0.001**	*3.24*
	DMG2				DMG3			
axle[kN]	front	rear	**virtual**	*optimal*	front	rear	**virtual**	*optimal*
D1	0.144	0.125	**0.003**	*0.71*	0.140	0.133	**0.002**	*0.82*
D2	0.148	0.109	**0.006**	*0.88*	0.143	0.120	**0.004**	*1.11*
D3	0.129	0.106	**0.006**	*1.17*	0.123	0.127	**0.004**	*1.52*

adding the deflection influence line of the virtual axle to the reference influence line matrix (see Eq. 3).

It is observed that compared to the INT condition, the proportion of the total distribution to the virtual axle weight increased at the measurement points due to damage and the identified virtual axle weight showed positive value. In addition, the virtual axle weight in damaged condition showed a different trend at each measurement point. In the damage scenario considering damage near the exit (DMG1), for each measurement point (see Fig. 2), the measurement point (D1) located far from the damage identified the highest positive value on the virtual axle weight. However, it can be seen that damage near the girder ends does not significantly affect the displacements and has little effect on the virtual axle weight. In the damage scenario considering damage between the quarter and the span center (DMG2), the measurement point (D3) located far from the damage identified the highest positive value on the virtual axle weight. Similar to the simulation considered in the previous section, optimal position of virtual axle for each measurement point was located in the forward from the vehicle. However, there was no improvement in accuracy in multiple damages scenario (DMG3).

Conclusions

This paper investigates feasibility of damage detection of bridges utilizing displacement responses, BWIM and the virtual axle. The increase in virtual axle weight is adopted as damage indicator. A laboratory moving vehicle experiment on a bridge and simulation on vehicle-bridge interaction are carried out for the feasibility investigation. Increases of deflection influence lines and identified axle weights due to damage in the bridge were observed in both simulation and experiment. It is observed that when damage occurs at the bridge, the virtual axle weight varied from the healthy condition. However, the identified virtual axle weights were found to be positive or negative, depending on the position of the virtual axle and the position of the damage. Therefore the optimal position of the virtual axle was examined, and it shows that the virtual axle weight is identified as the highest positive value at measurement points far from the damage. In other words, it shows a possibility of damage identification and damage location identification using the weight and location of the virtual axle.

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