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Research Paper

Numerical Analysis of Wheel Forces of a KTX Vehicle on a PSC Box Bridge

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ABSTRACT:*A dynamic numerical analysis of the wheel forces of a Korea Train eXpress(KTX) vehicle was conducted to compare the differences of wheel force (DWF) and wheel force rate (WFR) of the train while travelling on the ground and on the pre-stressed concrete (PSC) box bridge at high running speeds of 100 km/h to 500 km/h. The numerical finite element method with fourth-order Runge−Kutta was used to analyze the wheel forces by considering a 38 degree-of-freedom vehicle model and irregular surface roughness rails. The proposed evaluation method indices, DWF, and WFR, are recommended as traffic safety criteria for PSC train bridges.*

Keywords:*DWF, High-speed train, PSC box bridge, Traffic safety of bridge, WFR*

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I. INTRODUCTION

The PSC box bridge is a typical bridge type on the KTX railway system. The PSC box bridge was established as the most suitable bridge type for the railway system through trial and error, which incurred economic losses due to the failure to consider the stability required for a high-speed railway bridge at the onset of the design stage of the project. The results of the procedure have been reflected upon in “The study of stability and dynamic design criteria for railway bridge” by the Korea Railroad Research Institute, and the “Ho-Nam high speed railway design code (2007)” by the Korea Railway. Recently, various studies have investigated this topic in depth, such as “The next generation high-speed rail project”, which focused on developing a numerical model of interaction between the bridge and the train; “The infrastructure R&D”, which suggested a monitoring system of the train bridge to measure displacement and dynamic amplitude ratio [1]. In Europe, relevant research has been conducted, including “The dynamic behavior limit criteria of train bridge”, UIC 776-3R, UIC 779-8R, and Eurocode. Further, in Japan, the pertinent research included “The amendment design standard including the impact factor for running speed (2002)” and “The bridge limit displacement of stability and serviceability for train running speed (2006)”.

Infrastructure codes are limited to evaluating the operational safety of the train bridge and must put forward more suitable criteria. The traffic safety and serviceability of the train bridge are determined by a direct method based on the response of the vehicle in accordance with existing national codes. This practice is required to combine the vehicle mechanics and bridge technology. In commercial programs for the train bridge, the bridge responses that are predicted by the moving of idealized train loads are integrated with vehicle, track, and bridge behaviors. This led to the development of an improved numerical model that considers integrated interaction forces between the train and the bridge, by local and foreign researchers such as Park [2], Kim [3], Sim [4], Dinh [5], and Xia [6,7].Korea is successfully operating the KTX at a speed of 300 km/h and developing the high-speed electric multiple unit 430 km/h experimental (HEMU-430X), which is on track to become the next-generation high-speed train at a test speed of 428 km/h. The higher speeds of the next-generation train induced the development of relevant technology to equip most of the existing infrastructure for utilization with this next-generation train system. Traffic safety and serviceability for the higher speeds need to be studied, with a focus on intensive research to develop suitable upgrade standards.

For this study, a simply supported PSC box train bridge with a 40 m span length was selected for the analysis at higher speeds. An approach track on the ground of length 170 m was combined with the bridge; further, a 38 degree-of-freedom KTX vehicle model and a track with irregular power spectral density (PSD) were considered. To solve the equations of motion for the train–bridge system, the magnitude of interacting forces at the end of each time interval were determined. For the 38 degree-of-freedom model, which includes the masses of a train car, two bogies, and four axles, the integrating force between a given axle, track, and the irregular surface on the bridge is a function of the stiffness and deformation of its suspension spring assembly. The displacement, velocity, and acceleration of each axle serve as the initial conditions for the subsequent step. With the direct integration method, the coupled equations of motion between the train and bridge were solved using the Runge–Kutta method [8,9,10,11].

Dynamic numerical analysis of the wheel forces of the KTX vehicle was conducted to compare the new indices: differences of wheel force (DWF) and wheel force rate (WFR) of the vehicle on the ground and on the bridge tracks, at high running speeds of up to 500 km/h, in 10 km/h increments. The new traffic safety criteria for train bridges should incorporate these indices to complement the existing criteria (vertical deflection, acceleration, end rotation, and vertical profile).

II. TRAFFIC SAFETY OF THE BRIDGE

All the limitations of the traffic safety of the selected train bridge chosen from among the Gyungbu Express railway are revealed by the numerical analysis using interaction between bridge and train within a running speed range of up to 500 km/h. These limitations satisfy the existing traffic safety criteria of the PSC box bridge, which are too conservative to have been exposed by its operations in the past. The simply supported bridge span length of 40 m among the Gyungbu Express railway was chosen to be analyzed due to the critical behavior generated by the train action. The bridge was designed to satisfy the conservative existing criteria: deck deflection limit of under 23.5 mm, deflection acceleration below 0.35 g, bridge deck end rotation restrained within 0.5×10^{-3} radian, and vertical profile of deck of 1.2 mm by 3 m.

2.1 Dynamic amplification factor of the PSC box train bridge

The maximum deflection of the PSC bridge, 8 mm at a running speed of 430 km/h, was satisfied under 23.5 mm using dynamic analysis. The dynamic/static deflection ratio of the bridge (dynamic amplification factor, DAF) in relation to the running speed, is presented in Figure 1, as analyzed using the third-order regression equation [12]. The maximum factor DAF are predicted by 2.13 within the analyzed running speed range.

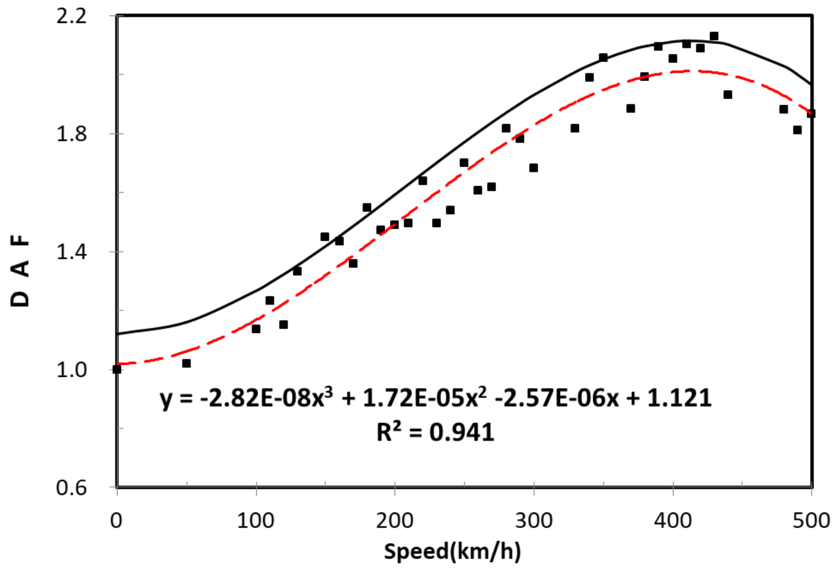


Figure1:DAF of PSC box bridge in relation to the running speed

2.2 Difference of wheel forces on the bridge

The difference between maximum and minimum wheel forces among four wheels of the front bogie of the KTX locomotive running on the PSC bridge, as well as the average of the four front wheel forces, the coefficient variation (%), and the ratio of the standard deviation of the mean value (CV), are shown in Figure 2. The DWF, in relation to the running speed, was interpreted using the third order of regression (1) as a statistical model with R^2 of 93.8%:

$$DWF = -2.0825E\text{-}07\, x^3 + 1.44428E\text{-}04\, x^2 - 1.19047E\text{-}02\, x \quad (1)$$

where x is the running speed of the KTX vehicle (km/h)

The trend of DWF is similar to that of DAF, but the peak value of DWF is observed at a speed of 380 km/h. The DWF on the bridge overcomes the average DWF of 2.65 tonf started from the running speed of 250 km/h, as well as the CV value between the wheel forces at the front bogie, which also increases significantly at the same speed range.

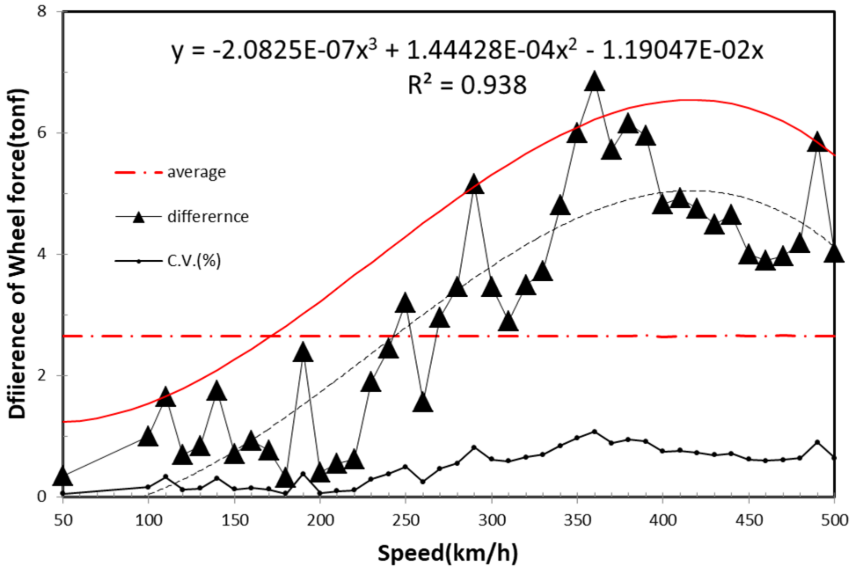


Figure2: Difference of wheel force

In the interpretation range (50 km/h~500 km/h):

(1) The mean value of the wheel forces of the KTX locomotive on the PSC bridge was interpreted as 2.65 tonf and remains constant in spite of increase in the running speed.
(2) The DWF value in relation to the running speed overcomes the mean value of the wheel forces, 2.65 tonf at a 250 km/h running speed. Additionally, the CV value of each running speed is shown to be over 0.50% at this speed.
(3) At the critical speed range of over 250 km/h, the DWF is greater than twice the mean value, even though the traffic operation safety criteria are satisfied as per the existing Korean national standard.
(4) The maximum DWF of 6.85 tonf at a running speed of 360 km/h is significant in its range, from comparisons with the other DWF.
(5) The limitations for traffic operation safety at the critical speed of 360 km/h records some atypical values, but these all fall within the allowable limits. Maximum deflection is 8.13 mm, with an allowable limit of 23.5 mm and acceleration is 1.875 mm/sec^2, which translates to 0.181 g with a limit of 0.35 g.
(6) The modifying regression DWF (2), which is higher than DWF (1) by 1.5, is shown to be more reliable for satisfying traffic operation safety criteria by the R^2 of 74.8% shown in Figure 3.

$DWFm = -2.0825E\text{-}07\, x^3 + 1.44428E\text{-}04\, x^2 - 1.19047E\text{-}02\, x + 1.5$ (2)

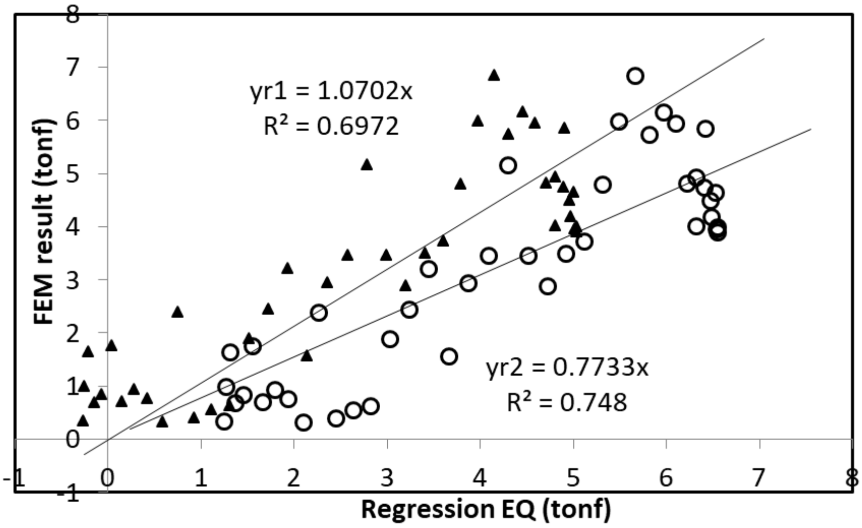


Figure 3: Comparison of regression equation 1 and 2

2.3 Wheel force rate on the bridge

The four-wheel forces of the front bogie on the PSC box train bridge at each running speed, using dynamic analysis are presented in Figure 4. The front-bogie wheel forces of the KTX vehicle were evaluated more critically than the back-bogie wheel forces because of the maximum pitching rotation which occurs at the entrance of the bridge. The mean value is −2.65 tonf at all running speeds analyzed, while the maximum difference is −6.85 tonf at a running speed of 360 km/h. The negative value indicates the gravitational direction.

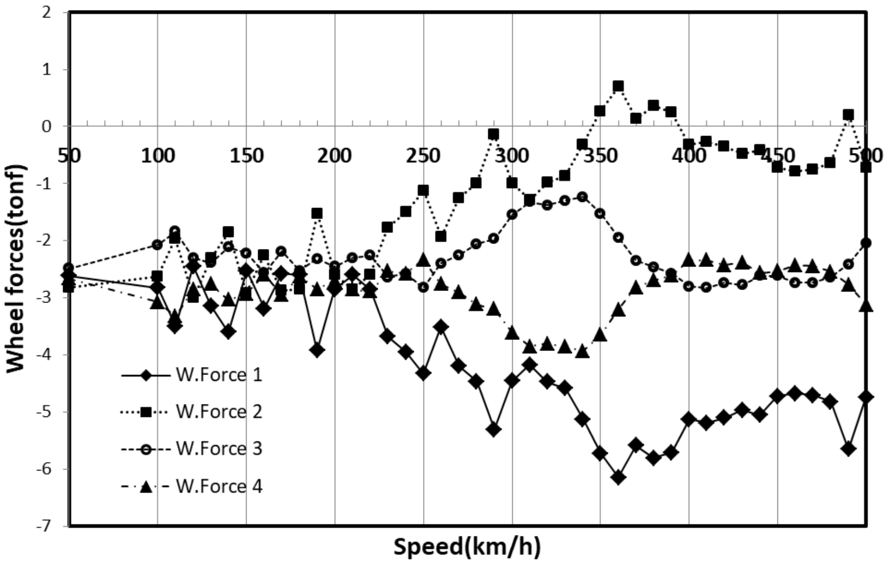


Figure 4: Wheel Forces on the bridge

To calculate wheel force effect, the wheel force rate is defined as the following equation:

WFR = (interpreted wheel force/average value) (3)

The cumulative WFR on the bridge is described in Figure 5. The maximum cumulative WFRs were calculated as 3.066 at a running speed of 350 km/h, which is higher than 3.057 at a maximum DWF speed of 360 km/h, as well as 1.843 at a maximum DAF speed of 430 km/h. Therefore, the wheel force indices of the train, DWF, and WFD, indicate that the critical running speed is between 350 km/h and 360 km/h, despite the bridge dynamic maximum displacement speed being 430 km/h.

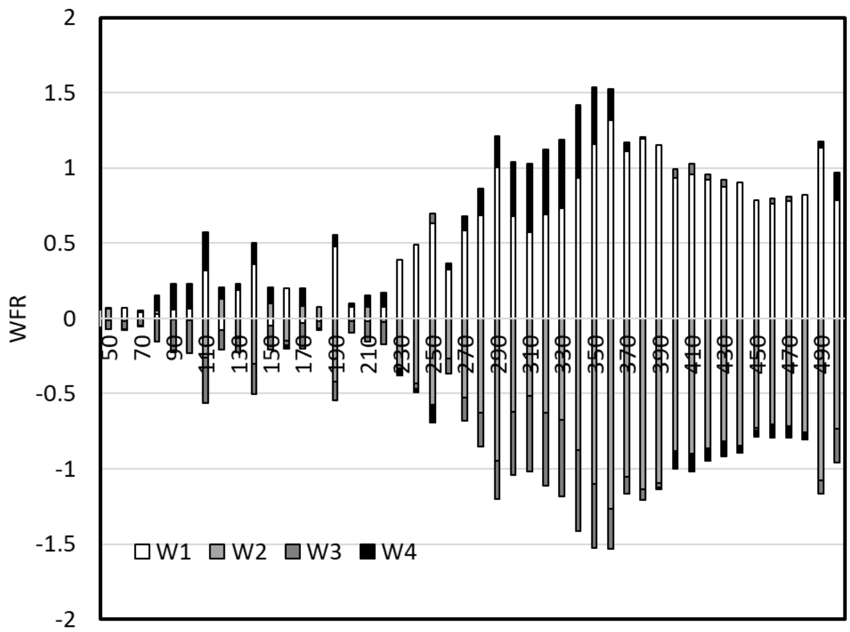


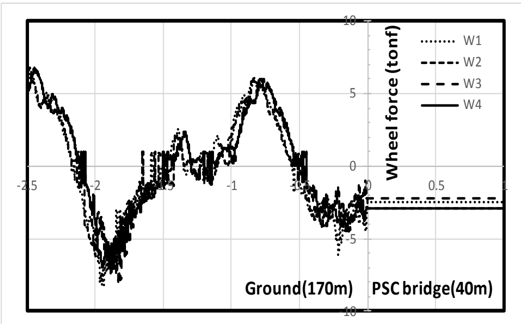
Figure 5: Cumulative Wheel Force Rate on the bridge

III. WHEEL FORCES ON THE GROUND AND THE BRIDGE

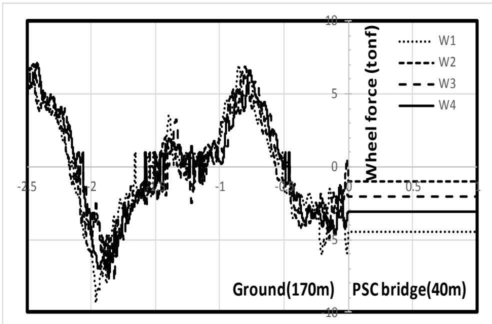
The wheel forces of the KTX vehicle on the bridge are constant along the PSC bridge with a mean value of 2.65 tonf, while on the ground it was observed to fluctuate between 7.36 tonf and -9.61 tonf, which is a significantly wide range. On the other hand, DWF on the bridge was observed to be higher than the wheel forces. Rising as high as 6.85tonf at a running speed of 360 km/h. DWF on the ground was independent of the running speed.

3.1 Wheel forces on the ground and the bridge

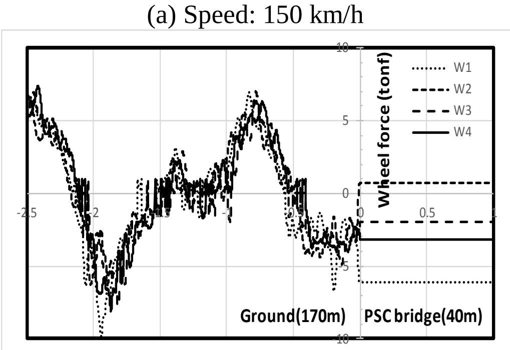
The four front wheel forces of the KTX locomotive are interpreted using a 38 degree-of-freedom model divided car body, two bogies, and four wheel-axles. As dynamic properties, the mass of the car body, primary sprung mass per bogie and unstrung mass per axle, are 54.96, 2.42 and 2.05 tonf respectively. To compare the analyzed results at various running speeds, of up to 500 km/h in increments of 10 km/h, the passing time through the bridge span length of 40 m makes to nominate 1 on the x range. The results for the four typical running speeds are presented in relation to the regular speeds of up to 200 km/h, high speeds of up to 300 km/h, and the next generation KTX speeds of up to 500 km/h, in Figure 6.



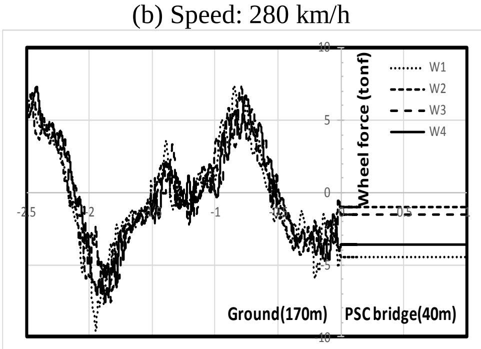
(a) Speed: 150 km/h



(b) Speed: 280 km/h



(c) Speed: 360 km/h



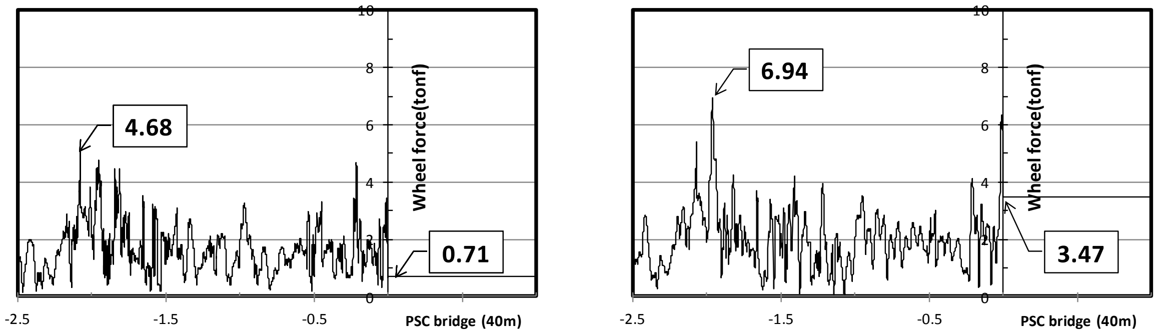
(d) Speed: 490 km/h

Figure 6: Wheel Forces of train

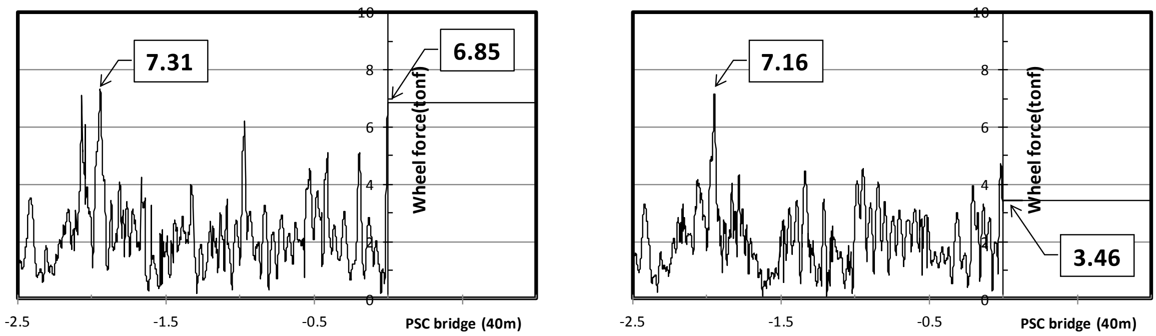
All the wheel forces of the KTX vehicle on the ground are shown as similar trend with their corresponding running speeds, while the difference of those between maximum and minimum value is extended significantly along the increasing speed as presented earlier in Figure 4. Track on the ground in the dynamic analysis did not allow vertical deflection (invalidated flexible ballast behavior) but considered the irregularity of rail surface against spectrum constants according to FRA Track Class using the PSD function. Therefore, the wheel forces of the KTX vehicle on the ground are interpreted as a typical steady trend which fluctuates continuously. The attenuation response of each wheel force as a result of the absorption of running energy which occurs simultaneously led that regular DWF of the wheel forces watched.

3.2 DWF of KTX vehicle on the ground and bridge

In the wheel force spectrum of the KTX vehicle on the ground, at a running speed of 360 km/h which was the observed the maximum DWF (ref. to Figure 2), the maximum wheel force changed from 7.35 tonf to -5.62 tonf. Also, the minimum wheel force varied from 5.77 tonf to -9.80 tonf in parallel. This variance is responsible for the large gap between the maximum and the minimum wheel forces as seen in Figure 7. Evaluations revealed it to be typical and independent of the various running speeds.



(a) Speed: 150 km/h (b) Speed: 280 km/h

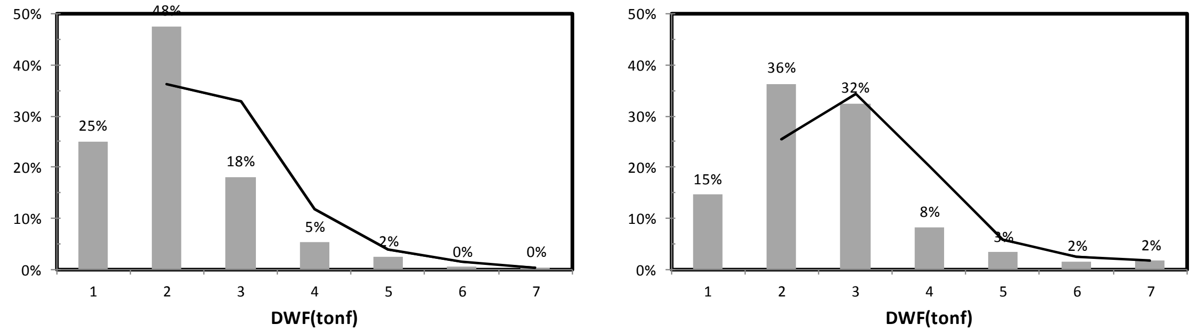


(c) Speed: 360 km/h (d) Speed: 490 km/h

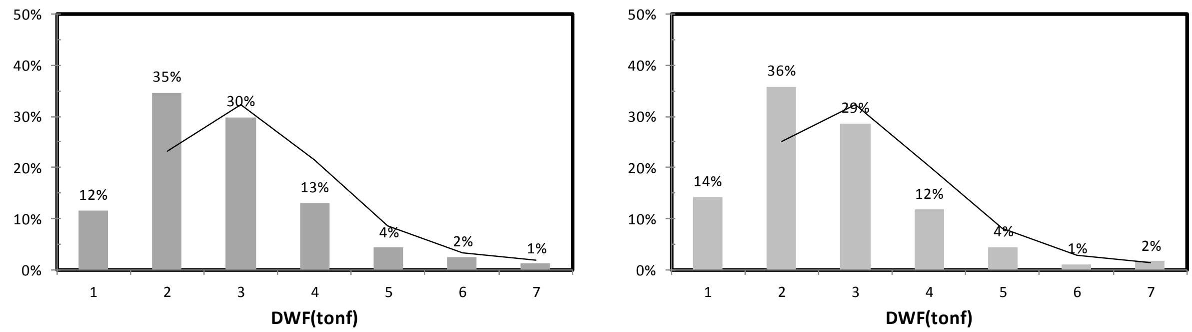
Figure 7: Difference between maximum and minimum wheel forces

The maximum difference in the wheel force spectrum of the KTX vehicle on the ground at the four typical running speeds are 4.68, 6.94, 7.31 and 7.16 respectively. The peak values were independent of the running speed, and the attenuation of the spectrum trend showed a similar pattern.

3.3 Histogram of DWF of KTX vehicle on the ground



(a) Speed: 150 km/h (b) Speed: 280 km/h



(c) Speed: 360 km/h (d) Speed: 490 km/h

Figure 8: Histogram of DWF on the ground

The histogram in Figure 8 shows an accurate representation of the symmetric and unimodal distribution of DWF on the ground. The patterns in the unimodal histogram are observed skewed right at a running speed of 150 km/h and become skewed left as the running speed increases. The DWF 1 tonf decreases from 25% to 12% while the DWF 3 tonf increases from 18% to 32% and the DWF 4 tonf becomes 13% at a speed of 360 km/h. Even though it shows fluctuations, the unimodal histogram can be evaluated as stable. This stability means that the DWF value of the KTX vehicle on the ground is independent of the running speed.

IV. CONCLUSION

This study was conducted to find traffic safety indices for a train bridge using dynamic numerical analysis of the wheel forces of a KTX vehicle running between on the ground and PSC box bridge track at high speeds of up to 500 km/h in increments of 10 km/h. The study was conducted on a train bridge selected from among the Gyungbu express railway. The results are summarised as follows.

1. The exist limitations according to the traffic safety criteria for the bridge; deflection 23.5 mm, acceleration 0.35 g, end rotation 0.5×10^{-3} radian, vertical profile 1.2 m are conservative.
2. The regression formula for DWF is proposed with a reasonable R^2 of 93.8%.
3. According to the formula, the maximum DWF on the bridge, 6.50 tonf occurs at 420 km/h. It is identical with the DAF of the bridge.
4. However, the maximum DWF according to the analysis, 6.85 tonf occurs at 360 km/h. It is identical with the cumulative WFR on the bridge.
5. The DWF on the ground was observed to be stable instead of the DWF on the bridge, for which this was expected at the given running speeds. The histogram of DWF on the ground shows symmetric and unimodal distribution which is stable as the running speed increases.
6. If the running speed of the KTX vehicle exceeds the current design speed, the results of evaluations based on the stability analysis standard of the vehicle will exceed the limit values. Therefore, more intensive experimental studies should be conducted on this subject and relevant fields.

V. ACKNOWLEDGEMENTS

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