Passenger Vehicle Effect on the Truck Weight Calculations using B-WIM System

Yahya M. Mohammed[1], Nasim Uddin[2]

[1]Research Assistant, Department of Civil Construction and Environmental Engineering, University of Alabama at Birmingham, Birmingham, AL, 35294, USA.
Email: yahya1@uab.edu.
[2]Ph.D., P.E., Professor, Department of Civil Construction and Environmental Engineering, University of Alabama at Birmingham, Birmingham, AL, 35294, USA.
Email: nuddin@uab.edu.

ABSTRACT

Bridge Weigh-in-Motion (BWIM) is the technology of using the bridge as a weigh scales to find the weights of passing trucks. Weight calculations should have a high level of accuracy to enable the B-WIM system from being a tool for direct overload enforcement. This paper focuses on improving the accuracy of the B-WIM system when a passenger vehicle travels over the bridge side by side with the target truck. A solution have been suggested to remove this effect by considering measurements on girders under the truck lane only and exclude the ones under the passenger vehicle lane. Since using the measurements under the vehicle lane will reduce measurements number and thus affect results accuracy, an approximate method are developed to deal with the lower number of measurements. The method has been discussed analytically and experimentally.

Keywords: Passenger vehicle effect; Moving Force Identification (MFI); Bridge Weigh in Motion (B-WIM); 3 Dimensional Finite Element Model (3D FEM); Multiple Vehicles;

INTROUDUCTION

America's bridges are in a critical situation where many of the nation's bridges are approaching the end of their design life. Over the past decade, there has been increased awareness of this fact, hence at all levels of government, a concerted effort has been made to improve the condition of the U.S. bridges. Meanwhile, the federal government spent $17.5 billion dollars on bridge capital projects. Frustratingly, the federal estimate for backlog rehabilitation projects is $123 billion dollars [1, 2, U.S. Government Accountability Office 3]. The current loading on these bridges is significantly different from the service loads at the time of design and construction. New techniques have been developed to calculate the weights of trucks as a trail to prevent the overloaded trucks from damaging the bridges. These techniques are varied from static weighing at weigh stations which has a good level of accuracy, but cannot covers a large numbers of trucks [4], Weigh-in-Motion (WIM) which is less accurate but can provide weights for all passing trucks, and B-WIM system that utilizes bridge response under moving loads to estimate the characteristics of passing vehicles.

B-WIM systems have the potential to provide an inexpensive portable method of rapidly assembling traffic weight data. The novel technique of using the bridge as an instrument to infer the dynamic wheel forces was first investigated by [5]. Since then the field of moving force identification (MFI) has progressed rapidly [6-10]. The MFI problem is an inverse dynamics process and like many, is ill-conditioned which means the solution is very sensitive to small perturbations in measurements, which requires the regularization approach to overcome this problem. Law and Fang [8] apply a dynamic programming technique to the MFI problem on a simply supported beam model using zeroth-order regularization to solve the state space formulation, then González [11] extend the algorithm to allow for the first order regularization of moving forces, which improved the solution accuracy.

According to [12], the accuracy of existing B-WIM systems is strongly affected by the number of vehicles present on the bridge during measurement, i.e., the accuracy is significantly reduced when even a car is present at the same time as a truck, while no result may be obtained if two trucks are present. When a heavy truck with car or light truck are traveled along an instrumented bridge, the measurement results are often poor, and the weights of the trucks may not be identified at all. This is because; the gross vehicle weight is determined by the global response of the structure to all of the vehicles crossing the bridge. If the vehicles are traveling along one lane, there is no issue. However, if two vehicles in adjacent lanes travel side by side, the MFI algorithm has difficulty separating the contributions of the individual vehicles from the global response [13]. As well, when multiple presences of vehicles occur (i.e., truck and vehicle) on an instrumented bridge, the measurement results are often poor, and in the worst cases, trucks are not identified at all [14]. This paper address the multiple presence of trucks and passenger vehicles (small car). It is not important to calculate the small vehicle weight because it's weight in not significant enough to damage bridges, but it's substantial to know it's effect on trucks weight. Also, this paper suggest a solution to remove this effect by considering measurements on girders under the truck lane only to calculate the truck axles and gross weight.

MOVING FORCE IDENTIFICATION ALGORITHM

The MFI algorithm uses the inverse dynamics theory to back-calculate a complete time force history of axles or wheels that move on the bridge. The algorithm adopted in this paper is one used by González et al. [11] who improve the work of Law et al. [8] by applying the first order regularization technique. The algorithm is explained here briefly.

Firstly, the equilibrium equation of motion is converted into a discrete system as shown in Equation (1).

$$[M_g]_{nxn}\,\{\ddot{y}\}_{nx1} + [C_g]_{nxn}\,\{\dot{y}\}_{nx1} + [K_g]_{nxn}\,\{y\}_{nx1} = [L(t)]_{nxnf}\,\{g(t)\}_{nfx1} \qquad \textbf{(Eq.1)}$$

Where M_g, C_g and K_g are the Mass, Damping and stiffness matrices respectively. The terms, $\ddot{y}$, $\dot{y}$ and y are the acceleration, velocity, and displacements of the DOFs. $L(t)$ is a time varying location matrix used to relate the forces (*nf*) of the vector $g(t)$ to the model degrees of freedom (n). The storage requirements of the dynamic programming routine for system of Equations (1) is considerable, especially for a large scale FE model. Therefore, some numerical techniques are necessary to reduce the dimensionality of the system. An eigenvalue reduction technique is employed for this purpose [15]. It is assumed that the displacement vector, $\{y\}$ can be replaced with an equivalent vector of modal coordinates, $\{z\}$, through Equation (2), where $[\Phi]$ is the matrix of normalized eigenvectors and nz is the number of modes.

$$\{y\} = [\Phi]_{nxnz}\,\{z\}_{nzx1} \qquad \textbf{(Eq.2)}$$

Substituting the previous equation into Equation (1) and performing some manipulations, Equation (8) can be written as the decoupled set of equations as expressed by Equation (3).

$$[I]_{nxn}\,\{\ddot{z}\} + 2\xi[\Omega]_{nxn}\,\{\dot{z}\}_{nx1} + [\Omega]_{nxn}\,\{z\}_{nx1} = [\Phi]^T\,[L(t)]_{nxnf}\,\{g(t)\}_{nfx1} \qquad \textbf{(Eq.3)}$$

Where $[\Omega]$ is a diagonal matrix contains the natural frequencies and ξ is the percentage damping. Equation (3) can now be formulated as a vector matrix differential equation as illustrated in Equation (4).

$$\left\{\frac{dx}{dt}\right\}_{2nx1} = [A]_{2nx2n}\{X\}_{2nx1} + [B]\{g\}_{nfx1} \qquad \textbf{(Eq.4)}$$

$$Where, \{X\}_{2nx1} = \begin{Bmatrix} z \\ \dot{z} \end{Bmatrix}, \quad [A] = \begin{bmatrix} 0 & I \\ -[\Omega] & -2\xi[\Omega] \end{bmatrix}, \quad [B] = \begin{bmatrix} 0 \\ [\Phi]^T[L(t)] \end{bmatrix}$$

The continuous system of differential equations can be converted into a direct integration scheme, often referred to as a zeroth order system [16]defined by Equations (5,6 and 7).

$$\{X\}_{j+1} = [M]\{X\}_j + [P]_j\{g\}_j \qquad \textbf{(Eq.5)}$$

$$[P]_j = \left[[A]^{-1}[[M]-[I]]\right]\begin{bmatrix} 0 \\ [\Phi]^T[L]_j \end{bmatrix} \qquad \textbf{(Eq.6)}$$

$$[M] = \exp([A] * h), \qquad h \text{ is the time step} \qquad \textbf{(Eq.7)}$$

The second step is applying the least square minimization with Tikhonov regularization parameter as given in Equation (8).

$$\sum_{j=1}^{m}\left(\left\{\{d_{me}\}_j-[Q]\{X\}_j\right\},[W]\left\{\{d_{me}\}_j-[Q]\{X\}_j\right\}+\{r\}_j,[B]\{r\}_j\right) \quad \textbf{(Eq.8)}$$

Where d_{me} is the measurement vector (strain, displacement, or velocity), [Q] is a vector to relate the measurements to the degree of freedom, {X} is the degree of freedom vector at each time step j, (x, y) denotes the vector product of x and y, [W] is an mxm identity matrix in the least squares error. $\{r\}_j$ is the increment change in the force between time step j and time step j-1, [B] is a regularized matrix and equal to $\lambda[I]$, where λ is the optimum regularization parameter. This minimization searches for the force increment $\{r\}$ that cause the system best match the given measurements d_{me}. The regularization parameter λ used to avoid the ill-conditioned solution in the previous minimization, also to control the amount of smoothness in force history. The L-curve technique used to calculate the optimal regularization parameter The optimal regularization parameter located at the corner of the L-curve, at the point of maximum curvature [17]. Dynamic programming and Bellman's principle of optimality [17, 18] are used to solve the minimization process.

SOLUTION FOR MULTIPLE-PRESENCE OF TRUCK AND PASSENGER VEHICLE

The normal in the B-WIM system that the measurements cover all the bridge girders [11, 19-22]. Since, the passenger vehicles has a small influence on girder strains especially girders under the other lanes, the author suggest to use measurements under the truck lane only when the multiple presence of trucks and passenger vehicles occur. This has been found to be more effective than using all sensors for every calculation. This concept cannot be applied when multiple presences of two truck occur as the truck has a significant influence on all the bridge girders.
Since the accuracy of the MFI algorithm is linked to the number of measurements $\{d_{me}\}$ [23], and using the measurements under the truck lane only will reduce this number and thus affect the accuracy, an approximate method is developed here to calculate the truck weight using the same measurements (under truck lane) used in normal case. The method uses each measurement in the field for two following elements in the FE model, which doubles measurements number. For example, the strain at the girder mid-span will be used as measurements for the element at the mid-span and the previous or the following element as shown in Figure 1.

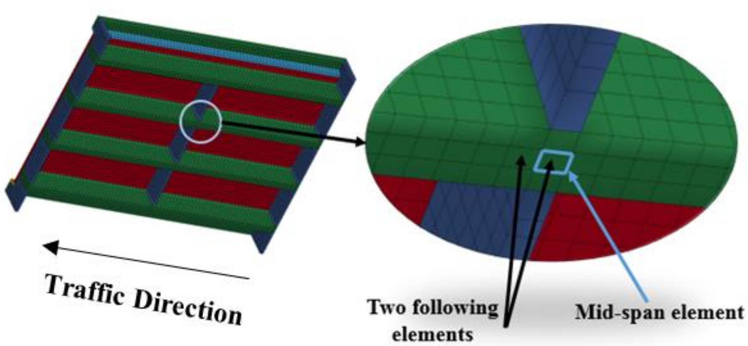


Figure 1. Same measurements for two following elements.

NUMERICAL STUDY FOR MULTIPLE-PRESENCE OF TRUCK AND PASSENGER VEHICLE

FE Model and vehicles specification

The FE program, LS-Dyna, utilized to build the FE model for a US-78 bridge in Birmingham, AL in the United States. The bridge has a simply supported span of 12.80 m, and consists of 4 concrete T-girders with mid and end diaphragms. The model was built utilizing 8 node solid elements, with 3 degrees of freedom (DOFs) per node (translation in x, y, and z directions). The bridge model has 55,916 DOFs. 1-D elements (track elements) are provided along each lane to allow the moving force to pass the bridge. A 1-D road profile with roughness class "A" has been generated randomly on the track elements according to the ISO specification [24]. The bridge model is shown in Figure 2.

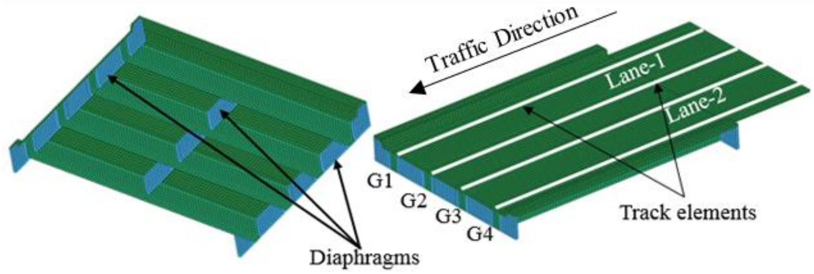
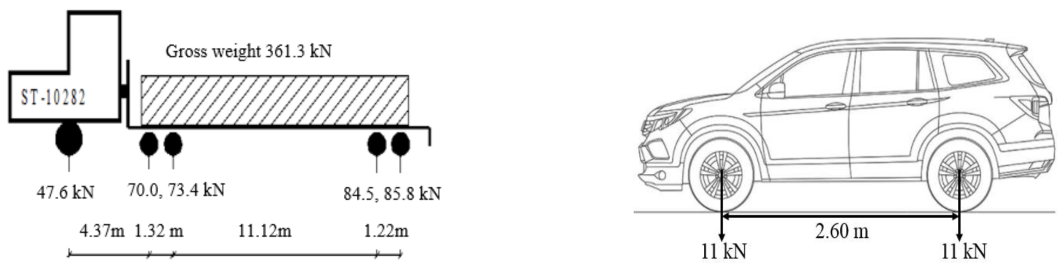


Figure 2. US-78 Bridge FE Model.

To study the passenger vehicles effect on the MFI accuracy, 10 moving forces were allowed to cross the bridge represent 5-axles truck, the truck configuration and axle weights are illustrated in Figure 3-a. These forces measured from a real truck using portable scales and the calibration process has been fully detailed in [25]. The passenger vehicle is simulated by 4 moving forces taking the "Honda Pilot 4DR SUV FWD LX" as an example with axles loads and configration after loaded with passenger as shown in Figure 3-b.

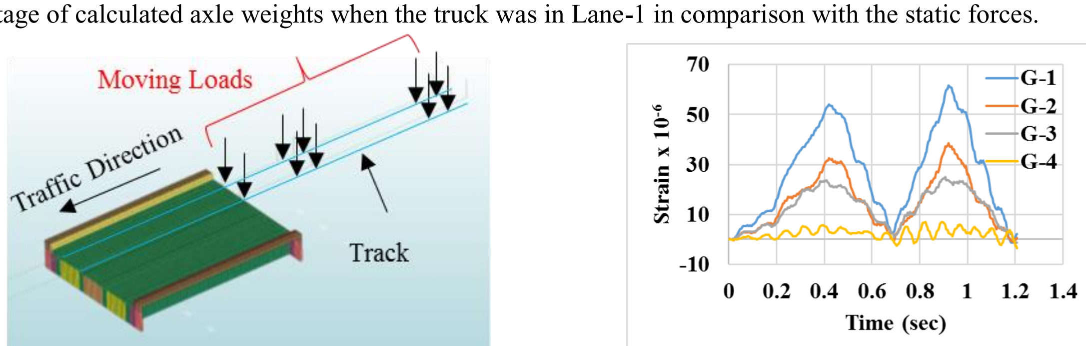


(a) (b)

Figure 3. (a) 5-axles truck, (b) passenger vehicle example.

Multiple presence of 5-axle trucks and passenger vehicle.

To study the effect of the passenger vehicle on the calculations of the axle weights, firstly, the 5-axles truck was allowed to cross over the bridge alone at 25.6 m/s speed (*Figure 4*-a). The strain measurements at the mid-span of each girder are extracted from the LS-Dyna program (Figure 4-b) to be used as an input of the MFI algorithm. As the spacing between the two tandem axle groups is almost the same as the span (11.125 ≅ 12.80 m), the first tandem has almost left the bridge when the second tandem arrives. This explains the two peaks of strain in each girder. Using the L-curve curvature technique to calculate the optimum regularization parameter [26-28] it is found equal to 2.512e-16. The axles load are calculated (Figure 5) and summarized in Table 1. Table 1 illustrates the errors percentage of calculated axle weights when the truck was in Lane-1 in comparison with the static forces.



(a) **(b)**

Figure 4. (a) Concentrated loads represent the 5-axles truck, (b) Strain measurements at mid-span of the bridge girders due to 5-axles moving force (G1=1st Girder).

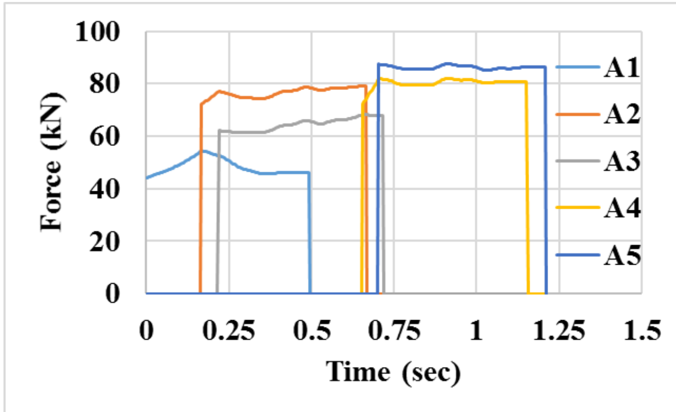
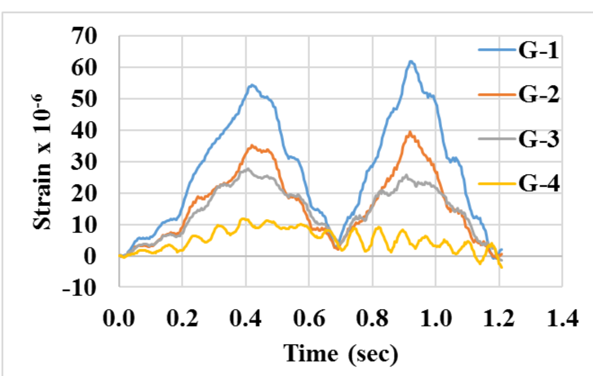


Figure 5. Axles force history in case of the truck only on the bridge (A1=1st axle).

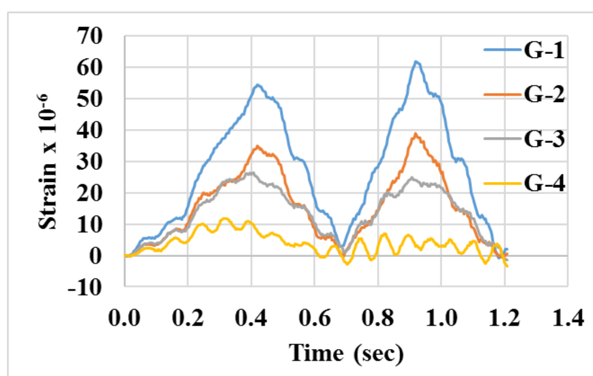
Table 1. A comparison between the statics and calculated axles force history

Item	**Static weight (kN)**	**Calculated (kN)**	**Error**
A1	47.6	49.8	4.6%
A2	69.9	76.5	+9.4%
A3	73.4	64.2	-12.4%
A4	84.5	80.5	-4.6%
A5	85.8	86.1	0.4%
A2+A3	143.4	140.7	-1.8%
A4+A5	170.3	166.6	-2.1%
GVW	361.3	357.1	-1.2 %

To show the effect of passenger vehicles on the truck weight, the previous data used as a baseline to capture this effect. With the same speed for the truck, the small vehicle traveled on the other lane with two different speeds 15, and 25 m/s. The strain measurements are collected at the mid-span of each girder and plotted in Figure 6(a-b). The figures show that the small vehicle effect appears clearly on girder-4 comparing with the case of the truck only (Figure 4-b). This effect is widespread in a large area of measurements at low speeds while confined to a small part as the speed increases



a- Truck 25.6 m/sec, vehicle 15.0 m/s.

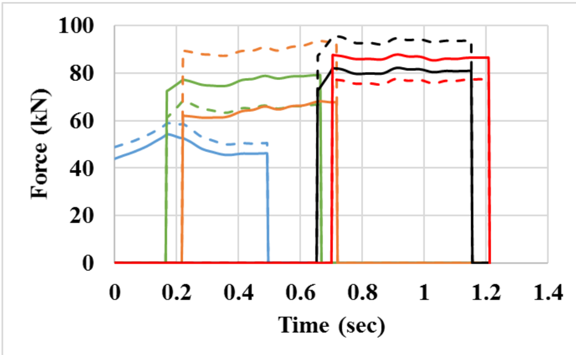


b- Truck 25.6 m/sec, vehicle 25.0 m/s.

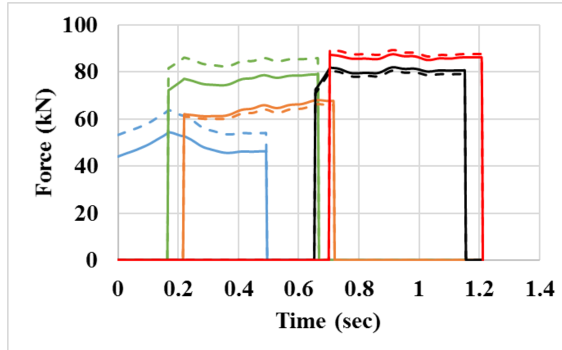
Figure 6. Girders strain at mid-span for different vehicle speed (G1=1st Girder).

Figure 7 (a-b) shows the result from the MFI algorithm where axles force history for the case of the truck beside the passenger vehicle appears in dotted while axles force history for the case of the truck only appears in straight lines. The results are summerized in

Table 2 which shows a comparison between axle weights in the case of the truck only and the cases of the trucks beside the passenger vehicle.



a- Truck 25.6 m/sec, vehicle 15.0 m/s.



b- Truck 25.6 m/sec, vehicle 25.0 m/s.

Figure 7. Truck axles force history for various vehicle speed.

Table 2. The weight of the truck via the weight of the truck + vehicle.

Item	**Truck Only**	**Truck + Vehicle (15 m/s)**	**Truck + Vehicle (25 m/s)**
A1	49.8	56.2	60.8
A2	76.5	65.0	83.2
A3	64.2	89.2	63.1
A4	80.5	91.2	76.1
A5	86.1	79.4	91.9
A2+A3	140.7	154.1	146.3
A4+A5	166.6	170.6	168.1
GW	357.1	381	375.2
Error		6.67%	5.0%

All forces are in kN.

The purpose of this study is to show two important facts; the first one is; when any axles from the truck entered the bridge while there is an existed vibration on the bridge due to another vehicle this axle will be affected and the axle weight calculation will has an error depending on how heavy is this vibration. This explains why all the axles are affected when the passenger vehicle speed was 15 m/s while the first three axles only affected when the speed increased to 25 m/s as the last two axles entered the bridge after the passenger vehicle left it. The second fact is, because of the tiny weight of the passenger vehicle comparing with the truck weight, the effect of the passenger vehicle has been appear only in the girders under the vehicle lane and almost no effect on the others.

MFI using measurements under the truck lane only

To overcome the problem, measurements under the truck lane only at the mid-span of girders 1 and 2 are considered. Because of the number of measurements become half the original, which may affect the accuracy. An approximate method is applied by considering the strain at the girders mid-span equal to the strain at the mid-span element and the previous element, so the total number of measurements still the same and equal to four.

Table 3 shows the MFI results when applied on measurements from the multiple presence of truck and passenger vehicle. The table shows the results when using two measurements only from girders 1 and 2, and when applying the approximate method. The approximate method has been showed a significant enhancement on the truck weight, and the error is less than 2% comparing with the actual weight. The results when using two strain measurements has a significant error as the number of measurements affect the results.

Table 3. The weight of the truck via the weight of the truck + vehicle.

Item	Truck + Vehicle (15 m/s)		Truck + Vehicle (25 m/s)	
	Two measurements	Approximate	Two measurements	Approximate
A1	58.2	50.5	58.2	50.9
A2	79.2	70.7	80.2	72.9
A3	76.5	73.5	76.8	70.7
A4	86.2	80.4	88.2	76.8
A5	98.9	88.1	97.4	90.8
A2+A3	156.4	144.2	157.0	143.6
A4+A5	185.1	168.5	185.6	167.6
GW	399.8	363.3	400.8	362.1
Error	10.6	+1.7%	10.9	+1.4%

All forces are in kN.

CONCLUSION

In conclusion, the multiple presence of trucks and passenger vehicles showed reduction in the MFI algorithm accuracy for both the axles and the gross weight. The method suggested by the author to remove the passenger vehicle effect considering the measurements under the truck lane only has been showed a significant improvement in the algorithm results. Also, this paper suggests an approximate method to calculate the truck weight when the number of measurements under the truck lane are not enough and affects the algorithm accuracy.

ACKNOWLEDGMENTS

The authors would like to express their gratitude for the financial support received from the National Science Foundation (NSF-CNS- 1645863) for this investigation.

REFERENCES

[1] FHWA, 2017. , "2015 Status of the Nation'sHighways, Bridges and Transit: Conditions and Performance."

[2] ASCE, 2017, "ASCE analysis of U.S. Department of Transportation, Federal Highway Administration.."

[3] , U. G. A. O., 2017, "Report to Congressional Committees: Highway Bridges—Linking Funding to Conditions May Help Demonstrate Impact of Federal Investment.."

[4] O'Brien, E. J., Znidaric, A., and Dempsey, A. T., 1999, "Comparison of two independently developed bridge weigh–in–motion systems," International Journal of Heavy Vehicle Systems, 6(1-4), pp. 147-161.

[5] Chan, T. H. T., and O'Connor, C., 1990, "Wheel loads from highway bridge strains: field studies," Journal of structural engineering, 116(7), pp. 1751-1771.

[6] Chan, T. H., Law, S., and Yung, T., 2000, "Moving force identification using an existing prestressed concrete bridge," Engineering Structures, 22(10), pp. 1261-1270.

[7] Jiang, R., Au, F., and Cheung, Y., 2003, "Identification of masses moving on multi-span beams based on a genetic algorithm," Computers & structures, 81(22), pp. 2137-2148.

[8] Law, S., and Fang, Y., 2001, "Moving force identification: optimal state estimation approach," Journal of Sound and Vibration, 239(2), pp. 233-254.

[9] Pinkaew, T., 2006, "Identification of vehicle axle loads from bridge responses using updated static component technique," Engineering Structures, 28(11), pp. 1599-1608.

[10] Mohammed, Y. M., and Uddin, N., "Bridge Damage Detection using the Inverse Dynamics Optimization Algorithm," Proc. 26th ASNT Research Symposium, pp. 175-184.

[11] González, A., Rowley, C., and OBrien, E. J., 2008, "A general solution to the identification of moving vehicle forces on a bridge," International journal for numerical methods in engineering, 75(3), pp. 335-354.

[12] Quilligan, M., Karoumi, R., and O'Brien, E. J., 2002, "Development and testing of a 2-dimensional multi-vehicle bridge-WIM algorithm," Third international conference on weigh-in-motion, pp. p. 199-208.

[13] Lydon, M., Taylor, S., Robinson, D., Mufti, A., and Brien, E., 2016, "Recent developments in bridge weigh in motion (B-WIM)," Journal of Civil Structural Health Monitoring, 6(1), pp. 69-81.
[14] Hitchcock, W. A., Salama, T., Zhao, H., Callahan, D., Toutanji, H., Richardson, J., and Jackson, J., 2011, "Expanding Portable B-WIM Technology," Rep, 8204.
[15] Busby, H. R., and Trujillo, D. M., 1987, "Solution of an inverse dynamics problem using an eigenvalue reduction technique," Computers & structures, 25(1), pp. 109-117.
[16] Trujillo, D. M., and Busby, H. R., 1997, Practical inverse analysis in engineering, CRC Press.
[17] Hansen, P. C., 1992, "Analysis of discrete ill-posed problems by means of the L-curve," SIAM review, 34(4), pp. 561-580.
[18] Trujillo, D., 1978, "Application of dynamic programming to the general inverse problem," International Journal for Numerical Methods in Engineering, 12(4), pp. 613-624.
[19] Rowley, C., OBrien, E. J., González, A., and Žnidarič, A., 2009, "Experimental testing of a moving force identification bridge weigh-in-motion algorithm," Experimental mechanics, 49(5), pp. 743-746.
[20] Kalyankar, R., and Uddin, N., "Field Verification and Optimization of Weighing Sensor Location on US Girder Bridges for Bridge Weigh in Motion (B-WIM)," Proc. Transportation Research Board 94th Annual Meeting.
[21] Zhao, Z., Uddin, N., and O'Brien, E., "Field verification of a filtered measured moment strain approach to the bridge weigh-in-motion algorithm," Proc. Proceedings of the international conference on weigh-in-motion (ICWIM 6), pp. 63-78.
[22] Schmidt, F., and Jacob, B., "Experimentation of a bridge WIM system in France and applications to bridge monitoring and overload screening," Proc. 6th International Conference on Weigh-In-Motion (ICWIM 6) International Society for Weigh-In-MotionInstitut Francais des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTARR) International Transport ForumForum of European National Highway Research Laboratories (FEHRL) Transportation Research BoardFederal Highway Administration.
[23] Rowley, C. W., 2007, "Moving force identification of axle forces on bridges," University College Dublin, Ireland.
[24] Elhattab, A., Uddin, N., and OBrien, E., 2016, "Drive-by bridge damage monitoring using Bridge Displacement Profile Difference," Journal of Civil Structural Health Monitoring, 6(5), pp. 839-850.
[25] Zhao, H., Uddin, N., O'Brien, E. J., Shao, X., and Zhu, P., 2013, "Identification of vehicular axle weights with a bridge weigh-in-motion system considering transverse distribution of wheel loads," Journal of Bridge Engineering, 19(3), p. 04013008.
[26] Law, S., Chan, T. H., Zhu, Q., and Zeng, Q., 2001, "Regularization in moving force identification," Journal of Engineering Mechanics, 127(2), pp. 136-148.
[27] Finney, R. L., Weir, M. D., and Thomas, G. B., 2001, Thomas' calculus: early transcendentals, Addison-Wesley.
[28] Rowley, C. W., 2007, Moving force identification of axle forces on bridges, University College Dublin.