CHAPTER II

LITERATURE REVIEW

2.1 General

In this chapter, relevant previous studies including vehicle-bridge interaction, weigh-in-motion system, moving load identification and bridge live load models are reviewed. Research works relating to theoretical and experimental studies of moving loads identification, numerical technique used for load identifications and bridge design live load are covered.

2.2 Weigh-In-Motion

Weigh-in-motion (WIM) system has been known for over 40 years, starting with weight data collection of trucks and its axles for statistical purposes required for pavement design and maintenance. Pavement and bridge structural design is based on the weight of heavy vehicles traveling on a highway. To protect the road infrastructure from damage and to reduce wear and tear, in the 1970's the first semi-automatic weighing stations consisting of pre-selection WIM scales and downstream axle weighbridges for enforcement in rest or parking areas were designed, built and are operated until today. Weigh stations have been in operation for many years for the purpose of ensuring that trucks do not exceed the legal weights of the localities that are being traveled through. Unfortunately, as the amount of trucks on highways increases, the queue lengths at the weigh stations also increase. When weigh station queues spill back on to the mainline travel lanes, the weigh stations are generally closed and violators can potentially go through the network. As a way of speeding up the process of weighing these heavy vehicles, WIM systems have been installed in many places to screen overweight vehicles.

WIM system provides highway planners and designers with traffic volume and classification data. In addition, WIM equipment also provides planners and designers with equivalent single axle loadings (ESAL) that heavy vehicles place on pavements. Road vehicle enforcement officers use heavy truck axle load data to plan enforcement activities. In summary, the uses of traffic and truck weight data include enforcement, pavement, bridge, and legislative and regulatory issues. The use of WIM data should determine the approach chosen in developing the WIM data collection site and the resources required to maintain the site over the expected site design life. The WIM can be divided into two systems which are (1) traditional WIM based on load transformation of the vehicle weight using load cell or other measurement embedded into the roadway pavement, and (2) bridge weigh-in-motion (B-WIM) conducting bridge response for the vehicle load transformation.

2.2.1 Traditional Weigh-In-Motion

The traditional WIM is a weight estimation system employing instrumented pavement of the roadway surface. Some of the existing measurement technologies for WIM sensors started with load cells, steel plates with strain gauges and were supplemented with low cost sensors using piezo materials, crystal or optical fiber technology (Jacob, 1999) embedded into roadway surface. Recently, research has also been conducted in determining vehicle weight by pavement strain; however, this technology has not been widely utilized. In each of the systems, a site processor is used to sort and analyze the information obtained from the WIM sensors. Thus, a communication device such as a modem is used to transfer the information to outside locations for further calculation and to assure that the system is operating properly. Operating software must also be used to interpret the signals from the WIM sensors and to be able to generate files that can be used and analyzed by monitoring agencies (McCall et al., 1997).

Due to the high infrastructure and operation costs of these semi-automatic weighing stations, investigations for fully automatic overload enforcement systems were initiated in recent years: WIM sites with multiple integrated sensor technologies were built and special algorithms were applied to the measurement data with the expectation to achieve higher weight accuracies than with one single sensor technology (Sainte-Marie et al., 1998, Stergioulias et al, 1998, Cebon, 1999, Dolcemascolo et al., 2002, Labry et al., 2004). Test sites with Multiple Sensor (MS) WIM arrays were built with different sensor technologies in France (Dolcemascolo, 1999), Germany (Balz/Opitz, 2002), UK, Netherlands and many other countries.

Benefit of operating the traditional WIM is of the aspect of computational time since the vehicle weight can be calculated directly from the load-measurement conversion. However, this system allows large vehicle weight error in the case of fast speed travel of the vehicle. This is because the duration of the vehicle passage on the weighing pad is very short. Moreover, the maintenance cost of this approach is very expensive. This is because the instruments are embedded into the pavement then the instrumented route is required to be closed for repairing and replacement of the sensors.

2.2.2 Bridge Weigh-In-Motion (B-WIM)

In order to overcome the problem of large weight estimation error and the expensive maintenance cost found in the traditional WIM system, an alternative approach based on an indirect weight estimation by returning the bridge responses into the acting load known as bridge Weigh-In-Motion (B-WIM) has been developed. Moses et al. (1979) developed the concept of using bridges as scales to weigh trucks in motion. In Australia, a similar system appeared a few years later but replaced by another that used culvert (Peters, 1986). In the nineties, the new Bridge WIM (B-WIM) systems were developed independently in Slovenia (Znidaric et al., 1991) and in Ireland (Dempsey et al., 1995). In 1999, the European specification on WIM of road and vehicles called COST 323 was presented as the recommendations and references for site selection, installation, operation, calibration and assessment by testing of WIM system. Then the further research on COST 323 project by the European Commission (WAVE, 2001) was continued for system development in many actions such as weighting capacity, weighing accuracy and standard calibration.

The B-WIM systems deal with an existing instrumented bridge or culvert from the road network as illustrated in Figure 2.1. The bridge or culvert structure are installed the instruments and measured the strains to provide information about its behavior under the moving vehicle. In addition, the axle or vehicle detectors are installed on the pavement to provide vehicle type, velocity and axle spacing. Strains are recorded during the whole vehicle passes over the structure and such redundant data provides useful information when the influence of dynamic effects due to vehicle-bridge interaction has to be taken into account.

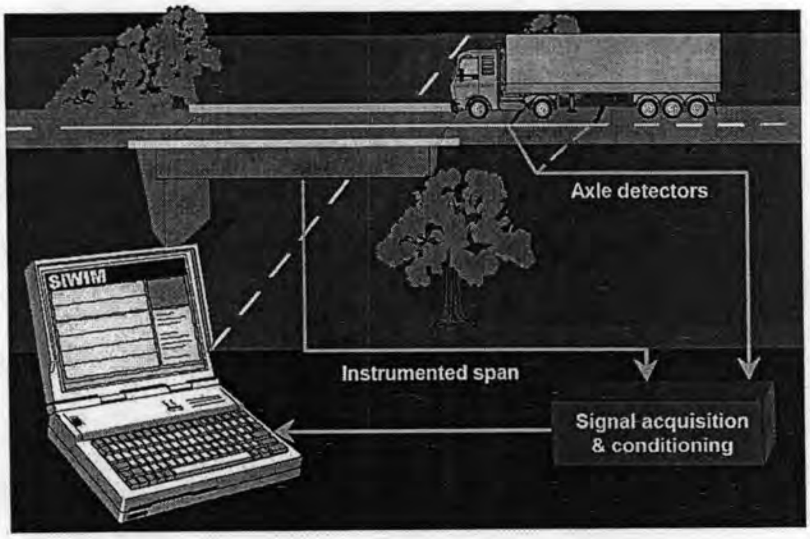

Figure 2.1 Bridge WIM system

2.2.3 Accuracy Classification of WIM

Several accuracy classes for individual measurements have been defined. Four main criteria are considered. These classes are defined by the confidence intervals of the relative errors with respect to the static loads or weights as shown in Table 2.1.

To date, no multiple sensors WIM system has been reported in the literature to have achieved Class A(5) accuracy - but in class B+(7) - in accordance with the COST 323 specification. The accuracy of a multiple sensors WIM array is related to the accuracy of the individual sensors. Moreover, the choice of WIM site has also a great influence on the accuracy, the reliability and the durability of any WIM system. The sites are classified according to the road geometry and the pavement characteristics. Table 2.2 represents the classification and criteria of WIM sites provided by COST 323.

Table 2.1 Width of the accuracy classes (COST 323)

Criteria (type of measurement)	Domain of use	Accuracy Classes: Confidence interval width (%)						
		A(5)	B+(7)	B(10)	C(15)	D+(20)	D(25)	E
1. Gross weight	Gross weight > 3.5 t	5	7	10	15	20	25	>25
Axle load:	Axle load > 1 t							
2. group of axles		7	10	13	18	23	28	>28
3. single axle		8	11	15	20	25	30	>30
4. axle of a group		10	14	20	25	30	35	>35
Speed	V > 30 km/h (1)	2	3	4	6	10	10	>10
Axle spacing		2	3	4	6	10	10	>10
Total flow		1	1	1	3	5	5	>5

(1) For sensors which do not work statically or at very low speed

Table 2.2 Classification and criteria of WIM sites (COST 323)

			WIM site classes		
			I Excellent	II Good	III Acceptable
Rutting (3 m – beam)		Rut depth max. (mm)	≤ 4	≤ 7	≤ 10
Deflection (quasi-static) (13 t – axle)	Semi-rigid Pavements	Mean deflection (10-2 mm)	≤ 15	≤ 20	≤ 30
		Left/Right difference (10-2 mm)	± 3	± 5	± 10
	All bitumen Pavements	Mean deflection (10-2 mm)	≤ 20	≤ 35	≤ 50
		Left/Right difference (10-2 mm)	± 4	± 8	± 12
	Flexible Pavements	Mean deflection (10-2 mm)	≤ 30	≤ 50	≤ 75
		Left/Right difference (10-2 mm)	± 7	± 10	± 15
Deflection (dynamic) (5 t – axle)	Semi-rigid Pavements	Mean deflection (10-2 mm)	≤ 10	≤ 15	≤ 20
		Left/Right difference (10-2 mm)	± 2	± 4	± 7
	All bitumen Pavements	Mean deflection (10-2 mm)	≤ 15	≤ 25	≤ 35
		Left/Right difference (10-2 mm)	± 3	± 6	± 9
	Flexible Pavements	Mean deflection (10-2 mm)	≤ 20	≤ 35	≤ 55
		Left/Right difference (10-2 mm)	± 5	± 7	± 10

The rutting and deflection values are given for the temperature below or equal 20°C and suitable drainage conditions.

The American Society for Testing and Materials (ASTM) "Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods" (ASTM Designation: E1318-02) classifies four types of WIM systems by different speed range, type of application, and data gathering capabilities. Table 2.3 shows the information for the four types of systems. Table 2.4 shows functional performance requirements for WIM systems (McCall et al., 1997 and ASTM E1318-02).

From the classification and specification listed in Tables above, it is noticed that the accuracy of the system is smallest as only 5% of static gross weight of the vehicle.

Although the WIM or the B-WIM systems can estimate the static gross weight of the vehicle accurately, the parameter directly affect to the structural health of the bridge is dynamic loading from moving vehicle which induces dynamic impact to the pavement. To monitor this action, the WIM system with static gross weight or static axle loads of the vehicle are inadequate. Therefore, the time-history of moving axle loads is necessary required. Additionally, the accuracy in axle loads identification of B-WIM systems is depended on the efficiency of hardware and software, and the cost of installation and maintenance for WIM and B-WIM is very expensive. Hence, the identification of dynamic axle loads from bridge responses becomes more attractive alternative, since it is much cheaper and easier to install and maintain.

Table 2.3 ASTM E1318-02, WIM system classification

	Classification			
	Type I	Type II	Type III	Type IV
Speed Range	10-70 mph (16-113 km/h)	10-70 mph (16-113 km/h)	15-50 mph (24-80 km/h)	0-10 mph (0-16 km/h)
Application	Traffic data collection	Traffic data collection	Weight enforcement station	Weight enforcement station
Number of Lanes	Up to four	Up to four	Up to two	Up to two
Wheel Load	X		X	X
Axle Load	X	X	X	X
Axle-Group Load	X	X	X	X
Gross Vehicle Weight	X	X	X	X
Speed	X	X	X	X
Center-to-Center Axle Spacing	X	X	X	X
Vehicle Class	X	X		
Site Identification Code	X	X	X	X
Lane and Direction of Travel	X	X	X	
Data and Time of Passage	X	X	X	X
Sequential Vehicle Record Number	X	X	X	X
Wheelbase	X	X		
Equivalent Single-Axle Load	X	X		
Violation Code	X	X	X	X

Table 2.4 Functional performance requirements for WIM systems, ASTM E1318-02

Function	Tolerance for 95% Probability of Conformity				
	Type I	Type II	Type III	Type IV	
				Value ≥ Ib (kg)	± Ib (kg)
Wheel Load	± 25 %		± 20 %	5000 (2300)	250 (100)
Axle Load	± 20 %	± 30 %	± 15 %	12,000 (5400)	500 (200)
Axle-Group Load	± 15 %	± 20 %	± 10 %	25,000 (11,300)	1200 (500)
Gross-Vehicle Weight	± 10 %	± 15 %	± 6 %	60,000 (27,200)	2500 (1100)
Speed	± 1 mph (2km/h)				
Axle-Spacing	± 0.5 ft (150 mm)				

2.3 Vehicle-Bridge Interaction

The major objective of WIM system is to identify the axle loads of vehicle. Therefore, the behavior of dynamic interaction between vehicle and bridge is an important part of moving load identification system. The simulation of bridge dynamic response under moving load has been studied and used to investigate the effectiveness of identification methods. Fryba (1973) investigated the vibration of simply supported beam subjected to various moving loadings. Lin et al. (1990) proposed the finite element method of discrete system for dynamic response analysis, and the accurate model has been studied against the degree of discretization of the structure for a moving load analysis (Rieker JR et al, 1996). It was found that beams with various support boundary conditions subject to a moving load system with general movement profile can be successfully analyzed.

Hwang and Nowak (1991) developed a procedure for calculation of the dynamic load for bridges. The developed model for trucks, road surface roughness and bridge were analyzed to obtain their dynamic interaction. The two-axle truck and tractor-trailer models were simulated with rigid body in mass, and the suspensions and tires were assumed by vertical springs. The equation motion of the system can be formulated from the vertical and rotational equilibriums. Road profiles were simulated using stochastic process (power spectral density function). A bridge was treated as a prismatic beam. The analysis was performed for single truck and for two trucks with side by side. The results were found that dynamic loads for heavier trucks are lower and also for two trucks. The simulation deflection indicated that dynamic component is not correlated with the static component. Therefore, the dynamic loads are usually lower for heavier trucks. As well as for the two trucks, the dynamic load is lower than single truck.

Green and Cebon (1997) was studied the bridge-vehicle interaction with a vehicle model with lumped masses supported by springs and dampers using iterative method. The dynamic interaction between dynamic responses of bridges to dynamic wheel loads is presented. Figure 2.2 is a schematic diagram of bridge-vehicle interaction. The roughness input to the vehicle is the sum of the initial surface profile of the bridge and the dynamic deflection of the bridge. This input excites the vehicle and results in dynamic tire forces. These forces are in turn applied to the bridge and cause larger dynamic displacements of the bridge. This feedback mechanism of interaction forces couples the dynamic responses of the bridge to that of the vehicle. From the diagram, the vehicle-bridge interaction is obtained from the comparison of the bridge responses with iterative manner.

Yang et al. (1995, 1999 and 2001) developed some vehicle-bridge interaction elements to solve the dynamic coupling problem. The equations of motion were written for the vehicle and bridge. The vehicle equations were first reduced to equivalent stiffness equations using Newmark's discretization scheme. Then the vehicle degrees of freedom were condensed to those of beam elements in contact. The effects of some parameters, such as bridge length, speed were discussed by using mass-spring-dashpot and beam elements (Yang et al. 1995).

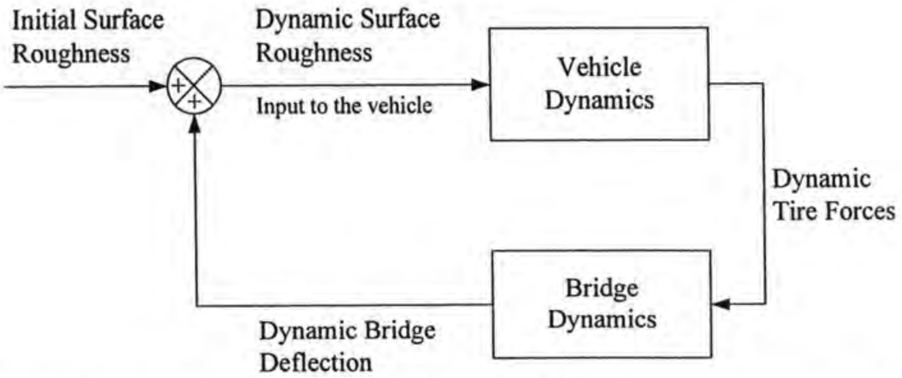

Figure 2.2 Schematic block diagram of dynamic bridge-vehicle interaction (Green and Cebon, 1997)

Henchi et al. (1998) proposed the efficient method to analyze the dynamic interaction problem between a bridge, discretized by a three-dimensional finite element model, and a dynamic system of vehicles running at a prescribed speed. The resolution is performed with step-by-step solution technique using central difference scheme to solve the coupled equation system. In general, there are two approaches to simulate the dynamic vehicle-bridge interaction. The first one is based on the uncoupled iteration method, in which each system (vehicles and bridge) is solved separately and an iterative process in each time step is performed to find the equilibrium between bridge and vehicle tires. The other approach to simulate the dynamic interaction between vehicles and bridge consists of solving the super system fully coupled, and the solution is given at each time step without iteration. This non-iteration approach has some advantages that reduced the computation time and easy and compact numerical implementation. However, the disadvantages are as follows: modal projection in subspace is indispensable, and if the high frequencies of the bridge participate to the response this will create a problem in the dynamic response; this method is well adapted only for a few number of vehicles present on the bridge at the same time (this remark also applies to the uncoupled modal iterative method).

Chan et al. (2003) presented the formulation of a bridge-vehicle system with validation using field data. The three-dimensional vehicle model including pitching and twisting motion was considered. For the tire-suspension system, the effect of interleaf friction is represented by a bilinear diagram of the hysteretic type (Veletsos and Huang, 1970). The bridge was modeled using shell elements. The interaction responses were solved using Newmark method. The obtained responses were validated from the test data and showed that the prediction was valid and feasible. By converting the bridge responses using FFT, the fundamental frequency of the test bridge can be obtained. The parametric study was also presented in terms of dimensionless parameters i.e. mass ratio, speed parameter, frequency ratio and axle spacing parameter. The results showed that the impact factor increases as the increasing of frequency ratio and decreases as the increasing of span length. For the mass ratio, the impact factor generally decreases as the mass ratio increases. However, for a low frequency ratio, the impact factor keeps almost constant with the mass ratio. In case of axle spacing parameter (ASP), the impact factor increases as well as the ASP. The impact factor varies with the vehicle speed but not obvious trend. For the same axle spacing parameter, the impact factor increases with the vehicle speed.

Li (2005) studies the dynamic behavior of vehicle-bridge system by analytical work and validated by field tests. Static and dynamic field tests were performed on a selected two-lane highway bridge on US 90 in northern Florida. The three-span bridge was a concrete structure with simply supported, precast girders and continuous, cast-in-place deck. One or two fully loaded truck(s) crossed over the bridge, which was instrumented with strain gauges, accelerometers and displacement transducers. Data collected from the tests were used for comprehensive assessment of the bridge under dynamic loading and validation of analytical procedures. The vehicle-bridge interaction was investigated using finite element models with different levels of representation. In the simple analytical model, the vehicle was modeled as a 3D mass-spring-damper system with eleven degrees of freedom. The bridge was discretized to a combination of plate and beam elements which represented slab and girders, respectively. The equations of motion for the vehicle were formulated with physical components while with modal components for the bridge. The coupled system was solved step by step using central difference method. More sophisticated bridge models with consistent stiffness and mass distribution and truck models with detailed representation of suspension systems and wheels were developed using LS-DYNA, a commercial explicit FE code. The advanced features of multi point constraint (MPC) and contact algorithm made it suitable in analysis of vehicle – bridge interaction. The advanced features of the truck model included the suspension system allowing wheel rotation, as well as application of internal pressure in tires. The results show that good agreement was found between the field measurement and FE simulations in both frequency domain and time domain. Impact factors were calculated for some overweight vehicles using the validated finite element procedures. The effect of some parameters to bridge response was also investigated, including road roughness, bridge length, vehicle weight, vehicle speed and vehicle/bridge frequency ratio.

2.4 Moving Loads Identification

In the last decade, series of moving loads identification have been presented. Most of identification methods are based on an inverse problem of vehicle-bridge interaction by using bridge responses as input. Many researches conducted on theoretical, experimental or field studies on vehicle weight or axle loads determination and some accuracy improvement methods as follows.

Thater et al. (1998) proposed the equivalent dynamic filter technique for gross vehicle weight on the bridge identification. This method separated the dynamic and pseudo static response by Fast Fourier Transform. The example applications of the proposed method are shown by using computer simulation. It was found that this method is fast and improves the predicted gross truck weight up to 5% of actual weight. However, this method cannot predict the axle load of truck. Moreover, in the case of high speed vehicle or short span bridge, the vibration frequency of the bridge from the moving vehicle is closed to the natural frequency of the bridge. Therefore, the filter technique cannot be used accurately.

Law et al. (1997) proposed the time-domain identification method for axle loads on the bridge by using a set of second order differential equations and identified the axle load histories by convolution in time-domain. The identified moving loads were assumed as group of point loads with constant spacing. The solution can be obtained by performing direct inverse of the relationship between measured responses and unknown acting loads. The study concluded that it is possible to use measured responses to identify moving forces in the time domain with good agreement between measured and calculated responses. However, the identified solution becomes large error at the times when axles approach and leave the bridge.

The frequency-time domain method was proposed by Law et al. (1999). This method identifies axle loads from only the vibration responses induced by the point loads as the input without knowledge of the vehicle characteristics. The method performs the Fourier transformation of the load-response relationship and identified the axle load histories by using least-square method. It was found that the maximum error of this method is up to 20 % when both measured bending moment and acceleration are used.

Chan et al. (1999) proposed a closed-form solution method to identify moving dynamic loads on bridges using the bridge responses caused by such loads. The closed-form solution can be obtained to identify the time-varying moving loads. The set of equations that leads to the solution is based on Euler's beam equation, and a two-axle vehicle model was developed to generate the theoretical responses and the corresponding interactive forces. The identification error was calculated from the percentage error between the generated interactive forces and the identified force. The study found that bridge responses used can be bending moment as obtained from strain gauges or displacement as obtained from linear transducers. The identification from bending moment gives better results compared with using displacement. Besides, although the problem is contaminated with noise, the acceptable solution can be obtained by performing noise filtering.

Chan et al. (2000a and 2001) theoretically and experimentally conducted the comparative studies on moving force identification. The laboratory study using bridge strain responses as input in the identification was presented. The comparative study among interpretive method, time-domain method and frequency-time domain method was discussed. The parametric study on related measurement and input parameters i.e. sampling frequency, number of used modes, vehicle speed level and number of sensors were conducted to obtain the most appropriate method corresponding to the accuracy and computational time. The study concluded that the best method was the time-domain method which is the most robust method to identify the problem with higher accuracy and also capable to identify axle loads of high speed vehicle. Moreover, the computational time for time-domain method is shorter than other methods.

Chan et al. (2000b) studied the moving force identification by using pre-stressed concrete bridge test. A two-axle heavy vehicle was hired for the calibration test of the field measurement. The dynamic bending moments caused by both hired and in-service vehicles were acquired. Dynamic axle forces were identified by means of the time-domain method. Gross weights were obtained by summing up the equivalent static axle load of each axle calculated by performing pseudo-static load, and were compared with those measured at the static weight station. Results show that the axle forces can be identified with the error of results least than 10 % for both hired and in-service vehicles.

Law and Zhu (2000) conducted the comparative study on different beam models in moving force identification. The Tikhonov regularization technique was employed in the least square formulation to provide bounds to the ill-conditioned results in the identification problem. The calculation of the optimal regularization parameter can be obtained by plotting L-Curve proposed by Hansen (1992). Although the problem is noise sensitive, the obtained results from experimental testing in laboratory identified by improved algorithm were less sensitive to noise and provided satisfactory accuracy. The results also indicated that Timoshenko beam model was found better than Euler-Bernoulli beam model.

Zhu and Law (2000) presented a method to identify moving loads on a bridge deck modeled as an orthotropic rectangular plate. The dynamic behavior of the bridge deck under moving loads is analyzed using the orthotropic plate theory and modal superposition principle, and Tikhonov regularization procedure was applied to provide bounds to the identified forces in the time domain. The identified results using a beam model and a plate model of the bridge deck are compared, and the conditions under which the bridge deck can be simplified as an equivalent beam model are discussed. Computer simulations and laboratory tests showed the effectiveness and the validity of the proposed method in identifying forces traveling along the central line or at an eccentric path on the bridge deck. However, the appropriate regularization parameter is required to use for the accuracy of identification.

Law, Chan and Zeng (2001) studied the identification procedure using the regularization technique. The accuracy of moving load identification was influenced by the regularization parameter. Therefore, the appropriate regularization parameter is required to accurately identify the loads. However, there were problems to find the appropriate parameter because it depended on vehicle properties such as the vehicle mass, moving speed, vehicle configuration and it uses significant effort consumes long computing time to determine the optimal regularization parameter.

Law and Fang (2001) presented a new method of moving force identification by using the dynamic programming technique with regularization parameter. The forces in the state-space formulation of the dynamic system are identified in the time domain using a recursive formula based on several distributed measurements of the responses of the structure. The results from the simulation study and laboratory work show great improvements over the previous methods in both accuracy and time consumption of identification. Similar to the previous research, it was found that the accuracy of identification depended on the appropriate regularization parameter.

European Commission DG VII – Transport: WAVE (2001) developed another identification technique for moving loads on bridge using least-square method with optimization technique. Since the axle loads are assumed to be constants on the bridge, the parameters in the optimization become velocity, number of axles, axle spacing and total weight. Two-dimensional bridge model is used to study the effect of eccentricity of the bridge. The field test was investigated to verify the accuracy of identification. The results show that the static load of vehicle has error in the range of ± 10 %.

Leming and Stalford (2002) presented recent work on the development of a weigh-in-motion (WIM) system for use on in-service highway bridges. The problem of processing a bridge's elastic response due to a passing truck and, from it, estimating the truck's axle weights and gross weight are considered. A dynamic model of the bridge that includes its inertial effects is constructed using a finite element model of an Euler beam. The truck is described using two moving point masses. The deflection of the beam at the midpoint is measured over time, and an optimization routine is employed to estimate the values of unknown parameters. The velocity is assumed to be measured by an independent sensor, and the axle spacing is determined from it, leaving only the weights unknown. The estimated values of the axle weights and total weight of the truck converge to within 0.03% of their true values when no measurement noise was present. When measurement noise was added, the axle weights could be estimated to within less than 3% for noise up to 0.1mm in a signal on the order of 0.2mm.

Zhu and Law (2002) presented a time domain method to identify moving loads on a continuous beam from the measured structural vibration response. The regularization technique is used to provide bounds on the solution. Numerical examples demonstrate that a larger number of modes should be included in the identification when accelerations are used instead of strains. The appropriate regularization can be reduced the effect of noise. This method can be used with moving load identification by time domain method and frequency-time domain method by using singular value decomposition (SVD). It was found that the regularization parameter is found to have a very important function to reduce the noise effect and it may also be used to reduce the errors in time domain method and frequency-time domain method.

Yu and Chan (2002) measured bending moment responses of bridge by using scaled model in laboratory. The time domain method (TDM) and frequency-time domain method (FTDM) are used for identifying the two moving wheel loads of a vehicle moving across a bridge. The pseudo-inverse matrix (PI) technique and singular value decomposition technique (SVD) are adopted for solving the over-determined system equation in the TDM and FTDM. The effects of bridge and vehicle parameters on the TDM and FTDM are also investigated. The results show that the SVD technique can effectively improve accuracy of identification when using TDM and FTDM. However, the variation of regularization parameter has more influence to the identification accuracy.

Zhu and Law (2002) conducted parametric study on moving force identification as the practical aspects. The limitations and merits of two identification methods were presented. One was based on the exact solution method (ESM) and the other was based on the finite element method (FEM) with orthogonal function expression. Simulation and laboratory studied on the effect of different influencing factors. It was found that identification using FEM can effectively reduce identification error due to measurement noise than those from ESM. In case of the modal truncation, the FEM requires smaller number of vibration modes than ESM at the same noise level. Both ESM and FEM provide the same order of identification error when six sensors or more are used but the error from ESM is much larger than FEM with respect to increasing of noise level. As well as other mentioned parameters, at the same sampling rate, FEM also provides lower identification error than ESM with the same noise level.

Zhu and Law (2003) applied the proposed identification method to identify moving loads on bridge deck. The dynamic behavior of bridge deck was analyzed by orthotropic plate theory and mode superposition technique. The regularization technique was again employed to stabilize the computations. It was found that the method can identified moving load with a small eccentricity and fail to identify loads with a large eccentricity. The torsional modes were found to be very important in the identification even when the group of loads was moving along the centerline of the bridge deck.

Law et al. (2004) proposed the moving load identification method based on finite element method and condensation technique. Numerical simulations and experimental results demonstrate the efficiency and accuracy of the method to identify a system of general moving loads or interaction forces between the vehicle and the bridge deck. The number of master degrees-of-freedom of the system should be selected smaller than or equal to the number of measured points, and the identified results are relatively not sensitive to the sampling frequency, velocity of vehicle, measurement noise level and road surface roughness when a minimum of eight beam elements are used to model the bridge with measured information from three measuring points.

Yu and Chan (2004) applied the time-domain and frequency-time domain methods to identify the multi-axle vehicle loads from bridge bending moment responses. Two direct solutions which are pseudo inverse and singular value decomposition methods used for over-determined set of equations were adopted. Three-axle vehicle model was designed and constructed in laboratory for validation tests. The results showed that the identified multi-axle vehicle loads were reasonable and acceptable for both the articulated and nonarticulated vehicles. The moving force identification system could correctly identify the multi-axle vehicle loads even if the middle axle of the nonarticulated vehicles was hanging in the air. Three different types of suspension systems, i.e. rigid connection, sprung connection, and pre-compressed sprung connection between vehicle frame and axle respectively, were incorporated in the vehicle models. Results showed that the suspension systems made an obvious impact on dynamic characteristics of vehicles and identification accuracy.

Zhu and Law (2005) developed a moving load identification method for multi-span continuous bridge with elastically supports. The method based on modal superposition and regularization technique was adopted. The vertical translation and rotational springs were included in the model to simulate the elastic bearings and support fixity conditions of the bridge. The results from numerical examples indicated that the proposed method could identify the moving loads accurately on the multi-span bridge with elastic restraints from strain or acceleration measurements. The identification from acceleration responses is less sensitive to the measurement noise than those from strains. The vertical support stiffness has large influence on identification error, particularly when the flexural stiffness of the beam is small.

Similar as in the past studies, the identified forces around internal bridge supports are subjected to large error with high fluctuation.

Chan and Ashebo (2006) theoretically and experimentally studied on the identification of moving force on continuous bridge. The bridge was analyzed using modal superposition satisfying all boundary conditions. The forces were identified from least square method without regularization through singular value decomposition method to avoid difficulty in determination of optimal regularization parameter and to provide the robust solutions. The number and location of sensors used in identification system were studied. The results indicated that it is possible to identify the moving load on continuous bridge with bending moment responses. However, the identified forces around bridge supports provide large identification errors. The identification using a target span was then considered and found that the accuracy was improved but the time-history of the force for all system was not completed.

Yu and Chan (2007) reviewed the current knowledge on factors affecting performance of moving force identification methods under main heading below; background of moving force identification, experimental verification in laboratory and its application in field. It mainly focuses on the potential of four developed identification methods, i.e. Interpretive Method I (IMI), Interpretive Method II (IMII), Time Domain Method (TDM), and Frequency-Time Domain Method (FTDM). Some parameter effects, such as vehicle-bridge parameters, measurement parameters and algorithm parameters, are also discussed. Although there are still many challenges and obstacles to be overcome before these methods can be implemented in practice, some conclusions that have been achieved on moving force identification are highlighted and recommendations served as a good indicator to steer the direction of further work in the field.

Rowley et al. (2008) proposed to apply the method of Tikhonov regularization to the original Moses equations to reduce some of the inaccuracies inherent to the algorithm for axle weights. The optimal regularization parameter is calculated using the L-curve criterion. The new regularized solution to the B-WIM equations is tested using measured data obtained from the passage of a vehicle over a bridge and compared to conventional (Moses) B-WIM solution. It was found that the regularization procedure requires an increase in computational time for the determining the optimal regularization parameter, but it delivers a more robust solution. The importance of choosing the correct influence line has also been demonstrated. The results which utilize the correct influence line, even without regularization, can provide an accuracy in axle weights close to that of gross vehicle weights in a suitable bridge. It appears clear that a combination of experimentally calibrated influence lines and regularization will lead to further improvements in accuracy, even for bridges with high roughness or other sources of inaccuracy.

Bouteldja et al. (2008) presented the last test results obtained with B-WIM carried out in France. The tests assessed the performance of the SiWIM2 on two integral bridges. The influence of the infrastructure on the system performances was pointed out. It was found that the accuracy of the bridge is strongly influenced by the geometrical and structural characteristics of the bridge, the road profile and the vehicle dynamics. A feasibility study must then be carried out before any installation of the system. It is recommended to measure the pavement evenness in order to detect any bump before the bridge, this will help to choose a good candidate bridge used for B-WIM application.

From all mentioned methods, the effective moving load identification methods need an optimal regularization parameter. To obtain the appropriate parameter, significant computation effort and time are required. Moreover, it was found that the optimal regularization parameter depends greatly on vehicle properties such as the vehicle mass, velocity, vehicle configuration, etc. Therefore, in actual application, only the sub-optimal regularization parameter can be determined. To overcome this problem, the regularization method with the iterative technique called the updated static component (USC) technique is proposed (Akarawittayapoom, 2003 and Pinkaew, 2006). This method decomposes the axle loads into static and dynamic components and keeps updating the static component through the regularization of the associated dynamic component until the convergent solution is achieved.

Akarawittayapoom (2003) studied the moving load identification method by dynamic programming method and improved the accuracy by adopting the USC technique. The computer simulation and scaled model test in laboratory are employed to investigate the accuracy of this method and effect of variables to identification method. It was found that the velocity and the roughness of the surface have more influence than other variables. The obtained results show that the accuracy of static weight identification is within the range of ±5 %.

Asnachinda (2004) and Pinkaew and Asnachinda (2007) studied the dynamic programming method to identify the truck weight by scaled model test in laboratory. The test investigated effects of the various factors including mass and velocity of truck, roughness of bridge surface, transverse position of truck, type of bridge supports e.g. simple support and continuous bridges, and number of truck axles. Moreover, the dynamic axle loads of the truck model are measured in order to study their characteristics. It was found that using the strain obtained from averaging strains in same section can significantly reduce the torsional effect of bridge due to transverse position of the truck. The identification error increases as the roughness level increases. The effect of support conditions is considered, the one-span bridge with simple supports yields better weight identification results than those from the continuous bridge. It is also found that, the weight error of about ± 5% is achieved when the two-axle truck moving on one-span simple support bridge with smooth surface. However this error becomes as high as ± 20% for the fixed end bridge having high surface roughness.

Foongsook (2005) studied the moving truck weight identification by actual field testing using the dynamic programming method with USC technique. The study considered the effects of mass, velocity, moving path of truck and surface roughness of bridge. The prestressed concrete bridge with 10 meters span length and 14 meters in width was chosen. A 10-wheel truck with weight between 20-26 tons was used. The 36 strain gauges were installed to record the strain signals during the passages of truck for using in moving load identification. From 51 runs of truck passages, it was found that using averaging of section strain with weighing procedure to identify the truck weight provides sufficient identification accuracy. In general, the identification results exhibit the identification errors within ± 50 %, ± 10 %, ± 6% for front axle weight, rear axle weight and total weight, respectively.

2.5 Bridge Live Load Models

Nowak and Hong (1991) summarized the available data base and formulated the approach to calculating maximum moments and shears for various time periods. The live-load data are based on truck-survey result. The maximum load effects for time periods from one day to 75 years are derived by extrapolations and simulations. It was found that the single lane is governed by a single truck for spans up to 100-120 ft (30-36 m) for moments and 90 ft for shears. Two trucks following behind each other govern for long span. For two lanes, the maximum effect is obtained for two trucks side-by-side, with fully correlated weights. The ratio of the mean maximum 75-year moment to AASHTO type HS20 moment (1989) per girder varies. It is larger for shorter spans and girder spacing.

Nowak (1993a) developed the live load model for highway bridges. The model is derived from truck surveys, WIM measurements and other observation. Extreme 75 year loads are determined by extrapolation. The maximum load is calculated by simulation. The analysis indicates that the AASHTO (1989) is conservative in most cases, in particular for larger girder spacing. The developed live load model served as a basis for the development of new design provisions in US (LRFD AASHTO) and Canada (Ontario Highway Bridge Design Code).

Nowak et al. (1993b) determined the truck-load spectra for highway bridges. The WIM data in this study is over 600,000. The information includes axle loads and axle spacing. Bridge load is considered in term of moments and shears. Therefore, maximum moments and shears are calculated for each truck for various span lengths. The results are plotted on the normal-probability paper to facilitate statistical interpretation. The cumulative distribution functions of moments and shears are used to extrapolate the results to predict the maximum forces in longer time periods, up to 75 years. It was observed that the surveyed trucks do not exceed Michigan's legal loads; however, a state police officer expressed his suspicion that the actual loads are higher and that very heavy trucks avoid weighing stations. The maximum moments and shears for longer time periods are calculated by extrapolation of the CDF's. For 75 years, the expected maximum moments are 2.05-2.30 times the HS-20 moments.

Nowak (1995) presented the procedures used in the calibration of new load and resistance factor design (LRFD) bridge code. The new code is based on a probability-based approach. Structural performance is measured in term of the reliability (or probability of failure). Load and resistance factors are derived so that the reliability of bridge designed using the proposed provisions will be at the predefined target level. A new live load model is proposed, which provides a consistent safety margin for a wide spectrum of spans. The reliability indices for bridges designed using the proposed code are compared with the reliability indices corresponding to the current specification. The proposed code provisions allow for a consistent design with a uniform level of reliability.

Miao and Chan (2002) proposed a new method for deriving highway bridge live load for short span bridges. The development is based on a 'repeatable' methodology to obtain extreme daily moments and shears using 10 years Hong Kong Weigh-In-Motion (WIM) data as compared to the traditional normal probability paper approach (Nowak, 1993a). The methodology can also be applied to the development of bridge live loading models in other parts of the world. Two types of loading are proposed. A methodology based on the equivalent base length concept is used to derive the lane loading model and the standard truck loading model is developed based on a statistical approach. The developed lane and truck loadings are compared with other loading models adopted locally and overseas. Based on the statistical and probability approach, the bridge design loading is developed at the first time in Hong Kong by using actual acquired load data.

Nowak and Ferrand (2004) presented the development of live load model using field measurement of truck load and live load effect in bridge components. The major truck parameters include gross vehicle weight (GVW), axle weights, and axle configuration (spacing). These parameters can be measured using Weigh-In-Motion technique, invisible to the drivers (to avoid bias). The tests were carried out on 7 bridges located on various types of road in the greater Detroit Area. The results of measurements indicate that the traffic is strongly site specific. The maximum lane moments and shears due to the measured trucks vary between 0.6 and 2.0 times AASHTO LRFD 1998 values.

2.6 Summary

From the past research studies, it is found that many approaches of moving load identifications have been continuously studied and developed. The vehicle-bridge system can be solved either model analysis using mode superposition through exact solution method or finite element method. It was found that using finite element method in moving load identification is more robust to noise level and appropriate for practice than exact solution method. The simple least square objective function has been widely used in optimization procedure. The regularization technique has been adopted to overcome this noise sensitive problem. The difficulty in assigning an optimal regularization can be carried out by updated static component (USC) technique.

Existing research studies have shown that the identification methods using the static axle load optimization with influence line method and regularization with USC technique can provide accurate identified axle loads and seem to be feasible for real application. However, most of the studies rely on the numerical simulation and the experimental investigation. Although a broad spectrum of the vehicle parameters and bridge properties can be extensively investigated, it is known that real vehicle-bridge interaction behaviors are complex and might significantly differ from those mathematical model used in numerical simulation or small-scale model used in experiment. Therefore, the full-scale investigation of moving vehicles on an actual bridge becomes a primary interest. In the past, there was a full-scale study on the actual bridge, the study, however, employed the identification method without regularization and only a limit number of test conditions was considered. In addition, the application of the B-WIM system, which is invisible to the truck drivers, for long-term monitoring of truck data has been never conducted. Therefore, the installation of B-WIM system in the actual road network can provide very useful traffic load information that may be used to evaluate the existing bridge design standard of the country.