Intelligent Weigh-in-Motion Systems

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Weigh-in-motion (WIM) systems are used to automatically determine the weights of trucks passing over transducers without requiring those vehicles to stop. Although these devices have been in existence for more than 40 years and are now being deployed on a significant scale, unresolved problems associated with their installation, maintenance, and use prevent them from attaining high levels of accuracy. These problems are directly related to the fact that WIM systems are used to estimate static weights on the basis of the dynamic forces produced by axles that are oscillating continuously and in a complex manner. Existing approaches to WIM rely on empirical methods to interpret dynamic measurements to provide equivalent static information. The algorithms used in these methods are generally more than 10 years old. Although they usually incorporate the best technology available at the time of their development, they do not explicitly address the vehicles, WIM transducers, pavement profile, and pavement structure as a single complex dynamic system. Recent advances in both hardware (sensors and computers) and software technology now allow the dynamic phenomenon of truck axle weight fluctuations in the context of the vehicle-transducer-pavement system to be identified, quantified, characterized, and explicitly included in the interpretation of WIM sensor output signals. The general problem of weighing trucks in motion and its proposed solution using advanced sensor technology, signal processing algorithms, and analytical techniques, including the application of artificial intelligence, are addressed. The current status of the research to accomplish these objectives is also presented.

A WIM system is defined in the new ASTM Standard E1318, *Standard Specification for Weigh-in-Motion (WIM) Systems with User Requirements and Test Method*, as a set of sensors and supporting instruments that measures the presence of a moving vehicle and the related dynamic tire forces at specified locations with respect to time; estimates tire loads, speed, axle spacing, vehicle class according to axle arrangement, and other parameters concerning the vehicle; and processes, displays, and stores this information.

Attempts have been made for more than 40 years to weigh vehicles without requiring them to stop. Reliable and durable weigh-in-motion (WIM) systems are now available and are being deployed in every state. However, many installations of WIM systems operate at marginally acceptable levels of accuracy because of the following factors that are external to the WIM system itself:

1. The dynamic response characteristics of the vehicle,
2. The dynamic response characteristics of the pavement as the tires of the vehicle pass over it, and
3. The profile of the pavement approaching the WIM weight sensor.

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An approach to reducing the adverse effects of these factors is offered. The next section discusses the most recent relevant efforts to define standard specifications for accuracy.

ACCURACY STANDARDS

The purchase of WIM equipment requires the specification of acceptable accuracy levels. This procurement process has been aided by the products of three recent relevant research activities, two of which have recommended levels of accuracy. These activities include a study within the heavy-vehicle electronic license plate (HELP) program, a volunteer effort within ASTM, and NCHRP Research Study 3-39, *Evaluation and Calibration Procedures for WIM Systems*.

WIM system standards were developed in the HELP project for both permanent and portable WIM systems (*1*). The HELP WIM accuracy standards were developed on the basis of results of field tests conducted at (assumedly) typical installations of each WIM system commercially available in the United States. This study was conducted to ensure that WIM specifications to be used within the HELP program would be reasonable both for vendors and for the participating states. Although efforts were made to select a good evaluation site for each system, it was recognized that the potential accuracy level for each system was likely to be adversely affected by a less-than-smooth approach pavement profile and other external factors such as those listed earlier.

WIM Standard E1318, which was developed within the consensus-building environment of ASTM, was completed and approved on January 2, 1990. The accuracy values used by ASTM were based on the experience of participants from industry, state and federal agencies, and academic and research institutions. The results of previous research, including the HELP WIM study, were considered in this process.

One of the most important elements of the ASTM document is its definition of the following four types of WIM systems (ASTM E1318):

1. Type I, designed for permanent or semipermanent installation at traffic data collection sites.
2. Type II, designed for portable use at traffic data collection sites.
3. Type III, designed for installation at weight enforcement stations to identify approaching vehicles suspected of weight violations.
4. Type IV, designed for use at weight enforcement stations to detect weight limit violations.

The ASTM standard recommends the accuracy levels presented in Table 1 for each type of WIM system.

TABLE 1 FUNCTIONAL PERFORMANCE REQUIREMENTS FOR WIM SYSTEMS

Function	Probability for 95% Conformity				
	Type I	Type II	Type III	Type IV	
				Value ≥ (lb)	± (lb)
Wheel Load	±25 %		±20 %	5,000	250
Axle Load	±20 %	±30 %	±15 %	12,000	500
Axle Group Load	±15 %	±20 %	±10 %	25,000	1,200
Gross Vehicle Weight	±10 %	±15 %	±6 %	60,000	2,500
Speed			±1 mph		
Axle Spacing			± 0.5 ft		

The values presented in Table 1 (and in the HELP WIM specification) are significantly greater than those defined for static scales under Handbook 44 (*2*), published by the U.S. Department of Commerce. These rather loose tolerances (compared to Handbook 44) were selected because the attainment of higher values of accuracy is limited by the previously listed factors related to the vehicles being weighed, pavement structural strength, and pavement profile. The ASTM WIM specification partially addresses the potential effects of these factors by providing standards for the profile of the pavement both approaching and departing the WIM sensor.

NCHRP Project 3-39 is intended to develop procedures for testing WIM systems during acceptance, calibration, and periodic verification. It is also providing data that can be used by the ongoing ASTM review activity to revise ASTM Standard 1318.

It is proposed that the WIM transducer, supporting pavement profile, pavement structure, and vehicle be treated as a system rather than independent interacting elements. This view is presented and discussed in the next section.

WIM VEHICLE-TRANSDUCER-PAVEMENT SYSTEM

The dynamics of the WIM vehicle-transducer-pavement system is facilitated by considering the simplified model of a wheel passing over this system as shown in Figure 1. The mass of the vehicle supported by the wheel is shown as m_4 in the figure. The stiffness and damping characteristics of the vehicle's suspension system are indicated by the constants k_4 and c_4, respectively. The mass of the wheel is m_3 and its stiffness and damping constants are k_3 and c_3, respectively. For a WIM transducer installed in the pavement, there are two separate components to be considered—the frame and the active transducer element. The mass of the active transducer is indicated by m_2 with stiffness constant k_2 and damping constant c_2. The mass of the frame is indicated by m_1. The mass of the pavement is indicated by m_p with stiffness constant k_1 and damping constant c_1. The displacement of the WIM transducer is $(x_2 - x_1)$. The vertical velocity of the wheel is $(\dot{x}_3 - \dot{x}_2)$ and the displacement of the wheel is $(x_3 - x_2)$. The vertical acceleration of the wheel is $(\ddot{x}_3 - \ddot{x}_2)$.

Four simultaneous equations describing the dynamics of Figure 1 can be written and solved to predict the vertical

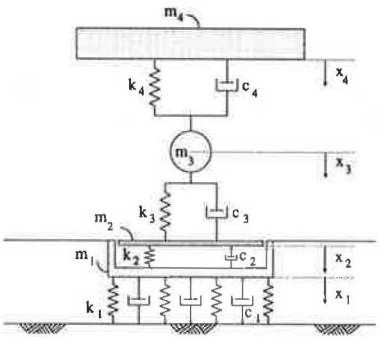

FIGURE 1 Simple dynamic model of a vehicle passing over a WIM device.

acceleration, velocity, and displacement of each of the masses as the vehicle passes over the WIM transducer-pavement subsystem.

The equations of motion are as follows:

$$(m_p + m_1)\ddot{x}_1 - c_1\dot{x}_1 - k_1x_1 = 0 \tag{1}$$

$$m_2\ddot{x}_2 - k_2(x_2 - x_1) = 0 \tag{2}$$

$$m_3\ddot{x}_3 - c_3(\dot{x}_3 - \dot{x}_2) - k_3(x_3 - x_2) = 0 \tag{3}$$

$$m_4\ddot{x}_4 - c_4(\dot{x}_4 - \dot{x}_3) - k_4(x_4 - x_3) = 0 \tag{4}$$

The portion of the force imparted by a passing wheel to the WIM transducer-pavement subsystem actually "seen" by the transducer is the quantity of interest in interpreting WIM data. Equation 5, which has been derived for this purpose, yields the ratio of the measured force to the actual force applied.

$$\frac{\text{Force measured}}{\text{Actual force applied}} = \frac{k_2(x_2 - x_1)}{k_3(x_3 - x_2) + c_3(\dot{x}_3 - \dot{x}_2)} \tag{5}$$

If the pavement is rigid, there is (theoretically) no vertical acceleration, velocity, or displacement of the pavement or the transducer frame. In that case, the term x_1 in the numerator of Equation 5 is zero and all of the force applied by the wheel

is actually seen by the WIM transducer. As x_1 increases from zero (i.e., when the pavement is not rigid), the force applied to the transducer is reduced proportionately.

A computer model based on the principles contained in the previous discussion is included in the intelligent WIM system being developed in this research.

Environmental Effects

When the performance of a particular WIM system varies significantly with temperature, the vendor supplies temperature correction capabilities through use of a temperature coefficient. However, in reality this approach can be accurately applied only to the placement of the WIM transducer on rigid pavement. When the pavement is flexible, the temperature constant used by the vendor cannot accommodate the change with temperature of the spring and damping constants of the pavement.

Moisture changes, not addressed by vendors, can have a significant effect on the pavement spring and damping coefficients. The impact of temperature and moisture on the pavement response and the ways to account for these factors are being addressed explicitly in the intelligent WIM system under development in this research.

Effect of Pavement Profile

It is well known that the approach pavement profile affects the performance of WIM systems. The effects of the dynamics of the vehicle are manifested in the complex oscillation of both the truck axles and truck body at frequencies between 1 and 30 Hz. If accurate weighing is to be achieved, it is necessary to monitor or predict these oscillations. The former can be accomplished by judicious wheel load sampling approaches.

The elimination of the dynamic effects caused by the pavement profile requires measurement of the profile of the road surface for approximately 500 ft in advance of and 100 ft after the location of the WIM sensor. This procedure is required because of the fact that the complex oscillation of the truck axles and body is induced, in part, by the stimulus caused by passing over a pavement surface that is not completely flat, smooth, and level.

The resulting data can then be used in a computer software program to eliminate the differences between dynamic and static weights. This approach is being taken in the development of the intelligent WIM system in this research.

Discussion of the details of the intelligent WIM system now under development is aided by presenting a brief overview of artificial intelligence in the next section.

ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) is "a field of study concerned with designing and programming machines to accomplish tasks that people accomplish using intelligence" (*3*). There are several important differences between AI and conventional computer-based approaches, as follows (*3*):

1. Viewpoint of plausible and logical reasoning instead of quantitative calculation;
2. Very knowledge-intensive;
3. Tolerance for errors and imprecise data;
4. Evolutionary design, anticipating addition and change;
5. Knowledge-based design;
6. Inference and deduction capabilities; and
7. Heuristic or approximate problem-solving approach.

These characteristics are well suited to application to an intelligent WIM system as discussed in the next section. It is also useful to consider the generic AI system shown in Figure 2, conceived by Schutzer (*3*).

INTELLIGENT WIM SYSTEM

The application of AI to WIM systems is based on the following assumptions:

1. If sufficient information could be obtained about the characteristics of the vehicle–WIM transducer–pavement system during the weighing of each truck, an intelligent person using appropriate computer hardware and software could determine the static weight of the vehicle.
2. A machine (computer hardware and software system) could be developed to process the same information as the intelligent person to produce the same result of determining the static weight of the vehicle.

The first step in the development of the intelligent WIM system was to design and test a version of the system on the basis of the approach an intelligent person would take to determine the static weight of a vehicle on the basis of data acquired from the vehicle-transducer-pavement system. As discussed previously, these measurements consist of the following types:

1. Pavement profile,
2. Pavement deflection response characteristics,

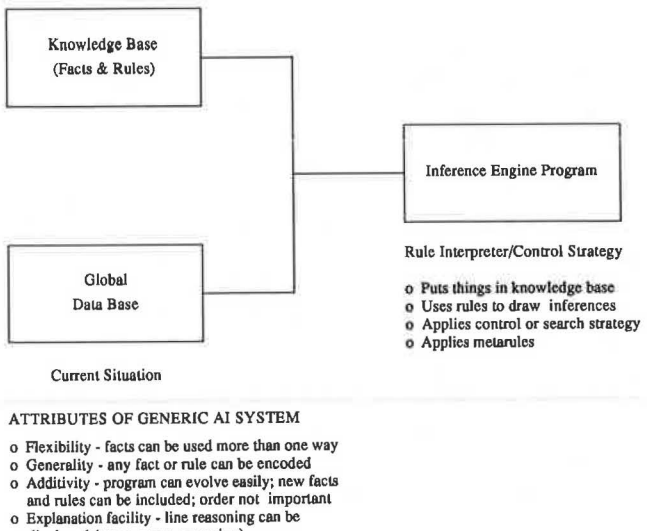

FIGURE 2 Generic AI system (*3*).

3. WIM transducer array output,
4. Pavement moisture content and temperature, and
5. Dynamic load oscillation pattern.

An intelligent person can determine the static load accurately if this information and an appropriate computer simulation program are available. The pavement profile data can be obtained by either automated or manual means. The pavement deflection response characteristics can be determined using nondestructive testing (NDT) devices. The output from the WIM transducer array is directly available. Pavement temperature and moisture content can be measured. The dynamic load oscillation pattern can be acquired either by using a pattern of load sensors in advance of the WIM transducer array or by using an array of WIM transducers.

The methodology used by an intelligent person to perform this analysis must then be defined. This process requires the identification and characterization of the logical decision process that is followed. By definition, this process must be flexible, general, and adaptive to changing conditions. It will be knowledge-intensive because the algorithms required to interpret the different types of data require it. Tolerance of errors and imprecise data is absolutely necessary because each type of data is likely to be imperfect. Because many of the types of data are constantly changing, the system must be evolutionary. The research is currently at this stage. The five types of data listed earlier are included in the process. The pavement profile and pavement response characteristic data are acquired at one time, whereas the WIM output, pavement moisture and temperature, and dynamic load oscillation pattern are acquired continuously.

Once the definition of the methodology is completed, it will be placed in a computer system that is continuously acquiring data from the sensor array. A large data base will then be acquired and used to "train" the system to perform its function with a minimum of errors.

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