2. The collection of truck weight data for all major road classes and for various traffic characteristics within each road class,

3. The capture of maximum variability of truck types, and

4. The selection of locations for the weigh stations so that the weight data can be used with the state's current classification data.

The methodology and plan for truck WIM stations were developed based on the amount of the available information on truck weights and truck classification counts for Texas. The method, however, can be directly applied to any other area of interest with some or no modification.

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The South Dakota Bridge Weigh-in-Motion System

DAVID L. HUFT

ABSTRACT

Following completion of Federal Highway Administration (FHWA)-sponsored research in high-speed weighing of vehicles using instrumented bridges as the load-sensing element, the South Dakota Department of Transportation became interested in the technology as an appropriate means for gathering truck weight information. After unsuccessful efforts to obtain a prototype system from the FHWA, the Department decided in late 1982 to develop its own bridge weigh-in-motion system. Electronic equipment was purchased, weighing software was designed and written, and a motorhome was purchased to house and transport the system. Two bridges were permanently instrumented and used for weighing in 1983. Although it was based on research published during the FHWA-sponsored contracts, the system has been developed independently and differs from the prototype systems. Permanently bonded strain gauges are used instead of removable transducers, and photocells are used rather than tapeswitches to sense axles. Calibration procedures are also different. As of fall 1985, eighteen bridge weigh-in-motion sites in South Dakota are being used to conduct the state's Truck Weight Study on interstate, main rural, secondary and urban highways.

In 1982, research sponsored by the Federal Highway Administration (FHWA) in weigh-in-motion technology--a method of weighing vehicles as they pass over instrumented highway structures--was being completed. One aspect of the research contracts involved development and delivery to the FHWA of three prototype systems that would later be made available to state agencies for purposes of evaluation and demonstration.

When the South Dakota Department of Transportation became aware of the prototype systems, an evaluation of the concept was made. Bridge weigh-in-motion appeared appropriate for use in South Dakota because of its portability, the large number of potential sites available throughout the state, and the relatively low traffic volumes of the state, which were consistent with the system's limitations at that time. The decision was made to pursue acqui-

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sition of one of the prototype systems primarily for collection of unbiased highway design and planning data with possible enforcement applications.

The Department requested that the FHWA make one of the prototype systems available on either a permanent or temporary basis. Other states had also made requests, however, so when timely acquisition seemed unlikely, the decision was made to develop a system independently. At the time the decision was made, commercially available systems appeared to have some shortcomings, particularly with regard to supplying weight information in formats consistent with established Department procedures. The development decision was practical because the necessary technical expertise already existed within the Department.

Equipment acquisition and system development occurred mainly during the winter of 1982-1983, and the first weighing was accomplished in the spring of 1983. Although the system was not completed in time for use in the state's 1983 Truck Weight Study, it was used for accuracy studies and demonstrations throughout 1983 and 1984. Following its present use for the 1985 Truck Weight Study, the system will be used to extend understanding of truck weight information, especially with regard to the effects of time of day, week, and year.

BRIDGE WEIGH-IN-MOTION THEORY

Bridge weigh-in-motion is unique in that the load-sensing element is a highway structure to which strain measurement instrumentation has been attached; the sensitivity of the scale depends on the structure's geometry and the strength of its girders. In contrast to platform scales, where each axle of a vehicle individually occupies the scale for some time interval, a bridge may contain any number of axles at a given time, with each axle's contribution to the girders' bending moment depending on both its weight and its changing location. Considerable computational effort is required to analyze this complex physical system. This section will consider the theoretical aspects of axle location and weight determination, as well as the methods of structure calibration and vehicle classification.

Vehicle Position and Geometry Measurement

Because a load's effect on the structure depends on its location, it is necessary to determine the position of each of the weighed vehicle's axles at the times when girder strain measurements are made. More specifically, it is necessary to compute both an equation of motion that relates vehicle position to time and the vehicle's axle spacings from the times at which each axle passes each of two sensors that are spaced a known distance apart.

If the vehicle's equation of motion $X(t)$ is assumed to be a polynomial in time t, then $X(t)$ may be expressed as

$$X(t) = X_f + \sum_{j=1}^{J} C_j \, t_j \tag{1}$$

where X_f is the coordinate of the first axle sensor and J is the order of the polynomial.

The distance from axle 1 to each other axle may be computed as the difference between the vehicle's position when axle 1 was detected by the first axle sensor and its position when the other axle was detected there. The axle distances may be expressed as

$$D_{fa} = X(t_{fa}) - X(t_{f1})$$

$$= X_f + \sum_{j=1}^{J} C_j t_{fa}^j - X_f - \sum_{j=1}^{J} C_j t_{f1}^j$$

$$= \sum_{j=1}^{J} C_j t_{fa}^j \tag{2}$$

where t_{fa} is the time at which axle a is detected by the first sensor and t_{f1}, the time at which axle 1 is detected at the first sensor, is zero.

Alternatively, the same axle distances may be computed in terms of times at which the axles were detected by the second sensor. If t_{sa} is the time at which axle a is detected at the second sensor, and X_s is the coordinate of the second axle sensor, the axle distances may be expressed as

$$D_{sa} = X(t_{sa}) - X(t_{s1})$$

$$= X(t_{sa}) - X(t_{f1}) + X(t_{f1}) - X(t_{s1})$$

$$= X(t_{sa}) - X(t_{f1}) + X_f - X_s$$

$$= X_f - X_s + \sum_{j=1}^{J} C_j t_{sa}^j \tag{3}$$

If the polynomial expression for $X(t)$ is of degree less than twice the number of axles, coefficients C_j can be found that minimize the differences between distances determined from sensor 1 transition times and those determined from sensor 2 transition times. If the error function E is defined as

$$E = \sum_{a=1}^{A} (D_{sa} - D_{fa})^2$$

$$= \sum_{a=1}^{A} \left\{ X_f - X_s + \sum_{j=1}^{J} \left[C_j \, (t_{sa}^j - t_{fa}^j) \right] \right\}^2$$

$$= \sum_{a=1}^{A} \left(X_f - X_s + \sum_{j=1}^{J} C_j \, H_{aj} \right)^2 \tag{4}$$

where A is the total number of axles, and

$$H_{aj} = t_{sa} - t_{fa}, \tag{5}$$

the coefficients C_j, which minimize E, may be found by equating partial derivatives with respect to each unknown to zero. Then

$$0 = dE/dC_k$$

$$= \sum_{a=1}^{A} \left(X_f - X_s + \sum_{j=1}^{J} C_j \, H_{aj} \right) (-2H_{ak})$$

$$= Y_k - \sum_{j=1}^{J} C_j \, Z_{jk} \tag{6}$$

where

$$Z_{jk} = \sum_{a=1}^{A} H_{aj} \, H_{ak} \tag{7}$$

and

$$Y_k = (X_f - X_s) \sum_{a=1}^{A} H_{ak} \tag{8}$$

It is possible to solve this system of equations,

which may be written in matrix notation as CZ = Y, for the vector C, which determines the axle spacing and equation of motion because Y and Z are known from sensor geometry and axle detection times.

The physical interpretation of this method is as follows. The axle transition times measured at the two sensors provide more information than is required to solve for a polynomial equation of motion. Coefficients most consistent with both sets of time measurements are found, providing the best available estimate of the equation of motion and axle spacings.

Axle Weight Determination

When a load is present on a structure, it induces a bending moment dependent on its magnitude and location on the structure. The total moment induced in a steel or concrete girder structure by a vehicle at any position p is distributed among the individual girders, so the sum of girder moments must equal the total moment. The moment in each girder is related to the girder's strain by the relation

$$M_{gp} = E_g S_g U_{gp} \qquad (9)$$

where E_g is the girder's modulus of elasticity, S_g is its section modulus, and U_{gp} is the strain measured in the girder at that vehicle position. If another term, M_O, is introduced to account for constant or slowly varying offsets related to temperature and instrumentation errors, the total apparent moment M_p measured by an instrumentation system may be expressed as

$$M_p = M_O + \sum_{g=1}^{G} M_{gp} \qquad (10)$$

In terms of axle weights and locations, the predicted moment may be expressed as

$$M'_p = \sum_{a=1}^{A} W_a I_{ap} \qquad (11)$$

where W_a is the weight of axle a. I_{ap} is the moment influence value--that is, the amount of moment induced at the measurement location per unit load applied--of the structure at the coordinate X_{ap} occupied by axle a. The unknown values W_a and M_O may be found by minimizing the error function defined by the squares of differences between measured and predicted moment summed over all vehicle positions as follows:

$$E = \sum_{p=1}^{P} (M_p - M'_p)^2$$
$$= \sum_{p=1}^{P} \left(M_O + \sum_{g=1}^{G} M_{gp} - \sum_{a=1}^{A} W_a I_{ap} \right)^2 \qquad (12)$$

If $M_O = W_O$ and $I(X_{op}) = -1$, this equation may be written as

$$E = \sum_{p=1}^{P} \left(\sum_{g=1}^{G} M_{gp} - \sum_{a=0}^{A} W_a I_{ap} \right)^2 \qquad (13)$$

The values of offset and axle weights that minimize E may be found by differentiating the expression with respect to each unknown and equating to zero as follows:

$$0 = dE/dW_b$$
$$= \sum_{p=1}^{P} \left(\sum_{g=1}^{G} M_{gp} - \sum_{a=1}^{A} W_a I_{ap} \right) (-2I_{bp})$$
$$= Y_b - \sum_{a=1}^{A} W_a Z_{ab} \qquad (14)$$

where

$$Y_b = \sum_{p=1}^{P} \sum_{g=1}^{G} M_{gp} I_{bp} \qquad (15)$$

and

$$Z_{ab} = \sum_{p=1}^{P} I_{ap} I_{bp}. \qquad (16)$$

The system of equations may be written in Matrix notation as Y = WZ, which may be solved for the offset and axle weight vector W, because the vector Y and matrix Z are known from the structure's moment influence line, the girder strain measurements, and axle position information.

Observed moment records contain significant dynamic components resulting from the interaction of the moving vehicle with the profile of the structure and its approach pavement (Figure 1). Because the axle-weight determination method finds weights that would generate moments most consistent with the record observed over the entire bridge length rather than at any one point on the structure, effects of dynamic loading are greatly diminished.

Structure Calibration

The method of axle weight determination assumes that the bridge's moment influence line is known. In practice, it is necessary to either define the line theoretically or determine it empirically. Because the actual behavior of a structure may deviate significantly from theoretical behavior, an empirical calibration method has been chosen.

If the moment influence line is approximated by a piece-wise linear function, calibration can be accomplished by measuring the strains induced by a vehicle of known axle spacing and weight at various positions on the structure. Specifically, if the line is designated by a set of moment influence values (B_j) defined at coordinates X_j, the moment influence value at any axle coordinate X_{ap} on the structure may be expressed as

$$I_{ap} = \sum_{j=1}^{J} B_j R_{jap} \qquad (17)$$

where

$$R_{jap} = (X_{j+1} - X_{ap})/(X_{j+1} - X_j) \quad \text{for } X_j < X_{ap} < X_{j+1}$$
$$= (X_{j-1} - X_{ap})/(X_{j-1} - X_j) \quad \text{for } X_{j-1} < X_{ap} < X_j$$
$$= 0 \quad \text{otherwise} \qquad (18)$$

The equation for total moment at position p may then be written as

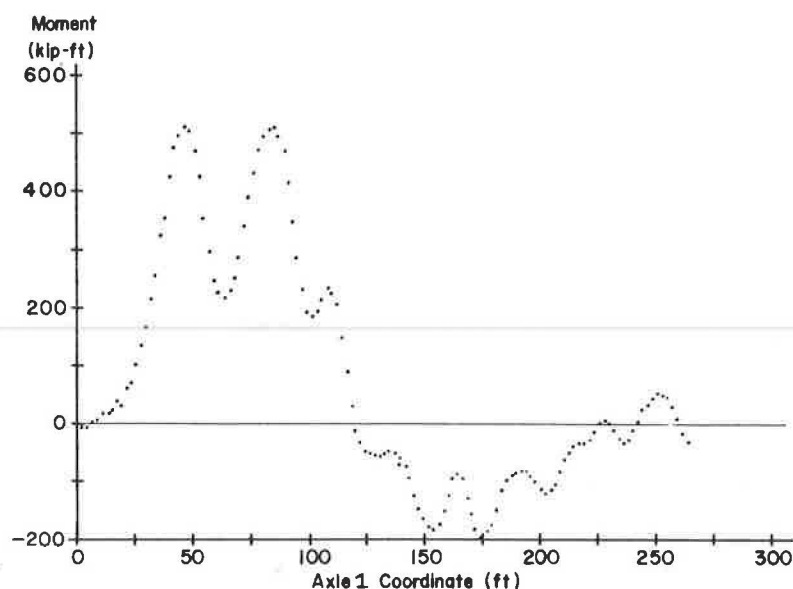$$M'_p = \sum_{j=1}^{J} \sum_{a=1}^{A} W_a B_j R_{jap} \qquad (19)$$

FIGURE 1   Record of total moment induced at strain gauge locations during passage of a five-axle truck-semitrailer combination (note the dynamic components due to vehicle suspension and highway profile interaction).

and the error function of Equation 12 may be written as

$$E = \sum_{p=1}^{P} \left(M_0 + \sum_{g=1}^{G} M_{gp} - \sum_{j=1}^{J} \sum_{a=1}^{A} W_a B_J R_{jap} \right)^2 \qquad (20)$$

If $B_0 = M_0$, and

$$H_{jp} = \sum_{a=1}^{A} W_a R_{jap} \qquad \text{for } j = 1, J$$

$$= -1 \qquad \text{for } j = 0 \qquad (21)$$

The error function can be generalized as

$$E = \sum_{p=1}^{P} \left(\sum_{g=1}^{G} M_{gp} - \sum_{j=0}^{J} B_j H_{jp} \right)^2 \qquad (22)$$

The values of the unknown offset and moment influence values, which minimize the error E, can be found by differentiating with respect to each variable and equating to zero as follows:

$$0 = dE/dB_k$$

$$= \sum_{p=1}^{P} \sum_{g=1}^{G} M_{gp} - \sum_{j=0}^{J} B_j H_{jp} \ (-2H_{kp})$$

$$= \sum_{p=1}^{P} \sum_{g=1}^{G} M_{gp} H_{kp} - \sum_{p=1}^{P} \sum_{j=0}^{J} B_j H_{jp} H_{kp}$$

$$= Y_k - \sum_{j=1}^{J} B_j Z_{jk} \qquad (23)$$

where

$$Y_k = \sum_{p=1}^{P} \sum_{g=1}^{G} M_{gp} H_{kp} \qquad (24)$$

and

$$Z_{jk} = \sum_{p=1}^{P} H_{jp} H_{kp} \qquad (25)$$

Equation 23 may be expressed in matrix notation as $Y = BZ$, and solved for the unknown offset and moment influence values B_j. It is clear that the calibration method is related inversely to the vehicle-weighing method. In the former, axle weights are known and influence values are determined; in the latter, influence values are known and axle weights are determined.

In order for the piece-wise linear moment influence line to be valid, moment influence points must be determined at locations of curve discontinuity. Points are therefore required at span endpoints and at the strain measurement location. In addition, calibration software locates points 50 percent more densely on the strain measurement span than on other spans. A total of 25 to 30 moment influence points will define the moment influence line of a 3-span structure adequately, as is shown in Figure 2.

Vehicle Classification

When trucks are weighed, it is desirable to obtain as much vehicle classification information as possible. By supplementing the computed axle spacing and weight information with the operator's observations, numerical codes for the vehicle, the body and commodity types may be ascertained.

For purposes of the Truck Weight Study, vehicle type is defined to be a 6-digit number specifying the vehicle's overall configuration and axle grouping. Automobiles are assigned a code of 100000, while trucks, tractor-semitrailer, truck-trailer, and tractor-semitrailer-trailer combinations are assigned codes of 200000, 300000, 400000, and 500000 respectively. Likewise, trucks with two full trailers, tractor-semitrailers with two full trailers, and trucks with three full trailers are assigned codes of 600000, 700000, and 800000.

For all heavy trucks, the second through sixth digits are used to specify the vehicle's axle con-
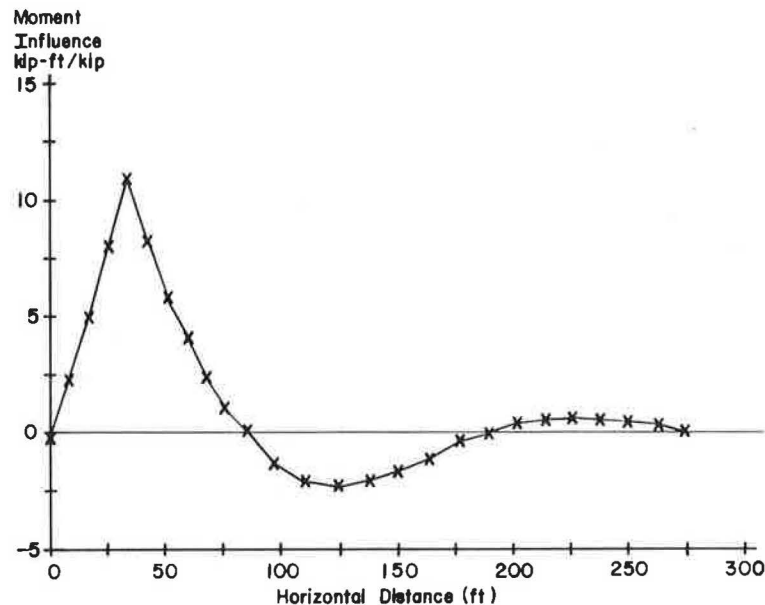
FIGURE 2 Moment influence line determined from calibration using a vehicle of known axle spacing and weight (maximum is attained at strain gauge location and zeros occur at span endpoints).

figuration. For example, a 5-axle tractor semi-trailer is assigned a code of 332000, specifying a 3-axle tractor and a 2-axle semitrailer. A tractor-semitrailer-trailer combination may have a vehicle code of 532400, specifying three tractor axles, two semitrailer axles, and four axles on the trailer. Finally, in the case of light vehicles, a separate towed trailer will modify the vehicle code, as the code for a car towing a cargo trailer 100300 illustrates. In every case, if the vehicle and trailer types (e.g., single unit and tractor semitrailer) are specified from visual observation, axle distance and grouping information can be added to completely and unambiguously specify the vehicle code.

Likewise, a 2-digit code is assigned on the basis of body type. Here, the code specifies whether the vehicle was a car or pickup body, a flatbed, tank, hopper, grain, van, or any other of 53 distinct body types. Although these body types can only be specified by visual observation, correct identification is generally possible even at high vehicle speeds.

Finally, a 5-digit commodity code that is consistent with the system developed by the Bureau of the Budget for transportation reporting purposes is assigned to the load. Because it is not possible to observe enclosed cargoes as they pass by a weighing location, uncertainty exists in the commodity code assignments for closed body types. Accurate assignment is generally possible for open body types.

The scheme developed for use with the weigh-in-motion system utilizes as much visual information as is possible to gather in the available observation period to specify vehicle, body, and commodity codes. In general, a vehicle is identified by up to three mnemonics of three characters each. The first identifies the general vehicle type--car, pickup, single-unit truck, tractor semitrailer, and so forth. If the vehicle is some kind of heavy truck, a body code is also entered. In the case of cars, pickups, and other light vehicle, the vehicle mnemonic itself defines the body code. Finally, if a separate trailer is towed, a trailer mnemonic is entered. A list of possible codes and their meaning is given in Table 1.

The scheme may be illustrated by a limited number of examples. The single mnemonic CAR specifies that the weighed vehicle is an automobile, while the paired mnemonics CAR/CGO designate a car towing a cargo trailer. Similarly, the mnemonic pairs SUT/GRN, 1ST/LUM, and 2ST/REF designate a single-unit grain truck, a tractor-semitrailer hauling lumber, and a refrigerated tractor-semitrailer-trailer combination. Software assigns most probable commodity codes on the basis of body type, so that a commodity code of 01100 corresponding to "field crops" is assigned to the grain truck, a code of 24200 corresponding to "lumber and dimension stock" is assigned to the tractor semitrailer, and a code of 20000 corresponding to "food and kindred products" is assigned to the refrigerated tractor-semitrailer-trailer combination.

A variation to the system described previously is necessary where traffic volumes preclude manual description of every vehicle. If motorcycles, cars, and pickups are automatically classified on the basis of vehicle length and weight, the requirement for manual identification is greatly lessened. Because of the large overlaps between car and pickup weights and dimensions, however, such a classification is only approximate.

SYSTEM DESCRIPTION

The weigh-in-motion system consists of instrumented and calibrated structures; strain, and vehicle position measurement electronics; a digital computer that executes weighing software written by the Department; and a motorhome, which houses the electronics system. Figures 3 and 4 show the general layout and location of components described in the following text.

Structures

Because highway bridges are used to sense vehicle loads, they must be listed first in the system de-

TABLE 1 Vehicle, Trailer, and Body Type Mnemonics and Corresponding Meanings

Classification	Mnemonic
Vehicle Type	
Motorcycle	MOT
Car	CAR
Pickup	PUP
Pickup with camper	PUC
Panel	PNL
Carryall	CYL
Light utility	LUT
Personnel and cargo	PNC
Single unit truck	SUT
Tractor-semitrailer	1ST
Truck-trailer	1TT
Tractor-semitrailer-trailer	2ST
Truck-trailer-trailer	2TT
Tractor-semitrailer-trailer-trailer	3ST
Truck-trailer-trailer-trailer	3TT
Trailer Type	
Camping	CAM
Mobile home	MOB
Cargo	CGO
Boat trailer	BTT
Equipment	EQU
Automobile	ATO
Truck	TRK
Slantback	SLB
Any other	ANY
Body Type	
Motorcycle	MOT
Car	CAR
Pickup	PUP
Pickup with camper	PUC
Panel	PNL
Carryall	CYL
Light utility	LUT
Personnel and cargo	PNC
Flatbed	FLT
Lowboy	LOB
Rack	RAK
Stock	STK
Drill or oil rig	RIG
Lumber	LUM
Log carrier	LOG
Canopy	CNP
Express	EXP
Box	BOX
Grain	GRN
Dump	DMP
Enclosed van	VAN
Refrigerated van	REF
Moving van	MOV
Beverage bottler	BOT
Delivery	DEL
Auto carrier	AUT
Armored	ARM
Boat carrier	BTC
Cement mixer	MIX
Wrecker	WRK
Utilities	UTL
Garbage	GAR
Container	CON
Equipment	EQP
Bare Chassis	CHS
Shop	SHP
Dwelling	DWL
Bus	BUS
Hopper	HOP
Empty log trailer	ELG
No trailer	NTR
Oil distributor	DST
Oil tanker	OIL
Other tank	TNK
Chemical	CHM

scription. As of July 1985, 18 steel girder structures had been instrumented and calibrated for weighing in South Dakota. (Concrete girder structures had been considered for use, but because of the relatively large number of steel structures available, none have been instrumented to date.) All of the instrumented structures have been 3-span, unskewed structures, varying in length from 117 to 337 ft, with six or fewer girders. Although both simple- and continuous-span structures have been used, all have had strain gauges installed on one of the end-spans and influence lines have been computed for the entire bridge length. Some of the structures have had exterior girders whose cross section varied from that of the interior girders; estimates of the girders' design section moduli have been made to compensate for these differences.

The loads passing across an instrumented bridge induce moments that generate strains in each of the structure's girders. Strain magnitudes depend on the magnitude and location of the loads as well as the strength and geometry of the structure, but typically strains of -50 to +200 microstrain will be observed as a single vehicle moves across the bridge.

Strain Measurement Instrumentation

Electrical resistance foil strain gauges are attached to the upper side of the lower flange of each girder, at points equidistant from the girder ends. Two gauges are mounted in a half-bridge configuration at each location; a longitudinally oriented gauge measures the girder's strain while a transversely oriented gauge measures a negative strain (equal to the longitudinal strain multiplied by Poisson's ratio) and provides temperature compensation. Two gauge types have been successfully used. The first is an array of two perpendicularly oriented gauges that are directly bonded to the girder with epoxy. The second consists of two similarly oriented gauges that have been already bonded to a piece of thin metal stock; this type is spot-welded to the girder by a portable, low-power welding unit specifically designed for the task. In either case, leadwires are soldered to the gauges after their attachment to the girder, and the gauge location is sealed with a polyurethane coating. Finally, layers of butyl and neoprene rubber approximately 1/8-in. thick are placed over the gauge location to provide additional protection from moisture and mechanical disturbance. A useful life of approximately 10 years is expected from this type of installation.

The leadwires are run to the end of the structure and terminated with waterproof connectors. During operation, the girder's leadwires are connected to a junction box attached to 100 or 200 ft of multipair, shielded cable, which is run to the instrumentation located in the instrumentation vehicle.

Individual variable excitation, variable-gain, strain gauge amplifiers power each girder's strain gauges and amplify their strain signals. With strain gauge factors of 2.0 and excitation voltages of from 7 to 15 volts, gains of approximately 2,500 to 5,000 are required to amplify the strain signals to levels consistent with the analog-to-digital converter's input range of ±5 volts. The amplifiers are self-balancing—that is, they will automatically balance themselves when a single button is pushed or a remote control balance signal is applied. In practice, it is necessary to rebalance approximately twice per hour to accommodate drifts caused by temperature variations, a task easily accomplished by the operator attending the system. Although the amplifiers were manufactured with switch-selectable, 10-, 100-, 1,000-, and 10,000-Hz, 6-pole, lowpass filters, a filtering frequency between 10 and 100 Hz is more suitable for bridge weighing purposes. By changing capacitor values, the 10,000-Hz filter was changed into a 30-Hz filter, which is used during weighing.

The output signal of each of the six amplifiers is displayed on a digital panel meter in the instrumentation vehicle. Although not required for weight calculation, the meters provide positive indication of proper amplifier balance and strain measurement.
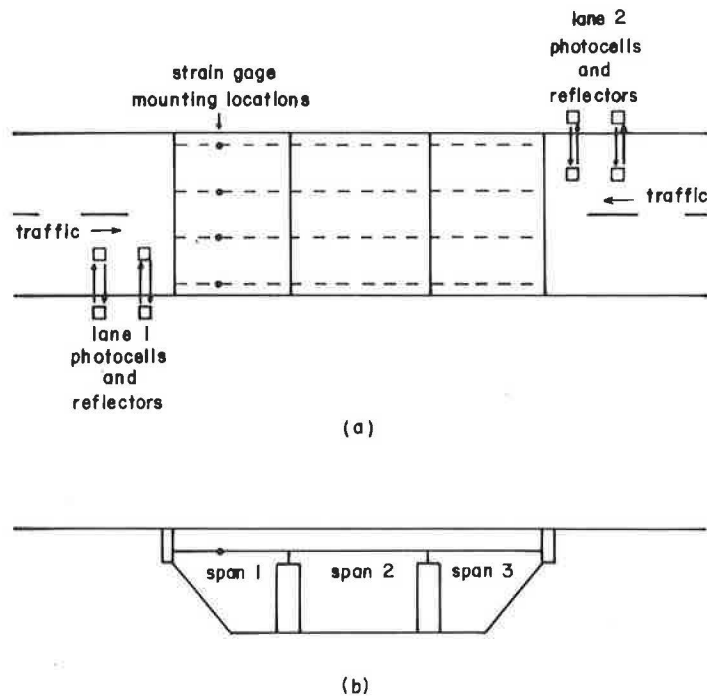
(a)

(b)

FIGURE 3 Plan (a) and profile (b) representations of a typical three-span, four-steel-girder bridge, showing the locations of strain gauges and axle-sensing photocell and reflector pairs.
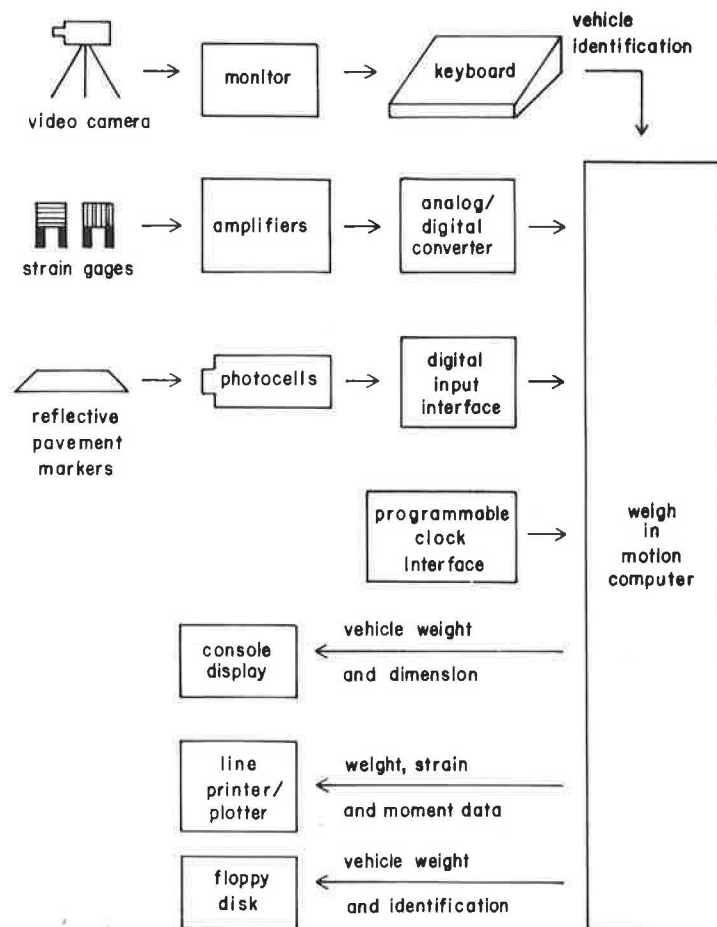

FIGURE 4 Functional diagram of weigh-in-motion instrumentation system.

Vehicle Speed and Geometry Instrumentation

Photocells positioned in the structure approach lanes detect the passage of axles through the bridge. Two infrared, retroreflective photocells are placed on each lane's shoulder a known distance, usually 10 ft, apart. Low-profile reflective pavement markers are placed midlane, at identical distances from the structure as the photocells. When no vehicle is present, the photocell's beam is projected to the pavement marker, then reflected back to the photocell's detection circuit. When a vehicle's axle is present, the beam is blocked and no reflected beam is detected.

The photocells modulate the transmitted infrared beam and then filter and demodulate the reflected beam to minimize the effect of ambient light conditions. The photocell output circuitry is an optically isolated transistor that is electrically equivalent to a mechanical switch contact. When the infrared beam is interrupted, the transistor conducts, as would a closed switch. Digital counters inside the instrumentation vehicle indicate the current status and the number of axles counted by each photocell in each lane, enabling verification or troubleshooting of photocell operation.

The Weigh-in-Motion Computer

A minicomputer continuously monitors girder strain and axle sensor signals, then computes vehicle speeds, axle spacings, and weights from the measurements. It consists of a central processing unit, 128 kilobytes of semiconductor memory, dual 512-kilobyte floppy disks for storage of programs and data, a console terminal for operator interaction, and a small line printer on which weight, moment, and strain data may be printed or plotted.

An optically isolated digital input interface detects transitions between open and blocked photocell conditions. Each input circuit is debounced to eliminate multiple transitions, then converted to logic levels compatible with the computer. When any transition occurs at any photocell, the interface interrupts the computer so that the times of the transitions may be immediately and accurately recorded by a programmable clock interface.

While a vehicle is on the bridge, each girder's strain signal is digitized by the computer's multichannel 12-bit analog-to-digital converter once every 32 msec, a time interval corresponding to a distance of 2.4 ft for a vehicle traveling 55 mph. These measurements are taken and stored in the computer's memory until the vehicle's last axle has left the bridge.

After a vehicle's induced strains and axle sensor times have been completely recorded, axle spacings and weights are computed. Because these computations occur asynchronously with, and at a lower priority than, analog and digital data collection, the computer can continue to collect raw measurement data while completing the analysis of preceding vehicles.

Video Vehicle Identification System

Although South Dakota has a limited number of sites that allow vehicle access beneath instrumented structures, this method of concealing weighing is used where possible. To provide visual information concerning the vehicle's body type and configuration, a portable television camera and video recorder are stationed alongside the highway. Traffic may be observed on a video monitor located in the instrumentation vehicle.

The operator enters a vehicle's identification mnemonics just after it is weighed and its axle configuration is displayed on the computer's monitor. To speed classification, all of the vehicle and trailer type mnemonics and 24 of the most common body type mnemonics may be entered by striking single function keys on the operator's console keyboard.

Motorhome

A standard 22-ft recreational vehicle houses the electronics and provides workspace for the operators. It was purchased complete with refrigerator, stove, water heater, and bath because the price of a standard configuration compared favorably to that of a stripped-down, custom-built vehicle. The only modifications required were removal of one of the captain's chairs to make room for the electronic instrumentation cabinet and installation of a small hatch through which cables are run. The standard air conditioner and 4,000-W gasoline-powered electrical generator have proved to be more than adequate to run the instrumentation system in a controlled climate. To minimize the possibility of passing traffic recognizing the weighing operation, the motorhome is not marked with transportation department insignia.

Costs

Approximate costs of the weigh-in-motion system, exclusive of manpower cost of development and test, are summarized as follows:

Equipment	Approximate Cost ($)
Minicomputer and interface modules	13,000
Strain gauge amplifiers	9,000
Gauges, cables, and connectors	2,000
Photocells and reflectors	1,000
Video camera, recorder, and monitor	1,000
Motorhome equipped with generator	22,000
Total	48,000

The cost of installing permanently attached strain gauges to a structure is between $100 and $200, depending on the number of girders and exclusive of manpower costs. Approximately 2 man-days are required for installation.

Although the system has been operated by one person, a 2-man crew consisting of a permanently assigned technician and one seasonal assistant is normally used for purposes of safety and convenience. Approximately 30 min is required to set up a previously calibrated site for weighing, and another 30 min to detach the system after weighing.

ACCURACY

System accuracy has been determined from comparison of in-motion measurements taken at bridge sites with static measurements taken at nearby permanent or portable enforcement scales operated by the state highway patrol. Vehicles are matched on the basis of detailed visual observation, including truck make, colors, axle configuration, cargo, insignia, and observation time. Because the in-motion sites are located several miles from the enforcement sites, only about one-half the vehicles weighed at one site are observed at the other.

Axle Spacing and Vehicle Speed

With axle sensors spaced 10 ft apart, the accuracy of axle spacings has been found to be plus or minus 0.1 ft within all normal vehicle operation speeds,

except when the vehicle stops or accelerates from a stop in the immediate area of the bridge. Ninety percent of measured speeds have been within 5 percent of speeds indicated by a hand-held radar gun, but the high level of accuracy in the axle spacings suggests that the weigh-in-motion system is probably more accurate than the radar gun used in the studies.

Gross and Axle Weights

Accuracy studies have shown the weighing accuracy to be strongly dependent on the structure used as the load sensing element. Although all of the structures studied to date have been three-span, steel girder structures, they have varied significantly in length and profile smoothness, and have included both continuous and simply supported spans.

Best results have been obtained on the long continuous girder structures with smooth decks and approaches (Figure 5). The probability distributions of the two I-90 sites show that approximately 20 percent of vehicles are weighed with errors of 1 percent or less, approximately 50 percent with errors of 3 percent or less, and virtually all with errors of 10 percent or less.

The poorest performance has been observed at a simply supported structure on U.S. 81 consisting of 3, 39-ft spans, each of which sags significantly. At this site, only 18 percent of trucks were weighed with errors less than 10 percent, and 46 percent of

vehicles had gross weight errors exceeding 20 percent. Unlike weights obtained at other sites, these weights show significant bias, averaging approximately 10 percent higher than static weights. Inspection of vehicle-induced moment plots generated by the weigh-in-motion computer has shown that the dynamic moment record differs from the static moment record not only in high frequency content, but also in overall magnitude and shape. This indicates that the interaction of trucks with the structure's profile is contributing to gross vehicle motion errors that the weight computation method cannot remove. Because these errors depend on vehicle suspension and speed, a general scheme for error compensation would be difficult, if not impossible, to devise. Selection of an alternative site is probably the only workable solution.

At all sites, the variability in axle or axle group weights is much greater than the variability in gross weights. It is not uncommon for an individual axle weight to be in error by 50 percent or more. As might be expected, axle weights are least accurate at sites where gross errors are greatest.

Vehicle, Body, and Commodity Codes

The 6-digit vehicle codes computed from the axle spacings and visual observations have been found to be 100 percent accurate when the operator identifies each vehicle. In the automatic light-vehicle classi-
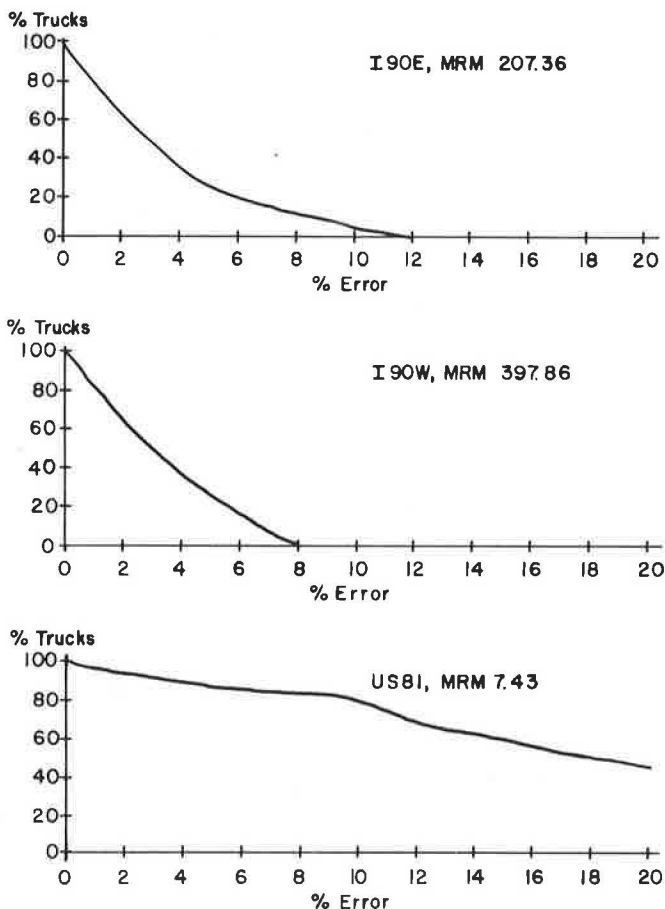

FIGURE 5 Gross weight accuracy illustrated by percent of heavy trucks with errors exceeding given percentages (note that the I-90 sites are long, smooth, continuous-span structures, although the US 81 site is a routh structure with short, simple supported spans).

fication mode, where motorcycles, cars, and pickup trucks are classified without operator input, an estimated 30 percent of cars are classified as pickup trucks or vice versa.

The accuracy of assigned body codes is dependent on factors that affect the quality of observation available to the operator, especially weather, light, and, in the case of vehicles observed by camera, the camera viewing angle. During accuracy studies, the body codes have been determined at 100 percent accuracy, but this level of accuracy is not attainable in all circumstances. It certainly is not possible during nighttime operation.

At the current level of differentiation, correct commodity codes are assigned for 90 percent of heavy trucks. Errors occur mainly from unexpected loads, such as a dump truck hauling steel pipe where a commodity code corresponding to mineral products is incorrectly assigned.

FUTURE PLANS

South Dakota's 1985 Truck Weight Study marks the beginning of sustained use of its bridge weigh-in-motion system. Trucks have been weighed and classified at interstate, main rural, secondary, and urban sites during the summer and fall months. The entire study has been performed at in-motion weighing sites; portable scales used in previous studies have not been used.

Although complete analysis of the data is awaiting changes to the analysis software, the knowledge already gained has prompted new questions and desires for increased system performance. Likewise, questions concerning the use of collected information have also arisen.

System Improvements

South Dakota's version of the bridge weigh-in-motion system does have some problems, some of which will require further system revision and development. First, the photocell and pavement reflector axle sensors will not operate in rain. High-speed vehicles, especially trucks, throw a spray behind their wheels that effectively blocks the photocell's beam, making correct axle count and timing impossible. Although rains are infrequent in South Dakota, the problem is serious enough to warrant development of an alternate axle sensor. Preliminary work has begun using piezoelectric cable sensors, but these are not yet operational.

The permanent strain gauge installations have been attacked by vandals at two different sites located in or close to towns. Steps have been taken to make the leadwires less accessible, but detachable sensors will be required to eliminate the problem.

It would be highly desirable to incorporate weight-validity checking into the weigh-in-motion system. The method of axle weight solution, for example, is mathematically similar to the problem of multiple regression; the unknown axle weights correspond to the unknown regression coefficients. Statistical methods that allow for the calculation of uncertainty in the regression coefficients could perhaps be applied to compute the uncertainty in the weight calculations. Suspect in-motion weights could be flagged and selectively included or excluded from data. To date, only preliminary work has been conducted in this area.

The current version of weighing software only allows for weighing of vehicles that were alone on the structure for a major fraction of its weighing period. Although most of the sites have low traffic volumes (less than 400 vehicles per hour), which minimize the probability of multiple vehicle presence, a significant portion of traffic at two Interstate 90 sites is unweighable because of this limitation. Major changes to the weighing software to compute and use moment influence lines for individual structure girders would allow weighing of simultaneous vehicles, but no decision has yet been made to add this capability.

Finally, development of a portable system capable of unattended operation would be extremely beneficial, especially for use on low-volume highways. Although the system would not enjoy the benefit of an operator's observation of the weighed vehicle's body type, its ability to weigh vehicles for several days would increase the statistical validity of the weights at decreased operator cost. Although no final design has been proposed, it is probable that such a system, which would use already instrumented structures, could be assembled for under $20,000. Work will proceed in this area subject to manpower availability.

Expanded Use in Weighing

Expansion of weighing coverage, both in terms of number of sites and times of weighing activity, will be possible with the system. Although the 1985 Truck Weight Study has been conducted at approximately the same number of sites as previous studies, and during approximately the same time periods, many more potential weigh-in-motion sites exist. Repeated visits to already calibrated sites during other seasons than summer will increase understanding of seasonal traffic and weight variations. Because 24-hr weighing is now feasible, it will be possible to observe time-of-day effects, particularly with regard to overweight loads. All of these options are presently being considered subject to information need and operational and manpower constraints.

Weight Data Implications

Perhaps the most significant future efforts will concern reevaluation of pavement designs and load predictions. Although the Truck Weight Study is not yet complete, it is likely that the loads weighed by in-motion equipment will average heavier than loads previously measured at portable installations because of less truck avoidance. Moreover, individual vehicle weights will have a higher level of uncertainty attached to them. Questions of how design procedures should be altered to accommodate the new information will become extremely important.

CONCLUSION

The bridge weigh-in-motion system developed by the South Dakota Department of Transportation has been proved capable of sustained weighing with accuracies comparable to other in-motion systems. Its continued use beyond the 1985 Truck Weight Study will open up new possibilities for improving the quality of truck weight information throughout the state.