Dynamic Response of Stress-Laminated-Deck Bridges

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The dynamic response of three stress-laminated wood bridges was determined from field test results using a heavily loaded truck. Deflections at the bridge midspan were measured at various vehicle speeds using a high-speed data acquisition system, and a dynamic amplification factor (DAF) was computed. These tests represent only a portion of the field testing, which is part of a larger research study that also includes analytical research. Experimental data described will be used to validate analytical models. The objective of the larger study is to determine the dynamic behavior of stress-laminated wood bridges so that reliable design specifications can be developed. The three bridges represent contrasting approach conditions at the bridge entrance, asphalt and gravel roadways and bridge surfaces, and different natural frequencies. Results show that for smooth in situ conditions at the bridge entrance and an asphalt roadway surface, maximum DAF is 1.08 for a bridge with a relatively high calculated natural frequency (10.6 Hz). For rough conditions at the bridge entrance approach and an asphalt roadway surface, maximum DAF is 1.34 for a bridge with a high calculated natural frequency (10.6 Hz) and 1.20 for a bridge with a low calculated natural frequency (3.2 Hz). The DAF was found to be very high (1.50) at high vehicle speeds for the bridge with gravel surface approach conditions and a calculated frequency of 7.8 Hz.

Wood has been used as a bridge material in the United States for hundreds of years. Despite the exclusive use of wood bridges during much of the 19th century, the 20th century brought a significant decline in the percentage of wood bridges relative to those of other materials. Currently, approximately 10 percent of the bridges listed in the National Bridge Inventory are wood (*1*). There has been a renewed interest in wood as a bridge material recently, and several national programs have been implemented to further develop wood bridge systems. The Timber Bridge Initiative and the Intermodal Surface Transportation Efficiency Act, passed by Congress in 1988 and 1991, respectively, made available funding for timber bridge research (*2*). Part of this research is aimed at refining and developing design criteria for wood bridge systems. This project to investigate the dynamic characteristics of wood bridges is part of that program and involves a cooperative research study among Iowa State University, the USDA Forest Service, Forest Products Laboratory; and FHWA. The first phase of the project is to assess the dynamic characteristics of stress-laminated deck bridges.

Stress-laminated timber bridge decks consist of a series of wood laminations that are placed edgewise between supports and stressed together with high-strength steel bars (*3*). The bar force, which typially ranges from 111.2 to 355.9 kN (25,000 to 80,000 lb), squeezes the laminations together so that the stressed deck acts as a solid wood plate. The concept of stress laminating was developed in Ontario, Canada, in 1976 as a means of rehabilitating nail-laminated lumber decks that delaminated as a result of cyclic loading and variations in wood moisture content (*4,5*). In the 1980s, the concept was adapted for the construction of new bridges, and many structures were successfully built or rehabilitated in Ontario using the stress-laminating concept. The first stress-laminated bridges in the United States were built in the late 1980s. Since then, several hundred stress-laminated timber bridges have been constructed, primarily on low-volume roads.

Background

Highway bridges must be designed for the dynamic loads imposed by passing vehicles. Traditionally, bridges have been designed for static loads and a factor is applied to increase loads to compensate for the dynamic effects. In AASHTO's *Standard Specifications for Highway Bridges*, the dynamic allowance is applied as an impact factor (*6*). The impact factor is computed on the basis of span length and is limited to a maximum of 1.3. Historically, AASHTO has not required that the impact factor be applied for wood bridges because of the ability of wood to absorb shock and carry greater loads for short durations. However, new AASHTO load and resistance factor design (LRFD) specifications require that wood bridges be designed for 50 percent of the dynamic allowance required for steel and concrete bridges.

Recently, the exclusion or reduction of dynamic loading design requirements for wood bridges has been questioned. Many in the design community believe that some adjustment for dynamic effect is appropriate for wood bridges. Unfortunately, little information is available to support changes to current design standards. Since the 1950s, a significant amount of research on the related topic of bridge dynamics, mostly of an analytical nature, and a moderate amount of experimental research have been performed. However, none of the research has dealt specifically with wood bridges, nor has it considered relatively short spans that are typical of wood bridges.

Over the past decade many articles have been published on bridge dynamic behavior. In the interest of brevity, only one article, which is a summary of most of the pertinent experimental dynamics research performed before its publication, is summarized here to discuss the important issues related to experimental evaluation of bridge dynamics. The article by Bakht and Pinjarkar (*7*) presents a testing procedure for determining a single dynamic amplification factor (DAF) for a bridge. Using a single vehicle is not representative of the loads that a bridge will encounter in its life; therefore, a single vehicle can only provide insight into dynamic loading behavior and should not be used to determine a single value of DAF. The only way that a representative value can be determined is to collect data under normal traffic over long periods. From data collected, a statistical procedure using the mean and variance of the measured DAF values with a safety index for highway bridges can be used to obtain a single value.

From previous research, Bakht and Pinjarkar (*7*) found that the DAF decreases with an increase in vehicle weight. Therefore light vehicles, whose loading is insignificant compared with design loads, cause dynamic amplifications that are misleading and excessive. To avoid this, data from light vehicles should not be used to calculate DAF. And DAFs at points away from the load can be greater than those directly under the load. Deflections at points away from the load, which are typically smaller and less important than those under the loading, should not be used in determining DAF; data should be taken only from locations where large deflections occur. Bakht and Pinjarkar suggest using only data from the point at which the maximum static deflection occurs at the monitored cross section.

The use of an artificial bump placed on the road surface to account for riding surface irregularities is common. Bakht and Pinjarkar note that this practice may produce overly conservative results on bridges where the road is well-maintained. A bump should be placed only if the bridge is not expected to be paved for a long time, or if unevenness at the bridge entrance or expansion joints is expected. The authors also point out that there is little uniformity in how the DAF is calculated. Bakht and Pinjarkar (*7*) list eight equations, all giving a slightly different value for a given situation.

Objective

The objective of the research presented here was to determine the dynamic performance characteristics of three stress-laminated timber bridges. The results for these bridges will be combined with results from additional tests still to be performed and complementary analytical research to prepare design criteria to be submitted to AASHTO for inclusion in the *Standard Specification for Highway Bridges* (*6*).

Research Methods

Static and dynamic tests were performed on the three bridges: Trout Road, Little Salmon, and Lampeter. Vertical deflections were measured for several vehicle velocities for two road approach roughnesses. Dynamic deflection data were compared with static deflections to quantify a DAF for each test. The field tests were designed to observe bridge deflections and vertical accelerations of the test vehicle axles. Only the bridge deflection data are presented in this paper.

Bridge Description

The three bridges—Trout Road, Little Salmon, and Lampeter—are located in the commonwealth of Pennsylvania. The bridges are conventional stress-laminated wood decks constructed of sawn lumber (Figure 1). A summary of the characteristics for each bridge is presented in Table 1.

Note that the Little Salmon Bridge was unpaved and the roadway was surfaced with gravel and contained potholes. The region approximately 1.53 m (5 ft) before the bridge entrance was smoothed by filling the potholes with gravel. There was a zero grade in the region approximately 4.58 m (15 ft) before the entrance and a downward grade of approximately 3 percent before this immediate region where no attempt was made to eliminate the potholes. For these reasons, the approach conditions were characterized as irregular.

Both Trout Road and Lampeter bridges were paved asphalt and contained zero grade approach profiles. Immediate approach conditions at the abutment for the Lampeter Bridge could be characterized as excellent (smooth). However, the Trout Road Bridge had a rut at the abutment joint at the entrance that created an irregular surface. The rut was approximately 38.1 mm (1½ in.) deep. Thus, the approach condition was defined as irregular.

Test Vehicles

The vehicles used for bridge testing were three-axle dump trucks provided by the bridge owner. Each vehicle had multileaf spring suspension on the rear axles. Specific vehicle configurations and loads for each bridge are presented in Figure 2. The track width of each test vehicle was 1.83 m (6 ft).

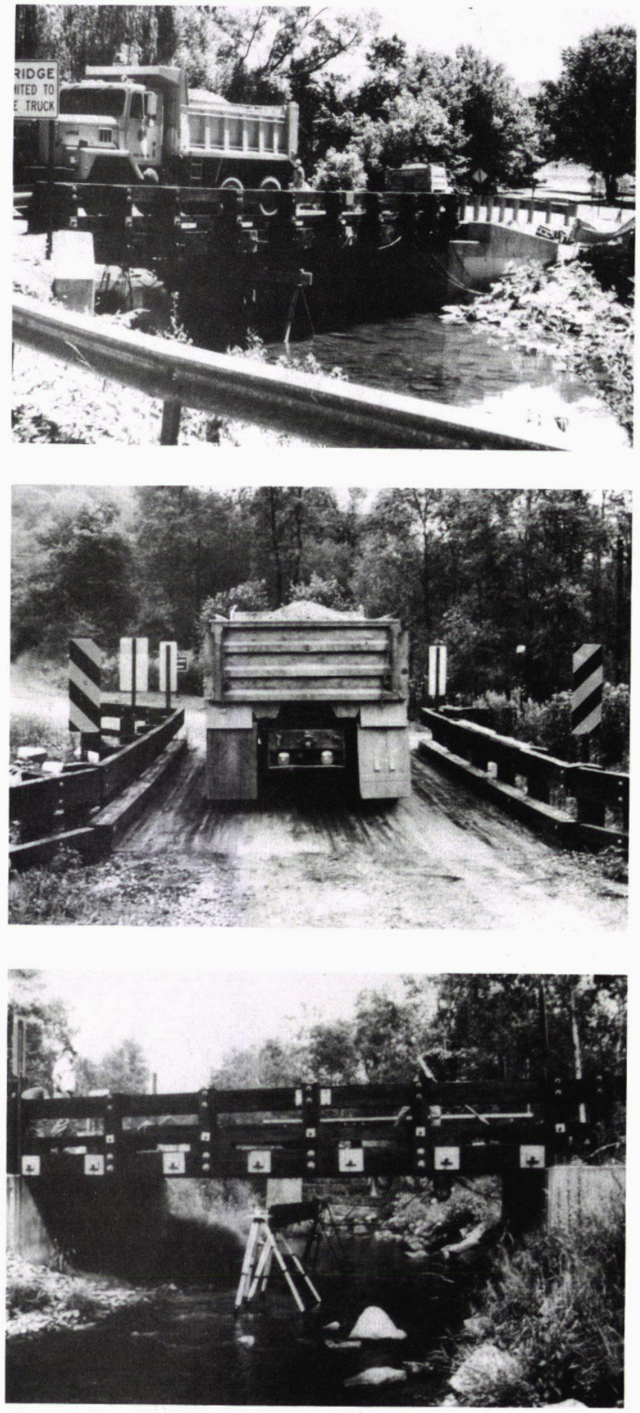


FIGURE 1 Field test bridges: *top*, Trout Road; *middle*, Little Salmon; *bottom*, Lampeter.

Instrumentation

The dynamic response of the bridge at midspan was recorded during the passage of three-axle trucks traveling at constant velocity. The instrumentation system was designed for portability and allowed several tests to be performed in a day. Deflections were measured at approximately 0.61-m (2-ft) intervals across the entire bridge width using a Celesco string-type direct current potentiometer. Such transducers have been used successfully for dynamic application in the laboratory for responses with similar frequency ranges found in these field tests. A frame consisting of

TABLE 1 Characteristics of Tested Bridges

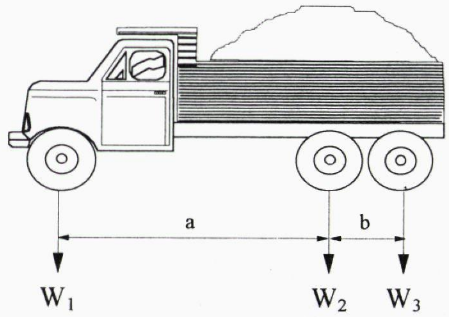
Item	Trout Road	Little Salmon	Lampeter
Year Built	1987	1988	1992
Wood Species	Douglas Fir	Red Oak	Red Oak
Bridge Width (out-out)	7.84 m	4.73 m	9.03 m
Bridge Length (out-out)	14.64 m	7.93 m	7.11 m
Bridge Span (c-c bearings)	14.00 m	7.62 m	6.76 m
Deck Thickness	406.4 mm	304.8 mm	406.4 mm
Approach Roadway Type	Smooth asphalt pavement	Irregular gravel	Smooth asphalt pavement
Approach Grade	0%	0%[a]	0%
Bridge Entrance Conditions	Irregular	Irregular	Smooth
Fundamental Experimental Frequency	3.9 Hz	8.6 Hz	N/A
Fundamental Calculated Frequency	3.2 Hz	7.8 Hz	10.6 Hz
Damping Ratio	4.0%	3.0%	N/A

[a]This grade applies to the region approximately 4.58 m (3.0 ft) in front of the bridge entrance. In the region prior to this, the grade was approximately 3% downward.
1 m = 3.28 ft

surveying tripods supporting a board 50.8 × 304.8 mm (2 × 12 in.) was used to support the displacement transducers (Figure 3). Data were collected using a Hewlett-Packard (HP) 3852A data acquisition/control system (DAS) equipped with two HP 44711 24-channel FET multiplexers and an HP 44702 14-bit high-speed voltmeter. The DAS was controlled and the data were processed and stored in a portable 486DX-33 PC running IBASIC for Windows. Figure 4 (*top*) is a schematic of the test components, and Figure 4 (*bottom*) is a photograph of the DAS setup in the field. The entire system was powered by a portable generator and triggered when the vehicle crossed the tap switch at the bridge entrance.

Acceleration data were also collected on the vehicle simultaneously with the bridge displacement transducer data. The setup consisted of a Gould digital storage oscilloscope (DSO) and two PCB accelerometers. The accelerometers were high-sensitivity integrated-circuit piezoelectrics with a quartz trishear design. The accelerometers were mounted on the vehicle frame over the front and rear axles (Figure 5). They were wired into conditioner modules and from there into the DSO. The DSO was connected to a laptop computer via IEEE-488 interface. Transition software from Gould controlled the DSO so that it waited for a trigger to collect the signals from both channels. Data were then transferred to the laptop, and the DSO was reset for the next trigger. Power to the laptop and oscilloscope was provided by either batteries or the electrical system of the vehicle through the fuse box or cigarette lighter.

A tape switch that was mounted to the front bumper of the vehicle was used to trigger the DSO. A board 50.8 × 304.8 mm (2 × 4 in.) was attached parallel to the bumper to extend the tape switch approximately 0.61 m (2 ft) to the side of the truck to hit a vertical rod placed on the roadway that would trigger the DSO. The rod was positioned so that the DSO was triggered simultaneously with the DAS. This allowed data from both files to be combined to analyze the interaction responses between the vehicle and bridge. A schematic of the vehicle DAS layout, which was located in the passenger cab of the vehicle, is shown in Figure 5 (*bottom*).



Item	Trout Road	Little Salmon	Lampeter
W1	68.9 kN	44.9 kN	60.9 kN
W2	92.3 kN	81.6 kN	79.2 kN
W3	91.6 kN	80.1 kN	76.5 kN
Total Weight	252.8 kN	206.6 kN	216.6 kN
a	3.52 m	3.68 m	4.09 m
b	1.37 m	1.30 m	1.40 m
Rear Suspension Type	Multi-leaf springs	Multi-leaf springs	Multi-leaf springs

1 m = 3.28 ft
1 kN = 0.2248 kips

FIGURE 2 Test vehicle properties.

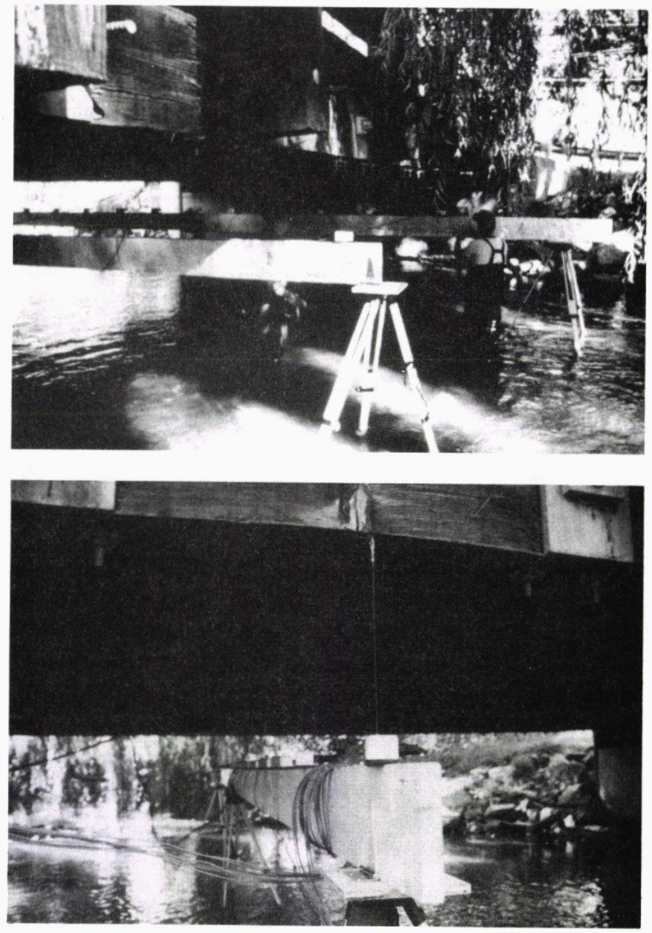


FIGURE 3 Layout of instrumentation for displacement transducer data.

Test Procedure

The dynamic load behavior of the bridge was evaluated for several vehicle velocities for in situ and artificial rough approach conditions at the bridge entrance. Two transverse vehicle positions were used for two-lane bridges: (a) eccentric, with the left wheel line (driver side) 2 ft to the right of centerline, and (b) concentric, with the axle of the truck centered on the bridge (i.e., straddling the centerline). For the single-lane bridge (Little Salmon), only the concentric vehicle position was used. String lines were used to provide a guide for the driver. Visual records were obtained on each run, indicating vehicle deviation from the string line position. Generally, the truck was very close to the required position.

To obtain a basis by which the dynamic load effects could be compared, crawl tests were performed for each loading position. During these crawl tests, the vehicle velocity was approximately 8.05 km/hr (5 mph). Deflections at higher velocities were then obtained; velocities ranged from 16.1 to 64.4 km/hr (10 to 40 mph), depending on the geometry and condition of the approach and available stopping distance beyond the bridge. The artificial rough approach condition was simulated using a board 50.8 × 304.8 mm (2 × 4 in.) placed at the bridge entrance (Figure 6).

The vehicle speedometer was used to control the desired vehicle speed during the tests. However, tape switches were installed at the entrance and at the end of the bridge to verify vehicle velocity.

Data Processing

A plot of bridge deflection and vehicle position along the bridge (using the vehicle front axle as a reference) was made for each displacement transducer location at the bridge midspan. Initially, crawl tests were performed on each bridge to establish a basis for calculating the bridge dynamic response. Figure 7 (*top*) shows a typical response for such a test. Note the small amount of dynamic activity even at crawl speeds, but this was smoothed by fitting a curve to the response. The maximum deflection obtained in this way is referred to by

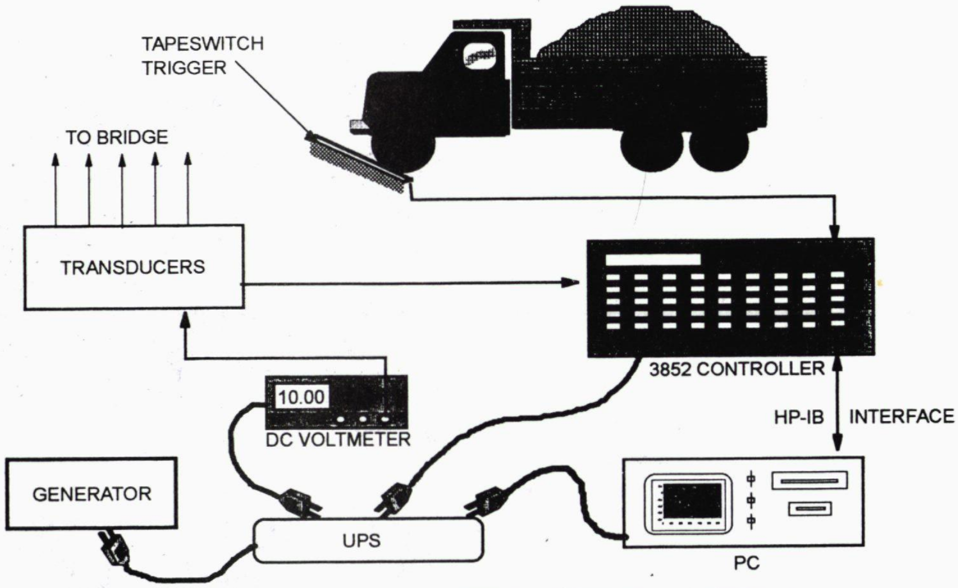


FIGURE 4 Bridge data acquisition system: *top*, layout of test components; *bottom*, data acquisition system in the field.

δ_{stat}. Figure 7 (*bottom*) shows a typical dynamic response relative to the static crawl response just described. The maximum dynamic deflection is referred to by δ_{dyn}.

The DAF was computed for each bridge. Each displacement transducer location was scanned to find the maximum absolute crawl deflection, and this data point was then used as the reference point for the calculation of DAF. As per recommendations by Bakht and Pinjarkar (7), this approach yields the most useful design information. Note that, typically, the data point that had the highest crawl deflection also had the highest dynamic response. Referring to Figure 7, the DAF was computed using the following:

$$\mathrm{DAF} = 1 + \left(\frac{\delta_{dyn} - \delta_{stat}}{\delta_{stat}}\right) \qquad (1)$$

Deflection data were also used to calculate the fundamental frequency of each bridge (Table 1), using the free vibrations of the bridge after the vehicle left the span. This free vibration was also used to determine the amount of damping in the bridge (Table 1). The free vibrations for the Lampeter Bridge were too small to allow a frequency domain analysis to be performed.

The calculated analytical fundamental frequency for each bridge shown in the table was based on finite element analysis. As noted, the experimental values are greater than the analytical values. This is typical, because analytical bridge models do not account for the rotational restraint at the abutments that is inherent in most bridges.

The deck was modeled using rectangular shell elements with four nodes, each with 6 degrees of freedom. However, during the analysis, the in-plane displace-

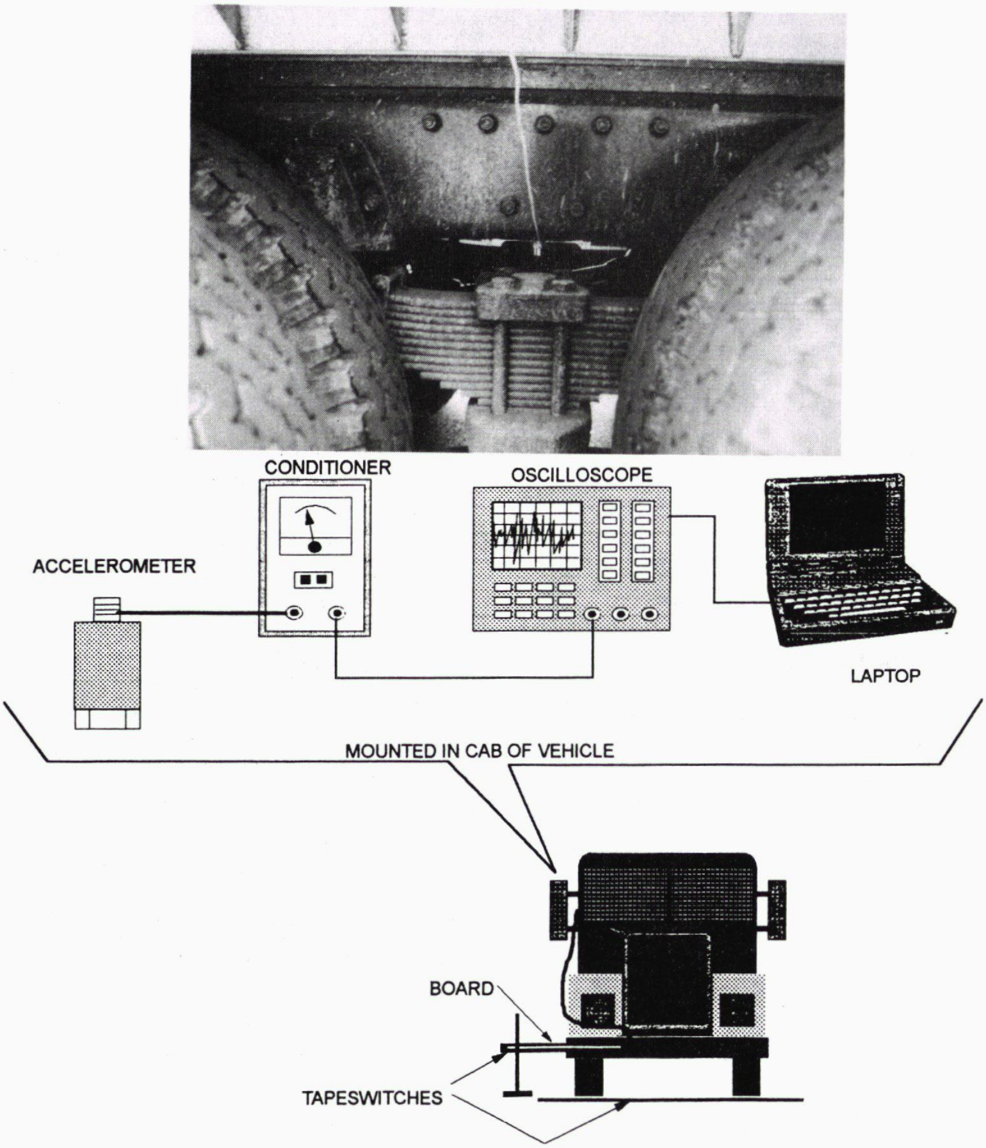


FIGURE 5 Vehicle data acquisition system: *top*, accelerometer mounted on frame; *bottom*, schematic of layout.

ments and rotation were restrained to reduce the total number of degrees of freedom of the bridge model. This had no effect on the analysis, because deck elements behave as plate elements and do not develop in-plane forces or moments.

Test Results

Plots of bridge deflection and vehicle position (using the front axle as the reference point) for various speeds and both in situ and artificial rough approaches are shown in Figures 8 through 10 for each bridge. The legends indicate transverse axle positions (eccentric or concentric), location of the displacement transducer data used for the plot, vehicle velocity, and in situ or artificial rough approach, denoted by (b) for bump along with the vehicle velocity. The Trout Road bridge, as previously mentioned, had an inherently rough approach as a result of ruts in the asphalt surface immediately in front of the bridge approach; therefore, these data should be assumed to be similar to a rough approach condition even though the data are presented as in situ.

A general observation for each bridge is that the dynamic response was significantly greater for the rough approach than for the in situ approach for the Lampeter

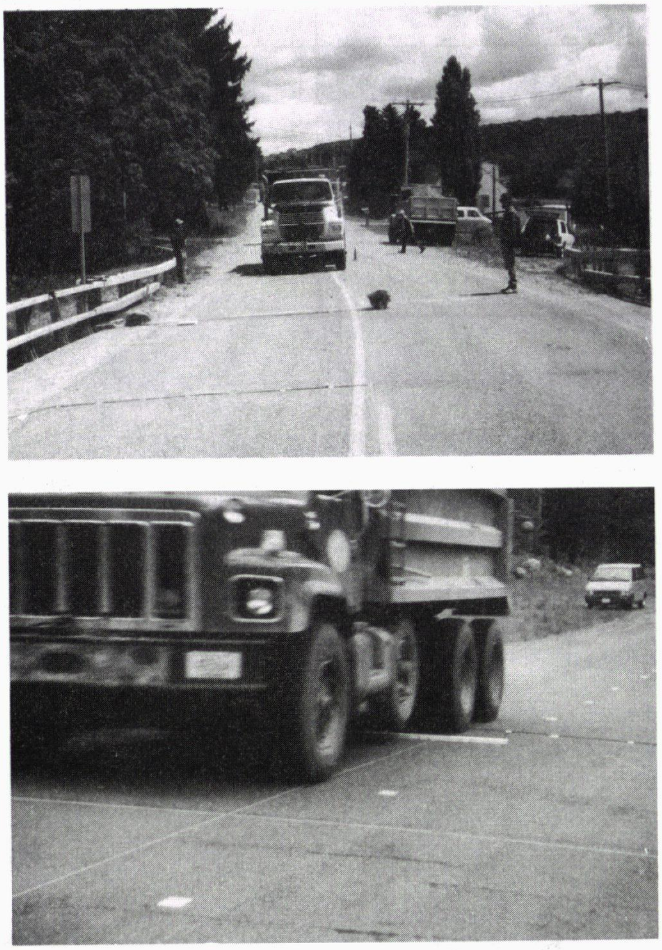


FIGURE 6 Artificial bump at bridge entrance.

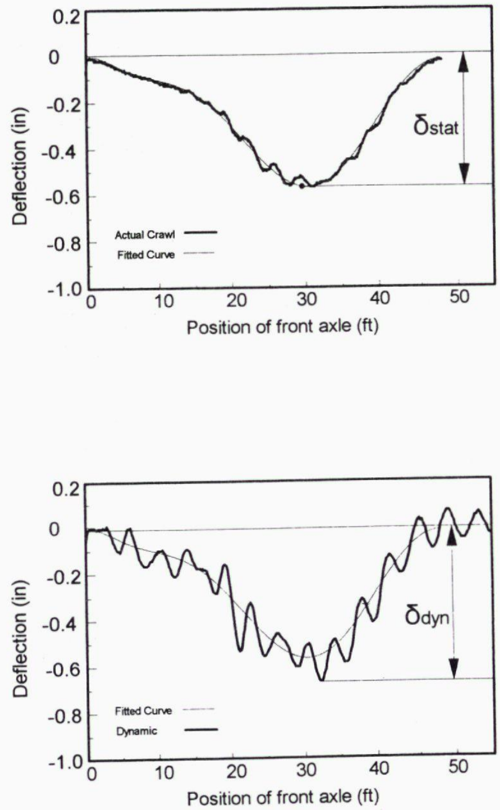


FIGURE 7 Typical displacement transducer data for bridge test: *top*, determination of δ_{stat}; *bottom*, determination of δ_{dyn} (1 in. = 25.4 mm; 1 ft = 0.3048 m).

Bridge. Also, for most velocities on the Little Salmon Bridge, the rough approach dynamic response was greater than the in situ response. Primarily because of the irregular approach condition, these comparisons were not as consistent for the Lampeter Bridge. Another general observation for both the Little Salmon and Lampeter bridges is that the dynamic response for the rough approach exhibited more oscillations than for the in situ approach for similar velocities. Also note for both the Trout Road and Lampeter bridges that the dynamic response was generally greater for the eccentric load position than for the concentric load position. There was excellent repeatability of the results for Lampeter at 53.0 and 52.0 km/hr (32.9 and 32.3 mph) for rough approach conditions.

To clearly quantify the dynamic behavior shown in the plots, the DAFs were calculated for each test for the three bridges and are shown in Figure 11. The maximum DAF for the Trout Road Bridge was 1.20 and occurred for an eccentric load position. As shown, the trend in DAF was similar for both concentric and eccentric positions, with the maximum values occurring at the lower velocities. Bridge roadway horizontal geometry did not allow tests to be performed at speeds in excess of 40.3 km/hr (25 mph).

The trend in DAF values for the Lampeter Bridge was similar for both the in situ and the rough (bump) approach conditions throughout the range of velocities. As shown, the DAF generally increased with increasing velocity, and the maximum DAFs occurred at the higher speeds. The values of DAF for eccentric loading were generally greater than for concentric loading. The maximum DAF was 1.08 for the in situ approach and 1.34 for the rough approach.

Trends in the Little Salmon responses of DAF and vehicle velocity were not as regular as for the other two bridges, primarily because of the irregularity of the approach conditions. For the concentric rough approach, the DAF generally decreased as velocity increased. The maximum DAF was 1.20 and occurred at the lower velocity. However, at lower speeds for the in situ conditions, the trend of decreasing DAF with increasing velocity was also observed; at high velocities, the DAF

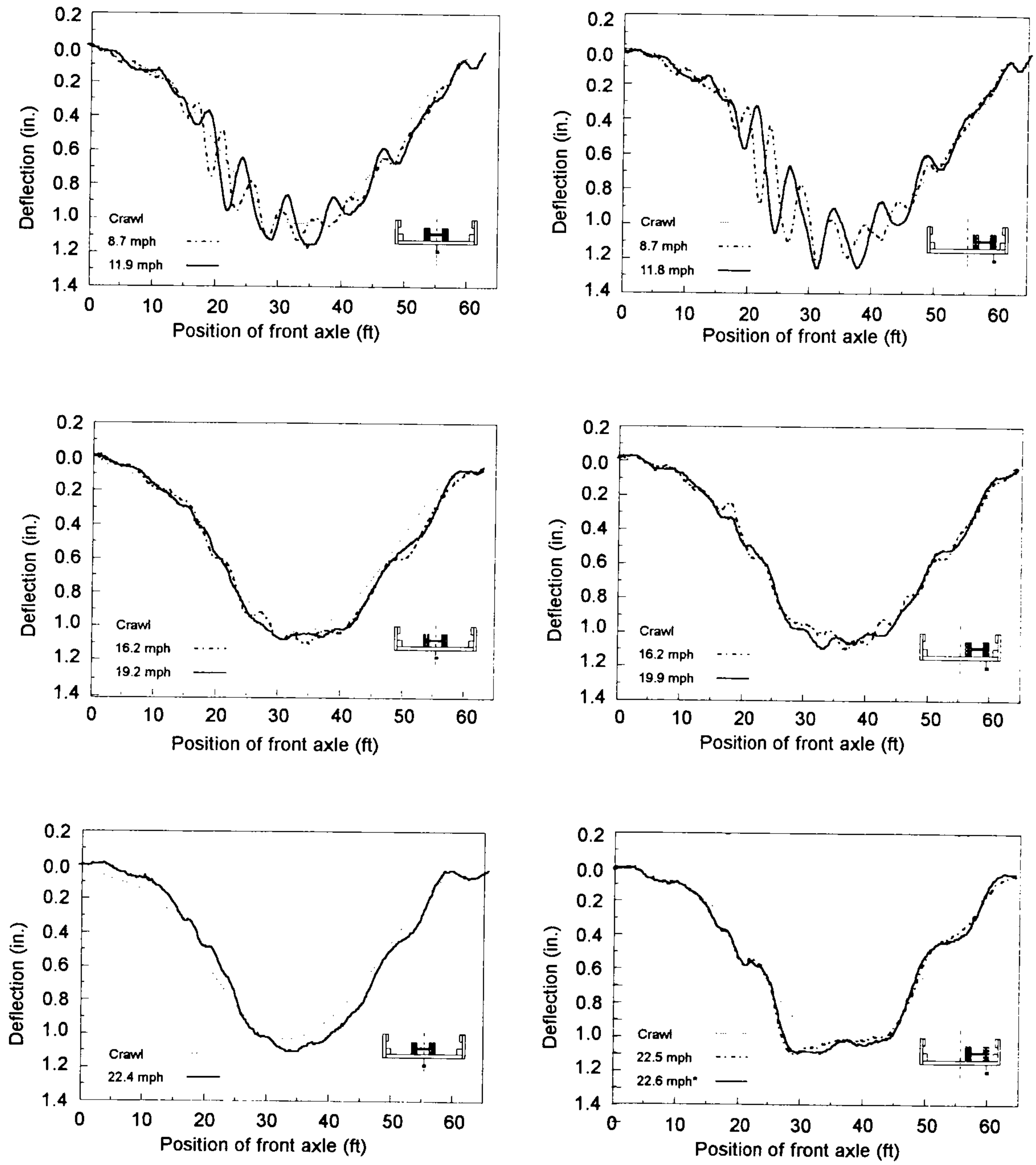


FIGURE 8 Dynamic response for Trout Road Bridge (1 in. = 25.4 mm; 1 ft = 0.3048 m).

increased. In fact, the maximum DAF occurred at the highest velocity and was extremely high (1.50). A possible explanation for this extreme value is that because of the highly irregular approach conditions, the high velocity accentuated the initial conditions of the vehicle (longitudinal pitch and vertical bounce).

Another observation involving the rear axle spacing parameter relative to vehicle velocity is worthy of mention. When the time for the two rear axles to pass a common point is equivalent to the natural period of the bridge, a pseudoresonance condition has been observed experimentally in research by Foster and Oehler (*8*). This condition may affect whether the components of the dynamic response due to each rear axle add or cancel. From the fundamental frequencies for each bridge (Table 1), the natural periods are 0.238, 0.12, and 0.10 sec. for the Trout Road, Little Salmon, and Lampeter bridges, respectively. The velocities at which the rear axle spacing for the test vehicle satisfied pseudoresonance conditions were 20.8, 38.8, and 50.6 km/hr

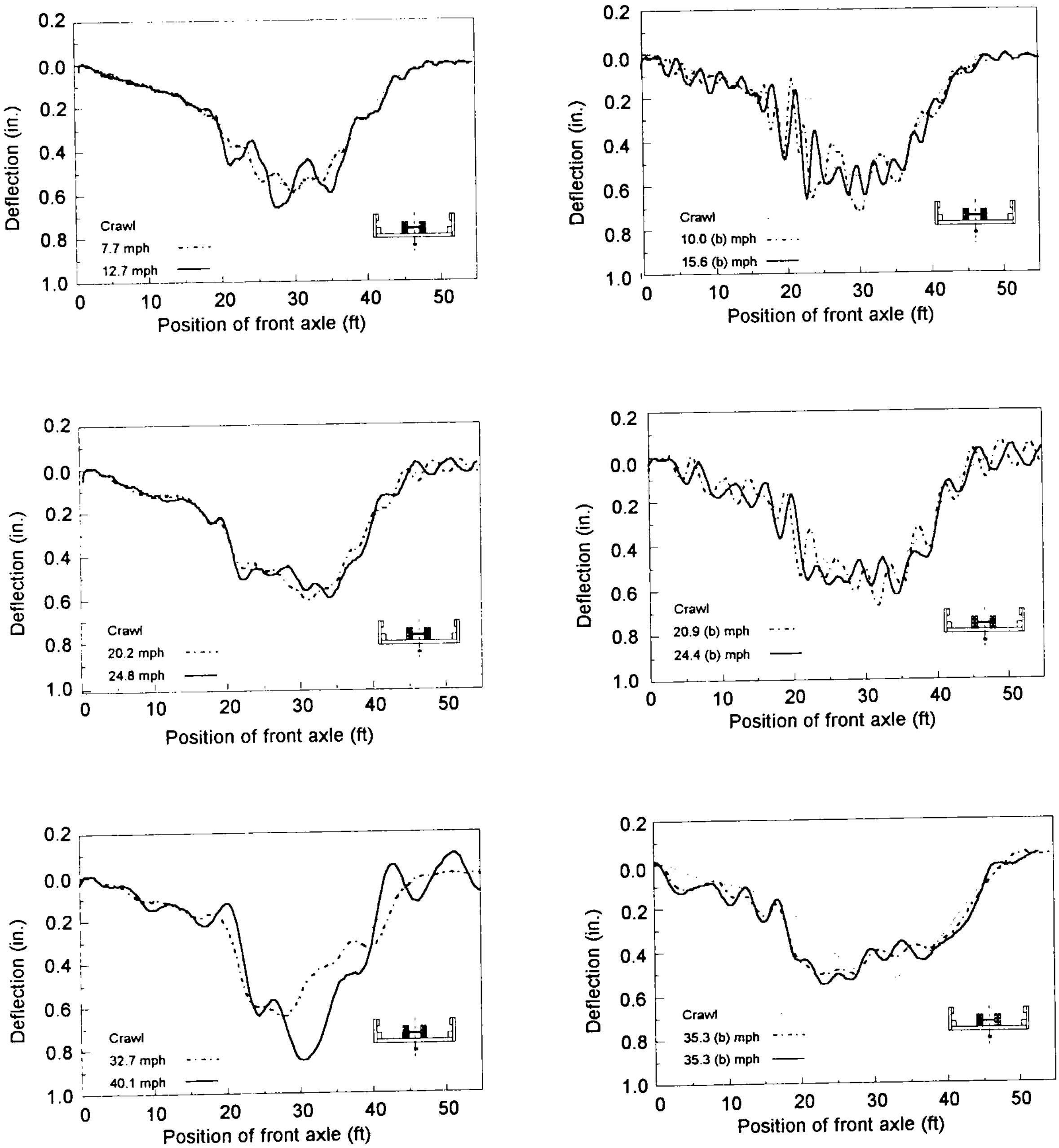


FIGURE 9 **Dynamic response for Little Salmon Bridge (1 in. = 25.4 mm; 1 ft = 0.3048 m).**

(12.9, 24.1, and 31.4 mph) for the Trout Road, Little Salmon, and Lampeter bridges, respectively. These velocities correspond reasonably well with the velocities at which the maximum DAF occurred for the Trout Road and Lampeter bridges.

Concluding Remarks

In this study, a field testing program was developed to measure the dynamic behavior of stress-laminated bridges. Three bridges with three distinct geometric, material, and roadway approach conditions were tested as part of a larger research program. The dynamic behavior of each bridge was described on the basis of deflections measured at midspan for a heavily loaded three-axle truck at different velocities. The monitoring system used for the field testing proved to be reliable, portable, and easy to set up.

DAFs were determined for each bridge, and the dynamic behavior was discussed. The trends in DAF and vehicle velocity were fairly consistent for the Lampeter

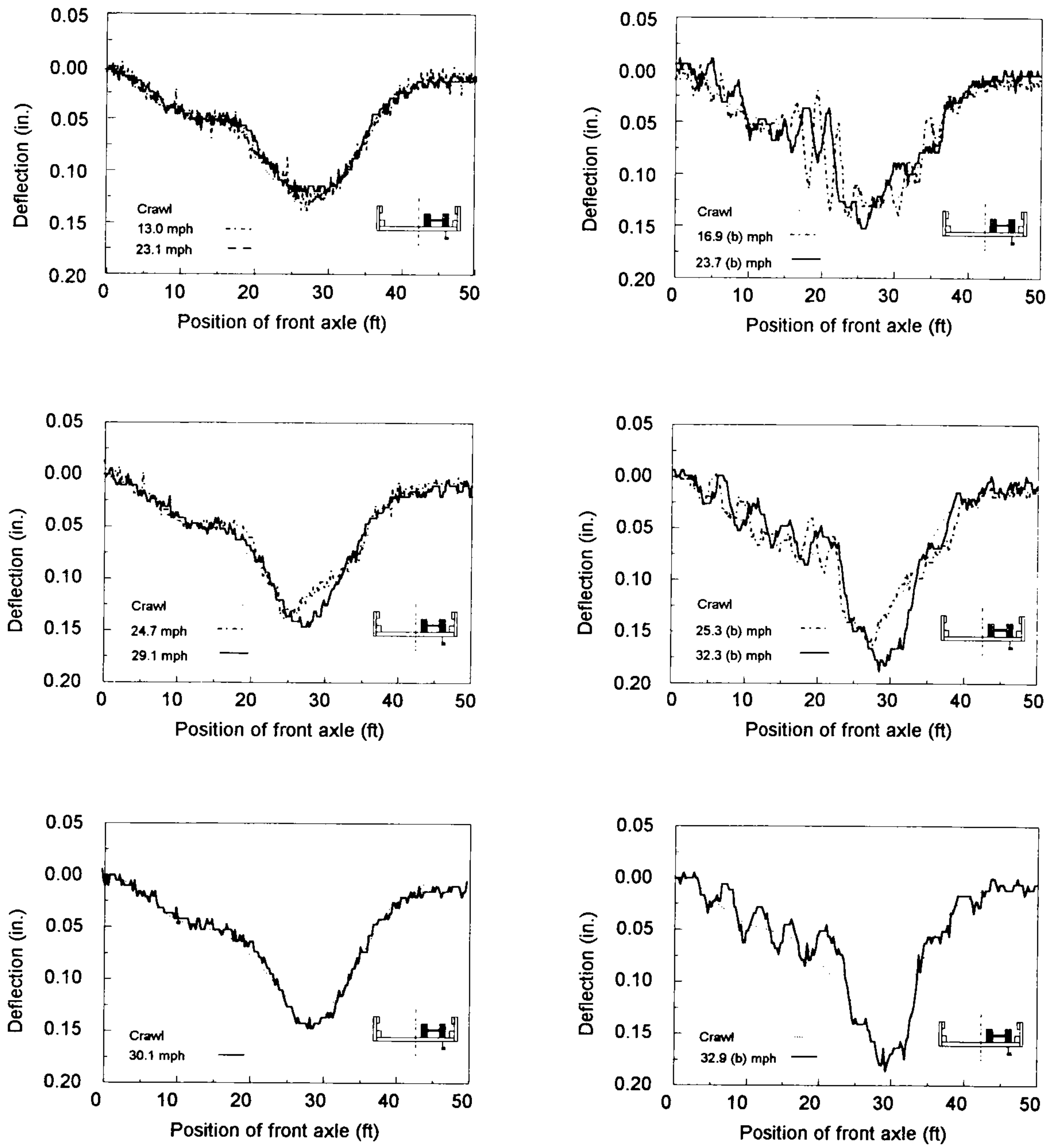


FIGURE 10 **Dynamic response for Lampeter Bridge (1 in. = 25.4 mm; 1 ft = 0.3048 m)** *(continued on next page).*

and Trout Road bridges, which had asphalt-paved roadways. In contrast, the DAF trends were not as consistent for the Little Salmon Bridge, which was on a gravel roadway. Generally, eccentric load positions resulted in higher DAFs than did concentric load positions. The DAFs for rough approach conditions (bump) were significantly greater than for in situ conditions for the Lampeter Bridge, which has a relatively high calculated fundamental frequency (10.6 Hz).

Results of the field tests clearly show that dynamic effects may be significant in short-span timber bridges. Further, the extremely high DAF measured for the Little Salmon Bridge at 64.4 km/hr (40 mph) verifies the significant effect of the initial conditions of a vehicle entering a bridge. These initial conditions can be random, depending on vehicle characteristics and approach conditions. Therefore, relying only on limited field data to describe overall dynamic behavior is not appropriate. A rational approach is needed that uses either significant statistical experimental data taken over a long period or analytical data based on validation from experimental tests. With regard to the latter, data presented

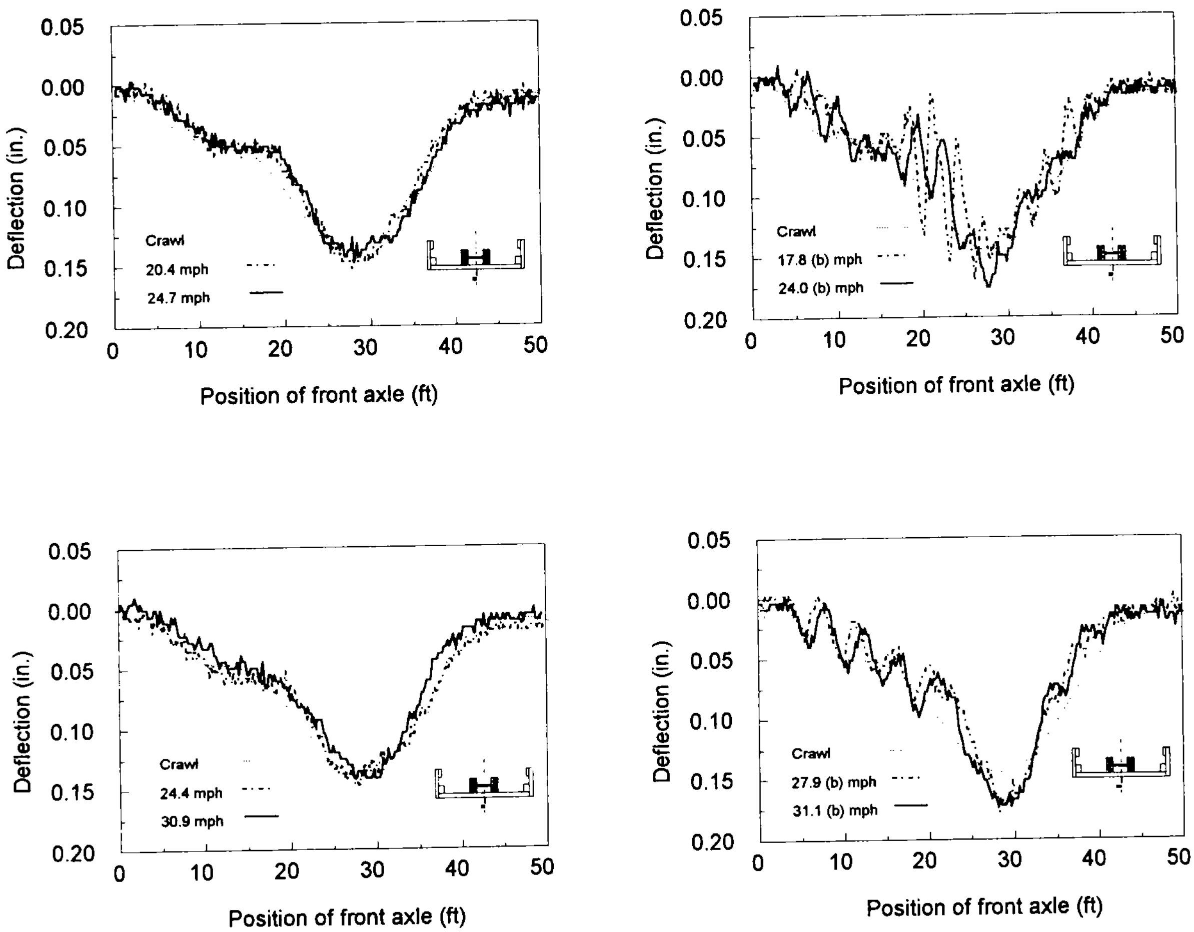


FIGURE 10 *(continued)*

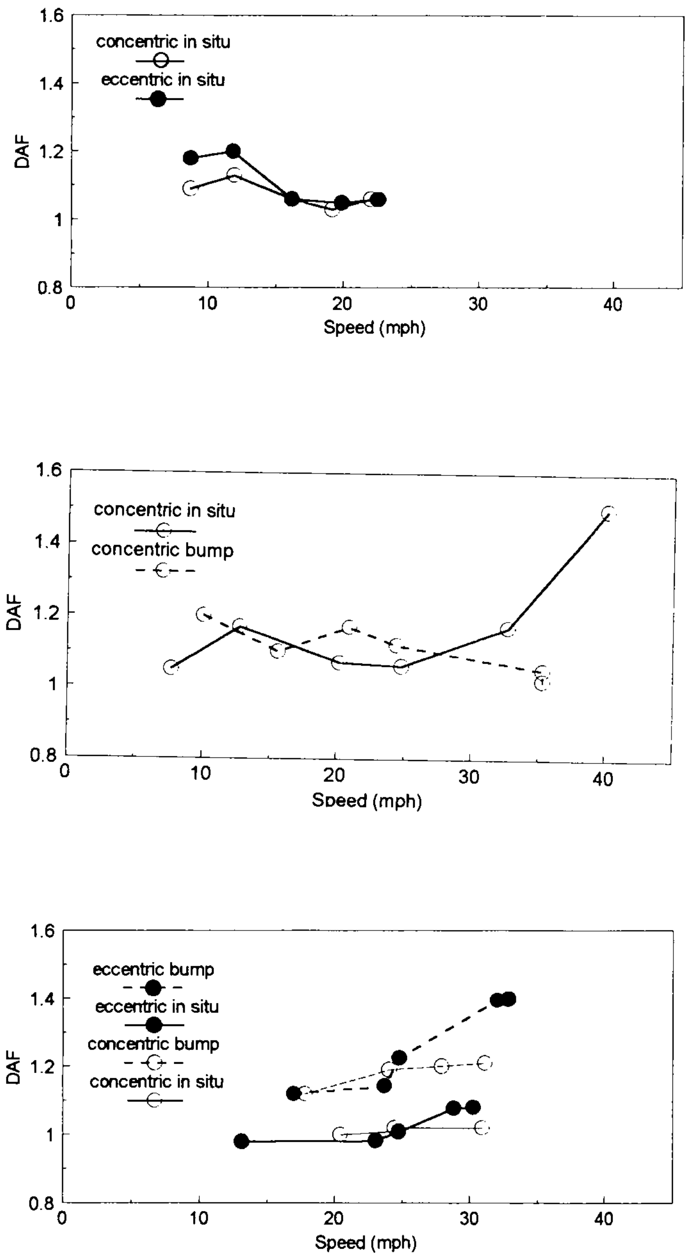


FIGURE 11 DAFs for field-tested bridges: *top*, Trout Road; *middle*, Little Salmon; *bottom*, Lampeter (1 mph = 1.61 km/hr).

in this paper should represent a significant contribution toward that end.

ACKNOWLEDGMENTS

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