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SIBILITY OF UTILIZING HIGHWAY BRIDGES TO WEIGH VEHICLES IN MOTION

Vol. III. Strain Gages at Bridge Bearings

H. J. Siegel

November 1974

Final Report

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16. Abstract This report provides the theoretical background and experimental data gained in the study of stresses to which bridges are subject, as so much of this background is directly applicable to this feasibility study. A method for weighing vehicles in motion using highway structures is provided, together with the theoretical analysis and justification for the proposed procedure. An instrumentation system is selected to provide automated processing of the high volume of data that would require analysis.

The information provided by the system includes traffic data such as headway, identification of the type of vehicle, number of axles per vehicle, axle spacing, headway between vehicles and time of arrival. Weight data such as gross vehicle weight, individual axle weight and dynamic vehicle loads are provided for vehicles weighing over 10,000 lbs.

It is recommended that the basic concept be subject to field tests to optimize the data processing circuitry before A/D conversion and computer programming are committed.

This report is the third in a series. The others in the series are:

FHWA No.	Short Title	NTIS (PB) No.
75-33	Exotic Sensors on the Bridge Deck	Not yet available
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PREFACE

In order to enable design of economic highway structures for a specified life from realistic fatigue considerations, provide a basis for reasonably and accurately predicting the remaining service life of existing highway structures and the effect of proposed weight law changes upon the service life of such bridges, and to provide traffic pattern data for use by traffic engineers in planning for highway considerations, the Structures and Applied Mechanics Division, Office of Research of the Federal Highway Administration contracted with ASE, Inc. to conduct a feasibility study entitled "Feasibility of Utilizing Highway Bridges to Weigh Vehicles in Motion". This final report describes the study conducted and the basis for our optimistic assessment of the feasibility of the proposed procedure.

ASE, Inc. wishes to express its appreciation to the Bridge Structures Research Group of the Structures and Applied Mechanics Division for the guidance and background material which helped so much to provide a solid basis for the study and to bring it to a successful conclusion. Special mention with thanks must be made of the efforts of Mr. William Armstrong, Mr. Charles F. Galambos and Mr. J. Nishanian.

November 1974

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF TABLES

SECTION 1

INTRODUCTION

1.1 Background

Highway structures such as pavements and bridges are designed to carry vehicular traffic safely and conveniently for many years with maximum service life. The specifications for highway bridge design are based on vehicle loadings, vehicle size and traffic patterns which have been growing and changing in character over the years. An accurate knowledge of the current heterogenous loadings to which these structures are subject is necessary in order to:

a) properly design economical highway structures for a specified life from realistic fatigue consideration
b) provide a basis for extrapolation of past and anticipated loading history so that reasonable accurate prediction of remaining service life may be made for existing structures
c) provide a basis for the assessment of the effect of proposed weight law changes upon the service life of highway bridges
d) provide traffic pattern data to highway traffic engineers and planners for their use in considerations of efficient traffic movement and weight law adjustments, and for predictions of future traffic.

Research for the development of analytical techniques for predicting the loading history of highway structures has resulted in computer programs for predcting long term stress ranges. The determination of present traffic characteristics is an essential input to these methods.

Techniques for measuring traffic characteristics such as numbers of automobiles and trucks, axle spacing and numberm and vehicle velocity are reasonably well developed. It is, however, necessary to provide dynamic wheel forces to supplement the data on traffic characteristics provided by the current techniques. This data should be obtained without requiring a change in vehicle speed, or other traffic interference, and preferably without driver awareness.

Different experimental methods have been used for the determination of dynamic wheel forces. These may be broadly categorized as on-board vehicle measuring techniques and dynamic wheel load sensing devices either embedded in the pavement or mounted on the pavement surface if the device has a very low profile. Among the on-board vehicle measuring techniques are wheel force transducers (Ref. 1), strain gaged axle housing transducers plus accelerometers (Refs. 1 and 2), and differential tire pressure transducers (Refs. 1, 2 and 3). These on-board methods, satisfactory for laboratory studies, are obviously unsuited for the purpose at hand because of the impracticality of instrumenting all the vehicles travelling on the highway.

Several types of individual dynamic wheel load sensing devices in the form of treadles mounted in the pavement have been developed and studied since the early 1950's (Refs. 4,5, and 6). A sensor with a flat profile, approximately 0.3" (0.76 cm) high, which requires no pavement modification has been marketed (Ref. 7). Aside from the long term vulnerability of these sensors to the environment because of the internal strain gage transducer elements, this class of equipment suffers from the same basic deficiency. The actual dynamic force imposed by a wheel of a moving vehicle is a randomly fluctuating cyclic load, affected by vehicle factors and roadway factors. The wheel is on the treadle for only a small portion of the cycle, and the sensor detects the force existing during that time interval only. As an example, for vehicles operating at 60 mph, a treadle length of 3 feet in the direction of travel would sense the load for only 0.068 cycles at a wheel frequency of 2 cps and 0.170 cycles at a frequency of 5 cps. For a treadle length of 5 feet, the load would be sensed for 0.114 cycles and 0.285 cycles for the same wheel frequencies, respectively. Since the deviations of the dynamic force from the static wheel force may vary for small road bumps as much as 100% (Ref. 8, p 204), depending on the speed of the vehicle and degree of wheel vibration excitation, the individual wheel load sensing devices may therefore be in error by the same percentage value.

Statistical treatments for single treadle readings and sampled data techniques for treating outputs from a multiplicity of treadles in a roadway have been advocated for determining the averages of many readings (Refs. 8 and 9). As the dynamic wheel forces are cyclic with randomly varying amplitudes, i.e. non-uniform amplitudes, (Ref. 10, p 127 and 129 - Figures 83, 84, and 85) such methods would not lend themselves readily for determining the static axle loads of any individual vehicle with accuracy.

A bridge might be considered a very long treadle, with a mass substantially greater than that of the vehicles which traverse it. As such, it should act like a mechanical filter and not respond to the higher vehicle frequencies. Instrumented properly, it should be able to indicate the weight of the vehicles passing over it, and possibly the individual axle weights. Considerable analytical and experimental work has been done on the effect that heavy vehicles have on individual bridges' members. However, no work has been done, to the best of the writer's knowledge, on the reverse problem, i.e., given the measured effects on the bridge structure, what are the axle weights and the weight of the vehicle or vehicles causing these effects?

1.2 Contract Objective

The stated contract objective is to "Determine the feasibility of utilizing steel girder with concrete slab highway bridges as a basis for weighing trucks in motion".

1.2.1 Scope of Work

This study will investigate the feasibility of utilizing an instrumentation system on highway bridges as a basis for weighing trucks, obtaining dynamic loads, and evaluating vehicle traffic conditions. For each vehicle crossing the bridge with a gross weight of more than 2,000 pounds, the following information shall be obtained:

1. Arrival time
2. Headway
3. Vehicle velocity
4. Bridge lane occupancy
5. Axle spacing and number of axles per vehicle
6. Vehicle type

For each vehicle crossing the bridge with a gross vehicle weight of more than 10,000 pounds, the following additional information shall be obtained:

7. Gross vehicle weight
8. Individual axle weight (over 10,000 pounds)
9. Dynamic load for vehicles with axle weights over 10,000 pounds

1.3 The Problem

The vehicle is basically an oscillating system with a number of frequencies not necessarily in phase, travelling over a bridge which is also an elastic system with its own natural frequencies. The wheels of the vehicle may be vibrating at different and random amplitudes depending on the degree of excitation caused by the roughness of the road preceeding the bridge, the roughness of the bridge deck itself, and the damping of the vehicle suspension system. These variable forces - the forcing functions - acting on the bridge structure cause the bridge to respond in an oscillating manner which is dependent on the vehicle forces, the bridge mass, the relationship of the vehicle and bridge natural frequencies, the speed of the vehicle, the configuration of the vehicle, the presence of other vehicles on the bridge in the same or other lanes, etc. Many of these variables are independent, will vary from vehicle to vehicle, and may vary from time to time in the same vehicle.

1.4 Method of Solution

Considerable data is available from numerous measurements which have been made of the interaction of heavy trucks moving across concrete slab and girder bridges, and of truck characteristics. This data will be used to provide the information necessary to accomplish the basic objectives within the project constraints.

The tasks undertaken under this study may be divided into three categories:

Task A - Literature Search

1. Data will be obtained on truck/bridge dynamic interaction, both theoretical and experimental.
2. Determination of significant parameters.
3. Current data on transducers and instrumentation.

Task B - Data Acquisition and Recording

1. Develop one or more concepts for weighing vehicles in motion by applying the data obtained in Task A to the fundamental consideration of the interaction of the vehicle and bridge. This should develop the requirements for data acquisition, recording, and information processing.
2. Conceive and analyze several possible alternate systems/procesures that will satisfy the concepts developed under B-1 above. The analysis will include: (a) consideration of the transducer type and installation, instrumentation interfacing, recording and monitoring, and (b) determination and cataloging of the characteristics of each system/procedure such as accuracy, operation, maintenance, cost and constraining factors.

Task C - Data Reduction and Interpretation

1. An analysis will be made of the concept developed under Task B-1 to ascertain the practicality of the measurement and information processing requirements.
2. Correlation between bridge signals and vehicle weight will be developed.
3. Techniques for obtaining static axle weights from bridge signals by processing procedures will be investigated.

1.5 Study Limitations

The basic objective of the contract will be most easily accomplished within project constraints by eliminating unnecessary complexity. This study will therefore concentrate on straight, non-skewed simple span structures, however, the influence of the effect of other types of bridges upon the developed concept will be assessed.

SECTION 2

SUMMARY

2.1 Study Objectives

The objective of this study is to investigate the feasibility of using an instrumentation system on slab and beam highway bridges as a basis for weighing trucks in motion, obtaining dynamic loads, and recording vehicle traffic conditions. For each vehicle crossing the bridge with a gross weight of more than 2000 pounds, the following traffic data shall be provided:

1. Vehicle arrival time.
2. Headway between vehicles on same lane.
3. Vehicle velocity.
4. Bridge lane occupancy
5. Axle spacing and number of axles per vehicle.
6. Vehicle type.

For each vehicle crossing the bridge with a gross vehicle weight of more than 10,000 pounds, the following additional data shall be provided:

7. Gross vehicle weight
8. Individual axle weight
9. Dynamic loads for vehicles with axle weights over 10,000 pounds.

2.2 Literature Survey

To develop a background that would facilitate the objectives of this study, a literature survey was made of the general field of bridge/vehicle interaction theory, correlation of experimental findings with this theory and current data on transducers and instrumentation.

It was found that the interaction between a rapidly moving vehicle and a bridge is complex, the wheels of the vehicle imposing varying forces on the bridge deck. The bridge structure, being an elastic system, responds in a complex vibratory fashion. The bridge motion consists of a cyclic dynamic increment varying at the bridge natural frequency, superimposed on a crawl curve, which is an influence line obtained by measuring the effects at a given station, of a very slowly moving calibrated vehicle. If the approach to the bridge and the bridge deck itself are relatively smooth with no abrupt discontinuities, the amplitude of the dynamic increment may reach between 15% to 30% of the crawl curve amplitude. There is no deterministic relationship between the gross vehicle weight and the amplitude of bridge motion.

It was found that the fields of traffic transducers, traffic instrumentation and recorders are relatively mature; the fields of micro-computers and micro-processor components are in a stage of rapid development. Data was also obtained on bridge and vehicle characteristics, which are described in some detail in Sections 3.4.2 and 3.4.3.

2.3 Determination of Static Axle Weights

After a study of the influence lines for a load slowly moving across a beam, and a review of the crossing frequency of vehicles and natural frequencies of simple bridges, it was determined that an electrical filter could separate the dynamic and crawl components of the total bridge response. It is further shown that static axle weights and gross vehicle weights can be obtained by adding the filtered low frequency component of the vertical reactions at both ends of the bridge, and scaling the resultant against calibration data.

2.4 Data Acquisition, Recording and Conversion

System relationships and functions are established by the application of system engineering techniques. A data acquisition, recording and conversion system based on direct digital recording is selected as the preferred system. Conventional traffic transducers, a set of pneumatic traffic tubes and an inductive loop, installed on the approach to each bridge lane, will provide the requisite traffic data. Linear variable differential transformers (LVDT) are the load transducers recommended for installation at each end and at the middle of the bridge, for the determination of static weights and dynamic loads respectively.

2.5 Conclusions and Recommendations

As a result of this study, it is concluded that gross vehicle weights, axle weights, and dynamic loads of moving vehicles can be determined using an instrumentation system in conjunction with slab deck and steel girder bridges. Traffic data can also be acquired using conventional traffic transducers and the load instrumentation system. Using the recommended techniques and equipment, large volumes of data may be acquired and processed with efficient digital computer usage for data reduction.

It is recommended as a first step in the instrument system procurement, when implemented, that tests be conducted to optimize the approach recommended in this study. The complete system need not be tested. Testing, study and experience with items such as filtering of bridge shear reaction signals and preprocessing this data to compensate for the effect of vehicle drift within a lane will serve to optimize the overall system performance and development costs. The operation of the traffic data transducers can be tested. The possibility of using load transducer data to reduce the traffic transducer complement can also be explored during these investigatory tests.

SECTION 3

LITERATURE SURVEY RESULTS

3.1 General

This section reports the data and information obtained by means of the literature survey. Initially, bridge/vehicle interaction theory are reviewed, including discussions on significant parameters. Correlation of theory with experimental data is next examined. In order to provide a realistic basis for estimating the ranges of parameters to be measured, bridge and vehicle data are then presented. The section closes with a compilation of transducer and instrumentation data together with comments as to their applicability to the proposed instrumentation system. To the extent possible, the data will be presented in tabular form.

Sources for this information are the literature reporting on the above general areas, including items such as the following: lateral distribution of loads on bridges; dynamic characteristics of vehicles; distribution of types of vehicles; and experience with instrumentation, and current data furnished by instrumentation manufacturers.

3.2 Bridge/Vehicle Interaction Theory

Schilling (Ref. 13) gives a short history of railroad and highway bridge analyses, starting with Willis in 1847 and continuing through the highway bridge efforts of the University of Illinois and M.I.T. Walker (Ref. 12) summarizes the investigation of dynamic effects in highway bridges at the University of Illinois Engineering Station from 1950-1967.

The University of Illinois' analytical effort started with an idealization of the bridge as a single-beam representation of a simple span bridge with simplified loadings. With the availability of the digital computer, additional factors and more realistic representations such as the following were included over a period of time to extend the mathematical model: a more realistic model of the vehicle, including interleaf friction in its suspension system; three-span continuous and cantilever bridges; static and dynamic transverse distributions for right, simply supported slab and girder bridges; initial vertical vehicle oscillations; the effect of road roughness; and inelastic behavior for the simple span, single beam analysis.

Laboratory studies of both a simple beam and a multi-girder bridge physical model were also conducted during this period at the University of Illinois to guide and experimentally verify the analytical results. The successful correlation of the AASHO Road Test bridge studies with the analytical studies on simple span bridges provided full scale verification of the basic bridge-vehicle idealization (Ref. 12, Part B, p. 2-4). It should be noted, however, that the bridge structures used for the AASHO Road Test (Ref. 10) were single lane bridges, typically consisting of a slab supported on three longitudinal beams. These bridges behaved essentially as a single beam, thus matching the assumptions of the simple beam analysis. The effect of static and dynamic lateral distribution, encountered in bridges of more common design, were thus not included in the correlation.

More exact studies, based on computerized finite difference methods, have been applied to continuous orthotropic plates on flexible girders (Ref. 14, p. 39).

In all of these analytical approaches, the thrust has been to obtain the dynamic effects of moving loads on bridges. Schilling, basing his work on the analyses developed at the University of Illinois, produced a simplified and more tractable closed form solution (Ref. 13, p. 12-26). This basic theory should also serve to provide an insight into the physics of the basic interaction, so that significant parameters may be examined for applicability to the basic objectives of this study.

3.2.1 Physical Concepts

The following explanation, in part excerpted from Ref. 13, p. 2-4 will serve to illustrate the differences in beam deflections caused by a slowly moving load as opposed to those caused by a rapidly moving load.

Let a single unsprung wheel load, P, move at a constant velocity, V, over a simply supported beam of length, L. The beam deflection at any arbitrary point B at a distance X from support A due to the load at distance X_p from A will be y_B. See Figure 1.

If the wheel load moves along the beam very slowly, the deflection y_B will be the static value corresponding to the position of the load X_p=Vt. Thus, point B deflects steadily from y_B=o, when the load is first applied at A, to some maximum value $(y_B)_{max}$ with the load between B and mid-span, then back to y_B=o, when the load leaves the span at D. At any intermediate load position, X_p=Vt, the deflection y_B lies between zero and $(y_B)_{max}$, depending on the position of the load. The beam thus exhibits a vertical velocity which carries the wheel load with it.

If the velocity of traverse, V, is very low, the resulting acceleration is also low and the dynamic effects may be neglected. If the velocity, V, is higher, the beam and the wheel will also experience a higher vertical velocity, $\dot{y}_p$, and higher acceleration, $\ddot{y}_p$, and the dynamic effects may no longer be neglected. Reference to Figure 2 will show that

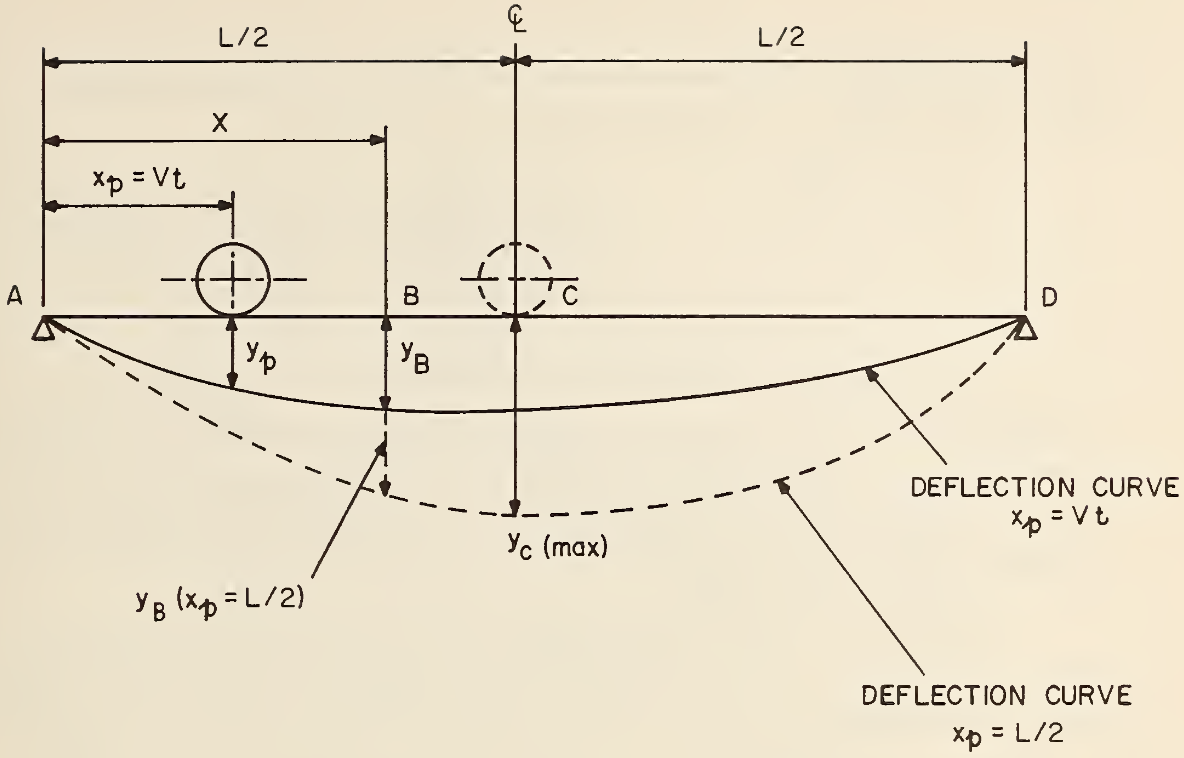


Figure 1. Beam Deflections Caused by Moving Unsprung Load

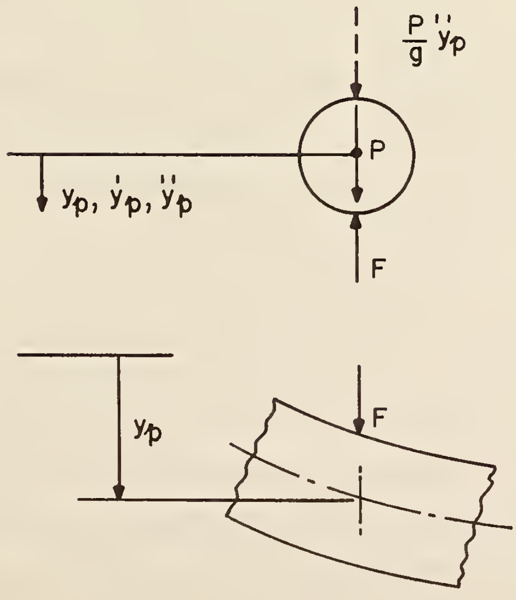


Figure 2. Equilibrium Diagram - Dynamic Forces

the acceleration forces must be included for equilibrium. Thus, the force, F, on the bridge is given by

$$F = P + \frac{P}{g}\ddot{y}_p$$

where the plus sign is used in its algebraic sense, g is the acceleration due to gravity, $\dot{y} = \frac{dy}{dt}$ and $\ddot{y} = \frac{d^2y}{dt^2}$

The external force on the bridge thus consists of two components, the static force, P, and a dynamic increment given by $\frac{P}{g}\ddot{y}_p$. For completeness, it should be noted that the effective mass of the beam must be included in considering the response of the beam.

Another basic approach to consideration of the dynamic deflection is to examine the response curve of a single degree of freedom system with damping subjected to a force of constant amplitude and variable frequency. See Figure 3.

The deflection curve of a simple beam may be approximated by a half sine wave, the half period of which is L/V. The full period is $T = \frac{2L}{V}$, and the corresponding frequency is $\frac{1}{T} = \frac{V}{2L}$. This represents the forcing frequency imposed on the beam. The ordinates of Figure 3 represent the total deflection normalized to the static deflection, and the abscissae represent the frequency, f, of the forcing function normalized to the natural frequency of the beam, f_b. This diagram is used for illustrative purposes only.

By inspection, it will be seen that with low values of V, the normalized deflection is essentially equal to one, i.e., the deflection is equal to the static deflection. As V increases, the deflection increases to an appreciable value over the static value. These approaches are admittedly gross simplifications of real life, but they serve to illustrate the basic system interaction. It will be noted that the abscissa, $\frac{f}{f_b} = \frac{V}{2Lf_b}$ is the definition of the speed

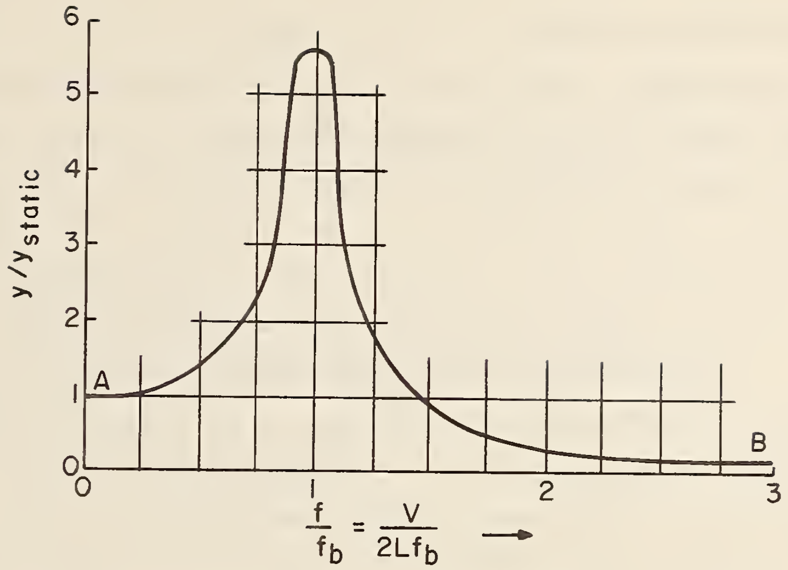


Figure 3. Response Curve* for the Absolute Motion of a Single Degree of Freedom System Subjected to a Force of Constant Amplitude and Variable Frequency (Illustrative Diagram).

*Adapted from Den Hartog, "Mechanical Vibrations", McGraw Hill, 1947, p. 59.

parameter α, see 3.2.2.1.1 (C). Figure 3 thus helps to understand the overriding importance of this parameter.

In the actual case of a vehicle crossing a highway bridge, many variables influence the vibratory characteristics of the system. Specifically, the vehicle body is supported upon its axles by leaf or coil springs and a damping mechanism; the axles, in turn, are supported by flexible tires which react with the deck of the bridge. The body, axles, and wheels of the vehicle is an interacting system which are influenced by such factors as wheel spacing, location of the center of gravity and the mass moment of inertia. Initial motion of the vehicle before entering the bridge span and multi-vehicular loadings also influence and complicate the problem.

The bridge itself also represents a complex system. The simple span highway bridge, for example, has longitudinal members whose deflections differ from each other according to which lane is loaded. These members, therefore, vibrate differently and, because they are interconnected through the deck and diaphragms, interact with each other as well as with the vehicle. Influencing these vibrations are factors such as type of bridge (i.e., plate girder, truss, etc.), bridge weight and its distribution, variable flexibility and end constraints. Also roughness of deck, bridge damping factors, and initial motions due to previously passed vehicles all influence and interact with the vehicle to produce vibrations.

3.2.2 Dynamic Analyses

Walker and Veletsos (Ref. 15), Veletsos (Ref. 16), and Nieto, Ramirez and Veletsos (Ref. 23) utilize the computer model developed at the University of Illinois to investigate the dynamic response of simple span and three span continuous bridges. Despite the recognized question as to whether the simple span highway bridge can be adequately represented as a simple beam, tests have shown that the model contains all the salient features necessary to adequately describe the dynamic bridge-vehicle responses.

Schilling (Ref. 13) further simplifies the problem by neglecting certain parameters in order to achieve better understanding of the major parameters. Building upon theory developed in References (15) through (22) inclusive, he solves the differential equation of motion for a constant force moving at a constant velocity across a simply supported beam. Parametric studies in References (15) and (16) are then used to investigate the significance of the other parameters.

The latter approach will be adapted in this study, supplementing the output with data on the effects of static and dynamic lateral distribution of load in multi-girder highway bridges, and other factors that may prove of significance.

3.2.2.1 Computer Model

3.2.2.1.1 Bridge Vehicle Parameter Definitions

The following is a summary of the bridge vehicle parameters and assumptions used in References 15 and 16. These were utilized in the computer programs referenced therein, and are semi-standard throughout the literature. Applicable parameters are also used in Reference 13.

A. Bridge Parameters

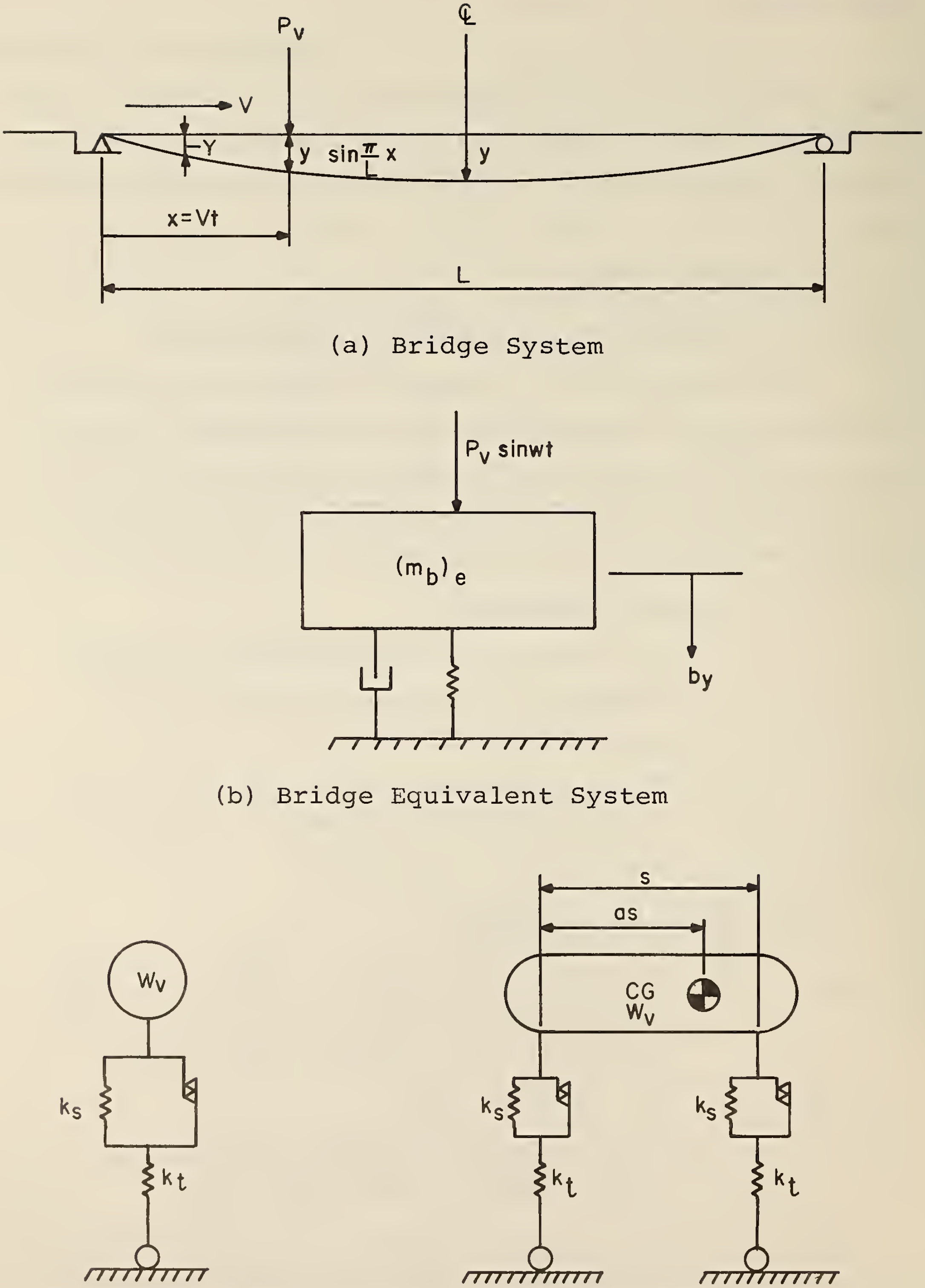
1. Span Ratio (for three span continuous bridges), a = ratio of side span to center span.
2. Viscous Damping Factor, β_b = ratio of coefficient of damping to the coefficient of critical damping.

B. Vehicle Parameters

3. Distance parameter, a. This parameter defines the location of the center of gravity of the tractor and trailer, See Figure 4(d).

4. The weight distribution parameters, w_1/W_v, w_2/W_v. See Figure 4(d).

5. The dynamic index, i, for the vehicle. The dynamic index is a measure of the pitching moment of inertia of the weight



(a) Bridge System

(b) Bridge Equivalent System

(c) Single-Axle Load Unit

(d) Two-Axle Vehicle

Figure 4. Equivalent Dynamic Systems (Diagramatic)

W_v, and is defined as

$$i = \frac{(\text{radius of gyration})^2}{(\text{distance of one support to cg}) \times (\text{distance of other support to cg})}$$

6. The coefficient of friction, u, for the suspension system of each axle. For the i^{th} axle, $u_i = F_i^1/P_{st,i}$, where F_i^1 is the initial value of the force due to inter-leaf friction for the i^{th} axle.

C. <u>Bridge-Vehicle Parameters</u>

7. The speed parameter

$$\alpha = \frac{V}{2Lf_b} = \frac{VT_b}{2L} \tag{3.1}$$

Where V is speed of vehicle, assumed to be uniform, L is span length of bridge and f_b is fundamental natural frequency of the bridge. $T_b = \frac{1}{f_b}$.

8. The weight ratio $R = W_v/W_b$ where W_v is total weight of vehicles and W_b is the weight of the bridge (or the center span of a three span continuous bridge).

9. The frequency ratios

$\phi_t = f_t/f_b$ and

$\phi_{ts} = F_{ts}/f_b$

f_t and f_{ts} are the frequency of the vehicle vibrating on its tires alone, and on the combined tire and suspension system in series. For the i^{th} axle,

$$f_{t,i} = \frac{1}{2\pi}\sqrt{\frac{g}{P_{st,i}/k_{t,i}}} \quad \text{and}$$

$$f_{ts,i} = \frac{1}{2\pi}\sqrt{\frac{g}{P_{st,i}/k_{t,i}}}$$

Where the limiting frictional force F_i^1 of the axle suspension is so large that the effective stiffness of the suspension-tire system for the i^{th} axle is always equal to $k_{t,i}$, or when F_i^1 is so small that the effective stiffness may be considered to be always equal to $k_{ts,i}$, then it is necessary to specify a single frequency, this frequency is denoted by $f_{v,i}$,

and $\phi_v = f_v/f_b$

10. The profile variation parameter $d_{Pi} k_{t,i}/P_{st,i}$. The numerator is the change in interacting force for the i^{th} axle when the tire spring is deflected by an amount = d_{p_i}.

11. The axle spacing parameter, s, see Figure 4(d).

12. The following parameter defines the initial conditions of the bridge-vehicle system and the bridge surface profile. The surface of the unloaded bridge is treated in two parts:

    a) a camber, which is approximated by a parabola with an arbitrary amplitude; and

    b) deck roughness having a specified number of half-waves of constant amplitude.

3.2.2.1.2 Assumptions and Treatments

The assumptions and treatments used in References (15) and (16) are given below to provide an indication of the limitations of the computer program:

1. The bridge is treated as a simple prismatic beam with damping assumed proportional to the absolute vertical

velocity of the bridge.

2. The effects of shear, axial deformation and rotary inertia of the beam are neglected.

3. Bridge camber is simulated by a second degree parabolic curve drawn through the supports.

4. Deck irregularities are treated as an integral number of sinusoidal half-waves of constant amplitude.

5. The vehicle is idealized as having no width and thus no rolling inertia.

6. The computer program used in References 15 and 16 has the capability of analyzing a one, two, or three axle vehicle, although studies were reported on only one or two axle vehicles. Pitching inertia is included, where the bottom springs are assumed to be made up of the tires and leaf springs, both of which are assumed linearly elastic. A hysteresis type of load deflection relation is assumed for the axles, because of the influence of interleaf friction. The suspension spring remains locked whenever the tire force is insufficient to overcome the frictional force in the spring. When the spring frictional force is exceeded in either direction, the suspension spring engages, and the effective spring constant reduces to that of two springs acting in series. See Reference 18.

3.2.2.2 Closed Form Analytic Solution

The closed form analytic solution will be used to investigate some of the major parameters. The importance of other parameters will be ascertained via parametric analysis as reported in References (15) and (16).

The solution of a single constant force moving at constant velocity across a simply supported prismatic beam is investigated by Schilling (Ref. 13, p. 17-26). This report will present the differential equations and the solutions derived in Reference (13) to aid in investigating the parameters. For the complete derivation of the solutions, see Reference (13).

Assumptions:

A. The bridge is represented as a simple beam of which only the first mode behavior is considered. Thus, a single-degree-of-freedom is assumed for the bridge.

B. Bridge damping is assumed to be viscous and its resistance is assumed to be distributed along the span.

C. The mass of the beam is assumed to be distributed evenly along its length.

D. The deck of the bridge is assumed to be smooth and free of irregularities.

E. The vehicle is idealized as a concentrated force whose mass is negligible with respect to that of the bridge.

Figures 4a and 4b show the bridge-vehicle system and the bridge equivalent systems, respectively. Notation is as follows:

C_c = damping of bridge equivalent system

EI = flexural rigidity of cross section of bridge

f_b = fundamental frequency of the bridge = $\frac{1}{2\pi}\sqrt{\frac{2K_b g}{W}}$

g = acceleration due to gravity

K_b = stiffness of bridge equivalent system = $\frac{48EI}{L^3}$

L = span length of bridge

$(m_b)_e$ = effective mass of bridge equivalent system
$= \frac{1}{2}\frac{W}{g}$

P = interacting force between vehicle axle and surface of bridge

P_v = total weight of vehicle

V = velocity of vehicle

W = weight of bridge

w = weight per foot of length of bridge

x = distance of vehicle from left end of span (see Fig. 4a)

Y = deflection of bridge at any point from left end of span (see Fig. 4a)

y = midspan deflection of bridge

α = speed parameter $= \frac{V}{2Lf_b} = \frac{VT_b}{2L}$

ω = crossing frequency

ω_b = circular bridge frequency

The equations of motions for the bridge and vehicle equivalent system, the forces for each are summed vertically.

For the bridge:

$$(m_b)_e\frac{d^2y}{dx^2} + C_b\frac{dy}{dx} + K_by = P_v\sin \omega t \qquad (3.2)$$

To obtain $(m_b)_e$, the equivalent bridge mass term, consider the differential equation of motion governing the transverse free vibrations of a prismatic beam (Ref. 21, p. 113):

$$EI\frac{d^2Y}{dx^2} + \frac{w}{g}\frac{\partial^2 Y}{\partial t^2} = 0, \qquad \text{also} \qquad (3.3)$$

$$EI\frac{d^4Y}{dx^4} = p(t,x), \qquad \text{and} \qquad (3.4)$$

$$Y = A\sin\frac{\pi}{L}x \qquad (3.5)$$

from which we may obtain

$$(m_b)_e = \frac{1}{2}(\frac{wL}{g}) = \frac{1}{2}(\frac{W}{g}).$$

Substituting in equation (3.5), the solution to which may be obtained:

$$y = \frac{P_v}{K_b}\left[(\frac{1}{1-\alpha^2}) \sin \omega t - (\frac{\alpha}{1-\alpha^2}) \sin \omega_b t\right] \tag{3.6}$$

P_v/K_b is maximum static midspan deflection $(y_{st})_{max}$, and the static or crawl deflection is

$$y_{st} = (y_{st})_{max} \sin \omega t \tag{3.7}$$

Subtracting equation (3.7) from both sides of equation (3.6),

$$(y-y_{st}) = (y_{st})_{max}\left[(\frac{\alpha^2}{1-\alpha^2}) \sin \omega t - (\frac{\alpha}{1-\alpha^2}) \sin \omega_b t\right] \tag{3.8}$$

The dynamic increment of deflection when normalized with respect to the maximum static deflection, is

$$DI_D = \frac{y-y_{st}}{(y_{st})_{max}} = (\frac{\alpha^2}{1-\alpha^2}) \sin \omega t - (\frac{\alpha}{1-\alpha^2}) \sin \omega_b t \tag{3.9}$$

DI_D refers to the dynamic increment of deflection. Dynamic increments may be obtained for moment, shear and strain, resulting in the following relationships:

For Moment

$$DI_M = \frac{\pi^2}{12} DI_D \tag{3.10}$$

For Shear

$$DI_V = \frac{\pi^3}{48} DI_D \tag{3.11}$$

For Strain

$$DI_{strain} = DI_M \tag{3.12}$$

$$= \frac{\pi^2}{12} DI_D = .82\ DI_D$$

3.2.3 Significance and Range of Parameters

The interaction of an actual bridge structure with a moving multi-axis vehicle with springs depends on many more parameters than is given in equations (3.6) and (3.9). The constant force solution, however, does provide insight into bridge-vehicle interaction. For small values of ϕ_V, the frequency ratio, the constant force solution is approached regardless of the weight ratio (Ref. 15). The constant force solution thus represents, to some degree, the bridge-vehicle system.

The degree of representation, and the parameters on which it depends, will now be discussed along with the parameters which govern bridge-vehicle interaction. Judgements based on analytical solutions and test results given in References 15 through 22, inclusive, will accompany the discussion.

3.2.3.1 General Bridge Response

The general nature of dynamic bridge response, predicted by theory and confirmed in general by field measurements, may be represented by a cyclic component of shorter wave length superimposed on the static influence line or crawl response for the bridge. The cyclic component, better known as the "dynamic increment" is defined as the algebraic difference between the total dynamic response and the corresponding static influence line.

The dynamic increment curve approaches a sinusoidal variation for the case of a simple beam loaded by a single moving constant force. For a sprung, multiaxle vehicle, the dynamic increment curve may be irregular. Equations (3.6) and (3.9) define the dynamic deflection and dynamic increment curves.

The relationship between the amplitude of the dynamic increments produced by a smoothly moving vehicle and α, is, in fact, nearly linear over the practical range of α for the simple span bridge. (Ref. 15).

For an initially oscillating vehicle, the speed parameter has two important effects. First, it governs the amplitude of the dynamic increment corresponding to the moving constant force effect, and second, it controls the point of "bottoming" of the vehicle - the position of the vehicle on the span at which the interacting force attains its maximum value.

It is shown in Reference 13 that the first maximum occurs at $X/L = \frac{3}{2}\alpha$, and that successive positive peaks occur at $X/L = 7/2\alpha$, $11/2\alpha$..... In order that these positive peaks occur at midspan, where the static moment is the greatest, $X/L = .5$, and $\alpha = \frac{1}{2} \times \frac{2}{3} = \frac{1}{3}$, above the range of practical interest. The next positive maximum will occur at midspan for $\alpha = \frac{1}{2} \times \frac{2}{7} = .143$ which is well within the practical range.

3.2.3.2 The Speed Parameter

The speed parameter, α, as can be seen from Equation (3.9), is the universal parameter of the system. A nearly linear relationship exists between maximum values of amplitudes and α. This can be seen by taking the absolute values of the term in Equation (3.9); this yields

$$(DI_D)_{max} = \left(\frac{\alpha^2}{1-\alpha^2}\right) + \left(\frac{\alpha}{1-\alpha^2}\right) = \frac{\alpha}{1-\alpha} \qquad (3.13)$$

Equations (3.10) and (3.11) become

$$(DI_M)_{max} = \frac{\pi^2}{12}\left(\frac{\alpha}{1-\alpha}\right) \qquad (3.14)$$

$$(DI_V)_{max} = \frac{\pi^3}{48}\left(\frac{\alpha}{1-\alpha}\right)$$

3.2.3.3 Axle Spacing Parameter

For a two axle vehicle, distances between axles, the quantity $(s/V)/T_b$ must be an integer, in order that each successive wheel entering the span be in phase with the natural period of the bridge. This quantity may be put into the form $(s/L/\alpha)$. If $(s/L/\alpha) = 2,4,6, \ldots.,$ then maximum response occurs; if $(s/L/\alpha) = 1,3,5, \ldots,$ then successive wheels are π radians out of phase with the bridge period and cancellation occurs. For the three-span continuous bridge or for any case where a number of natural modes contribute to the response, a simple relationship does not exist.

When more than two axles act on the span at the same time there is no clear cancellation of effects due to interference between the effects of the various axles nor is there a large amplification due to the addition of effects unless all axles are critically spaced and travelling at a critical speed.

The axle spacing is also significant in the case of initial oscillations of the vehicle and roughness on the bridge deck. The fact that the axle spacing also affects the value of the maximum static response is important to this feasibility study.

3.2.3.4 Weight and Frequency Ratios

These ratios, defined in 3.2.2.1.1, describe the mass and the stiffness of the bridge vehicle system, and taken separately influence the bridge response strongly. However, since both f_v and f_b are functions of the mass of the vehicle and bridge respectively, R and ϕ_v are not independent. Because of this interdependence, and because the values of these ratios are set primarily by the bridge, the response of the bridge-vehicle system is generally insensitive to the range of these parameters normally encountered in common types of heavy highway vehicles.

The frequency ratio determines the degree of correlation between the sprung vehicle and the constant force solutions. The degree of importance of ϕ_v, however, depends largely upon the initial oscillation of the vehicle. A summary of this interrelationship is as follows:

(1) For small initial oscillations (i.e., 15% of the static load), the frequency ratio has no effect.

(2) The responses for sprung vehicle approach those predicted by the constant force solution for a $\phi_v \leq .2$ for the two axle vehicle, and for a $\phi_v \leq .3$ for a single axle vehicle.

(3) For large initial oscillations, a $\phi_v = 1$ leads to large effects. (Ref. 15 and 21)

However, although $\phi_v = 1$ implies a resonant condition between the vehicle and bridge, the bridge response is limited by the initial energy and damping of the vehicle. In addition, the influence of ϕ_v diminishes as R increases.

The weight ratio R is of importance in the study of fatigue and life expectancy of the bridge, as this weight or live load ratio directly affects the stress range and mean stress.

The effect of the weight ratio can be generalized to a greater extent than the frequency ratio. Variations in R have practically no effect on bridge response if ϕ_b is low; for higher frequency ratios, and particularly for $\phi_v = 1$, the weight ratio was found to have a pronounced effect, but in decreasing the bridge responses. (Ref. 21)

For the smoothly rolling load, the maximum interacting force is shown to be almost in direct proportion to R, and the bridge response is considerably less sensitive. Also, maximum static effects are obtained for the higher weight ratios. (Ref. 15)

3.2.3.5 Vehicle Initial Conditions (Ref. 15 and 21)

The amplitude of vehicle motion as the vehicle enters the bridge strongly influences the dynamic response of the bridge. The smoothly moving vehicle, the vehicle with "small" initial oscillations, and the vehicle with "large" initial oscillations all produce larger and larger amplitudes of response respectively. If the other parameters are adjusted to produce relative maximum effects, there is a nearly linear relationship between the amplitude of initial motion of the vehicle and the magnitude of the resulting maximum response of the bridge.

The phase of the vehicle oscillation at the instant the vehicle enters the bridge is also important. In general, it is not possible to predict the phase value which would produce maximum response. For the two-axle vehicle with small initial oscillations, the in-phase relationship of the individual axles leads to the absolute maximum response.

For single-axled vehicles with small initial oscillations the maximum and average values of bridge-responses are approximately the same, even though details may differ and the parameter θ, R, ϕ_v and α are varied.

For double-axled vehicles, peak dynamic increments are, in general, equal or reasonably close to the corresponding effects for a single axle loading. These peak dynamic increments for moment are given by Reference 13 in terms of amplification factor and impact factor as:

$AF_M = 1 + I$, where

$$I = \frac{\frac{\pi^2}{12} \cdot \frac{\alpha}{1-\alpha} \cdot \frac{P_V L}{4}}{(M_{st})_{max.}} \qquad (3.15)$$

When 2 equal forces, each of magnitude P_V/L cross the span, equation (3.15) becomes

$$I = \frac{\pi^2}{12} \cdot \frac{\alpha}{1-\alpha} \cdot \frac{1}{1-s/L} \qquad (3.16)$$

and $I_{max} = 2\frac{\pi^2}{12} \cdot \frac{\alpha}{1-\alpha}$ if $s/L = 1/2$

and $I_{min} = \frac{\pi^2}{12} \cdot \frac{\alpha}{1-\alpha}$ if $s/L = 0$.

Equation (3.15), with reasonable accuracy, represents the impact factor for a two-axle smoothly rolling vehicle or a vehicle with no more than 15% initial oscillation (Ref. 15). On the basis of this data, the following equation was proposed by Reference 15 as a means of estimating the maximum value of the impact factor:

$$I = .15 + \frac{\pi^2}{12} \cdot \frac{\alpha}{1-\alpha} \cdot \frac{1}{1-s/L} \qquad (3.16)$$

The first and second terms represent the components due to the interacting force and the constant force respectively. Equation (3.16) is used directly when wheel load ratios are not known and modified for wheel load distributions other than 1/2 (Ref. 13 p.34).

3.2.3.6 <u>Vehicle Suspension</u>

This parameter describes the effects of the frictional characteristics of the vehicle suspension, namely, the initial and limiting values of interleaf frictional forces for conventional leaf-spring suspensions. The effect of interleaf friction on the response of the bridge is related to the amount of energy dissipated in the vehicle suspension and the corresponding reduction in the vehicle interacting force variations.

For a smoothly moving vehicle or one with small amplitudes of initial oscillation the energy loss in the suspension is generally insignificant since the vehicle oscillates primarily on its tires and the suspension is not engaged. However, for large amplitudes of initial oscillation, the energy loss is important and cannot be neglected. The presence of interleaf friction and the difficulty in evaluating the initial frictional characteristics of the vehicle suspension contribute substantially to the scatter usually seen in bridge response data. Thus, it may be concluded that the use of air springs or similar devices in heavy truck suspensions would produce some differences in the response observed in the bridge. Depending upon the damping present, the use of such suspensions may be favorable in reducing, somewhat, the dynamic response of the bridge (Ref. 12).

3.2.3.7 Dynamic Index

The dynamic index is a measure of the pitching moment of inertia of the vehicle and is defined as

$$i = \frac{r^2}{(a)(S-a)} \qquad \text{(see Figure 4d)}$$

Although the dynamic index range has not been fully determined or examined, it has been concluded through studies concerning two axle smoothly moving vehicles that maximum responses of the bridge-vehicle system is insensitive to variation in i (Ref. 15).

3.2.3.8 Roadway Unevenness

"Perhaps the single most important cause of large dynamic response in a bridge-vehicle system is the presence of roadway unevenness on the bridge deck and approach pavements (and abrupt discontinuities in level, as at joints or pot holes). Because of the difficulties in defining typical roadway roughness characteristics, the effect of unevenness has not been studied quantitatively in detail. It has been demonstrated that a sinusoidal form of unevenness can lead to a very great increase in dynamic effects. However, such a systematic unevenness is improbable in practice. It is felt that for unevenness on the bridge deck and approach of moderate amplitude and random distribution, the magnitude of the maximum dynamic effects produced in the bridge may not be significantly different from those computed for an initially oscillating vehicle with a moderate amount of initial oscillation, but operating on a smooth deck." (Ref. 12).

3.2.3.9 Multigirder Structure

The above discussions of the effects of parameters are drawn from a study of bridges idealized as a single beam. In the AASHO Road Test Studies, (Ref. 10) the test bridges, 50 ft. simple-span single lane structures behaved essentially as single beams and the beam theory was completely adequate for predicting the behavior of the structure. However, the applicability of beam theory to two-lane structures with a minimum width of 28 feet and span lengths as short as 20 ft. is not clear.

Walker and Veletsos (Ref. 15) applied the theory and computer program of Reference 20 to the problem of a specific heavy vehicle travelling over bridges with spans from 30 ft. to 70 ft. at 60 mph. One set of computer runs were taken over the center of the bridges, and another in one of the two lanes. Correlation with the single beam solutions showed good agreement with the most heavily loaded beam of the multi-girder structure, i.e., the beam nearest to the center of gravity of the load.

Other results of the study were that the fundamental beam mode of vibration, which has a uniform transverse shape, dominated the dynamic increment for the structure. However since this dynamic increment must be added to a non-uniform static distribution of effects, the total dynamic moments or deflections are usually highly non-uniform. It appears to be difficult for bridges of usual dimensions and flexibility to excite antisymmetrical or torsional modes of vibration in the multigirder structure, even for eccentric paths of travel for the vehicle (Ref. 12).

In view of the limited nature of the above study, these results should not be applied to the behavior of floor beams, slab, or other sub-elements, as the relationship had not been explored. In addition, the conclusions are based on the study of right, simple span bridges and should not be extended to skewed or continuous structures (Ref. 12 and 15).

Sanders and Elleby (Ref. 24) have investigated theories of the distribution of wheel loads on highway bridges and have correlated them with experimental data. Their objective was to provide data for updating the section of the AASHO Specification that deals with load distribution. Their investigations were restricted to right, simple-span bridges, between 20 to 130 ft. long, loaded with statically applied live loads.

A summary of their conclusions relative to beam and slab bridges and applicable to this study follows:

1. The moment coefficient (ratio of the individual beam moment to the average beam moment) is most accurately predicted for beam and slab bridges by the use of orthotropic plate theory, within the range of bridges studied.

All errors between the measured value of the moment coefficient of the most heavily loaded beam and the value predicted by orthotropic plate theory, for a total of 34 observations and 11 bridges were under 10% except for one 12% and one 28% error.

2. The Halcomb test bridge, when eccentrically loaded - the normal case - showed highest loading on the outside girder and not the girder nearest the center of gravity of the load. Other bridges have also exhibited this phenomenom.

3. The Halcomb test bridge, located in Ames, Iowa, is a two-lane 71 ft. simple-span composite bridge. The outside girders are 33WF194 and the inside girders are 33WF130, for a total of four members supporting the 8" concrete slab. The diaphrams, at the third points, are 16WF36 beams. Moment Distribution Coefficients for this bridge are shown in Figure 5, for two conditions of loading; eccentric and para-symmetric.

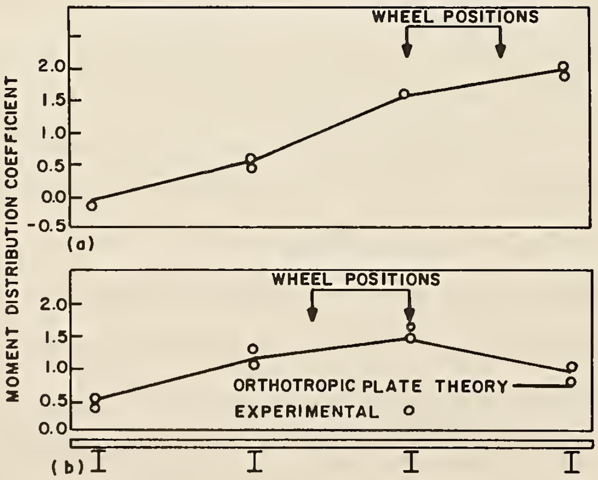


Figure 5 Transverse Moment Distribution in Holcomb Test Bridge. (Adapted from Ref. 20, Figure 5)

3.3 Correlation of Bridge/Vehicle Interaction Theory with Experimental Data

3.3.1 General

Numerous studies have been made in the past on the dynamic response of bridges under controlled and random moving loads. Several of the more recent reports were reviewed to correlate bridge/vehicle interaction theory with experimental data. Summaries of pertinent comments from References 10,11, 25 and 26 will be given below as representative of many of the reports which were reviewed. This correlation of theory and experimental bridge response should provide background of the parameters that are significant for the use of bridges to weigh trucks in motion.

Reference 11 is a report on the investigation of the dynamic stresses in three bridges, which although 2 or 3 span continuous span continuous design, provides insight into actual physical bridge/vehicle interaction. However, this data must be examined in the light of the non-composite nature of the design, which introduces some unique phenomena. Reference 10, the AASHO Road Tests, have provided source data for many subsequent reports, of which pertinent ones have already been discussed. Of significance is the reported correlation between actual static response with crawl response. Reference 25 reports on the results of an investigation of a bridge damper specially designed to suppress bridge vibrations on a simple span. Diagrams clearly show the characteristics of the dynamic increment curves. Reference 26, although reporting on a bridge of different design, adds some information on bridge-vehicle interaction and verifies other observations.

3.3.2 Total Dynamic Response

<u>Dynamic response</u> is consistent with bridge interaction theory in that the total dynamic response consists of two com-

ponents, a static or crawl history plus a dynamic increment.

The crawl component dominates because the dynamic increment is relatively small, on the order of 15 to 30 percent for the bridges studied. However, pavement discontinuities or rough surface conditions can significantly increase the dynamic response. (Ref. 11)

In general, the pattern for both strain and deflection is similar. The fundamental frequency of the bridge dominates the frequency content of the response curves. The transverse distribution of dynamic effect is substantially the same as in the static case. The oscillations of all beams of the bridge are substantially in phase, (indicating that the fundamental mode predominates. (Ref.11)

Throughout the AASHO Road Test runs of the simple span steel bridges, the frequency of oscillation was essentially the natural (fundamental) frequency of the bridge. Oscillations corresponding to the frequency of the interaction forces cannot be distinguished on the curves. (Ref. 10)

Figures 6 through 8 are reproduced from Reference 25 because of the clarity with which the total dynamic response in deflection of a simply-supported beam is shown. These diagrams also show irregularities in the dynamic increment (DI) curve in the early phases of the vehicle entering the 97 ft. long bridge which was the subject of experimentation. After the vehicle passes midpoint, the DI curve becomes more cyclicly regular.

This characteristic holds only for bridges whose span is long compared to the vehicle. The irregularities have been attributed to the interferences injected by the other axles of the vehicle entering the birdge span. Also of interest is Figure 9, which shows the residual vibrations of this span

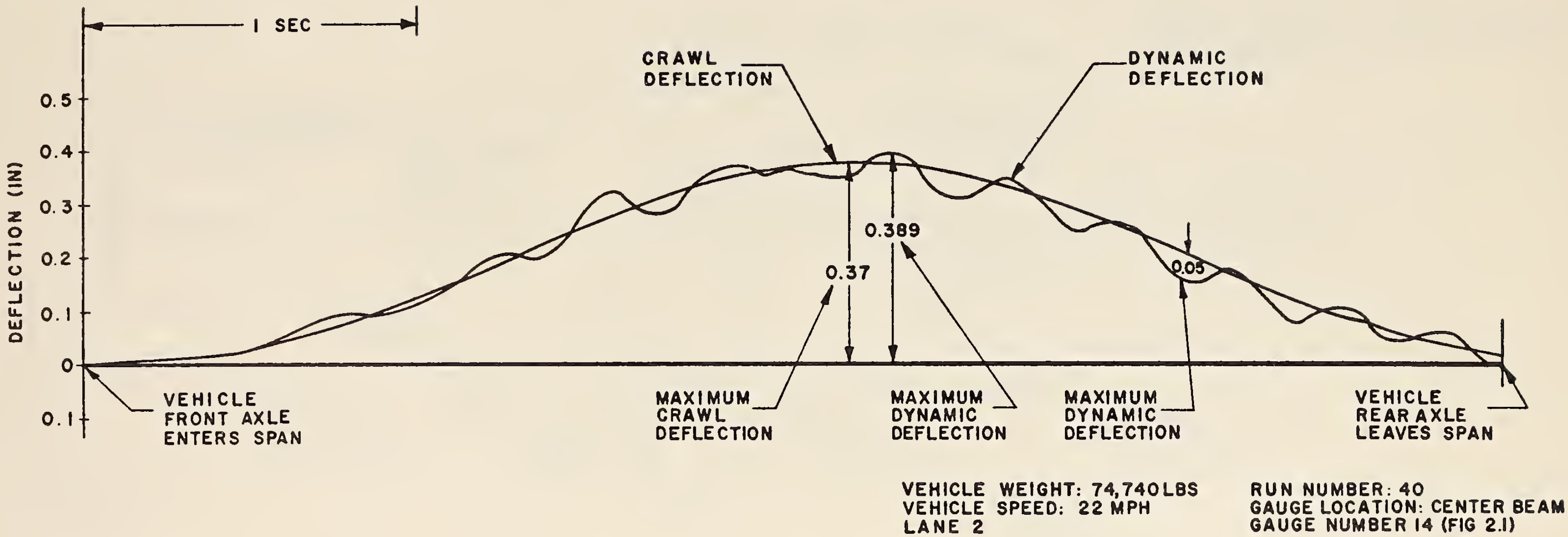


Figure 6 - Measured Midspan Crawl and Dynamic Deflections for 22 MPH Run (Reproduced from Ref. 25 Figure 2.5)

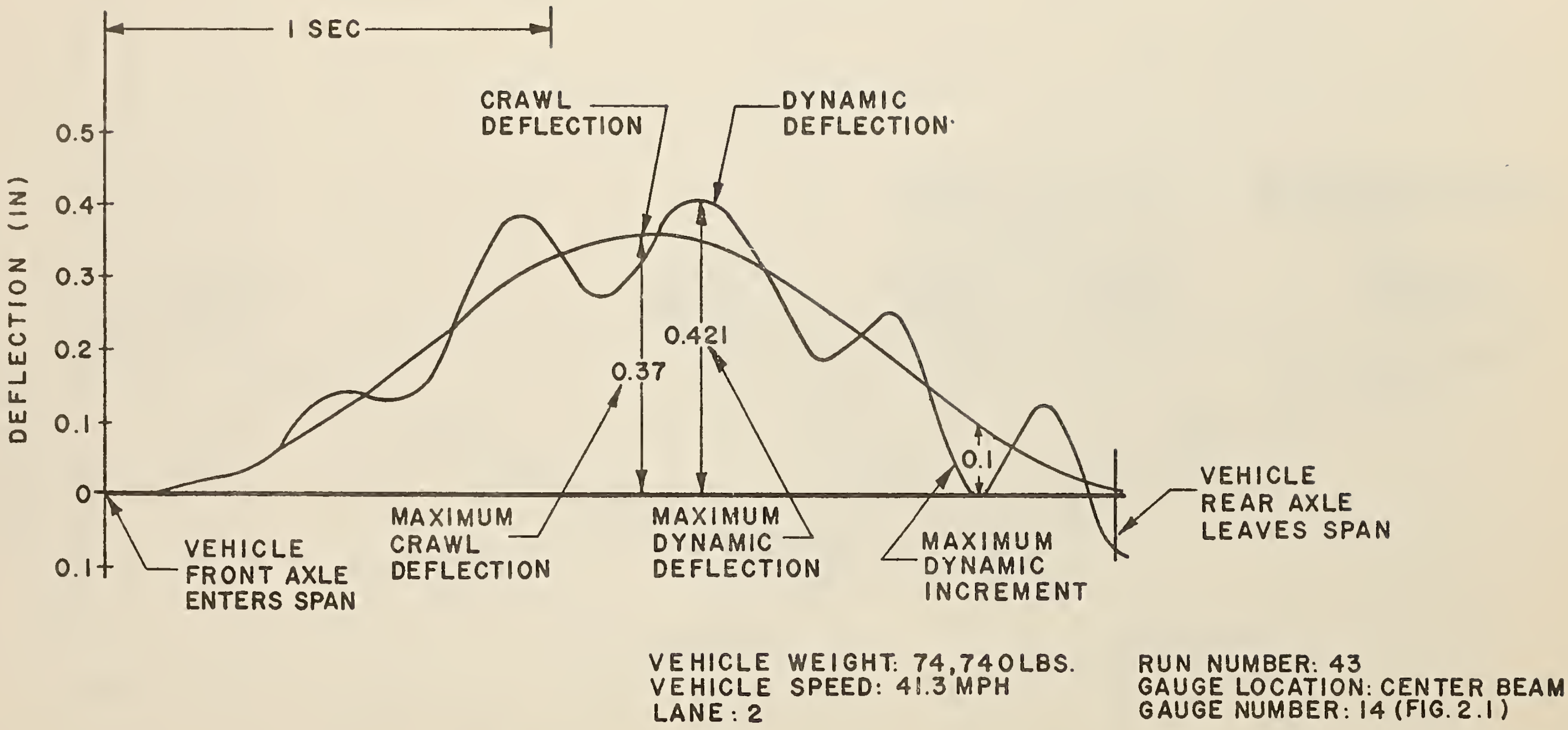


FIGURE 7 - Measured Midspan Crawl and Dynamic Deflections for 41.3 MPH Run
(Reproduced from Ref. 25 Figure 2.6)

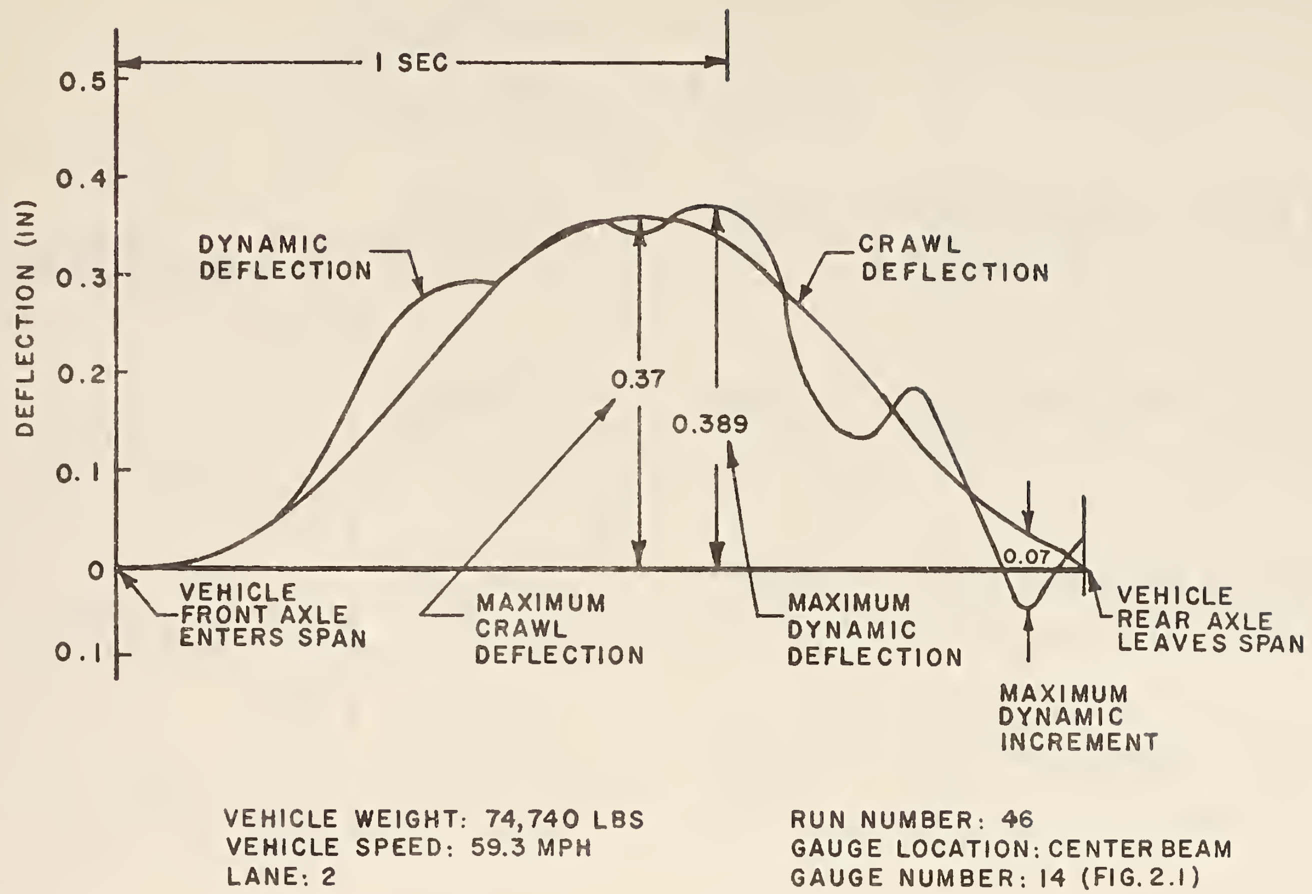


FIGURE 8 - Measured Midspan Crawl and Dynamic Deflections for 59.3 MPH Run (Reproduced from Ref. 25 Figure 2.7)

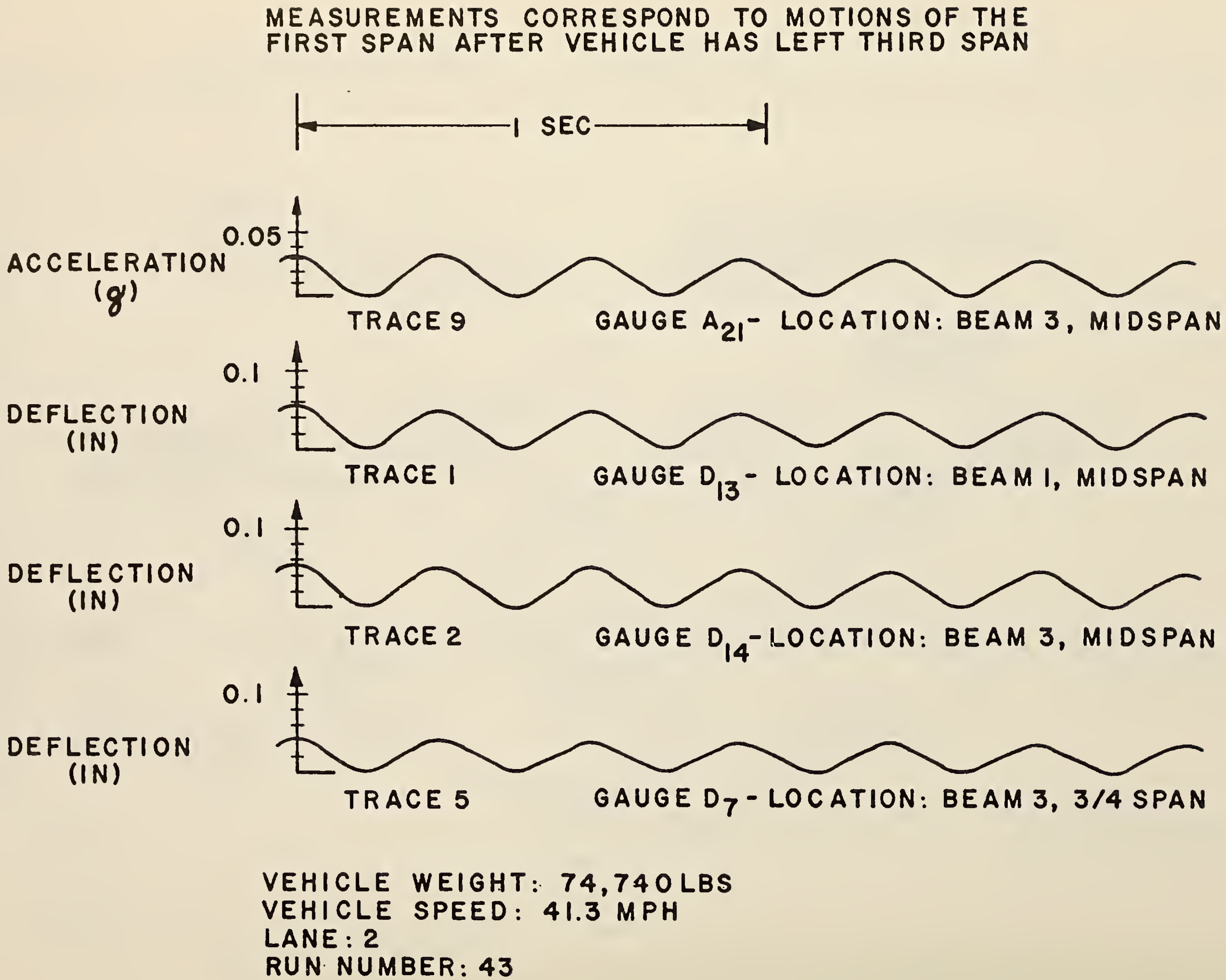


FIGURE 9 - Residual Acceleration and Deflection Time Histories (Reproduced from Ref. 25 Figure 2.8)

after the vehicle has left the bridge. This three-span bridge has simply supported spans with no continuity.

Reference 26 reports on measurements taken on a two-span partially continuous prestressed concrete bridge. Two general types of dynamic bridge response are noted: (a) those responses resembling an amplified crawl-speed response with little or no associated vibration and (b)harmonic responses at two distinct frequencies with peak responses occurring independent of the instantaneous locations of the test vehicle axle. There was no consistent correlation of the type of response with vehicle speed. In both cases, <u>the relative magnitudes of the test vehicle responses varied considerably without influencing the simultaneous bridge strain responses</u>. (Ref. 26)

The general irregularity of pattern of bridge response was a conspicuous feature noted in the dynamic bridge response. Except for brief periods on some runs, non-linear and abrupt transients obscured any periodic elastic response. (Ref. 26 p.134)

3.3.2.1 <u>Static or Crawl Response</u>

Static or crawl response curves, which resemble influence lines under a unit load, are a composite of the effects of all the axles of the vehicles. The features of these curves for the non-composite bridges tested are summarized by the authors:

"(a) The crawl curves for <u>deflection</u> are regular in shape and do not contain cusps. This is an expected result based on an idealization of the bridge as a single beam."

"(b) The curves for <u>strains</u> in the beams close to the load path contain cusp(s) which mark the instant of passage of the heavy axles over the section. The cusps are quite distinct. They are not apparent for the beams (transversely) further from the load." (Ref. 11 p. 55)

A typical crawl test made during the tests reported in Reference 10 is shown in Figure 10. Small dynamic effects

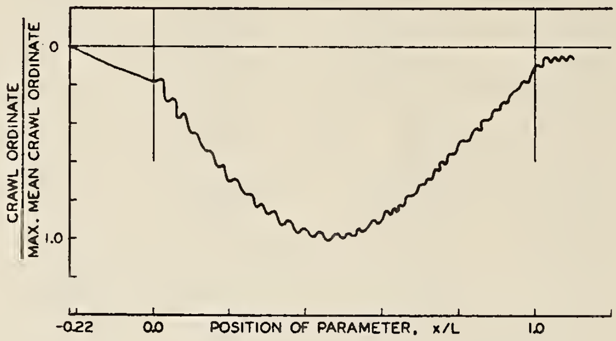


Figure 10. Typical Deflection Crawl Test
(Reproduced from Ref. 10 Figure 86)

amounting to several percent of the maximum response are visible, even at the low crawl speed (? mph). A study was made to determine whether the maximum ordinate of the mean crawl curve was a reliable measure of the maximum static effect, i.e., the vehicle standing on the bridge. Statistical analyses showed that:

"a - run to run variations in measured deformations were small for both static and crawl speed tests.

b - the maximum ordinates of the mean crawl curve gave the best approximation of the maximum static response for both strains and deflections.

c - the differences between the maximum ordinates in (b) above, were always small, in more than 50% of the cases, these were less than 1%. These differences were not statistically significant for the steel bridges." (Ref. 10 p.130)

No report was included in Reference 10 with regard to a comparison of the total static curve with the ordinates of the mean crawl curve.

3.3.2.1.1 Composite Action

The crawl response curves containing cusps, described in Reference 11, were prepared from tests conducted on non-composite bridges. Although the bridges tested were non-composite, they acted in composite fashion for light loads.

"There is evidence of a residual strain or deflection. This is felt to be the result of breakdown in composite action. When the vehicle is remote from the center of the span, the strain response in the top flange is neglible. When the vehicle is near the center of the span, there is a sharp increase in strain. The strains in the top flange must increase (sharply) if the neutral axis moves downward. Such a change would be consistent with a decrease in the friction forces between the slab and the beam flange" (Ref. 11).

3.3.2.2 Dynamic Increment Response

Dynamic increment curves were discussed in Section 3.3.2. Reference 11 provides some additional data from the non-composite bridges reported upon.

The speed parameter α (= $\frac{VT_b}{2L}$) varies over a relatively small range, within the normal speed range (40-70 mph) and bridge dimensions. Within this range, the amplitude of the DI curve varies directly as α, and the wave length of the curve oscillations varies directly with α. (Ref. 11 p.64)

"The dynamic increment curve for the Salt Fork River bridge shows equal positive and negatives amplitudes until the vehicle reaches about midspan. In the last third of the curve, there is an upward shift in the entire curve. This shift is characteristic of the experimentally derived dynamic increments and is due to inconsistent static and dynamic influence curves or variable composite action." (Ref. 11 p.66-67)

3.3.3 Transverse Distribution of Load

Reference 11 reports that the static lateral distribution of strains in the beams across the bridge is non-uniform, the beam laterally closest to the resultant of the load showing the greatest strain. The strain distribution reflects the type of loading, being symmetrical when the load is symmetrical, and eccentric when the load is eccentric.

For the bridges investigated, it is possible to estimate the effect of a second vehicle on the structure. The strain values of each beam can be combined for loads in both lanes to simulate the effect of side by side placement of two vehicles on the bridge. (Ref. 11 p.60,61) (It is not clear from the report whether this effect was physically verified by test, or whether the statement results from the application of superposition theory).

The sum of the maximum strain for all five beams at a given section is proportional to the total moment at that section, neglecting the longitudinal moment carried by flexure in the slab. Thus the sum of the maximum strains should remain constant regardless of vehicle transverse position. For the Salt Fork Bridge, the sums for loads on lanes 1,2 or 3 differed from each other by a factor of only 2 percent. For the Shaeffer Creek Bridge, the difference in sums of maximum strains between lanes 1 & 2 was 10%. The sum of maximum strains for load on lane 3 is not equal to one half for sums for lanes 1 and 2. This result implies that there is a difference in composite action for the various beams under the two loading conditions and thus superposition does not hold for total moments. (Ref. 11 p.62).

For the bridge measurements reported in Reference 11, the transverse distribution of dynamic effect is substantially the same as in the static case. (Ref. 11 p.68)

Reference 24 does not concur with Reference 11 in the statement that the beam laterally closest to the load resultant shows the greatest strain. Examination of Figure 5(a) shows that, by measurement, the exterior beam shows a greater strain than beam 3, which is directly under the load and which is closer to the load resultant. This observation is noted despite the greater stiffness of the exterior beams (33WF194 vs. 33WF130) and the stiffening effect of the parapet. An explanation for this effect may be found by an examination of the moment distribution. It can be seen that the interior moment is carried by several beams, whereas the exterior moment is carried by only the exterior beam.

3.3.4 Comparison of Deflection and Moment

The history curves of amplification factors $\left(\frac{\text{static + DI}}{\text{static}}\right)$ for deflection and moment (strain) show that the total dynamic response histories at the midspan were different.

This is attributed to the differences in the corresponding crawl curves, as the dynamic increment curves for both factors are practically identical, aside from amplitude. It was noted that the amplitude for dynamic increment of deflection is somewhat larger than that for moment (Ref. 10 p.131) (confirming equation 3.12 qualitatively).

(The differences between the crawl curves for moment and for deflection will bear investigation, as information existing on one curve may be non-existent on the other).

3.3.5 Effect of Vehicle Parameters

Vehicle parameters such as magnitudes of instantaneous axle load forces, phase relationship of the axle vertical motion to the bridge vertical motion, phase relationship between the driver and trailer axle forces, and periodic vibrations of the vehicle axle load, of themselves, had only a secondary influence on the bridge dynamic response. The factor of primary influence in controlling the amplitude of bridge dynamic response is the initial mode of vibration (of the vehicle) as the vehicle entered the bridge at some critical speed. (Ref. 26).

3.3.6 Gross Vehicle Weight vs. Strain Range

Of particular interest to this study is a typical plot from Reference 11 relating gross vehicle weight (GVW) and strain ranges. Strain range is plotted as a function of GVW in Figure 11 for a series of random traffic runs. The solid line is the best fit or linear regression line for the mean value of strain as a function of weight. The dashed lines represent strains at a level of one standard deviation above or below the mean regression line. (Ref. 11 Fig. 4.77). (From this data, approximately 68% of the runs show an error of approximately $\pm 13\%$, while 32% of the runs show a positive error between 13% to 30% and a negative error between 13% to 43%. It should be noted that this data is applicable only for the conditions stated on Figure 11.)

Although there is a clear relationship between the strain range and GVW, there is considerable scatter in the data. Other variables obviously influence the results. Among these are speed differences, distance between axles, transverse position of the vehicle, and other parameters which have been previously discussed (Ref. 11). (Although the data is of value in estimating the distribution of ranges of stress to be expected from given GVW's for fatigue considerations, the inverse function will give only a statistical value to the expected GVW, which is not the deterministic approach sought in this study.

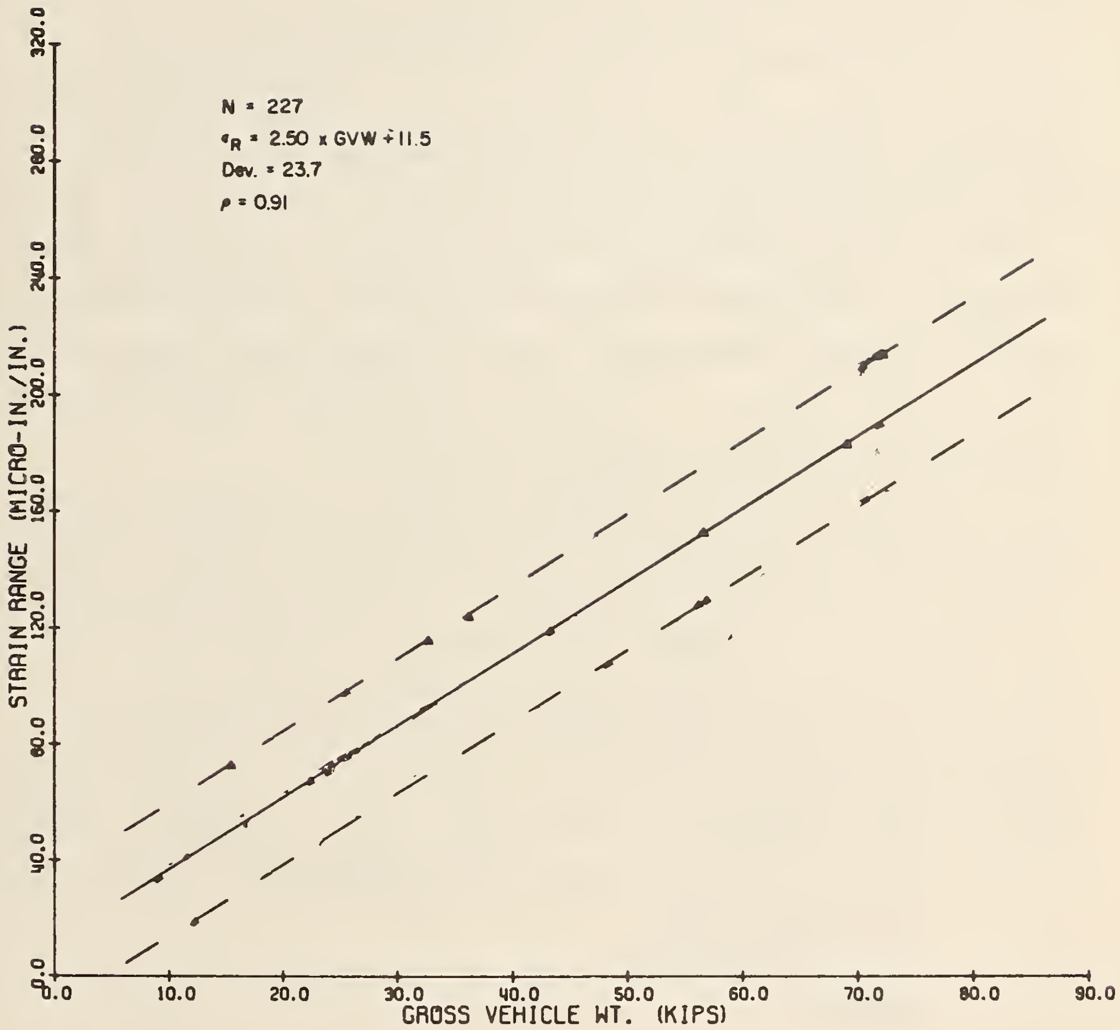


FIGURE 11 - Variation of Strain Range vs. GVW
(Reproduced from Ref. 11 Figure 4.77)

3.3.7 Stress Ranges

Reference 11 provides live stress ranges resulting from various parameters as investigated on three bridges. The data are repeated here because of their applicability to the objective of this study.

"In general, strains or stresses induced in the bridge are low. Mean stresses are on the order of 2,000 to 3,000 psi; maximum stress levels seldom exceed approximately 8,000 psi in the case of the Shaffer Creek Bridge. A number of significant parameters (for purposes of determining stress range) are identified and investigated, including gross vehicle weight, wheelbase, vehicle speed and transverse position of the vehicle. Of these parameters, gross vehicle weight predominates" (Ref. 11 p.111).

To the above parameters should be added one, the lack of which is implicit in the above - roughness or unevenness on the approach runway and the road deck. When the roughness becomes appreciable and the vehicle enters the roadway oscillating appreciably on its suspension, then the following additional parameters become significant to stress range; frequency of vertical vibration of the vehicle relative to the fundamental frequency of the bridge and damping in the vehicle springs, which are unknown for random traffic.

3.4 Collateral Data

3.4.1 General

In order to define the ranges of parameters required for the objectives of this study, it is necessary to utilize geometric and physical quantities characteristics of bridges and vehicles currently in use. Comprehensive data is not required as long as sufficient data is available to indicate the ranges that may be expected. Prior surveys reported in Reference 15 supplemented by data from other sources will be used. For the purpose of this study, effort will be restricted to steel bridges with concrete decks. Distribution of truck types currently in use will provide data to aid in establishing truck categories.

3.4.2 Bridge Characteristics

3.4.2.1 Bridge Types

The Catalog of Bridge Plans of the Bureau of Public Roads (Ref. 27) contains data obtained from various State Highway Departments in a survey made by the BPR in 1957. The designs are based on H20-S16 or heavier loadings. Although the survey was taken in 1957, the data is applicable for the purpose of this study.

As of the time of the survey, the distribution of U.S. bridge types is listed in Table 1. It will be seen that the bridges which are the subject of this study constitute a substantial majority of U.S. bridges.

TABLE 1

DISTRIBUTION OF BRIDGE TYPES, U.S., 1957

Type of Bridge	% of Survey Total
Steel I-beam/concrete slab	47
Reinforced concrete slab with T-beams	23
Prestressed concrete	11
Other types	19

3.4.2.2 Bridge Lengths

A survey of bridge lengths in California in 1957 compiled by Mitchell and Borrmann (Ref. 29) reported on highway bridges from simple spans to major suspension bridges. The distribution of bridge lengths for the California bridge system in 1957 is summarized in Table 2. The exact numbers are not important, as this information is sufficiently valid, even at this date, to indicate that approximately 50% of the bridges are less than 29 feet, to which consideration should be given in this study.

TABLE 2

DISTRIBUTION OF LENGTHS, CALIFORNIA BRIDGES, 1957

Bridge Length	% of Survey Total
Less than 19 ft.	19
19 ft. to 29 ft.	35
29 ft. to 69 ft.	38
69 ft. and over	8

It is not explicitly stated but is assumed that nearly all the bridges in this span range are simple-span type.

3.4.2.3 Bridge Weight

Bridge weight is required for the computation of the ratio of vehicle weight to bridge weight and of natural frequency of the bridge. The bridge weight includes all components of the structure which are supported by the beams - roadway slab, beams, sidewalks, parapets, diaphragms, bracing, wearing surface, drains, etc. The results of field tasks provide the data in Table 3, which includes a brief description of the bridge, weight and fundamental natural frequency. Analysis of Standard Plans for Highway Bridge Superstructures of the BPR provided the data for Figure 12, which graphically shows variation in bridge weight as a function of span length.

3.4.2.4 Bridge Frequency

Bridge frequency is required for calculations of dynamic effects, and to aid in the selection of transducers. The data summarized in Table 3 were obtained from field tests. The values of natural frequencies computed for the Standard Plans for Highway Bridges are summarized in Table 4, and are

TABLE 3 SURVEY OF BRIDGE CHARACTERISTICS (ADAPTED FROM REF. 15, TABLE 3.1)

No.	Designation	Type	Span (ft.)	Road-way Width (ft.)	W_b (kips)	Observed	
						f_b	T_b
1	Conway	I-Beam	69	14	198	6.0	0.167
2	Gilbertsville	"	114	24	792	4.3	0.234
3	Townsend M.	"	89	30	696	3.8	0.265
4	Townsend S.	Plate Girder	86	24	441	4.2	0.240
5	Ware	" "	77	18	147	5.5	0.182
6	Jackson No. 4	Plate Girder	84	29	-	5.5	0.182
7	No. 5	" "	84	29	-	5.5	0.182
8	No. 6	" "	76	29	-	6.4	0.156
9	No. 7	" "	82	29	-	5.9	0.168
10	No. 8	" "	76	29	-	-	-
11	Fenville No. 1	I-Beam	58	28	390	7.1	0.141
12	No. 2	"	59	28	376	7.0	0.143
13	No. 3	"	59	28	396	7.0	0.143
14	No. 4	"	59	28	396	6.9	0.145
15	No. 5	"	59	28	396	6.9	0.145
16	No. 6	"	58	28	390	7.2	0.139
17	X_3 of 33-6-1, No. 2	I-Beam	61	-	-	6.4	0.156
18	No. 3	"	61	-	-	6.3	0.158
19	No. 4	"	61	-	-	6.2	0.161
20	B_1 & B_2 of 33-6-1, No. 1	"	64	-	-	7.8	0.128
21	No. 2	"	65	-	-	6.4	0.157
22	No. 4	"	65	-	-	6.1	0.164
23	No. 5	"	65	-	-	-	-
24	B_1 of 56-12-6, No. 1	"	55	-	-	-	-
25	No. 2		56	-	-	7.3	0.137
26	B_2 of 39-3-8, No. 1	"	45	-	-	8.0	0.125
27	No. 2	"	49	-	-	7.9	0.126
28	Vancouver Ave.	I-Beam	75	-	348	4.1*	0.244*
29	Vancouver 582	"	69	-	253	5.6*	0.176*
30	Knightly	"	55	-	157	6.0*	0.167*
31	Skull Valley	"	60	-	163	-	-
32	Collins Bay	"	30	-	-	10.6	0.094
33	Rock River Bridge	"	97	30	635	3.1	0.323

*Note: Computed Values

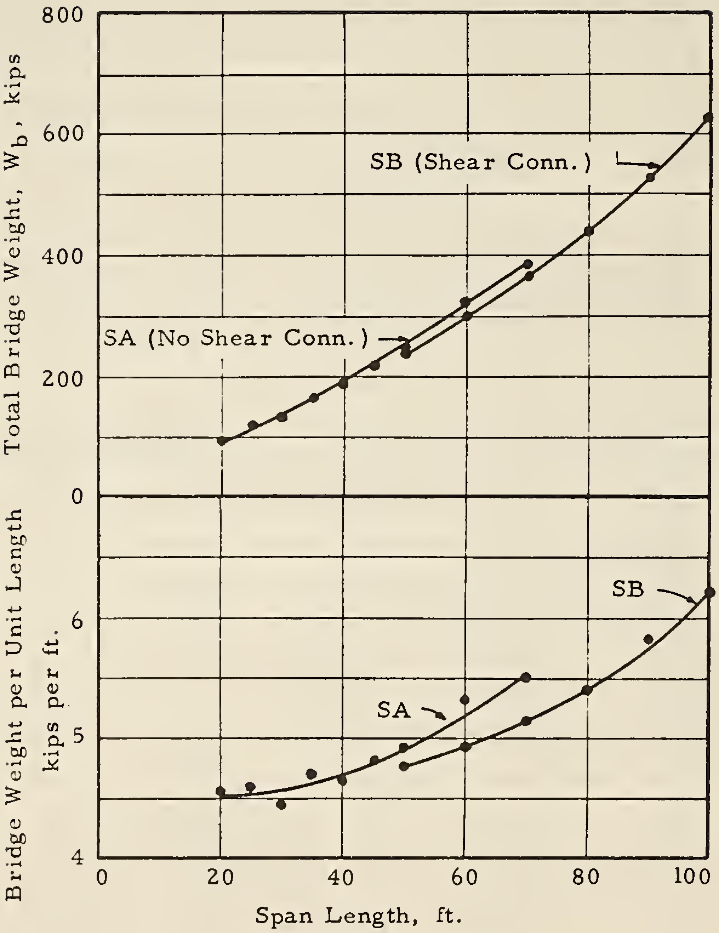


FIGURE 12 - BRIDGE WEIGHT DATA - STEEL I-BEAM STANDARD PLAN BRIDGES (REPRODUCED FROM REF. 15 FIGURE 3.5)

TABLE 4 - COMPUTED BRIDGE WEIGHT AND FREQUENCY CHARACTERISTICS -

STANDARD BRIDGE PLANS

H20-S16-44 Loading and 28 ft. - 0" Roadway

(Adapted from Ref. 15 Table 3.2)

Series	Description	Span Length, ft.	Total Weight W_b, kips	T_b (sec.)	f_b (cps)	$T_b/2L$
SA	I-beam, non-composite design	20	90	0.048	20.8	0.00120
		25	115	0.062	16.1	0.00124
		30	133	0.073	13.7	0.00122
		35	164	0.090	11.1	0.00129
		40	186	0.111	9.0	0.00139
		45	217	0.124	8.1	0.00138
		50	246	0.137	7.3	0.00137
		60	320	0.193	5.2	0.00161
		70	385	0.241	4.1	0.00172
SB	I-beam, composite design	50	239	0.171	5.8	0.00171
		60	295	0.207	4.8	0.00174
		70	360	0.254	3.9	0.00181
		80	434	0.307	3.3	0.00192
		90	527	0.372	2.7	0.00207
		100	623	0.420	2.4	0.00210

plotted in Figure 13, together with the observed data from Table 3.

3.4.2.5 Bridge Damping

From studies conducted on 15 spans, and reported by three sources, Reference 15 concludes that damping was generally a combination of viscous and frictional types. However, it may be assumed, with accuracy sufficient for practical purposes, that damping is viscous. The values of logarithmic decrements ranged from 0.03 to 0.4 (i.e., β values from 0.005 to 0.06), depending on bridge type and condition. It is concluded that bridge damping is usually less than 5% of critical, and that a value of 1 to 2 percent is representative of the data reviewed (Ref. 15 p.16).

3.4.3 Vehicle Characteristics

As previously stated, if the approach to the bridge and the bridge deck are relatively smooth and contain no abrupt changes to induce vehicle excitation, the dynamic characteristics of a vehicle do not significantly affect the dynamic bridge response. However, the static properties of a vehicle are significant, affecting both the bridge crawl (static) response and through that, the dynamic response. The static properties are the features of geometry of the vehicle: the spacing of the axles, the number of axles, and the static distribution of the vehicle weight to the axles.

Walker and Veletsos (Ref 15, p.18-21) recap the results of several vehicle surveys, and applies the data to the selection of three typical configurations as representative of medium-weight, heavy-weight, and extra-heavy-weight tractor-trailer combinations. This data is assumed valid as of the date of their study (1966). It is also recognized that change is constant and that current pressures are leading to increasing allowable gross vehicle weights. The data

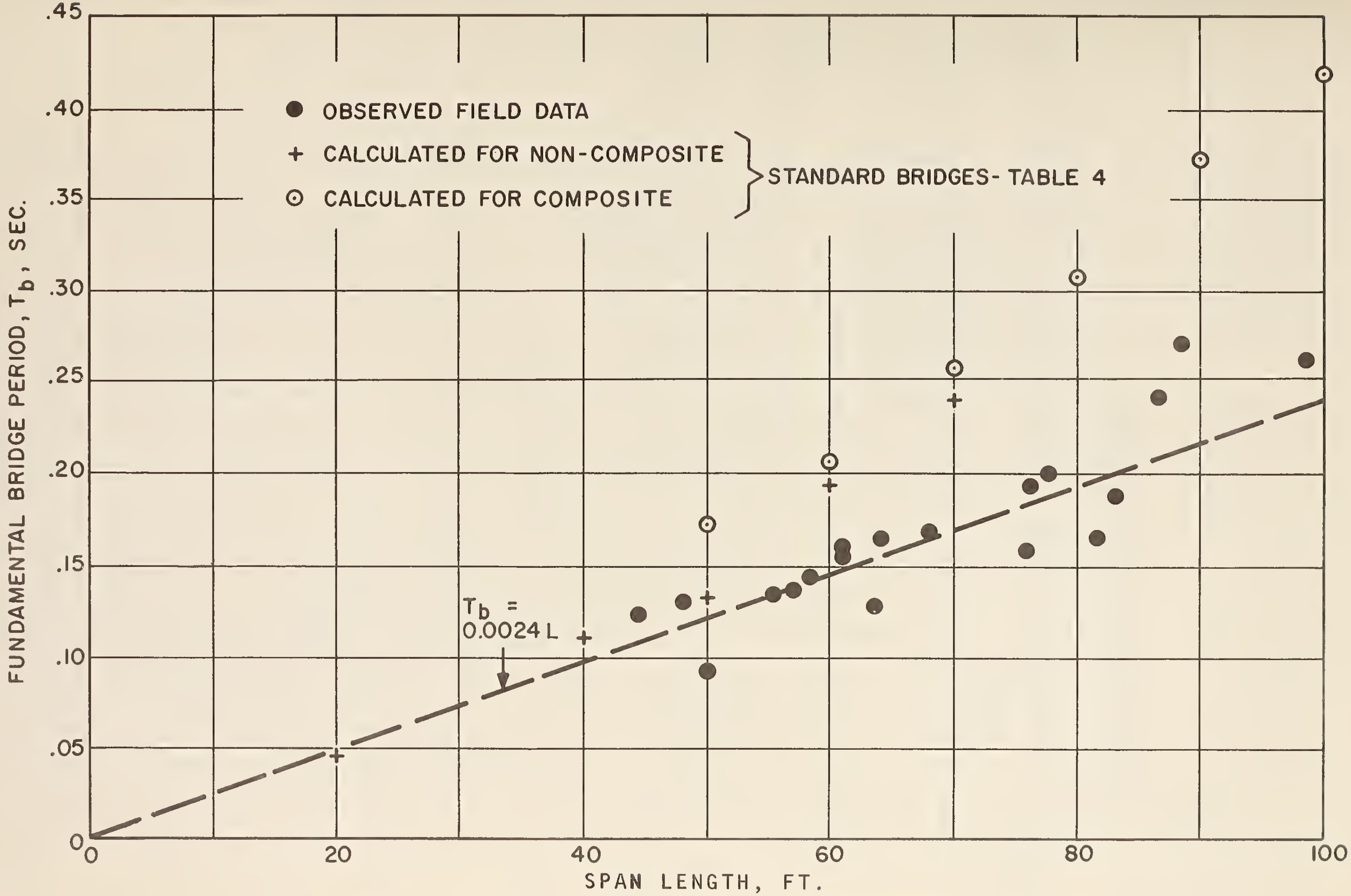


Figure 13 Observed Field Data for Bridge Periods (Adapted from Ref. 15 Figure 3.5)

is deemed sufficiently valid, however, to establish ranges of value satisfactory for the purpose of this study. For completeness, the dynamic properties of vehicles will also be recorded.

3.4.3.1 Vehicle Geometry and Weight

Table 5 provides the geometry and weights of the representative vehicles used in Reference 15. Some additional data of interest:

- The heaviest vehicle recorded in the survey corresponds closely to the AASHTO typical design vehicle except that the loads are carried on tandem-axle bogies rather than on a single axle.
- Very heavy off-the-road vehicles have an upper limit of 60,000 lbs. per loaded axle, as of 1966.
- The Army Tank Carrier, which under certain conditions must operate on civilian roads, has a triple bogie with 4 ft. axle spacing and with individual axle loading limited to 20,000 lbs.

3.4.3.2 Vehicle Vibration Characteristics

In the computer model, two characteristic frequencies are used to define the vibration characteristics of each vehicle axle. First is the vibration frequency of the vehicle acting on its tires alone. This is the characteristic observed when the vehicle is moving on a relatively smooth road. The second is the frequency of the vehicle vibrating on its combined suspension system and tires. This characteristic is observed when the moving vehicle is excited by an abrupt discontinuity in the road. Table 6 tabulates values for these characteristics, synthesized from a number of sources.

The stiffness chararacteristic of the suspension springs are usually constant but not linear for a given vehicle. Tire stiffness is non-linear, and is largely

Table 5 - Representative Vehicle Geometry and Weights

Characteristic	Medium-Wt Tractor-Trailer (2S-1)	Heavy Wt Tractor-Trailer (2S-2)	Extra-Heavy Wt.Tractor-Trailer (3S-2)
Gross Vehicle Weight	37,000 lb	55,000 lb	71,300 lb
Loaded Front Axle	4,250 lb	5,000 lb	7,300 lb
Loaded Tractor Rear Axle	16,750 lb	18,000 lb	
Loaded Tractor Bogie			32,000 lb
Loaded Trailer Rear Axle	16,000 lb	32,000 lb	
Loaded Trailer Bogie			32,000 lb
Tractor Wheel Base (to Bogie CL)	141 in	144 in	144 in
Trailer Wheel Base (to Bogie CL)	246 in	315 in	315 in
Tractor Tandem Axle (Bogie) Spacing			48 in
Trailer Tandem Axle (Bogie) Spacing		51 in	50 in
Unsprung Weight, Front Axle	600 lb	750 lb	850 lb
Unsprung Weight, Tractor Rear Axle	1,500 lb	2,000 lb	
Unsprung Weight, Tractor Rear Bogie			5,400 lb
Unsprung Weight, Trailer Rear Axle	1,200 lb		
Unsprung Weight, Trailer Rear Bogie		3,400 lb	3,400 lb

dependent on the load level and tire pressure. Air suspension systems are not included in the data presented herein.

Table 6 - Vehicle Vibration Frequencies

Axle	Frequency, cps	
	On Tires	On Tire-Springs
	Two-Axle Vehicles	
Front	3.0 - 4.9	2.1 - 2.9
Rear	3.5 - 4.9	2.4 - 2.6
	Three-Axle Vehicles	
Front	4.0 - 4.9	1.7 - 2.5
Rear of Tractor	3.0 - 4.9	1.7 - 2.2
Rear of Trailer	3.4 - 4.3	2.1 - 2.6

3.4.4 Parametric Ranges

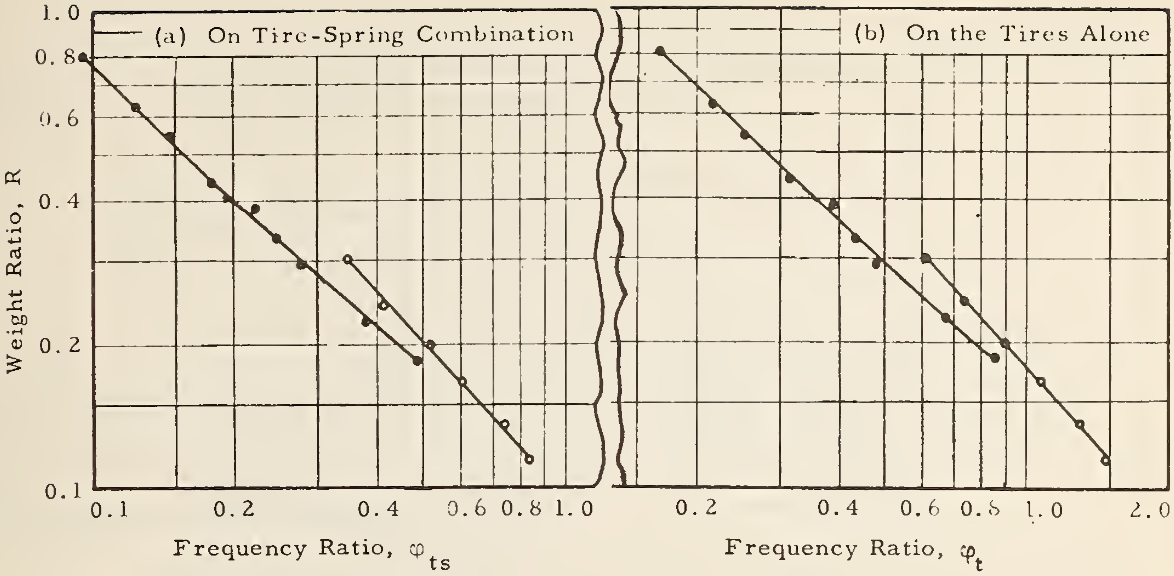
Reference 15 provides data on practical ranges of parameters which are reproduced in Figures 14 and 15, and are included for general interest. Figure 14 gives the relationship between the frequency ratios ϕ_{ts} and ϕ_t, and the weight ratio R, see Section 3.2.2.1.1 for definitions. Figure 15 gives the practical ranges of the speed parameter α for various speeds of vehicles as a function of the length of standard plan bridges.

3.5 Instrumentation Data

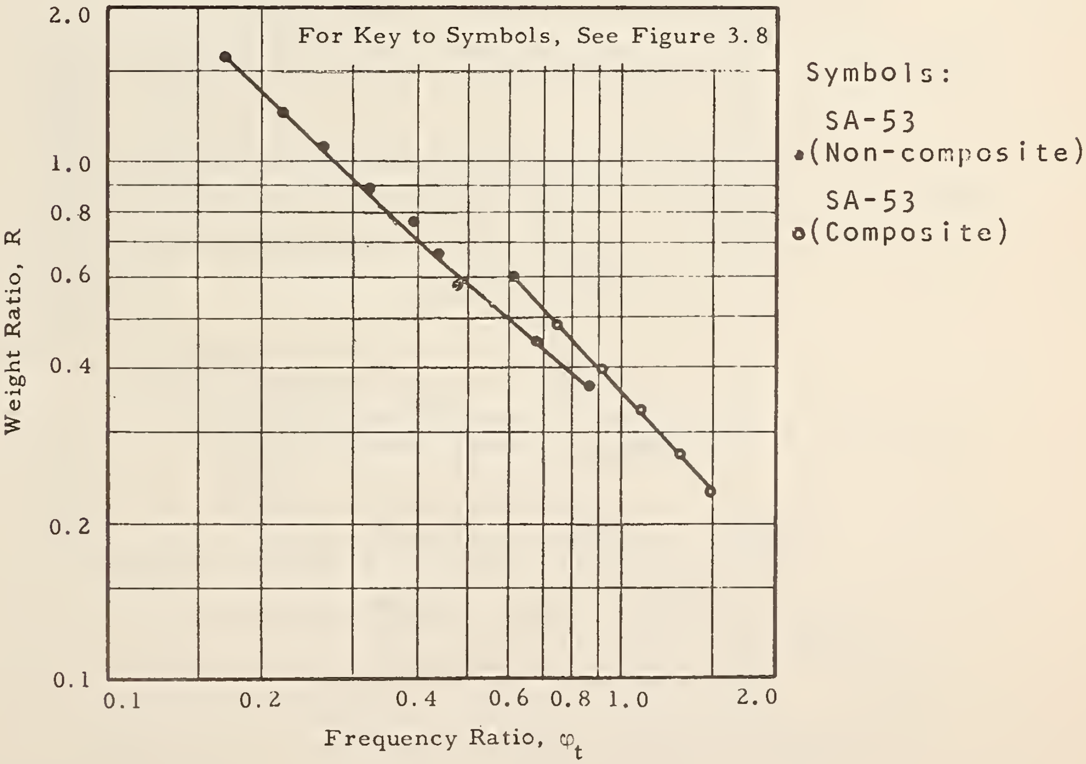
The transducers required for the objectives of this study may be divided into two categories; those required to provide traffic data, and those required to provide the load or weight data.

3.5.1 Traffic Data Transducers

Since the installation of transducers or other instrumentation is permitted in the bridge approach, it seems reasonable to explore the equipment currently in use for



(A) W_v = 72 kips, f_t = 3.5 cps, f_{ts} = 2 cps



(B) W_v = 144 kips, f_t = 3.5 cps, f_{ts} = 2 cps

Figure 14 - Dimensionless Weight and Frequency Parameters (Adapted from Reference 15, Figures 3-11 & 3-12)

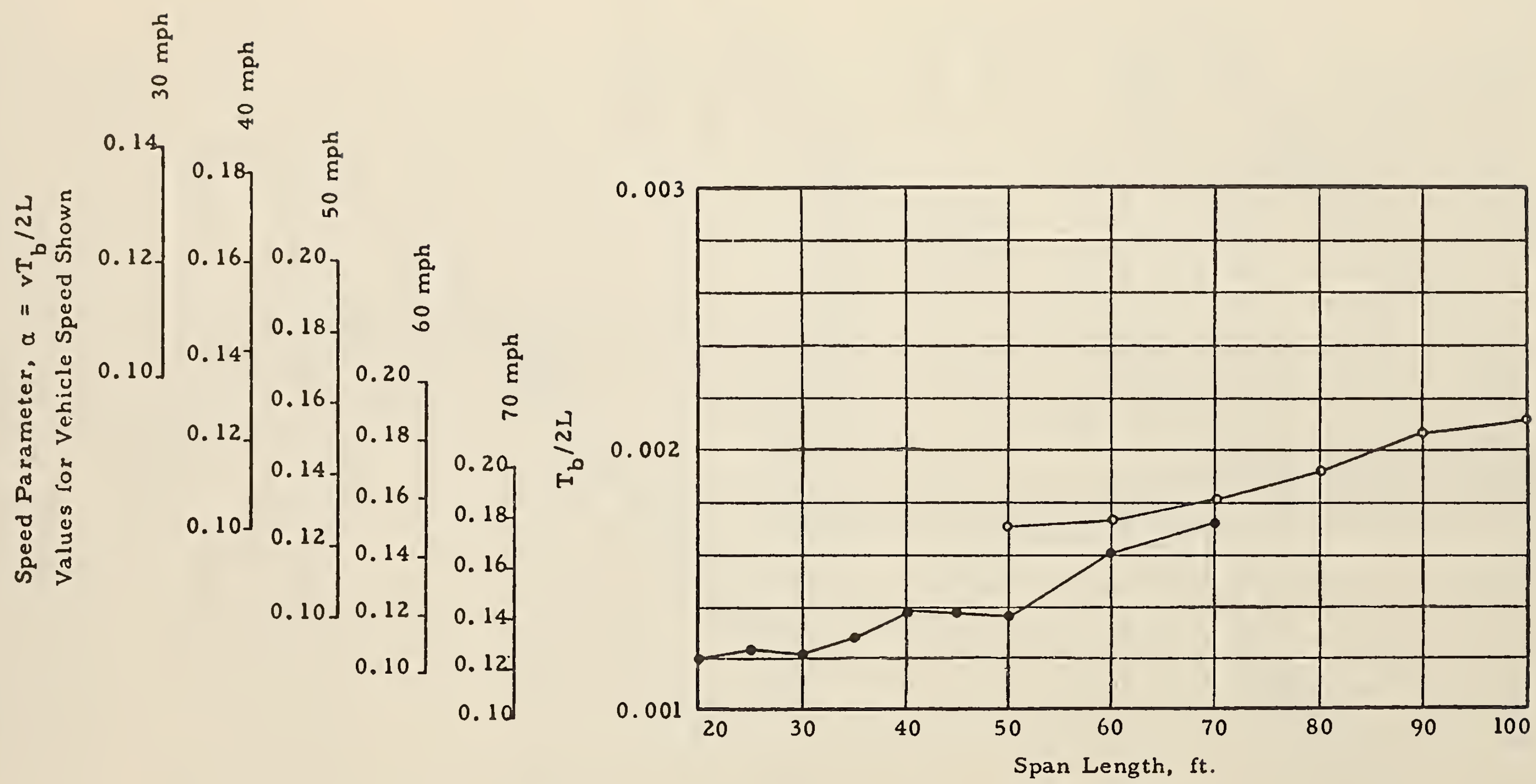


FIGURE 15. SPEED PARAMETER RANGE FOR STANDARD PLAN BRIDGES (ADAPTED FROM REF. 15 FIGURE 3.13)

traffic studies and traffic control purposes. Again, these may be categorized by purpose:

(a) Counting
(b) Vehicle presence detection
(c) Velocity determination

Reference 29 tabulates the results of a comprehensive study of vehicle detectors made by Barooshian for a Diamond Interchange Control System. The results of the study are entirely applicable to this study, and the tabulation is reproduced as Appendix A.

Additional information regarding current developments of vehicle detectors was obtained at the recent Federal Coordinated Program Research Review Conference held under the auspices of the FHWA at Arlington, Texas during September 9-13, 1974. Descriptions were given of the development status of two different vehicle detectors now under contract with the FHWA (Project 2L - Mr. L. G. Saxton and Mr. F. Mammano). The status of development should be investigated when the instrumentation system design is implemented. Table 7 provides data with respect to the current status of these vehicle detectors.

3.5.2 Strain Transducers

Numbers of instruments, based on mechanical linkages, mechano-optical principles, and electric systems, have been developed in the past for the measurement of strain. Because of the high volume of data to be processed, attention will be concentrated on those transducers which generate an electrical signal suitable for automated data reduction. Table 8 provides data relative to such transducers. Section 5.3 will discuss the transducers recommended for the selected instrumentation system.

Table 7 - Vehicle Detectors Under Development for FHWA as of September, 1974

Nomenclature	Present Status	Description	Function
Magnetic Gradient Vehicle Detector (MGVD)	Design of production model in process Prototype successfully tested	Insert in single strip in pavement. Electronics package at side of road.	Detection of all vehicles Determine speed Identify buses Advantages claimed - Reduced Costs - added reliability
Self powered (Sonic) vehicle detector	Design of engineering prototype in process	Imbedded in pavement in 4" dia x 9½" high hole - transmits to detector up to 500 ft distant	Detect vehicles in one lane with vehicles present in adjacent lanes. Advantages claimed - Reduced interference with traffic during installation - (4" dia hole bored) - no wires

Table 8 - Transducers for Strain Measurement

Type	Principle of Operation	Gage Factor Typical	Typical Measurement Range μ"/"	Linearity	Typical Costs $	Comments
Bonded Electrical Resistance Strain Gage Wire or Foil	Change of Electrical Resistance when strain-ed		± 1500 μ"/"	.1% to 1% with matched input cir-cuitry	3.10/GP gage 11.00/Rosette (excluding sig condition-er) Prices vary de-pending on design	•Poor reliability in outdoor environment despite water-proofing •Extreme care required in in-stallation •Special amplifier required to match strain gage impedance •Temperature compensation re-quired for applications with accurate read outs
Constantin		2				
Isoelastic (dynamic operations)		3.5				
Semi-Con-ductor (Piezo Resistive) Strain Gage	Change of Electrical Resistance when strain-ed	to 130	Satisfactory for Objective			•Output non-linear with strain •Strain sensitivity is markedly temperature dependent •Useful for "stiff" applica-tions
LVDT	Electrical Output Proportional to Displace-ment of Mov-able Trans-former Core		± .050"	.05%	44/hermeti-cally sealed unit (exclud-ing sig. con-ditioner)	•Reusable •High Reliability

3.5.3 Deflection Transducers

Various types of instrumentation can be used to measure the deflection of beams. Again, because of the high data volume required for automated data processing, attention will be concentrated on equipment which will generate electrical signals useful for this purpose.

A popular form of such deflectometer is an instrument similar to that designed and built by the FHWA. This consists of a short triangularly shaped flexible measuring beam, one end of which is anchored to the beam and the other end of which is anchored by a wire to an immovable reference, generally an area beneath the point at which the bridge deflection is to be measured. With no load on the bridge, the measuring beam is preloaded to deflect an amount greater than the expected bridge deflection. A strain gage, mounted on the measuring beam, is zeroed with the bridge in the zero deflection position. As the bridge deflects under load, the strain gage senses the deflection relief of the measuring beam as a strain. The shape of the measuring beam is selected to provide a constant strength beam, so that the strain is constant along the length of the beam.

An LVDT could be selected to measure deflection directly, but would also require a wire or linkage to establish a tie to the reference.

SECTION 4
DETERMINATION OF STATIC AXLE WEIGHTS

4.1 Bridge Response

The total dynamic response of a bridge is seen as a dynamic increment superimposed on a static component or static influence line. The static component dominates, as the dynamic increment is on the order of 15 to 30 percent of the maximum static value for reasonably smooth approaches or bridge decks, with no abrupt discontinuities in either the approach or the deck. The static component can be evaluated by relatively simple static solutions or by approximate empirical influence lines determined for selected locations in the structure. The input parameters for the static analysis depend on the geometry and dimensions of the bridge and the dimensions. axle weights and gross vehicle weight. The static component can be predicted with a reasonable degree of certainty (Ref. 11).

The dynamic increment (DI) is not deterministic with currently available analytical techniques, being a complex function of numerous variables. The speed parameter, α, is a dominant variable in the determination of the amplitude of the DI, but other vehicle and bridge parameters, not all of which are available, are also factors, as described in Sections 3.2.3 and 3.3. Suffice it to say, the scatter in the relationship between the gross vehicle weight (GVW) and the strain ranges discussed in Section 3.3.6 (See Fig. 11), reflects the difficulty in accurately determining the GVW from dynamic load data, taken at the center of the bridge.

4.2 Data Enrichment Through Processing

The mean crawl curve reflects the static response within 1%, see Section 3.3.2.1. If the crawl curve could be extracted from the total dynamic response curve, then the axle weights and the GVW could be determined from this data and the dimensions of the bridge and the vehicle.

The frequency of oscillation of the dynamic response curve for simple slab and girder bridges is essentially the natural frequency of the bridge. Oscillations corresponding to the frequency of the interacting forces cannot be distinguished on the curves. See Section 3.3.2. A reasonable difference between the bridge natural frequency and the vehicle crossing frequency would permit filtering of the dynamic increment from the bridge signal, resulting in the crawl curve.

Figure 13 indicates that natural frequencies of a simple span, 28 ft. (8.5 m) wide, slab on steel girder bridges range from 2.2 to 20 cps. Crossing frequency is expressed as $f_c = \frac{V}{2L}$. A vehicle crossing a 100 ft. (30.5 m) long bridge at 100 ft/sec (30.5 m/sec) will have $f_c = \frac{100}{2 \times 100} = 1/2$ cps, and for a 50 ft. (15.25 m) long bridge, $f_c = \frac{100}{2 \times 50} = 1$ cps. For lower velocities, f_c will be linearly lower. The ratio

$$\frac{f_n}{f_c} = \frac{2.2}{1}$$

is the minimum that may be reasonably expected, and is slightly more than an octave for the lowest practical ratio.

Filtering to yield 12 dB/octave/filter section attenuation of the dynamic increment can be easily achieved. A two section active filter will provide approximately 30 dB attenuation of the dynamic increment, reducing it to noise level. This will reduce the dynamic increment to approximately 2% of its value or .30 x .03 = .009, or approximately 1% of the value of the static response. For a bridge 100 ft. (30.5 m) long,

$$\frac{f_n}{f_c} = \frac{2.2}{1/2} = \frac{4.4}{1}$$

and the same filter will now provide approximately 60 db attenuation, which is more than ample. Filtering, easily and inexpensively achieved, can therefore be used in the processing of bridge signals to enable the determination of static weights.

4.3 Correlation of Bridge Output Signals and Axle Weights

4.3.1 Single Ended Approach

There are several characteristics for which crawl curves might be developed for static weight determination; reaction (shear), moment or strain, deflection and acceleration. Of these, shear seems most amenable for the most accurate calculation of axle weights and gross vehicle weight.

Figure 16 is a shear crawl curve referenced to the far end of the bridge, based on reasonable assumptions for the truck and bridge. It was developed by superpositioning the influence lines for each of the axles. For the interval 0-(1), the slope of the resultant is due to the influence of the front axle (F). For the interval (1) to (2) the slope of the resultant is due to the influence of the drive axle (D) and the front axle (F). For the interval (2) to (3) the slope of the resultant is due to the influence of all axles, (F), (D) and the tractor (T).

It is shown in Appendix B, that

$$F = m_1 (\frac{L}{V}) \quad = \text{front axle weight}$$

$$F+D = m_2 (\frac{L}{V})$$

$$D = (m_2 - m_1)(\frac{L}{V}) \quad = \text{drive axle weight}$$

$$F+D+T = m_3 (\frac{L}{V}) \quad = \text{gross vehicle weight}$$

$$T = (m_3 - m_2 - m_1)(\frac{L}{V}) \quad = \text{trailer axle weight}$$

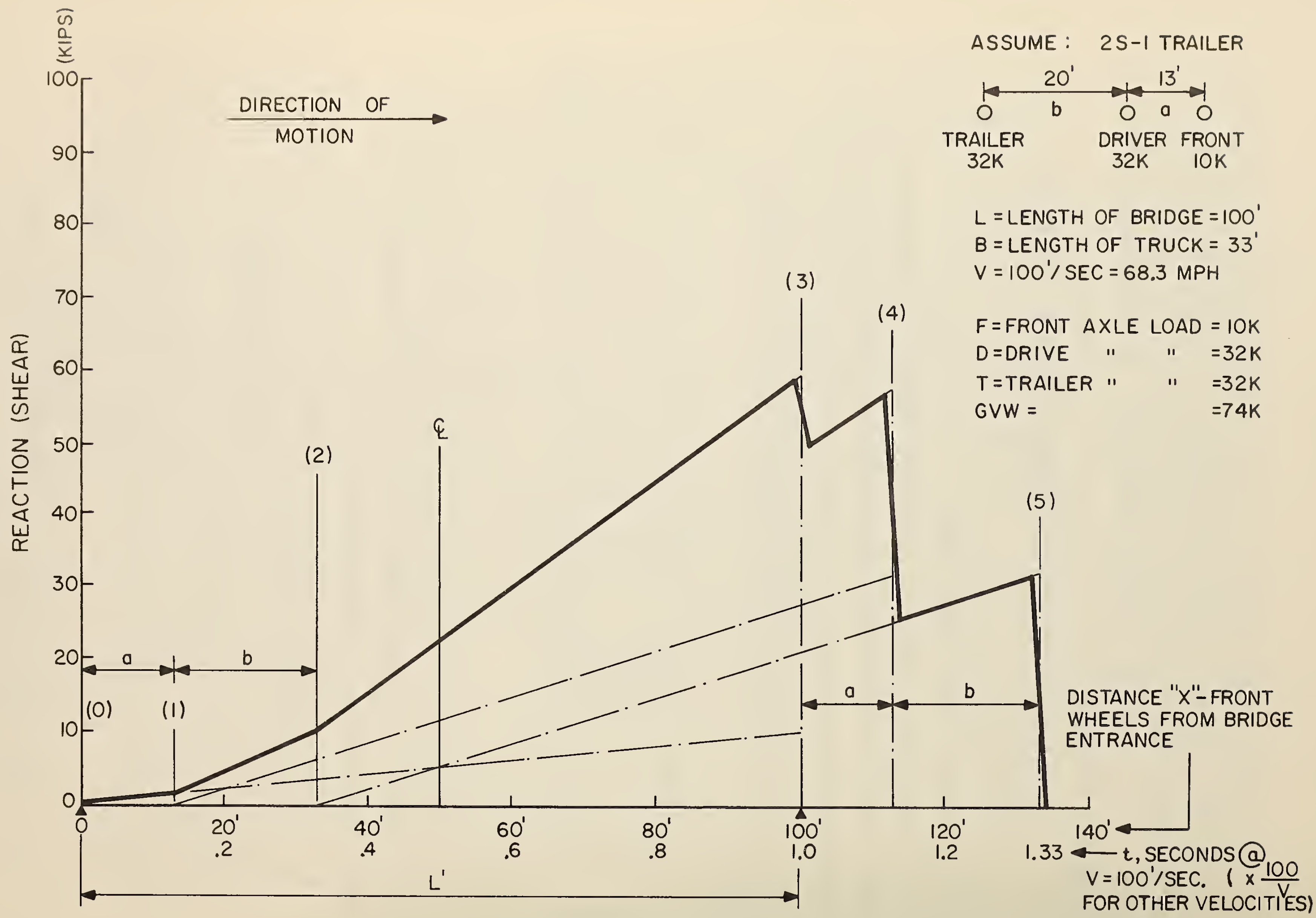


Figure 16. Reaction (Shear) Crawl Curve
Instrumented at Far End of Bridge

where m_1, m_2, and m_3 are the slopes of the crawl curve at the respective intervals, L the bridge span, and V the vehicle velocity.

These equations can be expanded for any number of axles, all that is required is the determination of the slopes of the curve, and the constant $(\frac{L}{V})$. L is known accurately from bridge measurements, and V is determined by instrumentation as described in Section 5.2.1.

It is expected that the filtered bridge response signals for a 2S-1 vehicle will resemble the curve of Figure 16, except that the various slopes will be joined by gentle curves, which will not affect the final results.

The advantages of this approach are:

- o The output is not dependent on the values of the maximum ordinates of the curve - (These values do not possess any significant value and will be lost in filtering).
- o The effects of beam action are completely eliminated in the determination of static weights - (the number of variables and associated errors to be handled in computation are reduced and uncertainties associated with composite/non-composite action in non-composite structures, see Section 3.3.2.1, are completely eliminated).
- o The effects of initial vehicle conditions on entering the bridge are minimized by locating the instrumentation on the far end of the bridge.
- o The time available for smoothing the bridge signal outputs is maximized.

The disadvantage of this approach is that the static weights are a function of the velocity. Should the velocity change after measurement or should any errors exist in velocity measurement or computation, then these will be reflected in weight errors. This leads to the double ended approach, where outputs from transducers at both ends of the bridge are summed.

4.3.2 Double Ended Approach

Figure 17 shows a shear crawl curve referenced to the near end of the bridge, which is shown by the solid line. The shear crawl curve referenced to the far end of the bridge is shown by the dotted line, and the curve resulting by superimposing both crawl curves is shown by the dash line.

Appendix C shows that the slopes of the near end bridge instrumentation output are identical with those of the corresponding intervals in Figure 16, but opposite in sign. The consequence is that the curve which results by adding both crawl curves is flat for the intervals (0)-(1), (1)-(2), (2)-(3), (3)-(4) and (4)-(5). The ordinates of these intervals, when the structure and instrumentation are properly calibrated, will reflect the static weight of the respective combinations of axles as noted on Figure 17. The static weights of the individual axles and the GVW may now be obtained by the appropriate simple arithmetic. As a matter of fact. if only the single vehicle is on the bridge, since values of each axle weight can be obtained from each end of the diagram, the accuracy of the results may be enhanced by averaging.

The advantages associated with the double ended approach are:

- The velocity and any associated velocity error are eliminated from static weight determination.
- Adding a greater number of transducer outputs will decrease the random error.
- The effects upon the static weight of a vehicle by a second vehicle entering the bridge in the same lane and close behind the first vehicle may be easily offset by the use of obvious algebraic techniques.

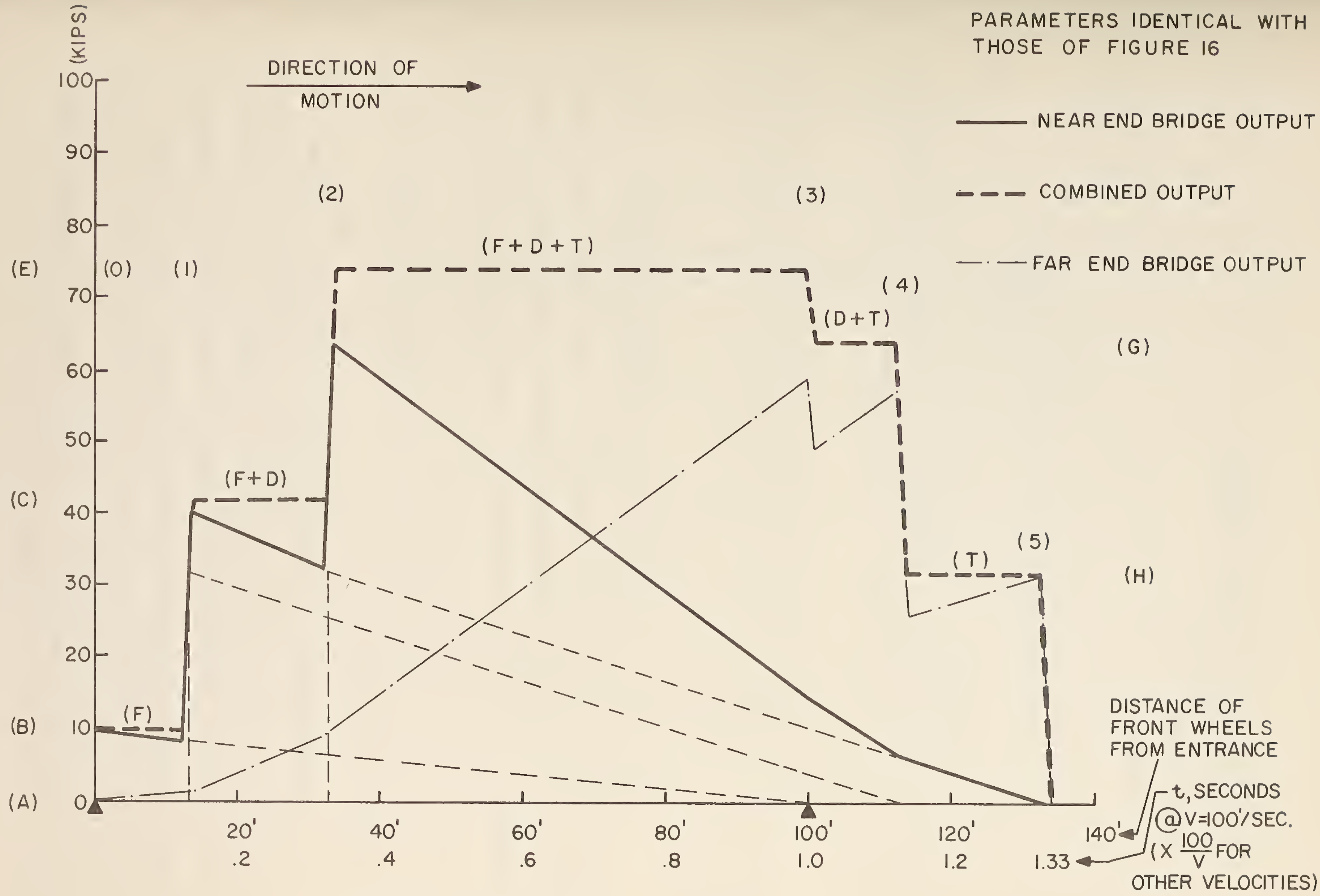


Figure 17. Reaction (Shear) Crawl Curve Instrumented at Both Ends of Bridge

4.4 Selection of Output Signals

4.4.1 Static Weights

Appendix C shows that when the shear crawl curve responses for both ends of the bridge are added, the resultant is a constant value proportional to the static weight of the axles on the bridge. The proportionality constant is the real part of the instrumentation system transfer function and the bridge parameters do not enter into the equation. The parameters which produce the dynamic increments are filtered out by the low pass filter, so that phase relationships drop out of consideration.

Since the shear value can be measured only by strain, the choice of instrumentation narrows down to strain gages of some sort. Section 5.3.2.2 discusses the selection of transducers for this application.

An alternate technique is to attempt to measure the static weights by transducers located at the midpoint of the bridge, where deflections and strains are greatest (neglecting points of stress concentrations for the purpose of this discussion). This would introduce unnecessary parameters and complexity. Beam action, area properties, composite/noncomposite action, decreased time for filter settling, and data gathered by only one set of transducers can serve only to decrease accuracy.

Novak, Heins and Looney (Ref. 30 p. 63), attempted to instrument the alternate (mid-point) technique to estimate the weight of any vehicle crossing a bridge. It was the intent that this procedure could then be utilized in predicting vehicle weights on other bridge structures. The maximum dynamic strain range in the maximum strained girder, reduced to static values by averaging techniques, average axle spacing and load distribution for various types of trucks were fed as inputs into a computer. The computer program was based on standard static load-moment-stress relationships, and the gross weight of the vehicle calculated. The vehicle actual weights, as determined by loadometer, were compared with the calculated weights to yield the errors listed in Table 9 (Ref. 30 p. 99).

Table 9 Error Distribution in Calculating Gross Vehicle Weight by the Method of Reference 30

Percentage Range	Numbers of (+) Errors	Numbers of (-) Errors
0 - 10%	9	9
10 - 20%	11	5
20 - 30%	6	5
30 - 40%	0	0
40 - 50%	0	1
50 - 80%	0	0
80 - 90%	1	0
Sub Totals	27	20
Total: 47		

Table 9 indicates that the errors associated with this method exceeded 10% in 62% of the 47 vehicles tested, and exceeded 20% in 28% of the tests. It is obvious that this approach is totally inadequate.

4.4.2 Dynamic Loads

Dynamic loads, the maximum forces imposed by the vehicle upon the bridge structure, can be measured by the total dynamic response of the structure to these forces. Since this data is required to enable design of the bridge stringers, be they rolled beams or built-up girders, this data must be taken at the center of the bridge where moment and strain are the greatest. By applying the filtering technique discussed in Section 4.2, the static value of strain or deflection can be separated from the bridge total response and the amplification factor $\left(\frac{\text{static + DI}}{\text{static}}\right)$ derived by simple division of these values. The dynamic load is obtained by multiplying the static weights by the amplification factor.

The amplification factor approaches infinity near the span ends, which would overload the circuitry. In the data processing therefore, the inverse of the amplification factor is found and searched for the maximum value.

The parameters that may be measured are strain, deflection, or acceleration. Strain is the parameter which is recommended for the purpose of this study. This recommendation is made as a result of several considerations.

Based on accelerations calculated for a 97 ft. bridge and a 50 ft. bridge in Appendix D, the use of accelerometers is contraindicated. The following values are excerpted from Appendix D and are used as typical values:

	97 ft. Bridge	50 ft. Bridge
Dynamic Increment Accel.	0.0855 g	0.440 g
Crawl Defl. Accel.	0.0037 g	0.00036 g
Accel. Ratio $\frac{DI}{CD}$	23.2	1220

Several factors militate against the use of accelerometers:

(1) The DI/CD ratios indicate that an accelerometer sensitive enough to record the crawl deflection accelerations would be swamped by the dynamic increment accelerations. A single accelerometer is desired for a valid comparison of the filtered DI and crawl deflection data.

(2) The crawl deflection acceleration is very low and would require special sensitive accelerometers.

(3) The purpose of filtering is to remove the dynamic increment from the dynamic signal and pass the crawl deflection. For acceleration, the dynamic component is so much greater that the crawl deflection could be separated if possible, only by the use of special and expensive techniques. As no special advantage is gained by using acceleration, further consideration of this parameter was dropped.

Strain data is preferred to deflection data because of the following considerations. Appendix E shows that moment (and strain) are completely linear with X, the distance moved by the moving load. For deflection, however, it is shown that as the vehicle approaches the center of the bridge, the linearity and hence the sensitivity of the deflection signal falls off.

This difference in linearity of the parameters is evident in the comparison of the crawl curves shown on Figure 18, which is reproduced from Reference 10, Figure 88. Early in the travel across the bridge, both curves contain the same information. Near the center of the bridge, the strain crawl curve peaks more sharply than the deflection crawl curve. A break in the slope of the strain curve near the center, showing the entrance of an axle, is lacking in the deflection curve. Another demonstration of this higher linearity or sensitivity of strain over deflection is contained in Reference 11, Figures 4.1 and 4.2. The "cusps" which appear in the crawl curves for strain (Figure 4.2) do not appear in the crawl curves for deflection (Figure 4.1), showing that the strain curves contain information lacking in the deflection curves.

Another approach to comparing strain and other parameters is to view the range of the transducers required to provide the raw data. In the design of bridges of like

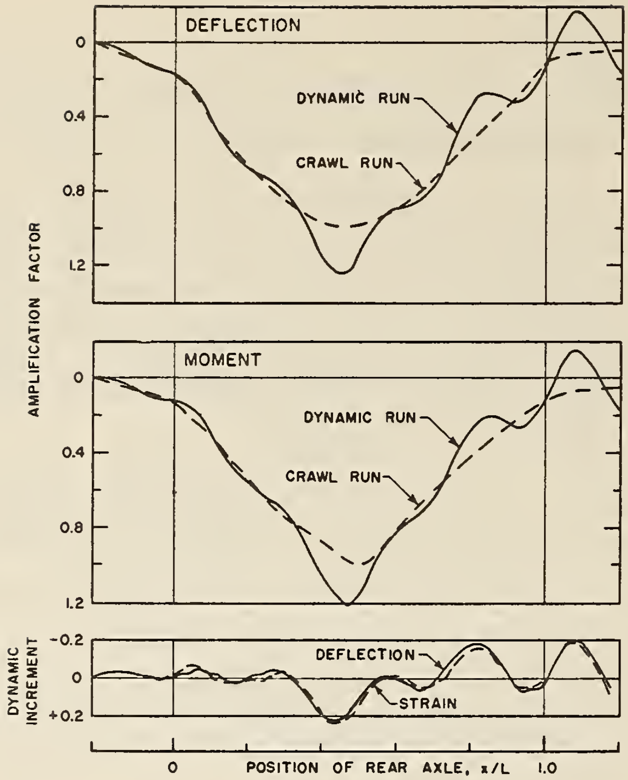


Figure 18. History Curves for a Regular Test Bridge Response, Midspan of Center Beam
(Reproduced from Reference 10, Figure 88)

construction, the designers keep the working stresses substantially in the same range for all bridge sizes. As a consequence, strain gages of whatever form, need have only a single range which is consistent for all bridges of the same basic design, e.g., steel stringer with concrete deck. Deflection, on the other hand, will vary with the length of the bridge, as will the natural fundamental frequency and hence the accelerations. This will require transducers of different ranges to handle different spans of bridges of the same basic design.

The bases for the preference for strain as the parameter for measuring raw dynamic data are summarized below:

- Strain data contains more information because the sensitivity and resolution of deflection data decreases as the vehicle approaches mid-point.

- Transducers of only a single range need be provided, regardless of the span of the bridge.
- Measurement of strain is self contained. Deflection measurements require attachment to a reference below the point where the deflection is being measured. Deflection cannot therefore be measured over a road or highway or navigable river without interfering with traffic. This provides an unnecessary and undesirable constraint in the selection of bridges to be measured.

4.5 Alternates Considered

Early in this study, because of the lack of definitive correlation of GVW with stress range, a concept known as "Signature Analysis" was considered. In this concept, the dynamic bridge response of a vehicle would be recorded, the axle spacing measured and static axle weights obtained by loadometers after bridge passage. A library of such signatures and correlated vehicle data would be developed for different speeds, weights and sizes and types of trucks, and placed in computer memory, as a look-up table. After the development of the library, the signatures of unknown trucks would be "looked-up" by the computer, and the desired data printed out.

This concept was abandoned for many reasons: the length of time to develop the signature files; the probability of change in the bridge structure characteristics with time and temperature, necessitating periodic updating of the signature files; and the large signature file that would be required because of variability in vehicle characteristics of the same GVW causing signature variations.

SECTION 5

INSTRUMENTATION AND DATA PROCESSING SYSTEM

5.1 System Engineering Analysis

The techniques for system functional analysis which have been developed and applied to the design and development of complex systems will be applied to the instrumentation and data processing system. These techniques are general in nature, and may be applied to any system to optimize the system configuration, and to establish the functions and allocate them to major elements.

5.1.1 System Development Guidelines

In analyzing the functional requirements and selecting a system, the following guidelines will be employed:

- The traffic and weight information is not required in real time or at the location of the instrumented bridge.
- The required information is not an end result in itself, but is to serve as an input to a sophisticated data processing system for further analysis. The output format must therefore be compatible with the existing computers and programs.
- Categorization of vehicles may be done as described in the literature - by the number of axles. The number of categories and the selection of same must be compatible with the user program. No problem is anticipated in satisfying this requirement.
- The amount of data that will normally be collected and processed for any one site can be overwhelming.

For this reason, it is assumed that once equipment has been installed and checked out, further data acquisisiton, processing, reduction and analysis must be automated as much as possible. It is assumed that an operator will be standing by to change tape reels or disc packs as necessary and to monitor operations. This function, of course, will be accomplished manually.

5.1.2 System Engineering Methodology

The method employed in system engineering analysis is described briefly below. The separate functions that emerge together with pertinent criteria will then be discussed.

A. Determine the mission to be performed from the operating requirements.
B. Analyze the mission requirements into major functions.
C. Define one or more candidate system implementations.
D. Allocate system functions to system equipment, data processing elements, or operators.
E. Estimate performance of candidate systems.
F. Synthesize an optimum system configuration.

5.1.3 Mission

The mission of the system is to determine the traffic conditions and weight data of the traffic traversing highway bridges of concrete slab with steel girder design.

A. For vehicles weighing less than 2,000 lbs., no data is required.
B. For vehicles weighing between 2,000 lbs. and 10,000 lbs., the following traffic data is required:
   (1) lane identification
   (2) arrival time
   (3) headway
   (4) velocity

(5) identification of vehicle type

(6) axle spacing and number of axles per vehicle

C. For vehicles weighing over 10,000 lbs., in addition to the traffic data identified above, the following additional weight or load data is required:

(1) static axle weights for axles weighing more than 10,000 lbs.

(2) gross vehicle weight

(3) dynamic load

5.1.4 System Functions

5.1.4.1 Definitions

Data Acquisition

To sense the physical effects of the truck traffic and convert these parameters into electrical signals for storage as real time analog or digital recordings.

Data Conversion

To play back the analog recordings or feed the analog signals in real time into an electronic system which is preset to automatically capture, sort, sample and convert to digital format and store the traffic/load data on magnetic tape or disc packs. The conversion system will contain logic to operate on the analog data for standard patterns of truck traffic.

Data Reduction

To extract the digitally stored truck event histories for interpretation and processing by a computer system. Computer programs will contain the logic and processing algorithms necessary to calculate, or determine for a stored data base, the desired load and traffic information.

Instrumentation

Analog transducers plus support electronics interfacing with multichannel analog recorder or a digital recorder via analog/digital converters.

5.1.4.2 Descriptions and Criteria

The functions which must be performed to accomplish the mission at any single bridge are listed below. Figure 19 shows the functional flow graphically.

A. Install Instrumentation

This provides the physical and electrical interface with site. The sensors are attached intimately to the bridge structure and approaches. The balance of the instrumentation, defined in Section 5.4., is assumed installed in a van, which is parked conveniently close to the bridge. The sensors are installed on the bridge so as to function with no effect on the bridge structure, and with minimal or no effect on bridge traffic during installation and operation.

B. Calibrate Sensors and Instrumentation

In this function, following an established procedure, operation of the sensors and instrumentation is verified and the equipment zeroed. The system is calibrated by running a test vehicle, with known axle weights over the bridge in each lane and recording sensor output. The system is then initialized by inputting the time of day, and such bridge parameters as are necessary for data reduction and interpretation.

C. Acquire Data

This function relates to recording transducer output on magnetic tape. The operation is monitored continuously to assure that all sensors and equipment are operating properly. Tape reels are changed manually as necessary. Techniques should be employed for efficient utilization of magnetic recording tape, i.e., no extensive blank spaces. This will reduce data processing and reduction time, as well as the storage and handling of the tape.

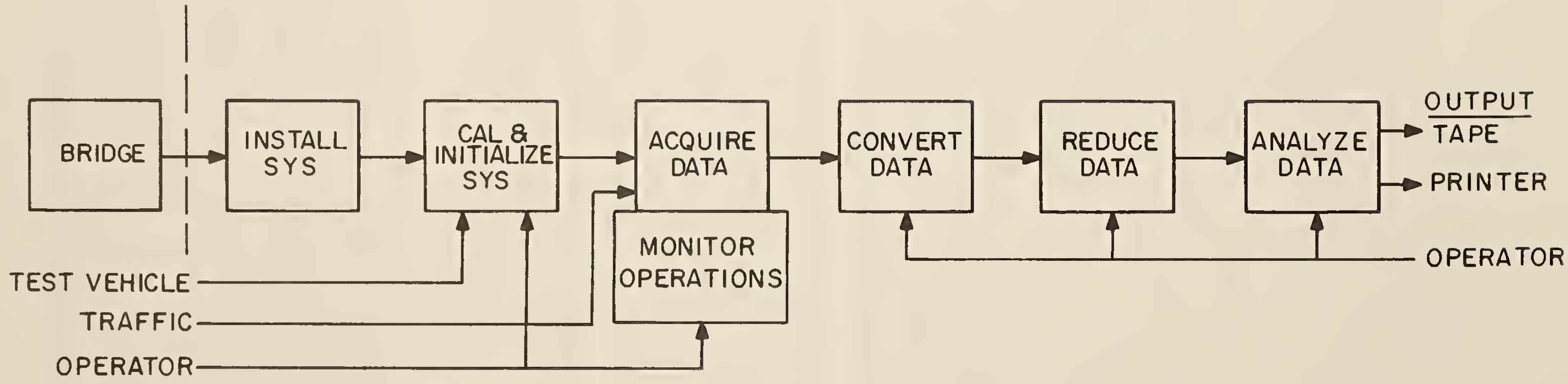


Figure 19. Functional Flow Block Diagram

D. Convert Data to Digital Form

This function converts the analog signals either directly in real time or from analog recorder tape into digital form, and records the data on digital tape in a format which is compatible with the computer and program to be used for data reduction. This function should be accomplished independently of the computer complex used for data reduction.

E. Reduce Data

From the event history recorded on the digital tape, the data reduction function computes the data to satisfy the mission requirements.

F. Analyze Data

The output from data reduction may require sorting and statistical analysis to provide compatibility with other computer programs. This function is recognized as a possible functional requirement but not within the scope of this study.

G. Output Data

The resulting data output may, as desired, be in the form of print-outs or digital tape in a format suitable for BRGSTRS or other desired program.

5.2 Candidate Instrumentation Systems

Two suitable instrumentation systems are shown in Figures 20 and 21. Figure 20 shows a system based on the use of analog recording, while Figure 21 shows a system based on the use of direct digital recording. These are essentially similar insofar as equipment complement is concerned. However, Figure 20 shows a system where the data is first recorded on a multichannel analog tape recorder. A/D conversion and recording on digital tape are accomplished optionally either in the instrumentation van or at the Data Reduction Center. The equipment complement shown in Figure

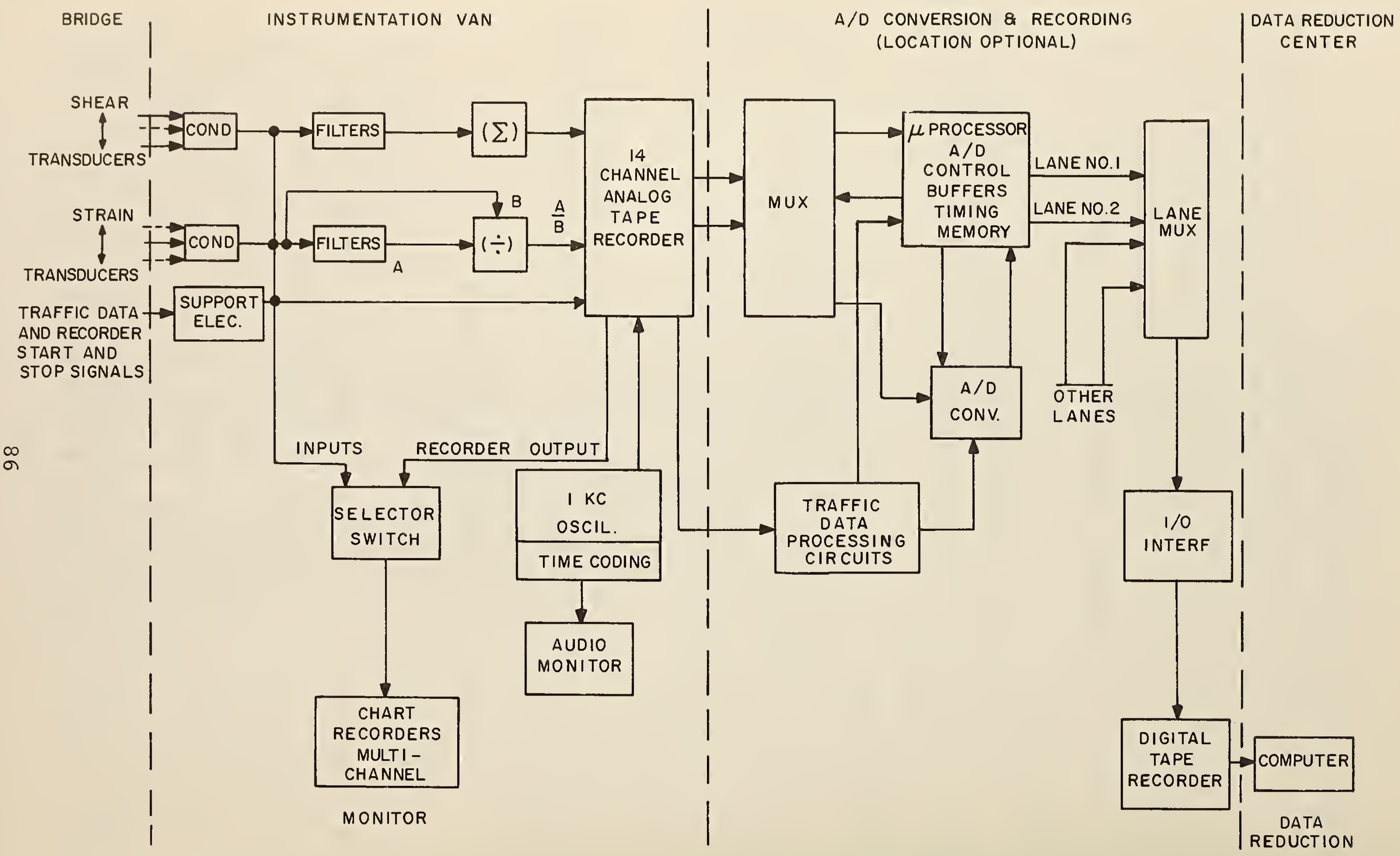


Figure 20. System Based on Analog Recording

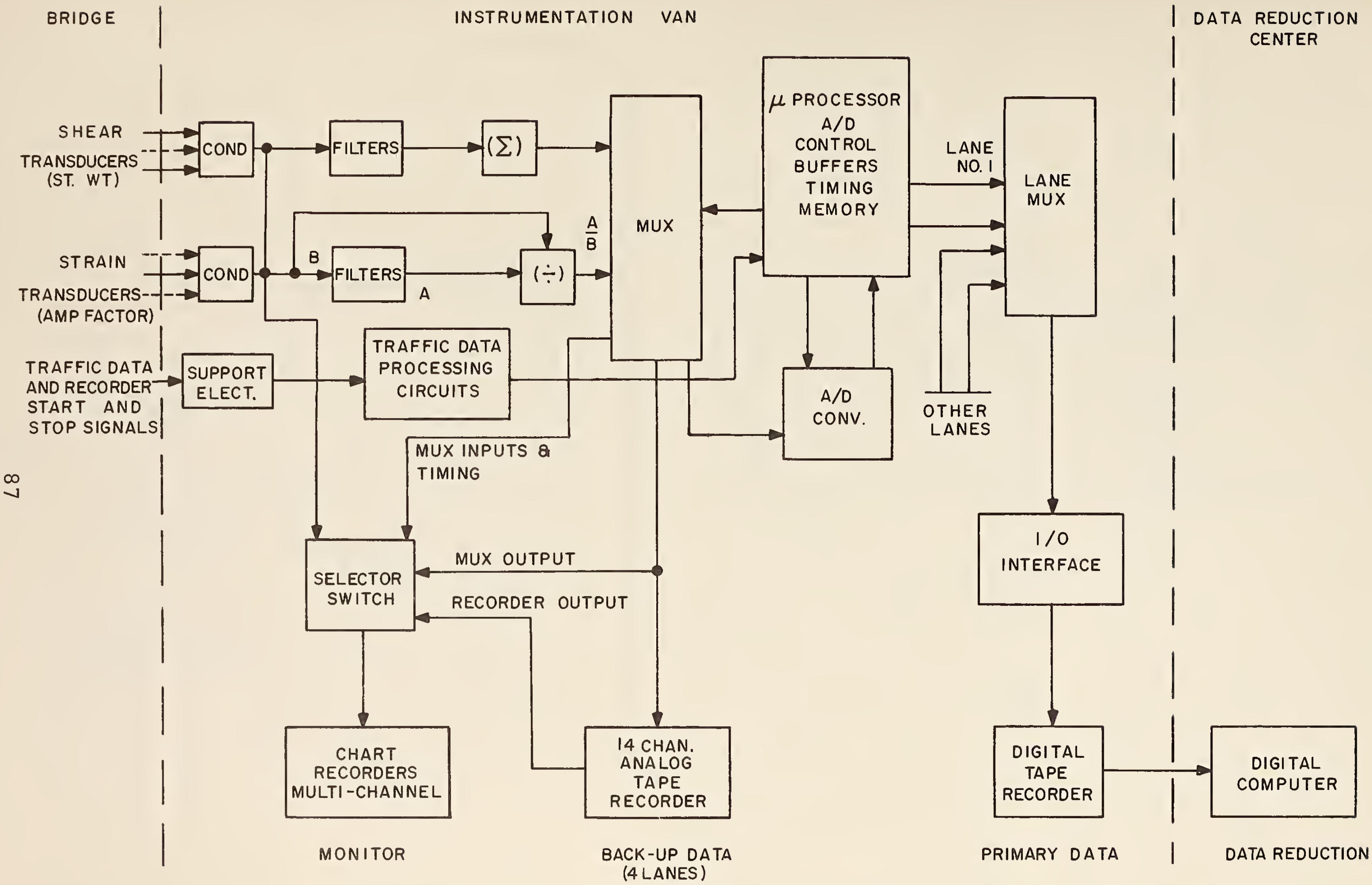


Figure 21. System Based on Direct Digital Recording

21 may be simplified to some extent by the elimination of the Lane Multiplexer (LANE MUX). In this case, the analog tape is converted sequentially for each lane. This approach increases the computer usage time substantially because the computer must now search the digital tape continuously for each event to merge concurrent events and thus enable decoupling of lanes. The decrease of hardware is thus offset by an increase in software and operating time for the computer.

In Figure 21, the analog data is converted to digital data and recorded digitally in the instrumentation van under the control of a microprocessor. The analog tape recorder, which is now optional, is bypassed, but provides back-up data in the event of a malfunction in either the conversion or digital recording process. The direct digital recording system is inherently more accurate than the analog recording system because the errors associated with analog recording are eliminated. This system is therefore preferred for that reason.

5.2.1 Physical Description and Operation of the System

Figure 22 shows the physical arrangement of the system as installed on a two-lane simple span bridge with five girders. The traffic data sensors are installed on the bridge approach and exit for each lane. The load sensors, used to determine axle weight, gross vehicle weight, and dynamic load are installed on the bridge structure proper. One set of load sensors is required for each lane.

The traffic data sensors consist of standard pneumatic traffic tubes used almost universally as traffic counters, and an inductive loop, used successfully as a vehicle detector for traffic control systems. As an axle passes over the pneumatic tubes, the air pressure pulse in turn closes an electric circuit, creating an electrical pulse. The entrance tube is used to start the analog

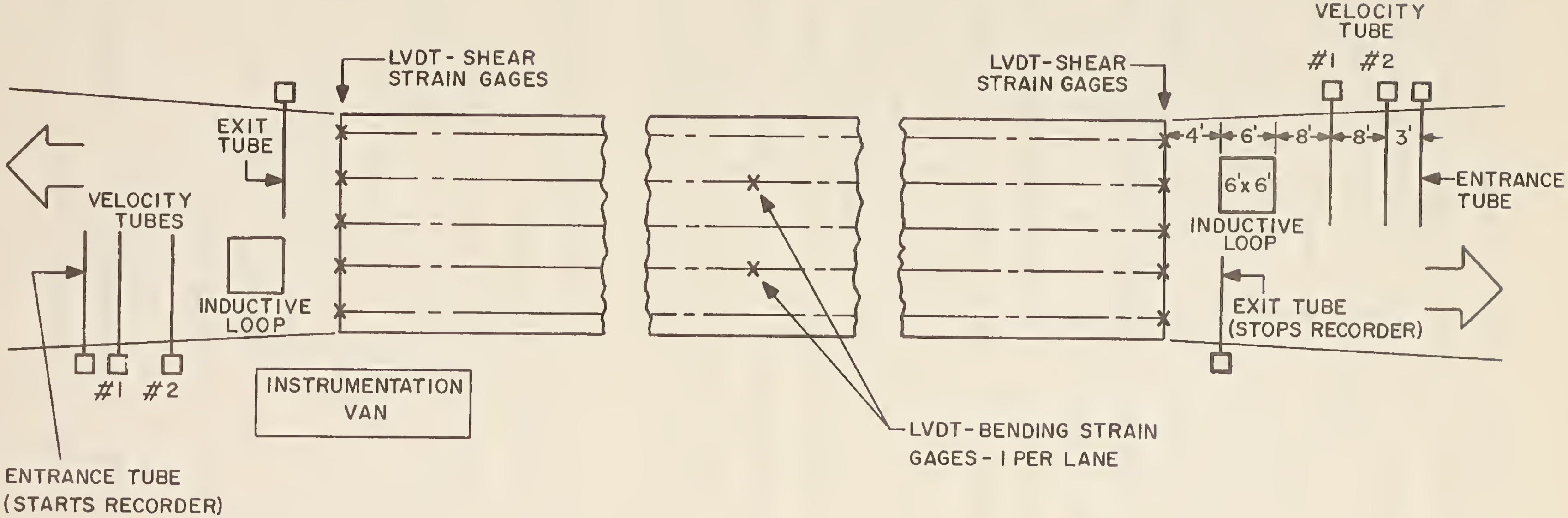


Figure 22. Physical Layout - Two Lane Simple Span with Five Girders

recorder. The two velocity tubes provide two pulses of opposite polarity as the front wheels of the vehicle pass over them. The distance between the velocity tubes, which is a known constant - approximately 8 feet - divided by the time interval between the pulses will yield the velocity. As the balance of the vehicle axles pass over the velocity tubes, the pulses from the first tube count the axles, while the time interval between pulses, given the velocity, determines the spacing. The pulses from the second tube, being of opposite polarity, may be and are, discarded.

The inductive loop, used widely as a detector in traffic control systems, is used here to eliminate any ambiguity resulting between tailgating passenger vehicles and trucks with similar axle patterns. The loop consists of three loops of wire inserted in slots sawed in the pavement, and sealed with asphaltic mastic. A 25 to 170 KHz signal constantly energizing the loops, induces a magnetic field. As a vehicle passes over the loop, the change in the field is sensed by the associated electronics, and the passage is indicated by a pulse.

The rationale for the spacing of the traffic transducers is contained in Section 5.4.1-I.

The load sensors for determining the static weights are installed on beams at both ends of the bridge. To account for tolerances in the lateral positioning of a vehicle in its lane, the outputs from the three beams nearest the lane are filtered and summed, as discussed in Section 4.3.2. Modest shifting of the vehicle in the lane should therefore have little or no effect on the total output.

The load sensor for determining the dynamic load should be installed at the center of the beam showing the greatest strain. As noted in Section 3.3.3, this could be either the beam nearest the vehicle resultant as it travels in the lane, or the outside beam in an exterior lane, depending on the bridge design. Measurements during set-up time should be made to determine the governing beam.

The signal conditioners and other transducer support electronics, the filters and adding circuits, together with the recorders, multiplexers, the microprocessor and the A/D converters are installed in an instrumentation van. At least one technician is required to monitor system operation, change tapes, and exercise surveillance over the sensors and traffic conditions on the bridge. He should record any unusual circumstances in connection with traffic or equipment, so that anomalous outputs from the recorders or the computers may be analyzed.

The bases for the selection of the load transducers is contained in Section 5.3. Descriptions of the equipment and system operation for the systems based on analog recording and direct digital recording are provided in Section 5.4, while data reduction is described in Section 5.5.

5.3 Transducer Selection

As previously noted in Section 3.5, the transducers required for the objectives of this study must provide two different categories of information - traffic data and load data. Traffic data transducers are in a relatively mature state of development and are in wide use in this country. Since transducer installation in the bridge approach is allowable, as is required for the traffic data transducers, it seems practical to utilize this body of experience for the traffic data information.

The theory in Appendix C suggests that the load data transducers and instrumentation might be used to provide some of the traffic data. However, it will be shown later that early velocity data is required to optimize the digital scan rates. Secondly, the lag and smoothing action of the filters may inhibit extraction of traffic data from the step inputs expected in the bridge reaction response. Although these filter characteristics will not inhibit determination of load data, the determination of traffic data is less certain. It is possible that after implementation of the system and with definitive experience gained with the overall system that the load transducer data may be applied to extract traffic data. However, the recommendations for transducer selection contained in Section 5.3.1 will assure positive control of traffic data sensing.

5.3.1 Traffic Data Transducers

Pneumatic traffic tubes are recommended to provide the inputs for the starting and exit functions, velocity determination, and the axle counting and the axle spacing determination. One each is required for the starting and exit functions, and two are required for the other functions, for a total of four per lane. One inductive loop per lane is recommended to provide vehicle sensing. These have been selected over other candidates because of their simplicity and reliability. The pneumatic tube characteristics, in particular, are admirably suited for temporary use in test programs. Developments in vehicle detectors,discussed in Section 3.5.1, should be explored when the instrumentation system is implemented.

5.3.1.1 Pneumatic Tubes

The traffic counter tube consists of a rubber tube sealed at one end and connected at the other end to a pressure sensitive switch. As a wheel passes over the tube, the switch senses the air pressure pulse and closes a switch to control an electrical circuit.

Objections have been levelled in the past to the use of rubber pneumatic tubes on two known accounts. One of these is the lack of tube life, the tubes apparently wearing out in several months of continuous use. The second apparent problem is the shape and dispersion of the pulses when the pressure switches close the electrical circuits. Since the tubes may be replaced at a cost of approximately $.20 per foot (1974), approximately $10.00 per lane, and a set of tubes should last for more than a year in the anticipated usage, the lack of long life is not considered a serious objection.

There is no unusual requirement for accuracy of pulse shape or timing for the entrance tube, used to start the analog recorder, or the exit tube, used to stop the recorder when a vehicle exits the bridge before the actuation of the time delay relay. However, the pair of tubes - the velocity tubes - will be used to provide pulses to measure the vehicle velocity and to count the axles and measure the axle spacing. For these tubes, the shape and dispersion of the pulses merit consideration.

To evaluate the significance of pulse shape and dispersion, assume a distance of 8 feet (2.44 m) between the velocity tubes. A vehicle travelling 100 feet (30.5 m) per second, 68 miles (109.5 km) per hour, will traverse the tubes in 0.08 seconds, with a count of 80 pulses of the 1 KHz frequency oscillator used for timing in the instrumentation circuitry. An error of one millisecond (a high value) caused by the dispersion of the two tube switch pulses about the mean value will cause a maximum error of 2.5% in the calculated velocity of the vehicle. For vehicles travelling at less than 100 feet (30.5 m) per second, the error will be proportionately less. The rise time of the tube switch pulse will be in the order of 50 μsecs. An error in initiating the oscillator pulse count on some indefinite point on the leading edge of the switch pulse can cause an additional maximum error of 0.1% in the velocity calculation. Also, pulse shape and the effects of contact bounce will be controlled by the use of pulse shaper circuitry. The penumatic tube therefore appears entirely suitable for the objective of this study.

Alternates have occasionally been used in place of pneumatic tubes. Photocells with light sources, and a sound level detector were used by the University of Illinois for stress investigations (Ref. 11 p. 24-26). The photocell produces a consistent pulse shape with a sharp pulse rise. However, problems arise because sensitivity adjustments must be made to adjust to changes in the ambient light conditions and glint from chrome, hubcaps, etc. Another problem arises because the light sources installed of necessity between the lanes for individual lane sensing, are subject to damage from passing vehicles. Other problems with photocells are reported in Reference 11 with signals of unanticipated length and amplitude. The sound level detector, also used by the University of Illinois, when adjusted to respond only to the normally higher sound level of trucks, also introduced problems by infrequently allowing trucks to pass by without triggering the system.

5.3.1.2 Inductive Loop Detector

An inductive loop detector consists of a loop of several turns of wire inserted in a 5/16" wide x 1-3/4" deep slot approximately 6 ft. x 6 ft. in the pavement and covered by a hot asphalt mix or by an epoxy compound. An RF signal in the range of 25 kHz to 170 kHz is applied by the small electronics detector package to the roadway imbedded loop. Passage or presence of the metallic mass of a vehicle changes the inductance of the loop. This change is electronically sensed by the detector, amplified and transmitted to a relaying circuit.

"The majority of traffic engineers in this country are convinced that inductive loop detectors are the best type currently available to use for freeway control and surveillance" (Ref. 11 p. 87), and it may be added, for the objective of this study. Their advantages and disadvantages are outlined in Appendix A, but salient points are worth stressing.

1. They are the simplest and best type of detector for sensing presence.
2. They have been found to be as reliable as most other forms of detector, if not more so. Most of the problems experienced with them were concerned with either pavement movement, or maintaining them "in tune". Problems with pavement movement can be eliminated by locating the loop so that crossing of expansion joints is eliminated. If the loop "lead-in" must cross an expansion joint, a piece of conduit can be used to bridge the joint. Problems with maintaining the loop "in tune" may be eliminated by the use of self tuning detectors, which are commercially available.
3. Vehicle counting can be achieved with an accuracy of 2%-3%. Allocating equal accuracies to both detection and counting, this implies that detection, on a root mean square basis, can be achieved with an accuracy of 1.4%-2%. Considering the simple requirements of this application, accuracies of better than 1% for detection are believed achievable.
4. A major disadvantage is the one-time traffic disruption when the slot is sawed in the pavement and the wire inserted. Reference 29 p. 167 estimates the time that a lane would be blocked off as approximately 1 hour and 55 minutes for a 3 man crew.

Other devices have been used and are commercially available for vehicle detection purposes. Magnetometers have been used in Houston and Dallas, and sonic (or ultrasonic) detectors have been used in Detroit and Houston.

Magnetometers operate by utilizing the voltage induced in a coil placed beneath the pavement resulting from the disturbance of the earth's magnetic field caused by the passage of a vehicle. They are not recommended for this application because their sensitivity to magnetic material distribution within vehicles may result in double counting. If adjusted for this condition, close following vehicles may be missed. Advantages and further disadvantages are discussed in Appendix A.

Sonic detectors operate by detecting the reflection of sonic pulses by the passing vehicles or by measuring the doppler shift of a continuous wave sonic emission. Aside from the greater total expense, they are not recommended for this application because of their:

- inaccuracy due to the conical detection zone and wide variations in vehicle configurations and height,
- inaccuracy under congested conditions,
- sensitivity to environmental conditions, dirt, traffic, vibrations, etc., with resulting lack of reliability,
- annoyance to humans and animals if sonic output is not properly adjusted

5.3.2 Load Transducers

Section 4.4 discusses the selection of output signals, and recommends the measurement of strain for the determination of both the static axle weights and dynamic loads.

There are three types of sensors that are readily available for measuring strain with a concomitant electrical signal; the metallic electrical resistance strain gage, the semiconductor strain gage and the linear variable differential transformer (LVDT). The resistance gage converts strains or unit deformation to change in resistance, which are transformed into electrical signals by an electrical bridge network. The semiconductor strain gage is used similarly to the metallic electrical resistance gage, but has a 50x-60x higher sensitivity, which is accompanied by a non-linear output coupled with a markedly temperature dependent strain sensitivity. The LVDT converts unit deformation directly into a change in an electrical signal since the dimensional change is coupled directly to the motion of a movable transformer slug.

Other types of strain gages exist, based on mechanical, optical, and mechano-optical principles. As these either do not produce an electrical signal which is required or are more suited for laboratory use, they will not be considered further.

The LVDT is recommended for use as the strain transducer to be used for the objective of this study. When correctly selected and used with the appropriate signal conditioner, it is resistant to the outdoor environment, has excellent linearity (< than 0.15%) and good sensitivity. A simple support bracket or stud is bonded to the member being measured, and the LVDT field coil and movable core are fastened to each by reusable hardware. Except for the bracket or stud, the LVDT is reusable from site to site.

Metallic electrical resistance strain gages have been used for similar purposes on many bridge investigations with good and useful results. However, subject to the environment as they are on an open structure, and being sensitive to water, extreme precautions must be taken to achieve reliability, and even with the current waterproofing techniques, frequent failures occur. Personal experience with a quantity of electrical resistance strain gages on a structural investigation showed an incidence of approximately 10% failures per week.

An economic analysis shows that the cost of a hermetically sealed reusable LVDT (about $44), is approximately four times the cost of a resistance strain gage rosette. Since the resistance strain gage is not reusable, the use of an LVDT is more economical if four or more bridges will be instrumented. This factor, coupled with the above-described unreliability which imposes an additional cost penalty, is the basis for the selection of the LVDT.

5.4 Data Acquisition, Recording and Conversion

Two candidate systems are discussed briefly in Section 5.2; a preferred system where the primary data recorder is a digital recorder, and a second system where the primary data recorder is an analog recorder. Figure 23, an elementary block diagram of the Digital Recording System, is an expanded version of Figure 21. Figure 24, an elementary block diagram of the Analog Recording System, is an expanded version of the data acquisition and recording subsystem shown in Figure 20. The data conversion for this system may be accomplished either as shown in Figure 25 or Figure 26. Figure 25 shows A/D conversion accomplished under microprocessor control while Figure 26 shows A/D conversion implemented by hardwired logic. The microprocessor, being programmable, offers the option of making changes in the system control by software changes. Because of this flexibility and the increased overall system speed, the microprocessor is the preferred system for controlling A/D conversion for the Analog Recording System, should this system be used.

It will be observed that there are three different types of data that will be transmitted through the system: traffic data, amplification factor profile and weight profile. The traffic data also supplies the logic to turn the analog recorder on or off. The flow of this data, the timing considerations, and general processing will be essentially the same, regardless of the method of implementation. The discussions that follow provide the rationale for these aspects, and apply to all systems.

5.4.1 Data Processing Rationale

The passage of one vehicle over a bridge will be considered one event.

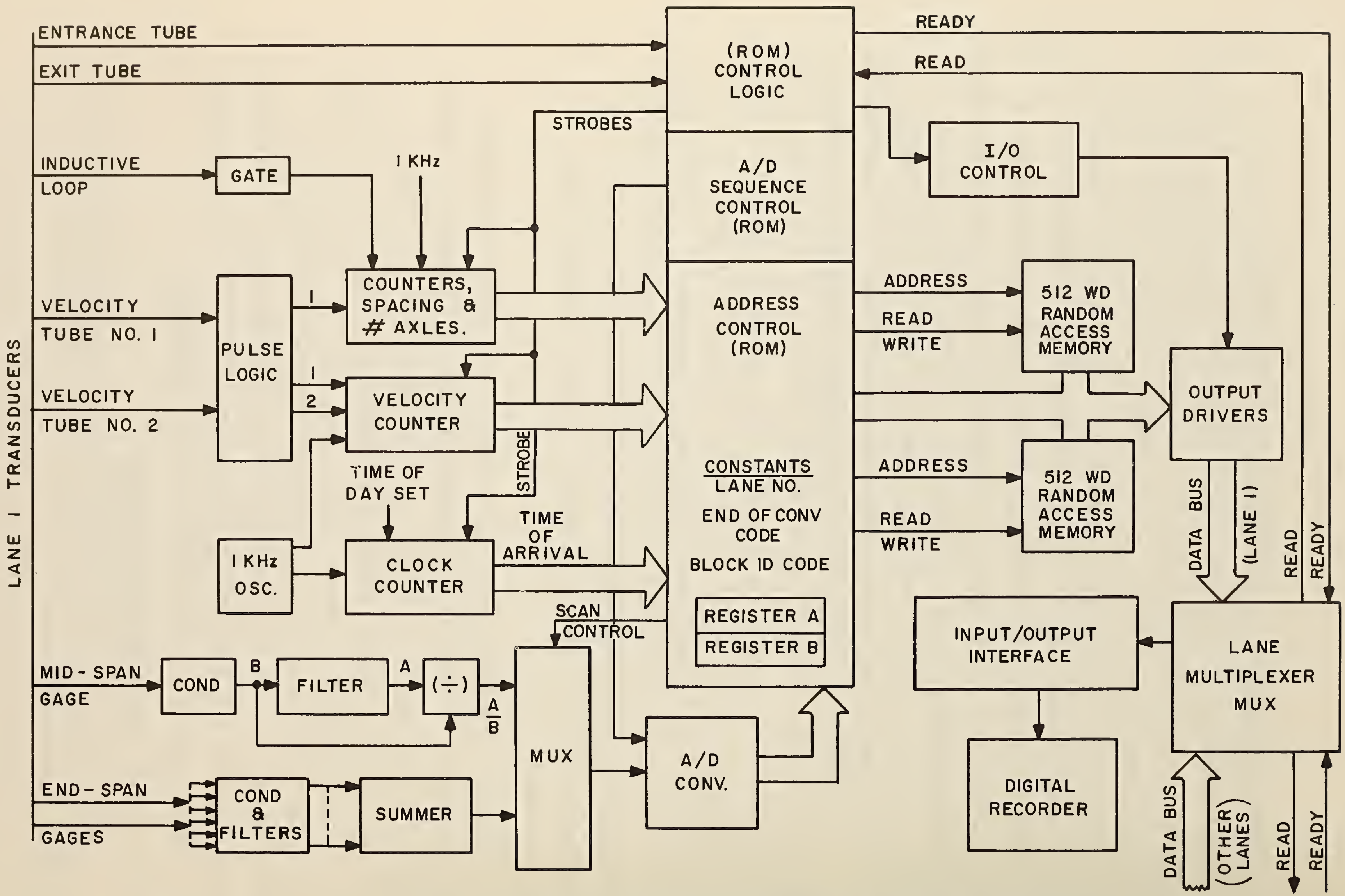


Figure 23. Digital Recording System - Elementary Block Diagram

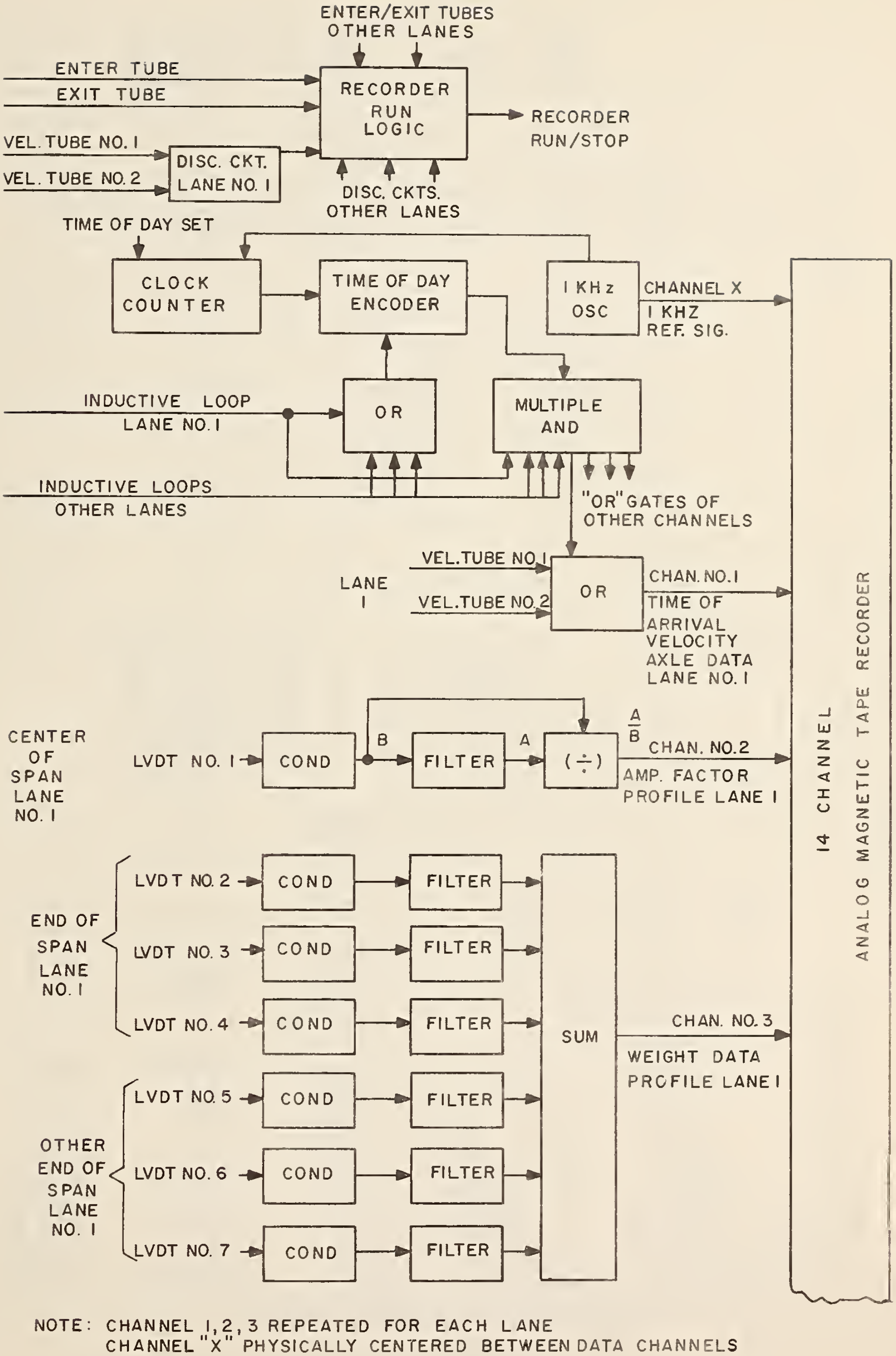


Figure 24. Analog Recording System Elementary Block Diagram

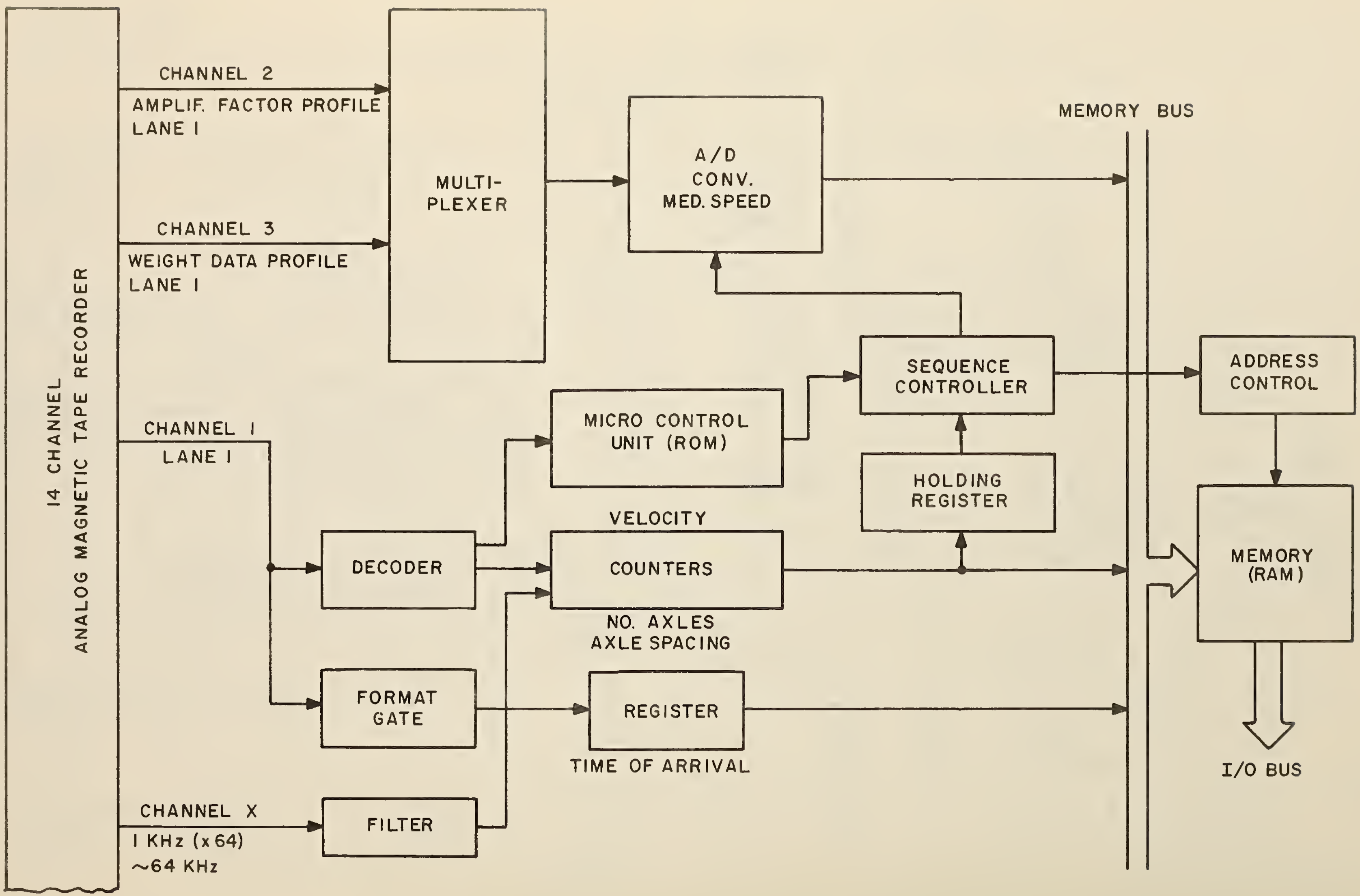


Figure 25. Analog Recording System - A/D Conversion Using Microprocessor Control

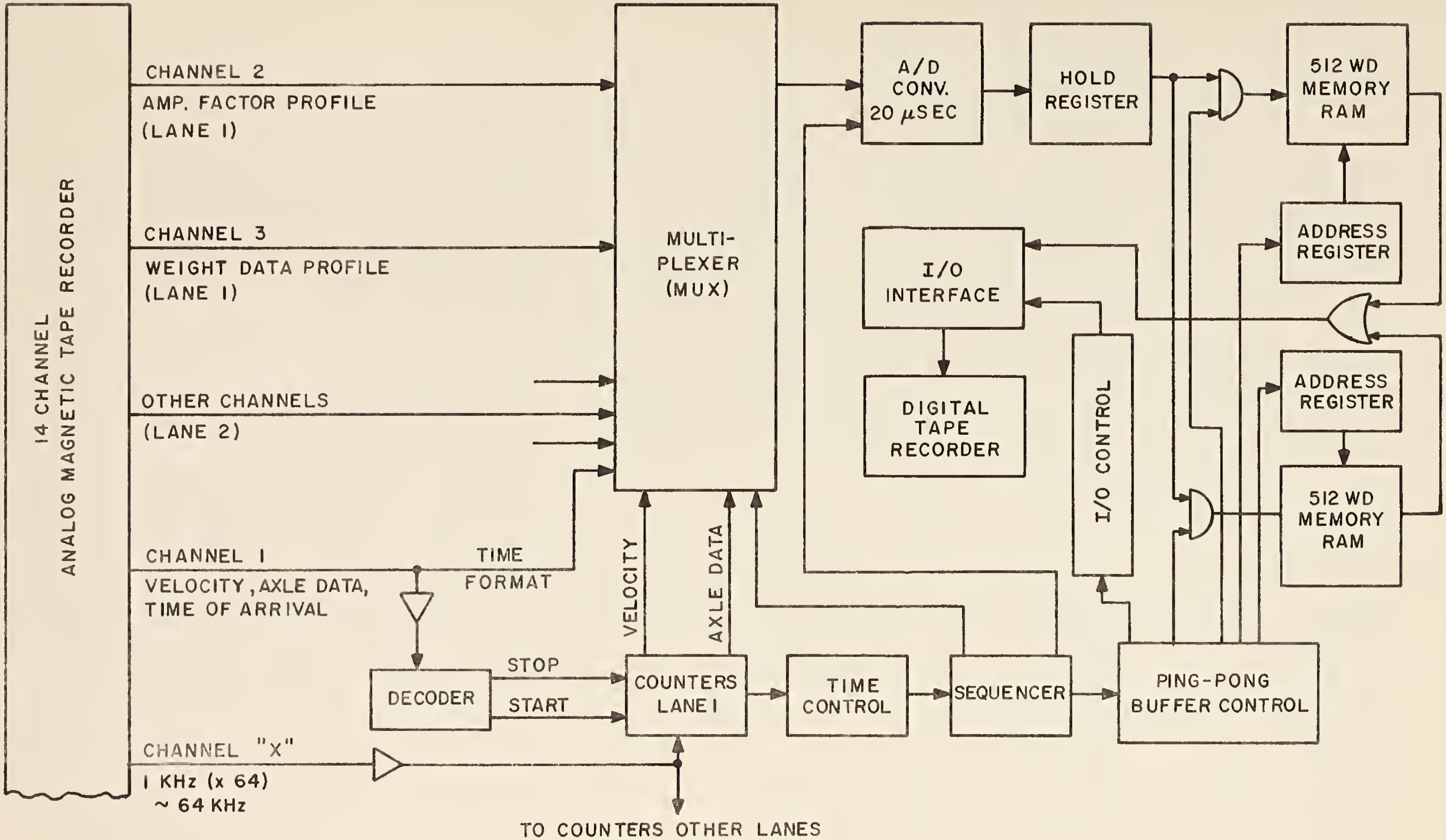


Figure 26. Analog Recording System - A/D Conversion Using Hardwired Logic Implementation

A. Sampling Rate: Assume 150 samples are adequate to define the weight data profile and the amplification factor profile. For a 100 ft. bridge, and a 40 ft. vehicle, this will provide data every 11 inches, yielding a total of 300 data points per event.

B. A/D Conversion Rate: Assume 0.6 second is the minimum traverse time for a fast truck over a short span - example: 68 mph (109 km/hr) over a 30 foot (9.15 m) bridge with a 30 foot (9.15 m) long truck = 100'/sec (30.5 m/sec) for 60 feet (10.3 m) = 0.6 seconds. Therefore, 300 A/D conversions in 0.6 sec. = 500/sec or2 ms per conversion in real time.

C. Digital Tape Recording (Data Tape)

Assume 800 frames/inch	7 channels = 6 data + 1 parity
2 frames/word	
∴400 words/inch	12 bit word (max.)

Tape Speed, forward = 120 inches/sec (305 cm/sec)
∴48,000 words/sec.

A/D conversion rate is 500 words/sec from analog tape at real time.

A/D process can be speeded up by $\frac{48,000}{500}$ or approximately 100:1 by analog tape playback at approximately 100 times the record speed.

Analog recording time is 2400 ft(730 m) at 1-7/8 in/sec (4.75 cm/sec) = $\frac{2400 \times 12}{1.875 \times 3600} \simeq$ 4-1/4 hrs.

Analog tape run at 120 in/sec (305 cm/sec) is 64:1 speed up. Velocity of 120 in/sec (305 cm/sec) is commercially available and will be used for playback during A/D conversion and recording onto digital tape.

This will compress the A/D process to

$$\frac{4.26 \times 60}{64} = 4 \text{ minutes.}$$

300 Data points are recorded from memory

in $\frac{300}{48,000}$ = 6.25 msec. The time available

is $\frac{0.600}{64}$ or 9.375 msec per event.

Approximately 1 record/inch will give 30,000 records on 2400 ft (730 m) digital tape.

D. <u>A/D Conversion Interval</u>: If the analog tape recorder is played back at 64 times the speed of record, 4-1/4 hours real time is reduced to 4 minutes extraction time. Then A/D conversion interval is $\frac{9.375}{300}$ = 31.25 microseconds maximum. Ten bit A/D converters are available at 20 μsec conversion time, at 30 ppm/^{o}C temperature coefficient. This allows 10 μsec for storage, sequencing, multiplexing, etc.

E. <u>Variable Sampling Rate</u>: Assume the system to be designed to convert the load data signals at a fixed rate of $\frac{300}{0.600}\ \frac{\text{data points/event}}{\text{seconds/event}} \times 64 = 32{,}000$ data points/second (31 μsec per cycle) for the truck speed and bridge length described in Paragraph B. Then any trucks at slower speeds will provide excessive data points. To keep the number of data points per event a constant value, the A/D converter interrogation rate must be a function of the transit time of the vehicle. The entrance velocity must be determined early in order to control the sequencing of the A/D converter. The length of the span involved must therefore be preset into the system.

F. Data Estimates. The following bit sizes are estimated for the digital data to be recorded:

Velocity - inverse function of count - 10 bits

No. of axles - direct count in register - 4 bits

Time of Arrival - time code format in register (2 words) - 17 bits

150 data points - Load data profile - 10 bits

150 data points - Amplification factor profile - 10 bits

Total = 304 data points per event

G. Minimum Velocity. If the velocity tubes are spaced at 8 feet (2.44 m); then the number of the one KHz oscillator pulses that will be counted during the interval between the pulses from the #1 and #2 velocity tubes will be, for the following velocities as examples;

100'/sec	= 0.08 sec =	80 counts
50'/sec	= 0.12 sec =	120 counts
10'/sec	= 0.80 sec =	800 counts
8'/sec	= 1.00 sec =	1000 counts

∴ a 10 bit counter (for 1000 counts) will accommodate a minimum velocity of 8 ft. (2.44 m) per second or 5.4 miles (8.7 km) per hour. Any vehicle travelling less than this velocity is considered an abnormal situation and will be entered at the lower limit. A lower velocity than this will penalize the data handling system by increasing the word size.

H. Memory Size Required for Data Reduction. The following is an estimate made for determining the size of the computer memory required for data reduction for a 3 lane bridge:

Data (for one lane)	30K words
Program	30K words
Scratch	5K words
Data for two additional lanes to allow for correlation of lane to lane effects.	60K words
Memory Size-for three lanes	125K words

I. Traffic Transducer Spacings.

(1) Off-Bridge Spacing for Inductive Loop. If 100 μsec is the logic time from time of day code until A/D sequencer initialization, then 64 x 100 μsec is required in real time lead for load recordings, = 6.4 msec. In addition, the time of day code, initiated by the trailing edge of the inductive loop pulse requires 17 bits, or 17 msec, for a total of 23.4 msec. The space provided, 4 feet (1.2 m), see Figure 22, provides an ample margin (total is 40 msec at velocity = 100 ft. (30.5 m) per second).

(2) Loop Size. Flexibility in loop size is claimed by the manufacturers of loop detectors. The inductive loop is therefore sized 6 ft. x 6 ft. (1.8 m x 1.8 m), so as to be able to differentiate between vehicles spaced approximately 6 ft. (1.8 m) to 8 ft. (2.4 m) apart.

(3) Loop to Second Velocity Tube Spacing. A distance of 8 feet (2.4 m) is allowed between the inductive loop and the second velocity tube. This is assumed sufficient to prevent the front wheel overhang of the vehicle from initiating inductive loop action prior to the velocity tube #2 activation.

(4) <u>Velocity Tubes #1 and #2 Spacing</u>. The velocity tubes will also be used to discriminate against light weight vehicles. Motorcycles and compact vehicles weighing less than 2000 lbs. can be assumed to have a wheelbase less than 8 ft. (2.4 m). If a vehicle with such a wheelbase enters the lane, then two pulses will be received from velocity tube #1 before the pulse is received from tube #2. The discriminator circuit can input the recorder run logic to stop the analog recorder, unless another and larger vehicle is on the bridge.

(5) <u>Entrance Tube to First Velocity Tube Spacing</u>. The distance between the entrance tube and the first velocity tube is governed by the acceleration time for the analog recorder. Available recorders accelerate to full speed of 1-7/8 inches (47.5 mm) per second between 1.5 to 3.0 milliseconds. The three feet (0.9 m) allocated to this distance allows 30 milliseconds, which is more than ample.

J. <u>Time of Arrival</u>. The exact time of arrival of each event will be recorded to the nearest second. A digital time code generator can be implemented from the 1 kHz frequency reference. By counting the 1 kHz pulses with appropriate decode logic, the elapsed seconds, minutes and hours can be established from an arbitrary zero time (master clear) or preset time synchronization to local time of day. A 17-bit format will encode 32 hours. When the recorder has come up to speed, a serial pulse train made up of pairs of 1 kHz pulses will be used to indicate the time of arrival. Suitable combinations of pulse pairs will indicate the "ones" and zeros" making up the binary coded hours-minutes-seconds time count with an appropriate start of word indicator code. Upon playback this serial code will be converted into two parallel data words for digital recording.

K. Headway. The relative time spacing between trucks crossing a bridge will be determined during the data reduction phase. A simple algorithm can extract headway from the recorded time of arrival. Hence, no special instrumentation is required for this parameter.

L. Identification of Vehicle Type. With the number of axles per vehicle and axle spacing determined, the category of vehicle can be established during data reduction based on ground rules in the data bank. The categories must be compatible with those of the companion programs, to which the output of this program will be an input.

M. Traffic Data Recording. The traffic data can be recorded on one channel of the analog tape recorder for each lane. Figure 27 shows the traffic data pulse timing for a 3S-2 vehicle, with assumed but realistic wheelbase dimensions, travelling at 100 ft. (30.48 m) per second. The spacing of the traffic transducers is in accord with Paragraph I above, as shown in Figure 22. The complement of traffic data transducers consists of 4 pneumatic tubes and the inductive loop.

The outputs from the entrance and the exit tubes are inputs to the analog recorder stop and start logic only, and are not recorded.

The output pulses from the two velocity tubes, shaped by the pulse former circuits, are of

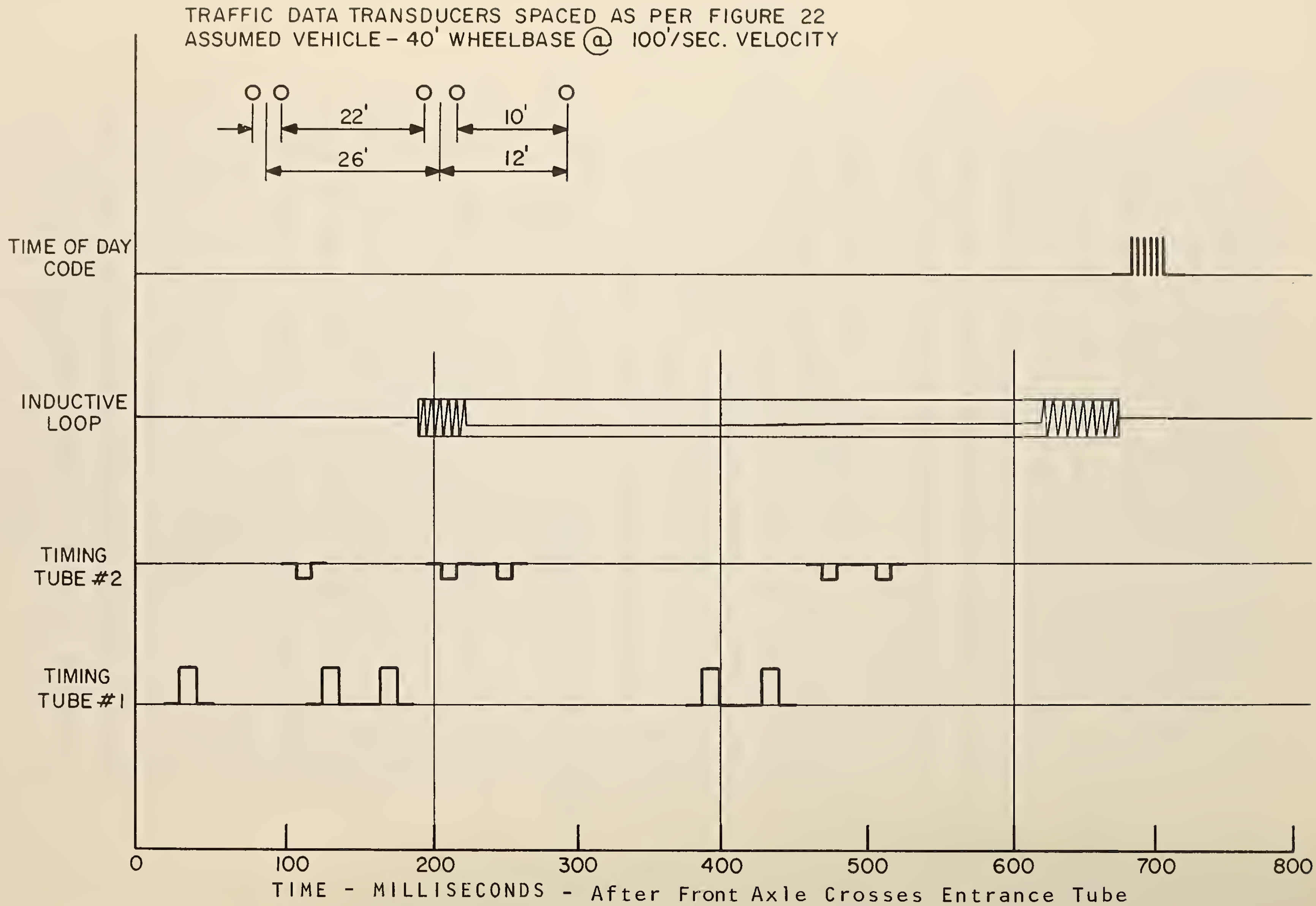


Figure 27 Traffic Data Pulse Timing Diagram

opposite polarity, and can be recorded on a single channel without mutual interference. These outputs provide data for vehicle velocity and axle count, which later in processing, together with the 1 kHz pulse count, also provide data for axle spacing.

The output of the inductive loop detector is not recorded, but serves to implement the time-of-day encoder. The time-of-day code is recorded on the traffic data channel of the recorder to indicate the time of arrival and the presence of a vehicle. This marks the conclusion of the axle count and enables the allocation of the axle count to that vehicle.

The output of the 1 kHz oscillator is recorded on a separate channel and is common to all traffic lanes.

N. Reference Timing Signals. Accurate timing of the pneumatic tube signals can be obtained regardless of the absolute speed of the analog recorder during record or playback, by recording the 1 kHz reference signal on an analog channel. Rather than time the separation of the velocity and axle spacing pulses, an accurate time base is obtained by counting the recorded pulses. The 1 kHz reference signal is recorded on a separate analog channel.

O. Signal Monitoring. Signal monitoring is accomplished by the use of multichannel strip chart recorders, which permit real time examination of the quality of all signals as they flow through the system. One channel of the chart recorder is allocated to each transducer. The selector switch enables the tracing of each signal through the data processing circuits and as an input to, and output from, the analog tape recorder. If chart recorders with sufficient channel capacity are available, then the selector switch may be eliminated. The 1 kHz oscillator is monitored with a switched speaker. The digital circuitry will be monitored with indicator lights.

5.4.2 Analog Recording System

A 14-channel analog magnetic tape recorder will record the necessary data for four traffic lanes; 3 channels per lane = 12 channels plus one common reference channel plus one spare channel. By recording data for all lanes on one tape, or at least with a common time base, the multilane traffic alignment correlations are simplified for the computer processing required to uncouple lane-to-lane load deflections.

The data channels for each lane are:

No. 1 - Time sequential pulses indicating time of arrival; vehicle velocity data; number of axles and axle spacing.

No. 2 - (Inverse) amplification factor profile, derived by dividing the filtered output from the dynamic load transducer (the crawl response) by the raw output from the same transducer (the bridge dynamic response). This transducer is located at the center of the beam closest to the lane centerline, or the outside beam for an exterior lane. See Section 5.2.1.

No. 3 - Weight data profile. This profile is derived by summing the output from each of the 3 transducers located at each end of the three beams closest to the lane. The shear measured by these transducers will provide weight data as discussed in Section 4.3.2.

Figure 24 is an elementary block diagram of the Analog Recording System. The method for deriving the arrival time and for starting and stopping the recorder are shown together with the filtering and arithmetic processing of the transducer outputs.

5.4.2.1 Data Conversion

A means of extracting the continuous analog data from the on-site recorders and converting and recording this data in digital form on a digital magnetic tape is required before any digital computer processing can occur. Previous timing estimates indicate that a 64:1 playback speedup can be used with a moderate speed A/D converter to provide 150 data points of each parameter desired (weight data profile and amplification factor profile). Since this capacity must be repeated for each lane of traffic across the bridge, either a speedup in conversion speed and digital recording data rate or a replay of the analog tape for each lane of data stored is required.

By repeating the conversion process on a per lane basis, commercially available converters and recording equipment, sized for one lane can be used at the cost of playing back the tapes a number of times. Now the speedup in conversion is reduced by a factor of 64/(no. of lanes) which is nominally 32:1 for a two lane bridge and 16:1 for a four lane bridge. Computer utilization in data reduction is increased because of the necessity of searching the tape for simultaneous multilane events to enable correlation and elimination of the lane-to-lane cross coupling.

Figures 25 and 26 are two alternate methods for A/D conversion of the analog data and recording the digital data on tape in a lane sequential basis. The data reduction computer can store this data for subsequent correlation of simultaneous multilane events with considerably simpler programming.

Figure 26 is a hardware logic type of implementation whereas Figure 25 is a micro-controlled data bus architecture type of implementation. By use of micro-controller and microprocessing components the actual logic can be developed and modified through computer programming techniques, thereby reducing costs and providing a more flexible system.

5.4.2.2 Analog Recorder Run Logic

No data is required for vehicles weighing less than 2000 lbs. The recorder will therefore not run when only such vehicles are on the bridge. Since such vehicles have a short wheelbase, assumed as 8 ft. (2.44 m) at the present, these vehicles will be screened on the basis of this value, see Section 5.4.1-I-(4). If two positive pulses are received from velocity tube #1 before the negative pulse is received from velocity tube #2, the discriminator circuit will input to the recorder run logic circuitry to turn the recorder off. The recorder will continue running only for other vehicles on the bridge. The following rules will guide the operation of the analog recorder.

- Start recorder whenever a vehicle crosses the entrance tube.
- Maintain recorder operation if wheel base >8'-0".
- Run recorder as long as such a vehicle is on the bridge.
- Stop recorder when the last such vehicle exits the bridge, as indicated by exit tubes.
- Vehicles can change lanes on bridge.
- Vehicles can pass on bridge.
- Vehicles can not back up after entering bridge.

5.4.3 On-Line Digital Recording System

The recording of traffic and load sensor data in digital form requires an instrumentation of transducers similar to that used for the analog recording scheme and an analog-to-digital conversion system similar to that used to convert the recorded analog data. The major differences are the bypassing of the analog recorder and the direct on-line conversion of sensor signals to digital form before recording.

This eliminates the errors contributed by the analog tape recorder and the complexity of the two step analog record-playback process. The analog recorder is retained however, as a back-up method for retaining data should a malfunction occur in the A/D conversion or recording processes. In the balance of this section, all reference to "recorder" that follows should be understood to refer to the digital recorder.

The conversion of sensor data in real time requires an intermediate storage facility and control interface for recording the traffic and load data stream associated with one or more events. Otherwise, the slow word transfer rate to the digital recorder will result in a gross inefficiency of digital tape usage. By storing the complete event data in a semiconductor random access memory (RAM) device, an efficient block transfer of 300 to 500 data words to the tape recorder is achieved. This method is expanded to collect data from all lanes by means of a multiplexer interface between each lane's sensor-converter instrumentation and the digital recorder. Digital recording of traffic and load data is described below: (See Figure 23.)

A. Single Truck Event in Lane

1. Recorder is run only when lane-event memory buffer in completed.
2. Lane converter-storage cycle is initiated by entrance tube pulse.
3. Block header identification code and lane number is stored in address No. 1.
4. Time of arrival is stored in address No. 2. (LSB = 1/32 sec.)
5. Entrance velocity counter (number of 1 KHz pulses between first pulse from Tube 1 and first pulse from Tube 2) contents are stored in address No. 3.

6. Axle counter (number of pulses from Tube 1 while Inductive Loop gate signal is active) contents are stored in address No. 4.
7. Each axle spacing counter (number of 1 KHz pulses between each pulse from Tube 1 while inductive loop gate is active) contents are stored in addresses No. 5, No. 6, No. 7, and No. 8.
8. Entrance velocity counter is gated into sequence controller logic to adjust A/D converter and multiplexer rate for approximately 300 conversions during the traverse of the span.
9. Multiplex is sequenced to interleave (alternately feed) amplification factor profile signals and weight data profile signals to A/D converter.

10. Output of A/D converter is stored in memory. Address controller is indexed so that the sequence of midspan gage data is stored in odd contiguous addresses and the sequence of end-span gage data is stored in the alternating even contiguous addresses using the following logic:

Conversion No.	MUX Setting	Memory Address	Register Logic	
			A	B
1	Mid-Span	11	11	0
2	End-Span	12	11	1
3	Mid-Span	13	13	0
4	End-Span	14	13	1
.				
.				
.				
299	Mid-Span	309	309	0
300	End-Span	310	309	1

10a. Register A is initialized to 11 and is incremented by +2 every other conversion.
Register B is set to 0 when MUX is set for Mid-Span and set to +1 when MUX is set for End-Span.
Memory Address is sum of Registers A and B.

11. Conversion data is stored in the above manner until address 500 is reached or the exit tube pulses are detected - for constant velocity vehicles this should occur at approximately address 310.

12. End of conversion data code is written into next address (A+B+1).

13. When the address control reaches address 500 of the storage memory, a memory buffer READY pulse is initiated to start the digital recorder and transfer the event data in a block.

14. The recorder channel multiplexer honors the lane data transfer request when the recorder is not busy. It holds the request in queue if the recorder is busy.

15. The recorder will read the memory up to address A+B+2. If the memory buffer contains 500 words, this will take approximately 10 milliseconds for a recorder data rate of 48,000 words/sec. Therefore the lane converter recycle for the next traffic event must wait at least 10 milliseconds for each lane converter in the ready queue. Normally, this will not cause loss of data since a truck will travel only 1 foot in 10 ms at 68 mph, should another truck enter the span as the observed truck exits.

B. <u>Multiple Truck Event in Same Lane</u>

1. For a second vehicle entering the span before the first one exits, a composite load effect will be recorded. In order to capture the total data stream, the control logic will add the number of entrance pulses and subtract the number of exit pulses to establish the presence of a vehicle, rather than stop the conversion process after the exit pulse as in step A-11. Now additional memory is required to preserve continuous traffic and load data. By adding a second memory block

of 512 words, data can be stored and transferred to the recorder in ping-pong fashion until all traffic clears the bridge span.

2. Appropriate modification to address logic can be designed to store each entering truck's velocity data and axle spacing data.

3. Appropriate interface control logic can be designed to transfer continuous lane data to the recorder.

4. Additional time out logic is required to protect a busy lane (or a missed exit pulse) from locking out other converter channels from gaining access to the recorder. This also protects the recorder from being run under abnormal traffic conditions.

5.5 Data Reduction

Because the memory required for simultaneous multi-lane correlation is greater than available in present mini-computers, as indicated in Section 5.4.1-(H), it is assumed that data reduction will be performed on a larger central digital computer. Descriptions of the program and operations are given below. The flow chart is given in Figure 28.

5.5.1 Computer Program

The computer program can be divided into the following functional categories:

A. Executive or Control Program: To allocate computer resources, schedule various tasks, communicate with peripheral devices, process interrupts according to allocated priorities and monitor the data processing flow either alone or in conjunction with an operating system if the data reduction is run in a large EDP environment.

B. Task Programs: The major logical and processing functions performed on the raw event data are broken into modules which are linked and scheduled by the executive program. These task modules consist of related routines, sub routines, local data base and scratch pad.

C. Common Data Base: Key parameters for the bridge and instrumentation system. Special initialization data sub routines callable and used by more than one task module and the calibration event data are stored in on-line (resident) memory areas which can be accessed by the various task modules.

D. Data Files: The raw event data read in from magnetic tape, the tables of pointers used to locate, coordinate and correlate the event data such as a

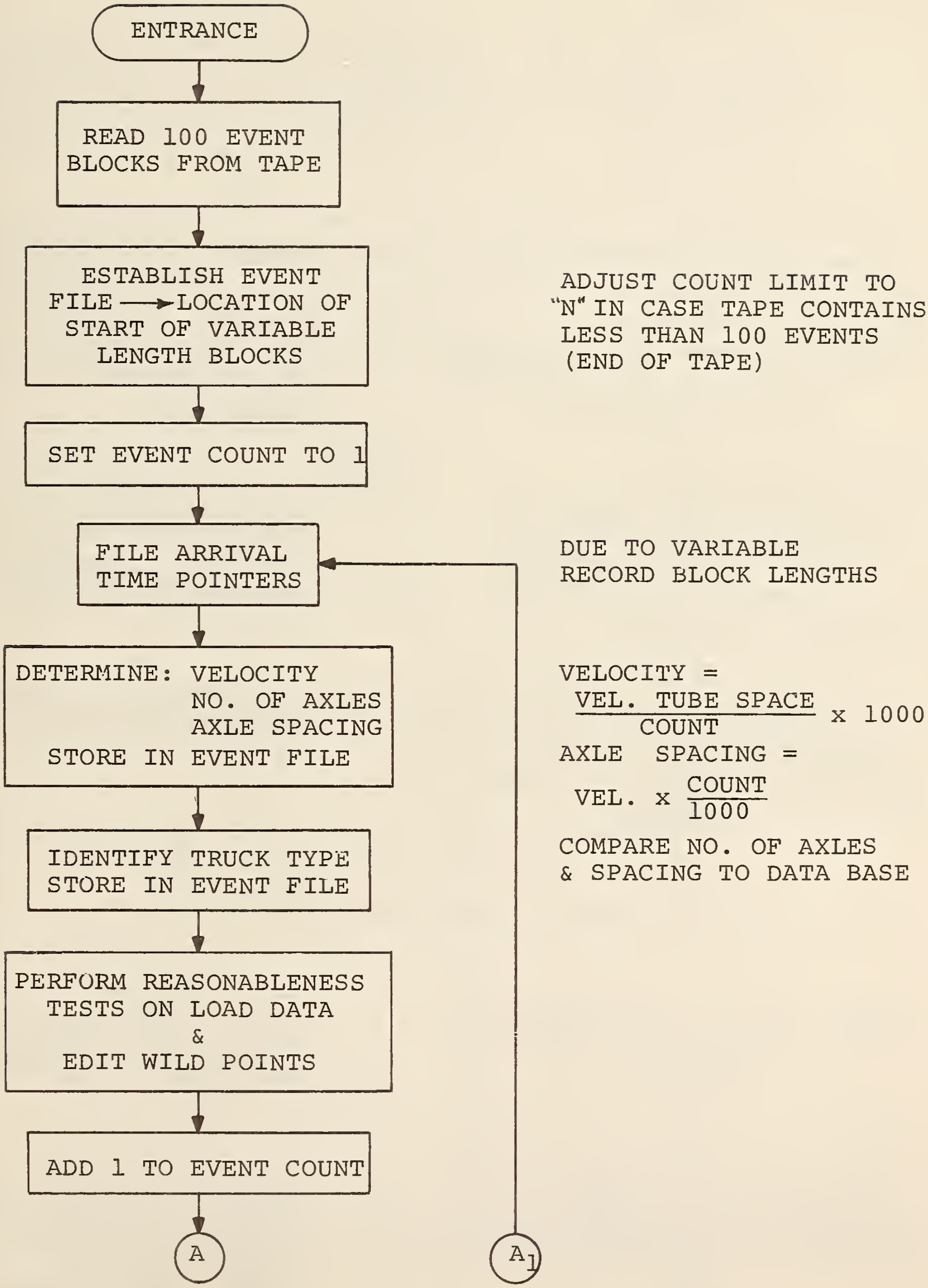


Figure 28 - Data Reduction Flow Chart

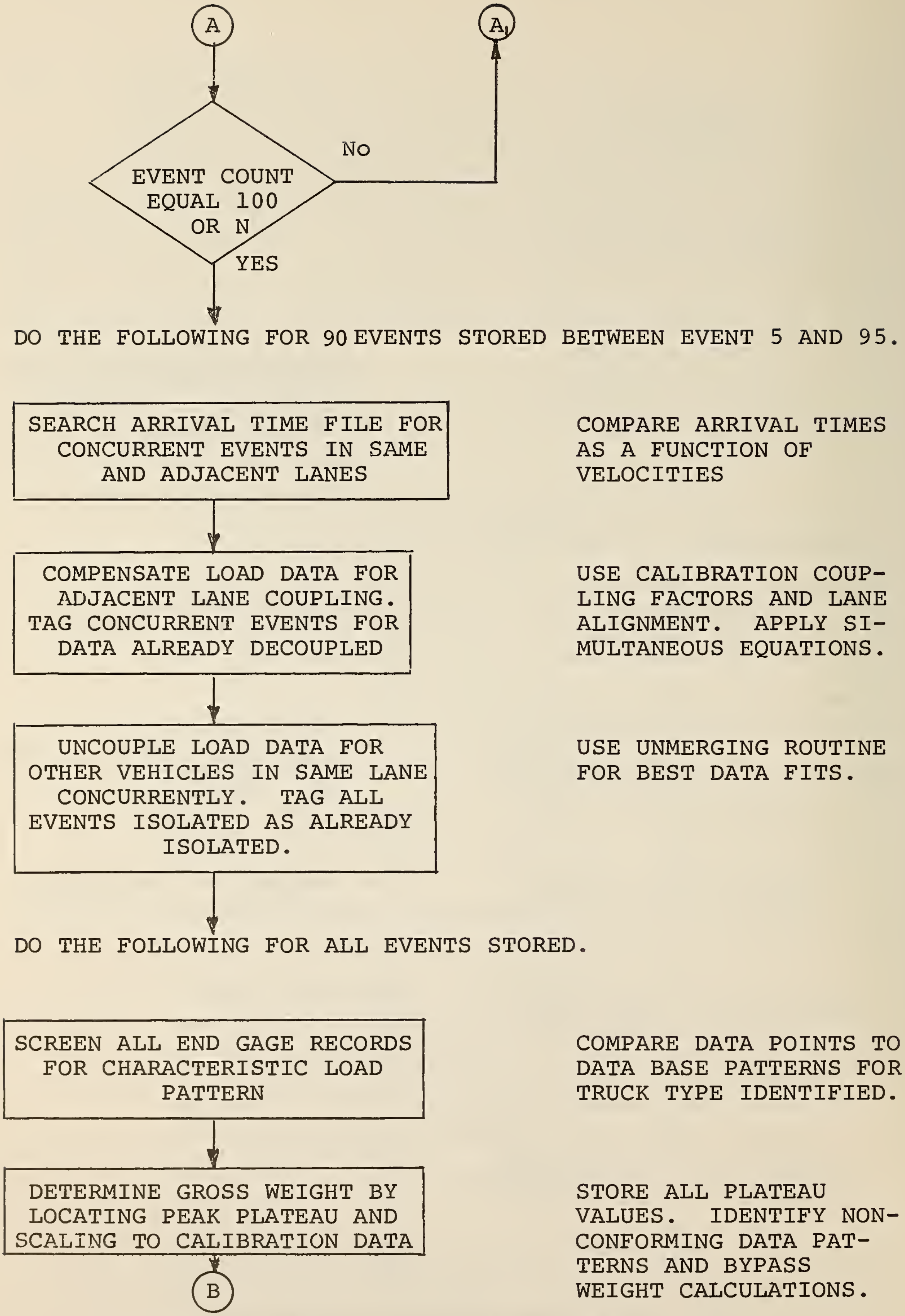


FIGURE 28 - Data Reduction Flow Chart (cont.)

B

CLASSIFY EVENTS FOR 2001 LBS. TO 10,000 LBS., AND GREATER THAN 10,000 LBS. IN EVENT FILE

DO THE FOLLOWING FOR ALL EVENTS CLASSIFIED AS GREATER THAN 10,000 LBS.

DETERMINE AXLE WEIGHTS FROM END GAGE DATA POINTS BY SCALING ALL PLATEAUS TO CALIBRATION DATA

USE SHEAR LOAD FORMULAS AND CHECKS

SEARCH FOR PEAK DYNAMIC AMPLIFICATION FACTOR

DYNAMIC LOAD EQUATED TO EQUIVALENT STATIC LOAD. TEST VALUE - SHOULD BE GREATER THAN 1.0.

DETERMINE DYNAMIC LOADS FOR AXLES

APPLY AMPLIFICATION FACTOR TO STATIC AXLE WEIGHTS DETERMINED ABOVE.

DETERMINE HEADWAY FOR ALL EVENTS

SEARCH ARRIVAL TIME FILE AND SUBTRACT SEQUENTIAL ARRIVAL TIMES FOR EACH LANE EVENT.

FORMAT EVENT FILE FOR ALL EVENTS

- Lane
- Truck Type
- Arrival Time
- Headway
- Velocity
- Axle Spacing
- Gross Weight if over 10,000 lbs.
- Axle Weight if over 10,000 lbs.
- Dynamic load if axle weight is over 10,000 lbs.

C

FIGURE 28 - Data Reduction Flow Chart (cont.)

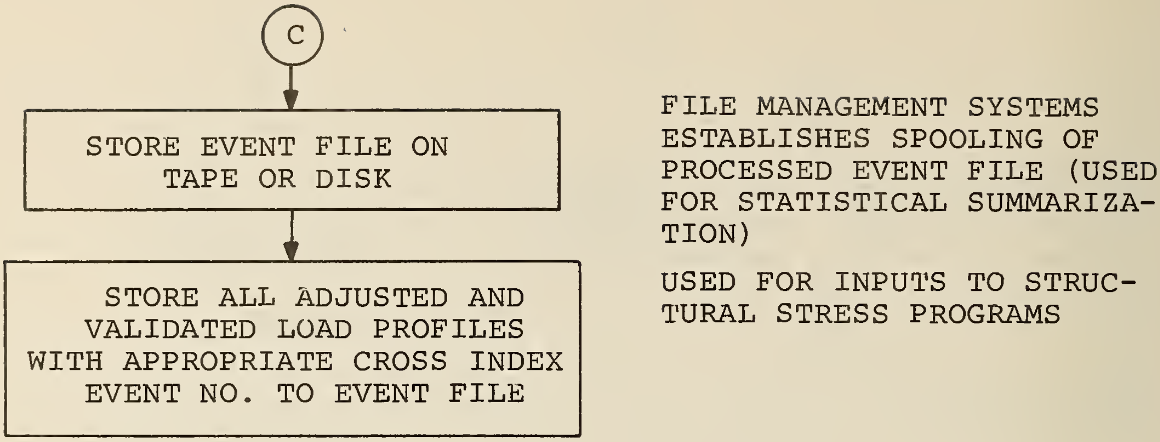


Figure 28 - Data Reduction Flow Chart (cont.)

file of pointers to locate the arrival time of each event, or processed event data required for output.

5.5.2 Calibration Data

The calibration data provides a means to verify the operability of the instrumentation system and the data processing system as well as provide the translation of strain gage outputs into actual load information. This can be accomplished by reading the calibration runs as event data after the program load, initialization and storage of the calibration data in the common data base. In this case, the data reduction program should be able to accept the calibration event data, recognize the strain gage patterns, scale the loads and output the actual calibration run weights, velocities, truck type and axle data all within the accuracy of the data processing system.

The calibration data is obtained under a controlled bridge environment.

A. No major traffic is present to add to the strain gage deflection readings.

B. Crawl speed runs are made to eliminate dynamic load deflections from the gage scale factor determination.

C. Load distribution between lanes is obtained for evaluation of the cross coupling coefficients of the multi-lane traffic load equations.

5.5.3 Load Profiles

The mid-span deflection data and the end-span load data are stored as a sequence of sampled data points. These points define the amplification factor and weight data profiles caused by the traffic events in traversing the span. When traffic occurs in more than one lane at a time or if the lane roadway is such that more than one vehicle is on an instrumented span, the load profiles will not conform to the standard patterns produced by the bridge structure for singular events. Hence, the cross coupling coefficients, determined by the adjacent lane data during a calibration run, are used to compensate the lane data points for multilane traffic. This is done by solving sets of simultaneous equations which equate the gage outputs to the sum of the contributing lane loads. Since the multilane traffic will be randomly spaced along the span and travelling at different velocities, the exact time of arrival and the velocity for each load producing vehicle must be used to rescale the cross coupling coefficient by the calculated offset distance between the lane load of interest (this event) and the other influences.

Once the load profiles are compensated for multilane cross couplings, the analysis and data reduction can proceed. The compensated load profiles and raw singular event data must be screened for reasonableness. Wild data points are edited out and replaced by interpolated data.

5.6 Procedures

5.6.1 Calibration Operations

It is assumed that the bridge has been selected, and that the instrumentation van has been parked at the desired location; 60 Hz power is available at the equipment, either through local power lines or via engine-generator set; all transducers have been installed, including an extra dynamic load transducer on the exterior (fascia) beams of outside lanes.

A. Power is turned on and the electronics system is allowed to reach equilibrium. Except for the recorders, all equipment runs continuously while data is being taken.

B. The time of day and bridge length are set into the system.

C. The transducers are zeroed.

D. The calibration truck is run across the bridge in all lanes.

   (1) The operation of all transducers is verified, and adjusted as necessary.

   (2) The dynamic load transducers giving the highest readings are connected to the appropriate circuitry via a patch board. See Section 5.2.1.

E. The calibration truck is operated over all lanes again, and the readings taken by the system are recorded as calibration inputs.

5.6.2 Traffic Data Acquisition

A. As the vehicle crosses the entrance tube, a start signal is sent to the analog recorder via the recorder run logic circuitry.

B. The vehicle then crosses the velocity tubes. If a greater than 2000 lb. vehicle wheelbase - longer than 8 ft. (2.43 m) - crosses the velocity tubes, the resulting electrical pulses, one positive (#1) and one negative (#2), are shaped by the pulse shaping circuitry and recorded. In the data processing and data reduction phases, having the 1 kHz count between the pulses from the velocity tubes #1 and #2, and knowing the distance between these tubes, the velocity is easily calculated.

   If a less than 2000 lb. vehicle, - wheelbase less than 8 ft. (2.43 m) - crosses the velocity tubes, then two positive pulses will be received from tube #1 before the negative pulse from tube #2 is received. The discriminator circuit will implement the recorder run logic to turn the analog recorder off, unless a larger vehicle is on the bridge. The two positive pulses which will have been recorded will be disregarded in the data processing phase.

C. The vehicle enters the inductive loop field, which energizes the solenoid or transistor switch in the loop detector, completing an electrical circuit. When the vehicle leaves the loop, the circuit is opened, and the voltage pulse goes to zero. The trailing edge of the pulse implements the time-of-day encoder, and the ensuing time-of-day coded pulses are recorded, marking the passage of the vehicle.

D. While the vehicle is in the inductive loop field, the balance of the vehicle wheels pass over the #1 and #2 velocity tubes, giving rise to a train of velocity tube pulses, one for each axle. The positive pulses only are counted to give the axle count, and in the data reduction phase, having the 1 Hz count between each of the wheel pulses, and now knowing the velocity, the wheel spacing is determined by a simple algorithm.

E. After the front wheel passes over velocity tube #2, if the vehicle is over 8 ft. (2.43 m) in length as determined by the discriminator circuit, a calibration reading is obtained automatically from the transducers to establish a zero reference. In the data reduction, calculations are based on excursions from the zero reference. This procedure compensates for any temperature drift in the transducers or the bridge.

F. When the vehicle enters the bridge the outputs from the shear strain and bending strain transducers are processed as previously described.

G. When the vehicle leaves the bridge, the pulses from the exit tube implement the analog recorder run logic circuitry, and the recorder stops, unless vehicles greater than 8 ft. (2.43 m) long are on the bridge. The recorder run logic circuitry keeps the recorder running until no vehicles are on the bridge.

H. During the calibration and traffic data gathering phases, a trained technician perioidically monitors transducer and equipment operation. Unusual circumstances with bridge traffic are noted so that computer output anomalies may be understood.

5.7 Other Bridge Designs

In Section 1.5, it was stated that this study would be limited to simple span, right (non-skewed) structures, so that the feasibility aspects would not be obscured by unnecessary complexity. The effects of continuous span and skewed bridge design on the concept will now be examined.

5.7.1 Continuous Span Bridges

One of the end spans of a continuous span bridge could be instrumented to provide weight data in accordance with the single ended approach discussed in Section 4.3.1. The double ended approach is inapplicable because the reaction between the end and center spans is reduced by the moment in the beam above. It would be possible to monitor the position of a vehicle as it traverses the bridge away from the center reaction, and thus knowing the moment, compensate for the reduction of reaction. This, however, introduces additional position sensors and complexity. The single ended approach offers more promise of applicability.

5.7.2 Skew Bridges

There is no apparent reason why the double ended approach could not be applied to a skew bridge. The fact that the transducers on the ends of the three beams laterally nearest the center of the lane are added, compensates for the differences in reaction seen by the outside beams of the trio. Errors will be introduced by the amount of the displacement of the beam trio from the center line of the lane. These would have to be evaluated individually for each bridge.

5.8 System Characteristics

The characteristics of the system proposed under this study are listed in Table 10. Inasmuch as all the systems discussed in this study have essentially the same complement, accuracy is given for the preferred system - the direct digital recording system. If the analog unit is selected as the prime recorder, or if the data from this machine in the back-up mode is used, the additional error introducted thereby is listed as a separate item.

Table 10 System Characteristics

Items	Comments
Accuracy	Direct Digital Recorder: 4.0%
Accuracy	When Analog Recorded Data is Used: 2.0% Add'l.
Operation	This system provides simple operational requirements and requires simple arithmetic algorithms to achieve deterministic results. It may be possible to simplify the system even further if the test plan recommendation in Section 6.2 is implemented.
Constraining Features	There are no constraining features other than those discussed in Section 5.7. Accuracy will be enhanced however, if the vehicle enters and travels smoothly on the bridge. This requires that the approach to the bridge and the bridge deck be relatively smooth, and that these contain no abrupt discontinuities to excite the vehicle suspension system.
Maintenance	It is expected that minimum maintenance will be required. All the data processing circuitry will be solid state or integrated circuit design. The reliability of these devices is well known. With the use of the LVDT, it is expected that the reliability of the strain transducers would be at least an order of magnitude greater than electric resistance strain gages.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

As a result of this study, it is concluded that gross vehicle weights, axle weights, and the dynamic loads of moving vehicles can be determined using slab and beam highway bridges together with the appropriate transducers and instrumentation system. The procedures and calculations are straightforward, resulting in deterministic values for the weights and loads. Using the recommended techniques and equipment, large volumes of data can be acquired and processed with efficient computer usage for data reduction.

The traffic pattern data objectives of this study can also be acquired, using conventional traffic transducers and the load instrumentation system. Developments in vehicle detectors now being pursued under the direction of the FHWA, if successful,may serve to reduce the installation time associated with the vehicle detector recommended by this study.

The amplification factor and associated dynamic loads, determined by measurement of their effects on the bridge structure, will be satisfactory for use in the design of other bridge structures. However, the values should not be taken as necessarily applicable to bridge decks, as no attempt was made to correlate the dynamic load seen by the bridge structure with the instantaneous wheel forces under the moving vehicle.

6.2 Recommendations

It is recommended that the Digital Recorder System shown in simplified form in Figures 21 and 23 be selected when the Data Acquisition and Recording System is implemented.

It is further recommended when the instrumentation system acquisition is implemented, that the first phase be a test program to optimize the approach recommended in this study. It is not necessary that the complete recommended system be tested, as the implementation of the A/D conversion and digital recording functions is a straightforward design problem and involves no particular advances in the state of the art.

However, with no known available field experience with filtering of bridge shear reaction signals and with processing of this data to compensate for the effect of lateral vehicle drift within the traffic lane, it seems prudent to obtain such experience before committing to complete system procurement and computer programming. During this test period, the operation of the traffic data transducers can be tested. The possibility of using load transducer data to reduce the traffic transducer complement can also be explored at this time. In this way, the overall system performance and development costs may be optimized.

6.2.1 Test Plan

The minimum effort seen as necessary to implement the test plan is:

A - Procure transducers and necessary signal conditioning equipment.

B - Design and procure or fabricate the filters and the circuitry for the traffic transducers and the preprocessing of load data.

C - Install this equipment in the FWHA instrumentation trailer, so that available strip chart recorders may be utilized.

D - Select a bridge to conduct tests.

E - After the transducers are installed, operate the test truck with no other vehicles on the bridge, making runs on all lanes, and recording data from all transducers.

F - Analyze this data, and make such equipment modifications as necessary to improve performance. In addition to study of the expected operation of the equipment, the analysis should include determination of:

- o cross coupling effects. It is anticipated that cross coupling may be negligible in reaction shear response. If so, the computer program module for static weight calculations could be considerably simpler. No such reduction is anticipated for the dynamic load transducers.

- o vehicle detection by filtered shear reaction weight signals. This is highly possible and may permit deletion of the inductive loop vehicle detector and its installation problem.

G - Remove the reaction shear transducers from all beams except the beam nearest the center of each lane, and operate the test vehicle, c.g. of load away from vehicle center, several times in each lane, varying its distance a constant value from and on each side of the center line of the lane.

- o If the test data shows an insignificant effect when the vehicle changes its position laterally within the lane, then the complement of static load transducers and associated signal conditions may be reduced to 1/3, and the adder circuitry simplified.

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APPENDIX A

TABULATION OF DETECTORS PRACTICABLE FOR HIGHWAY SURVEILLANCE AND CONTROL

This appendix reproduces data researched from many sources and tabulated in Reference 29. This data is applicable to the transducers for the traffic data required for this study.

APPENDIX A

TABULATION OF DETECTORS PRACTICABLE FOR HIGHWAY SURVEILLANCE AND CONTROL

Types of traffic detectors have been under intensive study in recent years, and the results of these studies are summarized in Reference 29, Table 16. Although the end use of the detector is different for this study than for Reference 29, the data contained therein is entirely applicable. For this reason, Table 16 of Reference 29 is reproduced in its entirety in this appendix.

Types of detector practicable for surveillance and control

Detector	Measurement capability					Principle of operation	Advantages	Disadvantages	Approximate costs	
	Passage/count	Presence	Speed	Occupancy	Queue length				Purchase	Total installation
1. Photoelectric	x	x	x	x	------	A light beam is radiated from a source on one side of the traffic lane to a photoelectric cell on the other. Passing vehicles interrupt the beam, actuating a relay. May also be used from above or below the roadway.	1. Accurate for vehicle passage in single lanes. 2. Most suitable for situations with uniform light (e.g., tunnels).	1. Acts as a passage detector only. 2. Inaccurate where more than one traffic involved lane.		
2. Infrared:										
(a) Interrupted beam	x	x	x	x	------	As above, only using radiation from the infrared part of the spectrum.	As above	As above		
(b) Reflected beam	x	x	x	x	------	Overhead marked transmitter-receiver receives reflected rays. Vehicle presence/ passage noted by change in reflectivity between pavement and tops of vehicles.	1. Most suitable for situations with uniform light (e.g., tunnels).	1. Oversophisticated and expensive for the degree of accuracy obtained. 2. Sensitive to ambient light conditions and color of reflective surface. 3. Sensitive to weather conditions. 4. Inaccurate due to reflectivity differences.	$1,200 (ref. 225)	
3. Sonic:										
(a) Pulsed	x	x	x	x	x	Emits bursts of 20 kHz at 20—25 times per second. Vehicle reduces path length, resulting in the return signal arriving when the receiver is open. Can be overhead or side mounted.	1. No disturbance to road and a minimum disturbance to traffic for its installation. 2. Can be used in locations with unstable pavement. 3. Does not produce electromagnetic radiation.	1. Can be expensive to install if no suitable pole or mounting available. 2. Inaccurate due to conical detection zone, and due to wide variations in vehicle configurations and height. 3. Insensitive to vehicle	$500	$600 to $1,200

Types of detector practicable for surveillance and control—Continued

Detector	Measurement capability					Principle of operation	Advantages	Disadvantages	Approximate costs	
	Passage/count	Presence	Speed	Occupancy	Queue length				Purchase	Total installation
							4. Can classify vehicles by height.	direction. 4. Sensitive to environmental conditions, dirt, traffic, vibrations, etc. 5. Inaccurate under congested conditions. 6. Sonic output can be annoying to humans or animals if not adjusted properly.		
(b) Continuous wave	x	------	x	------	------	Operates on the Doppler principle.	1. As 1, 2, and 3 above. 2. Improved accuracy for speed measurement.	1. As 1, 4, 5, and 6 above. 2. Expensive for limited amount of information. 3. Is not a presence detector, and cannot detect stopped vehicles (3 mph).	$1,000 with speed output	$1,000 to $1,600 with speed output
4. Radar........	x	------	x	------	------	Operates on the Doppler principle, and at 2,445 MHz or 10.525 GHz will detect vehicles at speeds from 2 to 80 mph. Most suitable if overhead transmitter and antenna, to eliminate vehicle interference.	1. Immune to electromagnetic interference. 2. No disturbance to road and minimum to traffic during installation.	1. Experienced personnel required for adjustment, maintenance, and installation. 2. Requires FCC license. 3. Excessive installation cost if mounting pole unavailable. 4. Expensive for limited amount of information.	$500 without speed capability	$600 to $12,000 without speed capability
5. Inductive loop: (a) Fixed tuned	x	x	x	x	x	Vehicle passage cuts the magnetic flux around a resonantly turned loop (at 100 kHz) thereby increasing or decreasing the inductance so that a change	1. Size and shape of detection zone is adjustable (necessary for queue detector). 2. Excellent presence detector.	1. Cost of installation can be excessive. 2. Traffic disruption during installation. 3. Difficult to tune so that both motorcycles and high-	$300	$500 to $600

Types of detector practicable for surveillance and control—Continued

Detector	Measurement capability					Principle of operation	Advantages	Disadvantages	Approximate costs	
	Passage/count	Presence	Speed	Occupancy	Queue length				Purchase	Total installation
						in resonant frequency, impedance, amplitude or phase shift is detected and transmitted to amplifying or relaying circuit. 1–4 turns of insulated wire installed in slot in pavement and covered by hot asphalt mix.	3. Relatively insensitive to weather conditions.	bed vehicles are counted.		
(b) Self-tuning	x	x	x	x	x	As above	As above, but in addition: 1. No initial or periodic calibration required.	As 1–3, 5–7 above, but in addition: 1. A number of self-tuning detectors located in the same controller cabinet have been known to interfere with one another, indicating importance of case shielding and cable coupling. 2. Response time may be slower than with fixed tuned ones.	As above	As above
6. Magnetic: (a) Magnetometer	x	x	------	x	------	Passage of vehicle disturbs vertical component of earth's magnetic field, thereby inducing a voltage in a coil placed beneath the pavement.	1. Relatively inexpensive to install. 2. Unaffected by weather conditions. 3. Does not produce any radiation.	1. Poorly defined detection zone that may necessitate more than one sensing head. 2. Will double count some vehicles due to magnetic material distribution within the vehicle (or may miss close-following vehicles if adjusted for this). 3. Subject to electromagnetic interference if not compensated.	$200	$350–$500

Types of detector practicable for surveillance and control—*Continued*

Detector	Measurement capability					Principle of operation	Advantages	Disadvantages	Approximate costs	
	Pas-sage/count	Pres-ence	Speed	Occu-pancy	Queue length				Purchaes	Total installation
								4. Are not very suitable where ferrous material is present (e.g., bridge decks).		
(*b*) Magnetic coupling	x	x	------	------	------	Vehicle passage disturbs magnetic field generated by emitter coil and is sensed by a second orthogonal coil.	1. May be used to obtain vehicle classifications.	1. May be unstable due to instability of orthogonal coils in pavement surface.		
7. Treadle------	x	------	------	------	------	Tire pressure causes two metallic contacts to close, completing a circuit so that an electronic effect is transmitted to a relay circuit.	1. Well-defined sensing zone. 2. Simple and rugged. 3. Can be used to give one-directional counts only. 4. Reliable. 5. Cheap. 6. Detects all moving vehicles (Other passage detectors have minimum speed of about 3 mph.)	1. Counts axles resulting in poor vehicle count accuracy. 2. Cannot measure presence. 3. Affected by bad weather conditions. 4. Excessive disruption of traffic during installation. 5. Difficulty in resurfacing roads. 6. Subject to mechanical failure.	$250	$500
8. Pneumatic----	x	------	x	------	------	Tire pressure causes air pulse in rubber tube to move metal diaphragm completing circuit.	1. Cheap, easy to install for temporary use. 2. Can measure speed if used in pairs.	1. Counts axles, hence poor vehicle count. 2. Needs replacement every few months. 3. Adversely affected by bad weather.		
9. Hydraulic----	x	------	x	------	------	As 8 above, only tube is liquid-filled and liquid movement may be detected photo-electrically.	------------------------	1. As 1, 2, and 3 in 8 above. 2. More complex than pneumatic detectors with little advantage.		

APPENDIX B

SHEAR CRAWL RESPONSE OF SIMPLE SPAN BRIDGE TO A THREE-AXLE VEHICLE REFERENCED TO THE FAR END OF BRIDGE

This appendix contains the derivation of the equations for determining static axle weights from the shear crawl response curve as determined from instruments located at the remote end of the bridge.

SHEAR CRAWL RESPONSE OF SIMPLE SPAN BRIDGE
TO A THREE-AXLE VEHICLE
REFERENCED TO THE FAR END OF BRIDGE

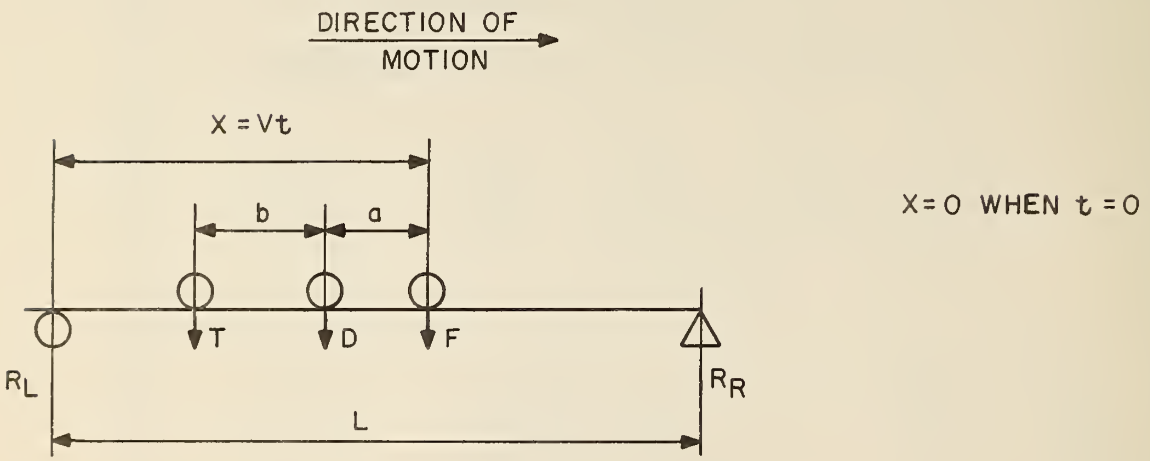


Figure B-1 - Loading Diagram - Three Wheel Vehicle on Simple Span Bridge

Figure 16, a history of the shear at the remote end of the bridge as a function of time, was prepared by superpositioning the individual influence lines of each of the axle weights of the vehicle. The dark solid line represents the composite values. The equations for the slope of the various sections of the plot are derived below.

Notation:

$$m_1 = \frac{\Delta R_{R1}}{\Delta t_1} \quad \text{for interval } (0)\rightarrow(1),\ o<x<a$$

$$m_2 = \frac{\Delta R_{R2}}{\Delta t_2} \quad \text{for interval } (1)\rightarrow(2),\ a<x<b$$

$$m_3 = \frac{\Delta R_3}{\Delta t_3} \quad \text{for interval } (2)\rightarrow(3),\ b<x<L$$

$$m_4 = \frac{\Delta R_4}{\Delta t_4} \quad \text{for interval } (3)\rightarrow(4),\ L<x<L+a$$

$$m_5 = \frac{\Delta R_5}{\Delta t_5} \quad \text{for interval } (4)\rightarrow(5),\ L+a<x<L+a+b$$

F = weight of front axle
D = weight of driver axle
L = bridge length
T = weight of trailer axle
V = vehicle velocity
a = distance between front and driver axles
b = distance between driver and trailer axles

Referring to Figure 16, for the interval (0) to (1), when x = a, and not allowing for filter lag and tire print,

$$R_{R1} = \frac{F(a)}{L} \qquad \Delta t_1 = \frac{a}{V}$$

$$\frac{\Delta R_{R1}}{\Delta t_1} = m_1 = \frac{\frac{F(a)}{L}}{(\frac{a}{V})} = \frac{FV}{L}$$

$$F = m_1(\frac{L}{V}) \tag{B-1}$$

For the interval (1) to (2), when x = b

$$R_{R2} = \frac{D(b)}{L} + \frac{F(a+b)}{L} \qquad \Delta t_2 = \frac{b}{V}$$

$$\frac{\Delta R_{R2}}{\Delta t_2} = m_2 = \frac{\frac{D(b)}{L} + \frac{F(a+b)}{L} - \frac{Fa}{L}}{\frac{b}{V}}$$

$$m_2 = \frac{\frac{D(b)}{L} + \frac{F(b)}{L}}{\frac{b}{V}} = (D+F)(\frac{V}{L})$$

$$(D+F) = m_2\left(\frac{L}{V}\right) \tag{B-2}$$

$$D = (m_2 - m_1)\left(\frac{L}{V}\right) \tag{B-3}$$

For interval (2) to (3), when X = L

$$R_{R3} = F + D\left(\frac{L-a}{L}\right) + T\left(\frac{L-(a+b)}{L}\right), \quad \Delta t_3 = \frac{L-(a+b)}{V}$$

$$\frac{\Delta R_{R3}}{\Delta t_3} = m_3 = \frac{F+D\left(\frac{L-a}{L}\right) + T\left(\frac{L-(a+b)}{L}\right) - D\left(\frac{b}{L}\right) - F\left(\frac{a+b}{L}\right)}{\frac{L-(a+b)}{V}}$$

$$m_3 = \frac{\frac{F(L-(a+b))}{L} \quad \frac{T(L-(a+b))}{L} \quad \frac{D(L-(a+b))}{L}}{\frac{L-(a+b)}{V}}$$

$$m_3 = (F+D+T)\left(\frac{V}{L}\right)$$

$$(F+D+T) = m_3\left(\frac{L}{V}\right) \tag{B-4}$$

$$T = (m_3 - m_2)\left(\frac{L}{V}\right) \tag{B-5}$$

For interval (3) to (4), when X = L+a

$$\Delta R_{R4} = D\left(\frac{a}{L}\right) + T\left(\frac{a}{L}\right), \qquad \Delta_{t4} = \frac{a}{V}$$

$$\frac{\Delta R_{R4}}{\Delta t_4} = m_4 = (D+T)\left(\frac{V}{L}\right)$$

$$D+T = m_4\left(\frac{L}{V}\right) \tag{B-6}$$

For interval (4) to (5), when X = L+a+b

$$\Delta R_{R5} = T\left(\frac{b}{L}\right) \qquad \Delta_{t5} = \frac{b}{V}$$

$$\frac{\Delta R_{R5}}{\Delta t_5} = m_5 = \frac{T\left(\frac{b}{L}\right)}{\frac{b}{V}} = T\left(\frac{V}{L}\right)$$

$$T = m_5\left(\frac{L}{V}\right) \tag{B-7}$$

$$D = (m_4 - m_5)\left(\frac{L}{V}\right) \tag{B-8}$$

APPENDIX C

SHEAR CRAWL RESPONSE OF SIMPLE SPAN BRIDGE TO A THREE-AXLE VEHICLE REFERENCED TO THE NEAR END OF BRIDGE

This appendix contains the derivation of the equations for determining static axle weights from the shear crawl response curves as determined by instruments located at the near end of the bridge. The slopes are shown to be equal but opposite in sign for the same intervals of the plot shown in Appendix B. When the composites of both Appendix B and this appendix are superimposed, the resultant third composite has plateaus of constant value stepped at the values representing combinations of static axle weights.

SHEAR CRAWL RESPONSE OF SIMPLE SPAN BRIDGE
TO A THREE-AXLE VEHICLE
REFERENCED TO THE NEAR END OF BRIDGE

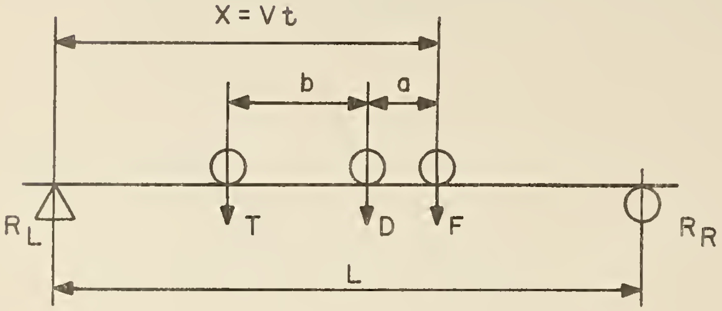


Figure C-1 - Loading Diagram - Three Wheel Vehicle on Simple Span Bridge

Figure 17, a history of the shear at the near end of the bridge as a function of time, was prepared in a manner similar to Figure 16. The solid line represents the resultant composite. The shear history at the far end of bridge is shown on Figure 17 as a dotted line. The superposition of shear histories at both ends of the bridge results in the plot drawn in dot and dash lines.

The equations for the slope of the various sections of the near-end plot are derived below. The notation is the same as for Appendix B.

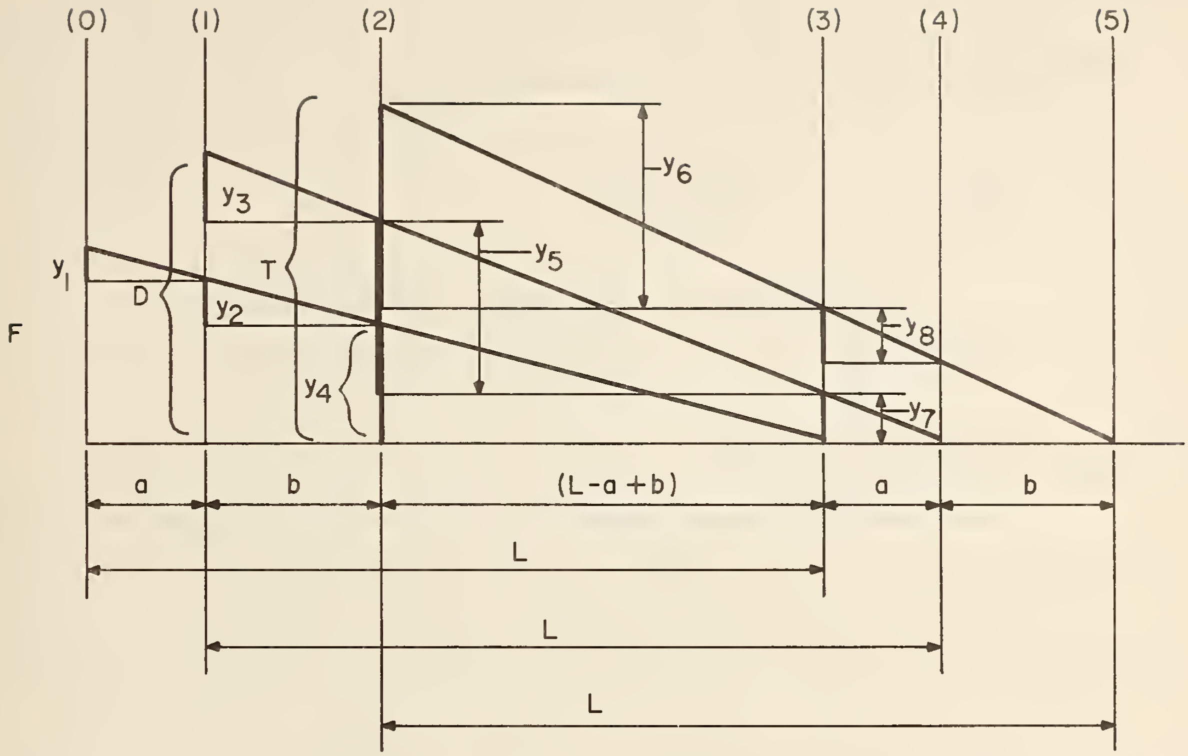


Figure C-2 - Geometry of Influence Lines

From Figure C-2 and Figure 17, for the interval (0) to (1), when X = a, and not allowing for filter lag and tire print,

$$\frac{\Delta R_{L1}}{\Delta t_1} = m_{L1} = \frac{-Y_1}{\frac{a}{V}} = \frac{-F(\frac{a}{L})}{\frac{a}{V}} = -F(\frac{V}{L})$$

$$m_{L1} = -F(\frac{V}{L})$$

$$F = -m_{L1}(\frac{L}{V}) \qquad \text{(C-1)}$$

For the interval (1) to (2), when X = b,

$$\frac{\Delta R_{L2}}{\Delta t_2} = m_{L2} = \frac{-Y_3-Y_2}{\frac{b}{V}} = -\left[\frac{D(\frac{b}{L})+F(\frac{b}{L})}{\frac{b}{V}}\right]$$

$$m_{L2} = -(D+F)(\frac{V}{L})$$

$$D+F = -m_{L2}(\frac{L}{V}) \qquad \text{(C-2)}$$

$$D = -(M_{L2} - m_{L1})(\frac{L}{V}) \qquad \text{(C-3)}$$

For the interval (2) to (3), when x = L

$$\frac{\Delta R_{L3}}{\Delta t_3} = m_{L3} = \frac{-(y_4+y_5+y_6)}{\frac{L-(a+b)}{V}}$$

$$m_{L3} = -\left[\frac{\frac{F(L-(a+b)}{L} + \frac{D(L-(a+b)}{L} + \frac{T(L-(a+b)}{L}}{\frac{L-(a+b)}{V}}\right]$$

$$m_{L3} = -(F+D+T)(\frac{V}{L})$$

$$(F+D+T) = -m_{L3}(\frac{L}{V}) \qquad \text{(C-4)}$$

$$T = -(m_{L3} - m_{L2})(\frac{L}{V}) \qquad \text{(C-5)}$$

For interval (3) to (4), when x = L+a

$$\frac{\Delta R_{L4}}{\Delta t_4} = m_{L4} = \frac{(y_7+y_8)}{(\frac{a}{V})} = -\left[\frac{D(\frac{a}{L}) + T(\frac{a}{L})}{(\frac{a}{V})}\right]$$

$$m_{L4} = -(D+T)(\frac{V}{L})$$

$$D+T = -m_{L4}(\frac{L}{V}) \qquad \text{(C-6)}$$

For interval (4) to (5), when x = L+a+b

$$\frac{\Delta R_{L5}}{\Delta t_5} = m_{L5} = -\frac{T(\frac{b}{L})}{(\frac{b}{V})}$$

$$m_{L5} = -T(\frac{V}{L})$$

$$T = -m_{L5}(\frac{L}{V}) \qquad \text{(C-7)}$$

$$D = -(m_{L4} - m_{L5})(\frac{L}{V}) \qquad \text{(C-8)}$$

The filtered responses from the instruments at both ends of the bridge may be added, since they are essentially DC. The addition of such signals, the rate of change of which (the slopes of the time history plot) are negative with respect to each other between the same intervals, will produce constant values between those intervals. The resultant plot, shown on Figure 17, has plateaus at the levels proportional to the static axle weight as shown:

$$
\begin{aligned}
\text{Level } B &= K(F) \\
C &= K(F+D) \\
E &= K(F+D+T) \\
G &= K(\quad D+T) \\
H &= K(\qquad T)
\end{aligned}
$$

where K is the overall system constant obtained by calibrating the structure and instrumentation system.

These equations are redundant, and can be manipulated to give two values for each axle weight which can then be averaged to increase the accuracy of the output, if necessary.

Another approach to viewing this concept is to consider the reactions of a simply loaded bridge when subjected to a cumulative series of loads, as by axles slowly moving across the bridge:

(1) As the front axle enters the bridge, the sum of the left and right reactions equals the front axle weight.

(2) As the second axle enters the bridge, the sum of the left and right reactions equals the sum of the first and second axle weights.

(3) The process will repeat for each succeeding axle of the vehicle, until the front axle leaves the bridge.

(4) As the front and each following axle leaves the bridge, the sum of the left and right reactions now equals the sum of those axles still on the bridge.

APPENDIX D

VALUES OF ACCELERATIONS FOR A BRIDGE APPROXIMATELY 100 FT. LONG

Estimates are presented for the crawl (static) and dynamic increment accelerations for a 100 ft. bridge. The variation in the relationship is also examined for a shorter bridge.

VALUES OF ACCELERATIONS FOR A BRIDGE APPROXIMATELY 100 FT. LONG

Acceleration values for crawl deflection and dynamic increment are calculated for a bridge approximately 100 ft. long to determine a range of values to be expected. These calculations are then used in Section 4.4.2 to assess the practicability of using accelerometers.

Reference 25 and Figure 8, assumed as typical and close to a 100 ft. (30.5 m) bridge, are used as the source of data for the calculations in this Appendix.

Bridge length = 97 ft. (29.5 m)

Bridge natural freq. (fundamental) = 2.9 Hz

For vehicle velocity of 41.3 mph (66.5 km/h) = 60.5 ft/sec (18.4 m/sec)

Maximum crawl deflection = 0.37 in.

Maximum dynamic increment = 0.1 in.

$$\text{Acceleration} = \frac{Aw^2}{g}$$

A = Amplitude
w = circular freq.
g = accel. of g = 386 in/sec.^{2}
f_c = crawl frequency
f_b = bridge natural frequency

<u>For crawl deflection</u>

$$f_c = \frac{V}{2L} = \frac{60.5}{(2)(97)} = .313 \text{ Hz}$$

$$\text{accel.} = \frac{0.37 \times (2\pi \times .313)^2}{386} = .0037 \text{ g}$$

<u>For dynamic increment</u>

$$\text{accel} = \frac{0.1 \times (2\pi \times 2.9)^2}{386} = .0855 \text{ g}$$

Ratio of Dynamic Incr./Crawl Deflection Accel.

$$= \frac{.0855}{.0037} = 23.2$$

For 50 ft. bridge,

$$f_c = .313 \text{ x } \frac{97}{50} = .606 \text{ Hz}$$

$$f_b = \frac{1}{T_b} = \frac{1}{.13} = 7.7 \text{ Hz (From Figure 13)}$$

Maximum crawl deflection (estimate) - for same stress level

$$\Delta_{st} \simeq 0.37 \text{ x } (\frac{50}{97})^2 = .098 \text{ in.}$$

Maximum dynamic increment, approximately proportional to α, the speed parameter,

$$\alpha_{100} = \frac{fc}{f_b} = \frac{.313}{2.9} = .108$$

$$\alpha_{50} = \frac{fc}{f_b} = \frac{.606}{7.7} = .079$$

$$DI_{50} = DI_{100} \text{ x } \frac{\alpha_{50}}{\alpha_{100}} = 0.1 \text{ x } \frac{.079}{.108} = .073"$$

For crawl deflection

$$\text{accel} = .0037 \text{ g x } \frac{.098}{0.37} \text{ x } (\frac{.606}{.313})^2 = .00036 \text{ g}$$

For dynamic increment

$$\text{accel} = .0855 \text{ g x } \frac{.073}{0.1} \text{ x } (\frac{7.7}{2.9})^2 = .440 \text{ g}$$

Ratio of Dynamic Incr./Crawl Deflection Accel.

$$\frac{.440}{.00036} = 1220$$

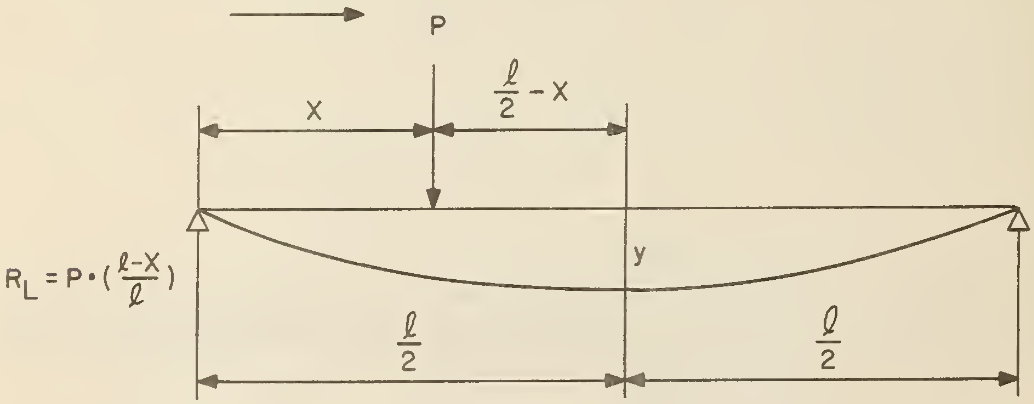
APPENDIX E

MOMENT AND DEFLECTION AT THE CENTER OF A BEAM DUE TO A MOVING LOAD

This appendix derives the equations for moment and deflection at the center of a beam caused by a load moving from one end to the center of the beam.

MOMENT AND DEFLECTION AT THE CENTER OF A BEAM DUE TO A MOVING LOAD

The amplification factor for the determination of the dynamic load induced by a vehicle moving across a bridge is to be processed from parameters measured at the center of the bridge. Either deflection or strain may be used as the parameter. In order to select the optimum parameter, equations for deflection and moment (which is linear with strain) due to a moving load as seen at the center of the bridge are derived below.



$$EI\frac{d^2y}{dx} = M$$

$$M_{yx} = P(\frac{\ell-x}{\ell}) \cdot \frac{\ell}{2} - P(\frac{\ell}{2} - x) = \frac{Px}{2} \qquad \text{(E-1)}$$

$$EI\frac{d^2y}{dx} = \frac{Px}{2}$$

$$EI\frac{dy}{dx} = \frac{Px^2}{4} + C_1$$

$$\text{when } x = \frac{\ell}{2},\ \frac{dy}{dx} = 0, \quad \text{and } C_1 = \frac{-P\ell^2}{16}$$

$$EI\frac{dy}{dx} = \frac{Px^2}{4} - \frac{P\ell^2}{16}$$

$$EIy = \frac{Px^3}{12} - \frac{P\ell^2}{16}(x) + C_2$$

when $x = 0$, $y = 0$, and $C_2 = 0$

$$EIy = \frac{Px^3}{12} - \frac{P\ell^2 x}{16}$$

$$y = \frac{P}{4EI}\left(\frac{x^3}{3} - \frac{\ell^2 x}{4}\right) \qquad \text{(E-2)}$$

The above equation holds between the limits $0 \leq x \leq \frac{\ell}{2}$.

Normalizing Equation E-2, and grouping variables,

$$y = \frac{P\ell^3}{48EI}\left[4\left(\frac{x}{\ell}\right)^3 - 3\left(\frac{x}{\ell}\right)\right] \qquad \text{(E-3)}$$

The first term of the right side of Equation E-3 is the well-known formula for the deflection of a simply supported beam with a concentrated load in the center. The second term, in brackets, is a factor which modifies the deflection formula depending on the instantaneous position of the vehicle on the bridge.

Figure E-1 shows how this factor varies with the normalized position of the vehicle on the bridge. It can be seen that as the vehicle approaches the center of the bridge, the linearity of the relationship falls off, and the sensitivity and resolution of the deflection signal decreases.

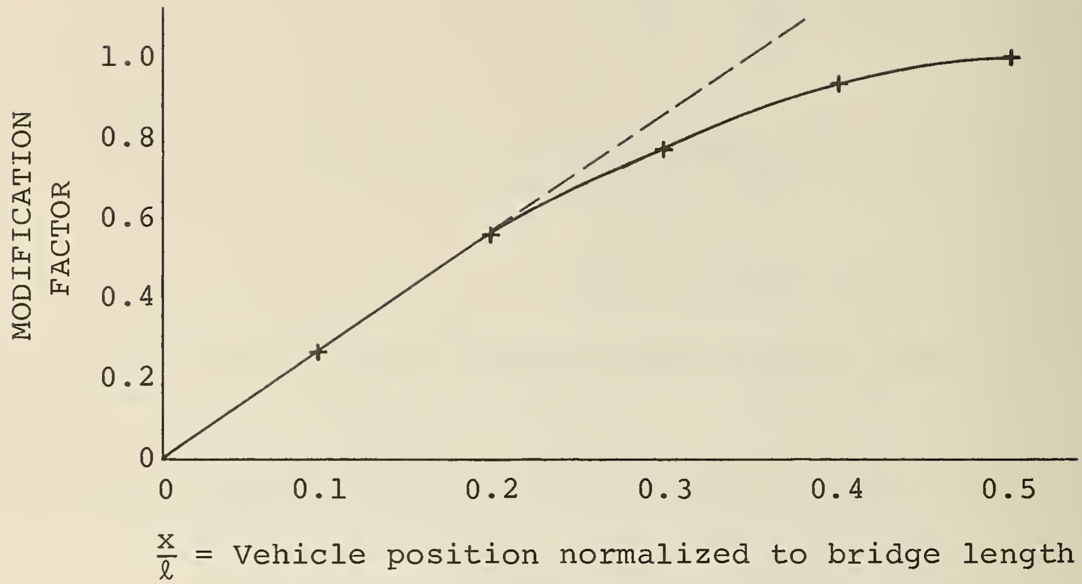


Figure E1 - Vehicle Position Modification Factor for Deflection Formula

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