A SIMULATION STUDY OF FATIGUE LIFE OF HIGHWAY BRIDGES

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Robert K. Wen
Major professor

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ABSTRACT

A SIMULATION STUDY OF FATIGUE LIFE OF HIGHWAY BRIDGES

by Egbert Hsi-Ting Chang

A study of the fatigue life of simple span highway bridges is made using computer simulation. The study begins with a deterministic analysis of a bridge traversed by a vehicle. The set-up of the simulation procedure follows. Numerical results were obtained to illustrate the procedure as well as to investigate the fatigue life of an existing bridge in Michigan. Finally, the effects of small variations of certain parameters that enter the problem are considered.

Five parameters are considered as random variables: (i) annual vehicle volume,(ii) vehicle type,(iii) vehicle speed,(iv) vehicle axle load level, and (v) interarrival time of vehicles.

The fatigue damage is considered at three "critical" points: the quarter span, mid-span, and three-quarter span, the last of which is taken to be the most critical section. The damage has been calculated on the basis of both the static and dynamic stresses.

Egbert Hsi-Ting Chang

For the real bridge studied, the fatigue life (referred to the three-quarter point) ranges from 12 years to 9,135 years, depending upon three factors: (i) dynamic or static stress, (ii) random or constant annual vehicle volume, and (iii) fatigue models. But it is reasonable to consider that value corresponding to the case of dynamic stress, random annual vehicle volume, and a certain model D as the best estimate. It is 45 years, which can reasonably be regarded as being within the service life of a structure of this type. Therefore, it seems that fatigue damage should be a major factor to be considered in the design of such bridges.

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by

Egbert Hsi-Ting Chang

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CHAPTER I

INTRODUCTION

1.1 Objective and Scope.

The purpose of this thesis is to study by computer simulation the fatigue damage and fatigue life of simple span highway bridges as caused by heavy vehicles. Because highway bridges are designed to have substantial reserve strength beyond their ordinary working loads, it is very rare that a bridge failure would be caused by a single passage of the vehicle or train of vehicles that governed the design. But in recent years, fatigue cracks have been observed in highway bridges (1,4,17)*. These cracks were caused and propagated by the repeated passage of heavy vehicles extending over a period of time. If the cracks are allowed to increase in size, failure will occur. To make appropriate provisions in the design of highway bridges to prevent fatigue failure economically presents a challenging task.

The 1965 AASHO specifications for bridges (16) explicitly consider fatigue as a possible mode of failure

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* Numbers in parentheses refer to items in the List of References.

for the first time. Currently, the specifications (the 1969 version) call for allowable fatigue stress as a function of "fatigue life" which is expressed in cycles of a fixed ratio of the design minimum stress to the design maximum stress and the type and location of material.

It has been pointed out (7) that the specifications do not account for the fact that fatigue damage can be done to a bridge by numerous loading situations different from that considered in design and much research is needed to improve the present practice. The present thesis is an effort toward that end.

There are two main features of the present study. Firstly, the stresses in the bridge are computed more accurately by considering the bridge-vehicles as a dynamic system. Secondly, the random nature of the vehicle loads (their types, weights, and speeds) is taken into account.

Therefore, the study involves the following two major parts:

(1) the development of a mathematical analysis of a dynamic bridge-vehicle system appropriate for the purpose of this study.

(2) the development of a computer simulation procedure to represent the random aspects of vehicle loading history, and the estimation of the corresponding fatigue damage and fatigue life of the bridge.

In order to simplify the bridge-vehicle system, the bridge is idealized as a single T-beam, simply supported at the ends. And the vehicle is represented by a set of sprung load units supported by linearly elastic springs and viscous dampers. The number of sprung load units of each vehicle depends on its type.

Lagrangian equation is used in deriving the equations of motion for the bridge-vehicle system. An unevenness of the bridge approach is considered in the analysis. Thus a given vehicle entering the bridge will be, in general, in a state of vibration. This analysis is described in Chapter II. Both the dynamic and static stresses approaches are calculated at three sections --- the quarter span,mid-span, and three-quarter span. The simple influence line method is used to calculate the maximum static stresses.

A fatigue model specifies a relationship between certain stress vectors and the number of cycles that the material can sustain without fatigue failure. Seven different fatigue models are used to estimate the fatigue life. In order to account for the cumulative fatigue damage suffered through the different stress levels corresponding to different vehicle loadings, the Miner's hypothesis is used. The preceding is described in detail in Chapter III.

The computer simulation procedure is described in Chapter IV. The procedure requires that the relative frequency distribution (denoted by RFD) or probability density function (denoted by PDF) of the following five random variables: vehicle type, vehicle speed, vehicle axle loading level, interarrival time, and annual vehicle volume.

The numerical results of the study are presented in Chapter V. They include a study of the fatigue life of an existing highway bridge in Michigan and the effects of small variations of certain parameters such as the RFD of axle loading level and the static strength of the bridge. The numerical results are obtained by use of three computer programs: STATIC, DYNAMIC, AND SIMU1 written in Fortran IV for use on the CDC 6500 Computer System at Michigan State University.

1.2 Literature Review.

AASHO Road Test Report (1) studied bridge fatigue damage using two approaches: i) Accelerated Fatigue Tests -- bridges were excited by mechanical oscillators which worked with a constant amplitude to replace actual heavy vehicle's dynamic loadings and, ii) Increasing Load Tests -- bridges were tested with two or three heavier truck types, for each truck, after 30 trips the axle loadings were increased and another 30 trips were made across the bridge, until the bridges were considered failed or further loading of the test vehicle was considered undesirable(unsafe).

Applying a fatigue model (Model G in chapter IV), it was found that the actual lengths of fatigue lives of the bridges tested were in good agreement with those computed based on Miner's hypothesis of cumulative damage.

Either approach, however, deviated substantially from the actual conditions of bridge-vehicle system in service. The first approach was actually a steady motion, i.e., with no random factors involved. The second was a very special kind of field test, because overloaded vehicles with speed less than 25 MPH were used, which produced a maximum static bending moment at mid-span up to 2.3 times greater than the design moment corresponding to a design stress of 18 ksi. Lower stress cycles were not considered in this approach, although such cycles could also produce fatigue damage.

In 1968, Cudney (3) reported field data on dynamic stress ranges, rebound stresses, RFD of vehicle types, etc. in time periods ranging from 24 hrs. to 96 hrs, for eight highway bridges in Michigan. In order to simplify the calculation, he grouped the stress ranges into a few levels. Munse and Stallmeyer's fatigue damage data were used together with certain assumptions in deriving a fatigue model (Model F in chapter III).

As in the preceding case and the cases to follow, Miner's hypothesis was used to calculate the fatigue damage,D, for one year's projected traffic. Then the fatigue life in years was taken to be inverse of that quantity,i.e., 1/D.

This study demonstrated the variability of such factors as vehicle types and annual vehicle volume. And hence, the dynamic stress history and its relation to fatigue life in years. Furthermore, the data, though necessarily incomplete because of the high cost of collecting them in the field, provide a great deal of valuable information much of which was used in this study. However, the very long fatigue lives(of the order of thousands of years) cast some doubt regarding the validity of the fatigue model used.

Werner,Heins,and Looney(22) discussed the fatigue damage based on static stresses in simple spans (continuous and cantilever spans were assumed to be cut into and act as several simple spans). Annual vehicle volume and the distributions of vehicle types and vehicle weights were estimated statistically from data collected within a ten-year period.

In 1969, Tung (21) adopted a more analytical approach to consider the fatigue damage problem. The simple Poisson process was used as the traffic model,

and the response of bridge was treated as a filtered Poisson process. Vehicles can be considered to be of different type and weight but must travel at the same constant speed. He gave a numerical example by considering that all vehicles were replaced by two constant forces having the same axle spacing. From the practical point of view, his method seems too complex, when applied to real systems.

1.3 Notation.

The symbols listed below have been adopted in this thesis.

a	=	length of bridge approach;
a_{ij}	=	horizontal distance between the jth axle and the centroid of the ith load unit. It is positive, when the jth axle is in front of centroid, otherwise negative;
b	=	depth of a sine curve bridge approach at center;
c_{ij}	=	damping coefficient of the jth axle in the ith load unit;
C	=	critical damping of vehicle axle;
D	=	energy dissipation function;
D	=	fatigue damage based on one sample year;
ds_{ij}	=	initial static compression in the jth axle of the ith load unit;

$\bar{d}_i$ = the ith level of fatigue damage;

$\bar{E}$ = simulated fatigue damage experiment;

EI = flexural rigidity of the idealized bridge;

f_b = natural frequency of the idealized bridge;

f_i = relative frequency of the ith vehicle speed level;

$f_{\bar{d}_i}$ = relative frequency of event $\bar{d}_i$;

f(t) = modal amplitude function (which varies with time);

F(x) = cumulative distribution function of the random variable X, i.e., F(x) = P(X < x);

f = natural frequency of vehicle axle;

g = gravitational acceleration;

h = number of load units of one idealized vehicle;

J_i = polar moment of inertia of the ith load unit;

K = spring stiffness of vehicle axle;

k_{ij} = stiffness of the jth axle in the ith load unit;

L = length of bridge span;

L_i = length of the ith load unit;

M_1,M ,M = sample spaces of vehicle type, speed, and axle loading level, respectively;

m_{1i} = the ith element of the sample space $\bar{M}_1$;

m_{2j} = the jth element of the sample space $\bar{M}_2$;

m_{3k} = the kth element of the sample space $\bar{M}_3$;

M_i = sprung mass of the ith load unit;

$M_{\bar{x}}$ = dynamic bending moment at a idealized bridge section having a distance $\bar{x}$ from the left support;

m = mass of idealized bridge per unit length;

N = sample size;

N = number of cycles of stress or strain of a specified character that a given specimen sustains before failure of a specified nature occurs;

N(i) = number of axles in the ith load unit;

N(t) = Poisson arrival process;

$\bar{n}$ = number of steps of one axle to pass through the bridge;

n = number of vehicles passed a given point within a time interval (0,t);

n = number of independent outcomes of $\bar{E}$;

n_i = number of cycles at stress range level i;

N_i = number of cycles at stress range level i which would cause a fatigue failure;

p = theoretical probability of event $\bar{d}_i$;

P_{ij} = instantaneous reaction between the jth axle of the ith load unit and the idealized bridge;

Q = defined on page 89;

r = number of load unit of a given vehicle type;

q_n = the nth generalized coordinate;

R_a = reaction at left support of bridge;

RN = random number;

s_i = number of springs in the ith load unit;

S = vehicle speed;

S = section modulus of the idealized bridge;

$S_r, S_{max}, S_{min}, S_{mins}, S_{rs}, S_{maxs}, S_{mind}, S_{rd}, S_{maxd}$ = quantities defined on page 30;

t = time;

T = kinetic energy of the whole bridge-vehicle system;

T = interarrival time ;

U_b = total strain energy in the idealized bridge;

U_v = total strain energy in the vehicle;

V = total potential energy of the bridge-vehicle system;

V_i = the ith vehicle speed level;

w = bridge approach curve;

w_{ij} = w value at the horizontal position of the jth axle of the ith load unit;

X = random variable;

x = distance of a given section from the left end of bridge;

x_{ij} = horizontal position between the left support and the jth axle of the ith load unit;

y = dynamic deflection of the idealized bridge measured from $\bar{y}$;

$\bar{y}$ = bridge deflection due to dead load;

y_{ij} = dynamic deflection of the idealized bridge corresponding to the horizontal position of the jth axle in the ith load unit;

$\bar{y}_{ij}$ = dead load deflection of the idealized bridge corresponding to the horizontal position of the jth axle in the ith load unit;

z_i = vertical displacement of the ith load unit measured from its static equilibrium position, it is positive when downward;

θ_i = angular displacement of the ith load unit about its centroid axis;

$\bar{x}$ = horizontal distance between the left support and the critical section;

$\bar{c}_1$ = 1, if idealized bridge is in vibration, i.e., $y \neq 0$, otherwise, zero;

$\bar{c}_{2i}$ = 1, if at least one axle of the ith load unit is on the idealized bridge or the bridge approach, otherwise, zero;

$\bar{c}_{3ij}$ = 1, if the jth axle of the ith load unit is on the bridge, otherwise, zero;

$\bar{c}_{4ij}$ = if the jth axle of the ith load unit is on the approach, otherwise, zero;

Δt = time increment;

δ, ϵ = defined on page 40;

λ = average interarrival time;

Δv_i = static deflection at the centroid of the sprung mass of the ith load unit.

CHAPTER II

COMPUTATION OF STRESSES

In this chapter are presented the derivation of the differential equations of motion of simple span bridge-vehicle system, the numerical solution of these equations, and the computation of the dynamic stresses in the bridge. In addition, the much simpler case of static stress analysis is explained in the last section of the chapter.

2.1 Idealization of Bridge.

In this study, a typical girder or I-beam and its tributary slab area are considered as a representative unit of the bridge. The effective width of the slab follows the AASHO Specifications, section 1.7.99 (16). The resulting T-beam is simply supported at its two ends, as shown in Fig.2-1. The flexural rigidity, EI, and the mass, m, of the beam are considered to be uniformly distributed along the length of beam. Internal damping and surface unevenness of the bridge are ignored. The usual beam theory is assumed applicable for the analysis.

The dynamic deflection configuration of the bridge at any instant is taken to be :

$$y(x,t) = f(t)\sin \frac{\pi x}{L} \qquad .....(2\text{-}1)$$

The form was first used by Timoshenko(19). Other investigators of bridge dynamics have also considered it and found it to be reasonably accurate. In the equation above,

x = distance measured from the entry point of the bridge;

L = length of the bridge span;

$f(t)$ = modal amplitude function (which varies with time);

$y(x,t)$ = dynamic deflection of the bridge measured from its static equilibrium position.

Thus, the idealized bridge is a single-degree-of-freedom system.

2.2 Idealization of Vehicles.

Because of the preceding approach, only one (longitudinal) line of wheels of the vehicles is considered. such wheel loads are assumed to act directly above the beam. For simplicity, the beam and the wheel loads will be referred to as the bridge-vehicle system. Each vehicle is idealized and represented by a set of load units, and each load unit consists of a point mass or a uniformly distributed mass connected to a linearly elastic spring or several springs. Viscous dampers are also placed in parallel with the springs. Fig.2-2 shows two idealized vehicles.

2.3 Bridge-Vehicle System.

The system considered is shown in Fig.2-2. It consists of three parts: (i) a simply supported beam (idealized bridge) spanned between two rigid supports, (ii) idealized vehicles, and (iii) the approach to the bridge. The following assumptions are made in regard to the passage of the vehicles over the approach and bridge.

(1) The analysis starts for each load unit when its front axle reaches the beginning of the bridge approach.

(2) Prior to that time, each load unit is in its static equilibrium condition in the vertical and angular coordinates. (The bridge approach imparts an initial vibration to the load units as they enter the bridge.)

(3) When the first axle of a vehicle enters the span, the bridge is either at rest having a deflection due to its own weight or in a state of vibration (caused by the passage of an earlier vehicle).

(4) If there are more than one load unit in the system, the speeds of these units are the same and they remain the same during the passage over the approach and bridge.

2.4 Expressions of Energy.

As indicated in Fig.2-2, two generalized coordinates are used to specify the configuration of the sprung mass of each load unit. One for the vertical displacement, z_i, and another for the rotational displacement, θ_i, of the sprung mass, where i refers to the ith load unit. Thus, the total number of generalized coordinates or degrees of freedom for the bridge-vehicle system is 2h+1, where h is the number of load units.

By considering the energy in the whole system, the equations of motion may be derived in the following manner. The initial energy level of this system is taken to be correspondent to the conditions that the beam is in an unstressed horizontal position and that the springs of the load units are undeformed.

(1) Total Strain Energy in the Bridge

$$U_b = \tfrac{1}{2}EI\int_0^L(\bar{y}+\bar{c}_1 y)^2_{xx}dx$$

$$= \tfrac{1}{2}EI\int^L(\bar{y}^2_{xx} + 2\bar{c}_1\bar{y}_{xx}y_{xx} + \bar{c}_1 y^2_{xx})dx \quad .....(2a)$$

where $\bar{y}$=bridge deflection due to dead load only; and $\bar{c}_1$= 1, if the bridge is in motion, i.e., $y \neq 0$, otherwise, zero. Each subscript x indicates a differentiation with respect to x.

(2) Total Strain Energy Stored in the Load Units

$$U_v = \sum_i^r \sum_j^{s_i} \tfrac{1}{2}[(ds)_{ij}+(z_i+a_{ij}\theta_i)\bar{c}_{2i}-(\bar{y}_{ij}+y_{ij})\bar{c}_{3ij}$$

$$- w_{ij}\bar{c}_{4ij}]^2 k_{ij} \quad .....(2b)$$

in which the sum of terms in square brackets represents the total deflection of the jth spring in the ith load unit, and

a_{ij} = horizontal distance between the jth axle and the centroid of the ith load unit; it is positive, when the jth axle is in front of centroid, otherwise,negative;

$\bar{c}_{2i}$ = 1, if at least one axle of the ith load unit is on the span or the bridge approach, otherwise, zero;

$\bar{c}_{3ij}$= 1, if the jth axle of the ith load unit is on the bridge, otherwise, zero;

$\bar{c}_{4ij}$= 1, if the jth axle of the ith load unit is on the bridge approach, otherwise, zero;

ds_{ij}= initial static compression in the jth axle of the ith load unit;

k_{ij} = stiffness of the jth axle spring in the ith load unit;

r = number of load units;

s_i = number of springs in the ith load unit;

w_{ij} = w value measured at the position of the jth axle in the ith load unit;

y_{ij} = dynamic deflection of the bridge at the location of the jth axle in the ith load unit;

$\bar{y}_{ij}$ = $\bar{y}$ value measured at the position of the jth axle in the ith load unit;

z_i = vertical displacement of the ith load unit measured from its static equilibrium position, it is positive when downward;

θ_i = angular displacement of the ith load unit about its centroid axis, it is positive when clockwise.

(3) Total Potential Energy of the Bridge-Vehicle System

The change of the potential energy of the beam is given by the expression

$$- mg\int_0^L \bar{y}dx - \bar{c}_1 mg\int_0^L ydx \qquad .....(2c)$$

The change of the potential energy of the load units is given by the expression

$$\sum_i^r [\,-M_i g(\Delta_v)_i - M_i g z_i \bar{c}_{2i}\,] \qquad .....(2d)$$

where M_i = sprung mass of the ith load unit, and $(\Delta_v)_i$ = initial static deflection of the centroid of the sprung mass M_i.

Adding expressions (2a) to (2d), one obtains the following expression for the total potential energy of the systems:

$$V = U_b + U_v - mg\int_0^L \bar{y}dx - \bar{c}_1 mg\int_0^L ydx$$
$$+ \sum_i^r [\,-M_i g(\Delta_v)_i - M_i g z_i \bar{c}_{2i}\,] \qquad .....(2e)$$

(4) Kinetic Energy

The kinetic energy of the system is given by the expression

$$T = \tfrac{1}{2}\bar{c}_1\int_0^L m\dot{y}^2 dx + \bar{c}_{2i}\sum_i^r \tfrac{1}{2}M_i \dot{z}_i^{\,2} + \bar{c}_{2i}\sum_i^r \tfrac{1}{2}J_i \dot{\theta}_i^2 \qquad .....(2f)$$

The first term on the right-hand side of this equation represents the kinetic energy of the beam, the second and third terms represent the kinetic energy of the sprung masses due to vertical and angular motion, respectively. Where the superscript dots denote derivatives with respect to time, and J_i is the polar moment of inertia of the sprung mass about its centroidal axis.

(5) Energy Dissipation Function

The energy dissipation function of the system is given by the expression

$$D = \frac{1}{2}\sum_{i}^{r}\sum_{j}^{s_i} c_{ij}\left[(\dot{z}_i + a_{ij}\dot{\theta}_i)\bar{c}_{2i} - (\dot{\bar{y}}_{ij} + \dot{y}_{ij})\bar{c}_{3ij} - \dot{w}_{ij}\bar{c}_{4ij}\right]^2 \quad \text{.....(2g)}$$

where c_{ij} = viscous damping coefficient in the jth spring of the ith load unit.

On substituting eq.(2-1) into the expression for V, T, and D, one obtains

$$V = \frac{1}{4}EILf^2\left(\frac{\pi}{L}\right)^4\bar{c}_1 + \frac{1}{2}\sum_{i}^{r}\sum_{j}^{s_i}\left[(ds)_{ij} + (\dot{z}_i + a_{ij}\dot{\theta}_i)\bar{c}_{2i} - (\dot{\bar{y}}_{ij} + \dot{y}_{ij})\bar{c}_{3ij} - \dot{w}_{ij}\bar{c}_{4ij}\right]^2 k_{ij} - \sum_{i}^{r} M_i g z_i + \text{constant} \quad \text{.....(2h)}$$

The constant term reflects the choice of the initial energy level at that corresponding to a "true" zero.

$$T = \frac{1}{4}mLf^2\bar{c}_1 + \frac{1}{2}\bar{c}_{2i}\sum_{i}^{r}(M_i\dot{z}_i^2 + J_i\dot{\theta}_i^2) \quad \text{.....(2i)}$$

$$D = \frac{1}{2}\sum_{i}^{r}\sum_{j}^{s_i} (\dot{z}_i + a_{ij}\dot{\theta}_i)\bar{c}_{2i} - \left(\dot{\bar{y}}_{ij} + \dot{f}\sin\frac{\pi x_{ij}}{L} + \frac{\pi s}{L}f\cos\frac{\pi x_{ij}}{L}\right)\bar{c}_{3ij} - \dot{w}_{ij}\bar{c}_{4ij}\Big]^2 \quad \text{......(2j)}$$

where s = vehicle speed; and x_{ij} = horizontal distance between the jth axle of the ith load unit and the beginning of the bridge approach.

2.5 Equations of Motion.

The Lagrangian form of the equation of motion is shown in the following

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_n}\right) - \frac{\partial T}{\partial q_n} + \frac{\partial V}{\partial q_n} + \frac{\partial D}{\partial \dot{q}_n} = 0 \qquad \text{.....(2-2)}$$

The symbols T, V, and D represent the quantities in the preceding section, and q_n represents the nth generalized coordinate. In this analysis, the generalized coordinates are z_i, θ_i, and f.

The governing differential equations of motion of the bridge-vehicle system are obtained by substituting expressions (2h) through (2j) into Lagrange's equation for each of the generalized coordinates of the system. The resulting equations are

$$\bar{c}_{2i}\Big[M_i\ddot{z}_i + \sum_j^{s_i}((z_i+a_{ij}\theta_i)-(\bar{y}_{ij}+y_{ij})\bar{c}_{3ij}-w_{ij}\bar{c}_{4ij})k_{ij}$$
$$+ \Sigma^{s_i}((\dot{z}_i+a_{ij}\dot{\theta}_i)-(\dot{\bar{y}}_{ij}+\dot{y}_{ij})\bar{c}_{3ij}-\dot{w}_{ij}\bar{c}_{4ij})c_{ij}\Big] = 0 \qquad \text{...(2-3)}$$

$$\bar{c}_{2i}\Big[\, J_i\ddot{\theta}_i + \sum_j^{s_i}((ds)_{ij}+(z_i+a_{ij}\theta_i)-(\bar{y}_{ij}+y_{ij})\bar{c}_{3ij}$$
$$-w_{ij}\bar{c}_{4ij})k_{ij}a_{ij} + \sum_j^{s_i}((\dot{z}_i+a_{ij}\dot{\theta}_i)-(\dot{\bar{y}}_{ij}+\dot{f}\sin\frac{\pi x_{ij}}{L}$$
$$+ \frac{\pi s}{L}f\cos\frac{\pi x_{ij}}{L})\bar{c}_{3ij}-\dot{w}_{ij}\bar{c}_{4ij})c_{ij}a_{ij}\,\Big] = 0 \qquad .....(2\text{-}4)$$

$$\bar{c}_1\Big[\tfrac{1}{2}mL\ddot{f} + \tfrac{1}{2}EIL(\tfrac{\pi}{L})^4 f - \sum_i^r \sum_j^{s_i}((ds)_{ij}+(z_i+a_{ij}\theta_i)-$$
$$(y_{ij}+y_{ij}))c_{3ij}k_{ij}\sin\frac{\pi x_{ij}}{L} - \sum_i^r \sum_j^{s_i}((\dot{z}_i+a_{ij}\dot{\theta}_i)-$$
$$(\dot{\bar{y}}_{ij}+\dot{f}\sin\frac{\pi x_{ij}}{L} + \frac{\pi s}{L}f\cos\frac{\pi x_{ij}}{L})\bar{c}_{3ij}c_{ij}\sin\frac{\pi x_{ij}}{L}\Big] = 0$$
$$.....(2\text{-}5)$$

2.6 Dynamic Moments and Stresses.

The dynamic bending moments are found by treating the instantaneous reactions between the axles and the beam as statically applied forces (D'Alembert's principle). Fig.2-3 shows the relations of those forces. By taking moments about the right-hand support, one obtains the reaction at the left-hand support.

$$R_a = \frac{1}{L}\Big[\sum_i^r \sum_j^{s_i} p_{ij}(L+a-x_{ij})\bar{c}_{3ij} + \int_0^L -m\ddot{y}(L-x)dx\,\Big]$$
$$= \frac{1}{L}\sum\sum\,(L+a-x_{ij})\bar{c}_{3ij}\big[((ds)_{ij}+(z_i+a_{ij}\theta_i)-$$
$$(\bar{y}_{ij}+y_{ij}))k_{ij}+((\dot{z}_i+a_{ij}\dot{\theta}_i)-(\dot{\bar{y}}_{ij}+\dot{y}_{ij}))c_{ij}\big]$$
$$-\frac{L}{\pi}m\ddot{f} \qquad .....(2\text{-}6)$$

where p_{ij} is the sum of the spring and damping forces corresponding to the jth spring and damping device of the ith load unit; and "a" is the length of the bridge approach. And then, the bending moment of any section having a distance $\bar{x}$ from the left support may be expressed as follows,

$$M_{\bar{x}} = R_a\bar{x} - \sum_{\substack{\text{for all} \\ x_{ij}<\bar{x}+a}} \sum \bar{c}_{3ij}(\bar{x}+a-x_{ij})[((ds)_{ij}+(z_i+a_{ij}\theta_i)$$

$$-(\bar{y}_{ij}+y_{ij}))k_{ij} + ((\dot{z}_i+a_{ij}\dot{\theta}_i)-(\dot{\bar{y}}_{ij}+\dot{y}_{ij}))c_{ij}]$$

$$- \int_0^{\bar{x}} -m\ddot{y}(\bar{x}-x)dx$$

$$= -mf\left(\frac{L}{\pi}\right)^2\sin\frac{\pi\bar{x}}{L} + \frac{\bar{x}}{L}\sum_i^r\sum_j^{s_i}(L+a-x_{ij})\bar{c}_{3ij}[((ds)_{ij}+$$

$$(z_i+a_{ij}\theta_i)-(\bar{y}_{ij}+y_{ij}))k_{ij} + ((\dot{z}_i+a_{ij}\dot{\theta}_i)-$$

$$(\dot{\bar{y}}_{ij}+\dot{y}_{ij}))c_{ij} - \sum_{\substack{\text{for all} \\ x_{ij}<\bar{x}+a}} \sum \bar{c}_{3ij}(\bar{x}+a-x_{ij})((ds)_{ij}+$$

$$(z_i+a_{ij}\theta_i)-(\bar{y}_{ij}+y_{ij}))k_{ij} + ((\dot{z}_i+a_{ij}\dot{\theta}_i)-(\dot{\bar{y}}_{ij}$$

$$+\dot{y}_{ij}))c_{ij}] \qquad \text{.....(2-7)}$$

The corresponding fiber stress at section $\bar{x}$ is given by

$$\sigma = \frac{M_{\bar{x}}}{S} \qquad \text{.....(2-8)}$$

where S is the section modulus.

2.7 Minimum Dynamic Stresses.

To study the fatigue life of a bridge, the minimum stress as well as the maximum stress should be considered. The former stress usually occurs after the passage of a vehicle and the bridge is in a state of free vibration.

following the same procedure as the preceding section, one obtains

$$R_a = \frac{1}{L}\int_0^L -m\ddot{y}(L-x)dx$$
$$= -\frac{L}{\pi}m\ddot{f} \qquad .....(2\text{-}9)$$
$$M_{\bar{x}} = R_a\bar{x} - \int_0^{\bar{x}} -m\ddot{y}(\bar{x}-x)dx$$
$$=-\frac{L}{\pi}m\ddot{f}\bar{x} + \frac{L}{\pi}m\ddot{f}(-\frac{L}{\pi}\sin\frac{\pi\bar{x}}{L} +\bar{x})$$
$$=- m\ddot{f}(\frac{L}{\pi})^2\sin\frac{\pi\bar{x}}{L} \qquad .....(2\text{-}10)$$

The corresponding normal stress is calculated by eq.(2-8)

2.8 Numerical Solution of the Equations of Motion.

In the preceding sections of this chapter the governing differential equations of the bridge-vehicle system have been derived. This section is concerned with the numerical solution of those equations of motion.

2.8.1 Modified $\beta = 0$ Method --- Governing eqs.(2-3), (2-4), and (2-5) of the bridge-vehicle system are solved numerically by a modified β-method of integration, with $\beta = 0$. As presented in Ref.(14), $\beta=0$ method is a step-by-step iteration method of integration. The integration formulae are as follows:

$$\dot{X}_{t+\Delta t} = \dot{X}_t + \tfrac{1}{2}\Delta t(\ddot{X}_t + \ddot{X}_{t+\Delta t}) \qquad .....(2\text{-}11)$$

$$X_{t+\Delta t} = X_t + \Delta t(\dot{X}_t) + \tfrac{1}{2}(\Delta t)^2\ddot{X}_t \qquad .....(2\text{-}12)$$

where Δt is the time increment.

For problems of structural dynamics without damping, the use of these integration formulae will circumvent the necessity of iteration. Since vehicle damping is included, iteration would still be necessary. However, an assumption is made here to avoid the time consuming iteration procedure. It is assumed that the viscous damping force in vehicle axle at time $t+\Delta t$ is represented by that at time t. This assumption has been found acceptable in other studies(10).

The initial conditions of the bridge-vehicle system are specified in section 2.3. To describe the numerical solution, it is only necessary to consider the procedure of computing the values of the variables at $t+\Delta t$ given their values at t. The following steps are used to evaluate the displacements, speeds, and accelerations of generalized coordinates z_i, θ_i, and f at the end of each time increment.

(1) Compute the position of each axle on the bridge approach or bridge span at time $t+\Delta t$ from the known speed;

(2) By applications of eq.(2-12), calculate values of $f_{t+\Delta t}$, $z_{i,t+\Delta t}$, and $\theta_{i,t+\Delta t}$, respectively;

(3) Substitute $z_{i,t+\Delta t}$, $\dot{z}_{i,t}$, $\theta_{i,t+\Delta t}$, $\dot{\theta}_{i,t}$, $f_{t+\Delta t}$, and $\dot{f}_t$ into governing differential equations, and solve for $\ddot{z}_{i,t+\Delta t}$, $\ddot{\theta}_{i,t+\Delta t}$, and $\ddot{f}_{t+\Delta t}$;

(4) By application of eq.(2-11), calculate $\dot{z}_{i,t+\Delta t}$, $\dot{\theta}_{i,t+\Delta t}$, and $\dot{f}_{t+\Delta t}$;

(5) By applications of eqs.(2-7),(2-8), and (2-10), one may calculate the dynamic bending moments and the corresponding bending stresses at the end of the time increment for any section.

2.8.2 Choice of Time Increment in Numerical Integration --- For the $\beta = 0$ method, Ref.(14) points out that the time increment must be no greater than 0.318T (in order to ensure stability), where T is the smallest natural period of the system. However, one may have to use still smaller values of Δt from the stand point of accuracy. For example, for the numerical problems considered in chapter V, the value of Δt was determined after examining solutions of the systems with several values of $\bar{n}$ which is the number of steps needed by an axle to cross the bridge, i.e.,

$$\bar{n} = \frac{1}{t}\left(\frac{L}{s}\right) \qquad .....(2\text{-}13)$$

The data are presented in Table 2-1. It is seen that $\bar{n} = 80$ would provide solutions with reasonable accuracy.

2.8.3 Computer Program DYNAMIC --- A computer program has been prepared for the analysis and numerical procedure described. It can compute the dynamic stress at any point on the bridge. In Figs.(2-4),(2-5), and (2-6) are presented typical graphs of the dynamic bending moment at mid-span as a function of time, the properties of the bridge and vehicles involved are described in detail in chapter V.

It may be mentioned that the maximum and minimum stresses needed for fatigue studies are essentially picked out from graphs of this kind.

The total computer time to calculate the bending stresses at three sections for the passage of 2365 vehicles is about 5100 seconds on the MSU-CDC 6500 computer.

2.9 Static Stresses.

The preceding sections of this chapter have considered the dynamic stresses in a bridge. For purpose of comparison, this study also considers the stresses in the bridge under the assumption that the vehicle loads are statically applied. The calculations of static stresses are of course much simpler.

A computer program has been written using the usual influence line method for the maximum stress. It might be noted that for this case, its minimum stress is simply the dead load stress (such is not the case if the bridge is statically indeterminate).

The computer time to calculate the maximum static bending stresses at three sections for 645 different vehicle loading conditions is about 5.0 seconds.

CHAPTER III

FATIGUE STRENGTH

An analysis of the dynamic stress in a highway bridge under the passage of a vehicle is given in the preceding chapter. Two complete computer programs are also written so that both dynamic and static stresses can be determined for a given deterministic bridge-vehicle system.

As mentioned in chapter I, fatigue damage of highway bridges is known to exist. But it is different to state in quantitative terms how much damage is done by a vehicle crossing. The fatigue life, or how many applications of loading or vehicle passages that a bridge can take without distress (fatigue crack), depends on a large number of variables, such as materials, distributions of stresses -- minimum stress, maximum stress, and stress range, sequence of the applications of the stresses, quality of construction, etc.

A major unknown factor of the problem is the fatigue strength of the bridge. For the purposes of the present study, the following assumptions are made.

(1) Fatigue failure (cracks) may occur only at certain "critical" sections.

(2) Fatigue failure results from a state of uniaxial stress.

(3) Certain fatigue strength models are applicable. Each model gives N, the number of cycles of "stress vector" that the material can sustain just prior to failure. The stress vector consists of one, two, or all three of the following: the minimum stress, the maximum stress, and the stress range.

(4) For a given passage of a vehicle resulting in a given stress vector at a critical section the fatigue damage is taken to be 1/N.

3.1 Critical Sections.

For simply supported beams with cover plate, Ref.(5) reported that cracks causing failure were initiated in the beam flange at the toe of the longitudinal or transverse fillet weld connecting the cover plate to the flange. At transversely welded cover-plate ends, cracks were initiated near the center of the transverse fillet welds. For cover-plate without transverse end welds, cracks were initiated at the ends of the cover plate.

In most bridges the cover plates are welded over approximately the middle half of span. Furthermore, although the middle span is usually considered the critical section for static stress, the maximum dynamic stress often occurs at a section some distance from it. Therefore, in this study, three critical sections are chosen to estimate the fatigue life. These sections correspond to the mid-span and the two quarter points of the beam as shown in Fig.2-1.

3.2 Fatigue Models.

Seven fatigue models relating the number of cycles N and the stress vector are listed as follows:

Model A $\text{Log } N = 6.9854-0.0876S_r-0.0051S_{min}$

Model B $\text{Log } N = 6.9003-0.0836S_r$

Model C $\text{Log } N = 9.1480-3.0086S_r-0.0050S_{min}$

Model D $\text{Log } N = 8.9754-2.8768\text{Log } S_r$

Model E $\text{Log } N = 9.0310-2.8416\text{Log } S_r-0.0050S_{max}$

Model F $\text{Log } N = 10.7310-4.1900\text{Log } S_r$

(for $11.4 \text{ ksi} < S_r < 3.8 \text{ ksi}$)

$\text{Log } N = 9.1980-2.7400\text{Log } S_r$

(for $35.0 \text{ ksi} < S_r < 11.4 \text{ ksi}$)

Model G $\text{Log } N = 7.1360-0.0742S_r-0.0102S_{min}$

in which the symbols S_{max}, S_{min}, and S_r denote the three uniaxial stress variables --- the maximum stress, minimum stress, and stress range. Their physical meanings are further illustrated in the stress history curves shown in Figs.3-1(a) and 3-1(b). More specifically, they are defined, for a given critical section, as follows:

For the static case:

S_{mins} = minimum static stress, i.e., the stress caused by the dead load of the bridge itself;

S_{maxs} = maximum static stress, i.e., the maximum stress caused by the weight of the vehicle and the dead load of bridge;

S_{rs} = $S_{maxs} - S_{mins}$.

For the dynamic case:

S_{mind} = minimum dynamic stress,i.e., the lowest value of the stress measured with reference to S_{mins}, it usually occurs, after the vehicle has left the span;

S_{maxd} = maximum dynamic stress, i.e., the sum of S_{mins} and the maximum dynamic stress due to the live load alone;

S_{rd} = $S_{maxd} - S_{mind}$.

The seven fatigue models may be grouped into two types according to the relationships between N and the stress vector.

(1) Exponential models -- models D and F;

(2) Semi-logarithmic models -- models A,B,C,E, and G.

Models A,B,C,D,and E are taken from Fisher's report (5). They were essentially derived from regression analyses of experimental data. The different models were proposed depending on the choice of stress variables. Among these Fisher recommended the use of Model D.

Model F was suggested by Cudney (3). For this model, the stress vector consists of only stress range. It was developed from certain experimental data obtained by Munse and Stallmeyer (13) who studied the effects of details such as splices, stiffeners, cover plates and attachments on the fatigue behavior of welded flexural members. Two assumptions were made to formulate the model:

(1) The S_r value at $200*10^6$ cycles is equal to one-third the stress range value at $2*10^6$ cycles. The former stress is taken as the "fatigue limit". That is , stresses below this level will not contribute to fatigue damage. This was also assumed in House Document 354 (12).

(2) The stress range and cycles to failure have a linear Log-Log relation.

Fisher (6) derived model G from the results of flexural fatigue tests of ten small welded beams, reported by Hall and Stallmeyer (8). Coefficients of model G were also estimated by a regression analysis.

In applying any of the seven models to this study, the following should be kept in mind. Firstly, the models were derived based on a constant stress vector while during the service of a bridge the stress vector varies. Secondly, no sufficient information is available regarding fatigue limit. Following the assumption of House Document 354 (12) as mentioned earlier, the fatigue limit (in stress range) is 2.60,2.40, 2.94, 2.84, 3.05, and 3.75 ksi, corresponding to models A,B,C,D,E, and G, respectively. The average of these is 2.93. A value of 3 ksi is used in this study for all models expecting model F, for which a fatigue limit has been specified as part of the model. It might be mentioned that an upper bound of the fatigue limit (in stress range) for cover-plated beam is 6 ksi.

3.3 Cumulative Damage Hypothesis.

As mentioned before, a fatigue model gives the number of stress cycles (fatigue life) for a fixed stress vector. However, a bridge is subjected to stress vectors that generally vary with the passages of vehicles. To account for this fact, the Miner's hypothesis of cumulative damage has found wide usage.

Miner's cumulative damage hypothesis simply states that the fraction of fatigue life, d_i, consumed by the number of cycles, n_i, of a given stress vector is equal to the ratio of n_i to N_i, which is the number of cycles that would produce failure, if the material is subjected only to that stress vector. That is

$$d_i = n_i/N_i \qquad \text{.....(3-1)}$$

When random cycles of stress vectors are applied to a structure or structural component, it is postulated that failure will occur when the sum of the fatigue damage accumulated reaches 1.0. In other words, failure occurs when

$$\sum_i d_i = \sum_i \frac{n_i}{N_i} = 1 \qquad .....(3\text{-}2)$$

If the fatigue life of a bridge is k years, then

$$\sum_j^k D_j = 1 \qquad .....(3\text{-}3)$$

where D_j is the fatigue damage occurred in the jth year.

Note that this hypothesis implies that the sequence of stress applications has no effect on fatigue life.

CHAPTER IV

COMPUTER SIMULATION

So far a method to estimate the fatigue damage caused by a given vehicle crossing a simple span highway bridge has been treated. But, in a real bridge-vehicle system, there exist many random factors, such as vehicle type, speed, weight, interarrival time, etc.. It is very difficult to formulate a mathematical model to represent this complex system and to solve it analytically. In a case like this, a practical approach to study the problem is by computer simulation. A simulation run in the computer describes the operation of the overall system in terms of individual events of the components of the system. In essence, it is analogous to an experimental observation of a real physical system.

The simulation approach used in this study is outlined as follows:

(1) For each of the random variables considered a relative frequency distribution (or a probability density function) is assumed, based on field data, if such are available.

(2) A random number is generated. This random

number can be used as an observation of the random variable, that is, corresponding to this random number a specific value for the random variable is obtained. For example, a certain random number may specify a vehicle speed of 50 MPH.

(3) After this is done for all the random variables, one has in effect a deterministic system which can be analyzed and the corresponding fatigue damage determined, as explained in chapter II and III.

(4) The process is repeated as many times as necessary. Enough observations should be made to make the data statistically significant. In general, the greater is the number of observations made the better are the data. Of course, the cost of computer time is a restraining factor on the number of observations.

By such simulation runs, the fatigue damage of the bridge for one year is computed and the fatigue life is extrapolated from that damage in one year. A computer program SIMU1 has been written to execute the simulation steps. These steps are discussed in detail as follows.

4.1 Generation of Random Numbers and Random Observations.

There are a number of methods to generate random numbers. Herein the MSU Computer Library Subprogram RANF(a) has been incorporated in SIMU1 to generate random numbers. RANF(a) generates positive random decimal numbers uniformly distributed between 0 and 1. It is based on the standard multiplicative congruential method (9), i.e., the (i+1)th random number, X_{i+1}, is obtained from the ith random number, X_i, as follows:

$$X_{i+1} = \lambda X_i (\text{modulo } m) \qquad .....(4-1)$$

where $\lambda = 5^{15}$ and $m = 2^{47}$.

The period of this generator is m. In each separate computer runs, RANF(a) generate the same random numbers in values and sequence provided the first random number used remains unchanged. Therefore, it has the property of a large fixed random number table. Sometimes these numbers are called pseudo-random numbers.

To obtain an observation of a random variable, such as vehicle speed, from a chosen random number, the following procedure is used:

(1) From the assumed relative frequency distribution for a given random variable X, construct the cumulative distribution function $F(x) = P(X \leqslant x)$.

(2) Generate a random number r (by calling sub-program RANF(a)).

(3) Set the cumulative distribution function $F(x) = r$ and solve for x. This value x is the desired random observation for the random variable.

This procedure is illustrated in Figs.4-1(a) and 4-1(b).

4.2 Random Variables.

In this simulation study, the following random variables are included:

(1) Annual volume of heavy vehicles;

(2) Interarrival time;

(3) Vehicle type;

(4) Vehicle speed;

(5) Vehicle's axle loading level.

The cumulative distribution function of these depend on many factors, such as the type of highway, location, time of the day, etc.. Specific choice of such functions are illustrated in a numerical example given in chapter V. Note that the initial condition (vertical motion) of the bridge has not been included as random variables. The possibility of vehicles crossing as a train, which would involve an non-zero initial condition, is considered in the following section.

4.3 Simulation Process.

This computer simulation process is as follows;

(1) The simulation starts out with the crossing of one vehicle with all the associated characteristics determined by observations of the random variables.

(2) Make an observation of the interarrival time, say, it is equal to t. Let T be the period of vibration of the bridge, and t_1 is the crossing time of the preceding

vehicle (which is known at this time). A assumption is made that

(i) if $t > nT+t_1$, where n is some prescribed integer, then the bridge is assumed to be at rest when the current vehicle enters it.

(ii) if $t < nT+t_1$, the vibration caused by the previous vehicle is taken into account. In this case, the deterministic system involving two vehicles is analyzed.

(3) After a train of two vehicles for which a deterministic solution is obtained, the bridge's initial conditions for the third vehicle is always taken to be zero.

(4) For each passage the fatigue damage to the bridge is calculated and accumulated. The total number of passages is equal to the sample size, which is discussed in the next section.

(5) Calculate the first year's fatigue damage by the following equation.

$$D_1 = D_{ss}\left(\frac{V_1}{S_s}\right) \qquad \text{.....(4-2)}$$

where D_1 = estimated fatigue damage at the end of the first year;

D_{ss} = cumulative fatigue damage based on the sample size;

V_1 = the first year's annual vehicle volume;

S_s = sample size.

(6) Estimate the fatigue life:

(i) if $D_1 \geq 1$, the estimated fatigue life is equal to or less than one year.

(ii) if $D_1 < 1$, make an observation of the 2nd year's annual vehicle volume, the fatigue damage at the 2nd year is

$$D_2 = D_1(\frac{V_2}{V_1}) \qquad .....(4\text{-}3)$$

The general form for the ith year's fatigue damage is

$$D_i = D_1(\frac{V_i}{V_1}) \qquad .....(4\text{-}4)$$

where D_i = the fatigue damage caused at the ith year, and V_i = the observation of the ith year's annual vehicle volume. Simulation experiment stops when

$$\sum_i^k D_i \geq 1 \qquad .....(4\text{-}5)$$

but

$$\sum_i^{k-1} D_i < 1 \qquad .....(4\text{-}6)$$

Eqs.(4-5) and (4-6) imply that the estimated fatigue life is k years.

4.4 Choice of Sample Size.

As mentioned previously, it is important to determine the sample size or the number of simulated runs. Let E denote the simulated fatigue damage experiment, and d_i be the fatigue damage caused by the passage of the ith vehicle. For all of those d_i values, i= 1,2,3, ...,N, one may group them into few levels, say $\bar{d}_1, \bar{d}_2, \bar{d}_3, \ldots, \bar{d}_n$. Consider N independent outcomes of $\bar{E}$. Let n_i be the number of times that fatigue damage levels d_i occurs among the N outcomes. Note that n_i is a binomially distributed random variable, then the expected value and variance of n_i are

$$E(n_i) = Np \qquad \ldots..(4\text{-}7)$$

$$Var(n_i) = Np(1 - p) \qquad \ldots..(4\text{-}8)$$

where p is the theoretical probability of the event $\bar{d}_i$. Now the relative frequency of $\bar{d}_i$ is $f_{\bar{d}_i} = n_i/N$. hence the expected value and the variance of $f_{\bar{d}_i}$ can be calculated as following

$$E(f_{\bar{d}_i}) = E(n_i/N) = E(n_i)/N = p \qquad \ldots..(4\text{-}9)$$

$$Var(f_{\bar{d}_i}) = Var(n_i/N) = Var(n_i)/N^2$$

$$= p(1 - p)/N \qquad \ldots..(4\text{-}10)$$

Applying Chebyshev's inequality to the random variable $f_{\bar{d}_i}$, one obtains

$$\text{Prob}\left[|f_{\bar{d}_i} - p| < k\sqrt{p(1-p)/N}\right] \geq 1 - \left(\frac{1}{k}\right)^2 \qquad \ldots..(4\text{-}11)$$

where k is any positive number. Letting $\epsilon = k(p(1-p)/N)^{\frac{1}{2}}$ and $\delta = 1 - (\frac{1}{k})^2$.

whenever

$$N = \frac{p(1-p)}{\epsilon^2(1-\delta)} \qquad .....(4\text{-}13)$$

The inequality (4-12) says that the probability of the event that "the relative frequency of $\bar{d}_i$ differs from the true probability p by less than ϵ " is at least equal to δ . By selecting values of ϵ and δ according to the bounds desired, a minimum value for the sample size N may be computed from eq.(4-13), provided p is known. Because one does not know the value of p, a conservative choice is to set p = ½, thus maximizing N. Therefore, eq.(4-13) is replaced by

$$N > \frac{1}{4\epsilon^2(1-\delta)} \qquad .....(4\text{-}14)$$

where N can be treated as the sample size for this simulated experiment.

CHAPTER V

NUMERICAL RESULTS

A simulation method for the study of the fatigue life of highway bridges has been described in the preceding chapter. In this chapter numerical results are presented. These results are obtained by use of programs written in Fortran IV for use on the Michigan State University CDC 6500 System. The results pertain to an existing bridge in Michigan subjected to heavy vehicular traffic that is reasonably representative of that of the state. Additional numerical results have also been obtained to consider the effects of small variations of certain parameters that enter in the modelling of the bridge-vehicle system. Such parameters include the annual vehicle volume, vehicle axle load level, vehicle speed, the geometry of the bridge approach, and the bending strength of the bridge.

5.1 Bridge Data.

The bridge considered is a composite simple span rolled I-beam bridge with welded tapered end cover plate. It has span length 78.5 ft., angle of skew 14°, and is located on US 23 SB over Huron River and NYC RR.

The idealized section and its properties are shown in Fig.5-1.

The bridge approach is assumed to be a half sine curve with a length of 50 ft. and an amplitude of 2 inches(dip). As mentioned in chapter II, the approach would cause the vehicle to vibrate before it enters the span.

5.2 Traffic Data.

Certain parts of the necessary data for the traffic characteristic needed for this simulation study are assumed to be probabilistic,and others are taken to be constants for simplicity. The latter are related essentially to the physical characteristics of the vehicles.

5.2.1 Annual Vehicle Volume --- To estimate the annual vehicle volume for the future is difficult.Generally speaking, it depends on the location of bridge,national economic growth rate,development of other transportation systems, etc.. For the years from 1962 to 1969, the annual vehicle volumes for a certain bridge have been estimated (3) to be 444940,488099,552040,615525,635222,688580,711992, and 732640, respectively. The data are used in two ways to model future annual vehicle volumes:

(1) Assume that the annual vehicle volume is a constant,equal to 444940.

(2) Use the annual vehicle volume from 1962 to 1969 as given. After that, the volume is taken to be a random

variable. It is assumed to have a uniform distribution between two reasonably chosen limits. The upper limit should be within a maximum acceptable number consistent with the class of highway and safety requirement. The choice of lower limit is even more a matter of judgement. In any case, for this study the limits used are 1,200,000 and 732,640, respectively.

Note that, as defined above, the constant annual vehicle volume case represents a lower density traffic than the random one.

5.2.2 Interarrival Time --- For the simulation study, it is necessary to specify the times of vehicle arrivals. The simple Poisson process N(t) is used. That is, the probability that n heavy vehicles arrive within a time interval (0,t) is given by

$$P[\,N(t) = n\,] = \frac{e^{-\lambda t}(\lambda t)^n}{n!} \qquad .....(5\text{-}1)$$

where λ = average number of vehicle arrivals per unit time, which is also equal to the annual vehicle volume divided by the number of time units in a year.

Eq.5-1 implies that the interarrival time, T, has an exponential distribution,

$$f_T(t) = \lambda e^{-\lambda t} \qquad \text{for all } t > 0 \qquad .....(5\text{-}2)$$

The cumulative distribution function of T is

$$F_T(t) = 1 - e^{-\lambda t} \quad \text{for all } t > 0 \qquad .....(5\text{-}3)$$

The mean and variance of T is $1/\lambda$ and $1/\lambda^2$, respectively.

Applying the procedure outlined in section 4.1, one may find that the relation between a random observation, t, and random number, RN, is given by

$$t = \frac{\ln(RN)}{-\lambda} \qquad .....(5\text{-}4)$$

5.2.3 <u>Vehicle Types</u> --- Forty three vehicle types varying from a 2-axle truck to a 12-axle tractor-semi-trailer-full trailer type are considered in this study. Fig.5-2 shows the figures of common truck types. In Ref.(2) are reported data of the distribution of vehicle types among a total of 2000 vehicles. The relative frequency distribution is listed in column three of Table 5-1. (It should be noted that in Ref.(2), only 21 "groups" were considered; in each group one or more of the forty three types are lumped together in the group. For a group that has more than one type, the assumption is made that the total number of vehicles in the group is equally divided among the types.)

5.2.4 <u>Maximum Axle Load and Axle Load Level</u> --- The maximum loads for the axles of the vehicles are listed in Table 5-2. They have been computed from empirical rules given in Ref.(20) as the maximum allowable loads depending on the axle type and spacing.

In Table 5-2 are also show vertical bars between certain axles. The axles between a given pair of such bars are modelled by a load unit in the analysis described in chapter II.

For each vehicle type, five levels of static axle loading are considered: they are 50%,70%,80%,90%, and 100% of the maximum axle loads. The cases of 100% and 50% are assumed to correspond to a fully loaded and empty vehicle, respectively. A RFD based on certain field data (18) of these levels is given in Table 5-3.

5.2.5 Speed Distribution --- Table 5-4 shows the RFD of heavy vehicle speed used herein. It is based on data from Ref.(15).

5.2.6 Axle Spacings --- Field data show that axle spacings of vehicles of a given type are not always the same. However, for simplicity the axle spacings for each vehicle type is considered to be fixed. They are listed in Table 5-5.

5.2.7 Polar Moment of Inertia --- The sprung mass of each load unit is assumed to be uniformly distributed. Hence the center of gravity coincides with the geometric center. And the polar moment of inertia can be calculated from the expression

$$J_i = M_i L_i^2/12 \qquad .....(5\text{-}5)$$

where J_i = polar moment of inertia of the ith load unit;

M_i = sprung mass of the ith load unit; and

L_i = length of the ith load unit.

5.2.8 Spring Constants and Damping Coefficients --- Measurements made of heavy vehicles (23) indicated that vehicle axles have natural frequency, f, varying from 1.6 to 4.1 cps. For simplicity, an average value of f = 2.8 cps has been used to calculate the spring stiffness k as follows:

$$k = 4\pi^2 f^2 M \qquad .....(5\text{-}6)$$

where M is the mass of the wheel load. In each axle, damping is assumed to be viscous and "critical". The coefficient of damping is therefore equal to

$$c = 4\pi f M \qquad .....(5\text{-}7)$$

5.2.9 Sample Size --- For this study a sample size of N = 10,000 vehicles has been used. Following the discussions in section 4.4, this corresponds to a value of ϵ = 0.900 and δ = 0.015.

5.3 Relative Frequency Distribution from Simulation.

Using a sample of 10,000, the distributions of vehicle type, speed, and axle load level from simulation are listed in the appropriate columns in Tables 5-1, 5-3, and 5-4 along with the postulated distributions. The agreement is seen to be excellent, which indicates that the sample size is sufficiently large.

Furthermore, the mean, variance, and standard deviation of the interarrival time are also calculated and shown in Table 5-6. These again are in excellent agreement with the theoretical values for the Poisson process.

5.4 Stress Ranges.

Fatigue models, as listed in section 3.2, indicate that stress range is a dominant variable in considering fatigue damage. Hence, the RFD of both the dynamic and static stress ranges at the three critical sections are tabulated in Tables 5-7(a) and 5-7(b) respectively. An examination of Table 5-7(a) shows the following:

(1) The mid-span has the largest stress ranges, which vary from 1 ksi to 11 ksi. Stress ranges at the quarter span and the three-quarter span vary from less than 1ksi to 8 ksi.

In spite of the difference, the situation at the center may not be as serious as at the other sections, This is because of the consideration that the quarter span and the three-quarter span are presumed to coincide with the ends of the cover plate.

(2) The RFD of the stress ranges at the quarter span and three-quarter span are roughly symmetrical, but the latter has a larger density for those stress ranges that exceed the fatigue limit. One might thus conclude that the three-quarter span is the most critical section so far as fatigue life is considered.

(3) At this critical section, approximately 20% of the stress ranges are greater than the fatigue limit of 3.0 ksi for models A,B,C,D,E, and G. From the probabilistic point of view, this means that only one of every five vehicles will cause fatigue damage. For model F, only four of every 100 vehicles will cause fatigue damage, this is due to the high fatigue limit 3.8 ksi for this particular model.

Table 5-7(b) is similar to Table 5-7(a). But two differences are worth noting. Firstly, the static stress ranges are lower than the dynamic ones. Secondly, the quarter span has a larger amount of stress ranges that are beyond the fatigue limit. This would imply that for the static approach the quarter span is more critical.

5.5 Fatigue Life.

For this numerical example, the fatigue lives at the quarter span, mid-span, and three-quarter span are computed in four ways. They are combinations from the following two factors: (i) dynamic or static stress; and (ii) constant or random annual vehicle volume.

Table 5-8 lists the values of the fatigue life corresponding to the random vehicle volume as explained in section 5.2.1 for four simulation runs. An inspection of the table indicates that the values for the different simulation run do not differ from one another appreciably.

This means that, for the purposes of this study, the size of sampling of the postulated vehicle volume distribution is sufficiently large. It should be remembered that the range of the vehicle volume, being from 732,640 to 1,200,000, is not very large.

5.5.1 Dynamic Stress - Random Vehicle Volume --- Table 5-9(a) shows that the mid-span has the lowest fatigue life for all seven fatigue models. And the fatigue life at the three-quarter span is less than that at the quarter span. These results are compatible with the observations made in the preceding sections.

For purposes of discussion, consider the most critical section —— the three-quarter span —— one will find that the fatigue life varies from 12 years for model B to 570 years for model F. In general, the values for the seven models can be grouped into three categories. They are

(1) Semi-Log Models —— models A,B,and G yield values of the same order of magnitude with an average of 14 years.

(2) Log-Log Models —— models C,D,and E yield higher values, with an average of 49 years.

(3) Log-Log Model —— model F gives the highest value, 570 years.

5.5.2 Dynamic Stress - Constant Vehicle Volume.--- Estimated fatigue lives for this case are listed in Table 5-9(b). The general pattern of variation of the fatigues in this table is similar to that of Table 5-9(a). But overall it has higher values of fatigue life. For example, the value for model D is twice as much as for the case considered previously. The differences between these two cases are expected,since the random vehicle volume corresponds to a denser traffic (see section 5.2.1).

5.5.3 Static Stress.--- Fatigue lives estimated by the static stress approach for both types of vehicle volumes are listed in Tables 5-9(c) and 5-9(d). They show that the static stress approach produces higher fatigue lives than the dynamic stress approach. One also notes an interesting difference in that while in the dynamic case the fatigue life for the three-quarter span is more critical(smaller) than that for the quarter span, the opposite is true for the static case. This, of course, is consistent with the observations made in section 5.4 on the stress ranges for the two cases.

It may be pointed out that for the four combinations, the case of dynamic stress with random vehicle volume would seem most realistic and should be given more weight in the estimation of fatigue life.

5.6 <u>Effect of RFD of Axle Loading Level.</u>

The preceding results are based on one RFD of axle loading level. In this section the influence of changes in RFD of axle loading level will be considered. As it is done in the following sections on the influences of small variations of parameters, three sets of data will be considered. The first set is the same as used in obtaining the preceding data. The others correspond to variations.

The second and third sets of the RFD of axle loading level are obtained by increasing the relative frequency of the largest axle loading level by 5% and 10%, respectively, with a corresponding decrease of the lightest axle loading.

The results for these three cases are listed in Table 5-10. For the dynamic stress approach, it is seen that at the critical section of the three-quarter span, the variations of fatigue life is within a negligibly small percentage. For the static stress approach, somewhat larger differences are noted at its critical section, the quarter span.

5.7 <u>Effect of Vehicle Speed.</u>

The second and third sets of the RFD of this parameter are formed as follows:

(1) If the relative frequency of speed V_i MPH is

f_i for the first set of RFD, a relative frequency equal to f_i is assigned to (V_i+5) MPH and (V_i+10) MPH to the second and third sets, respectively.

(2) When the speed is greater than 75 MPH, it is treated as 75 MPH. Therefore, the relative frequency for 75 MPH is larger for the second and third set than the first set.

The results of the estimated fatigue life are shown in Table 5-11. It is seen that the changes in RFD of vehicle speed have little influence on the fatigue life. In passing, it may be of some interest to note the effects of vehicle speed on stress range. Some representative results are shown in Figs.5-3(a) and 5-3(b) for vehicle types 2S1 and 3S1-2. It is noted that these curves are oscillatory in nature, and that both the amplitude and period increase with increasing value of the speed parameter. Higher speeds do not necessarily cause higher stress ranges.

5.8 Effect of Bridge Approach.

For a given bridge, the shape and size of its approach are not constant, they may change with weather, soil conditions, etc.. In the study based on dynamic stress, the bridge approach controls the rotational and vertical vibrations of the vehicle as it enters the span. Assume that the approach is a half sine curve with length "a" and amplitude "b" (dip). Recall that for the first set a_1 = 600" and b_1 = 2". The second and third sets of a and b values considered in this section are:

for the 2nd. set : a_2 =600" and b_2 = 4";

and the 3rd. set : a_3 =300" and b_3 = 1".

The results of the study pertaining to the effect of bridge approach based on all vehicle types and speeds are presented below, where the values of T_i/T_j represent the maximum dynamic stress range at the critical section, three-quarter span, under the influence of the approach with dimensions a_i and b_i to that of bridge approach with dimensions a_j and b_j,

$$\frac{T_2}{T_1} : 1.00 - 1.12$$

$$\frac{T_3}{T_1} : 0.98 - 1.02$$

It is seen that for small changes in the geometry of the bridge approach, the values of dynamic stress ranges do not change a great deal. The effect on fatigue life would thus seem to be not serious.

5.9 <u>Effect of Section Modulus.</u>

Because the stress vector is inversely proportional to the section modulus of the idealized bridge, it is clear that to increase the section modulus is an effective way to decrease the fatigue damage. Let the I- beam used in the preceding be replaced by two larger I-beams with the following properties:

I- Beam	36WF230	36WF280
Moment of inertia (steel only)	18935 $in.^4$	23025 $in.^4$
Moment of inertia (composite)	39768 $in.^4$	45005 $in.^4$
Distance from N.A. to bottom (at center)	25.91 in.	25.64 in.

The estimated fatigue lives are listed in Table 5-12. The fatigue lives (dynamic approach) at the three-quarter span are shown in Fig.5-4 as functions of section moduli and weight. The data do not include model F, because the corresponding values are too large to be plotted.

5.10 Effect of Magnitude of the Maximum Axle Load.

The case of 36WF230 considered in the preceding section dealt with the effect of an increase of the section modulus by 11.47%. It is of interest to consider the effect corresponding to a decrease of the static load level uniformly by the same percentage. This is done by a reduction of the magnitude of the maximum axle load by this percentage.

The results are shown in Table 5-13. Not unexpectedly, the values of fatigue life are very close to those presented in the preceding section. For statical consideration of fatigue life, these two sets of values should be the same. This comparison shows that small variations in properties of the dynamic system (changes in the frequencies of the bridge and vehicles) are not important, although the considerations of the dynamic nature (versus static) are important as indicated in section 5.5.

CHAPTER VI

SUMMARY AND CONCLUSIONS

In this thesis a study is made of the fatigue life of simple span highway bridges using simulation by computer. The study begins with a deterministic analysis of a bridge traversed by a vehicle. The set-up of the simulation procedure follows. Numerical results were obtained to illustrate the procedure as well as to investigate the fatigue life of an existing bridge in Michigan. Finally, the effects of small variations of certain parameters that enter the problem are considered.

In this study, five parameters are considered as random variables: (i) annual vehicle volume,(ii) vehicle type, (iii) vehicle speed,(iv) vehicle axle load level, and (v) interarrival time of vehicles.

The fatigue damage is considered at three "critical" points: the quarter span, mid-span, and three-quarter span. The damage has been calculated on the bases of both the static and dynamic stresses. Under the assumption that cover plates were welded to the I-beams from the quarter to the three quarter span, the latter point is considered to be the most critical section.

For the real bridge studied, the fatigue life (referred to the three-quarter point) ranges from 12 years to 9,135 years, depending upon three factors: (i) dynamic or static stress, (ii) random or constant annual vehicle volume, and (iii) fatigue models(A through G). But it is reasonable to consider that value corresponding to the case of dynamic stress, random annual vehicle volume, and model D as the best estimate. It is 45 years which is reasonably within the service life of a structure of this type. Therefore, it seems that fatigue damage should be a major factor to be considered in the design of such bridges.

Although the numerical results obtained are limited in scope, they appear to warrant the following observations that bear on the directions of future efforts of research in this area.

(1) In the estimation of fatigue life, the differences resulting from using the dynamic stresses or the static stresses seem to be sufficiently large as to warrant the use of the former approach. It may be mentioned that the simulation procedure presented here may be applied also to other types of bridges than simple spans.

(2) The traffic characteristics of heavy vehicles need to be specified more accurately. A probable weakness

of the present study is the assumption of the simple Poisson process to govern vehicle arrivals. For heavy vehicles, it seems likely that they would often travel in platoons. A study involving mathematical modeling from field observations would be useful. In this connection, it may be noted that not only the vehicle type but the axle load level is important. This study has indicated that no empty vehicle, regardless of its type,caused a stress range which exceeded 3.5 ksi. Besides, only three of the forty three vehicle types gave rise to dynamic stresses that surpassed the assumed fatigue limit of 3.0 ksi.

(3) Inasmuch as the values of the fatigue life are very sensitive to the fatigue models used, more research should be done to establish a fatigue model of more general validity. Such research probably would call for experimental work on fatigue strength involving random stress vectors including stress levels that are substantially lower than the lowest that has been used up to now.

(4) Before the necessary items of research are done and specific rules of method of design against fatigue failure are developed, it is worthwhile to note that the limited amount of numerical results obtained herein would indicate that a moderate increase of the section modulus would greatly increase the fatigue life of the structure.

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Table 2-1 Comparison of Numerical Solution for Different Values of $\bar{n}$ (stresses in ksi.)

$\bar{n}$	Vehicle type	Maximum stress range			Maximum dynamic stress			Minimum dynamic stress		
		a*	b	c	a	b	c	a	b	c
70	2D	1.28	1.79	1.14	6.32	8.97	6.18	5.04	7.18	5.04
80	2D	1.31	1.76	1.18	6.71	8.95	6.58	5.40	7.19	5.40
90	2D	1.32	1.79	1.18	6.71	8.97	6.52	5.40	7.18	5.40
200	2D	1.31	1.77	1.17	6.70	8.96	6.57	5.40	7.19	5.40
70	2S1-2	1.99	2.91	2.18	7.13	10.22	7.31	5.14	7.32	5.14
80	2S1-2	2.05	2.92	2.27	7.54	10.23	7.76	5.49	7.31	5.49
90	2S1-2	2.05	2.91	2.24	7.54	10.23	7.76	5.49	7.32	5.49
200	2S1-2	2.06	2.90	2.26	7.55	10.22	7.76	5.49	7.32	5.49
70	3S3-4	2.74	3.92	2.82	7.92	11.29	8.00	5.18	7.37	5.18
80	3S3-4	3.04	4.29	3.15	8.56	11.64	8.67	5.52	7.35	5.52
90	3S3-4	3.04	4.29	3.15	8.56	11.64	8.67	5.52	7.35	5.52
200	3S3-4	3.03	4.29	3.15	8.55	11.64	8.67	5.52	7.35	5.52

* a : quarter span.
b : mid-span.
c : three-quarter span.

Table 5-1 Relative Frequency Distribution of Vehicle Types

Vehicle Type	Vehicle Volume (Simulation)	Relative Freq. (Field Data)	Relative Freq. (Simulation)
2D	1878	0.18990	0.18780
3	217	0.01890	0.02170
2S1	1568	0.15480	0.15680
3S1	1191	0.12030	0.11910
2S2	1172	0.12030	0.11720
2S2L	1270	0.12030	0.12700
3S2L	219	0.02373	0.02190
3S2	252	0.02373	0.02520
2S3L1	268	0.02373	0.02680
2S3	222	0.02373	0.02220
2S3L	227	0.02373	0.02270
2S3L2	250	0.02373	0.02500
2S3LL	230	0.02373	0.02300
3S3LL	18	0.00162	0.00180
3S3L	23	0.00162	0.00230
3S3L2	18	0.00162	0.00180
3S3	18	0.00162	0.00180
3S3L1	17	0.00162	0.00170
3S4	8	0.00110	0.00080
3S5	17	0.00110	0.00170
2S1-2	107	0.01080	0.01070
2S2-2	92	0.00937	0.00920
2S2L-2	83	0.00937	0.00830
3S1-2	89	0.00937	0.00890
3S2-2	46	0.00472	0.00460
2S2-3	43	0.00472	0.00430
2S2L-3	40	0.00472	0.00400
3S2L-2	50	0.00472	0.00500
3S2-3	14	0.00150	0.00140
2S3-3	14	0.00150	0.00140
3S3-2	9	0.00150	0.00090
2S2-4	12	0.00150	0.00120
3S2-4	13	0.00190	0.00130
2S3-4	20	0.00190	0.00200
3S3-4	26	0.00405	0.00260
3S3-4	43	0.00405	0.00430
3S3-5	39	0.00460	0.00390
3S4-4	49	0.00460	0.00490
3S4-5	16	0.00220	0.00160
2-2	67	0.00600	0.00670
3-2	30	0.00380	0.00300
3-4	8	0.00110	0.00080
3-5	7	0.00110	0.00070

Table 5-2 Maximum Axle Loads

Vehicle Type	Maximum Axle Loads, kips.											
	1	2	3	4	5	6	7	8	9	10	11	12
2D	4.5	4.5										
3	4.5	4.0	4.0									
2S1	4.5	4.5	4.5									
3S1	4.5	4.0	4.0	4.5								
2S2	4.5	4.5	4.0	4.0								
2S2L	4.5	4.5	4.5	4.5								
3S2L	4.5	4.0	4.0	4.5	4.5							
2S2	4.5	4.0	4.0	4.0	4.0							
2S3L1	4.5	4.5	4.5	4.0	4.0							
2S3	4.5	4.5	3.3	3.3	3.3							
2S3L	4.5	4.5	4.5	4.0	4.0							
2S3L2	4.5	4.5	4.0	4.0	4.5							
2S3LL	4.5	4.5	4.5	3.3	3.3							
3S3LL	4.5	4.0	4.0	4.5	4.5	4.5						
3S3L	4.5	4.0	4.0	4.5	3.3	3.3						
3S3L2	4.5	4.0	4.0	3.3	3.3	4.5						
3S3	4.5	4.0	4.0	3.3	3.3	3.3						
3S3L1	4.5	3.3	3.3	4.5	4.0	4.0						
3S4	4.5	4.0	4.0	3.3	3.3	3.3	3.3					
3S5	4.5	4.0	4.0	4.5	3.3	3.3	3.3	3.3				
2S1-2	4.5	4.5	4.5	4.5	4.5							
2S2-2	4.5	4.5	4.0	4.0	4.5	4.5						
2S2L2	4.5	4.5	4.5	4.5	4.5	4.5						
3S1-2	4.5	4.0	4.0	4.5	4.5	4.5						
3S2-2	4.5	4.0	4.0	3.3	3.3	4.5	4.5					
2S2-3	4.5	4.5	4.0	4.0	4.5	3.3	3.3					
2S2L-3	4.5	4.5	4.5	4.5	4.5	3.3	3.3					
3S2L-2	4.5	4.0	4.0	4.5	4.5	4.5	4.5					
3S2-3	4.5	4.0	4.0	3.3	3.3	3.3	3.3	3.3				
2S3-3	4.5	4.5	3.3	3.3	3.3	4.5	3.3	3.3				
3S3-2	4.5	4.0	4.0	3.3	3.3	3.3	4.5	4.5				
2S2-4	4.5	4.5	3.3	3.3	3.3	3.3	4.0	4.0				
3S2-4	4.5	4.0	4.0	3.3	3.3	3.3	3.3	3.3	3.3			
2S3-4	4.5	3.3	3.3	3.3	3.3	4.5	3.3	3.3	3.3			
3S3-4	4.5	3.3	3.3	3.3	3.3	3.3	3.3	3.3	4.0	4.0		
3S3-4	4.5	4.0	4.0	3.3	3.3	3.3	4.5	3.3	3.3	3.3		
3S3-5	4.5	4.0	4.0	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	
3S4-4	4.5	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	
3S4-5	4.5	4.0	4.0	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
2-2	4.5	4.5	4.5	4.5								
3-2	4.5	4.0	4.0	4.5	4.5							
3-4	4.5	4.0	4.0	3.3	3.3	3.3	3.3					
3-5	4.5	3.3	3.3	3.3	3.3	3.3	3.3	3.3				

Table 5-3 Relative Frequency Distribution of Vehicle Speed

Speed (MPH)	Relative Frequency Field Data	Relative Frequency Simulated Data
75	0.0015	0.0013
70	0.0079	0.0081
65	0.0914	0.0930
60	0.2531	0.2477
55	0.3445	0.3469
50	0.1770	0.1737
45	0.0801	0.0843
40	0.0297	0.0301
35	0.0123	0.0126
30	0.0020	0.0017
25	0.0005	0.0006

Table 5-4 Relative Frequency Distribution of Axle Load Levels

Axle Load Levels	Relative Frequency Field Data	Relative Frequency Simulated Data
100% of M.A.L*	0.1203	0.1167
90% of M.A.L	0.1659	0.1687
80% of M.A.L	0.1659	0.1670
70% of M.A.L	0.1659	0.1606
50% of M.A.L	0.3820	0.3870

M.A.L = maximum axle loads

Table 5-6 Mean Value, Variance, and Standard Deviation of Interarrival Time

	Mean Value	Variance	Standard Deviation
Simulated Value	70.14	5028.15	70.91
Theoretical Value	70.87	5023.61	70.87

Table 5-5 Axle Spacings

Vehicle Type	Axle Spacings, ft.										
	1	2	3	4	5	6	7	8	9	10	11
2D	16.7										
3	12.2	4.4									
2S1	11.7	31.9									
3S1	14.7	4.1	35.9								
2S2	9.1	24.4	4.1								
2S2L	11.2	19.0	9.0								
3S2L	10.3	4.1	18.2	9.1							
3S2	11.5	4.5	22.5	4.0							
2S3L1	14.0	15.4	9.0	4.1							
2S3	12.1	11.2	4.0	4.0							
2S3L	11.7	18.0	10.1	4.0							
2S3L2	10.0	15.5	3.9	9.2							
2S3LL	12.1	11.2	9.2	9.0							
3S3LL	10.0	4.2	14.0	9.3	9.0						
3S3L	9.9	4.1	17.5	10.4	4.0						
3S3L2	9.9	4.4	20.4	4.0	9.1						
3S3	10.0	4.2	28.9	4.1	4.2						
3S3L1	10.7	4.0	16.7	9.3	4.0						
3S4	10.3	4.2	20.7	3.9	3.8	3.8					
3S5	9.8	4.3	11.3	9.2	4.1	3.9	4.0				
2S1-2	11.7	11.5	9.0	12.1							
2S2-2	11.6	9.1	4.1	10.0	9.4						
2S2L-2	13.0	9.0	9.1	9.3	11.2						
3S1-2	9.9	4.2	19.6	7.9	17.0						
3S2-2	10.2	4.1	9.7	4.0	11.6	11.1					
2S2-3	10.5	12.3	4.1	9.6	10.2	3.9					
2S2L-3	9.0	9.2	9.1	9.0	9.1	3.5					
3S2L-2	9.9	4.2	9.8	9.0	9.0	9.1					
3S2-3	10.5	4.0	9.3	4.2	8.9	10.1	4.0				
2S3-3	9.2	9.0	3.6	3.6	9.1	9.0	4.1				
3S3-2	10.4	4.0	9.7	3.6	3.6	8.8	9.5				
2S2-4	10.0	12.8	4.4	9.1	3.7	11.7	4.3				
3S2-4	11.2	4.3	9.8	4.1	6.6	4.2	7.0	3.8			
2S3-4	10.0	8.5	4.5	4.0	10.5	11.0	4.5	4.0			
3S3-4	10.5	3.8	10.5	3.6	3.6	5.4	3.6	9.0	3.6		
3S3-4	10.9	4.4	11.6	3.6	3.6	9.3	9.1	3.8	3.7		
3S3-5	9.2	3.8	10.8	4.2	4.0	6.4	3.7	4.3	3.7	4.8	
3S4-4	9.8	4.2	5.0	3.6	3.6	3.6	5.9	3.6	9.2	3.6	
3S5-5	9.9	3.9	6.2	3.7	3.4	3.4	5.5	3.6	4.9	3.3	3.4
2-2	11.8	10.4	9.4								
3-2	12.1	4.4	9.2	9.3							
3-4	11.7	4.2	9.4	3.6	5.1	3.5					
3-5	13.2	4.2	8.6	4.3	4.9	3.5	3.5				

Table 5-7(a) Simulated Relative Frequency Distribution of Dynamic Stress Ranges

Stress Range (psi.)	Relative Frequency of Stress Range Quarter Span	Mid-span	Three-quarter Span
0 - 1000	0.0021	0.0000	0.0015
1001 - 2000	0.4511	0.1650	0.4249
2001 - 3000	0.3712	0.4025	0.3711
3001 - 4000	0.1416	0.2318	0.1611
4001 - 5000	0.0280	0.1291	0.0336
5001 - 6000	0.0046	0.0497	0.0055
6001 - 7000	0.0012	0.0149	0.0021
7001 - 8000	0.0001	0.0040	0.0002
8001 - 9000	0.0000	0.0022	0.0000
9001 -10000	0.0000	0.0008	0.0000
10001 -11000	0.0000	0.0001	0.0000

Table 5-7(b) Simulated Relative Frequency Distribution of Static Stress Ranges

Stress Range (psi.)	Relative Frequency of Stress Range Quarter Span	Mid-span	Three-quarter Span
0 - 1000	0.0732	0.0000	0.0732
1001 - 2000	0.5066	0.3437	0.4974
2001 - 3000	0.3074	0.3419	0.3323
3001 - 4000	0.0964	0.2034	0.0809
4001 - 5000	0.0127	0.0784	0.0124
5001 - 6000	0.0033	0.0231	0.0038
6001 - 7000	0.0004	0.0058	0.0000
7001 - 8000	0.0000	0.0027	0.0000
8001 - 9000	0.0000	0.0010	0.0000
9001 -10000	0.0000	0.0000	0.0000
10001 -11000	0.0000	0.0000	0.0000

Table 5-8 Estimated Fatigue Life (Dynamic Case)

Fatigue	Estimated Fatigue Life, (years)											
Model	0.25L*	0.50L*	0.75L*	0.25L	0.50L	0.75L	0.25L	0.50L	0.75L	0.25L	0.50L	0.75L
A	12	8	11	13	8	11	13	8	12	14	9	13
B	11	8	10	12	8	10	12	8	10	13	9	12
C	63	21	50	63	21	52	66	22	53	65	23	53
D	53	19	44	55	19	44	56	20	46	56	22	45
E	57	20	46	59	20	47	60	22	49	60	22	48
F	926	116	568	927	117	570	929	120	568	924	120	570
G	17	11	16	17	11	16	19	11	16	19	12	18

*** 0.25L = quarter span; 0.50L = mid-span; 0.75L = three-quarter span**

Table 5-9 Fatigue Life as Affected by Dynamic and Static Computations and Vehicle Volume Models

	Fatigue Model	Estimated Fatigue Life, years. Quarter Span	Mid-span	Three-quarter Span
Dynamic Stress & Random Annual Vehicle Volume	A	14	9	13
	B	13	9	12
	C	65	23	53
	D	56	22	45
	E	60	22	48
	F	924	120	570
	G	19	12	18
Dynamic Stress & Constant Annual Vehicle Volume	A	22	12	19
	B	20	11	17
	C	133	41	107
	D	113	37	92
	E	122	39	98
	F	2011	251	1234
	G	33	18	29
Static Stress & Random Annual Vehicle Volume	A	43	17	50
	B	40	16	46
	C	250	63	285
	D	215	57	244
	E	229	59	261
	F	3953	510	4418
	G	64	23	74
Static Stress & Constant Annual Vehicle Volume	A	87	28	101
	B	79	26	92
	C	535	128	614
	D	455	114	522
	E	489	119	561
	F	8126	1102	9135
	G	130	41	151

Table 5-10 Effect of RFD of Axle Load Levels on the Fatigue Life

RFD of Axle Load Levels	Fatigue Model	Estimated Fatigue Life, years. Quarter Span	Mid-span	Three-quarter Span
	A	14	9	13
100% of M.A.L - 0.1203	B	13	9	12
90% of M.A.L - 0.1659	C	65	23	53
80% of M.A.L - 0.1659	D	56	22	45
70% of M.A.L - 0.1659	E	60	22	48
50% of M.A.L - 0.3820	F	924	120	570
	G	19	12	18
	A	14	9	12
100% of M.A.L - 0.1703	B	13	9	12
90% of M.A.L - 0.1659	C	63	23	51
80% of M.A.L - 0.1659	D	54	21	44
70% of M.A.L - 0.1659	E	58	21	47
50% of M.A.L - 0.3320	F	880	115	557
	G	19	12	17
	A	13	9	12
100% of M.A.L - 0.2203	B	12	8	11
90% of M.A.L - 0.1659	C	60	21	48
80% of M.A.L - 0.1659	D	51	19	42
70% of M.A.L - 0.1659	E	55	20	45
50% of M.A.L - 0.2820	F	818	109	128
	G	18	11	16

Table 5-11 Effect of RFD of Vehicle Speed on Fatigue Life

RFD of Vehicle Speed (MPH)	Fatigue Model	Estimated Fatigue Life, years. Quarter Span	Mid-span	Three-quarter Span
75 - 0.0015				
70 - 0.0079				
65 - 0.0914	A	14	9	13
60 - 0.2531	B	13	9	12
55 - 0.3445	C	65	23	53
50 - 0.1770	D	56	22	45
45 - 0.0801	E	60	22	48
40 - 0.0297	F	924	120	570
35 - 0.0123	G	19	12	18
30 - 0.0020				
25 - 0.0005				
75 - 0.0094				
70 - 0.0914				
65 - 0.2531	A	13	9	12
60 - 0.3445	B	12	9	11
55 - 0.1770	C	63	21	50
50 - 0.0801	D	54	20	43
45 - 0.0297	E	58	20	47
40 - 0.0123	F	853	116	525
35 - 0.0020	G	18	11	16
30 - 0.0005				
25 - 0.0000				
75 - 0.1008				
70 - 0.2531				
65 - 0.3445	A	13	9	12
60 - 0.1770	B	12	9	11
55 - 0.0801	C	63	22	51
50 - 0.0297	D	54	20	44
45 - 0.0123	E	58	21	47
40 - 0.0020	F	811	114	497
35 - 0.0005	G	18	12	17
30 - 0.0000				
25 - 0.0000				

Table 5-12 Effect of Section Modulus on Fatigue Life

I-Beam	Section Modulus ($in.^3$)	Fatigue Model	Estimated Fatigue Life, years, Quarter Span	Mid-span	Three-quarter Span
36WF194	1376.88	A	14	9	13
		B	13	9	12
		C	65	23	53
		D	56	22	45
		E	60	22	48
		F	924	120	570
		G	19	12	18
36WF230	1534.85	A	51	15	45
		B	44	14	39
		C	309	59	267
		D	249	52	217
		E	268	55	234
		F	5509	476	4090
		G	80	21	71
36WF280	1755.29	A	114	19	109
		B	98	17	95
		C	768	95	701
		D	612	82	562
		E	663	87	610
		F	x	1153	x
		G	178	27	172

x = values greater than 10000.

Table 5-13 Comparison of Effects of Section Modulus and Axle Load Level on Fatigue Life

	Fatigue Model	Estimated Fatigue Life, years. Quarter Span	Mid-span	Three-quarter Span
Increase of Section Modulus by 11.47%	A	51	15	45
	B	44	14	39
	C	309	59	267
	D	249	52	217
	E	268	55	234
	F	5509	476	4090
	G	80	21	71
Decrease of Static Axle Load Level by 11.47%	A	51	16	46
	B	46	15	42
	C	297	66	262
	D	253	59	224
	E	272	62	239
	F	5929	523	2751
	G	73	23	67

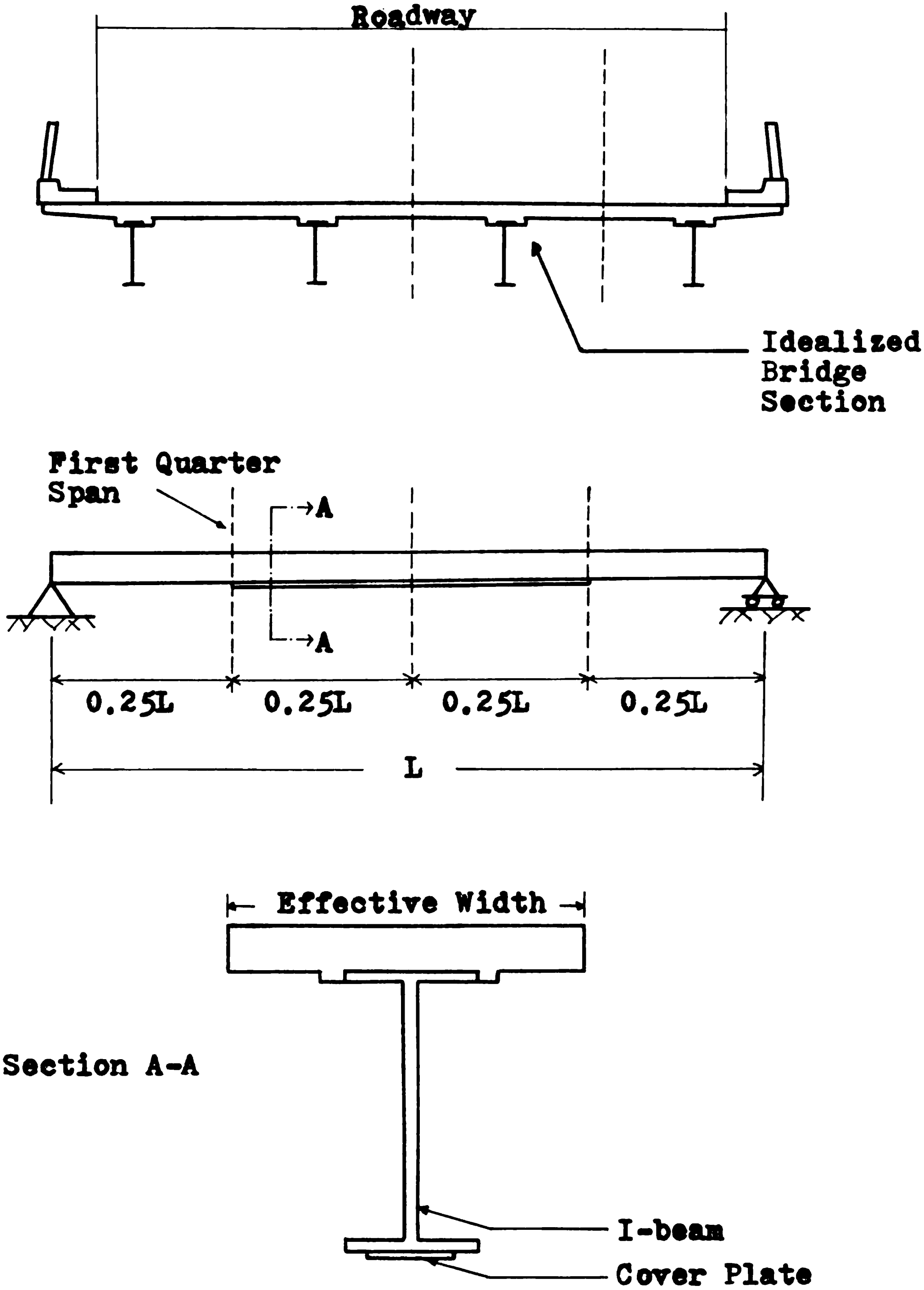


Fig. 2-1 Idealization of Bridge

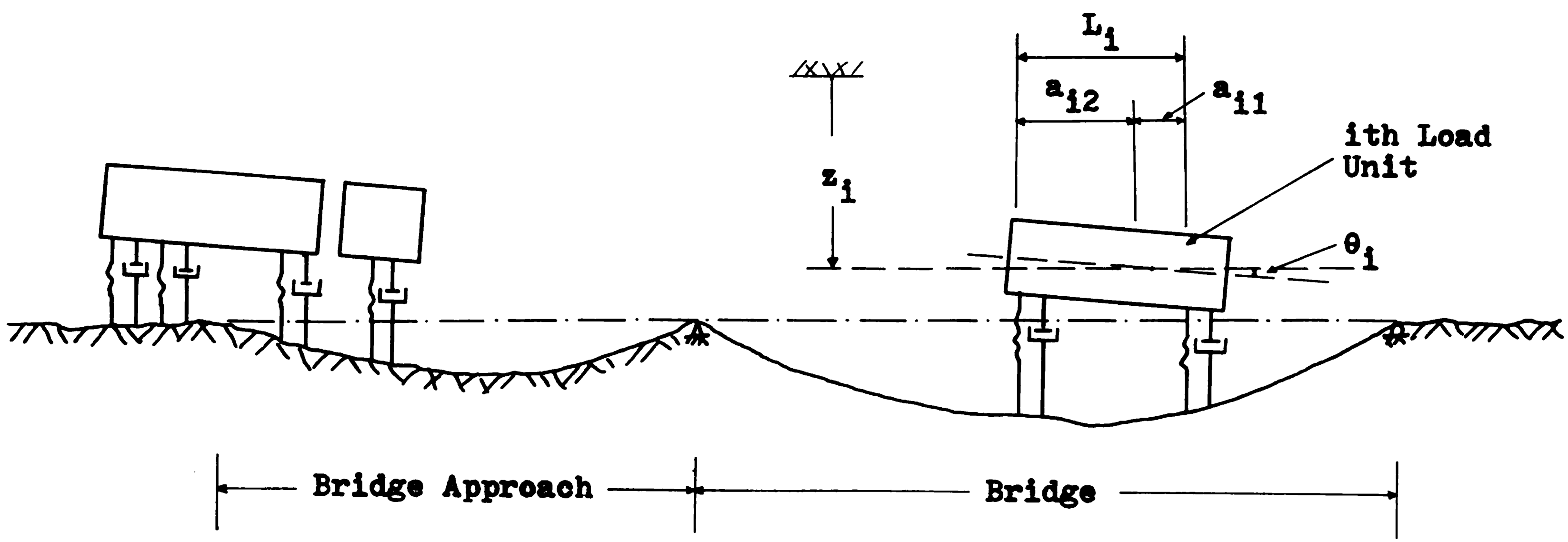


Fig. 2-2 Idealized Bridge-Vehicle System

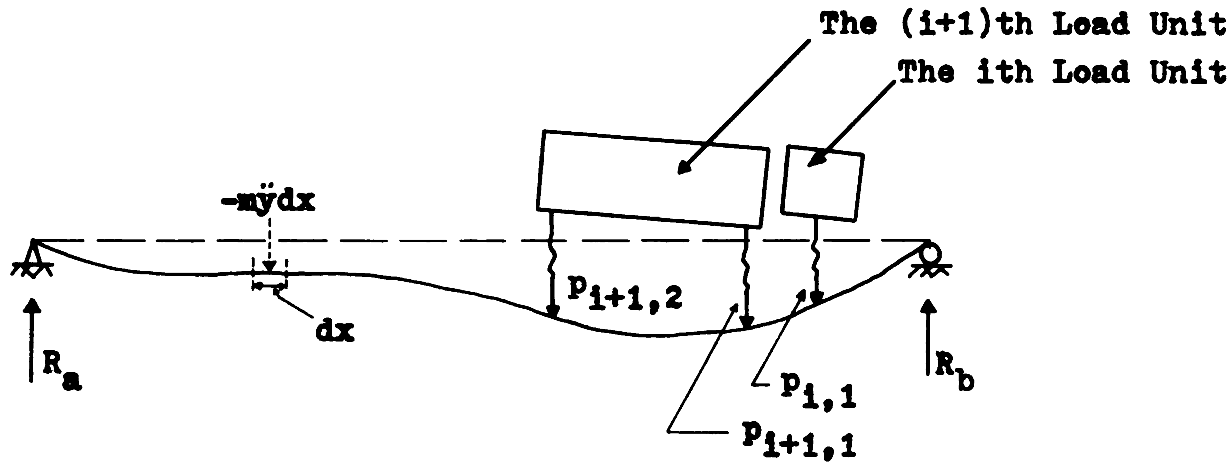


Fig.2-3 Actions and Reactions between Axles and Bridge

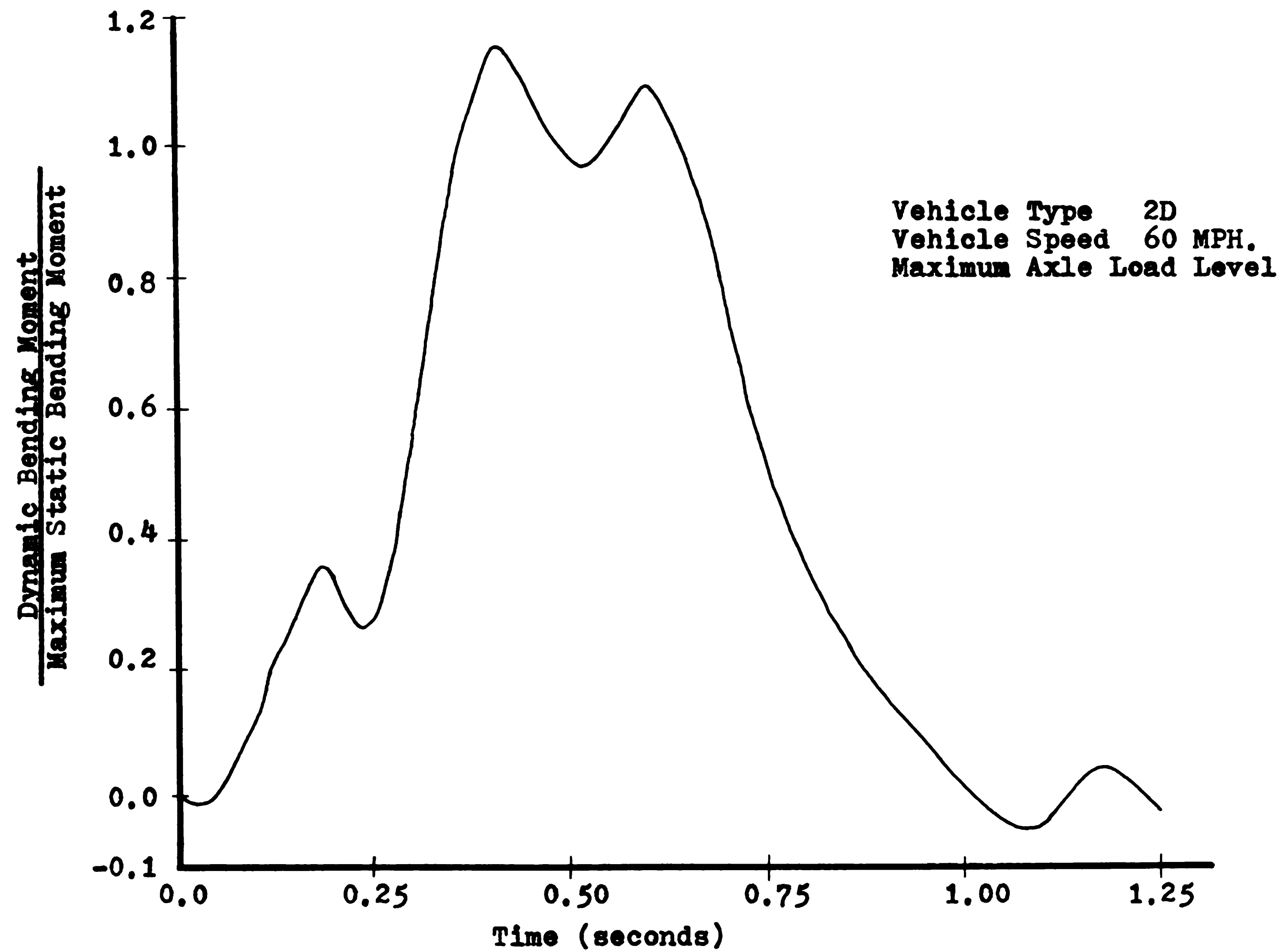


Fig. 2-4 Typical History Curve for Dynamic Bending Moment. (2-axle vehicle)

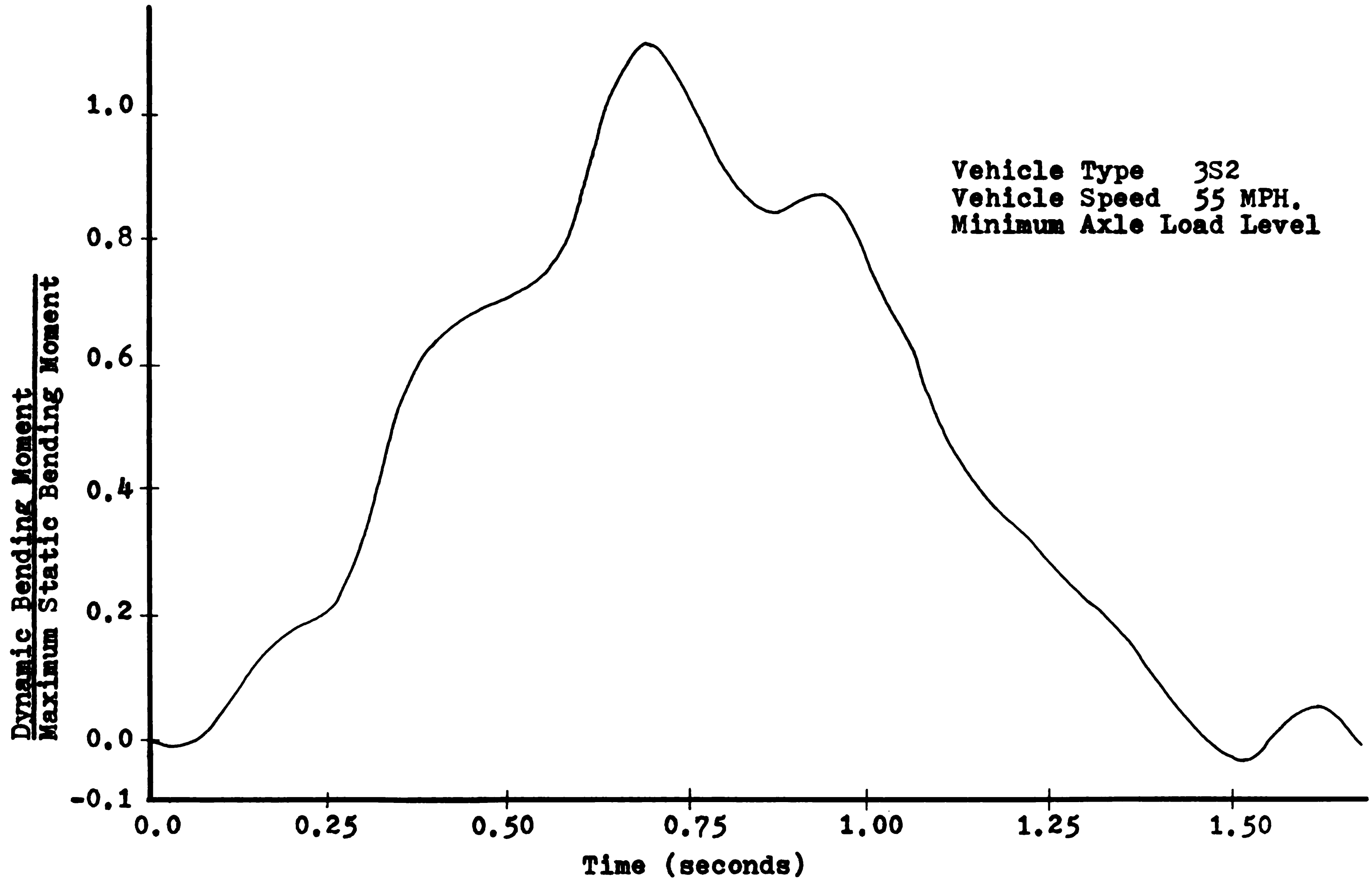


Fig. 2-5 Typical History Curve for Dynamic Bending Moment.
(5-axle vehicle)

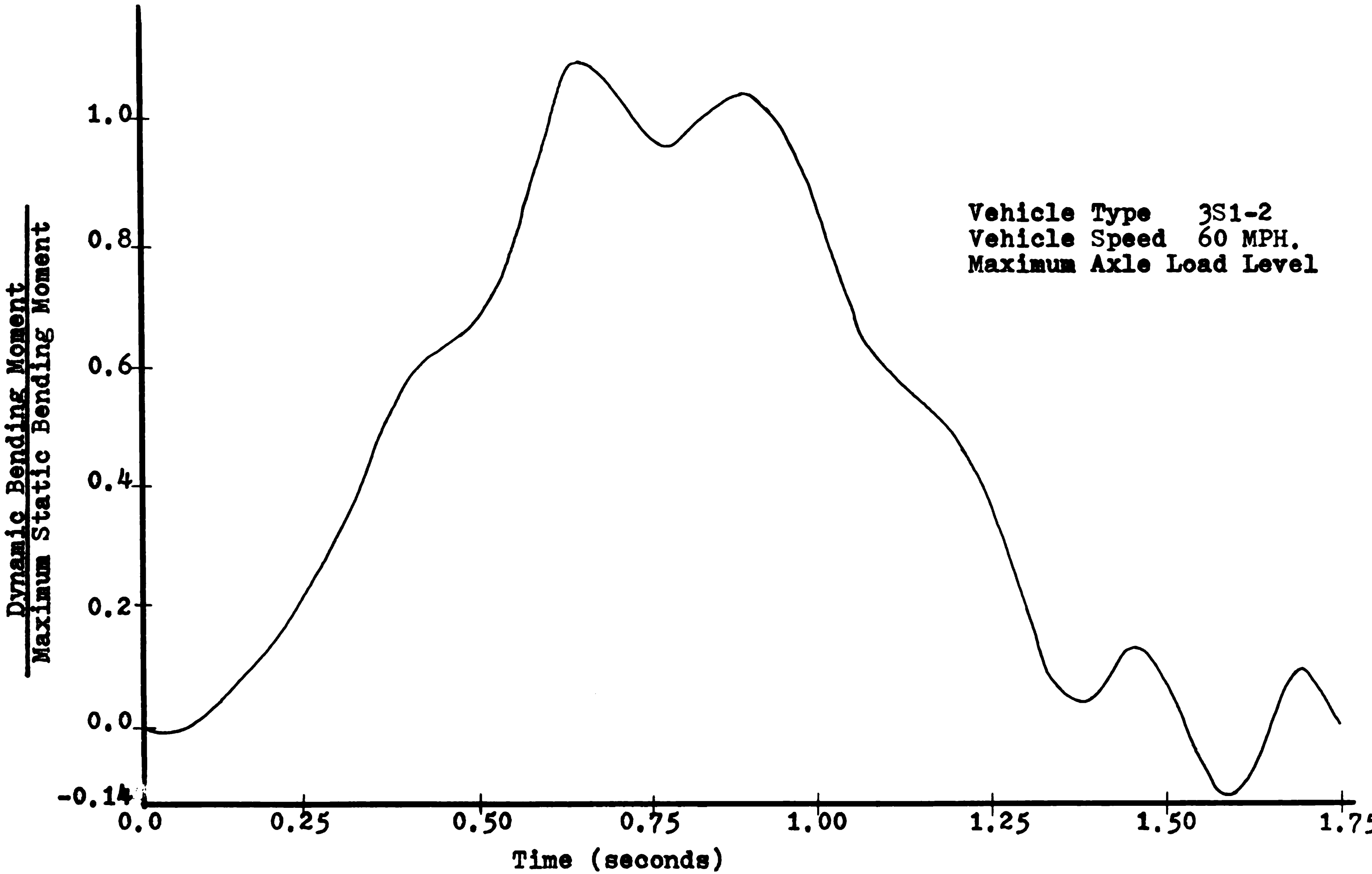
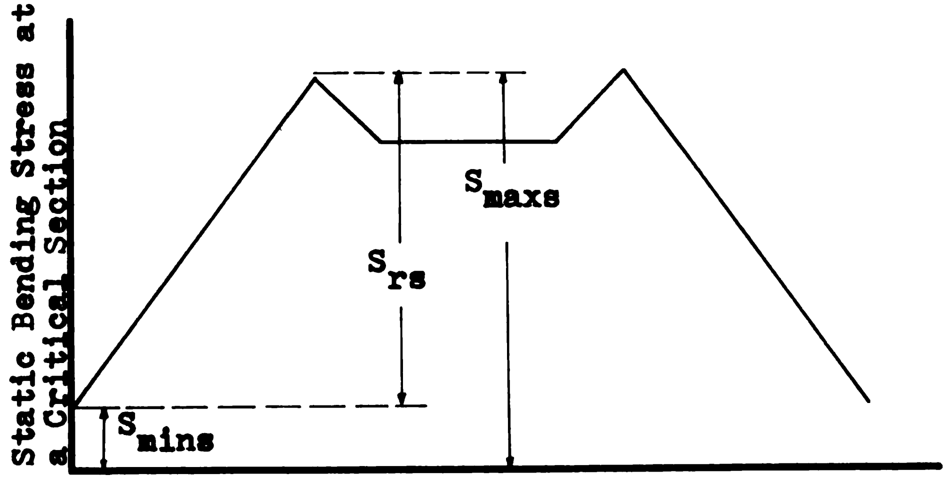
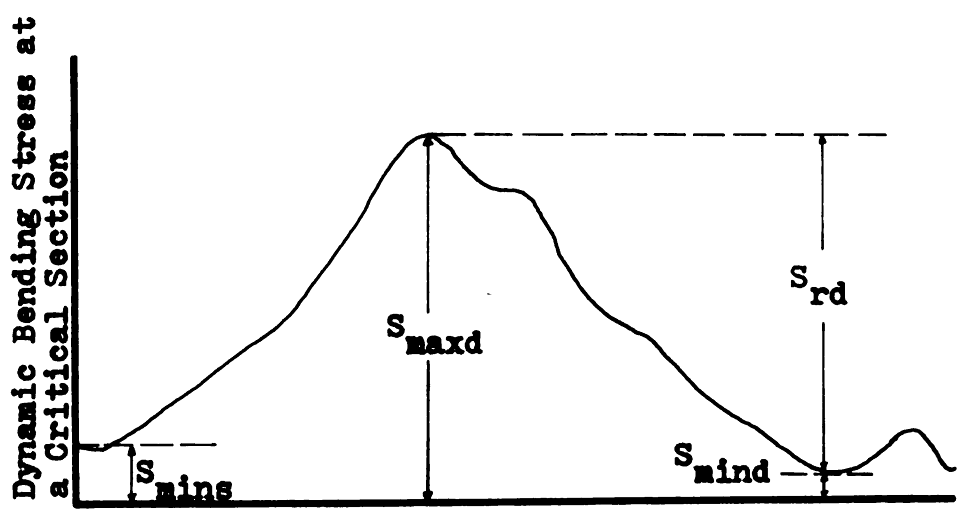


Fig. 2-6 Typical History Curve for Dynamic Bending Moment.
(6-axle vehicle)



$\frac{vt}{L} = \frac{\text{distance of the 1st. axle to left support}}{\text{span length}}$

Fig.3-1(a) History Curve for Static Bending Stress at a Critical Section



$\frac{vt}{L} = \frac{\text{distance of the 1st. axle to left support}}{\text{span length}}$

Fig.3-1(b) History Curve for Dynamic Bending Stress at a Critical Section

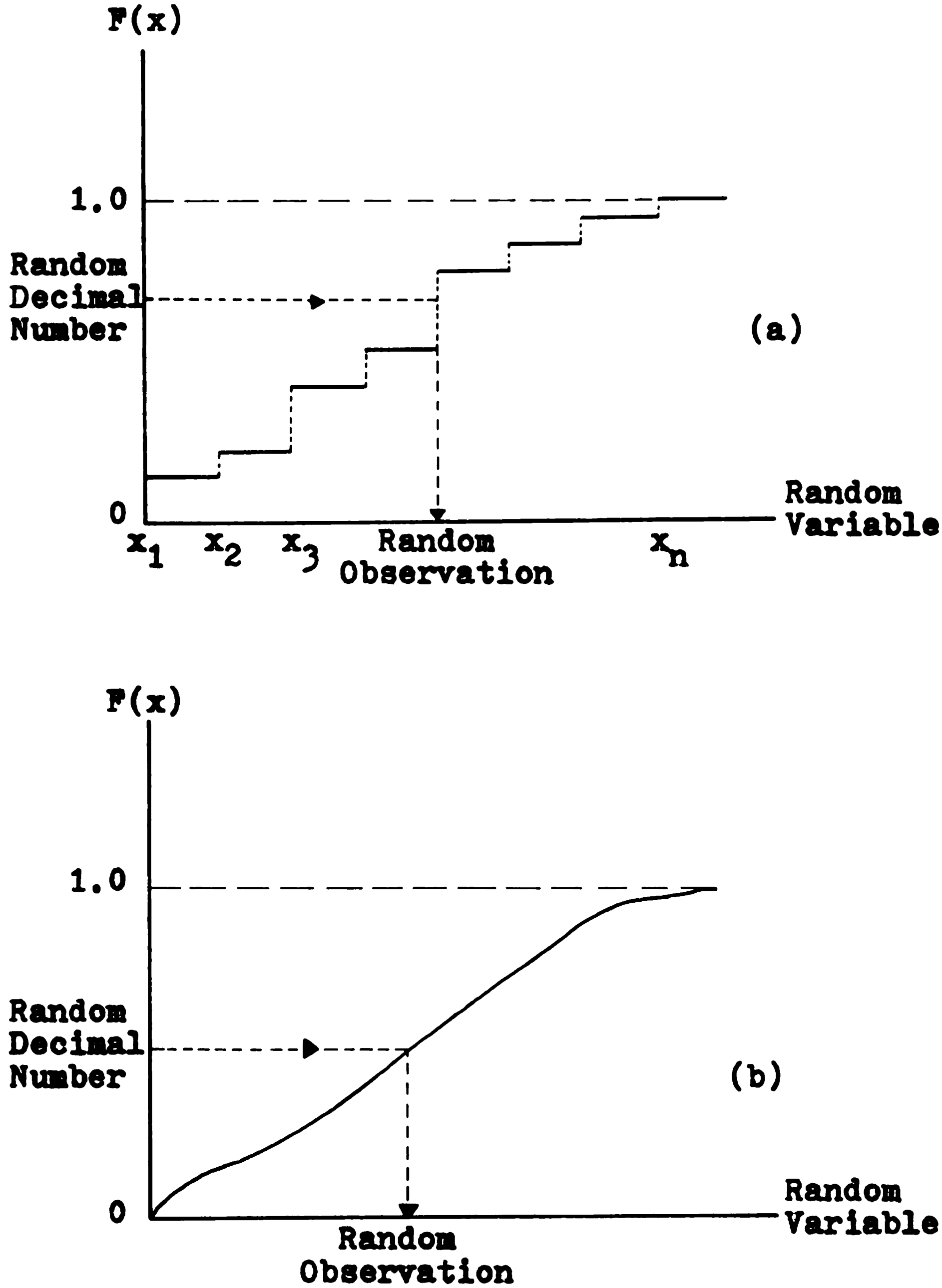


Fig.4-1 Illustration of Procedure for Obtaining a Random Observation from a given Cumulative Distribution Function. (a) Discrete Random Variable, (b) Continuous Random Variable.

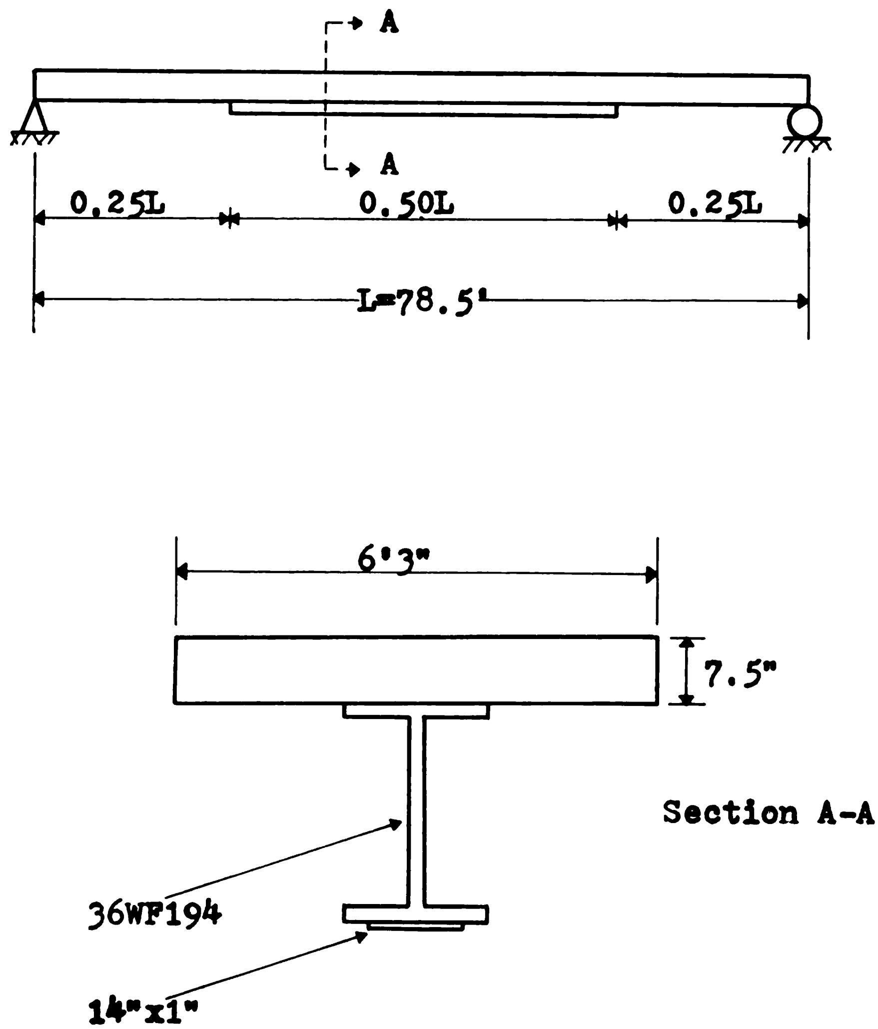


Fig. 5-1 Idealized Section of the Tested Bridge

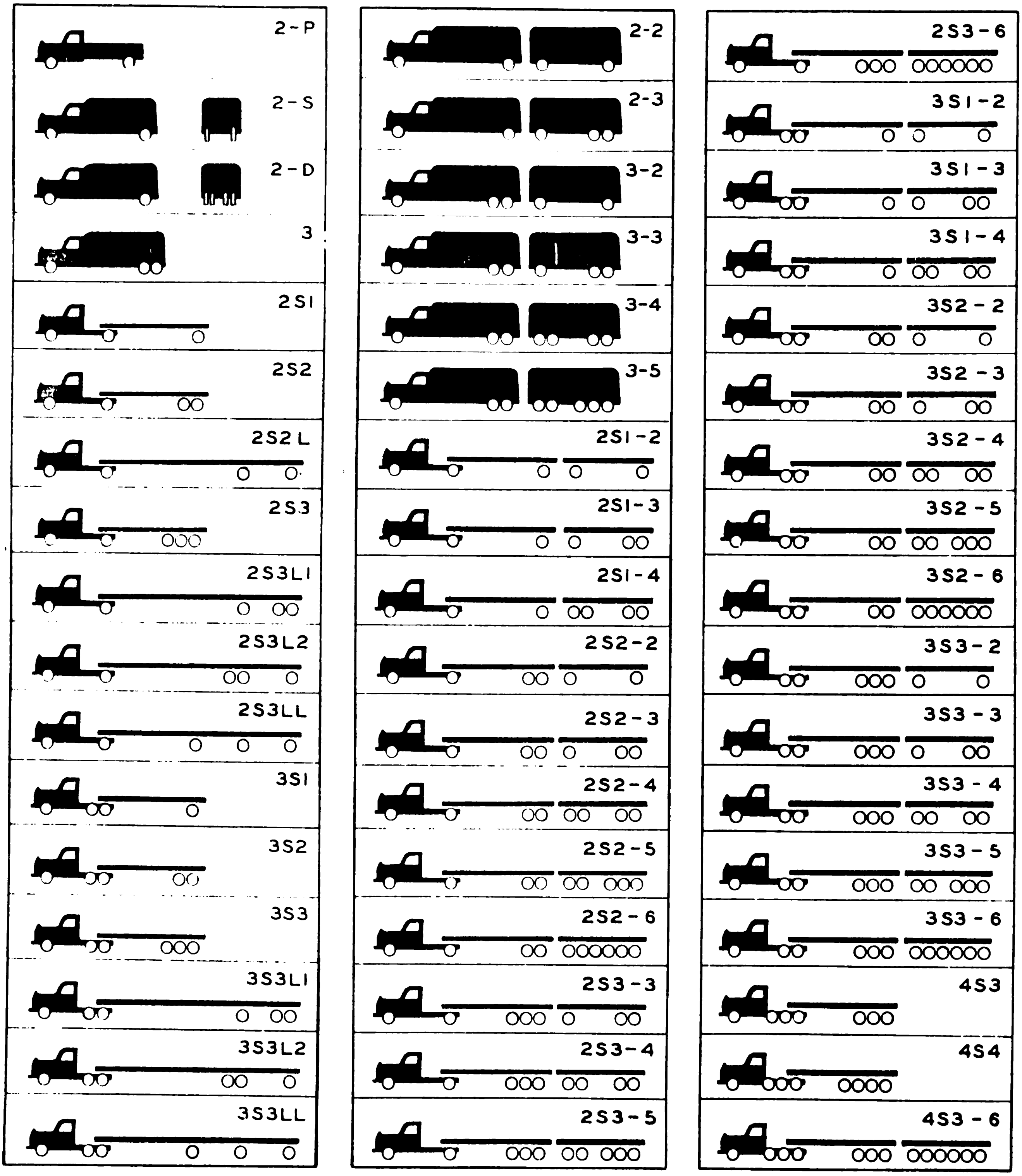


Fig. 5-2 Vehicle Types

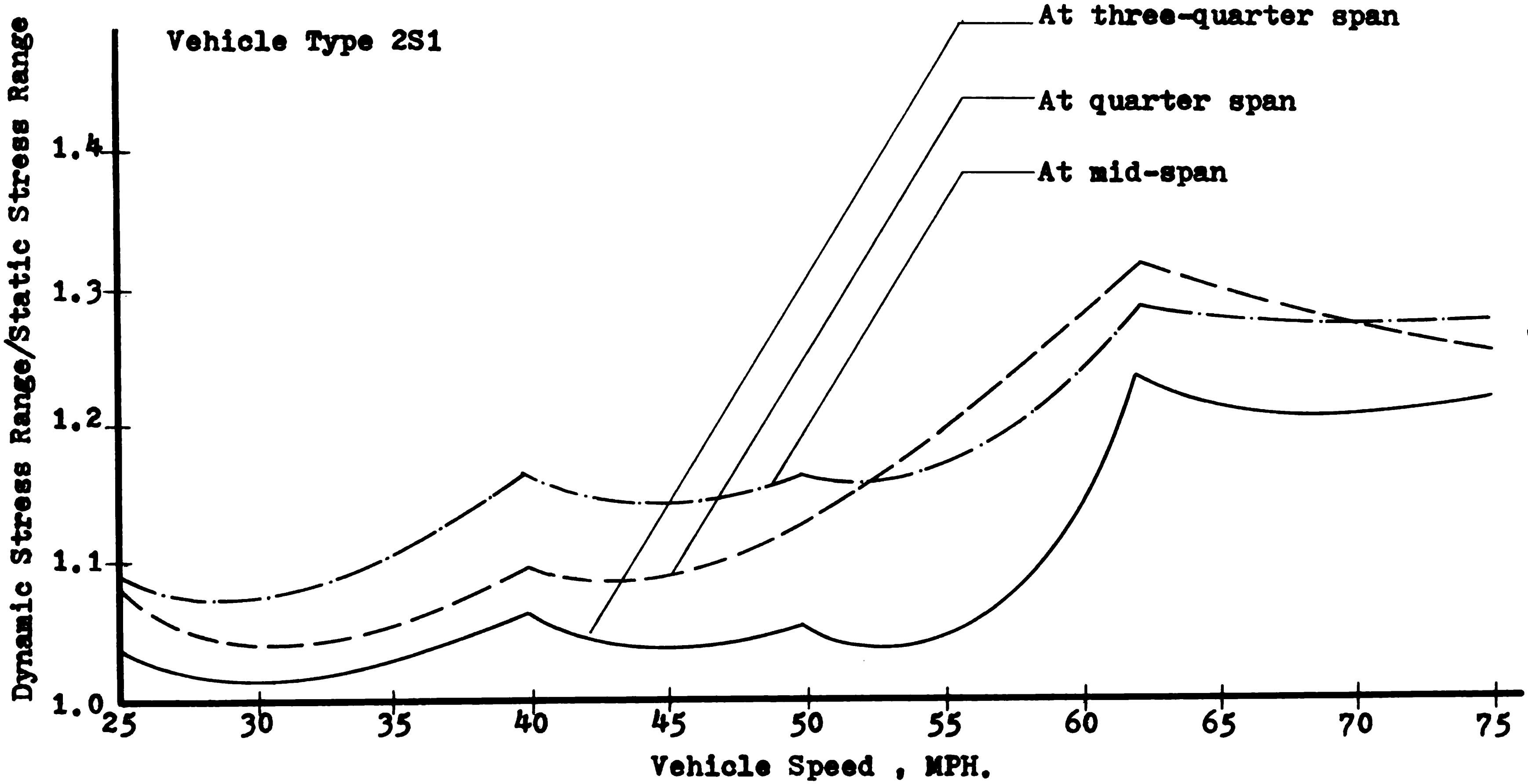


Fig.5-3(a) Effect of Vehicle Speed on Stress Range at Critical Sections

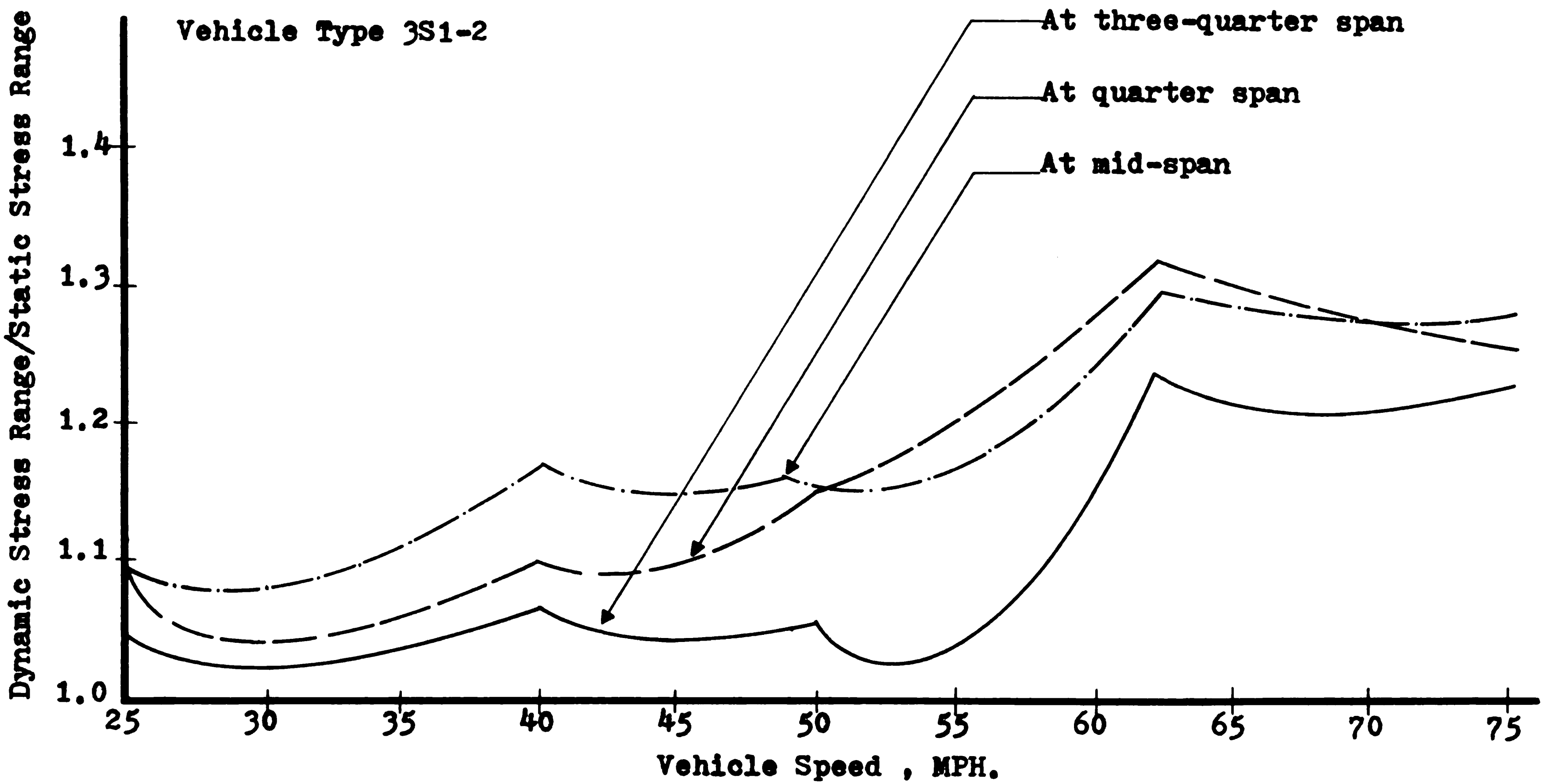


Fig.5-3(b) Effect of Vehicle Speed on Stress Range at Critical Sections

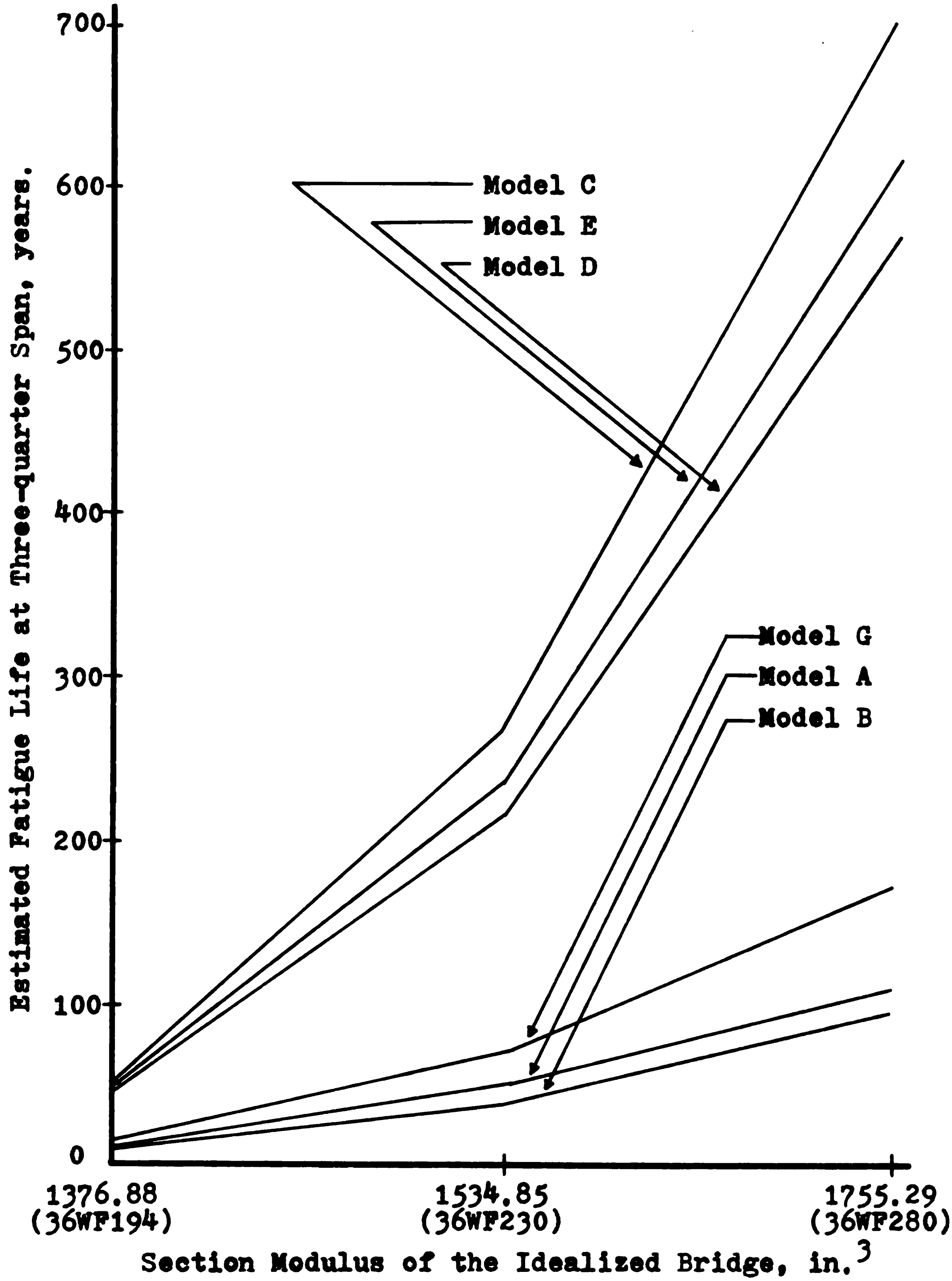


Fig. 5-4 Effect of Section Modulus

APPENDIX

COMPUTER PROGRAMS

For completeness the three main computer programs written for this study are given here. They are programs (i) DYNAMIC, (ii) STATIC, and (iii) SIMU1. As mentioned in sections 2.8.3 and 2.9, the first two programs are prepared to calculate the dynamic and static stress vectors: minimum stresses, maximum stresses, and stress ranges for three critical sections: quarter , mid-, and three-quarter spans. The program SIMU1 is written to estimate the fatigue life; it is explained in the next section in detail.

A.1 Program SIMU1

The procedure described in the section 4.3 is implemented by this program. If one considers the vehicle type, vehicle speed, and vehicle axle load level having sample spaces $\bar{M}_1$, $\bar{M}_2$, and $\bar{M}_3$, respectively, where $\bar{M}_1=\lfloor m_{11},m_{12},m_{13},\ldots,m_{1p}\rfloor$, $\bar{M}_2=\lfloor m_{21},m_{22},m_{23},\ldots,m_{2q}\rfloor$, and $\bar{M}_3=\lfloor m_{31},m_{32},m_{33},\ldots,m_{3r}\rfloor$.

The stress vectors are obtained by use of programs STATIC and DYNAMIC for all possible combinations of sample points from $\bar{M}_1$, $\bar{M}_2$, and $\bar{M}_3$. The data are punched out and serve as the input deck for SIMU1. They are loaded into 12 one-dimension arrays: SR1, SR2, SR3, SMAX1, SMAX2, SMAX3, SMIN1, SMIN2, SMIN3, SSR1, SSR2, and SSR3. The first nine arrays are data for the dynamic case --- dynamic stress range, maximum stress, and minimum stress at the three critical sections, and the last three arrays are data for the static case --- static stress ranges at the three critical sections. The static minimum stress is a constant for each section; it is simply the dead load stress. The maximum static stress is simply the minimum stress plus the stress range. Thus there is no need to store these stresses. Those data loaded in the 12 one-dimension arrays are needed to calculate the fatigue damage value, when the vehicles crossing the span are not in train.

The sequence of input data stored in the arrays can be expressed by the following relationships. For each array, the quantity associated with the event of vehicle type m_{1i}, vehicle speed m_{2j}, and axle load level m_{3k}, (where i, j, and k run to p, q, and r, respectively), is stored in the Qth element of that array where, for the dynamic case,

$$Q = p*q*(m_{3k} - 1) + q*(m_{1i} - 1) + m_{2j} \qquad .....(A-1)$$

and $1 < Q < p*q*r$, for the static case,

$$Q = p*(m_{3k} - 1) + m_{1i} \qquad .....(A-2)$$

and $1 < Q < p*r$

When the simulation calls for a platoon of two vehicles, program DYNAMIC is executed in program SIMU1. The two successive vehicles are treated as one special vehicle by SIMU1. While the type and axle load level of each vehicle are completely independent, the speeds for both are the same. The axle spacing between the last axle of the first vehicle and the first axle of the second vehicle is equal to the vehicle speed times the interarrival time. Note that such platooning is not considered in the static case.

Program SIMU1 also includes three subroutines: The subroutine SELECT1 is used to determine random observations from random numbers. The Binary Search technique (12) is used for this purpose. The subroutine RFD100 counts the number of occurrences of each stress level. The subroutine FATIG calculates the cumulative fatigue damage of the bridge.

A flow chart of the program SIMU1 is shown in Fig.A-1.

A.2 Variables Used in the Computer Programs

A.2.1 General - The main variable names used in the programs are listed below in the alphabetical order. The following nine names are applicable to all three major programs. Those applicable to specific programs are described under the various program names.

COMI = composite moment of inertia of the idealized bridge section;

INDEXWT(I) = axle load level;

L = span length of bridge;

NOA = number of axles of vehicle;

NOT = number of load units representing a vehicle;

NOCS = number of critical sections;

NOVT = number of vehicle types;

NOVW = number of axle load levels;

VT(I) = the ith vehicle type.

A.2.2 Program STATIC -

BM(I) = bending moment at a critical section, when the ith axle is at the section;

DB(I) = distance between the neutral axis and the lower extreme fiber at the ith section;

INDEX(I), INDEX1(I), INDEX2(I) = coefficients for bending moment influence line at the ith section;

MBM = maximum bending moment at a section;

SSR(I,J) = maximum static stress range, caused by the ith vehicle type, at the jth section;

WT(I) = maximum allowable load of the ith axle;

XX(I) = distance between the first and the ith axle.

A.2.3 Program DYNAMIC -

A(I,J) = horizontal distance between the jth axle and the centroid of the ith load unit;

BMASS = mass per unit length of the idealized bridge;

C(I,J) = damping coefficient of the jth axle in the ith load unit;

CPS = natural frequency of the idealized bridge;

D = amplitude of the sine curve representing the bridge approach;

DB1, DB2 = distance between the neutral axis and the lower extreme fiber at the quarter spans and mid-span.

DLD = dead load deflection of the idealized bridge;

DLDD = the first derivative of DLD;

DELTAT = time increment;

DS(I,J) = initial static compression in the ith axle of the jth load unit;

DS1, DS2 = static bending stresses, which are caused by the dead load of bridge, at the end of cover plate and the mid-span, respectively;

DYNM1(I), DYNM2(I), DYNM3(I) = dynamic bending moment at the critical sections, corresponding to the ith time increment;

E2(I), E3(I,J), E4(I,J) = quantities defined on p. , they are denoted by $\bar{c}_{2i}$, $\bar{c}_{3ij}$, and c_{4ij}, respectively;

EI = flexural rigidity of the idealized bridge;

F = amplitude of dynamic deflection, see Eq. 2-1;

FD, FDD = the first and the second derivative of F;

F1 = F, when time is equal to t+ t;

FD1, FDD1 = FD, FDD respectively, when time is equal to t+ t;

K(I,J) = spring stiffness of the jth axle in the ith load unit;

LL = length of bridge approach;

LLL = total length of bridge and bridge approach;

NOAOE(I) = number of axles of the ith load unit;

NOVV = number of vehicle speed levels;

P(I) = length of the ith load unit;

PERIOD = natural period of vibration of the idealized bridge;

POLARM(I) = polar moment of inertia of the ith load unit;

SMOE = Young's modulus;

SMOI = moment of inertia of I-beam(excluding slab);

SITA(I) = angular displacement of the ith load unit at time t;

SITAD(I), SITADD(I) = the first and second derivative of SITA(I), respectively;

SITA1(I) = angular displacement of the ith load unit at time t+ t;

SITAD1(I), SITADD1(I)= the first and second derivative of SITA1(I);

SPEED(I) = the ith vehicle speed level;

STORE = t times SPEED(I);

SR1, SR2, SR3 = maximum dynamic stress ranges at the critical sections;

STRESS1, STRESS2, STRESS3 = maximum dynamic stresses at critical sections;

STRESS4, STRESS5 = minimum dynamic stresses at critical sections -- quarter span (or three-quarter span) and mid-span, respectively;

TLL = length of bridge approach/vehicle speed;

TOTALWT(I) = weight of the ith load unit;

TXXLLL = time between the entry of the front axle of a vehicle to the bridge approach to the departure of the last axle from the bridge;

VMASS(I) = mass of the ith load unit;

WT(I,J) = the jth axle load of the ith load unit;

XXX(I,J) = distance between the first axle of the first load unit and the jth axle of the ith load unit;

Z(I) = vertical displacement of the ith load unit at time t;

ZD(I), ZDD(I) = the first and second derivative of Z(I);

Z1(I) = vertical displacement of the ith load unit at the end of time t+ t;

ZD1(I), ZDD1(I)= the first and second derivative of Z1(I);

YB(I,J) = vertical deviation of the bridge approach from the horizontal at the position of the ith axle in the jth load unit;

YBD(I,J) = the first derivative of YB(I,J).

A.2.4 <u>Program SIMU1</u>

AA(I,J,K) = horizontal distance between the kth axle and the centroid of the jth load unit for the ith vehicle type;

AAT = average interarrival time;

AB = index of fatigue model;

ADD(I) = number of vehicle type i observed;

AVV(I) = the ith annual vehicle volume;

SMAX1(I), SMAX2(I), SMAX3(I) = maximum dynamic stresses at the critical sections, corresponding to each index I(= INDEXR);

SMIN1(I), SMIN2(I), SMIN3(I) = minimum dynamic stresses at the critical sections, corresponding to each index I(= INDEXR);

SSR1(I), SSR2(I), SSR3(I) = static stress ranges at the critical sections, corresponding to each index I(= INDEXS);

STANDV = standard deviation of interarrival time, IAT;

STORESP(I) = number of vehicle speed i observed;

STOREWT(I) = number of axle load level i observed;

STORE1(I) = vehicle type i;

SRFD1(I), SRFD2(I), SRFD3(I) = simulated relative frequency of the ith dynamic stress range level at the critical sections;

SSRFD1(I), SSRFD2(I), SSRFD3(I) = simulated relative frequency of the ith static stress ranges level at the critical sections;

TOTAL = sample size;

UVT(I) = cumulative relative frequency of the ith vehicle type;

UVV(I) = cumulative relative frequency of the ith vehicle speed;

UVW(I) = cumulative relative frequency of the ith axle load level;

UPPERL = upper limit of the simulated annual vehicle volume;

VARIANS = sample variance of the interarrival time, IAT;

BLIFE(I,J) = estimated fatigue life at section j using fatigue model i;

CAR99(I,J) = cumulative fatigue damage at section j using the ith fatigue model;

CAR88(I,J) = the first year's fatigue damage at the jth section, estimated by using the ith fatigue model;

DLS1, DLS2 = dead load bending stresses at the critical sections;

IAT = interarrival time;

INDEXR, INDEXS = quantities defined by Eqs.(A-1) and (A-2), respectively;

J1 = random decimal number;

LITTLEN(INDEXR) = number of cycles, corresponding to the dynamic stress range with index INDEXR;

LOWERL = lower limit of the simulated annual vehicle volume;

NOA1(I) = number of axles of vehicle type i;

NOLU(I) = number of load units of vehicle type i;

NOAOELU(I,J) = number of axles in the jth load unit of vehicle typei;

NOFM = number of fatigue models;

RF1(I) = relative frequency of vehicle type i;

RFW(I) = relative frequency of axle load level i;

RFS(I) = relative frequency of vehicle speed i;

RN = random decimal number;

SMALLN(INDEXS) = number of cycles, corresponding to the static stress range with index INDEXS;

WT1(I.J.K) = the kth axle load of the jth load unit in the ith vehicle type;

XBAR = sample mean of IAT;

XXX1(I,J,K)= distance between the first axle of the the first load unit and the jth axle of the ith load unit;

YOGD = number of years for which the annual vehicle volumes are prescribed;

A.2.5 Subroutine SELECT1

K = index;

L1, L2, L3 = parameters used in binary search;

NN = total number of sample points of a random variable;

UL(I) = cumulative relative frequency of the ith sample point.

A.2.6 Subroutine RFD100

SRL = stress range value at quarter span;

SRM = stress range value at mid-span;

SRR = stress range value at three-quarter span;

SSSSS(I) = the ith stress range level.

A.2.7 Subroutine FATIG

N1,N2,N3,N4,N5,N6,N7 = for a given stress vector, the number of cycles which would cause a fatigue failure as defined by fatigue models A, B, C, D, E, F, and G, respectively;

SR11, SR22, SR33 = stress range value at the critical sections;

SMAX11, SMAX22, SMax11 = maximum stress values at the critical sections;

SMIN11, SMIN22, SMIN33 = minimum stress values at the critical sections;

NNNNN = number of cycles at a given stress range;

STORE(I,J) = cumulative fatigue damage at the jth section estimated by the ith fatigue model.

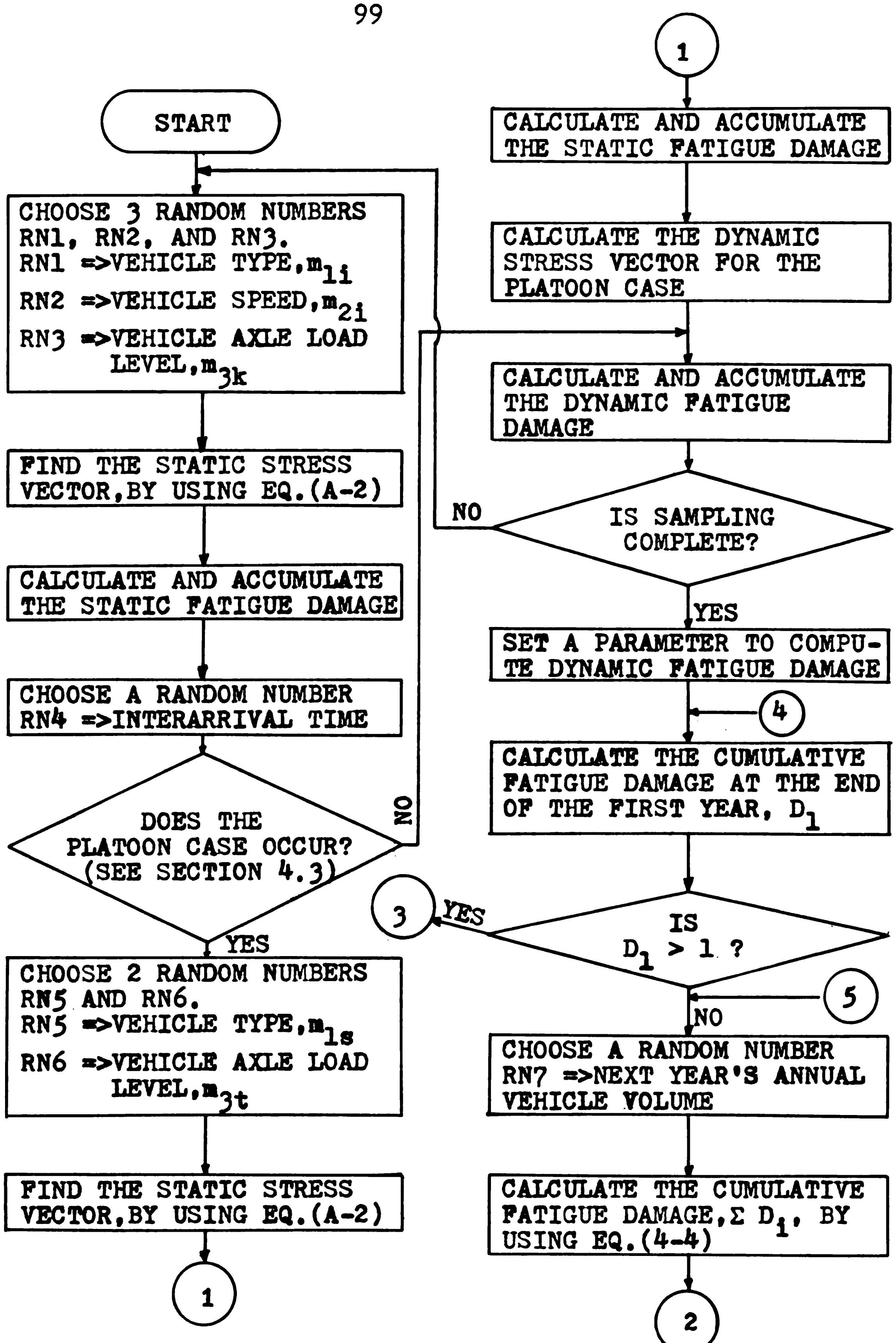
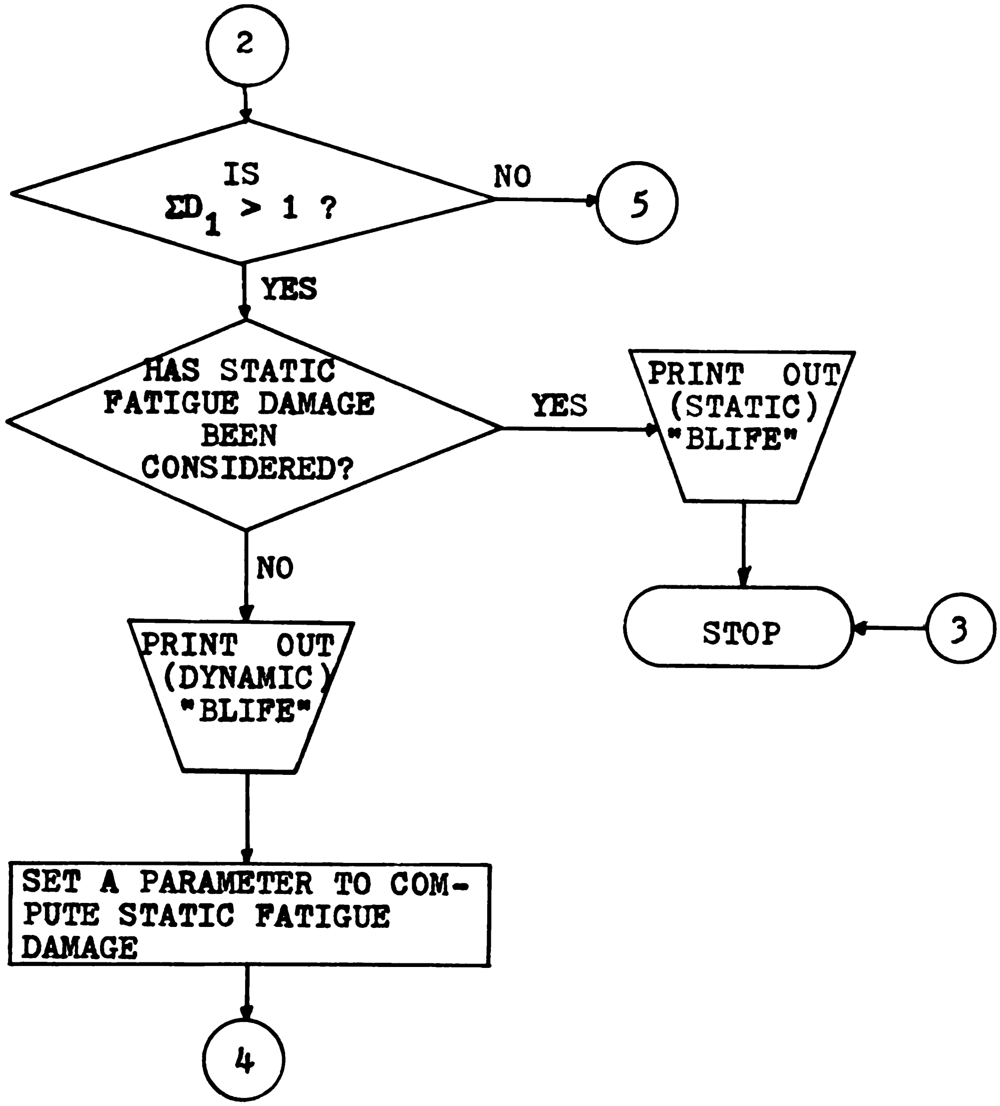


Fig. A-1 Flow Chart for Program SIMU1


2
IS
ΣD1 > 1 ?
NO
5
YES
HAS STATIC FATIGUE DAMAGE BEEN CONSIDERED?
YES
PRINT OUT (STATIC) "BLIFE"
STOP
3
NO
PRINT OUT (DYNAMIC) "BLIFE"
SET A PARAMETER TO COMPUTE STATIC FATIGUE DAMAGE
4

```
      PROGRAM DYNAMIC
C     THIS PROGRAM CALCULATES THE DYNAMIC STRESS VECTORS AT EACH SECTION
      DIMENSION XX(6,7), NOAOE(6), K(6,7), A(6,7), WT(6,7), DS(6,7),
     1TOTALWT(6), VMASS(6), E2(6), E3(6,7), E4(6,7), C(6,7), STEMP(6,7),
     2CTEMP(6,7), Z(6), Z1(6), ZD(6), ZD1(6), ZDD(6), ZDD1(6), SITA(6),
     3SITA1(6), SITAD(6), SITAD1(6), SITADD(6), SITADD1(6), TEMP1(6,7),
     4TEMP2(6,7), GKS(6), HCS(6), YB(6,7), YBD(6,7), G(6,7), GK(6,7),
     5H(6,7), HC(6,7), GKA(6,7), HCA(6,7), SUMZ(6),SUMS(6),P(6)
      DIMENSION SF1(150),SFD1(150),SFDD1(150),DYNM1(500),DYNM2(500),
     1DYNM3(500),POLARM(5),SPEED(15),XXX(3,7)
      REAL L,LL,LLL,L1,L2,L3,LLL1,LLL2,LLL3,K
C
C     READ BRIDGE DATA
C
    1 FORMAT (4F10.2)
    2 FORMAT (2F10.3,E8.1)
      READ 1, L, BMASS, LL, D
      READ 2, SMOI, CMOI, SMOE
      READ 1, DB1, DB2, CPS
      EI=SMOE*CMOI
      PERIOD=1.0/CPS
C
C     *** CONSTANTS ***
C
      C1=3.14159/L
      C3=97.40876/(L**3.0)
      C4=EI*C3/2.0
      C5=L*BMASS/2.0
      C6=BMASS*L**2.0/9.86958772
      C7=3.14159/LL
      C15=16.1*BMASS/(SMOE*SMOI)
      C10=C15*L**3.0
      C11=6.0*L*C15
      C12=4.0*C15
      DS1=5201.43
      DS2=7411.62
```

```
      LLL=LL+L
      L1=L/4.0    $    L2=L/2.0    $    L3=3.0*L1
      LLL1=LL+L1 $    LLL2=LL+L2 $    LLL3=LL+L3
      DELTAT=0.00892045
      DELTAT2=DELTAT*DELTAT
      PRINT 88
   88 FORMAT (*1*)
      PRINT 600
  600 FORMAT (T21,*----- THE AXLE LOADS ARE TREATED THE MAXIMUM ALLOWABL
     1E LOADS ------*)
      PRINT 150
  150 FORMAT (T5,*VEHICLE *,T15,*VEHICLE VELOCITY*,T34,*MAXIMUM STRESS R
     1ANGE(PSI) AT*,T66,*MAXIMUM DYNAMIC STRESS(PSI) AT*,T100,*MINIMUM D
     2YNAMIC STRESS(PSI) AT *)
      PRINT 151
  151 FORMAT (T5,*TYPE*,T21,*(MPH)*,T34,*0.25L        0.50L       0.75L*,
     1T66,*0.25L          0.50L         0.75L*,T100,*0.25L          0.50L
     2  0.75L*)
C
C     READ VEHICLE DATA
C
  500 FORMAT (A6,2I2)
  502 FORMAT (3I1)
  503 FORMAT (8F10.2)
  504 FORMAT (2I3)
      READ 504, NOVT, NOVV
      READ 503, (SPEED(I), I=1, NOVV)
      DO 505 MM=1,NOVT
      READ 500, VT,NOA,NOT
      READ 502, (NOAOE(I), I=1, NOT)
      DO 506 I=1, NOT
      M=NOAOE(I)
      READ 503, (XXX(I,J), J=1,M)
      READ 503, (A(I,J), J=1,M)
      READ 503, (WT(I,J), J=1,M)
      TOTALWT(I)=0.0
```

```
C
C     DEFINE THE SPRING CONSTANT AND THE DAMPING COEFFICIENT
C
      DO 501 J=1,M
      K(I,J)=0.80101*WT(I,J)
      C(I,J)=0.09106*WT(I,J)
      DS(I,J)=WT(I,J)/K(I,J)
      TOTALWT(I)=TOTALWT(I)+WT(I,J)
  501 CONTINUE
      IF (M.EQ.1) GO TO 601
      P(I)=XXX(I,1)-XXX(I,M)
      GO TO 602
  601 P(I)=0.0
  602 VMASS(I)=TOTALWT(I)/386.4
C     CALCULATE THE POLAR MOMENT OF INERTIA
  506 POLARM(I)=(VMASS(I)*(P(I)**2.0))/12.0
      DO 505 NN=1, NOVV
      VEL=SPEED(NN)
      DO 400 I=1,NOT
      M=NOAOE(I)
      DO 400 J=1,M
  400 XX(I,J)=XXX(I,J)
      TLL=LL/VEL
      TXXLLL=(-XX(NOT,NOAOE(NOT))+LLL)/VEL
      TIME=DELTAT
      C2=C1*VEL
      C8=C7*VEL
      INDEX=1
C     INITIAL CONDITIONS
      FDD=0.0   $   FD=0.0   $   F=0.0
      FDD1=0.0  $   FD1=0.0  $   F1=0.0
      DO 23 I=1,NOT
      Z(I)=0.0   $   ZD(I)=0.0   $   ZDD(I)=0.0
      SITA(I)=0.0   $   SITAD(I)=0.0   $   SITADD(I)=0.0
   23 CONTINUE
      STORE=VEL*DELTAT
```

```
909 CONTINUE
    ALL=0.0
    PART1=0.0    $    PART2=0.0    $    PART3=0.0
    ADDG=0.0     $    ADDH=0.0
907 CONTINUE
    DO 24 I=1,NOT
    Z1(I)=0.0       $     ZD1(I)=0.0       $     ZDD1(I)=0.0
    SITA1(I)=0.0    $     SITAD1(I)=0.0    $     SITADD1(I)=0.0
 24 CONTINUE
C   CALCULATE THE HORIZONTAL POSITION OF EACH AXLE
    DO 20 I=1,NOT
    KKK=NOAOE(I)
    DO 20 J=1,KKK
 20 XX(I,J)=XX(I,J)+STORE
C   DEFINE THE INDEXES ***** E1, E2, E3, E4
    DO 21 I=1,NOT
    KKK=NOAOE(I)
    DO 21 J=1,KKK
    E3(I,J)=0.0
    E4(I,J)=0.0
    STEMP(I,J)=0.0
    CTEMP(I,J)=0.0
    IF (XX(I,J).GT.LL.AND.XX(I,J).LT.LLL) GO TO 26
    IF (XX(I,J).GT.0.0.AND.XX(I,J).LT.LL) E4(I,J)=1.0
    GO TO 21
 26 E3(I,J)=1.0
    HALL=C1*(XX(I,J)-LL)
    STEMP(I,J)=SIN(HALL)
    CTEMP(I,J)=COS(HALL)
 21 CONTINUE
    DO 22 I=1,NOT
    E2(I)=0.0
    KKK=NOAOE(I)
    DO 25 J=1,KKK
    IF (XX(I,J).GE.LLL) GO TO 29
    IF (E3(I,J).EQ.1.0.OR.E4(I,J).EQ.1.0) GO TO 29
```

```
 25 CONTINUE
    GO TO 22
 20 E2(I)=1.0
 22 CONTINUE
C
C     SOLVE THE GOVERNING EQUATIONS OF MOTION
C
    IF (TIME.GT.TLL) F1=F+DELTAT*FD+0.5*DELTAT2*FDD
    DO 100 I=1,NOT
    GKS(I)=0.0       $      HCS(I)=0.0
    IF (E2(I).EQ.0.0) GO TO 100
    SUMS(I)=0.0
    SUMZ(I)=TOTALWT(I)
    KKK=NOAOE(I)
    IF (KKK.EQ.1) GO TO 30
    SITA1(I)=SITA(I)+DELTAT*SITAD(I)+0.5*SITADD(I)*DELTAT2
 30 Z1(I)=Z(I)+DELTAT*ZD(I)+0.5*DELTAT2*ZDD(I)
    DO 101 J=1,KKK
    G(I,J)=0.0       $      GK(I,J)=0.0
    H(I,J)=0.0       $      HC(I,J)=0.0
    GKA(I,J)=0.0     $      HCA(I,J)=0.0
    TEMP1(I,J)=0.0   $      TEMP2(I,J)=0.0
    YB(I,J)=0.0      $      YBD(I,J)=0.0
    IF (E3(I,J).EQ.0.0.AND.E4(I,J).EQ.0.0) GO TO 105
    IF( E3(I,J).EQ.0.0) GO TO 103
    YY=XX(I,J)-LL
    DLD=C10*YY-(C11/3.0)*YY**3.0+(C12/4.0)*YY**4.0
    DLDD=C10-C11*YY**2.0+C12*YY**3.0
    TEMP1(I,J)=DLD+F1*STEMP(I,J)
    TEMP2(I,J)=DLDD+FD*STEMP(I,J)+F*C2*CTEMP(I,J)
103 CONTINUE
    IF (E4(I,J).EQ.0.0) GO TO 105
    C9=C7*XX(I,J)
    YB(I,J)=D*SIN(C9)
    YBD(I,J)=D*C8*COS(C9)
105 CONTINUE
```

```
      G(I,J)=-DS(I,J)-Z1(I)-A(I,J)*SITA1(I)+TEMP1(I,J)+YB(I,J)
      GK(I,J)=G(I,J)*K(I,J)
      H(I,J)=-ZD(I)-A(I,J)*SITAD(I)+TEMP2(I,J)+YBD(I,J)
      HC(I,J)=H(I,J)*C(I,J)
      GKA(I,J)=GK(I,J)*A(I,J)
      HCA(I,J)=HC(I,J)*A(I,J)
      IF (E3(I,J).EQ.0.0) GO TO 108
      GKS(I)=GKS(I)-GK(I,J)*STEMP(I,J)
      HCS(I)=HCS(I)-HC(I,J)*STEMP(I,J)
      ALL=ALL-(LLL-XX(I,J))*(GK(I,J)+HC(I,J))
      IF (XX(I,J).GE.LLL1) GO TO 120
      PART1=PART1+(LLL1-XX(I,J))*(GK(I,J)+HC(I,J))
      GO TO 109
  120 CONTINUE
      IF (XX(I,J).GE.LLL2) GO TO 121
  109 PART2=PART2+(LLL2-XX(I,J))*(GK(I,J)+HC(I,J))
      GO TO 107
  121 CONTINUE
      IF (XX(I,J).GE.LLL3) GO TO 108
  107 PART3=PART3+(LLL3-XX(I,J))*(GK(I,J)+HC(I,J))
  108 SUMZ(I)=SUMZ(I)+GK(I,J)+HC(I,J)
      SUMS(I)=SUMS(I)+GKA(I,J)+HCA(I,J)
  101 CONTINUE
C     CALCULATE ZDD AND SITADD
      ZDD1(I)=SUMZ(I)/VMASS(I)
      IF (KKK.EQ.1) GO TO 31
      SITADD1(I)=SUMS(I)/POLARM(I)
C     CALCULATE ZD AND SITAD
      SITAD1(I)=SITAD(I)+0.5*DELTAT*(SITADD(I)+SITADD1(I))
   31 ZD1(I)=ZD(I)+0.5*DELTAT*(ZDD(I)+ZDD1(I))
  100 CONTINUE
C
C     CHECK E1
C
      IF (TIME.LE.TLL) GO TO 998
      DO 403 I=1,NOT
      ADDG=ADDG+GKS(I)
```

```
  403 ADDH=ADDH+HCS(I)
C     CALCULATE FDD1 AND FD1
      FDD1=(-C4*F1+ADDG+ADDH)/C5
      FD1=FD+0.5*DELTAT*(FDD+FDD1)
C     CALCULATE THE DYNAMIC BENDING MOMENT AT THREE CRITICAL SECTIONS
      DYNM1(INDEX)=0.25*ALL+PART1-0.7071*C6*FDD1
      DYNM2(INDEX)=0.50*ALL+PART2-C6*FDD1
      DYNM3(INDEX)=0.75*ALL+PART3-0.7071*C6*FDD1
      INDEX=INDEX+1
  998 TIME=TIME+DELTAT
      DO 300 I=1,NOT
      Z(I)=Z1(I)
      ZD(I)=ZD1(I)
      ZDD(I)=ZDD1(I)
      SITA(I)=SITA1(I)
      SITAD(I)=SITAD1(I)
  300 SITADD(I)=SITADD1(I)
      IF (TIME.LE.TLL) GO TO 997
      F=F1
      FD=FD1
      FDD=FDD1
      IF (TIME.GE.TXXLLL) GO TO 200
      GO TO 999
  200 CONTINUE
      INDEX=INDEX-1
      STORE1=0.0    $    STORE2=0.0    $    STORE3=0.0
C     CHOOSE THE MAXIMUM BENDING MOMENT
      DO 202 II=1,INDEX
      DBM1=AMAX1( STORE1, DYNM1(II))
      DBM2=AMAX1( STORE2, DYNM2(II))
      DBM3=AMAX1( STORE3, DYNM3(II))
      STORE1=DBM1
      STORE2=DBM2
  202 STORE3=DBM3
      STRESS1=DBM1*DB2/CMOI
      STRESS2=DBM2*DB1/CMOI
```

```
      STRESS3=DBM3*DB2/CMOI
C     CALCULATE THE REBOUND STRESS
      INDEX=PERIOD/DELTAT
      DO 250 JJJ=1,INDEX
      SF1(JJJ)=F+DELTAT*FD+0.5*DELTAT2*FDD
      SFDD1(JJJ)= -C4*SF1(JJJ)/C5
      SFD1(JJJ)=FD+0.5*DELTAT*(FDD+SFDD1(JJJ))
      F=SF1(JJJ)
      FD=SFD1(JJJ)
      FDD=SFDD1(JJJ)
      DYNM1(JJJ)=-0.7071*C6*FDD
      DYNM2(JJJ)=-C6*FDD
      DYNM3(JJJ)=DYNM1(JJJ)
  250 CONTINUE
      STORE1=0.0      $      STORE2=0.0
C     CHOOSE THE MINIMUM BENDING MOMENT
      DO 203 II=1, INDEX
      DBM1=AMIN1(STORE1, DYNM1(II))
      DBM2=AMIN1(STORE2, DYNM2(II))
      STORE1=DBM1
  203 STORE2=DBM2
      STRESS4=ABS(DBM1*DB2/CMOI)
      STRESS5=ABS(DBM1*DB2/CMOI)
      SR1=STRESS1+STRESS4
      SR2=STRESS2+STRESS5
      SR3=STRESS3+STRESS4
      VEL2=VEL/17.6
      STRESS1=STRESS1+DS1
      STRESS2=STRESS2+DS2
      STRESS3=STRESS3+DS1
      STRESS4=DS1-STRESS4
      STRESS5=DS2-STRESS5
      PRINT 800, VT,VEL2,SR1,SR2,SR3,STRESS1,STRESS2,STRESS3,STRESS4,
     1STRESS5,STRESS4
  800 FORMAT (T5,A6,T19,F7.1,T33,F8.2,T44,F8.2,T54,F8.2,T65,F8.2,T77,F8.
     12,T88,F8.2,T99,F8.2,T111,F8.2,T122,F8.2)
```

```
801 FORMAT (A8, 9F8.2)
505 CONTINUE
    STOP
    END
C
    PUNCH 801, VT,SR1,SR2,SR3,STRESS1,STRESS2,STRESS3,STRESS4,STRESS5,
   1STRESS4
C   ******************************************************************
C
    PROGRAM STATIC
C   THIS PROGRAM COMPUTES THE MAXIMUM STATIC STRESS RANGES
    DIMENSION  XX(20), WT(20), X(20), BM(20), STORE(45,3), PERCENT(5)
    DIMENSION VT(45), SSP(45,3), INDEX(3), INDEX1(3), INDEX2(3), DB(3)
    REAL L, MBM, INDEX, INDEX1, INDEX2
  1 FORMAT (3I2)
  3 FORMAT (A6,I2)
  4 FORMAT (8F10.1)
  5 FORMAT (8F10.4)
314 FORMAT (4X,A6,7X,F10.3,2(8X,F10.3))
315 FORMAT (3F10.3)
400 FORMAT (* VEHICLE TYPE*,T20,*STATIC STRESS RANGE OF CRITICAL SECTI
   1ON AT*)
401 FORMAT (T20,*0.25L*,T40,*0.50L*,T60,*0.75L*,/)
C   READ BRIDGE AND VEHICLE DATA
    READ 1, NOVT, NOVW, NOCS
    READ 5, L, CMOI
    READ 5, (DP(I), I=1, NOCS)
    READ 4, (PERCENT(I), I=1, NOVW)
    READ 5, (INDEX(I), I=1, NOCS)
    READ 5, (INDEX1(I), I=1, NOCS)
    READ 5, (INDEX2(I), I=1, NOCS)
    DO 300 MM=1, NOVT
    READ 3, VT(MM), NOA
    READ 4, (XX(I), I=1, NOA)
    READ 4, (WT(I), I=1, NOA)
    DO 300 III=1, NOCS
```

```
      DUMMY=L*INDEX(III)
      TEST=DUMMY
C     DEFINE THE HORIZONTAL POSITION OF EACH AXLE
      DO 40 I=1,12
   40 BM(I)=0.0
      DO 11 J=1, NOA
      DO 10 I=1, NOA
      X(I)=DUMMY-XX(I)
      IF (X(I).LE.0.0) GO TO 10
      IF (X(I).GE.L   ) GO TO 10
      IF (X(I).GT.TEST) GO TO 12
      BM(J)=BM(J)+INDEX1(III)*X(I)*WT(I)*0.8857
      GO TO 10
   12 BM(J)=BM(J)+INDEX2(III)*WT(I)*(L-X(I))*0.8857
   10 CONTINUE
      DUMMY=TEST+XX(J+1)
   11 CONTINUE
C     CHOOSE THE MAXIMUM BENDING MOMENT
      MBM=AMAX1(BM(1),BM(2),BM(3),BM(4),BM(5),BM(6),BM(7),BM(8),BM(9),
     1BM(10),BM(11),BM(12))
  300 SSR(MM,III)=(MBM*DR(III))/CMOI
  301 FORMAT (/,* STATIC AXLE LOADINGS OF EACH VEHICLE ARE TREATED AS TH
     1E MAXIMUM ALLOWABLE AXLE LOADINGS*,/)
  302 FORMAT (/,* STATIC AXLE LOADINGS OF EACH VEHICLE ARE TREATED AS 90
     1 PERCENT OF THE MAX. ALLOWABLE AXLE LOADINGS*,/)
  303 FORMAT (/,* STATIC AXLE LOADINGS OF EACH VEHICLE ARE TREATED AS 80
     1 PERCENT OF THE MAX. ALLOWABLE AXLE LOADINGS*,/)
  304 FORMAT (/,* STATIC AXLE LOADINGS OF EACH VEHICLE ARE TREATED AS 70
     1 PERCENT OF THE MAX. ALLOWABLE AXLE LOADINGS*,/)
  305 FORMAT (/,* STATIC AXLE LOADINGS OF EACH VEHICLE ARE TREATED AS 50
     1 PERCENT OF THE MAX. ALLOWABLE AXLE LOADINGS*,/)
      PRINT 555
  555 FORMAT (*1*,///)
      DO 306 IJK=1, NOVW
      IF (IJK.EQ.1) GO TO 307
      IF (IJK.EQ.2) GO TO 308
```

```
      IF (IJK.EQ.3) GO TO 309
      IF (IJK.EQ.4) GO TO 310
      IF (IJK.EQ.5) GO TO 311
  307 PRINT 301      $     GO TO 312
  308 PRINT 302      $     GO TO 312
  309 PRINT 303      $     GO TO 312
  310 PRINT 304      $     GO TO 312
  311 PRINT 305      $     GO TO 312
  312 PRINT 400      $     PRINT 401
      DO 306 I=1, NOVT
      DO 313 J=1, NOCS
  313 STORE(I,J)=SSR(I,J)*PERCENT(IJK)
      PRINT 314, VT(I), (STORE(I,J), J=1, NOCS)
  306 PUNCH 315, (STORE(I,J), J=1, NOCS)
      STOP
      END
C
C     ************************************************************************
C
C     PROGRAM SIMU1
C     THIS PROGRAM IS PREPARED TO ESTIMATE THE FATIGUE LIFE OF HIGHWAY
C     BRIDGES, IT INVOLVES THREE SUBROUTINES ... SELECT1,RFD100,FATIG
      DIMENSION INDEXWT(5), ADD(43), STORE1(43), NOA1(43), NOLU(43),
     1NOAOELU(43,3), XXX1(43,3,7), AA(43,3,7), WT1(43,3,7), VT(2366),
     2SR1(2366),SR2(2366),SR3(2366),SMAX1(2366),SMAX2(2366),SMAX3(2366),
     3SMIN1(2366),SMIN2(2366),SMIN3(2366),LITTLEN(2366),SMALLN(215),
     4SSR1(215),SSR2(215),SSR3(215),UVT(43),UVV(11),UVW(5),RF1(43),
     5RFW(5),RFS(11),SPFED(11),AB(7),CAR99(7,3),MMMMM(7,3),STOREWT(5),
     6SRFD1(11),SRFD2(11),SRFD3(11),SSRFD1(11),SSRFD2(11),SSRFD3(11)
      DIMENSION STORESP(11),SCALE(11),NOAOE(6),XX(6,7),A(6,7),WT(6,7),
     1TOTALWT(6),K(6,7),C(6,7),DS(6,7),VMASS(6),P(6),POLARM(6),Z(6),
     2ZD(6),ZDD(6),SITA(6),SITAD(6),SITADD(6),Z1(6),ZD1(6),BLIFE(7,3),
     3ZDD1(6),SITA1(6),SITAD1(6),SITADD1(6),E3(6,7),E4(6,7),STEMP(6,7),
     4CTEMP(6,7),E2(6),SUMS(6),GKS(6),HCS(6),SUMZ(6),G(6,7),GK(6,7),
     5H(6,7),HC(6,7),GKA(6,7),HCA(6,7),TEMP1(6,7),TEMP2(6,7),YB(6,7),
     6YBD(6,7),DYNM1(1200),DYNM2(1200),DYNM3(1200),SUM(43),RF2(43)
```

```
      DIMENSION AVV(6000), CHECK(7,3), CAR88(7,3)
      REAL L,LL,LLL,L1,L2,L3,LLL1,LLL2,LLL3,K,IAT,INDEXWT,LITTLEN,LITTLE
     1M,J1,LOWERL
      INTEGER SUM,TOTAL,SPEED,BLIFE,STORE11
      EQUIVALENCE (LITTLEN(1), VT(1))
      EQUIVALENCE (SMIN1(1), SMIN3(1))
      EQUIVALENCE (DYNM1(1), AVV(1))
      EQUIVALENCE (DYNM2(1), AVV(1202))
      EQUIVALENCE (DYNM3(1), AVV(2403))
      EQUIVALENCE (SR1(250), AVV(3604))
    1 FORMAT (16I5)
    2 FORMAT (10A1)
    3 FORMAT (8F10.5)
    4 FORMAT (A8, 9F8.2)
    6 FORMAT (4F10.2)
    7 FORMAT (2F10.3,E8.1)
    8 FORMAT (I6)
12345 FORMAT (8F10.1)
      READ 1, NOVT,NOVV,NOVW,NOEM,NOCS
      READ 3, AAT
 1501 FORMAT (A6,2I2)
 1502 FORMAT (3I1)
 1503 FORMAT (8F10.2)
      READ 6, L,BMASS,LL,D
      READ 7, SMOI,CMOI,SMOE
      READ 6, DB1, DB2, CPS
      READ 3, (INDEXWT(I), I=1, NOVW)
      EI=SMOE*CMOI
      PERIOD=1.0/CPS
      DO 1500 MM=1, NOVT
      ADD(MM)=0.0
      READ 1501, STORE1(MM),NOA1(MM), NOLU(MM)
      M=NOLU(MM)
      READ 1502, (NOAOELU(MM,I), I=1, M)
      DO 1500 I=1, M
      M1=NOAOELU(MM,I)
```

```
      READ 1503, (XXX1(MM,I,J), J=1, M1)
      READ 1503, (AA(MM,I,J), J=1, M1)
 1500 READ 1503, (WT1(MM,I,J), J=1, M1)
C
C     *** CONSTANTS ***
C
      C1=3.14159/L
      C3=97.40876/(L**3.0)
      C4=EI*C3/2.0
      C5=L*BMASS/2.0
      C6=BMASS*L**2.0/9.86958772
      C7=3.14159/LL
      C15=16.1*BMASS/(SMOE*SMOI)
      C10=C15*L**3.0
      C11=6.0*L*C15
      C12=4.0*C15
      LLL=LL+L
      L1=L/4.0    $   L2=L/2.0    $   L3=3.0*L1
      LLL1=LL+L1  $   LLL2=LL+L2  $   LLL3=LL+L3
C     DEFINE TIME INCREMENT
      DELTAT=0.00892045
      DELTAT2=DELTAT*DELTAT
C
C     READ ***** STRESS RANGE, MAX.STRESS, MIN. STRESS
C     ***** DYNAMIC
      INDEXA=NOVV*NOVT
      INDEXB=NOVT*NOVW
      INDEX=NOVW*NOVV*NOVT
      DO 119 I=1, INDEX
      READ 4,  VT(I),SR1(I),SR2(I),SR3(I),SMAX1(I),SMAX2(I),SMAX3(I),
     1SMIN1(I),SMIN2(I), SMIN3(I)
      SR1(I)=SR1(I)/1000.0
      SR2(I)=SR2(I)/1000.0
      SR3(I)=SR3(I)/1000.0
      SMAX1(I)=SMAX1(I)/1000.0
      SMAX2(I)=SMAX2(I)/1000.0
```

```
      SMAX3(I)=SMAX3(I)/1000.0
      SMIN1(I)=SMIN1(I)/1000.0
      SMIN2(I)=SMIN2(I)/1000.0
      SMIN3(I)=SMIN3(I)/1000.0
  119 LITTLEN(I)=0.0
C
C     READ ***** STRESS RANGE, MAX.STRESS, MIN.STRESS
C     ***** STATIC
      DO 601 I=1, INDEXB
      SMALLN(I)=0.0
  601 READ 3, SSR1(I), SSR2(I), SSR3(I)
C     READ THE RFD OF RANDOM PARAMETERS
      READ 3, (UVT(I), I=1, NOVT)
      READ 3, (UVV(I), I=1, NOVV)
      READ 3, (UVW(I), I=1, NOVW)
      READ 3, (RF1(I), I=1, NOVT)
      READ 3, (RFW(I), I=1, NOVW)
      READ 3, (RFS(I), I=1, NOVV)
      READ 1, (SPEED(I), I=1, NOVV)
      READ 2, (AB(I), I=1, NOFM)
      READ 8, TOTAL
      READ 3, DLS1, DLS2
C     READ VEHICLE VOLUME LIMIT
      READ 1503, LOWERL, UPPERL
      RANGE=UPPERL-LOWERL
      FTOTAL=TOTAL
      FTOTAL1=FTOTAL
      DO 34 I=1, NOVW
   34 STOREWT(I)=0.0
      DO 35 I=1, NOVV
      SRFD1(I)=0.0        $      SRFD2(I)=0.0       $      SRFD3(I)=0.0
      SSRFD1(I)=0.0       $      SSRFD2(I)=0.0      $      SSRFD3(I)=0.0
   35 STORESP(I)=0.0
      DO 33 I=1, NOFM
      DO 33 J=1, NOCS
   33 CAR99(I,J)=0.0
```

```
      XYZ=0.0
      DO 36 I=1, 11
      SCALE(I)=1.0+XYZ
   36 XYZ=1.0+XYZ
      INDEX99=100
      IIJJKK=1
      XSQUARE=0.0       $       XBAR=0.0
      I101=1
C     CHOOSE A RANDOM NUMBER ********** FOR VEHICLE LOAD
 9908 J1=RANF(-1)
      DO 26 I=1, NOVW
      IF (J1.LE.UVW(I)) GO TO 21
   26 CONTINUE
   21 INDEX1=I
      STOREWT(I)=STOREWT(I)+1.0
C     CHOOSE A RANDOM NUMBER ********** FOR VEHICLE TYPE
      J1=RANF(-1)
      CALL SELECT1(10,20,30,NOVT,INDEX2,J1,UVT)
      ADD(INDEX2)=ADD(INDEX2)+1.0
C     CHOOSE A RANDOM NUMBER ********** FOR VEHICLE SPEED
      J1=RANF(-1)
      CALL SELECT1(3,6,9,NOVV,INDEX3,J1,UVV)
      STORESP(INDEX3)=STORESP(INDEX3)+1.0
      INDEXR=INDEXA*(INDEX1-1)+NOVV*(INDEX2-1)+INDEX3
      LITTLEN(INDEXR)=LITTLEN(INDEXR)+1.0
      INDEXS=(INDEX1-1)*NOVT+INDEX2
      SMALLN(INDEXS)=SMALLN(INDEXS)+1.0
      SSR10=SSR1(INDEXS)
      SSR20=SSR2(INDEXS)
      SSR30=SSR3(INDEXS)
      CALL RFD100(SSR10,SSR20,SSR30,SCALE,SSRFD1,SSRFD2,SSRFD3)
      IIJJKK=IIJJKK+1
C     CHECK THE INTERARRIVAL TIME
      RN=RANF(-1)
      IAT=-1.0*ALOG(RN)/AAT
      XSQUARE=XSQUARE+IAT*IAT
```

```
      XBAR=XBAR+IAT
      WAY99=0.0
      VEL=SPEED(INDEX3)
      VEL=17.6*VEL
      TL=L/VEL
      TLIMIT=2.0*PERIOD+TL
      INDEZ=1
      IF (IAT.GE.TLIMIT) GO TO 550
      WAY99=2.0
      IF (IAT.LT.TL) GO TO 10
      GO TO 566
   10 WAY99=1.0
      FTOTAL1=FTOTAL1-1.0
  566 LITTLEN(INDEXR)=LITTLEN(INDEXR)-1.0
      J1=RANF(-1)
      DO 28 I=1, NOVW
      IF (J1.LE.UVW(I)) GO TO 29
   28 CONTINUE
   29 INDEX4=I
      STOREWT(I)=STOREWT(I)+1.0
      J1=RANF(-1)
      CALL SELECT1(10,20,30,NOVT,INDEX5,J1,UVT)
      ADD(INDEX5)=ADD(INDEX5)+1.0
      STORESP(INDEX3)=STORESP(INDEX3)+1.0
      INDEXS=(INDEX4-1)*NOVT+INDEX5
      SMALLN(INDEXS)=SMALLN(INDEXS)+1.0
      I101=I101+1
      SSR10=SSR1(INDEXS)
      SSR20=SSR2(INDEXS)
      SSR30=SSR3(INDEXS)
      CALL RFD100(SSR10,SSR20,SSR30,SCALE,SSRFD1,SSRFD2,SSRFD3)
      IIJJKK=IIJJKK+1
      NOA=NOA1(INDEX2)+NOA1(INDEX5)
      NOT=NOLU(INDEX2)+NOLU(INDEX5)
      MAA=NOLU(INDEX2)
      DO 1000 I=1, MAA
```

```
 1000 NOAOE(I)=NOAOELU(INDEX2,I)
      MBB=NOLU(INDEX5)
      DO 1001 I=1, MBB
      MAA=MAA+1
 1001 NOAOE(MAA)=NOAOELU(INDEX5,I)
      MAA=NOLU(INDEX2)
      DO 1002 I=1, MAA
      TOTALWT(I)=0.0
      MBB=NOAOELU(INDEX2,I)
      DO 1002 J=1, MBB
      A(I,J)=AA(INDEX2,I,J)
      XX(I,J)=XXX1(INDEX2,I,J)
 1002 WT(I,J)=WT1(INDEX2,I,J)*INDEXWT(INDEX1)
      DISTANS=IAT*VEL- XX(MAA,MBB)
      MAA=NOLU(INDEX5)
      MAB=NOLU(INDEX2)
      DO 1003 I=1, MAA
      TOTALWT(I+MAB)=0.0
      MBB=NOAOELU(INDEX5,I)
      DO 1003 J=1, MBB
      A(I+MAB,J)=AA(INDEX5,I,J)
      XX(I+MAB,J)=XXX1(INDEX5,I,J)-DISTANS
 1003 WT(I+MAB,J)=WT1(INDEX5,I,J)*INDEXWT(INDEX4)
C
C     DEFINE THE SPRING CONSTANT AND THE DAMPING COEFFICIENT
C
      DO 501 I=1, NOT
      M=NOAOE(I)
      DO 506 J=1, M
      K(I,J)=0.80101*WT(I,J)
      C(I,J)=0.09106*WT(I,J)
      DS(I,J)=WT(I,J)/K(I,J)
  506 TOTALWT(I)=TOTALWT(I)+WT(I,J)
      VMASS(I)=TOTALWT(I)/386.4
      IF (NOAOE(I).EQ.1) GO TO 611
      P(I)=XX(I,1)-XX(I,M)
```

```
      POLARM(I)=(VMASS(I)*(P(I)**2.0))/12.0
      GO TO 501
  611 P(I)=0.0
      POLARM(I)=0.0
  501 CONTINUE
      TLL=LL/VEL
      TXXLLL=(-XX(NOT,NOAOE(NOT))+LLL)/VEL
      TIME=DELTAT
      C2=C1*VEL
      C8=C7*VEL
      INDEY=1
C     INITIAL CONDITIONS
      FDD=0.0    $   FD=0.0    $   F=0.0
      FDD1=0.0   $   FD1=0.0   $   F1=0.0
      DO 23 I=1,NOT
      Z(I)=0.0    $   ZD(I)=0.0    $   ZDD(I)=0.0
      SITA(I)=0.0    $   SITAD(I)=0.0    $   SITADD(I)=0.0
   23 CONTINUE
      STORE9=VEL*DELTAT
 1909 CONTINUE
      ALL=0.0
      PART1=0.0    $   PART2=0.0    $   PART3=0.0
      ADDG=0.0      $   ADDH=0.0
  907 CONTINUE
      DO 24 I=1,NOT
      Z1(I)=0.0       $      ZD1(I)=0.0      $      ZDD1(I)=0.0
      SITA1(I)=0.0    $      SITAD1(I)=0.0   $      SITADD1(I)=0.0
   24 CONTINUE
C     CALCULATE THE HORIZONTAL POSITION OF EACH AXLE
      DO 20 I=1,NOT
      KKK=NOAOE(I)
      DO 20 J=1,KKK
   20 XX(I,J)=XX(I,J)+STORE9
C     DEFINE THE INDEXES ***** E1, E2, E3, E4
      DO 27 I=1,NOT
      KKK=NOAOE(I)
```

```
      DO 27 J=1,KKK
      E3(I,J)=0.0
      E4(I,J)=0.0
      STEMP(I,J)=0.0
      CTEMP(I,J)=0.0
      IF (XX(I,J).GT.LL.AND.XX(I,J).LT.LLL) GO TO 1026
      IF (XX(I,J).GT.0.0.AND.XX(I,J).LT.LL) E4(I,J)=1.0
      GO TO 27
 1026 E3(I,J)=1.0
      HALL=C1*(XX(I,J)-LL)
      STEMP(I,J)=SIN(HALL)
      CTEMP(I,J)=COS(HALL)
   27 CONTINUE
      DO 22 I=1,NOT
      E2(I)=0.0
      KKK=NOAOE(I)
      DO 25 J=1,KKK
      IF (XX(I,J).GE.LLL) GO TO 1029
      IF (E3(I,J).EQ.1.0.OR.E4(I,J).EQ.1.0) GO TO 1029
   25 CONTINUE
      GO TO 22
 1029 E2(I)=1.0
   22 CONTINUE
C
C     SOLVE THE GOVERNING EQUATIONS OF MOTION
C
      IF (TIME.GT.TLL) F1=F+DELTAT*FD+0.5*DELTAT2*FDD
      DO 100 I=1,NOT
      GKS(I)=0.0      $      HCS(I)=0.0
      IF (E2(I).EQ.0.0) GO TO 100
      SUMS(I)=0.0
      SUMZ(I)=TOTALWT(I)
      KKK=NOAOE(I)
      IF (KKK.EQ.1) GO TO 1030
      SITA1(I)=SITA(I)+DELTAT*SITAD(I)+0.5*SITADD(I)*DELTAT2
 1030 Z1(I)=Z(I)+DELTAT*ZD(I)+0.5*DELTAT2*ZDD(I)
      DO 101 J=1,KKK
```

```
      G(I,J)=0.0        $      GK(I,J)=0.0
      H(I,J)=0.0        $      HC(I,J)=0.0
      GKA(I,J)=0.0      $      HCA(I,J)=0.0
      TEMP1(I,J)=0.0    $      TEMP2(I,J)=0.0
      YB(I,J)=0.0       $      YBD(I,J)=0.0
      IF (E3(I,J).EQ.0.0.AND.E4(I,J).EQ.0.0) GO TO 105
      IF( E3(I,J).EQ.0.0) GO TO 103
      YY=XX(I,J)-LL
      DLD=C10*YY-(C11/3.0)*YY**3.0+(C12/4.0)*YY**4.0
      DLDD=C10-C11*YY**2.0+C12*YY**3.0
      TEMP1(I,J)=DLD+F1*STEMP(I,J)
      TEMP2(I,J)=DLDD+FD*STEMP(I,J)+F*C2*CTEMP(I,J)
  103 CONTINUE
      IF (E4(I,J).EQ.0.0) GO TO 105
      C9=C7*XX(I,J)
      YB(I,J)=D*SIN(C9)
      YBD(I,J)=D*C8*COS(C9)
  105 CONTINUE
      G(I,J)=-DS(I,J)-Z1(I)-A(I,J)*SITA1(I)+TEMP1(I,J)+YB(I,J)
      GK(I,J)=G(I,J)*K(I,J)
      H(I,J)=-ZD(I)-A(I,J)*SITAD(I)+TEMP2(I,J)+YBD(I,J)
      HC(I,J)=H(I,J)*C(I,J)
      GKA(I,J)=GK(I,J)*A(I,J)
      HCA(I,J)=HC(I,J)*A(I,J)
      IF (E3(I,J).EQ.0.0) GO TO 108
      GKS(I)=GKS(I)-GK(I,J)*STEMP(I,J)
      HCS(I)=HCS(I)-HC(I,J)*STEMP(I,J)
      ALL=ALL-(LLL-XX(I,J))*(GK(I,J)+HC(I,J))
      IF (XX(I,J).GE.LLL1) GO TO 120
      PART1=PART1+(LLL1-XX(I,J))*(GK(I,J)+HC(I,J))
      GO TO 109
  120 CONTINUE
      IF (XX(I,J).GE.LLL2) GO TO 121
  109 PART2=PART2+(LLL2-XX(I,J))*(GK(I,J)+HC(I,J))
      GO TO 107
  121 CONTINUE
```

```
      IF (XX(I,J).GE.LLL3) GO TO 108
  107 PART3=PART3+(LLL3-XX(I,J))*(GK(I,J)+HC(I,J))
  108 SUMZ(I)=SUMZ(I)+GK(I,J)+HC(I,J)
      SUMS(I)=SUMS(I)+GKA(I,J)+HCA(I,J)
  101 CONTINUE
C     CALCULATE ZDD AND SITADD
      ZDD1(I)=SUMZ(I)/VMASS(I)
      IF (KKK.EQ.1) GO TO 31
      SITADD1(I)=SUMS(I)/POLARM(I)
C     CALCULATE ZD AND SITAD
      SITAD1(I)=SITAD(I)+0.5*DELTAT*(SITADD(I)+SITADD1(I))
   31 ZD1(I)=ZD(I)+0.5*DELTAT*(ZDD(I)+ZDD1(I))
  100 CONTINUE
C
C     CHECK E1
C
      IF (TIME.LE.TLL) GO TO 998
      DO 403 I=1,NOT
      ADDG=ADDG+GKS(I)
  403 ADDH=ADDH+HCS(I)
C     CALCULATE FDD1 AND FD1
      FDD1=(-C4*F1+ADDG+ADDH)/C5
      FD1=FD+0.5*DELTAT*(FDD+FDD1)
C     CALCULATE THE DYNAMIC BENDING MOMENT AT THREE CRITICAL SECTIONS
      DYNM1(INDEY)=0.25*ALL+PART1-0.7071*C6*FDD1
      DYNM2(INDEY)=0.50*ALL+PART2-C6*FDD1
      DYNM3(INDEY)=0.75*ALL+PART3-0.7071*C6*FDD1
      INDEY=INDEY+1
  998 TIME=TIME+DELTAT
      DO 1300 I=1, NOT
      Z(I)=Z1(I)
      ZD(I)=ZD1(I)
      ZDD(I)=ZDD1(I)
      SITA(I)=SITA1(I)
      SITAD(I)=SITAD1(I)
 1300 SITADD(I)=SITADD1(I)
```

```
      IF (TIME.LE.TLL) GO TO 997
      F=F1
      FD=FD1
      FDD=FDD1
      IF (TIME.GE.TXXLLL) GO TO 200
      GO TO 1999
  200 CONTINUE
      INDEY=INDEY-1
      INDEY1=INDEY
      IF (WAY99.EQ.1.0) GO TO 2000
      WAY77=PERIOD+TL
      IF (IAT.LE.WAY77) INDEY =WAY77/DELTAT
      IF (IAT.GT.WAY77) INDEY =(WAY77+PERIOD)/DELTAT
 2000 CONTINUE
      STORE0=0.0   $   STORE2=0.0   $   STORE3=0.0
      DO 202 II=INDEZ, INDEY
      DBM1=AMAX1( STORE0, DYNM1(II))
      DBM2=AMAX1( STORE2, DYNM2(II))
      DBM3=AMAX1( STORE3, DYNM3(II))
      STORE0=DBM1
      STORE2=DBM2
  202 STORE3=DBM3
      STRESS1=DBM1*DB1/CMOI
      STRESS2=DBM2*DB2/CMOI
      STRESS3=DBM3*DB1/CMOI
      INDEW=PERIOD/DELTAT
      INDEW=INDEY-INDEW
      IF (WAY99.EQ.2.0) GO TO 2001
C     CALCULATE THE REBOUND STRESS
      INDEY=PERIOD/DELTAT
      DO 250 JJJ=1,INDEY
      SF1=F+DELTAT*FD+0.5*DELTAT2*FDD
      SFDD1=-C4*SF1/C5
      SFD1=FD+0.5*DELTAT*(FDD+SFDD1)
      F=SF1
      FD=SFD1
```

```
      FDD=SFDD1
      DYNM1(JJJ)=-0.7071*C6*FDD
      DYNM2(JJJ)=-C6*FDD
      DYNM3(JJJ)=DYNM1(JJJ)
  250 CONTINUE
      INDEW=1
 2001 STORE0=0.0      $      STORE2=0.0      $      STORE3=0.0
      DO 203 II=INDEW, INDEY
      DBM1=AMIN1(STORE0, DYNM1(II))
      DBM2=AMIN1(STORE2, DYNM2(II))
      DBM3=AMIN1(STORE3, DYNM3(II))
      STORE0=DBM1
      STORE2=DBM2
  203 STORE3=DBM3
      STRESS4=ABS(DBM1*DB1/CMOI)
      STRESS5=ABS(DBM2*DB2/CMOI)
      STRESS6=ABS(DBM3*DB1/CMOI)
      SR10=(STRESS1+STRESS4)/1000.0
      SR20=(STRESS2+STRESS5)/1000.0
      SR30=(STRESS3+STRESS6)/1000.0
      SMAX10=(STRESS1+DLS1)/1000.0
      SMAX20=(STRESS2+DLS2)/1000.0
      SMAX30=(STRESS3+DLS1)/1000.0
      SMIN10=(DLS1-STRESS4)/1000.0
      SMIN20=(DLS2-STRESS5)/1000.0
      SMIN30=(DLS1-STRESS6)/1000.0
      LITTLEM=1.0
      CALL RFD100(SR10,SR20,SR30,SCALE,SRFD1,SRFD2,SRFD3)
      CALL FATIG(SR10,SR20,SR30,SMAX10,SMAX20,SMAX30,SMIN10,SMIN20,SMIN3
     10,CAR99,LITTLEM)
      IF (WAY99.EQ.1.0) GO TO 999
      INDEZ=INDEY+1
      INDEY=INDEY1
      WAY99=1.0
      GO TO 2000
  550 CONTINUE
```

```
      SR10=SR1(INDEXR)
      SR20=SR2(INDEXR)
      SR30=SR3(INDEXR)
      CALL RFD100(SR10,SR20,SR30,SCALE,SRFD1,SRFD2,SRFD3)
  999 CONTINUE
      IF (IIJJKK.GT.TOTAL) GO TO 9999
      GO TO 9998
 9999 XNUMBER=IIJJKK-2
      XBAR=XBAR/XNUMBER
      VARIANS=(XSQUARE-XNUMBER*(XBAR**2.0))/XNUMBER
      STANDV=SQRT(VARIANS)
      STORE11=0.0     $      STORE2=0.0      $      STORE3=0.0
      DO 305 I=1, NOVT
      SUM(I)=ADD(I)
      RF2(I)=ADD(I)/FTOTAL
      STORE11=STORE11+SUM(I)
      STORE2=STORE2+RF1(I)
  305 STORE3=STORE3+RF2(I)
      PRINT 88
   88 FORMAT (*1*,////)
      PRINT 211
  211 FORMAT (T20,* SIMULATION RESULTS---------  DYNAMIC APPROACH*,//)
      TOTAL=44.4940*FTOTAL
      PRINT 208, TOTAL
  208 FORMAT (T20,* ANNUAL HEAVY VEHICLE VOLUME IN THE FIRST YEAR  =*,I6
     1)
      PRINT 201
  201 FORMAT (T20,* VEHICLE      VEHICLE VOLUME      RELATIVE FREQ.      RE
     1LATIVE FREQ.*)
      PRINT 206
  206 FORMAT (T20,*   TYPE        (SIMULATION)        (FIELD DATA)        (
     1SIMULATION)*,/)
      DO 293 I=1, NOVT
  293 PRINT 292, 2TORE1(I), SUM(I), RF1(I), RF2(I)
  292 FORMAT (T21,A6,T36,I6,T54,F8.5,T73,F8.5)
      PRINT 297 , STORE11,STORE2, STORE3
```

```
207 FORMAT (/,T21,*SUM*,T36,I6,T54,F8.5,T73,F8.5)
    PRINT 950, I101
950 FORMAT (//,T21,*I101 = *,I5)
    SUMWT1=0.0      $      SUMWT2=0.0
    SUMSP1=0.0      $      SUMSP2=0.0
    DO 301 JI=1, NOVW
    STOREWT(JI)=STOREWT(JI)/FTOTAL
    SUMWT1=SUMWT1+STOREWT(JI)
301 SUMWT2=SUMWT2+RFW(JI)
    DO 309 JI=1, NOVV
    STORESP(JI)=STORESP(JI)/FTOTAL
    SUMSP1=SUMSP1+STORESP(JI)
309 SUMSP2=SUMSP2+RFS(JI)
    PRINT 302
302 FORMAT (*1*, /////)
    PRINT 306
306 FORMAT (T20,* NOTATION ----- M.A.A.L = MAXIMUM ALLOWABLE AXLE LOAD
   1INGS*,//)
    PRINT 303
303 FORMAT (T22,* CLASS OF AXLE*,10X,*RELATIVE FREQ.*,5X,*RELATIVE FRE
   1Q.*)
    PRINT 304
304 FORMAT ( T25,* LOADINGS*,13X,*(FIELD DATA)*,7X,*(SIMULATION)*,//)
    NOVW1=NOVW-1
    K1=100
    DO 308 I=1, NOVW1
    PRINT 307, K1, RFW(I), STOREWT(I)
308 K1=K1-10
307 FORMAT (T21,I3,* PER. OF 7.A.A.L*,8X,F8.4,11X,F8.4)
    K1=K1-10
    PRINT 307, K1, RFW(NOVW), STOREWT(NOVW)
    PRINT 453, SUMWT2, SUMWT1
453 FORMAT (/,T29,*SUM*,T48,F8.4,T67,F8.4,///)
    PRINT 303
    PRINT 450
450 FORMAT (T25,*SPEED (MPH)*,12X,*(FIELD DATA)*,6X,*(SIMULATION)*,//)
```

```
      DO 452 I=1, NOVV
  452 PRINT 451, SPEED(I), RFS(I), STOPESP(I)
  451 FORMAT (T29,I2,17X,F8.5,11X,F8.5)
      PRINT 458, SUMSP2, SUMSP1
  458 FORMAT (/,T29,*SUM*,T48,F8.5,T67,F8.5)
      PRINT 350, XBAR,VARIANS,STANDV
  350 FORMAT (///,T25,*THE MEAN VALUE OF INTERARRIVAL TIME IS*,F7.2,
     1*  VARIANCE*,F10.2,*STANDARD VARIANCE*,F7.2)
      PRINT 302
  808 PRINT 502
  502 FORMAT (T20,*STRESS   RANGE*,20X,*RELATIVE FREQUENCY OF STRESS RAN
     1GE AT*)
      PRINT 503
  503 FORMAT (T24,*(PSI.)*,T56,*0.25L*,11X,*0.50L*,9X,*0.75L*)
      SUMSR1=0.0      $      SUMSR2=0.0      $      SUMSR3=0.0
      DO 1506 LL9=1,11
      SRFD1(LL9)=SRFD1(LL9)/FTOTAL1
      SRFD2(LL9)=SRFD2(LL9)/FTOTAL1
      SRFD3(LL9)=SRFD3(LL9)/FTOTAL1
      SUMSR1=SUMSR1+SRFD1(LL9)
      SUMSR2=SUMSR2+SRFD2(LL9)
 1506 SUMSR3=SUMSR3+SRFD3(LL9)
      K01=0      $      K00=1000      $      KBB=65B
      PRINT 504, K01,KBB,K00,SRFD1(1),SRFD2(1),SRFD3(1)
  504 FORMAT (T21,I5,1X,R1,1X,I5,T54,F7.4,9X,F7.4,7X,F7.4)
      K01=1001      $      K00=K00+1000
      DO 505 IXY=2, 11
      PRINT 504, K01,KBB,K00,SRFD1(IXY),SRFD2(IXY),SRFD3(IXY)
      K00=K00+1000
  505 K01=K01+1000
      PRINT 507, SUMSR1, SUMSR2, SUMSR3
  507 FORMAT (/,T27,*SUM*,T54,F7.4,9X,F7.4,7X,F7.4)
      PRINT 204
  204 FORMAT (///,T20,*ESTIMATED FATIGUE LIFE OF THE TEST BRIDGE AT*,10X
     1,*ESTIMATED FATIGUE LIFE OF THE TEST BRIDGE AT*)
      PRINT 205
```

```
  205 FORMAT (T20,*0.25L*,T39,*0.50L*,T59,*0.75L*,10X,*0.25L*,15X,*0.50L
     1*,15X,*0.75L*)
      PRINT 209
  209 FORMAT (T37,*BY EQ.(4-5)*,T89,*BY TAKING 1/D*)
      DO 300 IJK=1, INDEX
      SR10=SR1(IJK)
      SR20=SR2(IJK)
      SR30=SR3(IJK)
      SMAX10=SMAX1(IJK)
      SMAX20=SMAX2(IJK)
      SMAX30=SMAX3(IJK)
      SMIN10=SMIN1(IJK)
      SMIN20=SMIN2(IJK)
      SMIN30=SMIN3(IJK)
      LITTLEM=LITTLEN(IJK)
      CALL FATIG(SR10,SR20,SR30,SMAX10,SMAX20,SMAX30,SMIN10,SMIN20,SMIN3
     10,CAR99,LITTLEM)
  300 CONTINUE
      IF (INDEX99.EQ.200) GO TO 829
      DO 821 I=1, 6000, 8
  821 READ 12345, AVV(I),AVV(I+1),AVV(I+2),AVV(I+3),AVV(I+4),AVV(I+5),
     1AVV(I+6),AVV(I+7)
  829 CONTINUE
C
C     CALCULATE THE BRIDGE LIFE
C
      DO 800 III=1, NOFM
      DO 800 JJJ=1, NOCS
      CAR88(III,JJJ)=CAR99(III,JJJ)
      BLIFE(III,JJJ)=1
  800 MMMMM(III,JJJ)=1.0/CAR99(III,JJJ)
      DO 803 KKK=2, 6000
      CHECK1=0.0
      DO 801 III=1, NOFM
      DO 801 JJJ=1, NOCS
      IF (CAR99(III,JJJ).GE.1.0) GO TO 802
```

```
      BLIFE(III,JJJ)=BLIFE(III,JJJ)+1
      CAR99(III,JJJ)=CAR99(III,JJJ)+CAR88(III,JJJ)*AVV(KKK)/AVV(1)
      GO TO 801
  802 CHECK(III,JJJ)=1.0
      CHECK1=CHECK1+CHECK(III,JJJ)
  801 CONTINUE
      IF (CHECK1.EQ.21.0) GO TO 822
  803 CONTINUE
  822 CONTINUE
      DO 900 KKK=1, NOFM
  900 PRINT 180, AB(KKK),(BLIFE(KKK,NNN),NNN=1,NOCS),(MMMMM(KKK,MMM),MMM
     1=1, NOCS)
  180 FORMAT (* MODEL  *,A1,T20,I5,T39,I5,T59,I5,T74,I5,13X,I5,15X,I5)
      IF (INDEX99.EQ.200) STOP
      PRINT 88
      PRINT 807
  807 FORMAT (*  ANNUAL VEHICLE VOLUME  *)
  820 FORMAT (8(3X,F10.1))
      DO 806 III=1, KKK, 8
  806 PRINT 820,AVV(III),AVV(III+1),AVV(III+2),AVV(III+3),AVV(III+4)
     1AVV(III+5),AVV(III+6),AVV(III+7)
      INDEX=INDEXB
      INDEX99=INDEX99+100
      DO 702 I=1, 11
      SRFD1(I)=SSRFD1(I)
      SRFD2(I)=SSRFD2(I)
  702 SRFD3(I)=SSRFD3(I)
      DO 701 I=1, INDEXB
      SR1(I)=SSR1(I)
      SR2(I)=SSR2(I)
      SR3(I)=SSR3(I)
      SMIN1(I)=DLS1/1000.0
      SMIN3(I)=SMIN1(I)
      SMAX1(I)=SMIN1(I)+SSR1(I)
      SMIN2(I)=DLS2/1000.0
      SMAX2(I)=SMIN2(I)+SSR2(I)
```

```
      SMAX3(I)=SMIN3(I)+SSP3(I)
  701 LITTLEN(I)=SMALLN(I)
      DO 500 I=1, NOFM
      DO 500 J=1, NOCS
  500 CAR99(I,J)=0.0
      FTOTAL1=FTOTAL
      PRINT 302
      PRINT 703
  703 FORMAT (* SIMULATION RESULTS ---------- STATIC APPROACH*,//)
      GO TO 808
      END
C
C
      SUBROUTINE SELECT1
C     THIS SUBROUTINE DETERMINS RANDOM OBSERVATIONS FOR VEHICLE TYPE,
C     AND SPEED.
      DIMENSION UL(45)
      IF (RN.GT.UL(L2)) GO TO 10
      IF (RN.GT.UL(L1)) GO TO 11
      DO 1 I=1, L1
      IF (RN.LE.UL(I)) GO TO 2
    1 CONTINUF
   11 LA1=L1+1
      DO 3 I=LA1, L2
      IF (RN.LE.UL(I)) GO TO 2
    3 CONTINUF
   10 CONTINUE
      IF (RN.GT.UL(L3)) GO TO 12
      LA2=L2+1
      DO 4 I=LA2, L3
      IF (RN.LE.UL(I)) GO TO 2
    4 CONTINUE
   12 LA3=L3+1
      DO 5 I=LA3, NN
      IF (RN.LE.UL(I)) GO TO 2
    5 CONTINUE
```

```
    2 K=I
      RETURN
      END
C
C
C     THIS SUBROUTINE COUNTS THE NUMBER OF STRESS RANGES AT 3 SECTIONS
      SUBROUTINE RFD100
      DIMENSION SSSSS(11),RFD1(11),RFD2(11),RFD3(11)
      DO 750 I=1, 11
      IF (SRL.LE.SSSSS(I)) GO TO 751
  750 CONTINUE
  751 RFD1(I)=RFD1(I)+1.0
      DO 752 I=1, 11
      IF (SRM.LE.SSSSS(I)) GO TO 753
  752 CONTINUE
  753 RFD2(I)=RFD2(I)+1.0
      DO 754 I=1, 11
      IF (SRR.LE.SSSSS(I)) GO TO 755
  754 CONTINUE
  755 RFD3(I)=RFD3(I)+1.0
      RETURN
      END
C
C
C     THIS SUBROUTINE CALCULATES THE CUMULATIVE  FATIGUE DAMAGE BASED ON
C     SAMPLE SIZE
      SUBROUTINE FATIG
     1,SMIN33,STORE,NNNNN)
      DIMENSION STORE(7,3)
      REAL N1,N2,N3,N4,N5,N6,N7,NNNNN
      J=1
      DO 100 IJK=1, 3
      IF (SR11.LT.3.0) GO TO 500
      N1=10.0**(6.9854-0.0876*SR11-0.0051*SMIN11)
      N2=10.0**(6.9033-0.0836*SR11)
      N3=10.0**(9.1480-3.0086*ALOG10(SR11)-0.0050*SMIN11)
```

```
      N4=10.0**(8.9754-2.8768*ALOG10(SR11))
      N5=10.0**(9.0310-2.8416*ALOG10(SR11)-0.0050*SMAX11)
      N7=10.0**(7.1360-0.0742*SR11-0.0102*SMIN11)
      IF (SR11.LT.3.80) GO TO 101
      IF (SR11.GT.11.40) GO TO 102
      N6=10.0**(10.73136-4.191817*ALOG10(SR11))
      GO TO 103
  102 N6=10.0**(9.19845-2.741434*ALOG10(SR11))
  103 STORE(6,J)=STORE(6,J)+(44.4940*NNNNN)/N6
  101 STORE(1,J)=2TORE(1,J)+(44.4940*NNNNN)/N1
      STORE(2,J)=STORE(2,J)+(44.4940*NNNNN)/N2
      STORE(3,J)=STORE(3,J)+(44.4940*NNNNN)/N3
      STORE(4,J)=STORE(4,J)+(44.4940*NNNNN)/N4
      STORE(5,J)=STORE(5,J)+(44.4940*NNNNN)/N5
      STORE(7,J)=STORE(7,J)+(44.4940*NNNNN)/N7
  500 J=J+1
      IF (J.EQ.3) GO TO 600
      IF (J.EQ.4) GO TO 100
      SR11=SR22
      SMAX11=SMAX22
      SMIN11=SMIN22
      GO TO 100
  600 SR11=SR33
      SMAX11=SMAX33
      SMIN11=SMIN33
  100 CONTINUE
      RETURN
      END
```