INSTITUTIONEN FÖR BYGGNADSTEKNIK
TEKNISKA HÖGSKOLAN I LUND

DIVISION OF BUILDING TECHNOLOGY
LUND INSTITUTE OF TECHNOLOGY

SPECTRA OF LOADS AND LOADEFFECTS FOR BRIDGES. APPLICATIONS TO PREFABRICATED BRIDGE SLABS WITH ESTIMATION OF DYNAMIC EFFECTS.

A LITERATURE SURVEY, JULY 1973

PER CHRISTIANSSON

REPORT 46

LUND SWEDEN 1973

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(SPEKTRA ÖVER LAST OCH LASTEFFEKTER FÖR BROAR.
TILLÄMPNINGAR PÅ MONTERINGSFÄRDIGA FARBANEELEMENT
MED UPPSKATTNING AV DYNAMISKA EFFEKTER.

EN LITTERATURÖVERSIKT, JULI 1973)

SUMMARY.

3.5 Man´s perception of loadeffect.

4 MEASURING EQUIPMENT.

5 DESIGN AND DESIGNPRINCIPLES.

6 BIBLIOGRAPHY.

FOREWORD

At the Division of Structural Engineering, directed by Prof., Dr. Techn. Lars Östlund, Lund Institute of Technology, Sweden, the author of this survey, civil engineer Per Christiansson, carries out an investigation titled "Spectra of loads and loadeffects for bridges. Applications to prefabricated bridge slabs with estimation of dynamic effects", that was started 1972.

In the literature survey are those references mentioned that I have found during the research work. It shall not be regarded as a complete survey of what is done in the field. It is also my intention that the survey might serve as an introduction to the load and loadeffect spectra problem for bridges.

The project is sponsored by "The National Road Administration", Sweden.

I wish to thank Mrs. Mary Lindqvist, who wrote out the manuscript and Miss Ingbritt Liljekvist who prepared the figures.

Lund July 1973

Per Christiansson

SUMMARY

The literature survey mainly consists of two parts.

Chapter 2 deals with the construction of spectra for loads and loadeffects. A load spectrum may define frequencies of vehicle loads that act on a certain road section. When the loads pass the bridge several loadeffects may arise as stressvariation in respect of time for a certain point of the structure. The loadeffect spectrum defines, in the case of stresses, the distribution of stressranges that will arise in a certain point due to the load spectrum.

Chapter 3 deals with that part of the load - loadeffect spectra problem, that is related to the dynamic behaviour of the vehicle-bridge system and the dynamic effects that behaviour will cause. This chapter also contains a chapter (3.5) called "Man´s perception of loadeffect".

Finally in Chapter 4 and 5 is very briefly discussed the "measuring equipment" beeing used and "design and design principles" concerning spectrum loading.

1 INTRODUCTION.

1.1 Background.

When a vehicle is passing a bridge there will arise stresses in different parts of the structure which will vary in respect of time. If there is no risk of fatigue or dynamic effects, the bridge can be designed to resist a constant load. If there is a risk of fatigue it is possible to let the load vary between two values a certain number of times. The allowable load amplitude or if the amplitude is fixed, the allowable number of load repetitions then can be determined from Wöhler curves.

The above made assumption about one alternating maximal load is not very favourable and may lead to structures with too high strength.

The stresses in the actual structure is caused by, besides the dead load, a spectrum of loads, vehicleloads, and for more local effects by axle-bogie loads. It is possible to represent the applying forces with a load spectrum, which for example tells how many loads, with amplitudes exceeding certain values, that will act on the structure.

The loads also cause effects other than stresses. Sometimes it might be more suitable to deal with the forces and deformations and so on, that will arise in a point of the structure. A common name to all these, of the loads caused effects, is loadeffects. In the same manner as mentioned above, for the loads, one can construct a spectrum of loadeffects that tells how many loadeffect repetitions will occur with amplitudes exceeding certain values.

When it comes to design, the loadeffectspectrum can be reproduced in a testing machine and one can get an idea about how many repetitions a structural member can withstand, if the amplitudes are distributed in accordance with the loadeffect spectrum. Another way to carry out the design is to make an estimate of the damage with the help of some cumulative fatigue hypothesis. In this latter case one can either, if the shape of the loadeffect spectrum is given, determine the total number of permissible repetitions or if the number of repetitions is given, that will act on the structural member, one can determine permissible shapes of the spectrum.

As steelqualities with higher ultimate strength and greater tendency to fatigue have come to use, for example as prestressing wires in prestressed concrete, there will be a greater demand for a more qualified way to attack the problem as has been outlined above.

In the more common used prefabricated bridge structures it might be a wish to permit high stresses to get small dimensions on the members. Since such a structure consists of less firmly connected elements than a homogeneous structure does, there is a risk that the dynamic effects will be more pronounced in this type of structure.

1.2 Objectives and research plan.

The objective of the investigation is

to put up a model for calculating the number and amplitudes of loads that acts and in the future will act upon the bridgestructure, load spectrum.

to put up a model which can be used to calculate expected loadeffect spectra for different points in the structure, if the expected load spectrum is known.

to apply the theories to a theoretical model of a bridge deck consisting of prefabricated slabs. In this study the dynamic effects will be estimated and furthermore it will be shown how a design for spectrum loading can be carried out.

The work with putting up suitable models for load and loadeffect spectra is running parallel with the development and testing of the analytical models of the prefabricated bridge deck and the vehicles that will pass it.

The load and loadeffect part has been going on a little more than half a year, which has resulted in an unpublished internal report (in swedish) /4/.

The investigation is financed by and carried out in cooperation with "The National Road Administration" in Sweden, Statens Vägverk, that in 1965 measured axle-bogieloads for a number of different roads. Further measurements are now planed, in consultation with the author, at which stresses in some points of the bridge structure will be recorded together with a type classification of the vehicles, trucks, and if possible measurements of axleloads. The lateral position of the vehicles when passing the bridge will also be recorded.

The theoretical model for calculation of loadeffect spectra will later be tested against the fieldmeasurements and probably will some spectra be simulated on computer with a Monte Carlo method to prove the validity of the theories.

1.3 Literature survey.

In the present literature survey is presented bibliographies that I have found either by manual search or in lists received from the SDI-service, Selektiv Delgivning av Information, (Selective Delivering of Information). The SDI-service means that a computer reads of magnetic tapes that contain titles of articles written in journals. Only those articles that have a title consisting of the same wordcombination as in the searchprofile are caught. The searchprofile consists of expressions like

A and B and (C or D)

where A, B, C and D define a group of words with synonymous meaning. Most references are found through manual searching.

The survey is divided into 4 parts. Chapter 2 deals with literature about load and loadeffect spectra and probably covers a great deal of what has been done during the last years and points out references that might be useful for further studies and deeper penetration of a specific field.

Chapter 3 deals with the dynamic effects caused by vehicles passing a bridge and also shows the influences some variables have on the magnitude of these effects. Such results have been achieved both from field tests and theoretical studies. Chapter 3 also gives an idea of the theoretical models used by other authors for describing the bridgedecks, the vehicles and the combined action when a vehicle passes the bridgedeck. Chapter 3 is not as complete as chapter 2 because of the greater researchfield it covers. Chapter 3.5 "Man´s perception of loadeffect" is though rather complete.

Chapter 4 mainly gives tips to references for further study as well as chapter 5 does. In chapter 5 is also mentioned some of the few designrules there are in the world considering design for fatigue.

2 LOAD- AND LOADEFFECT SPECTRA.

2.1 General.

It is possible today to go out and by measurements determine the distribution of loads, that is total vehicle weights and axle-bogieweights, that act on a specific roadsection and also it is possible to measure and evaluate the timevariations of stress for a certain point in a bridgestructure. How this evaluation shall be done or more precise, how shall one repetition of loadeffect be defined, is a question which is very hard to answer definitively, as it is strongly coupled to the fatigue behaviour of the subjected material.

If it is possible to break down the problem and then put up analytical models for construction of load spectra and load-effect spectra two very important advantages will be gained, besides the better understanding of the mechanism of the problem.

First, because of the break down, the effect of the input variables can be determined and the most important ones washed out.

Second, hopefully one can estimate the values that these variables will get in the future and a more accurate design can be made for the estimated loadeffect spectrum.

Not very much is done to develop models which can be used to the construction of load spectra though numerous measurements have been carried out.

/7/ According to Cudney /7/ the first stress histories, that is the variation of the stress in respect of time for a certain point at the structure, was measured in connection with the AASHO road test, bridge research 1956-1961. These stresses were however induced by special test vehicles and not by trucks in a regular traffic flow.

Later, stress histories or in other word loadeffect processes, have been analysed and spectra over stress ranges set up. Some authors have outlined or developed theories dealing with the translation of load spectra into loadeffect spectra.

/16/ Most of the work in the area seems to be done in the USA and Great Britain. In USA the theoretical stress prediction studies are coordinated through the Federal Highway Administration´s Office of Research, Galambos /16/. According to the same reference the research in USA about bridge behaviour subjected to repetitive loads can be divided into three general areas as follows

"1. Laboratory fatigue studies on large welded members subjected to both constant and variable cycle loads. Such studies are underway at Lehigh University, U.S. Steel Corporation Laboratories, the University of Illinois, and to a lesser degree with some other organizations. The studies include long time, small stress range test up to as many as 200.000 cycles.

2. Bridge loading history field tests. Such studies are continuing and have been conducted in the States of Alabama, Connecticut, Illinois, Iowa, Louisiana, Maryland, Michigan, Minnesota, Ohio, Kentucky, Pennsylvania, Virginia and Tennessee.

3. Theoretical stress prediction studies. In these studies it is desired to forecast the stresses likely to be encountered in a bridge member. Some of the studies use computer simulation techniques, and some use mathematical probabilistic approaches. The studies are all coordinated through the Federal Highway Administration´s Office of Research."

/7/, /8-12/ References 7 and 8-12 can serve as guides to get startingreferences for further study of what is done, particularly in USA, concerning subjects presented in chapter 2 of the survey.

2.2 Characteristics of loads, trucks.

Private cars are not included in the study because they do not induce stress of such magnitude that is of any importance. It is instead the heavy traffic, trucks, busses and some delivery vans that are of interest.

There are of course many variables to characterize a truck. But if one does not take the dynamic effect in consideration, at this stage, the following variables are considered to be of interest

total vehicle weight,

axle-bogie weights, (distribution of gross weight on axles)

axlespacings (may define type of vehicle),

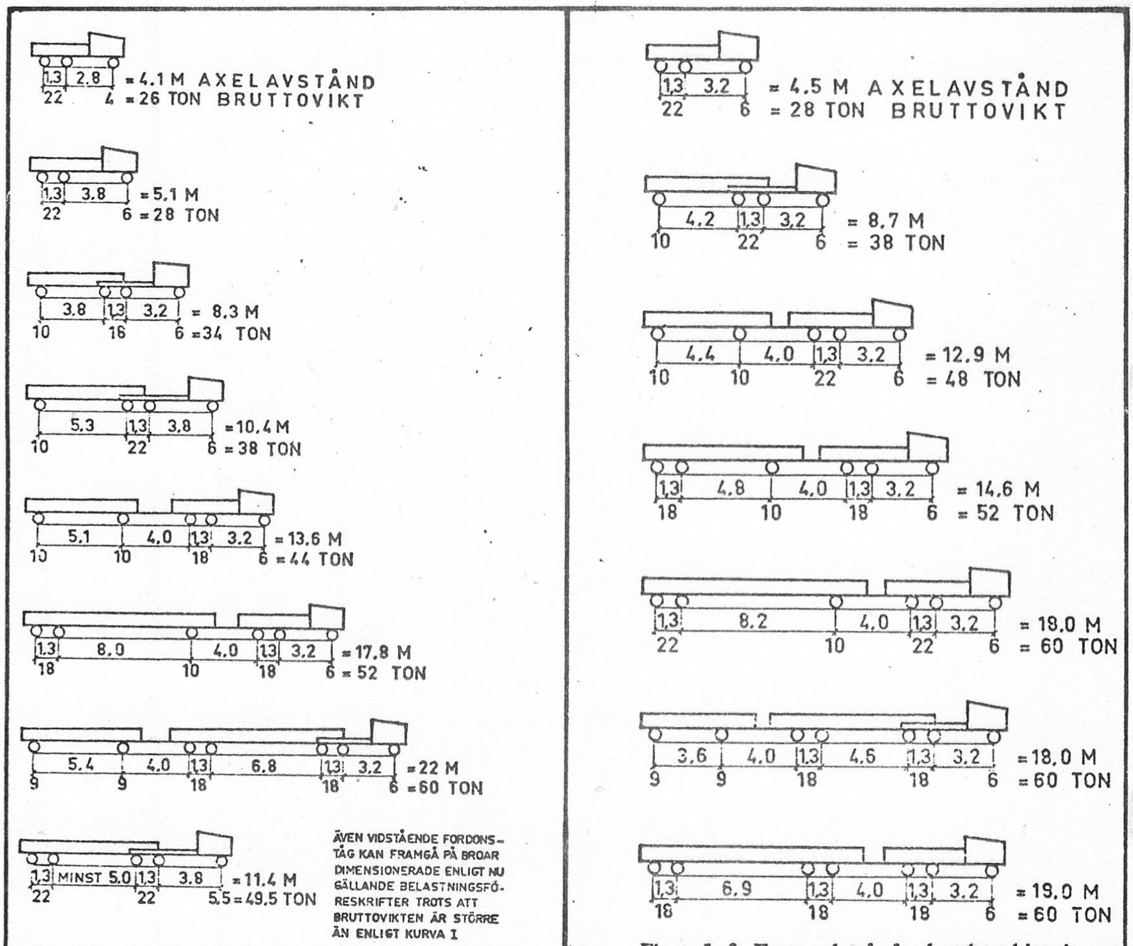
ratio gross vehicle weight/total vehicle weight (indicates the loading level, that is how much cargo the vehicle carries)

distribution of vehicles (registered or for a specific roadsection) due to weight and type

distribution of loading levels for trucks within a class, as type or total vehicle weight.

FIG. 1 In FIG. 1 are listed different types of trucks that would be permitted to drive on roads designed according to suggested alternative regulations, in Sweden, concerning allowable gross-weights. (The alternatives and those curves valid today are

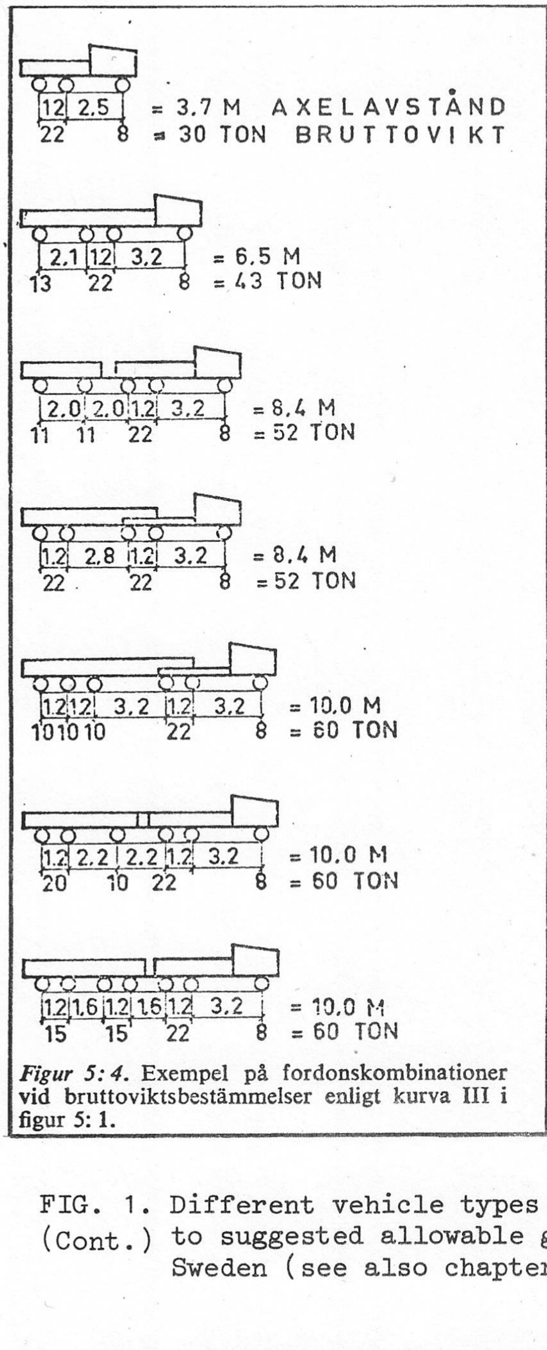
/26/ found in "Vägplan 1970", Bilaga /26/.)



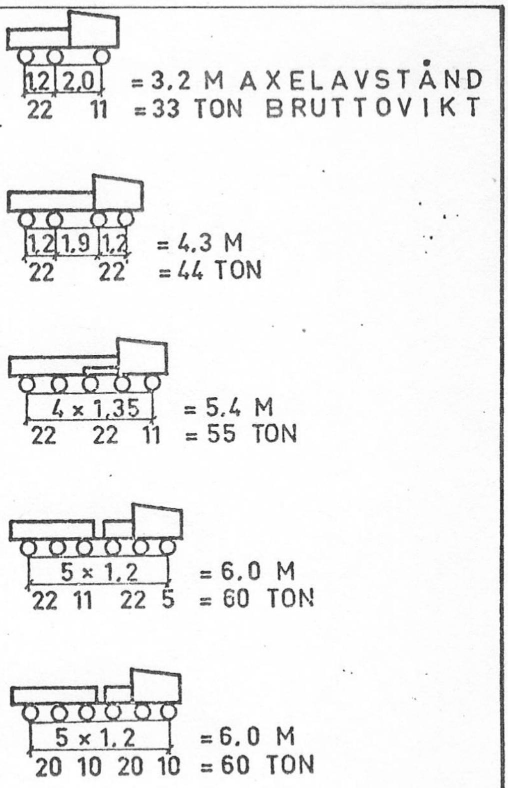
Figur 5: 2. Exempel på fordonskombinationer vid bruttoviktsbestämmelser enligt kurva I i figur 5: 1.

Figur 5: 3. Exempel på fordonskombinationer vid bruttoviktsbestämmelser enligt kurva II i figur 5: 1.

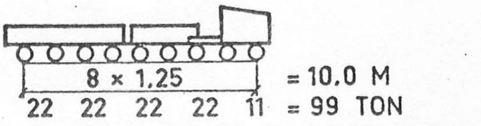
FIG. 1. Different vehicle types that can be permitted due to suggested allowable grossweight regulation in Sweden (see also chapter 5), /26/.



Figur 5: 4. Exempel på fordonskombinationer vid bruttoviktsbestämmelser enligt kurva III i figur 5: 1.



Figur 5: 5 a. Exempel på fordonskombinationer vid bruttoviktsbestämmelser enligt kurvorna IV och V i figur 5: 1.



Figur 5: 5 b. Exempel på fordonskombination vid bruttoviktsbestämmelser enligt kurva V i figur 5: 1.

FIG. 1. Different vehicle types that can be permitted due
(Cont.) to suggested allowable grossweight regulation in
Sweden (see also chapter 5), /26/.

FIG. 2 /6/, /57/ In FIG. 2 is shown a truck type coding system used by, among others, Cudney /6/, Wittermore, ... /57/ in USA.

/2/ Information concerning the number of existing trucks and their total weights can be obtained rather easily from official institutions. In "Bilismen i Sverige 1972" /2/ are for example some statistics of this kind gathered.

The lowest value of (gross vehicle weight/total vehicle weight)

APPENDIX B

VEHICLE TYPE DESIGNATION

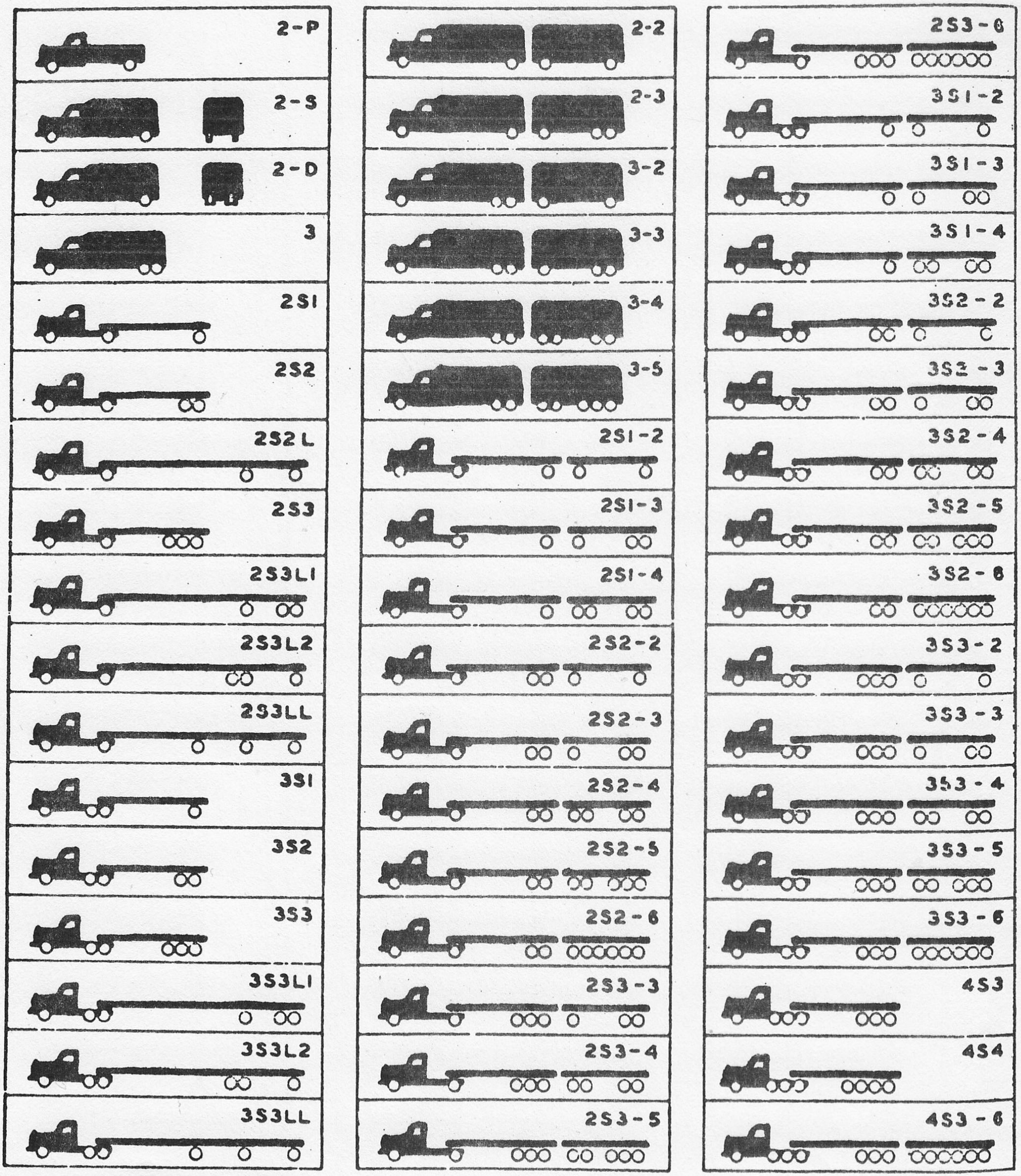


Figure B-1. Vehicle type designation.

FIG. 2. Truck coding system (USA), /6/, /57/.

FIG. 3 is valid for a truck driving without any cargo. FIG. 3 shows the range of this value, where the ratio is plotted against the minimum grossweight (no cargo). The scheme is valid for trucks fabricated in 1971 with totalweights over 5000 kp, Christiansson /4/. /4/

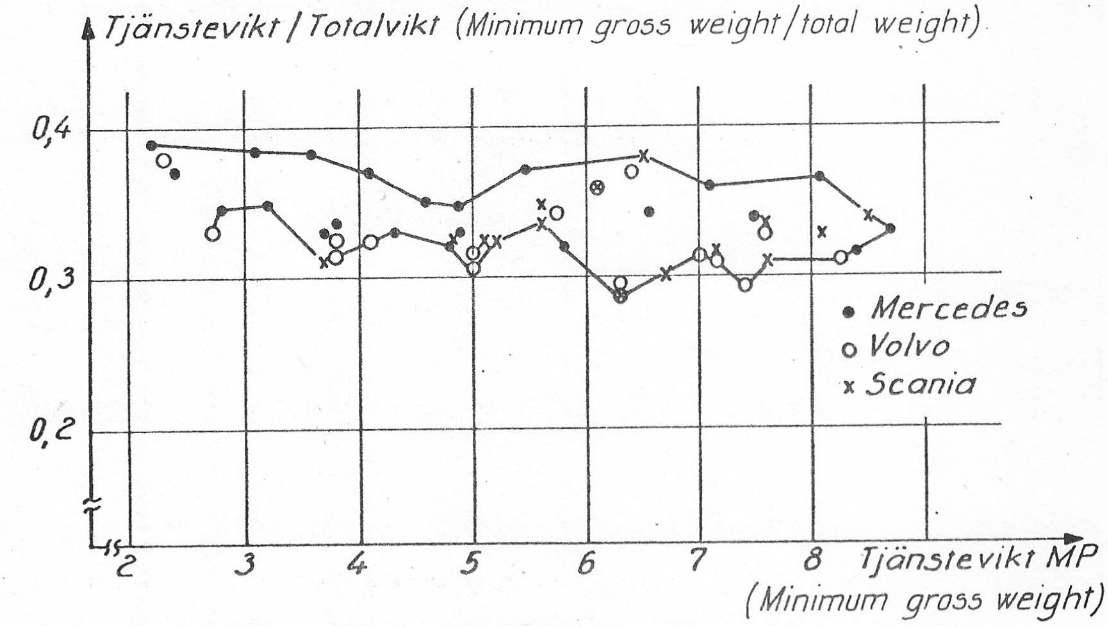


FIG. 3. Minimum gross weight/total weight (3 manufactures) plotted against minimum gross weight (1971), /4/

/2/ In reference /2/ one can also find values for the mean value, one for each year, of the ratio grossweight/total weight, that is the mean loading level. See also FIG. 8 in chapter 2.3, where mean loading levels can be found related to (total) grossweights (% of Cap. Util., Canada). FIG. 8

Numerous numbers of overloads are also reported but are not found in the statistics. Those loads are detected at the weighing stations. More details about this can be found in Douglas /9/, "Lastbil och taxi" /19/ and Jonsson /18/. In general it can be said that the overloads can be considerable. /9/,/19/,/18/

In connection with weighing of axles, see chapter 2.4 "Construction of load spectra", classification of vehicletypes is often made. It can be done either automatically (transducers on the road surface, filming) or visually. This kind of clas-

sification seems to be rather common and results from Swedish
measurements made 1961-1963 can be found in "Fordonskombina-
/25/ tioner" /25/. Results of measurements made in USA can be found
/6/,/8/,/9/ in Cudney /6/, Christiano, ... /8/, Douglas /9/, Heins, ...
/10/,/11/ FIG.4 /10/ and McKeel, ... /11/. In FIG. 4 and FIG. 5 are schemes
FIG.5 from Cudney /6/ and Douglas /9/ presented.

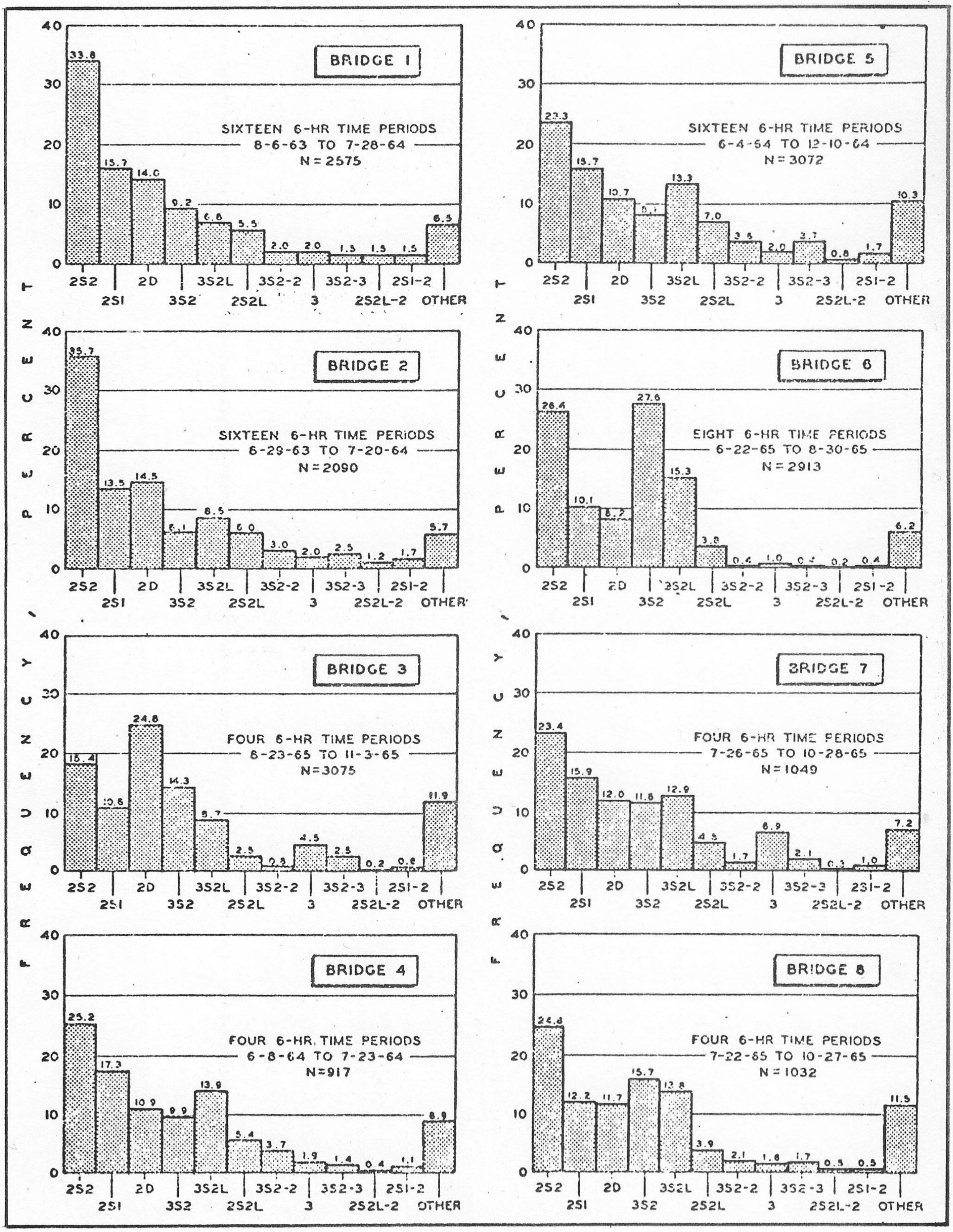


FIG. 4. Distribution of vehicle due to type, Cudney /6/.

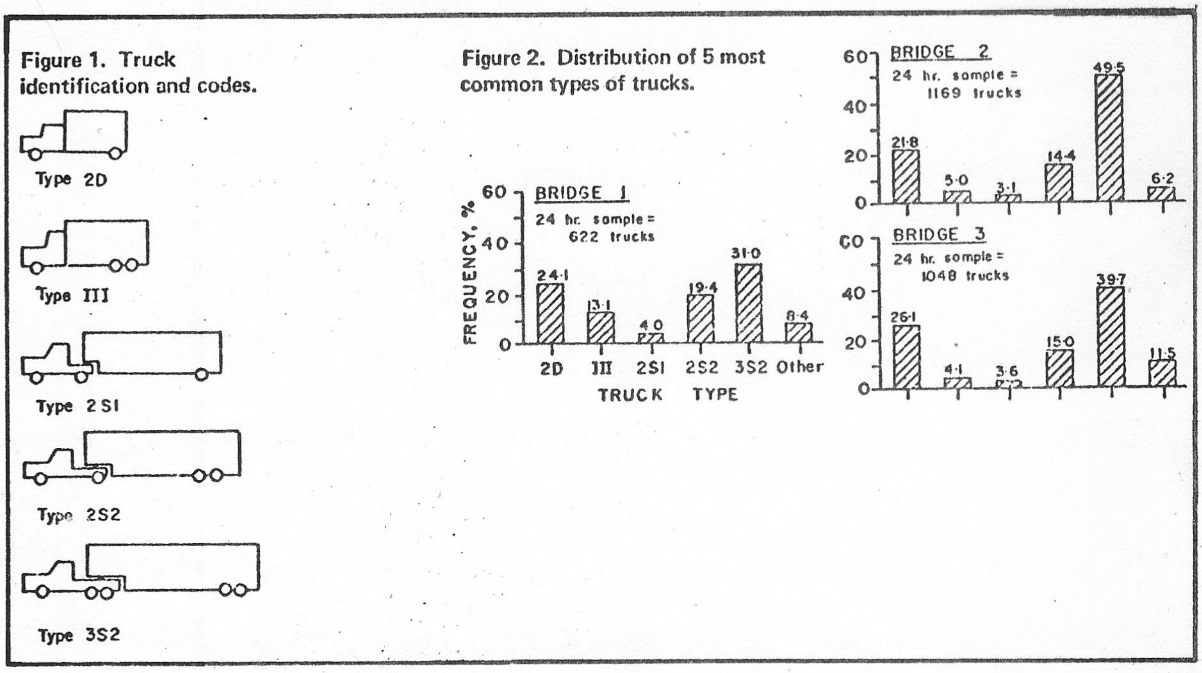


FIG. 5. Distribution of vehicle due to type, Douglas /9/.

2.3 Characteristics of trafficflow.

The characteristics of trafficflow does not directly influence the appearance of the load spectrum. But when loads, for example axle loads, cause stress in a point in the bridgestructure, the magnitude of these stresses depend on these characteristics, because the influences of many axles may overlap. The axles do not necessarily have to belong to one vehicle.

If one knows the position of the individual vehicle in the trafficflow it is possible to predict the probability that two vehicles will meet within a certain length of the road (bridge).

/29/,/30/ Stephenson /29/, /30/, calculates probabilities (time intervals between occurence) for 2, 4, 6 and (8) vehicles (specified as heavy or not) to be within a specified length of road, based upon the following assumptions:

1. Vehicles, both individually and by types, are distributed at random in ordinary highway traffic.

2. The average composition, volume and speed of traffic remain

constant during the time period under consideration. /29/

FIG. 6 Stephenson uses Poisson frequency distribution for describing time and distance spacings of vehicles. Inf FIG. 6 results from his calculations are shown.

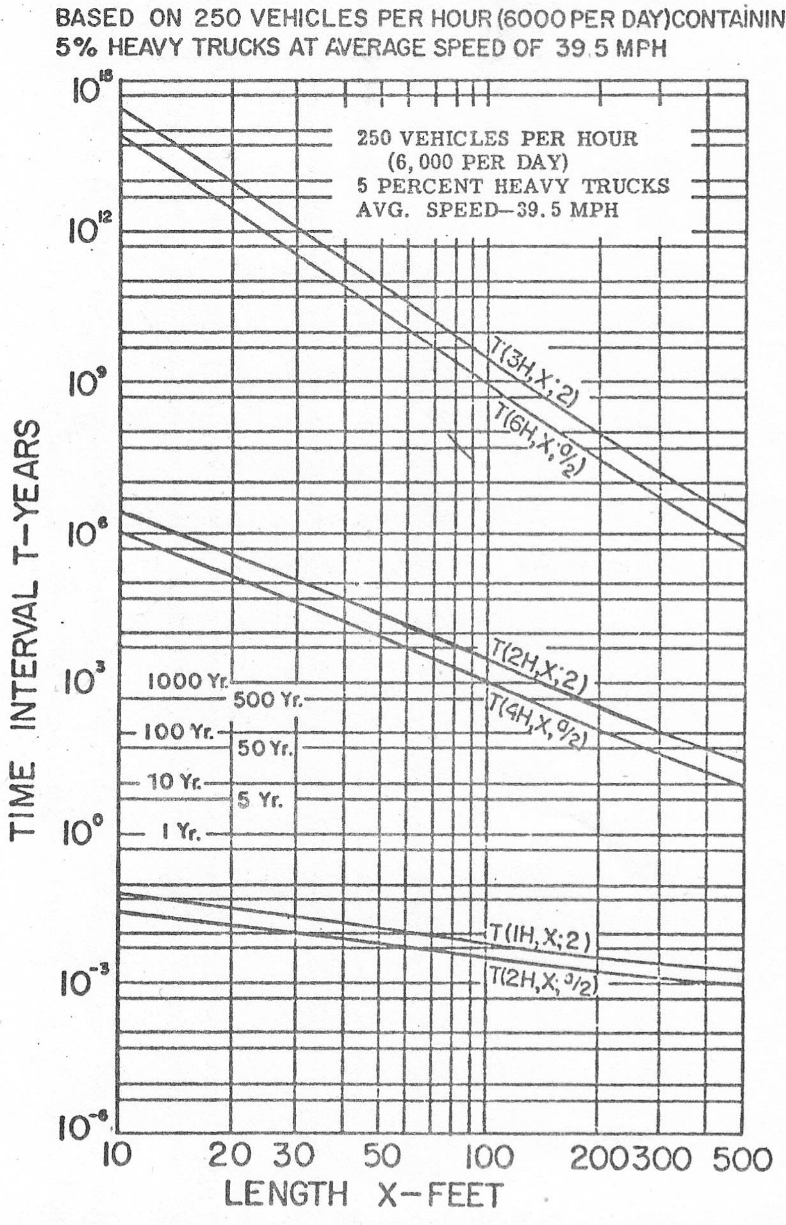


Figure 1. Time interval for typical specified vehicle groups occurring within specified lengths.

FIG. 6. Time intervals between overlaping, Stephenson /30/.

/13/ Ditlevsen /13/ assumes that in a flow, characterized as something between completely undisturbed and compact (queues), the distances within a trafficblock are constant and the distances intermediate blocks are exponentially distributed.

/17/ Haight, ... /17/ propose that a Pearson Type III, gamma, distribution can be used to describe the same intermediate type of trafficflow as mentioned above. They also have adopted the distribution to measured values.

/25/ Measurements of frequencies and length of queues can be found in "Fordonskombinationer" /25/.

/32/ /14/ FIG. 7 Another factor of importance is the fact that vehicles choose different tracks in the lane and therefore cause more or less influence, especially for secondary members. Not very much is found about the lateral distribution of vehicles. During the AASHO road test, bridge research /32/, the lateral position was detected, with pressure hoses with varying lengths in 12 in.-increment (0.3 m), when the vehicles passed the bridge. Ekbladh, ... /14/ visually and by filming determined this distribution for cars, when leaving a highway by an off-ramp. FIG. 7 gives an example of a typical result. One must not forget that the measurements were made on cars and that the roadsection is rather special.

FIG. 8, /23/ If one will construct load spectra outgoing from a static distribution of vehicles (as vehicle distribution due to totalweight) one might be interested in knowing the average length of annual drives for different groups of vehicles. In FIG. 8 is presented a table from Richardson, ... /23/ that tells the annual mileage per truck (average) correlated to grossweight.

/20/ Perhaps one can expect different compositions of vehicletypes in different areas. Lynch /20/ for example, who uses loadometerstudies conducted in Kentucky as basis for his calculations, presents percentfigures for different types of vehicles (6 types of trucks) in urban and rural regions.

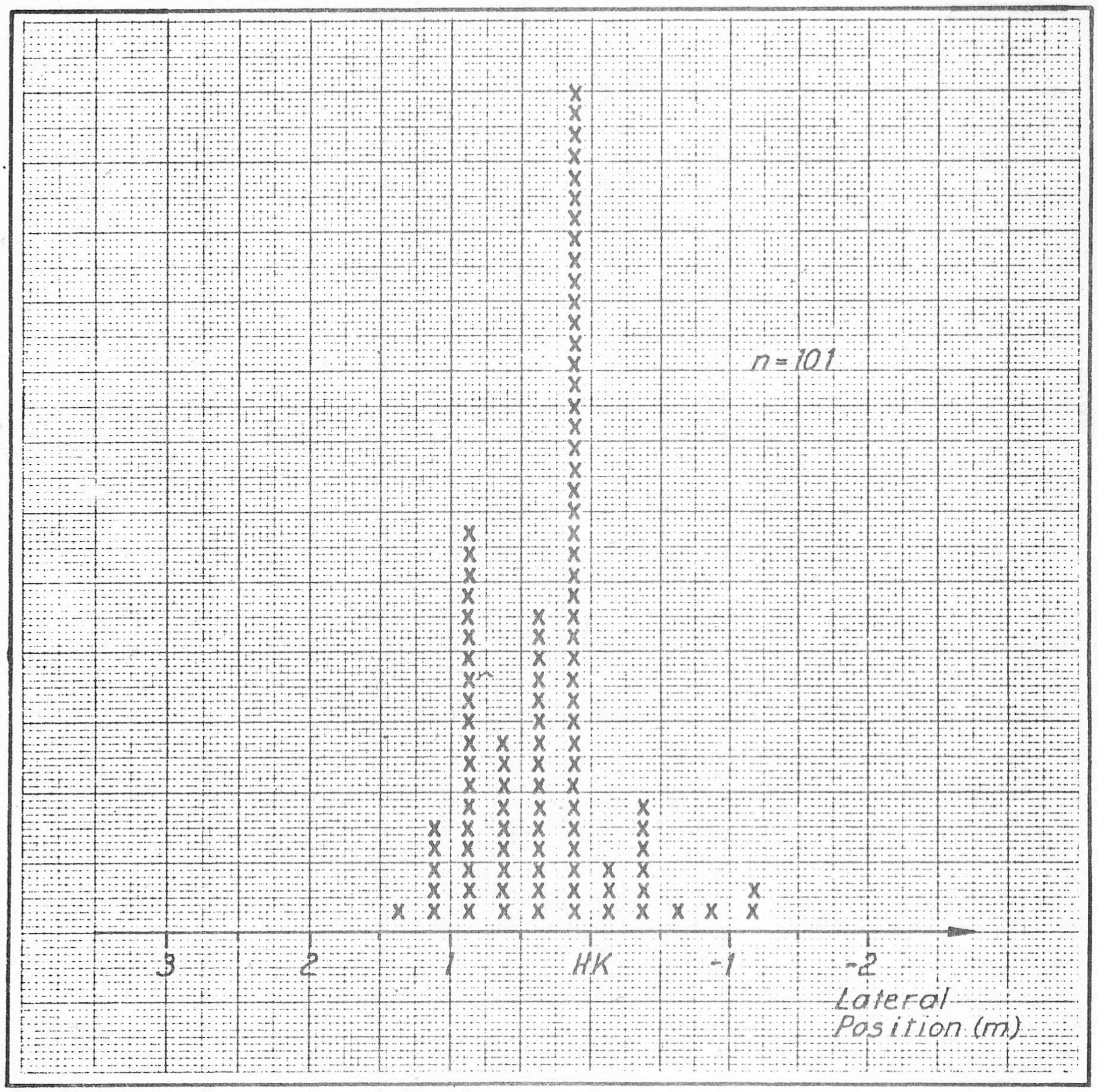


FIG. 7. Example on lateral distribution of cars when leaving a highway by an off-ramp, Ekbladh, ... /14/.

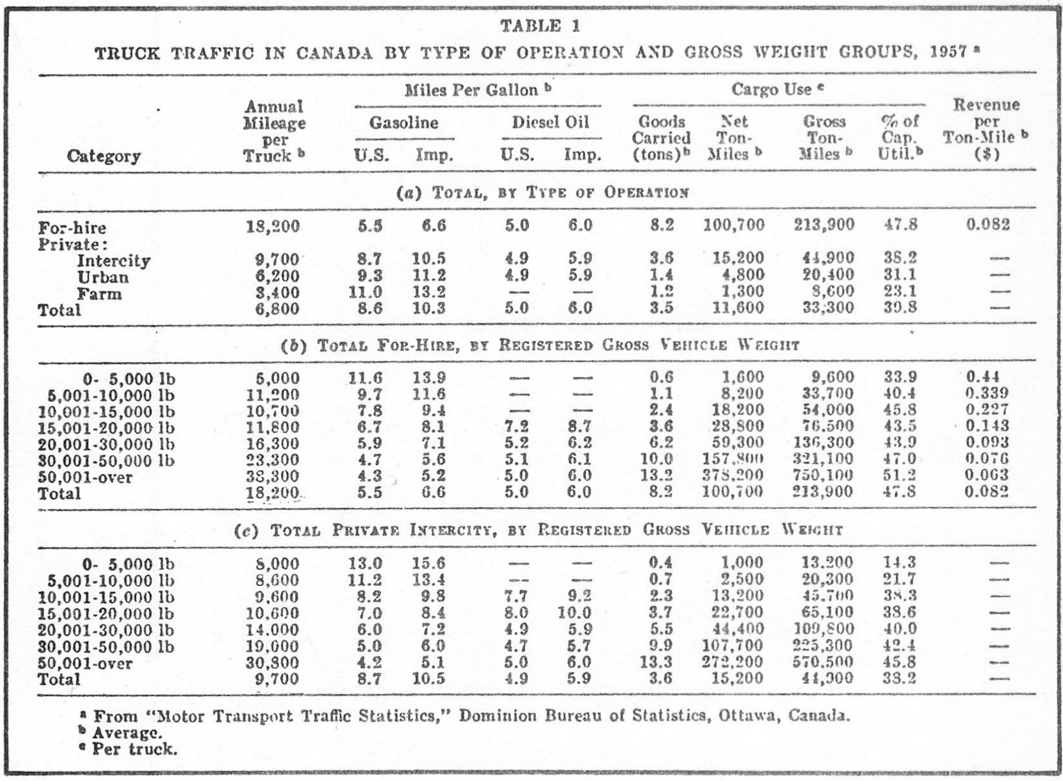


TABLE 1

TRUCK TRAFFIC IN CANADA BY TYPE OF OPERATION AND GROSS WEIGHT GROUPS, 1957 [a]

Category	Annual Mileage per Truck [b]	Miles Per Gallon [b]: Gasoline U.S.	Gasoline Imp.	Diesel Oil U.S.	Diesel Oil Imp.	Cargo Use [c]: Goods Carried (tons) [b]	Net Ton-Miles [b]	Gross Ton-Miles [b]	% of Cap. Util. [b]	Revenue per Ton-Mile [b] ($)
(a) TOTAL, BY TYPE OF OPERATION										
For-hire	18,200	5.5	6.6	5.0	6.0	8.2	100,700	213,900	47.8	0.082
Private:										
Intercity	9,700	8.7	10.5	4.9	5.9	3.6	15,200	44,900	38.2	—
Urban	6,200	9.3	11.2	4.9	5.9	1.4	4,800	20,400	31.1	—
Farm	3,400	11.0	13.2	—	—	1.2	1,300	8,600	23.1	—
Total	6,800	8.6	10.3	5.0	6.0	3.5	11,600	33,300	30.8	—
(b) TOTAL FOR-HIRE, BY REGISTERED GROSS VEHICLE WEIGHT										
0- 5,000 lb	6,000	11.6	13.9	—	—	0.6	1,600	9,600	33.9	0.44
5,001-10,000 lb	11,200	9.7	11.6	—	—	1.1	8,200	33,700	40.4	0.339
10,001-15,000 lb	10,700	7.8	9.4	—	—	2.4	18,200	54,000	45.8	0.227
15,001-20,000 lb	11,800	6.7	8.1	7.2	8.7	3.6	28,800	76,500	43.5	0.143
20,001-30,000 lb	16,300	5.9	7.1	5.2	6.2	6.2	59,300	136,300	43.9	0.093
30,001-50,000 lb	23,300	4.7	5.6	5.1	6.1	10.0	157,800	321,100	47.0	0.076
50,001-over	38,300	4.3	5.2	5.0	6.0	13.2	378,200	750,100	51.2	0.063
Total	18,200	5.5	6.6	5.0	6.0	8.2	100,700	213,900	47.8	0.082
(c) TOTAL PRIVATE INTERCITY, BY REGISTERED GROSS VEHICLE WEIGHT										
0- 5,000 lb	8,000	13.0	15.6	—	—	0.4	1,000	13,200	14.3	—
5,001-10,000 lb	8,600	11.2	13.4	—	—	0.7	2,500	20,300	21.7	—
10,001-15,000 lb	9,600	8.2	9.8	7.7	9.2	2.3	13,200	45,700	38.3	—
15,001-20,000 lb	10,600	7.0	8.4	8.0	10.0	3.7	22,700	65,100	38.6	—
20,001-30,000 lb	14,000	6.0	7.2	4.9	5.9	5.5	44,400	109,800	40.0	—
30,001-50,000 lb	19,000	5.0	6.0	4.7	5.7	9.9	107,700	225,300	42.4	—
50,001-over	30,800	4.2	5.1	5.0	6.0	13.3	272,200	570,500	45.8	—
Total	9,700	8.7	10.5	4.9	5.9	3.6	15,200	44,900	33.2	—

[a] From "Motor Transport Traffic Statistics," Dominion Bureau of Statistics, Ottawa, Canada.
[b] Average.
[c] Per truck.

FIG. 8. Annual mileage per truck, Richardson, ... /23/.

/1/

A very important factor is the annual trafficvolume expected to pass a roadsection. Abeles, ... /1/ is referring to E. R. Leonard, Great Britain, when he says, that a practical upper level of flow of all vehicles in one lane is about 20.000 vehicles per day, and maximum percentage of commercial vehicles observed is about 60 percent, giving 12.000 commercial vehicles per day as an upper limit (that is about 200 millions in 50 years).

2.4 Construction of load spectra.

/3/
FIG. 9, FIG 13
/20/, FIG 10

Numerous measurements of axle-bogie weights have been conducted, mainly by official institutions, for several years, which have been used to construct load spectra. Measurements made in Sweden about 1965 are reported in Brinck /3/. FIG. 9 (see also FIG. 13) and from Kentucky, USA, by Lynch /20/, FIG. 10.

Distribution of truck traffic by gross weight according to the 1965 loadometer studies

Road category	Type of vehicle	No. of vehicles by gross weight							Total No. of vehicles
		≤ 5	6–10	11–15	16–20	21–30	31–40	> 40	
All roads	2-axle	47,182 21.7	118,571 54.6	43,695 20.1	7,566 3.5	282 0.1	0	0	217,296 100.0
	3-axle	5,529 8.1	11,407 16.7	18,848 27.6	14,897 21.8	16,871 24.8	665 1.0	0	68,217 100.0
	4-axle	1,449 2.1	4,599 6.6	19,738 28.1	18,509 26.3	15,063 21.4	9,567 13.6	1,347 1.9	70,272 100.0
	5-axle	113 0.2	983 1.7	2,753 4.6	8,179 13.8	14,810 24.9	20,363 34.3	12,185 20.5	59,391 100.0
	>5-axle	18 0.1	289 1.3	606 2.6	1,350 5.9	4,442 19.4	5,905 25.7	10,324 45.0	22,934 100.0
	Total	54,291 12.4	135,849 31.0	85,640 19.6	50,501 11.5	51,468 11.8	36,505 8.3	23,856 5.4	438,110 100.0

FIG. 9. Loadometer studies 1965 in Sweden, Brinck /3/.

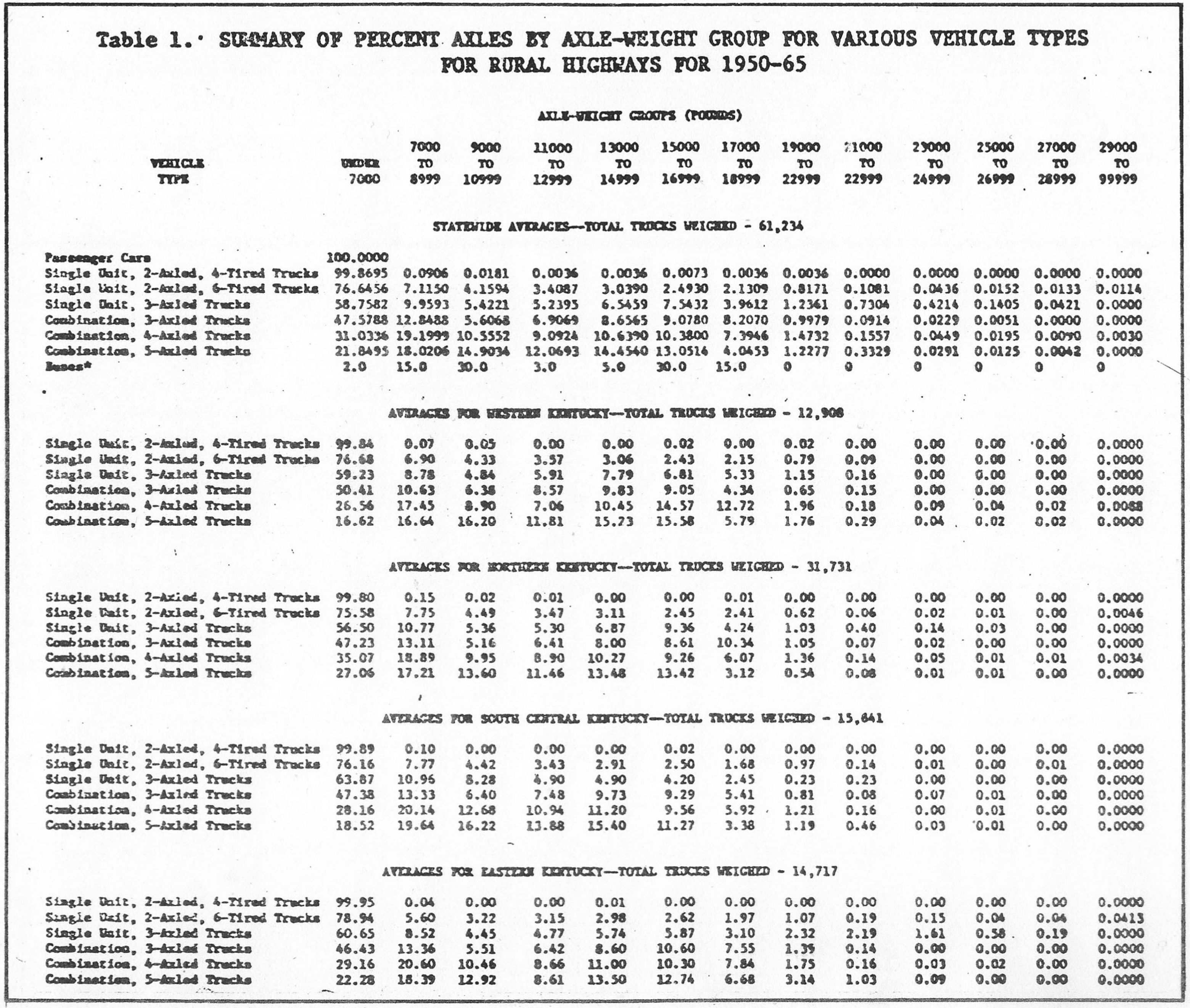


Table 1.· SUMMARY OF PERCENT AXLES BY AXLE-WEIGHT GROUP FOR VARIOUS VEHICLE TYPES FOR RURAL HIGHWAYS FOR 1950-65

VEHICLE TYPE	AXLE-WEIGHT GROUPS (POUNDS)												
	UNDER 7000	7000 TO 8999	9000 TO 10999	11000 TO 12999	13000 TO 14999	15000 TO 16999	17000 TO 18999	19000 TO 22999	21000 TO 22999	23000 TO 24999	25000 TO 26999	27000 TO 28999	29000 TO 99999
STATEWIDE AVERAGES—TOTAL TRUCKS WEIGHED - 61,234													
Passenger Cars	100.0000												
Single Unit, 2-Axled, 4-Tired Trucks	99.8695	0.0906	0.0181	0.0036	0.0036	0.0073	0.0036	0.0036	0.0000	0.0000	0.0000	0.0000	0.0000
Single Unit, 2-Axled, 6-Tired Trucks	76.6456	7.1150	4.1594	3.4087	3.0390	2.4930	2.1309	0.8171	0.1081	0.0436	0.0152	0.0133	0.0114
Single Unit, 3-Axled Trucks	58.7582	9.9593	5.4221	5.2395	6.5459	7.5432	3.9612	1.2361	0.7304	0.4214	0.1405	0.0421	0.0000
Combination, 3-Axled Trucks	47.5788	12.8488	5.6068	6.9069	8.6565	9.0780	8.2070	0.9979	0.0914	0.0229	0.0051	0.0000	0.0000
Combination, 4-Axled Trucks	31.0336	19.1999	10.5552	9.0924	10.6390	10.3800	7.3946	1.4732	0.1557	0.0449	0.0195	0.0090	0.0030
Combination, 5-Axled Trucks	21.8495	18.0206	14.9034	12.0693	14.4540	13.0516	4.0453	1.2277	0.3329	0.0291	0.0125	0.0042	0.0000
Buses*	2.0	15.0	30.0	3.0	5.0	30.0	15.0	0	0	0	0	0	0
AVERAGES FOR WESTERN KENTUCKY—TOTAL TRUCKS WEIGHED - 12,908													
Single Unit, 2-Axled, 4-Tired Trucks	99.84	0.07	0.05	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.0000
Single Unit, 2-Axled, 6-Tired Trucks	76.68	6.90	4.33	3.57	3.06	2.43	2.15	0.79	0.09	0.00	0.00	0.00	0.0000
Single Unit, 3-Axled Trucks	59.23	8.78	4.84	5.91	7.79	6.81	5.33	1.15	0.16	0.00	0.00	0.00	0.0000
Combination, 3-Axled Trucks	50.41	10.63	6.38	8.57	9.83	9.05	4.34	0.65	0.15	0.00	0.00	0.00	0.0000
Combination, 4-Axled Trucks	26.56	17.45	8.90	7.06	10.45	14.57	12.72	1.96	0.18	0.09	0.04	0.02	0.0088
Combination, 5-Axled Trucks	16.62	16.64	16.20	11.81	15.73	15.58	5.79	1.76	0.29	0.04	0.02	0.02	0.0000
AVERAGES FOR NORTHERN KENTUCKY—TOTAL TRUCKS WEIGHED - 31,731													
Single Unit, 2-Axled, 4-Tired Trucks	99.80	0.15	0.02	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.0000
Single Unit, 2-Axled, 6-Tired Trucks	75.58	7.75	4.49	3.47	3.11	2.45	2.41	0.62	0.06	0.02	0.01	0.00	0.0046
Single Unit, 3-Axled Trucks	56.50	10.77	5.36	5.30	6.87	9.36	4.24	1.03	0.40	0.14	0.03	0.00	0.0000
Combination, 3-Axled Trucks	47.23	13.11	5.16	6.41	8.00	8.61	10.34	1.05	0.07	0.02	0.00	0.00	0.0000
Combination, 4-Axled Trucks	35.07	18.89	9.95	8.90	10.27	9.26	6.07	1.36	0.14	0.05	0.01	0.01	0.0034
Combination, 5-Axled Trucks	27.06	17.21	13.60	11.46	13.48	13.42	3.12	0.54	0.08	0.01	0.01	0.00	0.0000
AVERAGES FOR SOUTH CENTRAL KENTUCKY—TOTAL TRUCKS WEIGHED - 15,641													
Single Unit, 2-Axled, 4-Tired Trucks	99.89	0.10	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.0000
Single Unit, 2-Axled, 6-Tired Trucks	76.16	7.77	4.42	3.43	2.91	2.50	1.68	0.97	0.14	0.01	0.00	0.01	0.0000
Single Unit, 3-Axled Trucks	63.87	10.96	8.28	4.90	4.90	4.20	2.45	0.23	0.23	0.00	0.00	0.00	0.0000
Combination, 3-Axled Trucks	47.38	13.33	6.40	7.48	9.73	9.29	5.41	0.81	0.08	0.07	0.01	0.00	0.0000
Combination, 4-Axled Trucks	28.16	20.14	12.68	10.94	11.20	9.56	5.92	1.21	0.16	0.00	0.01	0.00	0.0000
Combination, 5-Axled Trucks	18.52	19.64	16.22	13.88	15.40	11.27	3.38	1.19	0.46	0.03	0.01	0.00	0.0000
AVERAGES FOR EASTERN KENTUCKY—TOTAL TRUCKS WEIGHED - 14,717													
Single Unit, 2-Axled, 4-Tired Trucks	99.95	0.04	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0000
Single Unit, 2-Axled, 6-Tired Trucks	78.94	5.60	3.22	3.15	2.98	2.62	1.97	1.07	0.19	0.15	0.04	0.04	0.0413
Single Unit, 3-Axled Trucks	60.65	8.52	4.45	4.77	5.74	5.87	3.10	2.32	2.19	1.61	0.58	0.19	0.0000
Combination, 3-Axled Trucks	46.43	13.36	5.51	6.42	8.60	10.60	7.55	1.39	0.14	0.00	0.00	0.00	0.0000
Combination, 4-Axled Trucks	29.16	20.60	10.46	8.66	11.00	10.30	7.84	1.75	0.16	0.03	0.02	0.00	0.0000
Combination, 5-Axled Trucks	22.28	18.39	12.92	8.61	13.50	12.74	6.68	3.14	1.03	0.09	0.00	0.00	0.0000

FIG. 10. Percent axles by axleweights 1950-1965, Lynch /20/.

/1/ Abeles, ... /1/ says the following about research-needs

"(1) Load Spectrum:

More research is needed generally, but particularly about proportions of heavy loads. Some bridges located near factories, cement works, guarris, etc. would undoubtedly experience a larger proportion than 5 % of heavy trucks and this would likely effect fatigue considerations."

It shall be pointed out that the load spectra are not constant for a roadsection or area but changes between hours, days, weeks and years depending on the composition of vehicletypes and perhaps due to other loading conditions (loading level, type of cargo). There can also be a big difference depending on what lane is looked at, at least in the number of loadings.

FIG. 11, /11/ See FIG. 11 from McKeel, ... /11/.

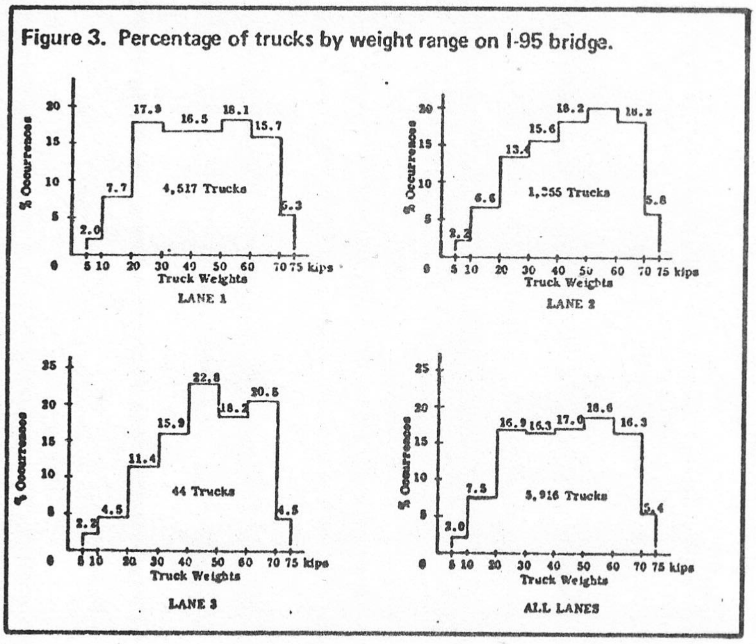


Figure 3. Percentage of trucks by weight range on I-95 bridge.

FIG. 11. Percentage of trucks by weight, range and lane (3 northbound lanes), McKeel, ... /11/.

/20/ Lynch /20/ modifies measured load spectra for axles to be valid for critical axle loads. Critical loading combination

FIG. 12 on two lane bridge is shown in FIG. 12. He then makes assumptions as: The vehicle axles and their spacings occur randomly with respect to time and each other, and that all axles are considerred as single axles whether they be single or tandem.

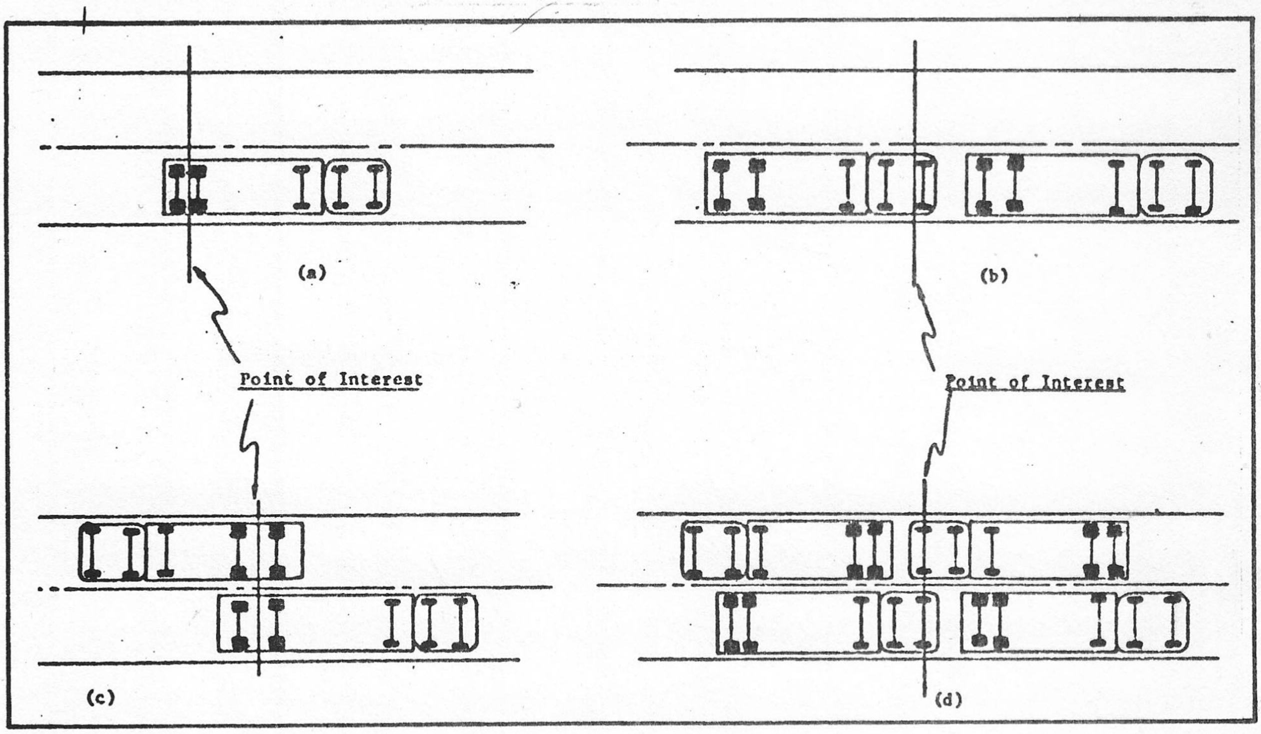


FIG. 12." "Critical loading combinations on two-lane Bridges", Lynch /20/.

As mentioned before it is of great importance to know the connection between the load spectrum and the loadeffect spectrum caused. As will be seen in chapter 2.6 "Analysis of loadeffect process. Construction of loadeffect spectra." most of the measured loadeffect spectra are compared with the corresponding load spectra. It is though not that easy to weigh the corresponding axles, because most equipment used are stationary weighingstations situated apart from the bridge. There are some equipments that can measure without interfering the traffic (the speed is not reduced) and which also are small and mobile, see also chapter 4 "Measuring methods and Measuring accuracy".

To predict a load spectrum requires some knowledge of different variables. The more complex these variables are the harder it is to determine their future value. Christiansson

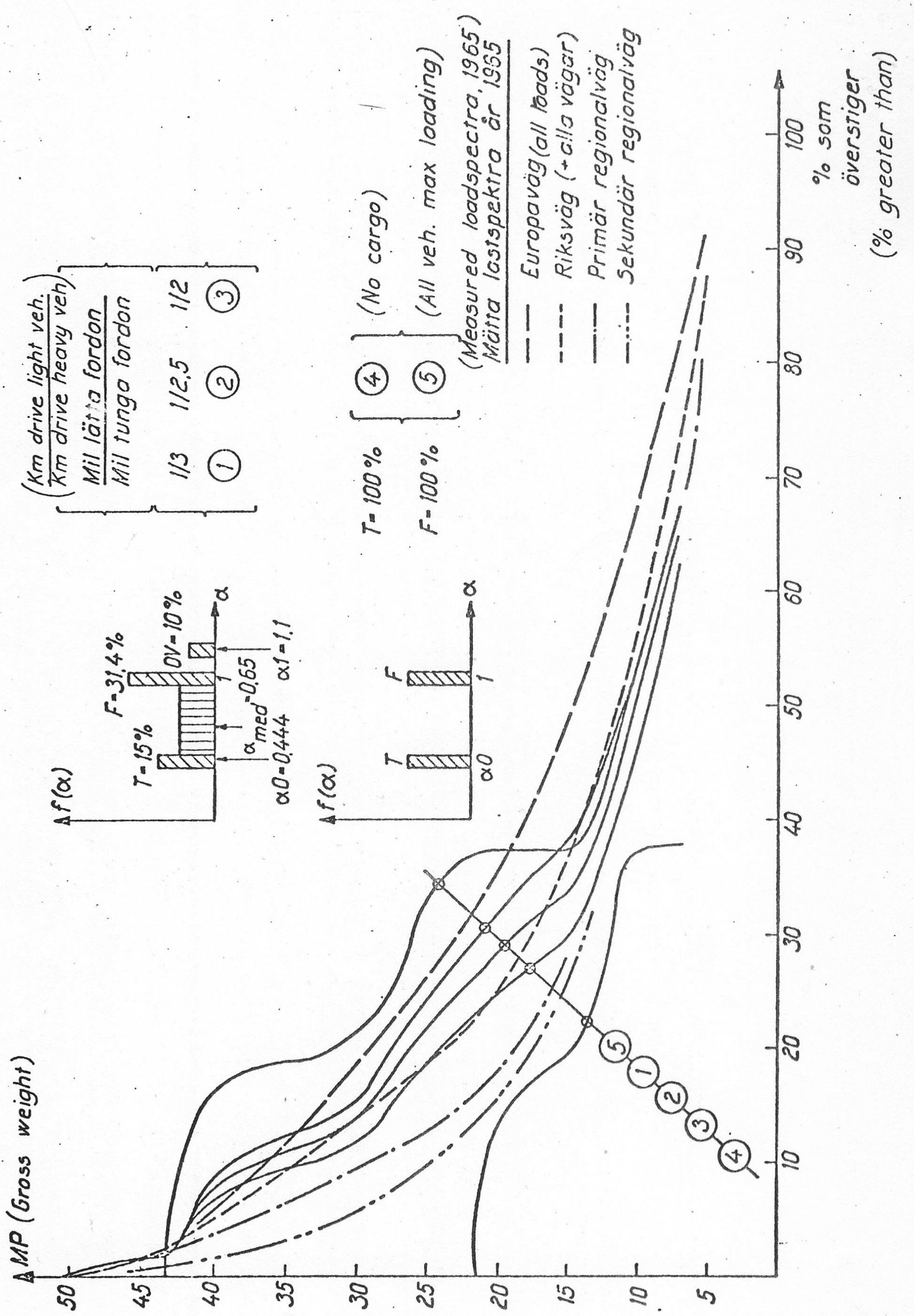


FIG. 13. Measured and calculated load spectra for 1965, Christiansson /5/.

/4/ /4/ has put up a simplified model with input-variables as weight distribution of "existing" vehicles, average length FIG. 13 of drive and distribution of loading level. FIG. 13 shows calculated spectra ① - ⑤ and measured 1965 taken from /3/ Brinck /3/.

2.5 Loadeffects on bridgestructure, vehicle and man.

As mentioned earlier the loads (vehicles) that pass the bridge cause other loadeffects than stresses in different structural members.

Deformation of the bridge surface is an effect that might cause fatigue on asphalt surfacing, especially if the bridge deck is weak or is formed of elements somehow hinged together.

Sometimes it is more convenient to express the loadeffect as a force. For example the interacting force, between wheel and bridge surface, which may cause fatigue on asphalt surfacing, Raithby, ... /22/. /22/

The loadeffects expressed as deformation spectra or force spectra can be used for the design of certain structural members whose task among other things is to withstand these effects, as joints and supports.

When a vehicle is passing the structure in a crawlspeed one does not expect dynamic effects. But when the speed is higher several dynamic effects arise.

The literature survey covering dynamic effects will be found in chapter 3, "Dynamic effects. Prefabricated bridge slabs".

The most obvious dynamic effects are those which magnifies the amplitudes of the above mentioned load effects. Hopefully it is possible to take these effects into consideration by calculating dynamic amplification factors. But there are also other types of dynamic effects.

Due to the vibration of the bridge-vehicle system additional repetitions of loadeffects may arise that perhaps can not
/16/ be neglected, Galambos /16/. One possible way to take this kind of effects into account is to multiply the number of load effect repetitions, with amplitudes in the lower range with amplification factors.

As the vehicle begins to oscillate the passengers in the vehicle feel discomfort to some degree. In chapter 3.5 "Man´s perception of load effects" are results presented from research in this field.

There are of course more effects than those mentioned above, as effects on the vehicle that will act on the road holding
(/53/) (Sinha /53/) but those effects will not be dealt with here.

2.6 Analysis of loadeffect process. Construction of loadeffect spectra.

This chapter mainly deals with the loadeffect called stress. If the stressamplitude is plotted in respect of time a so
FIG. 14 called loadeffect process is achieved. FIG. 14 shows an idealized part of such a loadeffect process, or loadeffect history.

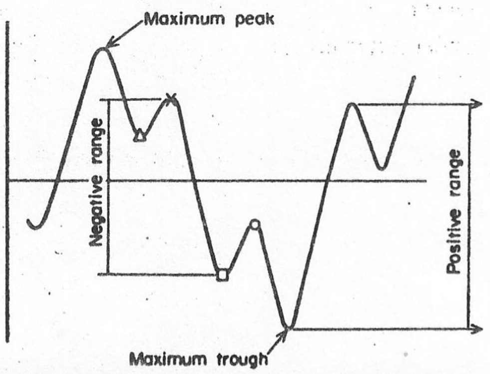


Figure 10. Simple waveform illustrating some terms used in statistical counting methods. ×, Positive peak; ○, negative peak; △, positive trough; □, negative trough.

/21/ FIG. 14. Idealized part of loadeffect process, Mercer, ... /21/.

The loadeffect process can be generated either theoretically, (for example statistical or by simulation), or by a real stream of vehicles. In both cases it has to be analysed and represented in some way, for example as a loadeffect spectrum. The analysis can be carried out in many ways, depending on what the loadeffect spectrum shall be used for. If the loadeffect causes fatigue one is interested in how many repetitions of certain amplitudes that occur and if one believes in a cumulativ fatigue hypothesis that does not take into account the order in which repetitions take place, Miner´s hypothesis, some kind of statistical counting method can be used.

/21/ Mercer, ... /21/ discuss 12 kinds of statistical counting methods and also compare them with Fourier analysis and Power Spectral Density analysis. They found that the statistical counting methods are superiour to the analytical analysis. In most of the investigations presented below the stressrange has been defined (roughly) as the difference between the maximum and minimum stress that occurs when the vehicle passes the bridge, thus defining one loadeffect repetition. This kind of statistical counting is often precised of the measuring equipment used.

One main task is to find the connection between the load spectrum and the loadeffect spectrum caused. Not many attempts have been made to do this. The author of this survey has started on this by treating the influence functions (influence lines), caused by one or several vehicles, in a partly statistical way.

Linear regression analysis have also been made to fit the gross vehicle weights to the induced stress ranges, but is of a more empirical nature, Cudney /6/, Heins, ... /10/. /6/, /10/

/29/,/30/,/31/ Stephenson /29/, /30/, Tung /31/ attacks the problem from another angle.

The result of the loadeffect analysis can also be presented as one value, namely the number of years the structure will stand before a severe damage or collaps is expected (see chapter 5 "Design and design principles").

Below is given a brief survey over analysis of loadeffects that are found in the literature.

/29/, /30/

Stephenson /29/, /30/:

As mentioned in chapter 2.3 Stephenson made the assumption that the trafficflow was Poisson distributed. He carries out the analysis for maximum bending stresses of a simple span steel beam bridge, by the means of translating the actual vehicle load to an "equivalent" H-truck, Hx. The Hx loading induces the same maximum bending stress, caused by x tons, in a span of a particular length, as the actual vehicle does. He also says that (/29/): "It should be mentioned also that Poisson´s law has also been found to provide a good estimate of the frequency distribution of various intensities of heavy vehicle loads measured in terms of their H truck loading equivalencies on a given span". In FIG. 15 (from /30/) are shown results from the calculations. A total of 500 vehicles/hour (two lanes) are assumed with 5 % heavy trucks, that is about 11 million repetitions in 50 years. The impact factors are calculated outgoing from existing design formula. Not more than two vehicles are on the bridge at the same time. FIG. 15 also includes spectra where "vehicles are assumed to be positioned laterally according to some logical pattern".

FIG. 15

/6/, /7/

Cudney /6/, /7/:

In this fieldstudy are the fatigue lifes of longitudinal stringers estimated, for 8 bridges (2 welded plate girders, 5 rolled beam with tapered end cover plates and 1 prestressed concrete I-beam) with spans 14-39 meters. The stress range was defined as "the algebraic difference between the peak maximum stress and the maximum peak half-cycle of negative or rebound stress for any vehicle or combination of vehicles producing this stress".

The vehicles that passed the bridges were type classified.

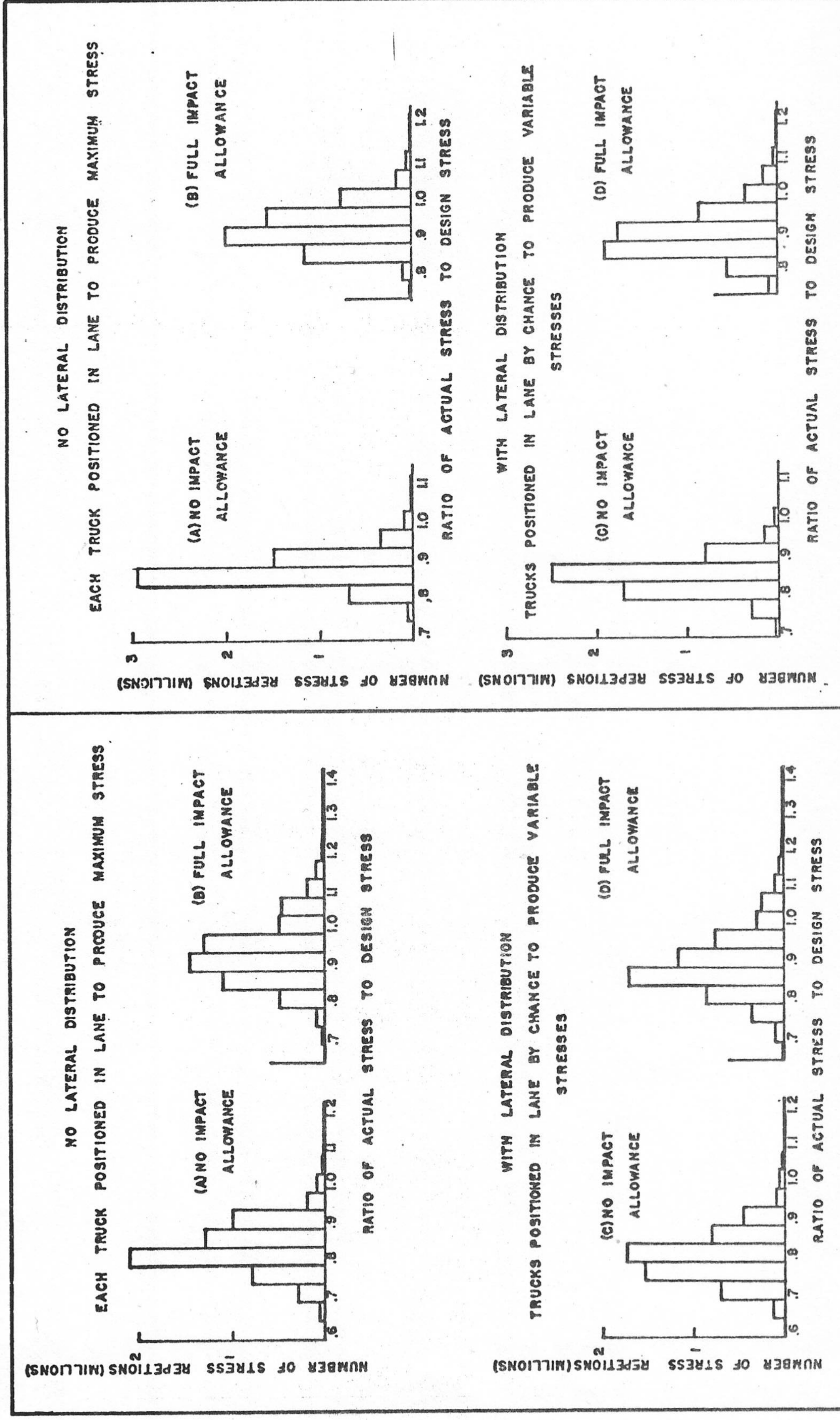


Figure 3. Number of repeated stresses produced in a 50-ft simple-span bridge of H15-44 design during an assumed useful life of 50 years (design-stress ratios based on continuous traffic volume of 500 vph containing five percent heavy trucks weighing 13 tons or more).

Figure 4. Number of repeated stresses produced in a 100-ft simple-span bridge of H15-44 design during an assumed useful life of 50 years (design-stress ratios based on continuous traffic volume of 500 vph containing five percent heavy trucks weighing 13 tons or more).

FIG. 15. Calculated loadeffect spectra, Stephenson /30/.

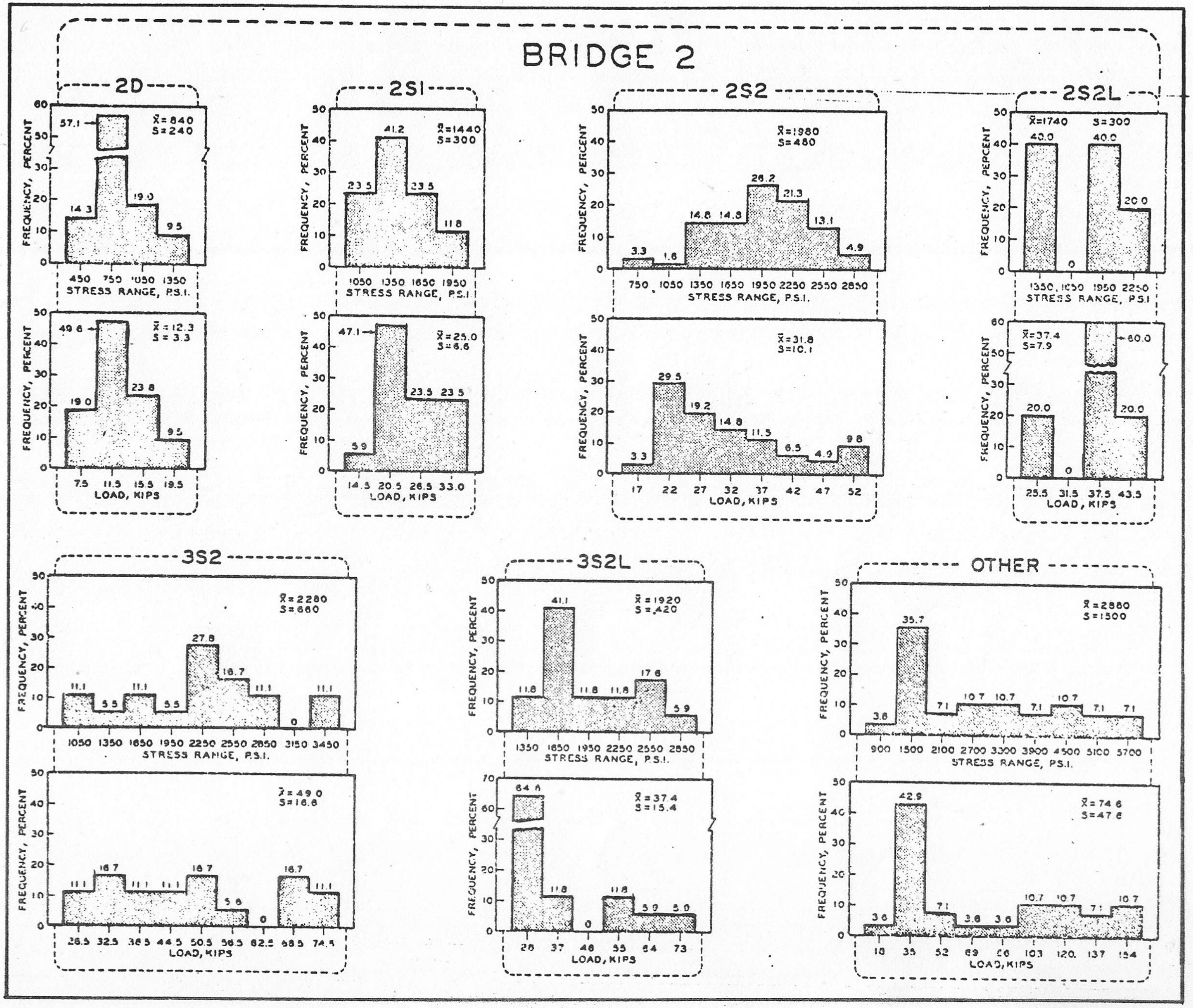


FIG. 16. "Gross load and maximum stress range frequency distributions at stress concentration point of most highly stressed stringer of rolled beam with welded cover plate structure", Cudney /6/, /7/.

Vehicle weights and axle-spaces were measured about 50 km away in suplementary tests for bridge 1 and 2 and the data were used in a linear regression analysis, for maximum live load stress of the mid-point versus gross vehicle weight.

FIG. 16, 17 FIG. 16 and 17 show measured load- and loadeffect spectra

FIG. 18 FIG. 18 shows distribution of extra oscillations. Cudney says that "it was noted that certain vehicles and vehicle combinations produced supplementary stress cycles with greater amplitudes than the maximum peak stress amplitude caused by other vehicles ".." the 600 psi to 900 psi range ... were primarly the result of the free vibration mode of this particular structure".

In /6/ are also found results from drives with a special test vehicle showing lateral stress distribution in the bridges for different speeds of the test vehicle.

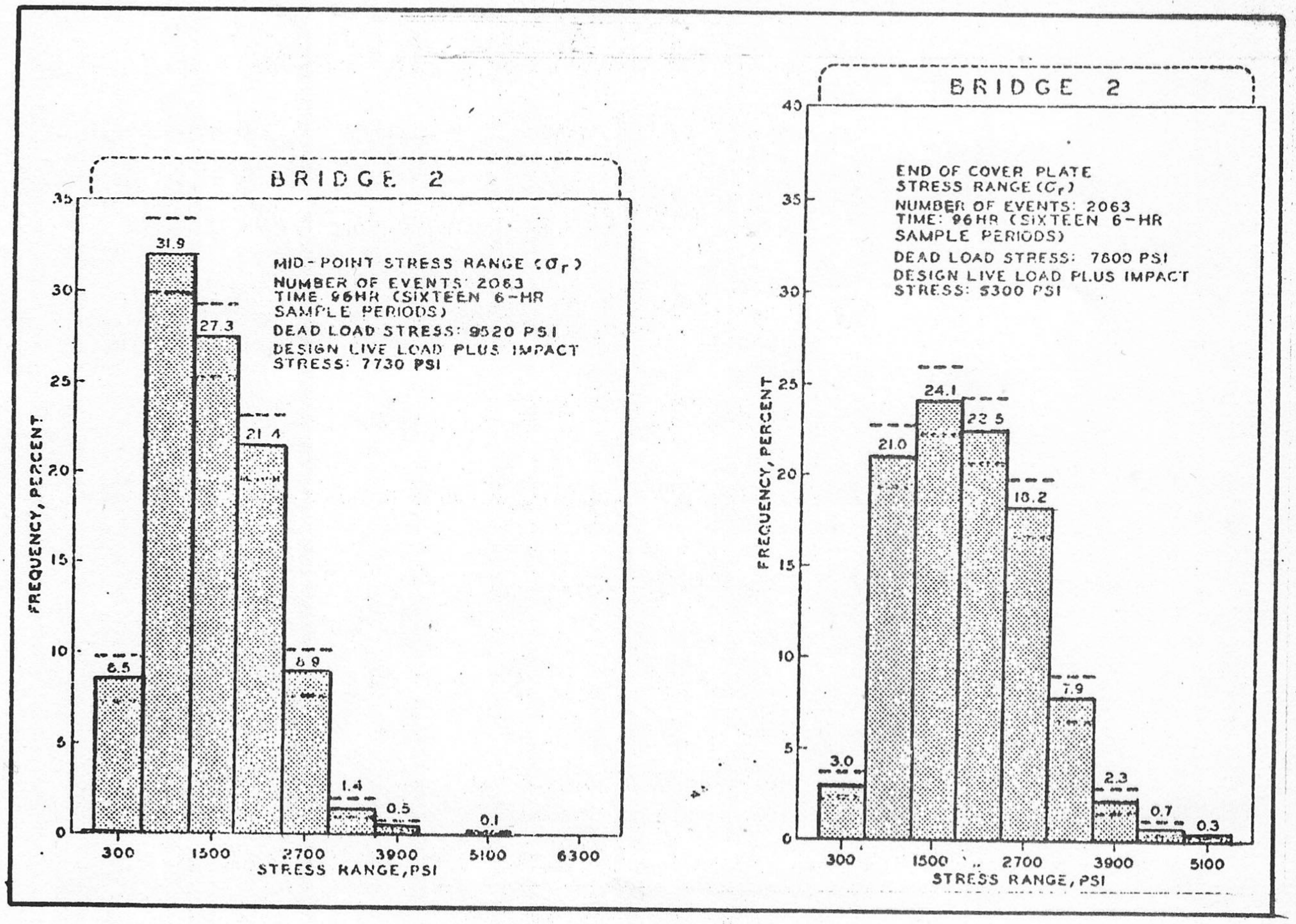


FIG. 17. Measured loadeffect spectra, bridge 2, Cudney /6/.

Further there are showed oscillograph records of typical stress histories for most common vehicle types.

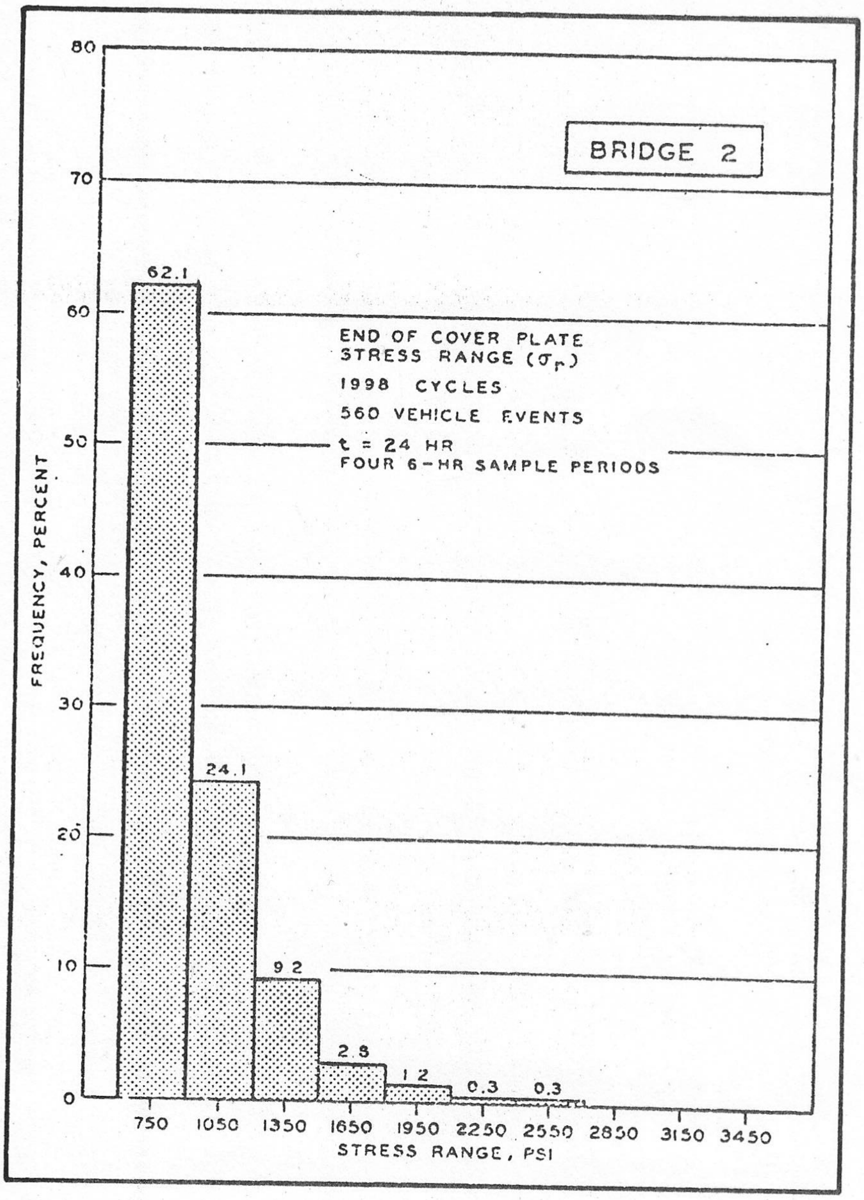


FIG. 18. "Distribution of extra oscillations of stress range at the stress concentration point", bridge 2, Cudney /6/.

/31/ Tung /31/ has outlined a probabilistic model for the calculation of fatigue lifes with the help of a response-function for the bridge, with the input variables weight and type of vehicles. As an example he calculates the fatigue life under simplified assumptions for one of the bridges in the Cudney investigation, and gets a somewhat more favorable result.

/15/ Galambos, ... /15/:

FIG. 19 In the article is reported loadeffect spectra based upon different definitions of stress range, see FIG. 19. In the same figure is also shown the corresponding loadeffect spectra measured on a steel beam of a three-span continous structure. If the stressranges below 3 k.s.i. were not included in the spectrum there were no significant difference in shape.

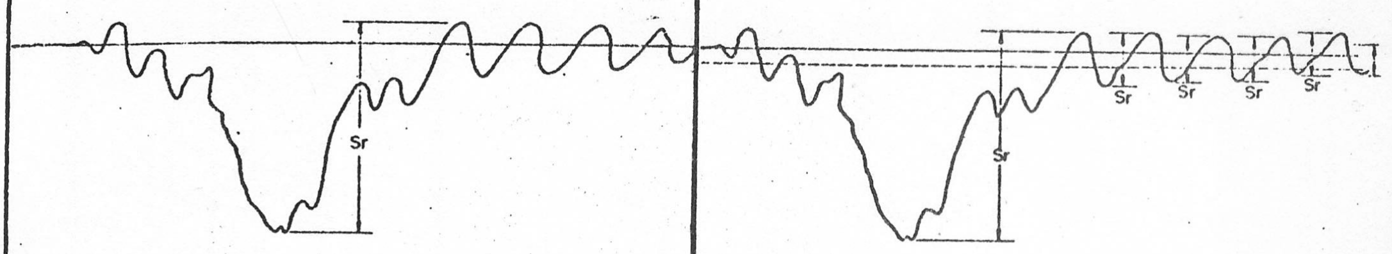
/8/,/9/,/10/ /11/ In "Loading history of bridges, 7 reports", Highway Research Records, Number 382, 1972, are reported field studies dealing with measureing of loadeffect spectra /8/, /9/, /10/ and /11/. Below are given short descriptions of the investigations.

/8/ Christiano, ... /8/:

The stress range is defined thus: algebraic difference between peak to first valley below zero. The vehicles were type classified and some weighings were made at a weighing station about 13 km away (much of the traffic had then left the road). The bridge was a 3-span continuous-stringer highway bridge (11.5, 18.6, 11.5 meters) with a total of 24 strain gauges installed. Runs with two testvehicles were made at different speeds. Stress range spectra are shown for the 5 different stringers, at two sections, under the same traffic. Good correlation is found between the frequency distribution of stress ranges in the most severely stressed stringer at midspan and the frequency distribution of vehicles according to grossweight.

/9/ Douglas /9/:

Two simple span and one 3-span steel girder bridge were



Typical strain trace caused by 3-axle dump truck.

Definition of stress ranges, S_r.—FHWA equipment.

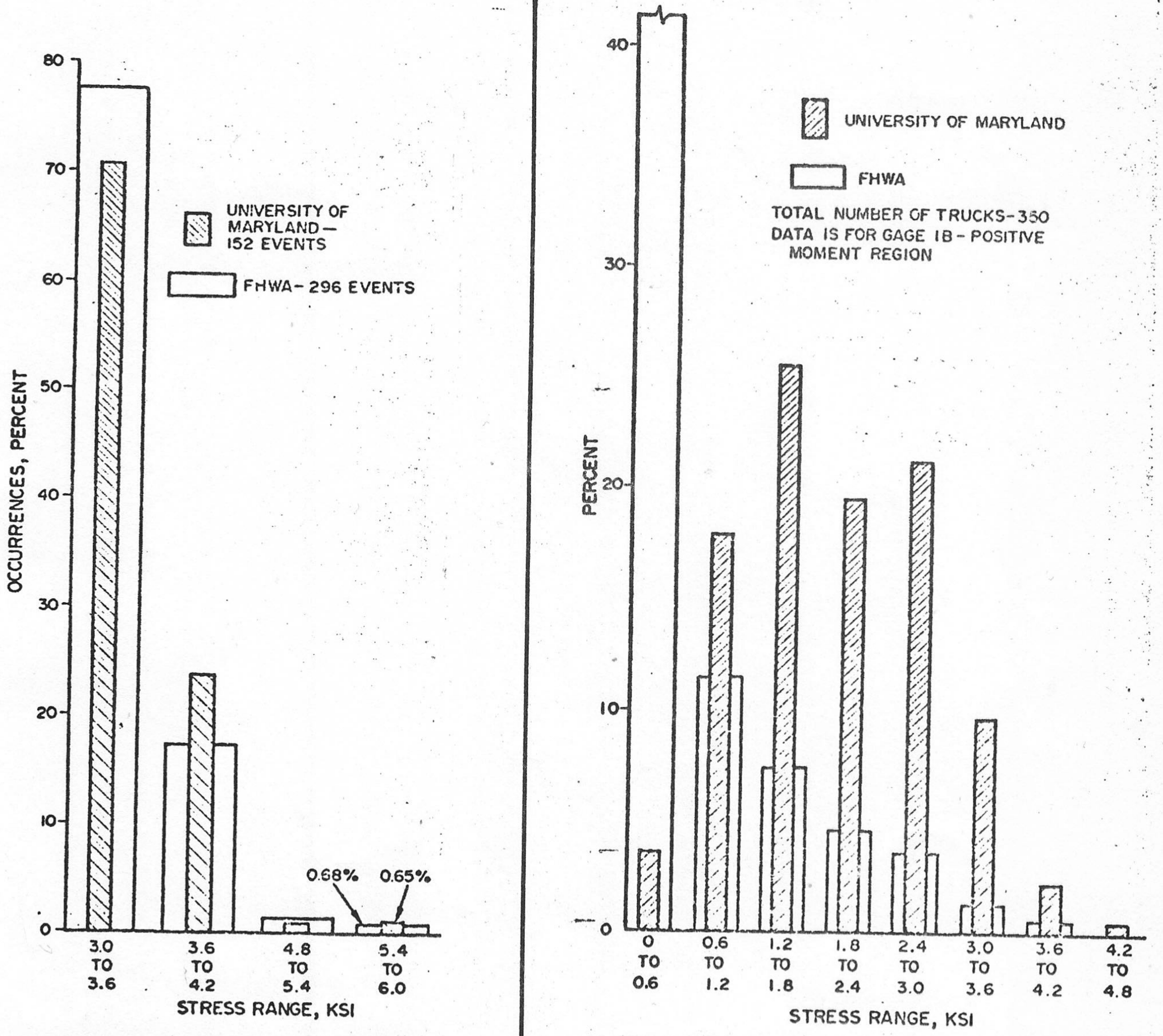


Figure 8.—Stress ranges above 3.0 k.s.i.

Figure 5.—Comparison of stress range histograms.

FIG. 19. Measured loadeffect spectra. Two stress range definitions, Galambos, ... /15/.

selected. Stress range were defined as the algebraic difference between maximum and minimum stresses. Three stress range spectra are presented. FIG. 20.

FIG. 20

/10/

Heins, ... /10/:

Measurements made in 1968 for four bridges, simply supported composite structure, of vehicle weights and stressranges were used in linear regression analysis. The following formula was assumed

$$\sigma_r(S/L) = A + B(G)$$

where

σ_r = induced dynamic stress range on girder, Ksi;
G = gross weight of vehicle that induces stress range, kips;
S = elastic section modulus on bottom flange of girder, in.^{3};
L = girder span length, in. ; and
A,B = coefficients obtained from a regression analysis of data.

Solutions were obtained for different vehicle types and measuring points.

/11/

McKeel, ... /11/:

Two typical highway spans were studied. One 23 meter steel beam composite span and one 18 meter prestressed concrete beam span. Stresses as well as axle spacing and lateral position of the trucks were recorded at the bridge. About 85 % of the trucks were also weighed at a permanent weighing station near the bridge. Load spectra over truck weights for each lane were presented (see FIG. 11) as well as stress range spectra from different sections of the stringers. A different definition of stressrange was made. "A strain range was measured from peak to valley; the computer sought a peak strain when the signal exceeded the minimum test level, and it sought a valley when the signal dropped to or below the zero level. An event was counted each time the signal passed the minimum test level and returned to zero. It was not uncommon for a single truck to produce more than one strain range above the minimum test level". (Compare to FIG. 19.)

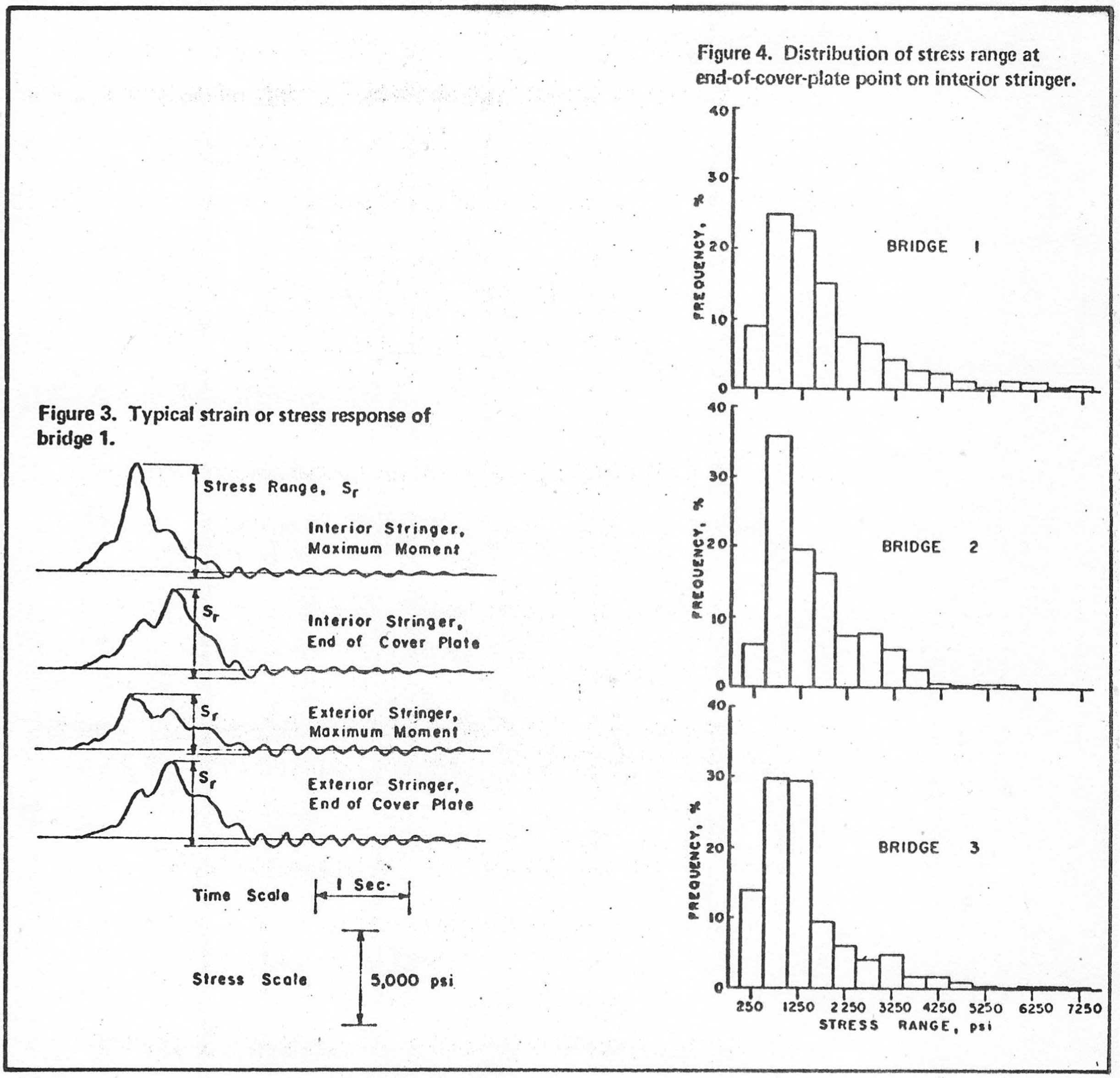


Figure 3. Typical strain or stress response of bridge 1.

Figure 4. Distribution of stress range at end-of-cover-plate point on interior stringer.

FIG. 20. Measured loadeffectspectra. Stress range, Douglas /9/.

3 DYNAMIC EFFECTS. PREFABRICATED BRIDGE SLABS.

3.1 General.

Chapter 3 covers a much greater field than chapter 2 and will therefore be presented more summarily. Many of the references mentioned give possibilities for further studies in the different areas.

A great deal of dynamic load studies have been carried out.
/55/ Varney, ... /55/ give a summary of "Field Dynamic Loading
Studies of Highway bridges in the U.S. 1948-1965". Armstrong
/33/ /33/ gives a table over nine field-tests of curved girder
bridges which have been performed in U.S.A. since 1964.
/32/ "AASHO Road Test, Bridge Research" /32/ contains information about, Tests with repeated stresses and Dynamic load tests.

Chapter 3.2 "Analysis of prefabricated bridge slabs" deals with the static analysis of bridge decks, mainly consisting of slabs jointed together. Some dynamic properties of bridges are found in chapter 3.4. "Theoretical analysis of vehicles passing a bridge. Influences of different variables on dynamic effects".

"Distribrution of Wheel Loads on Highway Bridges", National
/39/ Cooperativ Highway Research Program, Report 83, 1969, /39/,
includes a bibliography with 297 references, covering a wide area of the titles in chapter 3 except for chapter 3.5 "Man´s perception of dynamic effects".

In chapter 3.5 are criterions presented that make it possible to estimate the subjectiv riding comfort for passengers as a function of the vibrational mode of the vehicle.

3.2 Analysis of prefabricated bridge slabs.

Bridge decks consisting of elements jointed together are often refered as multibeam bridges. They are for example used in USA and the traffic lane then goes parallel to the elements. The transverse distribution of loads is obtained by shear keys between the elements or by transverse prestressing. A concrete continuous in situ covering may be put on and will then contribute to the load distribution.

There are mainly two ways to handle the analysis of this kind of deck, with orthotropic plate theori or to treat the deck as beams or plates connected somehow.

TAB. 1 This chapter only deals with the static analysis of the decks. In table 1 below are the references and authors listed, that are mentioned in this chapter.

/38/,/50/ Cusens, Pama /38/, /50/ develop solutions for the deck assuming no transverse flexural stiffness, which is equivalent to having hinges between the beams, so called articulated plate theory. The analysis are compared with laboratory test /38/ and full scale test /50/. The authors say that "articulated plate theory, as presented, provides an effective method of predicting the distribution of load to the different members of a multibeam bridge of low transverse flexural stiffness".

/45/ Hudson, ... /45/ have developed a method, using discrete elements, which "provides for discontinuities, freely variable stiffness, and variable foundation support. An alternating-direction iteraction (ADI) method of solution is used.", FIG. 21. FIG. 21

/36/ Banerjee, ... /36/ presents a solution for the coupled elements in terms of Fourier series. The elements have rigid sections and are hinged together with shear keys that can take only vertical joint forces and cannot resist moment. The elements are freely supported at their ends. The solution was compared to half scale experiments and good correlation was found if the quotient (flexural rigidity/torsional rigidity), which was very hard to calculate, was properly chosen.

YEAR	1958	1960	1964	1965			1967		1968	1972
Banerjee, Basole	x									
Arya			x	x		x				
Pool						x	x			
Lohtia			x	x						
Duberg		x								
Robinson						x	x			
Khachaturian		x				x	x			
Fradinger		x								
Cusens					x			x		
Pama					x			x		
Hudson, Matlock									x	
Jirousek										x
REF.	/36/	/40/	/34/	/35/	/38/	/51/	/47/	/50/	/45/	/46/

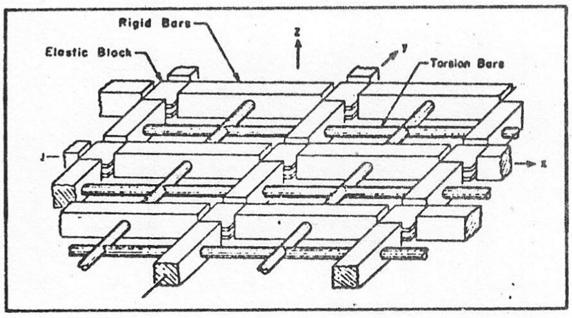


FIG. 21. "Discrete-element model of plate or slab", Hudson, ... /45/.

/40/ Duberg, ... /40/ analyse beam elements hinged together, FIG. 22, and present influence lines for moment in multibeam bridges having two, three and ten beam elements with a square section. The shear key can take forces in the three principle directions. The analysis is carried out with the help af Fourier series and the following assumptions are made:

"1. The beam elements are made up of homogeneous, isotropic, and elastic material.

2. The shear strains are small and can be neglected.

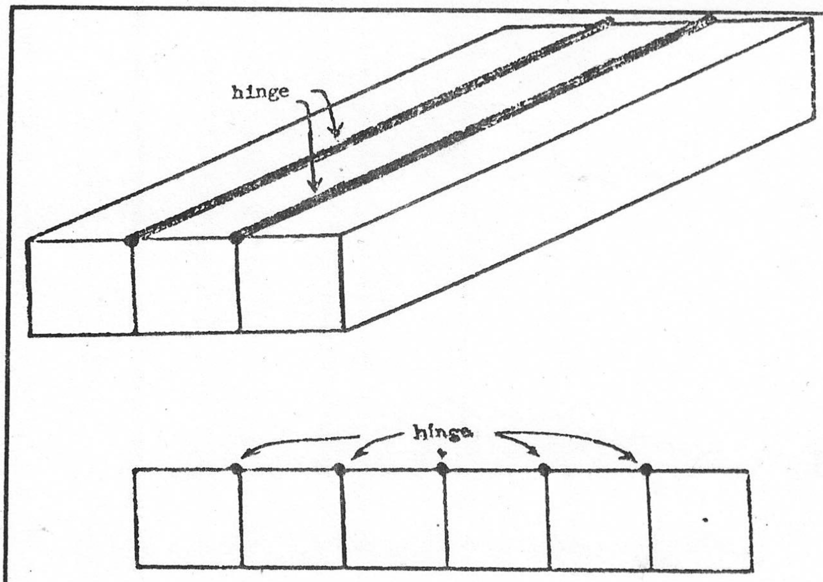
3. The cross section of each element is rigid, that is, the relative deformation of the parts forming the beam element is small in comparison with the deformation of the beam element as a whole.

4. All beam elements have the same cross-sectional properties and are of the same material.

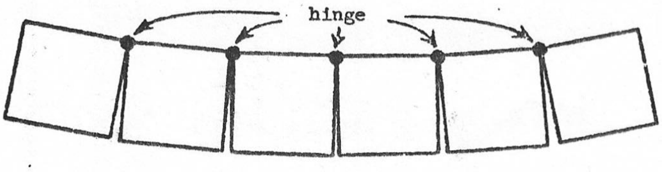
5. Each beam element is simply-supported over the abutments or piers.

6. The beam elements are prismatic.

7. The external forces are concentrated loads and act vertically down."



(b) Cross-Section of the Idealized Structure



(c) Deflected Shape of the Idealized Structure Due to Downward Loads

FIG. 22. "Idealised structure", Duberg, ... /40/.

/51/ Pool, ... /51/ have on the basis of the theories presented in /40/ analysed multibeam bridges. The beams have solid or box sections and warping is therefor neglected. Solutions are shown for bridges with 4 and 8 elements, supported with figures showing the distribution of joint forces.

/47/ In Khachaturian, ... /47/ the theories are extended to be
valid for open sections (channel sections) and warping is
allowed. Solutions are given for two 4 element bridges with
FIG. 23 figures showing the distribution of joint forces. FIG. 23
shows a principle view of the bridge.

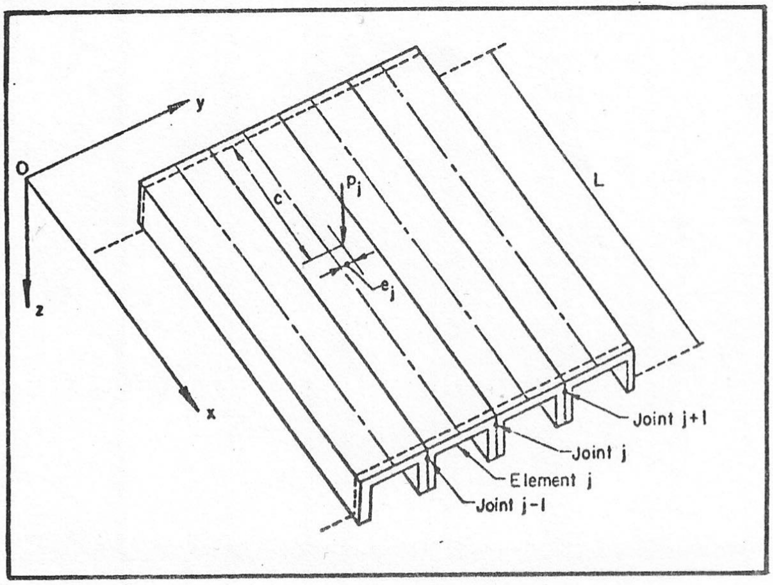


FIG. 23. Multibeam bridge with elements of channel section, Khachaturian, ... /47/.

/34/,/35/ In references Arya, ... /34/, /35/ are laboratory experiments compared to the theories and good correlation are
reported. In /35/ it is said that the longitudinal distribution of joint forces differs between channel and closed
sections in that the forces die out faster for closed sec-
FIG 24 tions, FIG. 24.

If the joint forces in two directions are removed (q and r in FIG. 24) and only the vertical forces are left there will only be 5 % change in lateral distribution of load in a multibeam bridge consisting of closed sections.

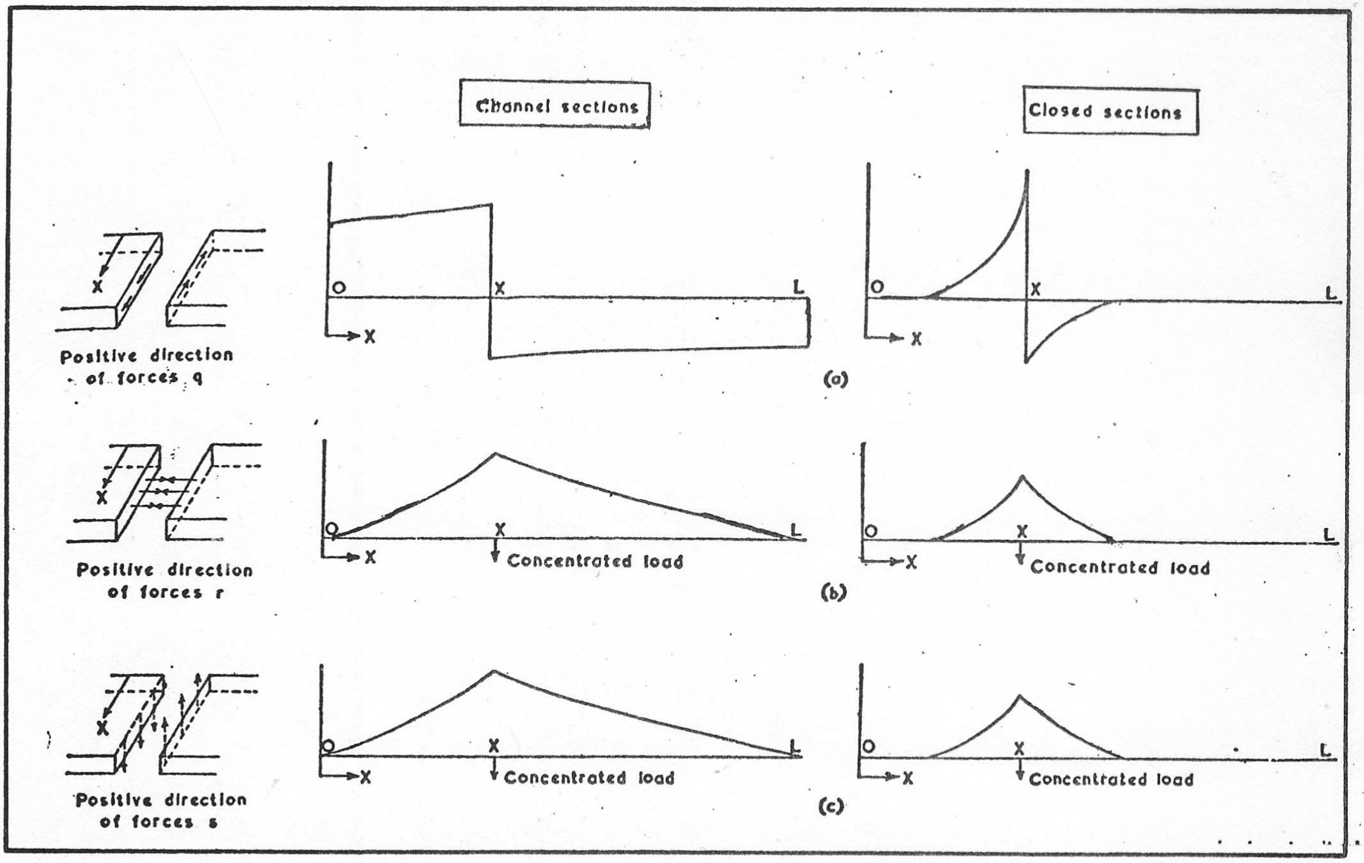


FIG. 24. "Typical distribution of joint forces in the longitudinal direction", Arya, ... /35/.

/46/ Jirousek /46/ also has analysed multibeam bridges, with the help of finite element method, for element hinged together having box sections. He carries out some calculations for ordinary and skew bridges and makes comparisons with experimental solutions and solutions with other methods.

For further references see /34/, /35/, /38/, /51/.

3.3 Theoretical models of trucks. Truck properties.

Depending on in what kind of analysis the truckmodel will be used, one is interested in different characteristics of truck behaviour. The models presented in this chapter are among other things suited for evaluating interacting forces (forces between wheels and roadsurface) and vibration of the sprung and unsprung masses.

The number of degrees-of freedom will increase fast with the complexity of the model. The principal motions of the vehicle are referred as

bounce,	vertical oscillation of the vehicle body
pitch,	angular oscillations of the vehicle body in the "longitudinal" vertical plane
wheel hop,	oscillations of the axles and wheels in the vertical direction.

FIG. 25,/52/ FIG. 25, from "Shock and vibration handbook", /52/, shows a schematic diagram of truck and it´s suspension system.

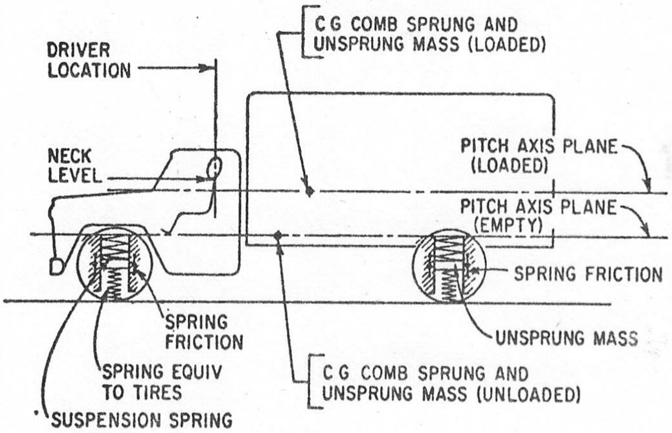


Fig. 45.2. Schematic diagram of a truck and its suspension system. The sprung mass includes the body and chassis of the truck, the unsprung mass the tires and axles. The spring friction represents interleaf friction of the suspension springs. (*R. N. Janeway.*[1])

FIG. 25. Schematic diagram of a truck and its suspension system, "Shock and vibration handbook", /52/.

FIG. 26 In FIG. 26 are the models shown used in the theoretical studies made in connection with the AASHO road test, bridge
/32/, /41/ research, /32/. See also Fenves, ... /41/.

FIG. 27, /56/ The models shown in FIG. 27 were used by Walker, ... /56/.

As shown in the figures the suspension system is represented by a spring parallel to a frictional damper and a tire-spring.

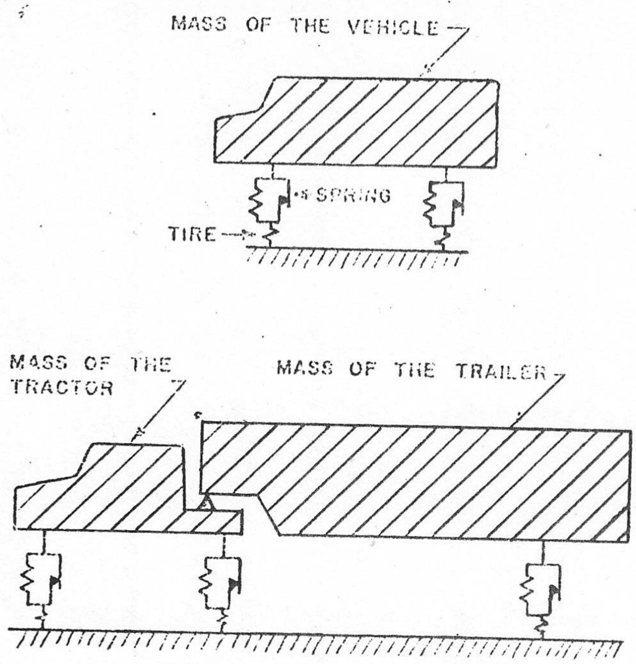
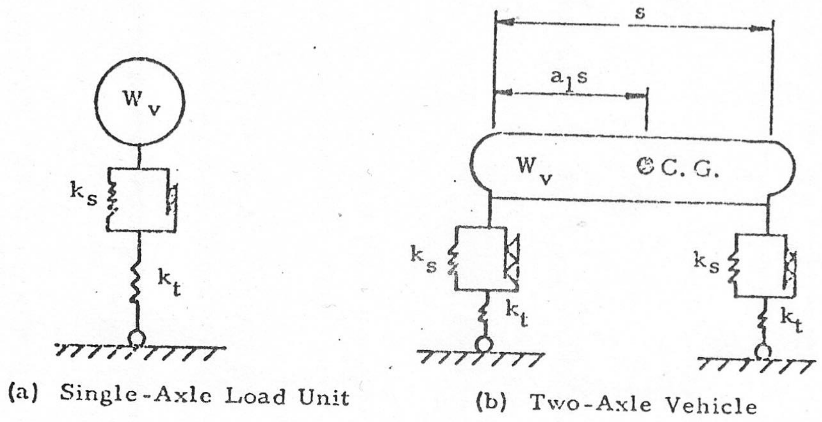


Figure 127. Models of test vehicles.

FIG. 26. Vehicle models, AASHO road test, bridge research /32/.



(a) Single-Axle Load Unit

(b) Two-Axle Vehicle

FIGURE 2.2 IDEALIZATION OF VEHICLE

FIG. 27. Vehicle models, Walker, ... /56/.

/41/ Fenves, ... /41/ say that the tiredamping can be considered as viscous and of the magnitude 1 % of critical damping.

/56/ Walker, ... /56/say: "It has been noted that the stiffness characteristics of the suspension springs are usually constant, allthough seldom linear for a given vehicle.

The tire stiffness is also non-linear and is largely dependent upon the load level and tire pressure."

/41/ Fenves, ... /41/ report from measurements on 14 testvehicles in the AASHO road research:

Springstiffness of tires (2 or 4 tires per axle)
8.9 to 29.0 kips/inch

Springstiffness of suspension springs
3.6 to 24 kips/inch

FIG. 28 From the same reference are typical load deflection curves for tire and suspension spring taken, FIG 28.

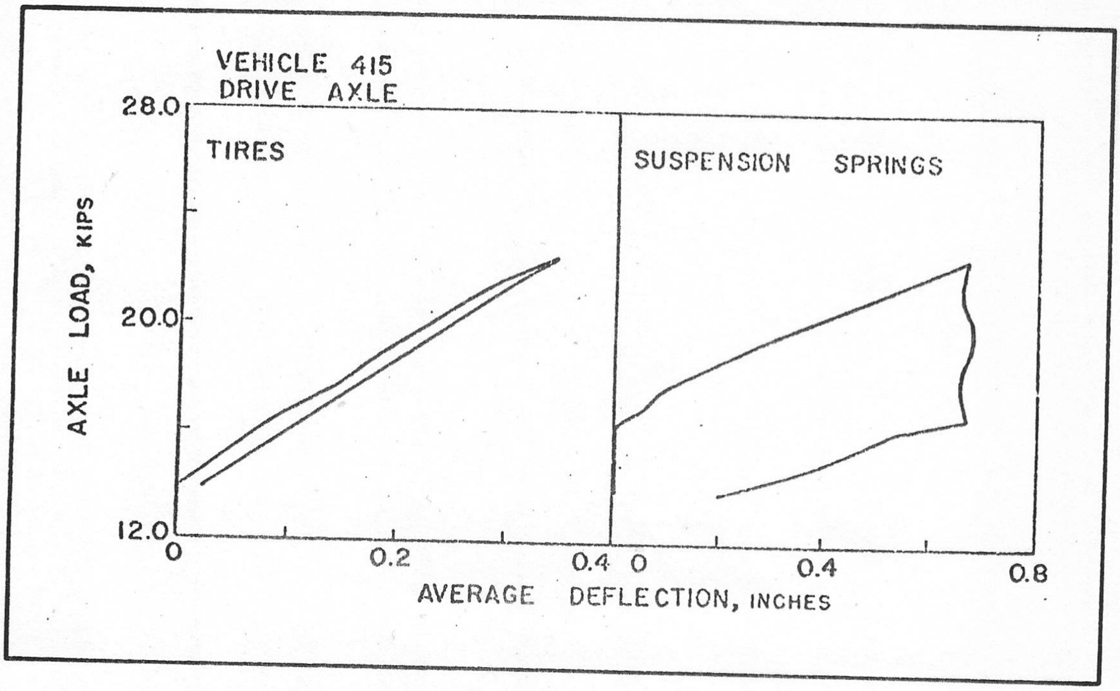


FIG. 28. "Typical load deflection curves", Fenves, ... /41/.

/57/, FIG. 29 Corresponding measurements on one of the testvehicles used in Whittermore, ... /57/ are shown in FIG. 29.

TAB 2.

/56/

Table 2 shows ranges of natural frequencies and coefficients of interleaf friction (μ) from a survey on trucks, among others those used in the AASHO road test, Walker, ... /56/. Table 2 does not reflect "any recent development in the area of air-suspension system". It is further said "The unsprung weight of ordinary truck trailer combinations seem to be from 10 to 15 per cent of the total axle load. The higher precentage is applicable to the drive axles."

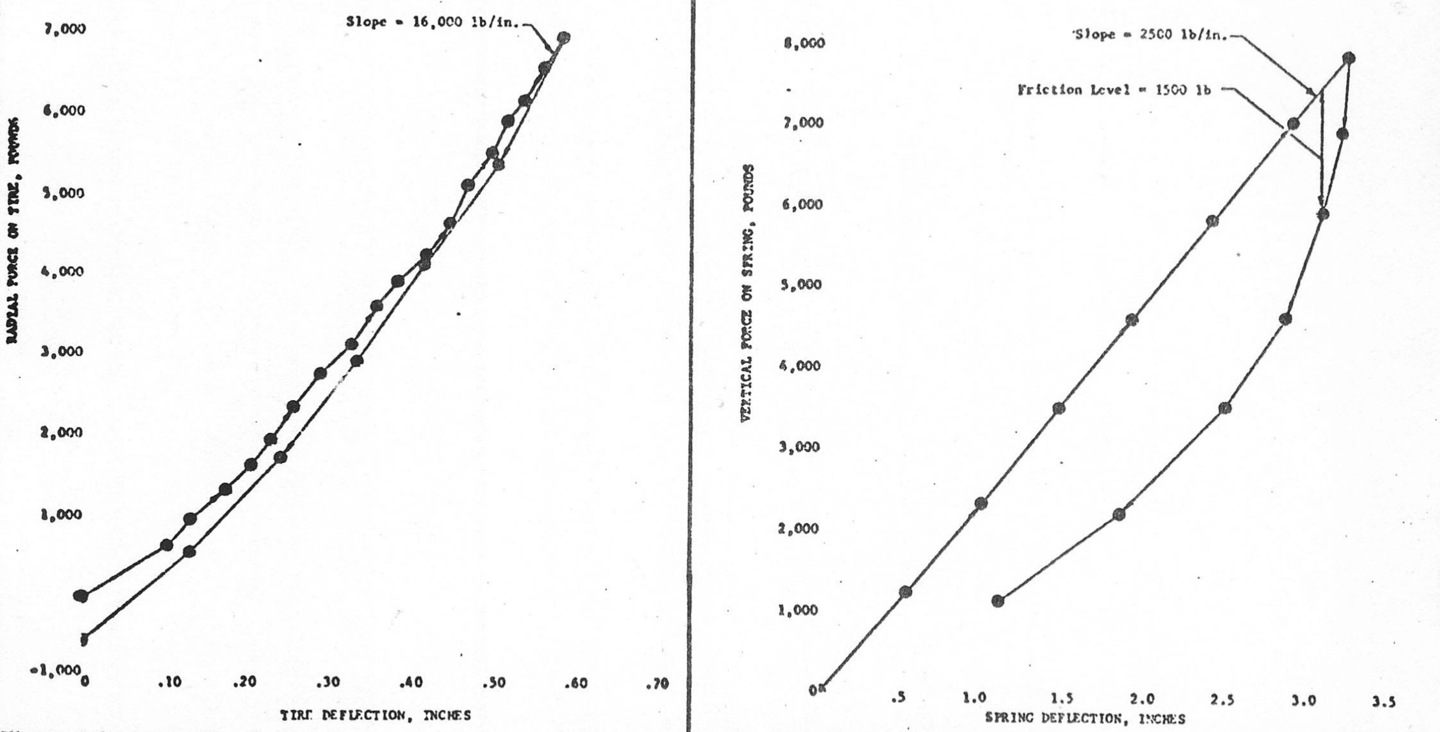
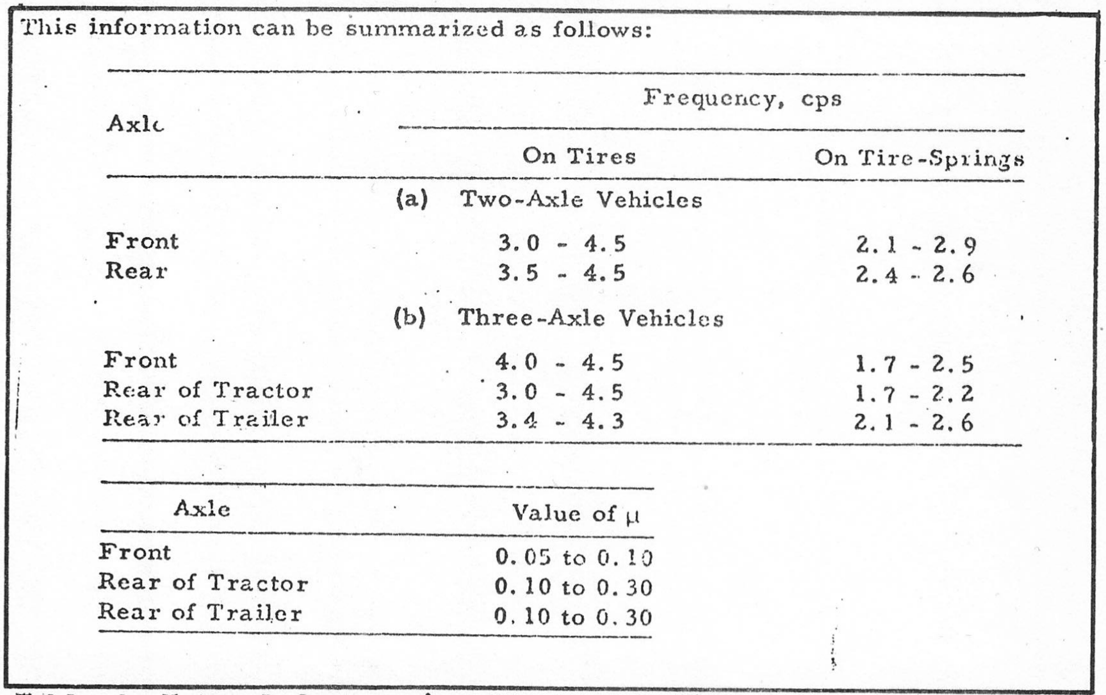


Figure S-3. Nonrolling load-deflection curve for a rear dual tire set on Test Vehicle No. 1.

Figure S-2. Load-deflection curve for rear leaf spring on Test Vehicle No. 1.

FIG. 29. Load deflection curves of test vehicle, Whittermore, ... /57/.



This information can be summarized as follows:

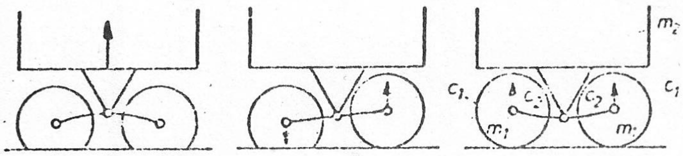
Axle	Frequency, cps	
	On Tires	On Tire-Springs
	(a) Two-Axle Vehicles	
Front	3.0 - 4.5	2.1 - 2.9
Rear	3.5 - 4.5	2.4 - 2.6
	(b) Three-Axle Vehicles	
Front	4.0 - 4.5	1.7 - 2.5
Rear of Tractor	3.0 - 4.5	1.7 - 2.2
Rear of Trailer	3.4 - 4.3	2.1 - 2.6

Axle	Value of μ
Front	0.05 to 0.10
Rear of Tractor	0.10 to 0.30
Rear of Trailer	0.10 to 0.30

Table 2. Natural frequencies for trucks. First column with blocked springs, Walker, ... /56/.

/52/ From "Shock and vibration handbook", /52/ one can see that the pitching frequencies are somewhat higher than the corresponding natural frequencies of vertical oscillations.

/42/, FIG. 30 From Gauss /42/ is FIG. 30 picked, showing natural frequencies for body on tandem axle and for tandem axle against body (vertical and angular).



$$\omega_2^2 \approx \frac{2c_1 \cdot c_2}{(c_1 + c_2)m_2} \qquad \omega_{1,2}^2 = \frac{c_1}{m_1} \qquad \omega_{1,1}^2 \approx \frac{c_1 + c_2}{m_1}$$

Eigenschwingzahlen [Hz]

leer	*≈ 3*	*7,5*	*9,8*
beladen	*≈ 2*	*8,5*	*10,3*

Bild 4. Schwingungsformen der Waagebalkenachse mit entsprechenden Eigenschwingzahlen

FIG. 30. Natural frequencies for body on tandem-axle and for just tandem axle, Gauss /42/.

3.4 Theoretical analysis of vehicles passing a bridge. Influences of different variables on dynamic effects.

Very seldom can simple analytical solutions be obtained for the combined action when a vehicle passes a bridge structure. Simplifications must be made and models put up. An important aid in solving the equations offer the computers, which for example make it practical to make stepwise solutions of the differential equations in respect of time. The analytical solutions then never have to be evaluated.

FIG. 31, /5/ The author of this survey intends to estimate the dynamic effects of the prefabricated bridge slabs in using models presented in FIG. 31, Christiansson /5/.

There are many important parameters which are difficult to estimate, such as initial oscillation conditions of the vehicle, which properly accounted for will cause a great deal of scatter in the solutions. Yet the relative importance of the different parameters can be estimated as well as which parameters are critical. It will also be possible to get an idea of the magnitude of the dynamic effects as well as the principle behaviour of the vehicle-bridge system in respect of time.

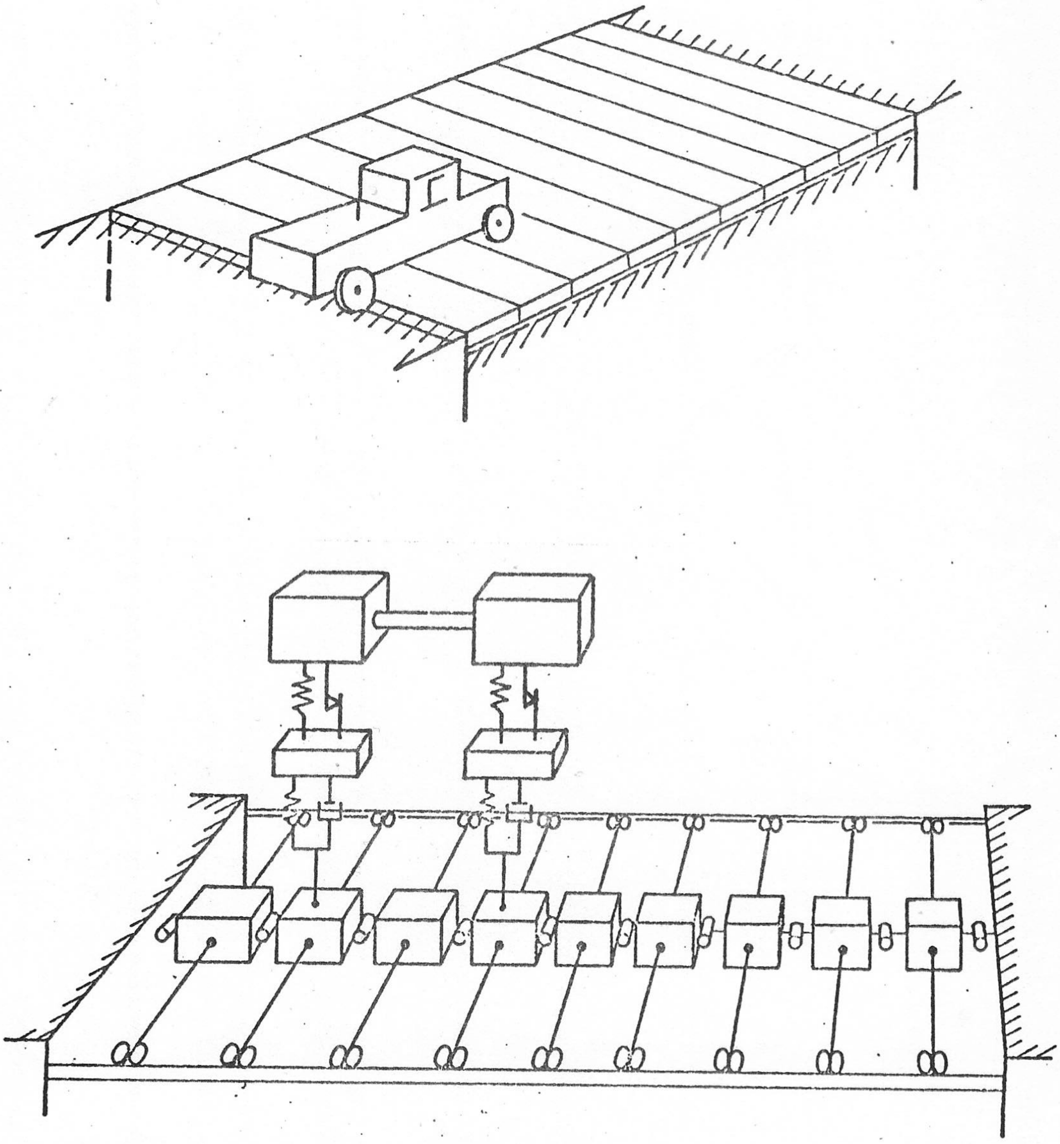


FIG. 31. Schematic model of vehicle-bridge system, Christiansson /5/.

Many investigations have been made through out the years on the dynamic behaviour of the vehicle-bridge system.

Just a few are mentioned in this survey. They all deal with the response of simple span highway bridges, and more references are found in Walker, ... /56/.

/44/ Hillerborg /44/ has analysed loads passing a simply supported girder and made corresponding experimental model studies. The vehicle models mainly consisted of one mass carried of a spring. Comparisons between analysis and experiment show fairly good agreement.

/37/ Biggs /37/ uses about the same model. He means that it is possible to represent the vehicle as a one degree system if the axlespacing is small in comparison to the bridge span (ratio less than 1/5). He also says that it is enough to study the fundamental mode of the bridge "since the higher modes contribute little to deflection of bending moment at midspan". The most important vehicle motion, with respect to bridge vibration, is that when all elements of the vehicle act in phase, therefore the vehicle can be represented as a one degree system.

The above mentioned solutions have been obtained in an analytical way.

/41/ In Fenves, ... /41/ are the most important findings of the AASHO bridge research discussed. FIG. 32 shows the analytical model of the vehicle-bridge system and the solutions were obtained numerical in a computer.

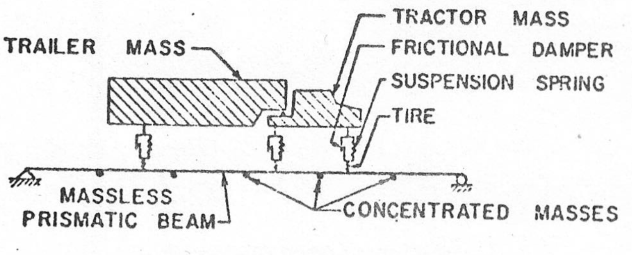


Figure 13. Analytical model.

FIG. 32. "Analytical model", Fenves, ... /41/.

Good correlation was found between measured and computed values, and the auhthors mean that this was a very important result of the AASHO bridge research.

FIG. 33 shows the principle of what happens when a load passes the bridge.

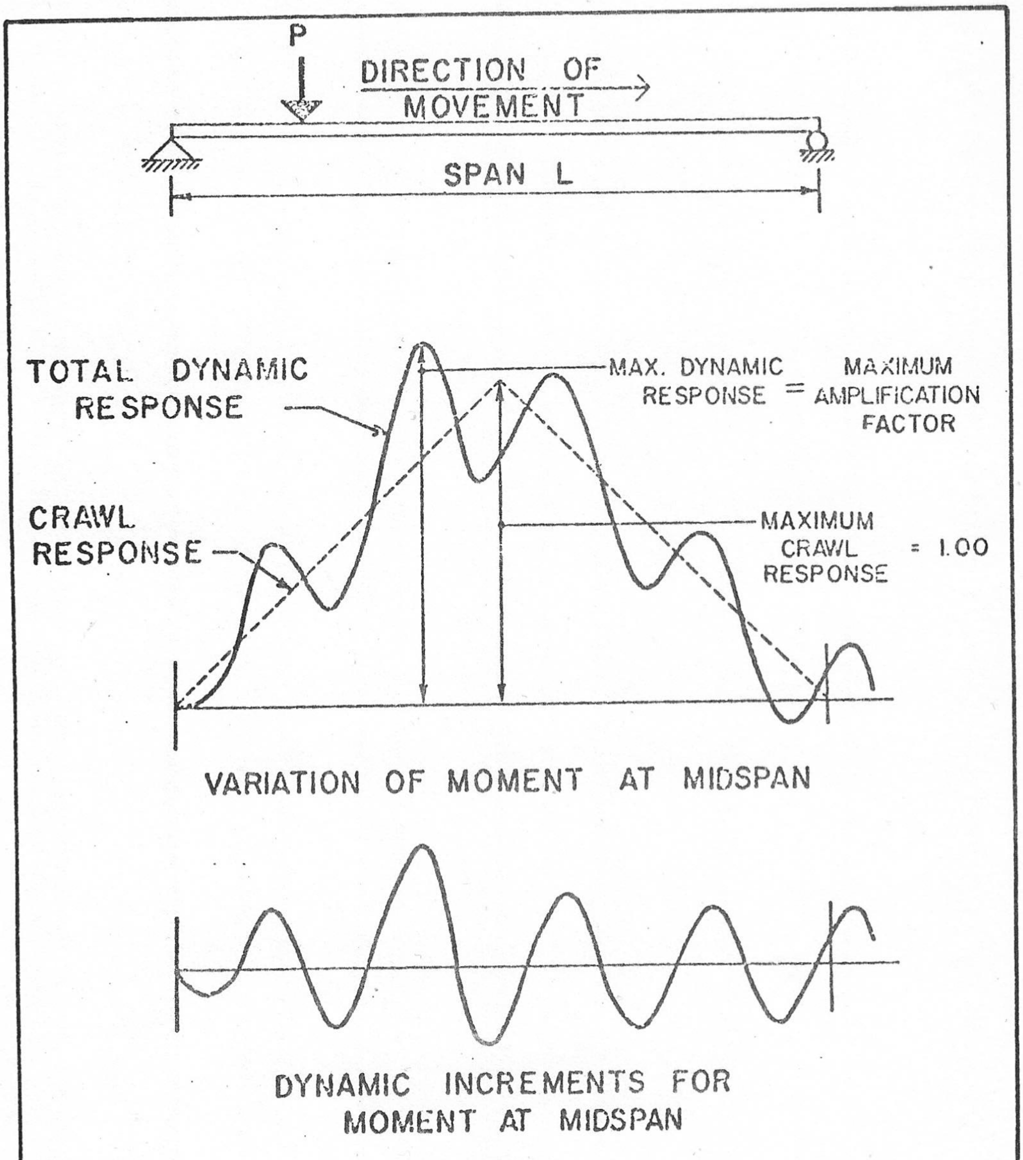


Figure 1.

FIG. 33 Load passing a bridge, Fenves, ... /41/.

/56/ In Walker, ... /56/ are similar computations made. The bridge was represented as a beam with concentrated masses. Effects of shearing deformations and axial forces were neglected as well as the rotary inertia. The computer program could also take inte account irregularities of the bridge surface.

Following parameters were used

weight ratio R = (total weight of bridge/total weight of vehicle)

frequency ratio $\psi_t = f_t/f_b \quad \psi_{ts} = f_{ts}/f_b$

where f_t and f_{ts} denote, respectively, frequency of the vehicle vibrating on its tire alone, and on the combined tire and suspension and f_b, natural frequency of bridge.

speedparameter $\alpha = \frac{v \cdot T_b}{2 \cdot L}$

where v = speed of vehicle (constant during passage)
$T_b = 1/f_b$
L = span length

damping of bridge

interleaf friction coefficient of vehicle

There was also a second group of parameters namely initial configuration of the vehicle-bridge system and the state of the roadway surface,

vehicle (each axle):	initial value of interacting force (plus its change with time) initial value of interleaf frictional force
bridge surface:	critical deflected shape initial velocity destribution
profile of unloaded bridge:	parabolic form or sinusoidal shape.

FIG. 34, /41/

FIG. 34, Fenves, ... /41/, shows dynamic increment curves for deflection at midspan ($\alpha = 0.105$ means 33.7 mph)

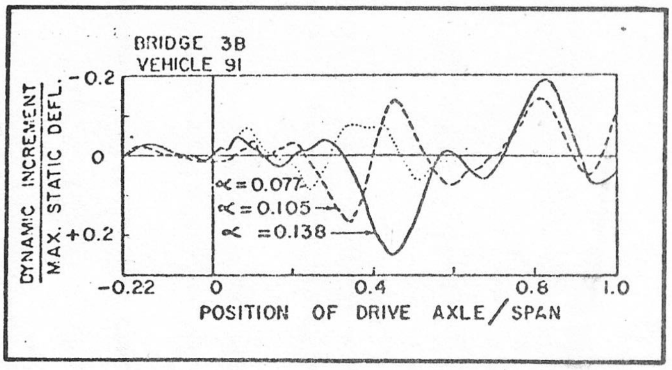


FIG. 34. Variation of dynamic increment with α, Fenves, ... /41/.

FIG. 35 In FIG. 35 are the maximum effects gathered with a computed curve for the vehicle running smoothly on the road before entering the bridge. In the figure is seen scatter due to irregularities of the road surface that causes initial oscillations of the car.

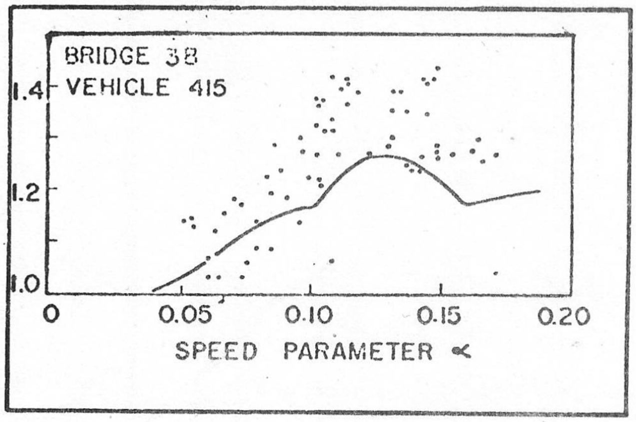


FIG. 35. Amplification factors for deflection at midspan, Fenves, ... /41/.

/56/ Walker, ... /56/ say:

Generally the dynamic effect increases with speedfactor.

The axle spacing considered in relation to speedfactor is also important.

Weight and frequency ratios taken separately may have considerable effect on the response. But weight and natural frequencies are interrelated which must be kept in mind in the analysis.

Initial conditions for vehicle are very important. Walker, ... /56/ found in their study a nearly linear relationship between the amplitude of the initial motion and the magnitude of the resulting maximum response in the bridge.

The same authors say that the road unevenness parameter is of about the same importance as initial vehicle conditions. But in the case of regular uneveness it seems as if the effect can be considerable.

/56/ This chapter will finally give som "dynamic" data of bridges according to a survey made by Walker, ... /56/. The bridge damping is neither purely viscous or frictional, but can in most practical cases be treated as viscous. The bridge damping is usually less than 5 % of critical and a representativ value is 1-2 %. The logarithmic decrement for reinforced concrete structures is about double that for steel. The unevenness of the dominating waves of the bridgesurface could be expressed as

amplitude/length ≃ 0.001-0.002

with max amplitudes of 0.1-1 inch

It shall be said that the above mentioned references deal more with the response of the bridge than the response of the vehicle

3.5 Man´s perception of loadeffect.

As the vehicle body vibrates due to irregularities of the road surface and deformation of the bridge, the passenger will also oscillate and feel uncomfort to some degree. The vibrations have to be transmitted through a seat to the human body.

Through subjectiv tests where man is subjected to a harmonic oscillation, in most cases vertical, some criterions concerning comfort and state of oscillation have been achieved. The state of oscillation is then most commonly described with the parameters, frequency and amplitude of accelaration. It is also desirable to get a transferfunction so that the vehicle body oscillations can be transfered to the human body.

/49/ /53/ Mitsche, ... /49/ make a survey over investigations in the field and in Sinha /53/ can references also be found. In the latter reference, different criterions (seven) are expressed analytically and also some discussions about transferfunctions and absorbed power of human body is carried out.

/49/ FIG. 36 Mitschke, ... /49/ have made an investigation about vibration of man travelling in a car. They present the VDI-Richtlinie 2057, FIG. 36, which is mainly based on laboratory tests of Reiher, Meister and Dickman. The dashed part of the curves include the resonance area of the human body.

They further say:

Human body is a highly damped system.

The corresponding acceleration of man can be greater than of the car body.

Vibrations of the car with frequencies over 5 Hz were strongly damped by the seat.

The vertical oscillations had a resonance peak at about 3.5 Hz for seat + man and about 5 Hz for man.

The fact that subjective measurements are based on harmonic oscillations does not seem to make the criterions less usefull to random vibrations.

/48/ Lehtinen /48/ presents further curves for subjective response. He studies several investigations and puts up following criterions valid for 10 Hz

threshold of perception 0.003 · g
" " annoyance 0.05 · g
" " tolerance 0.25 · g

FIG. 37

and then uses an ISO proposal for the rest of the frequency domain, FIG. 37.

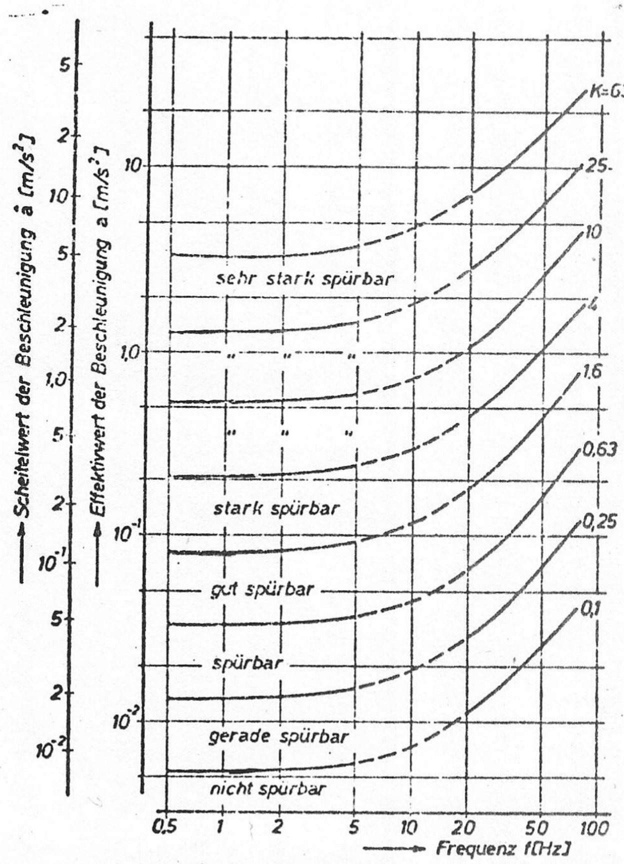
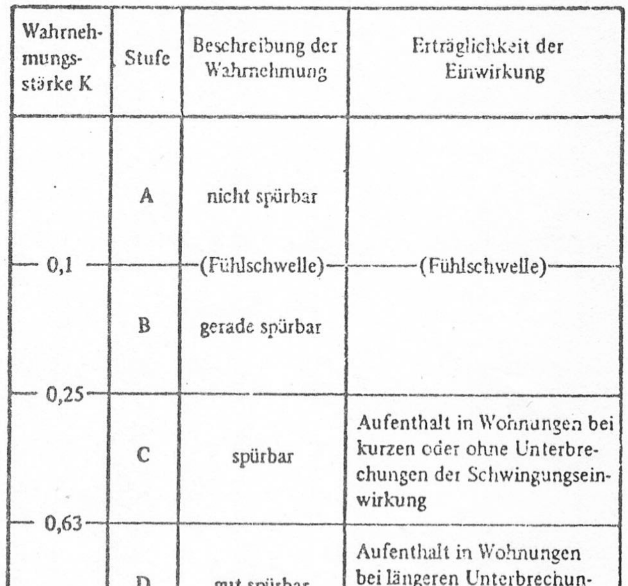


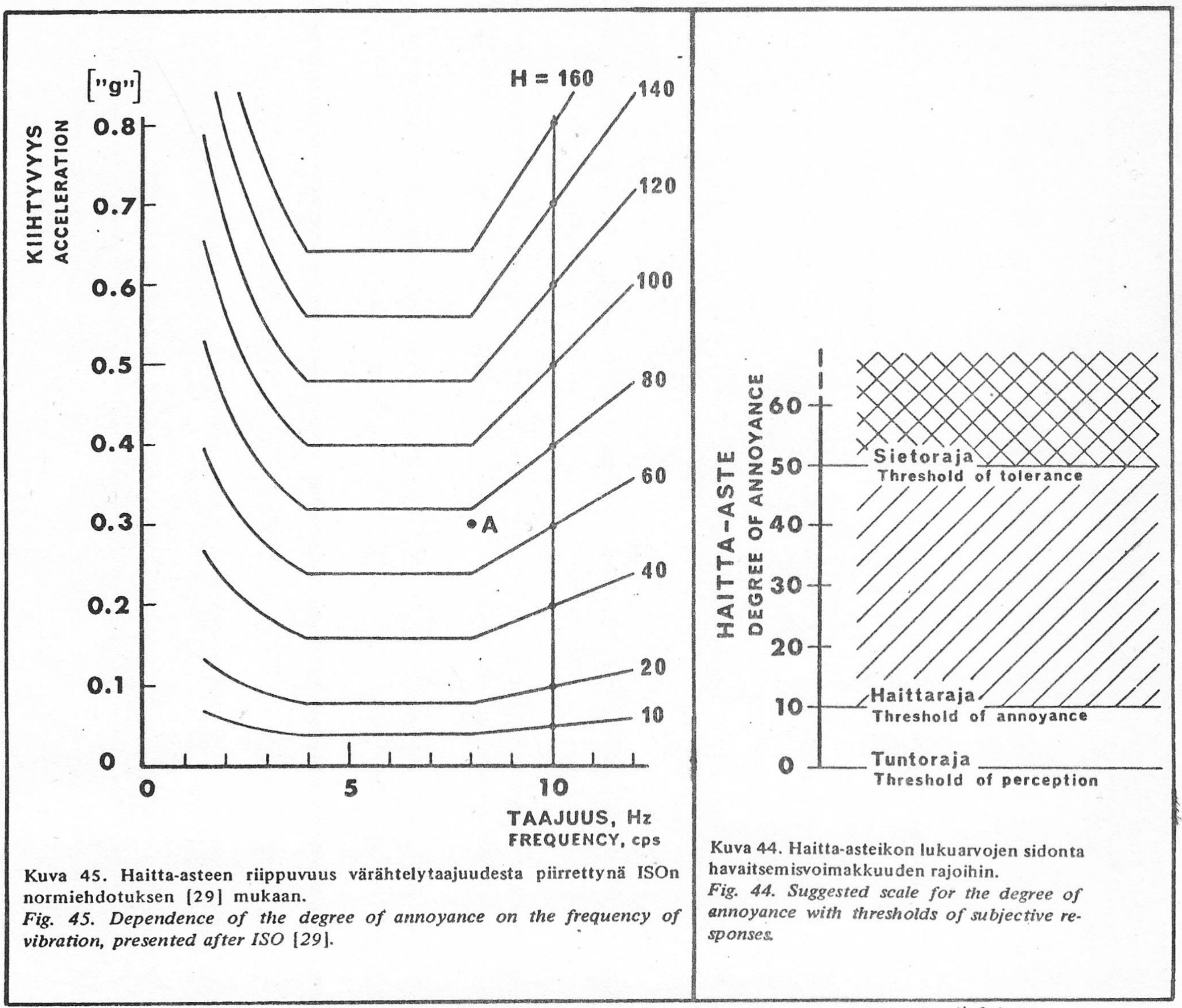
Bild 1. Kurven gleicher Wahrnehmungsstärke K für Sinusschwingungen im Frequenz-Beschleunigungsdiagramm, aus VDI-Richtlinie 2057



Wahrnehmungsstärke K	Stufe	Beschreibung der Wahrnehmung	Erträglichkeit der Einwirkung
	A	nicht spürbar	
0,1		(Fühlschwelle)	(Fühlschwelle)
	B	gerade spürbar	
0,25			
	C	spürbar	Aufenthalt in Wohnungen bei kurzen oder ohne Unterbrechungen der Schwingungseinwirkung
0,63			
	D	gut spürbar	Aufenthalt in Wohnungen bei längeren Unterbrechungen
1,6			
	E	stark spürbar	körperliche Arbeit ohne Unterbrechungen
4,0			
	F	sehr stark spürbar	körperliche Arbeit mit kurzen Unterbrechungen
10,0			
	G		körperliche Arbeit mit längeren Unterbrechungen, Fahrt in Fahrzeugen über längere Zeit
25			
	H		Fahrt in Fahrzeugen über kürzere Zeit
63			
	J		

Tabelle 1. Zusammenhänge zwischen gemessener Schwingungsstärke, subjektiver Wahrnehmungsstärke und Erträglichkeit von Schwingungen nach der VDI-Richtlinie 2057

FIG. 36. VDI-Richtlinien, Mitschke, ... /49/.



Kuva 45. Haitta-asteen riippuvuus värähtelytaajuudesta piirrettynä ISOn normiehdotuksen [29] mukaan.
Fig. 45. Dependence of the degree of annoyance on the frequency of vibration, presented after ISO [29].

Kuva 44. Haitta-asteikon lukuarvojen sidonta havaitsemisvoimakkuuden rajoihin.
Fig. 44. Suggested scale for the degree of annoyance with thresholds of subjective responses.

FIG. 37. Comfort criterion from a survey by Lehtinen /48/.

/54/ Thiery /54/ has made comfort studies for truckdrivers in the range ± 1 g and 0-100 Hz, including a method that makes it possible to objectively determine the degree of comfort for the driver, through measurements of the vibrations of the attachment of the seat, FIG. 38.

The vibration of man was measured on the chest in three principle directions. The testpersons had to fill in a form covering characteristics of the experienced vibrations. The input oscillations were recorded earlier during drives on different roads and were then input through the seat attachment in the simulator. Results are presented in FIG. 39 (FIG. 39) showing the levels which the input spectrum of vibrations not may exceed for a certain degree of comfort. FIG. 40 shows (FIG. 40) measured transfer functions man-seat.

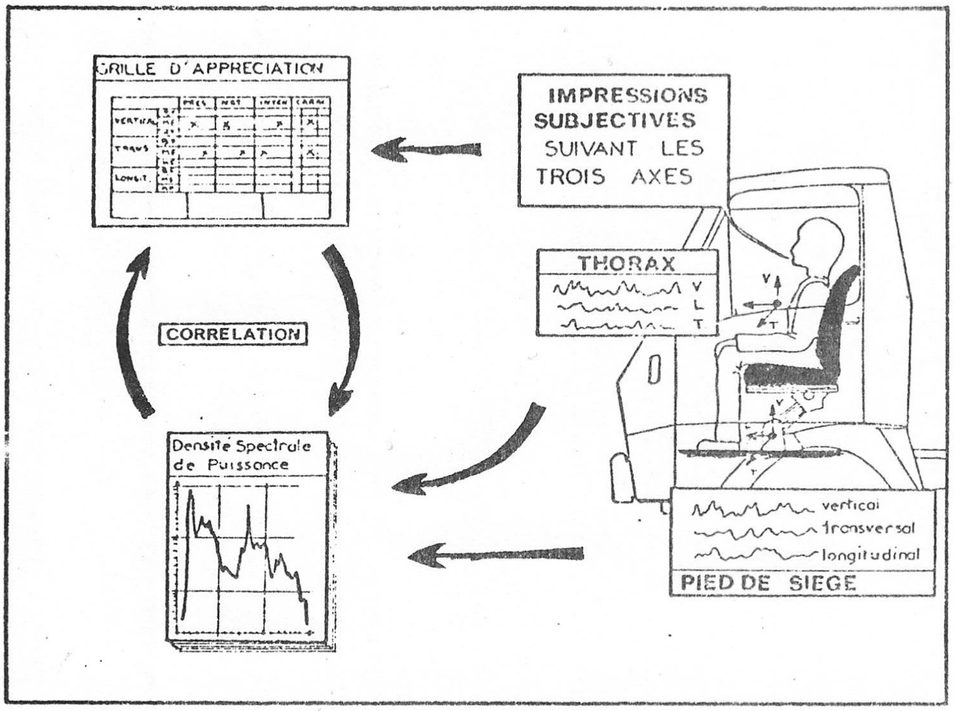


FIG. 38. Comfort studies in trucks, Thiery /54/.

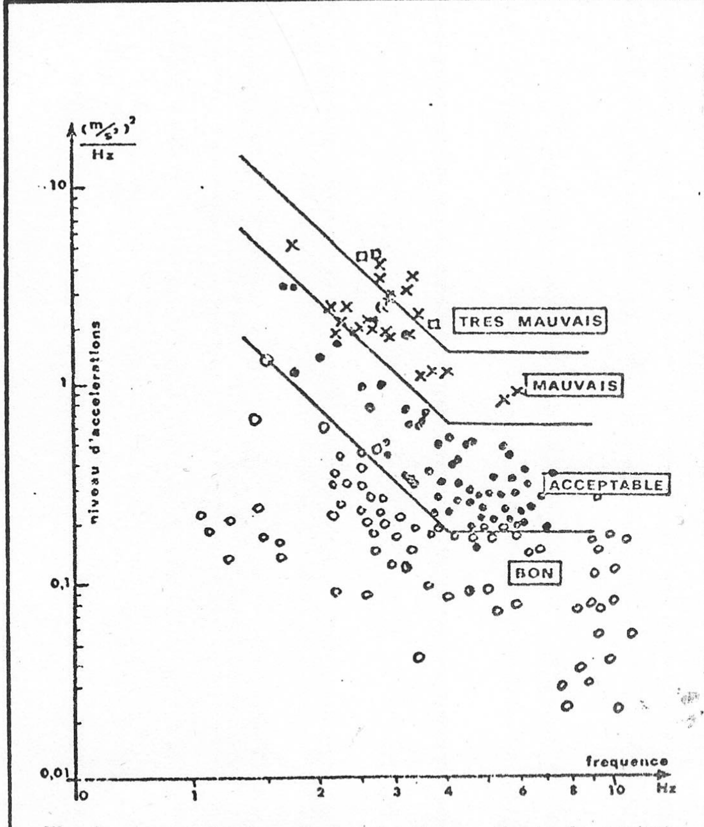


Fig. 5 — *Vibrations verticales du thorax. Zones de confort.*

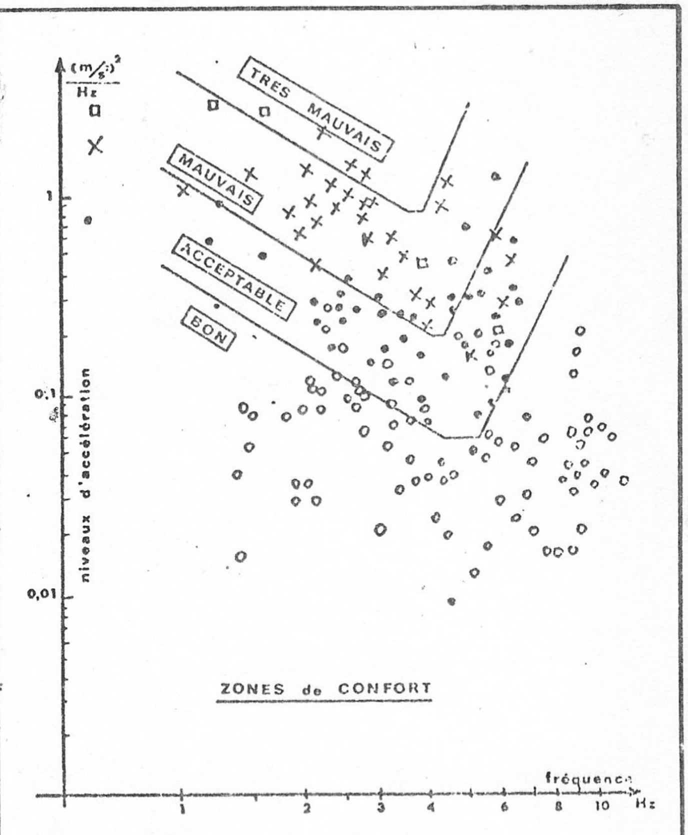


Fig. 7 — *Vibrations longitudinales du thorax.*

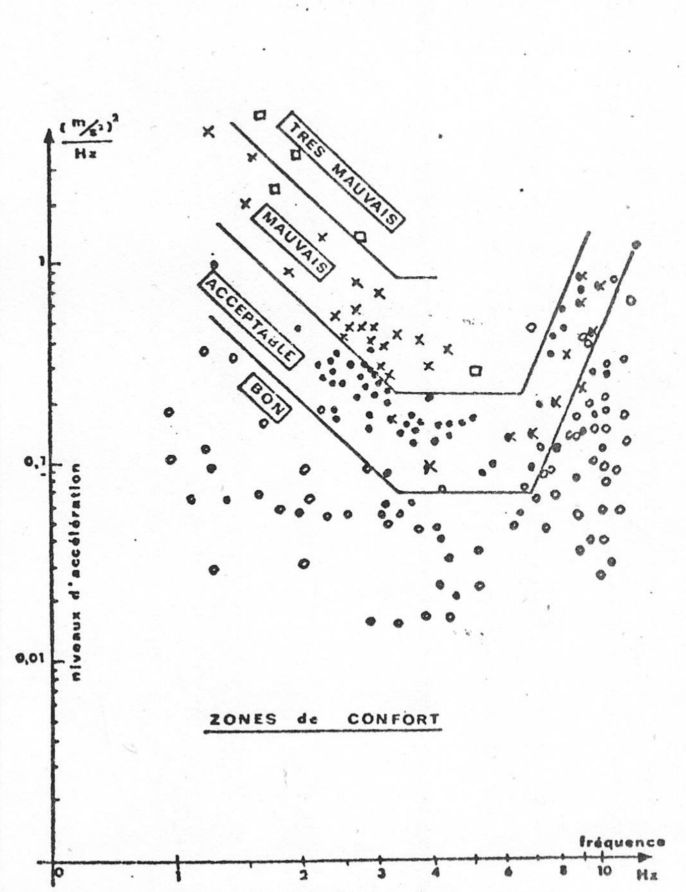


Fig. 6 — *Vibrations transversales du thorax.*

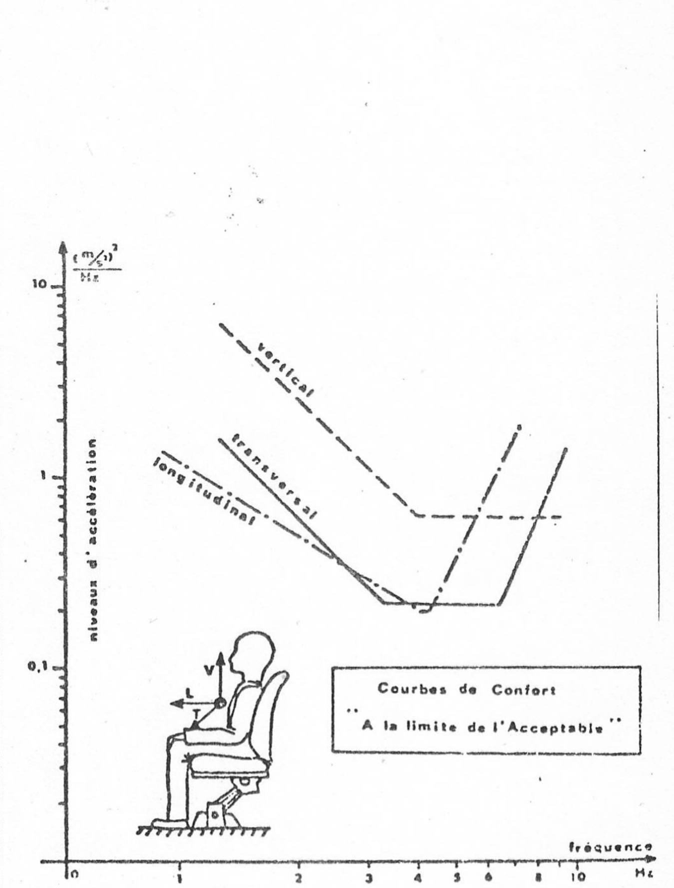


Fig. 8 — *Sensibilité du corps humain aux vibrations.*

FIG. 39. Comfort criterions, Thiery /54/.

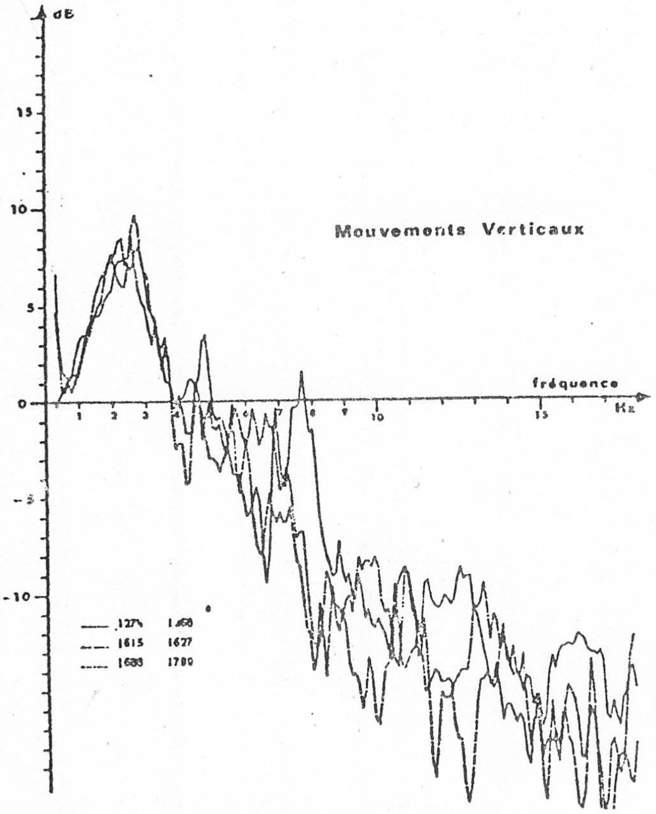


Fig. 11 — *Fonction de transfert homme-siège.*

FIG. 40. Transferfunction man-seat, Thiery /54/.

/43/ Further references can also be got through Griffin, ... /43/. Finally one more of the numerous comfort criterions /52/ is shown. It is from "Shock and vibration handbook" /52/.

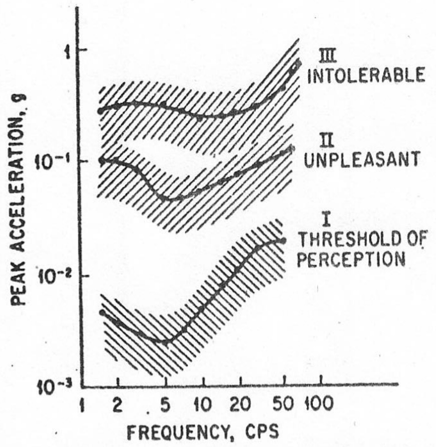


Fig. 44.20. Average peak accelerations at various frequencies at which subjects perceive vibration (I); find it unpleasant (II); or refuse to tolerate it further (III). Exposures of 5 to 20 min. Shaded areas are about one standard deviation on either side of mean. Data averaged from seven sources. (*Goldman.*[72])

FIG. 41. Comfort criterions, "Shock and vibration handbook, /52/.

4 MEASURING EQUIPMENT.

Below are briefly mentioned references that contain information and further references on measuring equipments.

The measurements may be more or less automatically performed. Due to the computer and the fast forward stepping electronique digital technique the measuring equipments are beeing more and more refined.

/24/ Rörbeck /24/ gives a brief survey of different transducers used in connection with traffic measurements.

The weight of vehicle and axles may be measured on permanent weighing stations, requiring reduced speed or not.

/57/ Whittermore, .../57/ briefly discuss a weighing platform (no speed reduction) built down into the surface and with a maximum resolution of about ± 8 %.

Such platforms may use electronique strain gauges as transducers. There are three such platforms in use in Denmark, one is delivered by Bofors AB, Sweden.

There are also small mobile weighing stations (no reduction of speed) which use a capacitor transducer imbedded in hard rubber that is glued to the road surface.

When it comes to registering quantities, that has a more complex variation in respect of time one has to choose either to let the measuring equipment do some predefined calculations or have them done later. When it is possible to define the calculations before the measuring it is obviously an advantage to let the equipment do the calculations thus saving time and reducing the amount of output data.

/21/ Mercer, ... /21/ give an example on statistical counting used in connection with strain-histories and mention equipment that can do this, (Vickers Armstrong strain range counter).

/6/ Cudney /6/ got the results from the strain-gauges on an oscillograph for further treatment.

/7/ Cudney /7/ says further: "Recent developments in the mechanics involved in the measurement and storage of transducer data, i.e., strain, pressure force, etc., have resulted in a mobile, automatic electronic data acquisition system owned by the U.S. Department of Transportation, Bureau of Public Roads".

/8/, /11/ /15/ Christiano, ... /8/, McKeel, ... /11/ and Galambos, ... /15/ used an equipment (owned by the Federal Highway Administration) that mainly consisted of wheatstonebridges, analog to digital converter (10 channels) a computer and a teletype (typewriter) all housed in a trailer.

/16/ According to Galambos /16/, Road Research Laboratory in England "have developed bridge vibration equipment and truck wheel load dynamic weighing platforms".

5 DESIGN AND DESIGNPRINCIPLES.

There are very few design rules for spectrum loading at this time in the world. Most of the fatigue design methods seem to be based on cumulative fatigue hypothesis, such as Miner´s hypothesis.

The following authors in the reference list have calculated or discussed fatigue lifes:

/1/,/6/,/8/ /9/,/10/,/11/ /15/,/21/,/22/ /31/ Abeles, ... /1/, Cudney /6/, Christiano, ... /8/, Douglas /9/, Heins, ... /10/, McKeel, ... /11/, Galambos, ... /15/, Mercer, ... /21/, Raithby, ... /22/ and Tung /31/.

/16/ Galambos /16/ made a study in 1972 covering USA, England, France, Switzerland, Germany, Belgium and the Netherlands on "Fatigue, Fracture and Stress corrosion problems of highway bridges". He concludes the survey by saying "There appears to be no traffic related fatigue problem in highway bridges". The same conclusions are drawn by Galambos
/12/ /12/, in the closing remarks to /8/-/11/ but "Some authors believe that it will only be a very short time before fatigue cracking on certain bridges will be a major problem", because of "the very high-volume, heavy-truck arteries in the congested urban areas of the country".

/16/ Following is from Galambos /16/ about fatigue problems in the U.S. "The great majority of highway bridges are serving their intended function with only a minimum of maintenance. Yet in recent years several traffic induced fatigue failures have come to light which are of concern, since they may be the forerunner of a more widespread problem. The greater part of these failures have been in floor beams and load distribution members, and are therefore the result of wheel loads rather than total truck loads".

It shall be mentioned that the AASHO bridge specifications,
/27/ /27/ include a simple formula with which an allowable maximum fatigue stress can be calculated.

In Sweden there is a provisory edition of building-weld-designrules which takes into account design for spectrum load.

/28/, /16/ Below are finally three pages, picked from "Steel Girder Bridges" /28/ (England), which according to Galambos /16/ are "probably the most detailed and comprehensiv fatigue rules for bridges in the world".

Table 1. Total variation in allowable stresses

Case I refers to all loadings *excluding* Type HB loading and the 112 kN force wheel loads of Type HA loading.

Case II refers to all loadings when combined with Type HB loading or the 112 kN force wheel loads of Type HA loading.

Stress combination	**Increase or decrease of allowable stresses given in Clauses 7 to 18 inclusive (but see Clauses 6 and 11.2).**	
	Case I	**Case II**
	%	%
A. *Solid web girders* and *Vierendeel trusses*		
Combination of forces (1)	no increase	+25
(2)	+25	+30
(3)	+30	–
B. *Triangulated structures.*		
1. Primary stresses only or where primary stresses are combined with calculated secondary stresses of 3.1(1) (self weight and wind on member ignored) and with secondary stresses of 3.1(2) left uncalculated but provided for as in 3.4.		
a. All members except tension web members where stresses due to live load and its dynamic effects are greater than those due to dead load.		
Combination of forces (1)	no increase	+25
(2)	+25	+30
(3)	+30	–
b. Tension web members where stresses due to live load and its dynamic effects are greater than those due to dead load.		
Combination of forces (1)	–10	+12.5
(2)	+12.5	+17
(3)	+17	–
2. Where primary stresses are combined with calculated secondary stresses of both 3.1(1) (including self weight of members and wind on members) and 3.1(2).		
Combination of forces (1)	+20	+50
(2)	+50	+56
(3)	+56	–
C. Maximum stresses due to *Combination* (4)	At the discretion of the engineer	

6. Fluctuations of stress (fatigue)

NOTE. Members which are subjected to fluctuations of stress are liable to suffer from fatigue failure, and this may be caused by loads which are very much lower than those which would be necessary to cause failure under a single application. The initiation of fatigue cracks is due, primarily, to stress concentrations introduced by the constructional details. Discontinuities such as bolt or rivet holes, welds and other local or general changes in geometrical form set up such stress concentrations from which fatigue cracks may be initiated, and these cracks may subsequently propagate through the connected or fabricated member.

6.1 General. All details shall be designed to avoid, as far as possible, stress concentrations likely to result in excessive reduction of the fatigue strength of members or connections. Care shall be taken to avoid sudden changes of shape of a member or part of a member, especially in regions of tensile stress or local secondary bending, and steps shall be taken to avoid aerodynamic and similar vibrations.

6.2 Loads and stresses to be considered. Working stresses shall be reduced, where necessary, to allow for the effects of fatigue, as described below. Allowance for fatigue shall be made for combinations of stresses due to dead load, live load, impact, lurching and centrifugal force, including secondary stresses as defined in 3.1(1). Stresses due to wind, temperature and longitudinal and nosing forces, and secondary stresses, as defined in 3.1(2) may be ignored in considering fatigue.

Elements of a structure may be subjected to a very large variety of stress cycles varying both in range (f_{min}/f_{max}) and in magnitude (f_{max}) of maximum stress. Each element of the structure should be designed for the number of cycles of different magnitudes to which that element is liable to be subjected during the expected life of the structure. The number of cycles of each magnitude must be estimated by the engineer in the light of available data regarding the probable frequency of occurrence of each type of loading. For bridges carrying railway tracks on British Railways and London Transport, these are given in Appendix E of Part 3A.

The working stresses referred to below are the principal stresses at the point under consideration. Thus, in the design of girder webs, the combined effect of both bending and co-existent shear stresses shall be considered.

In order to allow for the effect of fatigue the procedure set down in 6.4 shall be followed, using the information supplied in Table 2. This table covers mild and high yield stress steels fabricated or connected by welding, riveting or bolting, as described below, giving the maximum allowable stress p for different values of f_{min}/f_{max} and N, or, conversely, values of N for different values of f_{min}/f_{max} and f_{max}, where

p = maximum allowable tensile or compressive working stress;
f_{min} = the minimum stress in the element during a particular stress cycle;
f_{max} = the maximum stress in the element during the same stress cycle;
N = the allowable number of repetitions of this stress cycle.

6.3 Allowable working stresses

6.3.1 In the case of members subjected to a number of repetitions, n, of a single stress cycle, the allowable working stresses shall be those given in Table 2, taking $n = N$ and $f_{max} = p$. In such cases, if the stress level f_{max} is smaller than the allowable stress p specified for 10^7 cycles, fatigue need not be considered.

6.3.2 In the more general case of members subjected to a stress spectrum, i.e. to number of cycles n_1, n_2 etc. of different maximum stress levels f_1, f_2, etc., or of different ratios of f_{min}/f_{max}, or both, the following design method shall be used:

(1) All cycles with a maximum stress equal to or lower than the allowable stress quoted in Table 2–Class G for 10^8 cycles and for the relevant ratio of f_{min}/f_{max} shall be ignored.

(2) Where the loading conditions do not give rise to groups of clearly defined stresses, all stresses greater than the allowable stress obtained from Table 2–Class G, as defined in (1) above, shall be divided into at least five selected representative stress levels approximately equally spaced between the minimum and the maximum of the stresses to be considered.

(3) For each of the stress cycles the maximum allowable number of cycles N_1, N_2, etc., shall be determined from Table 2, by graphical interpolation if necessary.

NOTE. If the stress level under consideration (f'_{max}) is smaller than the allowable stress p specified for 10^8 cycles, or larger than that specified for 10^5 cycles, the relevant value of N can be found by extrapolating the design curve for the particular detail and value of f_{min}/f_{max} by means of the formula:

$$\log_{10} N = \frac{\log_{10} f_8 - \log_{10} f'_{max}}{\log_{10} f_7 - \log_{10} f_8} + 8$$

where f_7 and f_8 are the allowable stresses for 10^7 and 10^8 cycles respectively, as given in Table 2.

(4) Designating the expected number of cycles for each stress level n_1, n_2, etc., the element shall be designed so that

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \ldots + \frac{n_n}{N_n} \not> 1$$

6.3.3 Under no circumstances shall the basic permissible stresses given in Clause 7, or lower stresses required by any other clause in this standard, be exceeded.

Table 2. Values of p and N for fluctuating stresses

Class A Constructional details

$\frac{f_{min}}{f_{max}}$ \ N	p or f_{max} tensile (N/mm²)					p or f_{max} compressive (N/mm²)				
	100 000 CYC	600 000 CYC	2 000 000 CYC	10 000 000 CYC	100 000 000 CYC	100 000 CYC	600 000 CYC	2 000 000 CYC	10 000 000 CYC	100 000 000 CYC
1.0	432.4	432.4	432.4	432.4	432.4					
0.9	403.3	393.2	386.1	376.3	361.7					
0.8	377.9	360.5	348.7	333.1	310.9					
0.7	355.5	332.8	318.0	298.8	272.6					
0.6	335.6	309.0	292.2	270.9	242.7					
0.5	317.8	288.5	270.3	247.7	218.7					
0.4	294.3	267.1	250.3	229.4	202.5					
0.3	274.0	248.7	233.0	213.6	188.5					−432.4
0.2	256.3	232.7	218.0	199.8	176.4		−432.4	−432.4	−432.4	−390.5
0.1	240.8	218.6	204.8	187.7	165.7	−432.4	−412.1	−386.1	−353.9	−312.4
0.0	227.0	206.1	193.1	177.0	156.2	−378.3	−343.4	−321.8	−294.9	−260.4
−0.1	214.2	194.4	182.1	166.9	147.4	−324.3	−294.4	−275.8	−252.8	−223.2
−0.2	202.7	184.0	172.4	158.0	139.5	−283.8	−257.6	−241.3	−221.2	−195.3
−0.3	192.4	174.6	163.6	150.0	132.4	−252.2	−228.9	−214.5	−196.6	−173.6
−0.4	183.1	166.2	155.7	142.7	126.0	−227.0	−206.1	−193.1	−177.0	−156.2
−0.5	174.6	158.5	148.5	136.1	120.2	−206.4	−187.3	−175.5	−160.9	−142.0
−0.6	166.9	151.5	142.0	130.1	114.9	−189.2	−171.7	−160.9	−147.5	−130.2
−0.7	159.9	145.1	136.0	124.6	110.0	−174.6	−158.5	−148.5	−136.1	−120.2
−0.8	153.4	139.2	130.4	119.6	105.6	−162.1	−147.2	−137.9	−126.4	−111.6
−0.9	147.4	133.8	125.4	114.9	101.4	−151.3	−137.4	−128.7	−118.0	−104.1
−1.0	141.9	128.8	120.7	110.6	97.6	−141.9	−128.8	−120.7	−110.6	−97.6

NOTE. The ratio f_{min}/f_{max} is positive or negative respectively if the maximum and minimum stresses are of like or unlike sign.

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