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Rating Bridges for Special Permit Loadings with Considerations of Future Life — Case Studies

Evaluation de la durée de vie des ponts et charges extraordinaires — Etudes de cas

Lebenserwartung von Brücken und ausserordentliche Lasten — Fallstudien

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SUMMARY

Special permit loads continue to get heavier and more numerous with each passing year. This paper describes case studies of special analyses for heavy permit loads resulting either in 1) tables of permissible Gross Vehicle Weights (GVW) for vehicles of special interest and rules-of-thumb for particular bridges to be used by toll takers, or 2) tables of permissible Gross Vehicle Weights (GVW) for vehicles of special interest and bridge-specific computer programs to be used by permit officers. These studies have had considerations for fatigue of special details or typical details based on use history for the particular beidges as indicated in roll records or ADT and loadometer studies.

RESUME

Chaque année, les cas de charges extraordinaires deviennent de plus en plus nombreux et les charges de plus en plus élevées. L'article présente des études de cas pour la détermination de charges exceptionnelles admissibles. Il en résulte des tabelles de charges exceptionnelles admissibles pour des véhicules spéciaux, ainsi que des conseils pour le choix des ponts à franchir et des programmes spécifiques de calcul à l'ordinateur à l'intention de l'autorité exploitant les ponts. Ces études traitent les problèmes de fatigue de certains détails constructifs typiques ou spéciaux tels qu'ils apparaissent sur les protocoles de mesure de certains ponts, et sur la base de campagnes de mesures.

ZUSAMMENFASSUNG

Jedes Jahr werden die ausserordentlichen Verkehrslasten häufiger und grösser. Fallstudien wurden unternommen, um die zulässigen ausserordentlichen Verkehrslasten zu definieren. Daraus ergeben sich Tabellen zulässiger ausserordentlicher Verkehrslasten für Sonderfahrzeuge sowie Empfehlungen für die Auswahl von befahrbaren Brücken und spezielle EDV-Programme zu Handen der Brückenbehörden. Diese Studien behandeln Ermüdungsprobleme verschiedener typischer oder spezieller konstruktiver Details wie sie in Zustandsprotokollen gewisser Brücken erscheinen oder aufgrund von Messkampagnen resultieren.

CASE STUDY #1 - ST. GEORGES BRIDGE

INTRODUCTION

St. Georges Bridge is a fixed, high-level, four-lane highway bridge crossing the Chesapeake and Delaware Canal at St. Georges, Delaware. The main span is a 540 ft. (164.6 m) steel tied arch. The approaches consist of 3,714 feet (1132 m) of beam and girder spans of varying lengths and framing. The strucutre was designed under AASHO 1935 Specifications for a live load of H20 and subsequently rehabilitated in 1971 to HS20-44 loading in accordance with 1969 AASHO Specifications, as amended in 1970. At that time, a sidewalk was removed to widen the cartway. The original presence of a sidewalk resulted in a transversely unsymmetrical floor system. A rating analysis of the entire bridge was completed in 1973.

SCOPE OF WORK

The following is a summary of the Scope of Work for this Project. Some simplifications have been made in small details which do not affect the content of this paper.

- The floor systems and girders of the approach span and the floor systems and main members of the tied arch channel span were investigated. Splices in the stringers and girders and connections in the main bridge were evaluated only if a review of previous rating calculations indicated that they could control the evaluation. Previous rating calculations were used to eliminate sections which could not conceivably control permissible GVW. One hundred and fifty (150) possible sections remained to be checked for each loading.

- The girders, stringers and arch tie were evaluated for both bending and shear.

- The effects of loss-of-section were included.

- The latest edition of AASHTO Standard Specifications for Highway Bridges and Manual for Maintenance Inspection of Bridges was used modifications as indicated herein.

- Only AASHTO Group I loads were investigated and the "service load" method was used. The distance between the face-of-curb and the center of a wheel was 1.5 feet (0.457 m).

- Live and impact loads were in accordance with the latest AASHTO Specifications, except as follows. "Special" vehicles were used as determined from types found in the State of Delaware. Three transverse configurations of load were considered, with the vehicles located in parallel lanes:

  (a) CASE I LOADING: Special vehicle, HS15, HS15, HS20 at normal design allowable stresses.

  (b) CASE II LOADING: Special vehicle, special vehicle, HS15, HS20 at normal design allowable stresses.

A "Bottom Line" composite of Cases I and II was developed to represent the maximum GVW's of the special loads travelling in routine traffic.

(c) CASE III LOADING: Special vehicle with all other live loads prohibited. This loading case was analyzed with and without impact.

- o Longitudinally, the loadings for CASE I consisted of two special vehicles separated by 30 feet (9.1 m) from front wheel of one vehicle to rear wheel of the other vehicle and the standard configurations of the AASHTO lane loading. For CASE II, the longitudinal loading consisted of the special vehicle and the standard configurations of the AASHTO lane loading. For CASE III, only the special vehicle was assumed to be on the bridge.

VEHICLE CONFIGURATIONS

Delaware motor vehicle regulations concerning weight limitations for trucks on Interstate routes follow the Federal formula, which is:

$$GVW = 500 \left[\frac{LN}{(N-1)} + 12N + 36 \right]$$

$$\left(GVW = 2.224 \left[3.28 \frac{LN}{(N-1)} + 12N + 36 \right] \right)$$

where: GVW = gross vehicle weight in pounds (kN)
L = distance in feet (m) between front and rear axles
N = number of axles

In addition to the limitations given by the above formula, there are specific limits placed on overall length, gross vehicle weight and maximum axle weight for both single and tandem axles, which apply to vehicles on all routes in Delaware. These limitations are shown below.

Vehicle Type	Max. Length (ft)	Gross Vehicle Wt. (k)	Max. Axle Weight (k) Single (Tandem)
1	40 (12.2 m)	40 (178 kN	20 (89 kN)
2	40 (12.2 m)	65* (289 kN)	None
3	40 (12.2 m)	73.28 (326 kN)	None
4	65 (19.8 m)	60 (267 kN)	20 (89 kN)
5	65 (19.8 m)	70 (311 kN)	20/40 (89/178 kN)
6-10	65 (19.8 m)	80 (356 kN)	20/40 (89/178 kN)
11	60 (18.3 m)	80 (356 kN)	20/40 (89/178 kN)

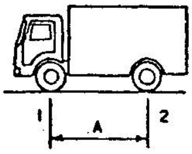
*70 (311,000 N) with Special Annual Permit

Any vehicle which operates in the State of Delaware and exceeds the limitations set forth by the State for size or weight must request and receive a Special Hauling Permit. Information listed on the permit includes gross vehicle weight, legal vehicle weight, vehicle length, and the route which the vehicle will take. No information on axle spacing and axle

NOTE: Table in Feet and Kips
Feet x 0.3048 = m
Kips x 4.4482 = kN

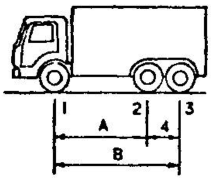
TYPE

1



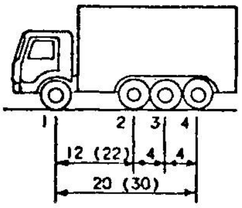
TYPE	SPACING A (FT)	AXLE WEIGHT (K) 1	2	TOTAL	NOTES
1A	15	7	20	27	(6)
1B	10	20	20	40	(1)
1C	30	20	40	60	(3)
1D	35	40	50	90	(3)

2



TYPE	SPACING (FT)		AXLE WEIGHT (K)				NOTES
	A	B	1	2	3	TOTAL	
2A	15	19	16	17	17	50	(5)
2B	12	16	18	26	26	70	(2) (6)
2C	12	16	14	28	28	70	(2)
2D	26	30	14	28	28	70	(2)

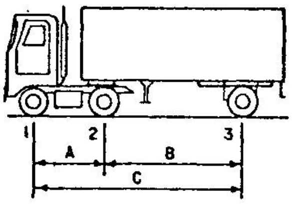
3



TYPE	AXLE WEIGHT (K)					NOTES
	1	2	3	4	TOTAL	
3A	13.28	20	20	20	73.28	(2)
3B	8	21.76	21.76	21.76	73.28	(2)
3C	18.32	18.32	18.32	18.32	73.28	(2) (6)
3D	13.28	20	20	20	73.28	(2)

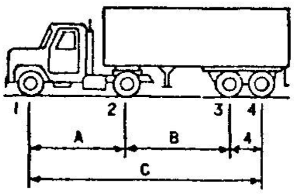
( ) DENOTES SPACING FOR TYPE 3D

4



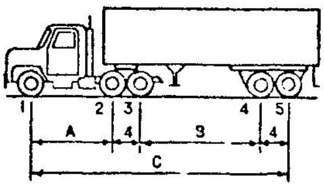
TYPE	SPACING (FT)			AXLE WEIGHT (K)				NOTES
	A	B	C	1	2	3	TOTAL	
4A	10	10	20	11	20	20	51	(1)
4B	10	25	35	11	20	20	51	(1) (6)
4C	12	20	32	20	20	20	60	(1)
4D	12	38	50	20	20	20	60	(1)

5



TYPE	SPACING (FT)			AXLE WEIGHT (K)					NOTES
	A	B	C	1	2	3	4	TOTAL	
5A	11.5	24	39.5	5	20	12.5	12.5	50	(1) (6)
5B	10	18	32	10	12	20	20	62	(1)
5C	10	18	32	10	20	16	16	62	(1)
5D	10	20	34	10	14	20	20	64	(1)
5E	10	20	34	10	20	17	17	64	(1)
5F	12	28	44	10	20	20	20	70	(1)
5G	12	34	50	10	20	20	20	70	(1)

6

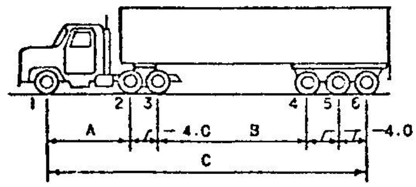


TYPE	SPACING (FT)			AXLE WEIGHT (K)						NOTES
	A	B	C	1	2	3	4	5	TOTAL	
6A	12	12	32	8	16	16	16	16	72	(2)
6B	11	22	41	10	15.5	15.5	15.5	15.5	72	(5)
6C	10	28	46	10	16	10	20	20	76	(1)
6D	11.5	22	41.5	16	16	16	16	16	80	(6)
6E	10	34	52	10	18	12	20	20	80	(1)
6F	11.5	29.5	49	15	27	27	27	27	123	(4)
6G	11.5	29.5	49	18	23	28	23	28	130	(3)

FIGURE 1 - VEHICLES FOR ANALYSIS (1/2)

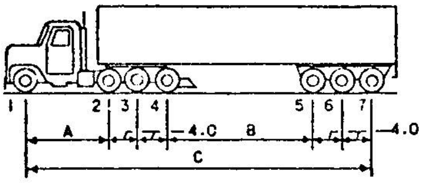
TYPE

7



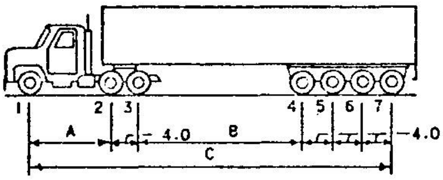
TYPE	SPACING (FT)			AXLE WEIGHT (K)				NOTES
	A	B	C	1	2-3	4-6	TOTAL	
7A	10	26	46	8	2 at 15	3 at 14	80	(1)
7B	12	26	50	15	2 at 27	3 at 27	150	(4)
7C	12	30	54	12	2 at 33	3 at 24	150	(3)

8



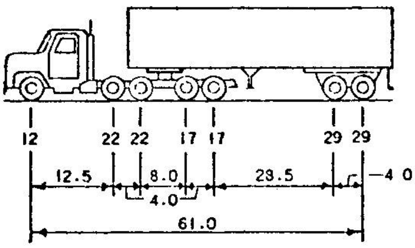
TYPE	SPACING (FT)			AXLE WEIGHT (K)				NOTES
	A	B	C	1	2-4	5-7	TOTAL	
8A	9.33	24.67	50.0	8	3 at 12	3 at 12	80	(1)
8B	9.33	31.67	57.0	9	3 at 22	3 at 25	150	(3)
8C	9.33	24.67	50.0	15	3 at 27	3 at 27	177	(4)

9



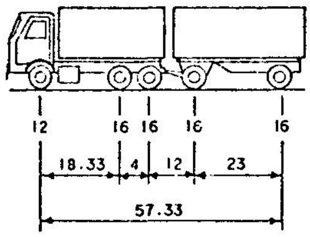
TYPE	SPACING (FT)			AXLE WEIGHT (K)				NOTES
	A	B	C	1	2-3	4-7	TOTAL	
9A	12	22	50	8	2 at 20	4 at 8	60	(1)
9B	11.5	34	61.5	12	2 at 25	4 at 22	150	(3)
9C	12	22	50	15	2 at 27	4 at 27	177	(4)

10, 11



(KIPS)

(FT.)



NOTES:

(1) GROSS VEHICLE WEIGHT LESS THAN OR EQUAL TO MAXIMUM ALLOWED BY FEDERAL BRIDGE FORMULA.

(2) GROSS VEHICLE WEIGHT FROM DELAWARE DMV LAWS.

(3) AXLE WEIGHTS AND SPACING FROM DELAWARE DMV SPECIAL PERMITS.

(4) AXLE WEIGHTS FROM PENNDOT SPECIAL PERMITS.

(5) AXLE WEIGHTS AND SPACING FROM AASHTO MANUAL FOR MAINTENANCE INSPECTION OF BRIDGES - 1978.

(6) AXLE SPACING AND WEIGHT DISTRIBUTION FROM UNPUBLISHED NATIONWIDE STUDY.

FIGURE 1 - VEHICLES FOR ANALYSIS (2/2)

weight is required for vehicles with a gross weight between 80 kips (356 kN) and 120 kips (534 kN). For vehicles exceeding 120 kips (534 kN), a sketch is attached to the permit which shows axle spacings and axle weights.

A search was made through all of the nearly 25,000 Special Hauling Permits issued for 1979. Almost 400 vehicles which exceed the appropriate legal weight followed a route which could take them over the St. Georges Bridge. Approximately 100 vehicles exceeding 120 kips (534 kN) received permits in 1979, and all the information given on the permit sketch was recorded regardless of whether or not the vehicle crossed the St. Georges Bridge. Representatives of many of these vehicles are included in the set of proposed special vehicles. Sixteen vehicles exceeding 120 kips (534 kN) were routed over the St. Georges Bridge, and every one of these 16 vehicles is represented in the set of special vehicles.

From the information compiled from these studies, 41 vehicle configurations were developed which represented the axle combinations, spacings and axle weight ratios found. The 41 vehicle configurations are shown in Figure 1.

COMPUTER ANALYSIS

The computer program written to execute the Scope of Work uses data from two sources. The first is disk files of influence lines and member load and property data which are stored by several small "service" programs. The second source of data is to be provided by the user for each truck to be investigated. These data include:

(1) Three lines of descriptive titles.

(2) A description of the loading in each lane given as (1) any negative number to indicate a special vehicle, or (2) the "HS number" (e.g. "20" for HS20, "15" for HS15, etc.).

(3) The multiple of the design allowable stresses to be used, i.e., the provision to use 110% etc. of design allowable stress.

(4) The longitudinal distance between two trucks in a lane.

(5) The number of axles, axle spacing and weights for the special vehicle.

If the inputted distance between tandem vehicles is not zero, a duplicate set of axle weights and distances is appended to the original set such that the rear axle of the first vehicle and the front axle of the second vehicle are the inputted distance apart. The complete train of axle weights and distances are then copied in reverse.

The two (i.e. forward and reverse) axle trains are then moved along previously stored influence lines for the moment, shear, reaction or axial force being investigated. Each wheel of both axle trains is positioned over selected points on the influence line and the result is compared with previous results and retained if it is a maximum or minimum.

If Case I or Case II loading has been described (i.e. more than one lane of traffic), then the AASHTO lane load uniform load of 640 #/ft per lane(9.34 kN/m) is placed on the influence line. The uniform load is placed only as appropriate to add, algebraically, to maximums and minimums after allowance is made for the location of the special vehicle.

There are six permissible analytical lane positions on the bridge. Lanes 1-4 are the normal traffic lanes; 5 and 6 are additional positions for use with loading Case III. Lane 5 is in the middle of normal traffic Lanes 1 and 2, Lane 6 is in the middle of Lanes 3 and 4. (Note that there is a permanent median barrier on the bridge.) The user defines what vehicles are in the lanes using the following rules:

- The special vehicle must be in at least one lane.
- Lane 5 must not be used if Lane 1 and/or Lane 2 is used, and likewise for Lanes 3, 4 and 6.
- Any other combinations of lanes is permissible.
- The special vehicles should be in the left lanes of any lane pattern chosen.

The previously stored disk files contain the force in the member being studied corresponding to HS20 which are scaled to "HSXX", a distribution factor is applied to the member force corresponding to live load in each lane, impact is applied and the member forces corresponding to each lane rank-ordered. If stringers for which the S/11 distribution factor is applicable in design are being studied with a loading involving only one loaded lane, then the distribution factor will be taken as S/14. (S is the stringer spacing.)

Once the maximum and minimum live load forces are found, they are combined with the dead load forces and stresses and interaction values are computed using data on the disk files. The stresses resulting from the combined loads using the original axle weights are saved for output.

The computation of allowable GVW proceeds by a straight-forward algebraic calculation for stringers for which the S/11 distribution factor is applicable. For all other approach and floor system members, a trial and error process based on the classical interval halving procedure is used to find the scaled GVW for which an interaction value is equal to 1.000 ± 0.001. The special vehicle lane force is scaled up or down, as required, and the live and dead loads are recombined and stresses and interaction values are re-evaluated for 1 or 2 lanes at 100%, 3 lanes at 90% and 4 lanes at 75%. A trail and error procedure is used so that any possibility that a different combination of lanes would create higher combined live load forces for varying weights of the special vehicle is accounted for.

The main members of the arch have the additional complication of having an axial load and two end moments, each of which could be maximized by a different position of the special vehicle and the HSXX vehicles in the other lanes, if any. This was handled by looping through the entire process three times for each main bridge member processed. Each pass through the loop maximized and minimized one of the three forces (axial load and two moments) caused by the special vehicle. The maximum and minimum of the other two forces were found corresponding to the positions of the special vehicles required by the first force. Combining lanes, computation of stresses and interaction values and trial and error solution for allowable GVW proceeded. The second force was maximized and minimized and the process repeated. Finally, the third force was maximized and minimized and the process repeated again. The output for the given member contained one set of controlling values from all three loops.

The result of an analysis is a set of stress tables for floor system and main bridge members as shown in Figure 2. The tables for the floor system contain a description of each section of the floor system which was studied, the allowable stress, dead load stress, positive and negative live load stress, total stress and the allowable gross vehicle weight. The live load stresses and total stress are computed using the special truck exactly as inputted. The allowable gross vehicle is the scaled weight of the original vehicle such that the total stress is equal to the allowable stress.

The output for the main bridge members is essentially the same as the output for the floor system, except that yield point of the material is printed instead of the allowable stress, and an interaction value is printed. The allowable gross vehicle weight is scaled such that the interaction value is $1.0 \pm 0.1\%$. It is possible that the live load stresses

ST. GEORGES BRIDGE
LOADING IS: SPECIAL, HS15, HS15, HS20
7-9-80 JMF MAX GVW REPORTED = 3 X ORIGINAL GVW

HS NUMBERS -1.0 15.0 15.0 20.0 0.0 0.0 STRESS SCALE 1.0000
SINGLE VEHICLE IMPACT INCLUDED
AXLE WT 7.00 20.00
DISTANCES 0.00 15.00

MEMBER IDENTIFICATION		ALLOW STRESS	DL STRESS	+LL STRESS	-LL STRESS	TOTAL STRESS	ALLOW GVW
FASCIA STRINGERS	CENTERLINE	18.00	2.18	5.37	0.00	7.56	81.0
	SHEAR	13.50	1.24	3.49	0.00	4.73	81.0
STRINGERS(S3,S53)	CENTERLINE	18.00	3.43	7.29	0.00	10.72	55.1
STRINGER(S4)	CENTERLINE	18.00	3.45	7.04	0.00	10.49	57.1
STRINGERS(S5,SS5)	CENTERLINE	18.00	3.53	6.89	0.00	10.42	58.3
INT R B STRG(SS2-4,S2-54)	CENTERLINE	18.00	7.02	4.91	0.00	11.93	69.4
INT R B STRG(SS5,6,55,56)	CENTERLINE	18.00	6.60	6.26	0.00	12.86	55.2
MAIN SPAN STRINGER(S101)	CENTERLINE	18.00	5.84	6.66	0.00	12.51	52.4
	FATIGUE-WELD SHEAR	15.66	0.52	0.80	0.00	1.32	81.0
MAIN SPAN STRINGER(S102)	CENTERLINE	18.00	6.02	6.17	0.00	12.19	56.0
	FATIGUE-WELD SHEAR	15.66	0.54	0.80	0.00	1.34	81.0
MAIN SPAN STRINGER(S103)	CENTERLINE	18.00	5.36	5.51	0.00	10.87	66.9
MAIN SPAN STRINGER(S104)	CENTERLINE	13.00	6.35	6.38	0.00	12.73	52.5
	FATIGUE-MOM.(9.13)	18.00	3.12	4.85	0.00	7.97	81.0
	FATIGUE-WELD SHEAR	15.66	0.62	0.87	0.00	1.49	81.0
MAIN SPAN STRINGER(S105)	CENTERLINE	20.00	4.39	6.40	0.00	11.29	69.0
MAIN SPAN STRINGER(S105C)	CENTERLINE	18.00	6.02	5.57	0.00	11.59	62.5
	FATIGUE-SHEAR	15.66	0.40	0.75	0.00	1.15	81.0
END FLOORBEAMS(FB1,FB51)	FIRST CUT-OFF	18.00	3.74	8.71	0.00	12.45	81.0
	(P3) CENTERLINE	18.00	3.50	7.98	0.00	11.48	81.0
	(P4) CENTERLINE	18.00	3.60	8.37	0.00	11.97	81.0
END FLOORBEAMS(FB2,FB52)	FIRST CUT-OFF	18.00	2.88	7.62	0.00	10.50	81.0
	SECOND CUT-OFF	18.00	3.48	8.10	0.00	11.58	81.0
	(P3) CENTERLINE	18.00	3.46	7.89	0.00	11.35	81.0
	(P4) CENTERLINE	18.00	3.56	8.27	0.00	11.84	81.0
INT FLOORBEAMS(FB3,FB53)	FIRST CUT-OFF	18.00	5.63	7.88	0.00	13.52	81.0
	(P3) CENTERLINE	18.00	5.14	6.84	0.00	11.99	81.0
	(P4) CENTERLINE	18.00	5.29	7.18	0.00	12.47	81.0
INT FLOORBEAMS(FB4,FB54)	FIRST CUT-OF	18.00	5.57	7.52	0.00	13.08	81.0
	(P3) CENTERLINE	18.00	5.60	7.23	0.00	12.83	81.0
	(P4) CENTERLINE	18.00	5.77	7.59	0.00	13.35	81.0
INT FLOORBEAMS(FB5,FB55)	FIRST CUT-OFF	18.00	7.42	7.02	0.00	14.44	81.0
	SECOND CUT-OFF	18.00	7.53	6.65	0.00	14.18	81.0
	THIRD CUT-OFF	18.00	6.74	5.87	0.00	12.60	81.0
	(P3) CENTERLINE	18.00	6.31	5.45	0.00	11.76	81.0
	(P4) CENTERLINE	18.00	6.48	5.72	0.00	12.19	81.0
	SHEAR	11.00	4.06	3.33	0.00	7.39	81.0
MAIN SPAN END FLOORBEAMS	FIRST CUT-OFF	18.00	6.11	6.29	0.00	12.40	81.0
	AT STRINGER P4	18.00	5.09	5.27	0.00	10.36	81.0
	AT STRINGER P5	18.00	5.78	6.31	0.00	12.09	81.0
	AT STRINGER P6	18.00	5.89	6.60	0.00	12.50	81.0
	AT STRINGER P7	18.00	5.39	5.62	0.00	11.02	81.0
MAIN SPAN INTERMED FLBMS	FIRST CUT-OFF	18.00	8.56	5.50	0.00	14.06	81.0
	SECOND CUT-OFF	18.00	8.02	5.10	0.00	13.13	81.0
	AT STRINGER P4	18.00	6.47	4.17	0.00	10.64	81.0
	AT STRINGER P5	18.00	7.34	4.76	0.00	12.09	81.0
	AT STRINGER P6	18.00	7.49	4.98	0.00	12.46	81.0
	AT STRINGER P7	18.00	6.86	4.34	0.00	11.20	81.0
BUILT-UP STRG(SS1,SS51)	FIRST CUT-OFF	18.00	6.20	5.22	0.00	11.42	67.9
	SECOND CUT-OFF	18.00	6.47	5.04	0.00	11.52	68.7
	CENTERLINE	18.00	6.49	5.09	0.00	11.58	70.2
	SHEAR	10.64	2.48	2.44	0.00	4.92	81.0
	SECOND PANEL SHEAR	6.54	2.27	2.14	0.00	4.40	60.1
BUILT-UP STRG(SS7,SS57)	FIRST CUT-OFF	18.00	9.44	4.92	0.00	14.36	50.9
	SECOND CUT-OFF	18.00	9.19	4.72	0.00	13.91	55.4
	CENTERLINE	18.00	8.05	4.44	0.00	12.49	69.6
	SHEAR	10.64	2.48	2.46	0.00	4.93	81.0
	SECOND PANEL SHEAR	6.54	2.27	2.15	0.00	4.42	59.6
BUILT-UP STRG(SS8,SS58)	FIRST CUT-OFF	18.00	6.28	5.19	0.00	11.47	67.8
	SECOND CUT-OFF	18.00	5.96	4.45	0.00	10.41	81.0
	THIRD CUT-OFF	18.00	6.07	4.66	0.00	10.73	79.0
	CENTERLINE	18.00	5.77	4.53	0.00	10.30	81.0
	FOURTH CUT-OFF	18.00	6.10	4.65	0.00	10.75	77.8
	SECOND PANEL SHEAR	3.90	1.94	1.83	0.00	3.77	81.0
BUILT-UP STRG(SS9,SS59)	FIRST CUT-OFF	18.00	9.46	4.62	0.00	14.08	54.6
	SECOND CUT-OFF	18.00	7.87	3.98	0.00	11.85	77.9
	THIRD CUT-OFF	18.00	7.64	4.05	0.00	11.69	79.3
	CENTERLINE	18.00	7.35	3.93	0.00	11.28	81.0
	FOURTH CUT-OFF	18.00	9.06	4.45	0.00	13.51	60.7
	SECOND PANEL SHEAR	8.90	1.94	1.84	0.00	3.79	81.0

FIGURE 2 - SAMPLE OUTPUT (1/3)

```
ST. GEORGES BRIDGE
LOADING IS: SPECIAL, HS15, HS15, HS20
7-9-80          JHF          MAX GVW REPORTED = 3 X ORIGINAL GVW

HS NUMBERS   -1.0   15.0   15.0   20.0   0.0   0.0          STRESS SCALE  1.0000
SINGLE VEHICLE                                              IMPACT INCLUDED
AXLE WT        7.00   20.00
DISTANCES      0.00   15.00
```

MEMBER IDENTIFICATION		ALLOW STRESS	DL STRESS	+LL STRESS	-LL STRESS	TOTAL STRESS	ALLOW GVW
80 FT. GIRDERS(G4,G54)	FIRST CUT-OFF	18.00	8.83	4.12	0.00	12.95	81.0
	SECOND CUT-OFF	18.00	10.71	4.79	0.00	15.50	75.5
	CENTERLINE	18.00	10.40	4.68	0.00	15.08	81.0
	SHEAR	9.65	3.64	2.83	0.00	6.47	81.0
	SECOND PANEL SHEAR	6.89	3.53	2.59	-0.00	6.11	55.3
98 FT. GIRDER(G56)	FIRST CUT-OFF	18.00	7.69	4.19	0.00	11.87	81.0
	SECOND CUT-OFF	18.00	8.84	4.47	0.00	13.31	81.0
	THIRD CUT-OFF	18.00	8.93	4.57	0.00	13.50	81.0
	CENTERLINE	18.00	9.12	4.57	0.00	13.68	81.0
105 FT. GIRDER(G3)	FIRST CUT-OFF	18.00	8.14	4.18	0.00	12.32	81.0
	SECOND CUT-OFF	18.00	8.68	4.23	0.00	12.91	81.0
	THIRD CUT-OFF	18.00	8.99	4.33	0.00	13.32	81.0
	FOURTH CUT-OFF	18.00	9.11	4.39	0.00	13.50	81.0
	CENTERLINE	18.00	9.10	4.32	0.00	13.42	81.0
	SECOND PANEL SHEAR	8.40	3.93	2.18	-0.00	6.11	81.0
120 FT. GIRDERS(G2,G52)	FIRST CUT-OFF	18.00	8.94	3.93	0.00	12.87	81.0
	SECOND CUT-OFF	18.00	9.72	4.10	0.00	13.82	81.0
	THIRD CUT-OFF	18.00	9.33	3.99	0.00	13.33	81.0
	FOURTH CUT-OFF	18.00	9.55	3.99	0.00	13.54	81.0
	CENTERLINE	18.00	9.61	3.94	0.00	13.55	81.0
130 FT. GIRDERS(G1,G51)	FIRST CUT-OFF	24.00	12.77	5.20	0.00	17.97	81.0
	SECOND CUT-OFF	24.00	12.51	5.22	0.00	17.73	81.0
	THIRD CUT-OFF	24.00	12.83	5.23	0.00	18.06	81.0
	CENTERLINE	24.00	12.69	5.10	0.00	17.78	81.0
CONT. GIRDER(61.67 SPAN)	FIRST CUT-OFF	18.00	-6.97	4.74	-5.91	-12.88	81.0
	SECOND CUT-OFF	18.00	-10.68	1.58	-5.10	-15.78	76.1
	THIRD CUT-OFF	18.00	-11.07	0.34	-4.51	-15.58	81.0
CONT. GIRDER(INT SUPPORT)	INTERIOR SUPPORT	18.00	-10.88	0.00	-4.33	-15.22	81.0
CONT. GIRDER(105.67 SPAN)	FIRST CUT-OFF	18.00	-10.21	0.14	-3.96	-14.17	81.0
	SECOND CUT-OFF	18.00	-8.91	0.59	-3.52	-12.44	81.0
	THIRD CUT-OFF	18.00	-9.22	1.37	-3.95	-13.18	81.0
	FOURTH CUT-OFF	18.00	7.67	6.32	-1.63	13.99	81.0
	FIFTH CUT-OFF	18.00	7.73	5.32	-1.06	13.05	81.0
	SIXTH CUT-OFF	18.00	9.46	5.33	-0.67	14.79	81.0
	SPAN CENTERLINE	18.00	8.70	4.92	-0.52	13.61	81.0
	62.94 FROM INT SUPP.	18.00	9.53	5.09	-0.42	14.62	81.0
	73.43 FROM INT SUPP.	18.00	8.56	4.74	-0.31	13.31	81.0
	SEVENTH CUT-OFF	18.00	9.36	5.15	-0.32	14.51	81.0
	EIGHTH CUT-OFF	18.00	9.51	5.19	-0.27	14.69	81.0
	NINTH CUT-OFF	18.00	8.23	5.00	-0.23	13.23	81.0
END FAS BRKTS(B1,2,51,52)	MOMENT	13.50	3.57	4.53	0.00	8.10	59.3
END FAS BRKTS(B2A,52A)	MOMENT	26.00	6.77	8.61	0.00	15.38	60.5
INT FAS BRKTS(B3,53)	MOMENT	26.00	12.07	9.45	0.00	21.51	42.3
INT FAS BRKTS(B4,54)	MOMENT	26.00	12.20	9.55	0.00	21.75	41.3
INT FAS BRKTS(B4A,54A)	MOMENT	18.00	6.84	5.35	0.00	12.19	61.9
	SHEAR	13.50	5.46	4.77	0.00	10.23	49.0
SPECIAL BRKTS(B5,55)	MOMENT	26.00	9.38	3.48	0.00	12.86	81.0
	SHEAR	13.50	6.60	3.98	0.00	10.59	50.2
INT FAS BRKTS(B6,56)	MOMENT	13.50	5.38	4.63	0.00	10.01	50.3

FIGURE 2 - SAMPLE OUTPUT (2/3)

```
ST. GEORGES BRIDGE
LOADING IS: SPECIAL, HS15, HS15, HS20
7-9-80          JMF                 MAX GVW REPORTED = 3 X ORIGINAL GVW.

HS NUMBERS   -1.0   15.0   15.0   20.0    0.0    0.0         STRESS SCALE 1.0000
SINGLE VEHICLE                                               IMPACT INCLUDED
AXLE WT         7.00   20.00
DISTANCES       0.00   15.00
```

MEMBER IDENTIFICATION			YIELD STRESS	DL STRESS	+LL STRESS	-LL STRESS	MAX STRESS	INTER VALUE	ALLOW GVW
HANGER	U1-L1	INTERACTION	45.00	13.26	2.91	-1.11	16.17	0.6534	81.0
	U2-L2	INTERACTION	33.00	10.74	3.61	-1.90	14.35	0.7904	81.0
	U3-L3	INTERACTION	33.00	9.20	4.45	-3.14	13.65	0.7522	81.0
	U4-L4	INTERACTION	33.00	8.48	5.13	-3.90	13.62	0.7503	81.0
	U5-L5	INTERACTION	33.00	7.89	5.73	-4.52	13.62	0.7504	81.0
	U6-L6	INTERACTION	33.00	7.35	6.97	-5.65	14.21	0.7832	81.0
	U7-L7	INTERACTION	33.00	6.78	7.31	-5.95	14.00	0.7712	81.0
ARCH RIB	L0-U1	INTERACTION	45.00	-15.25	0.47	-2.39	17.57	0.8747	81.0
	U1-U2	INTERACTION	45.00	-14.51	0.95	-2.68	16.64	0.8253	81.0
	U2-U3	INTERACTION	45.00	-15.74	1.12	-2.96	18.35	0.9168	81.0
	U3-U4	INTERACTION	45.00	-15.60	1.34	-3.18	18.45	0.9152	81.0
	U4-U5	INTERACTION	45.00	-15.97	1.31	-3.22	18.92	0.9250	81.0
	U5-U6	INTERACTION	45.00	-16.13	0.96	-3.07	18.60	0.9125	81.0
	U6-U7	INTERACTION	45.00	-16.42	0.57	-3.07	19.10	0.9244	81.0
	U7-U7'	INTERACTION	45.00	-15.31	0.23	-2.82	19.55	0.9458	81.0
TIE GIRDER	L0-L1	INTERACTION	45.00	10.90	3.82	-2.90	14.72	0.5949	81.0
		SHEAR	45.00	0.96	1.68	-1.23	2.64	0.1776	81.0
	L1-L2	INTERACTION	45.00	11.30	5.87	-4.79	17.15	0.6928	81.0
		SHEAR	45.00	0.53	1.22	-0.91	1.75	0.1130	81.0
	L2-L3	INTERACTION	45.00	11.17	6.35	-5.22	17.50	0.7072	81.0
		SHEAR	45.00	0.57	0.98	-0.83	1.55	0.1045	81.0
	L3-L4	INTERACTION	45.00	11.48	6.40	-5.27	17.75	0.7172	81.0
		SHEAR	45.00	0.50	0.90	-0.87	1.40	0.0943	81.0
	L4-L5	INTERACTION	45.00	11.90	6.51	-5.14	18.09	0.7309	81.0
		SHEAR	45.00	0.46	0.99	-1.10	1.45	0.0978	81.0
	L5-L6	INTERACTION	45.00	12.06	5.82	-4.25	17.64	0.7126	81.0
		SHEAR	45.00	0.40	1.18	-1.29	1.58	0.1063	81.0
	L6-L7	INTERACTION	45.00	13.86	5.56	-3.49	19.20	0.7759	81.0
		SHEAR	45.00	0.33	1.31	-1.37	1.64	0.1106	81.0
	L7-L7'	INTERACTION	45.00	13.90	4.59	-2.66	18.31	0.7397	81.0
		SHEAR	45.00	0.30	1.37	-1.37	1.67	0.1122	81.0

SUMMARY -	STRINGERS	FLOORBEAMS	GIRDERS	BRACKETS	MAIN BR
	52.426	81.000	50.922	41.331	81.000
CONTROLLING VALUE =		41.331			

FIGURE 2 - SAMPLE OUTPUT (3/3)

and dead load stress printed in the output tables will not add up to the printed value of the total stress. This is because the dead load stress and the maximum and minimum live load stresses may be computed at different locations along the member. The total stress is computed using dead load and live load stresses which occur at the same locations.

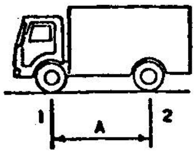
The final table is a summary of all the preceeding tables and contains the controlling GVW for the stringers, floorbeams, girders, brackets and main bridge members, and the final controlling value.

The computer program was used repeatedly to analyze all 41 vehicle configurations for each of the loading cases indicated in the Scope of Work. As an example of the final product, Figure 3 shows the final results for loading Cases I and II. These summary figures are to be used as permit-issuance guides. Vehicles not adequately represented by one or a combination of the 41 configurations are to be analyzed using the program.

NOTE: Table in Feet and Kips
Feet x 0.3048 = m
Kips x 4.4482 = kN

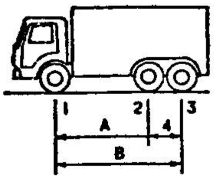
TYPE

1



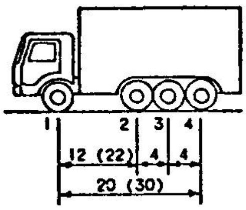
TYPE	SPACING A (FT)	ORIG. AXLE WT. (K) 1	2	TOTAL	ALLOW. GVW (K)
1A	15	7	20	27	41.3
1B	10	20	20	40	43.1
1C	30	20	40	60	51.2
1D	35	40	50	90	61.4

2



TYPE	SPACING (FT) A	B	ORIGINAL AXLE WT. (K) 1	2	3	TOTAL	ALLOW. GVW (K)
2A	15	19	16	17	17	50	49.7
2B	12	16	18	26	26	70	44.7
2C	12	16	14	28	28	70	43.3
2D	26	30	14	28	28	70	47

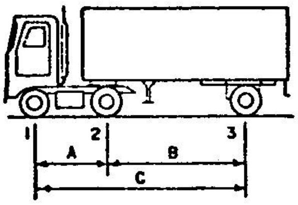
3



TYPE	ORIGINAL AXLE WT. (K) 1	2	3	4	TOTAL	ALLOW. GVW (K)
3A	13.28	20	20	20	73.28	46.6
3B	8	21.76	21.76	21.76	73.28	44
3C	18.32	18.32	18.32	18.32	73.28	50.5
3D	13.28	20	20	20	73.28	49.8

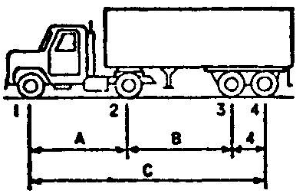
( ) DENOTES SPACING FOR TYPE 3D

4



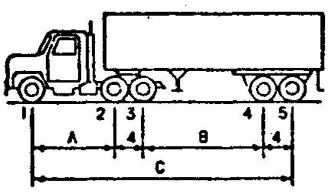
TYPE	SPACING (FT) A	B	C	ORIGINAL AXLE WT. (K) 1	2	3	TOTAL	ALLOW. GVW (K)
4A	10	10	20	11	20	20	51	51
4B	10	25	35	11	20	20	51	68.4
4C	12	20	32	20	20	20	60	64.3
4D	12	38	50	20	20	20	60	70.3

5



TYPE	SPACING (FT) A	B	C	ORIGINAL AXLE WT. (K) 1	2	3	4	TOTAL	ALLOW. GVW (K)
5A	11.5	24	39.5	5	20	12.5	12.5	50	68.6
5B	10	18	32	10	12	20	20	62	57.6
5C	10	18	32	10	20	16	16	62	62.8
5D	10	20	34	10	14	20	20	64	60.9
5E	10	20	34	10	20	17	17	64	64.1
5F	12	28	44	10	20	20	20	70	65.6
5G	12	34	50	10	20	20	20	70	65.6

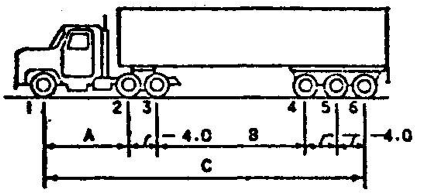
6



TYPE	SPACING (FT) A	B	C	ORIGINAL AXLE WT. (K) 1	2	3	4	5	TOTAL	ALLOW. GVW (K)
6A	12	12	32	8	16	15	16	16	72	62
6B	11	22	41	10	15.5	15.5	15.5	15.5	72	72.1
6C	10	28	46	10	16	10	20	20	76	71.3
6D	11.5	22	41.5	16	16	16	16	16	80	74.5
6E	10	34	52	10	18	12	20	20	80	75
6F	11.5	29.5	49	15	27	27	27	27	123	80
6G	11.5	29.5	43	18	23	28	23	20	130	80.7

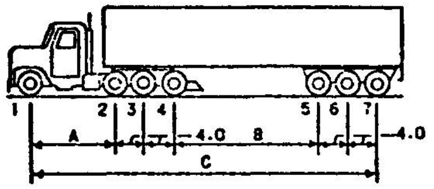
FIGURE 3 - COMBINED RESULTS FOR CASE I AND CASE II (1/2)

7



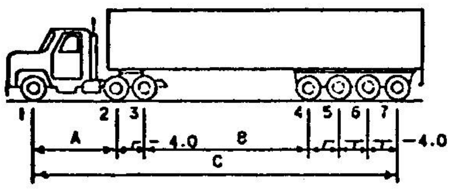
TYPE	SPACING (FT)			ORIGINAL AXLE WT. (K)				ALLOW. GVW (K)
	A	B	C	1	2-3	4-6	TOTAL	
7A	10	26	43	8	2 at 15	3 at 14	80	76.4
7B	12	26	50	15	2 at 27	3 at 27	150	75.6
7C	12	30	54	12	2 at 33	3 at 24	150	83.1

8



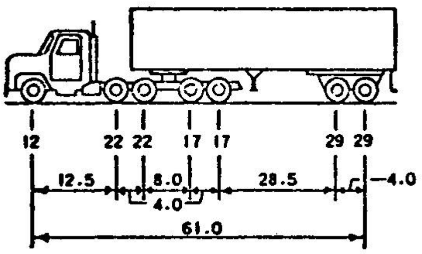
TYPE	SPACING (FT)			ORIGINAL AXLE WT. (K)				ALLOW. GVW (K)
	A	B	C	1	2-4	5-7	TOTAL	
8A	9.33	24.67	50.0	8	3 at 12	3 at 12	80	81.6
8B	9.33	31.67	57.0	9	3 at 22	3 at 25	150	81.5
8C	9.33	24.67	50.0	15	3 at 27	3 at 27	177	80.6

9



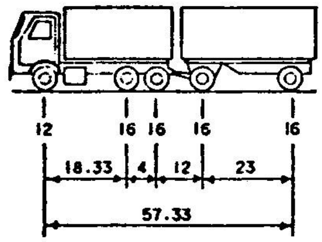
TYPE	SPACING (FT)			ORIGINAL AXLE WT. (K)				ALLOW. GVW (K)
	A	B	C	1	2-3	4-7	TOTAL	
9A	12	22	50	8	2 at 20	4 at 8	80	74.5
9B	11.5	34	61.5	12	2 at 25	4 at 22	150	74.7
9C	12	22	50	15	2 at 27	4 at 27	177	74.4

10, 11



(KIPS)

(FT.)



ORIGINAL GVW - 148^K
ALLOWABLE GVW - 90.6^K

ORIGINAL GVW - 76^K
ALLOWABLE GVW - 79.3^K

FIGURE 3 - COMBINED RESULTS FOR CASE I AND CASE II (2/2)

FATIGUE ANALYSIS

Information provided by DelDOT indicated that in 1978 the ADTT was 1,881 trucks per day in one direction, and that the ADTT projected for 1995 was 3,128 trucks per day in one direction. The distribution of gross vehicle weights was assumed to be represented by the total of the 1977 and 1979 Delaware Loadometer Surveys for the stations near the bridge, given below. The DelDOT surveys found no vehicles with a GVW over 120 kips (534 kN). The permits reviewed by Modjeski and Masters indicated that in 1979, 16 vehicles weighing up to 150 kips (667 kN) traveled a route which could have taken them over the St. Georges Bridge. Assuming an ADTT of 1,954 trucks per day in one direction of 1979, these 16 vehicles could constitute 0.00112% of the traffic if they crossed only once per permit evenly divided between northbound and southbound traffic. Most of the permits reviewed were for one-way trips. Even if 10 times as many of these vehicles, each weighing 150k (667 kN), crossed the bridge in both directions, they would affect the percent of HS20 equivalent stress cycles only about 1/2%. Therefore, the DelDOT loadometer data is considered sufficiently representative of all traffic using the St. Georges Bridge, including the occasional extremely heavy permit vehicles. Application of Miner's Rule with an exponent of 3 as shown in Reference 1 yields 41.6% equivalent HS20 trucks. This compares to 35% equivalent HS20 trucks found in the 1970 FHWA Nationwide Loadometer Survey.

Wt. Range	No. of Vehicles	Average Wt. Kips (kN)	No. of HS20
0 to 5	323	4.3 (19.1)	0.1
5 to 10	204	6.8 (30.2)	0.2
10 to 15	72	12.2 (54.3)	0.3
15 to 20	83	17.6 (77.8)	1.2
20 to 25	87	22.5 (100.1)	2.7
25 to 30	127	27.6 (122.8)	7.1
30 to 35	83	32.4 (144.1)	7.6
35 to 40	103	37.8 (168.1)	14.9
40 to 45	59	42.2 (187.7)	11.9
45 to 50	42	47.6 (211.7)	12.1
50 to 55	29	52.4 (233.1)	11.2
55 to 60	46	57.6 (256.2)	23.6
60 to 65	53	63.0 (280.2)	35.5
65 to 70	66	67.4 (299.8)	54.1
70 to 75	92	72.5 (322.5)	94.0
75 to 80	79	77.3 (343.8)	97.7
80 to 90	101	85.3 (379.4)	168.0
90 to 100	72	93.6 (416.3)	158.1
100 to 110	5	102.7 (456.8)	14.5
110 to 120	1	117.6 (523.1)	4.4
Total	1727		719.0
Percentage of Total			41.6

Use of the ADTT data and the DelDOT loadometer data resulted in a calculation of 7.4 million equivalent HS20 vehicles crossing the bridge in 70 years in each direction. This is based on an average ADTT of 2,033 and a projected ADTT of 4,555 at the end of a 70 year life. By comparison, the current AASHTO Specification requires design for 2.0 million cycles (longitudinal members) and over 2.0 million cycles (transverse members) for an ADTT of over 2,500.

Initial calculations indicated that the stress range in some riveted details and the shear range in stud connectors of composite members were so high relative to the current AASHTO allowable stress ranges that more sophisticated calculation procedures had to be found to avoid placing undue restrictions on the use of the bridge. Research was reviewed and several experts were contacted for opinions and advice. It was decided that the current specifications, while suitable for the design of new structures, contain many assumptions which can be quite conservative in some cases, particularly as it relates ADTT to design cycles of equivalent HS20 trucks. It also reflects some editorializing by the committees involved with developing the specifications. The following considerations were evaluated in developing criteria to be used on the St. Georges Bridge:

- The current AASHTO fatigue specification is generally believed to result in safe designs despite its many simplifications and assumptions. There are, however, other technically acceptable, presumably more sophisticated procedures which can be used to relate random loading to design cycles and allowable stress ranges. One approach would be to evaluate the most extreme loading possible, and if the stress range corresponding to this loading is below the "runout limit" for the detail under consideration, fatigue cracks will not propagate regardless of the number of cycles. Alternatively, it is possible to compute an "effective stress range" using either Miner's rule or a root-mean-square approach. The "effective stress range" is the stress range corresponding to the total number of cycles which will occur during the design life of the structure, i.e. ADTT x 365 x design life in years. If the point corresponding to the effective stress range and the total number of cycles is below the lower confidence limit for a given fatigue category by some reasonable margin, failure due to fatigue crack propagation is not to be expected during the design life.

- The values of α , a variable used to relate measured stress to calculated design stress, built into the AASHTO Specifications are also conservative. The chosen values were 0.7 for longitudinal members and 0.8 for transverse members. Values somewhat less than this could be used in evaluating existing structures, 0.6 was used for longitudinal members and 0.7 was used for transverse members when computing the effective stress range, and 0.9 was used when computing the extreme value.

- Stresses caused by vehicles were assumed to be proportional to their gross vehicle weight. While not precisely correct, this assumption is necessary to convert the random loading indicated by loadometer histograms into equivalent cycles of constant amplitude loading so that allowable stress ranges may be determined from published data.

- Applications of assumptions above and the equation below results in an effective stress range equal to 44.8% and 52.3% of the HS20 stress range for longitudinal and transverse members, respectively.

$$\sigma_{eff} = \left[\alpha^3 \Sigma \phi_i \, (GVW/GVW\text{-}HS20)_i^{\,3}\right]^{\frac{1}{3}}$$

where: ϕ_i = % of a given GVW range in a loadometer survey

α = Stress ratio defined above

- There is no technical reason to evaluate existing structures using the criteria for non-redundant members. These criteria were established somewhat arbitrarily by AASHTO with the intent of penalizing certain details, particularly Category "E" details, so badly that designers would choose other details.

- Riveted details can be evaluated using Category "C" instead of "D" if there is reason to believe the rivets are tight.

- In the case of the St. Georges Bridge, use of four loaded lanes as a fatigue loading is unduly restrictive. The "extreme value" case was based on all lanes loaded without the AASHTO multiple lane reduction factors, but the "effective stress range" was based on single vehicle loadings with some allowance for multiple occurrences.

- In the particular case of shear stress range in welded studs, the values in the AASHTO Specification were developed from tests of relatively small specimens which contained only four studs, and which were loaded so as to pry the concrete slab off of the flange of the specimen. Thus, the specification values do not take into account the bond and friction between the concrete deck and the flange. This bond and friction significantly reduces the stress range in the stud connector. The result is that the design values are again, quite conservative. Furthermore, the failure of stud connectors is not a catastrophic event and, if it occurred repeatedly, would lead to slip of the deck relative to the beam which would be detectable during annual inspections. Finally, unless the deck is of modern construction utilizing deck protection systems, the deck will probably have to be replaced before the stud connectors fail. Additional stud connectors could be added when the deck is replaced.

- Impact is a statistical quantity and the AASHTO impact may be regarded as an extreme value. It was thought that statistical analysis of actual impacts might lead to an average impact of about 1/3 of the AASHTO impact value.

- In some cases, design stresses are computed using distribution factors calculated by crowding the vehicles to one side or the other of their design lanes and/or crowding the design lanes into a position of maximum effect. The actual position of vehicles is also a statistical quantity and all cycles of loading will not occur with the same distribution factors.

Implicit in some of the assumptions above is the replacement of the deck slab in the near future, i.e. about 1990 or before. Stress cycles accumulated by the stud connectors (added in 1974) will be on the order of 1.1 million equivalent HS20 cycles by that time (average ADTT = 2,172, 1974-1990). If the actual shear stress was further reduced by only 25 percent due to bond and friction, this would be equivalent to about the 0.5 million cycles for which they were designed. When the deck slab is replaced, shear studs can be added and other members can be upgraded to the then existing AASHTO requirements if so desired.

The findings of fatigue analyses are summarized below.

Item	Acceptable by AASHTO As Amended	Acceptable by Effective Stress Range
Rolled Stringers	Yes	Yes
Built-up Stringers	Yes	Yes
Simple Span Girders	Yes	Yes
Floorbeams	No	Yes
Continuous Girders	Yes	Yes
Brackets	No	No
Main Bridge Members	Yes	Yes

Only the floorbeams will be discussed further.

Stress ranges in floorbeams resulting from three lanes of AASHTO HS20 vehicles at 100% were computed and exceed the 10 ksi (68.9 MPa) AASHTO allowable stress range for Category "C" details on transverse members in 1/3 of the cases investigated. (By comparison, if the riveted details were considered Category "D", the AASHTO allowable stress range would be only 7.0 ksi (48.3 MPa). Accounting for the multi-lane reduction factors, only two of the 30 floorbeam sections investigated met this criterion.)

Some of the stresses computed for 3 lanes of loading were higher than the Category "C" runout limit of 10 ksi (68.9 MPa), so the extreme value concept could not be used. The floorbeams were investigated further using the effective stress range concepts. When only one exterior lane is loaded, the maximum HS20 stress range is 3.3 ksi (22.7 MPa) in controlling floorbeams. The single exterior lane truck loading is the most common form of loading for the floorbeams. This corresponds to an effective stress range of 1.73 ksi (11.9 MPa) which is clearly acceptable. If both exterior lanes were loaded simultaneously, the HS20 stress range would be 4.02 ksi (27.7 MPa) which results in an effective stress range of 2.10 ksi (14.47 MPa) and is still obviously acceptable.

A more severe loading results when both lanes on one side of the bridge are loaded. A maximum HS20 stress range of 8.92 ksi (61.5 MPa) and a corresponding effective stress range of 4.67 ksi (32.2 MPa) were computed for this loading. If the full one directional ADTT was applied to two vehicles at a time, there would be about 25.6 million cycles of loading with an allowable stress range of 6.0 ksi (41.3 MPa). Considering the statistical nature of impact and the vehicle position within lanes, this is acceptable even for so severe a loading.

Another evaluation of floorbeams could be undertaken by assuming some hypothetical distribution of vehicles to account for multiple occurrences such as: (1) 50 vehicles crossed the bridge in the exterior lanes such that 25 were in each exterior lane, corresponding to 50 cycles of loading, (2) 20 vehicles (10 pairs) crossed in adjacent southbound lanes, (3) 20 vehicles (10 pairs) crossed in adjacent northbound lanes, (4) 20 vehicles (10 pairs) crossed in opposing exterior lanes, and (5) 12 vehicles (3 quads) crossed with all lanes loaded. This traffic distribution results in a total of 83 cycles of load per 122 trucks crossing the bridge. Assuming that this distribution applies to the entire histogram of vehicle weights results in an effective single vehicle stress range of 3.34 ksi (23.0 MPa) in the controlling floorbeams. The number of cycles is 83/122 times the total number of vehicles in both directions or approximately 69.7 million cycles. The allowable stress range would then be about 4.3 ksi (29.6 MPa) which is acceptable.

It was therefore concluded that, while the floorbeams do not satisfy the current AASHTO criteria, as amended herein, they are adequate for a 70 year life.

CASE STUDY #2 - BLUE WATER BRIDGE

INTRODUCTION

The Blue Water Bridge connects the State of Michigan with the Province of Ontario at Port Huron, Michigan. The main bridge is an 871 foot (266 m) cantilever truss. The Michigan approach structures consist of a concrete beam and column supported slab approach (not in project), 1,731 feet (528 m) of steel beam and girder approach spans of varying spans, and 508 feet (155 m) of approach truss spans. The Canadian approach structures consist of 2,100 feet (640 m) of steel beam and girder spans and 508 feet (155 m) of approach truss spans. In addition, there is a flared toll plaza area on structure on the Michigan side, and a flare-on-structure approaching the Ontario toll plaza. The bridge was opened in 1938 and both toll plazas were widened in 1954, and the Ontario plaza was widened again in 1974. The bridge carrys a three lane cartway with passing permitted on the up-grade of the approach structures.

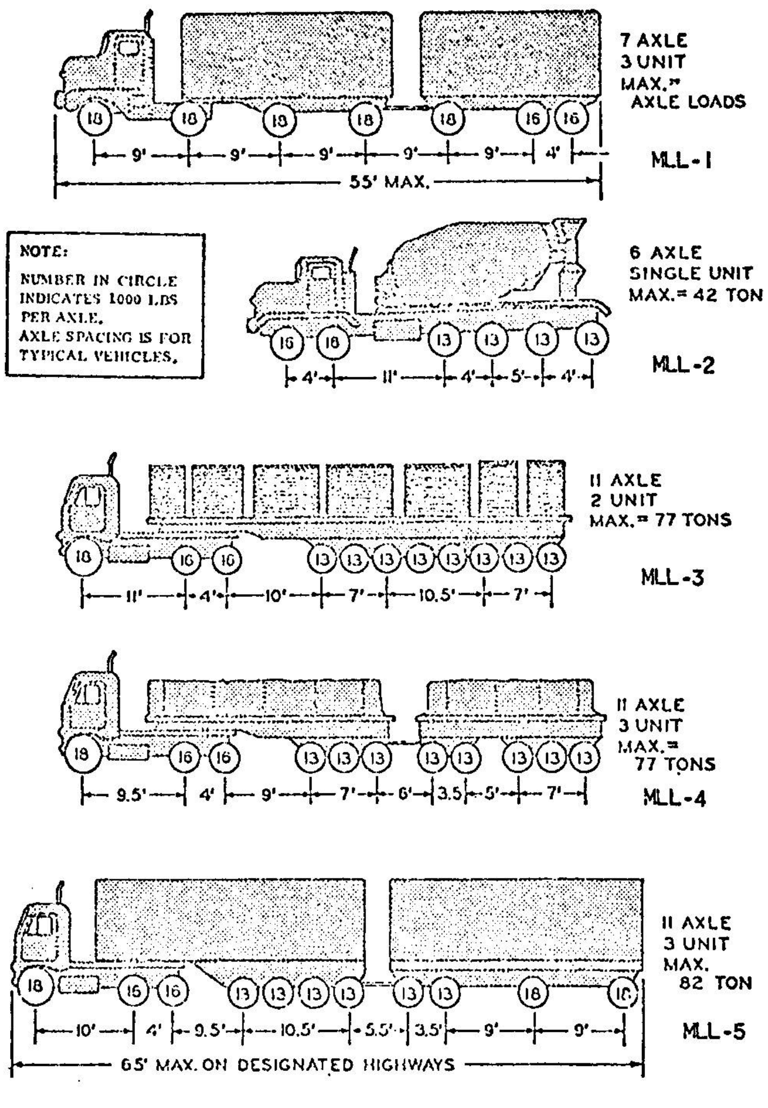
SCOPE OF WORK

This project involved the analysis of fifty-eight vehicles, in two levels of operation, applied to 56 components the steel floor system from end-to-end of the bridge. The fifty-eight vehicle configurations are shown schematically in Figure 4 and consist of:

- o Seventeen vehicles, MPL-1 to MPL-17, described in the Michigan Department of Transportation's "Table of Overloads Permissible on Bridges" dated 6/30/78.
- o Five vehicles, MLL-1 to MLL-5, shown on the Department's figure "Maximum Gross Vehicle Weights in Michigan in 1970".
- o Four vehicles, MMSL-1 to MMSL-4, selected by the Department from the list of Special Vehicles studied prior to 1968.
- o Thirty-two vehicles, BWBA-1 to BWBA-32, submitted by the Blue Water Bridge Authority's consultant, which were developed from a study of vehicles crossing the bridge during a three-day period in February, 1979.

The two levels of operation were called the "maintenance condition" which simulated traffic patterns during closure of an exterior lane during maintenance operations, and the "closed bridge condition" in which traffic would be limited to passenger vehicles only to maximize the permissible weight of a special vehicle.

In the "maintenance condition", distinctions were made for operation in the toll plaza areas. Except in the toll plaza areas, two special vehicles were centered in the worse exterior lane and the center lane. Girders and stringers were to be evaluated using 120 percent of the design allowable stress; floorbeams were to be evaluated using 130 percent of the design allowable stress. Stringers in the toll plaza areas were also to be evaluated using 120 percent of design allowable stress. Floorbeams and girders in the plaza areas were to be evaluated using the more critical of (1) a single special vehicle positioned for maximum effect at 110 percent of design allowable stress, or (2) a special vehicle positioned for maximum effect, and adjacent HS20 vehicles centered in 12 foot (3.7 m) lanes, at 80 percent of yield stress.



MAXIMUM GROSS VEHICLE WEIGHTS IN MICHIGAN IN 1970

MICHIGAN DEPARTMENT OF STATE HIGHWAYS
AND TRANSPORTATION
OVERLOADS PERMISSIBLE ON BRIDGES

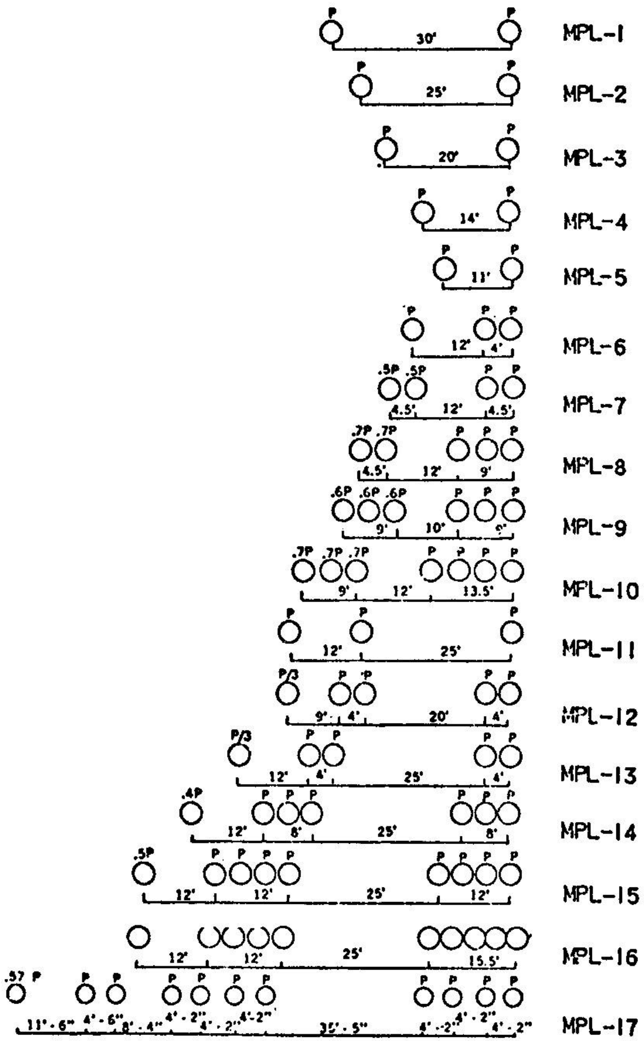


FIGURE 4 - SPECIAL VEHICLES - BLUE WATER

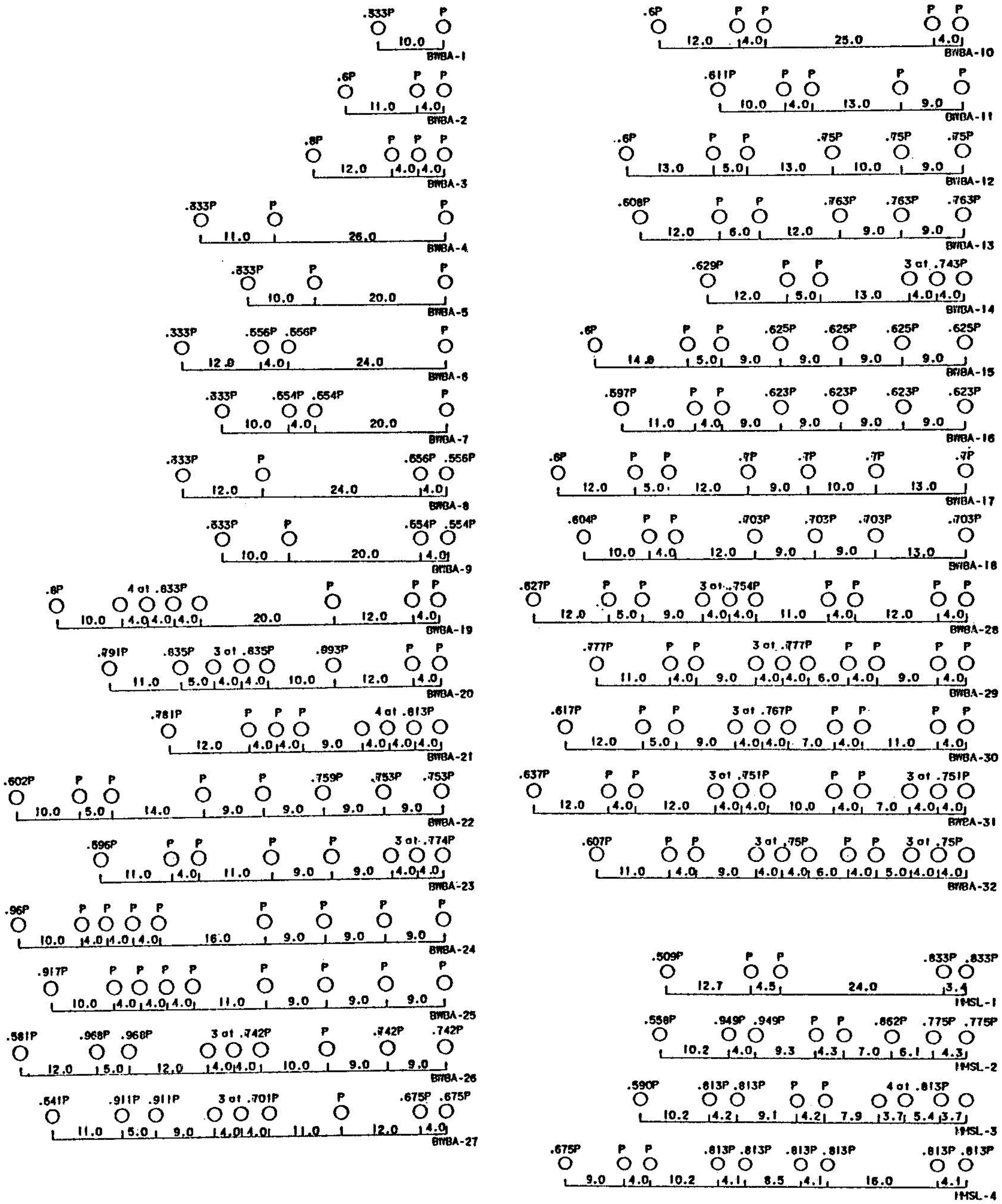


FIGURE 4 - SPECIAL VEHICLES - BLUE WATER

For the "closed bridge condition", one special vehicle was positioned in the center of the middle lane, or centered on either one of the middle lane stripes. In the plaza areas, the special vehicle was assumed to be centered along the projected centerline of bridge, or centered 5 feet (1.4 m) from the projected bridge centerline. All members were evaluated using 110 percent of the design allowable stress.

The objectives of this project were:

- o To develop a set of tables to be used by the MDOT Bridge Section to define the maximum permissible axle weight and corresponding gross vehicle weight for all 58 vehicle configurations for both the "maintenance condition" and the "closed bridge condition". The maximum permissible axle weights and gross vehicle weights were those determined by rigorous analysis.

- o Developed a set of tables based on simple rules-of-thumb, to define permissible gross vehicle weights for given length vehicles to be used by the MDOT Permit Section. The rules-of-thumb were established for both "maintenance condition" and the "closed bridge condition" using only the vehicle configurations developed by the Blue Water Bridge Authority's consultant (BWBA-1 to BWBA-32).

- o The impact of strengthening selected floor system members on the permit load capacity was to be evaluated. (This requirement not discussed herein.)

SUMMARY OF RESULTS

The allowable GVW's for each of the 58 vehicles for both conditions of operation are shown in Figure 5; the top band of points correspond to the "closed bridge condition", the lower set to the "maintenance condition". The source of the individual loads is also indicated by the symbols in the legend of Figure 5. These data points, tabulated by vehicle name, satisfied all requirements of the Scope of Work calling for data obtained by rigorous analysis.

Also shown on Figure 5 are three bi-linear curves which are the "rules-of-thumb" required for use by the Department's Permit Section. The lowest curve is defined as:

$$
\begin{array}{lll}
L < 20 & W = & 40{,}000 + 1{,}000\ L \\
(L < 6.1 & W = & 178 + 14.6\ L) \\
L > 20 & W = & 36{,}000 + 1{,}200\ L \leqslant 120{,}000 \\
(L > 6.1 & W = & 160 + 17.5\ L \leqslant 534)
\end{array}
$$

"W" is the gross vehicle weight in pounds (kN) and "L" is the distance between the centers of the front and rear wheels in feet (m).

The intermediate lines shown in Figure 5 represent an upper bound for gross vehicle weights for the "maintenance condition" based on all fifty-eight vehicle configurations and is given by the following rule-of-thumb.

$$L < 20 \quad W = 35{,}500 + 2{,}100\ L$$
$$(L < 6.1 \quad W = 158 + 30.7\ L)$$
$$L > 20 \quad W = 55{,}500 + 1{,}100\ L \leq 130{,}000$$
$$(L > 6.1 \quad W = 247 + 16.1\ L \leq 578)$$

Vehicles falling above the highest lines can be authorized passage only after review by the Bridge Section using the rigorous data points corresponding to the "closed bridge condition".

The upper curve is for the "closed bridge condition", developed from the thirty-two vehicle configurations submitted by the Blue Water Bridge Authority's consultant. This curve is defined as:

$$L < 50 \quad W = 55{,}000 + 1{,}500\ L$$
$$(L < 15.2 \quad W = 245 + 21.9\ L)$$
$$L > 50 \quad W = 30{,}000 + 2{,}000\ L \leq 170{,}000$$
$$(L > 15.2 \quad W = 133 + 29.2\ L \leq 756)$$

To further expedite issuance of routine permits, the rules-of-thumb given above were at one-foot (.3048 m) intervals. These tables are the "working format" for the Permit Section. The rigorous data are the "working format" for the Bridge Section.

FATIGUE CONSIDERATIONS

The Scope of Work for this project limited fatigue investigations to one detail which induced a weld between filled grid deck and stringers on the main bridge. This weld was considered a Category "C" detail.

A load spectrum was provided by the Michigan Department of Transportation and was reduced to 29.0% equivalent HS20 vehicles based on Miner's Rule. The average ADTT was 286.2 for 70 year life based on the toll records of previous truck traffic and the Department's projections of future traffic. The data above lead to a projection of 644,100 cycles of an HS20 stress range of 14.2 ksi (97.9 MPa) over 70 years. The comparable allowable stress range was estimated to be 18.3 ksi (126.2 MPa). Therefore, fatigue considerations did not control the capacity of stringers supporting the filled grid deck.

REFERENCE

1. Fisher, J. W., "Bridge Fatigue Guide Design and Details", American Institute of Steel Construction, New York, 1977.

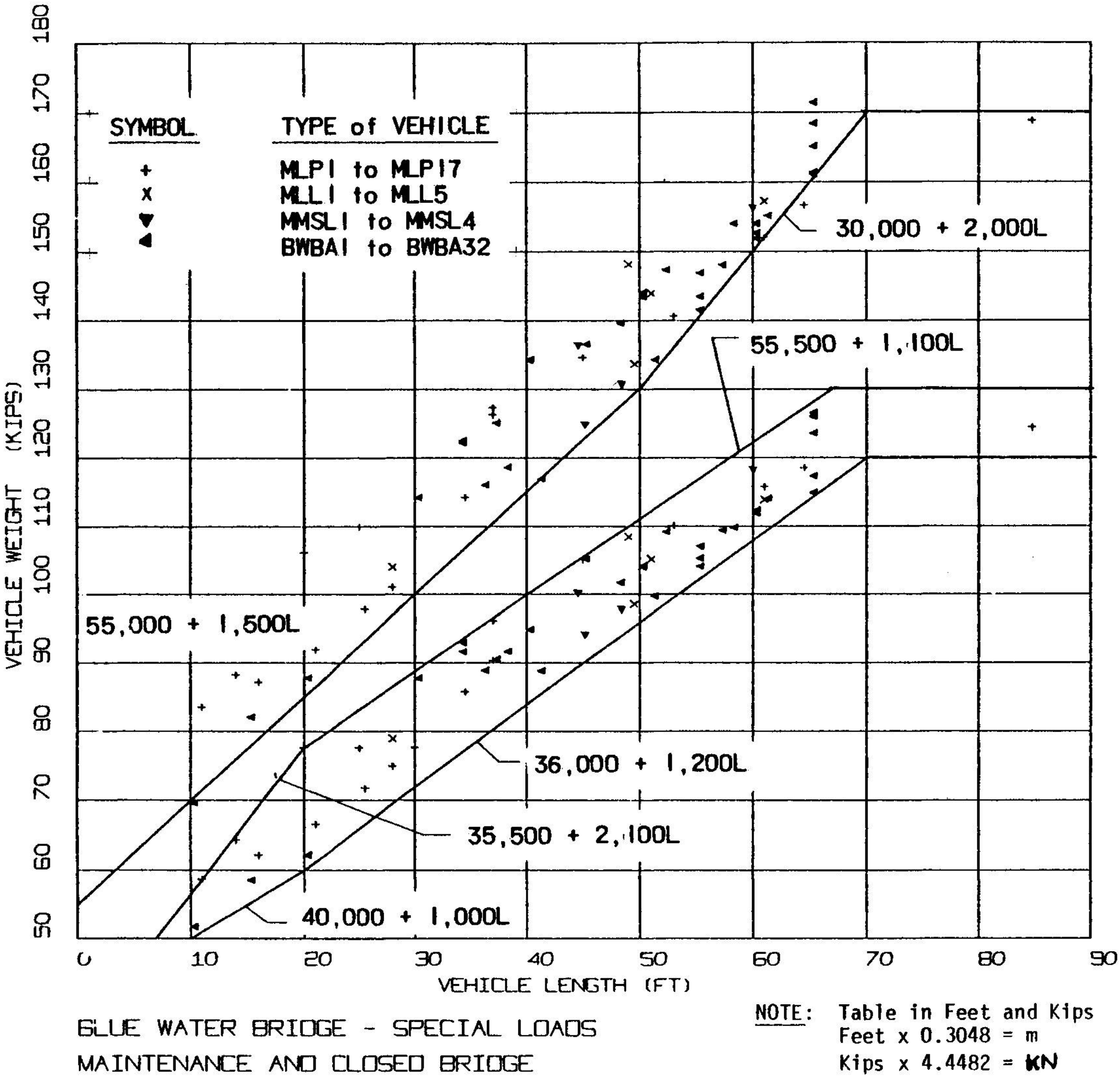


FIGURE 5 - GVW Vs Vehicle Length