Final Report

ESTIMATING THE FREQUENCY OF MULTIPLE TRUCK LOADINGS ON BRIDGES

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INTRODUCTION

Each vehicle traveling the length of a bridge causes the structural members to deflect slightly and then rebound. The repetition of these loadings less than the maximum allowable will cause the structure to weaken due to bending fatigue. Heavy trucks will naturally cause larger deflections and increase fatigue. Loadings of more than one heavy truck on a bridge will cause even greater fatigue. If the volume of trucks is large, the fatigue caused by single and multiple truck loadings, hereafter MTL, may cause an early failure of the bridge that could not be anticipated by the designers.

To guard against early fatigue failure the designers should have available information about truck weights, truck volumes and truck loading situations on bridges. Truck weight and volume information is obtainable from the state highway departments. Desrosiers (1) developed a model which makes use of truck weight and volume data to estimate the number of trucks, and their weight distributions, that will pass over a given bridge. This model accounted for all the truck loadings on a bridge, but assumed that all loadings were single, that is, only one truck was considered to be on a bridge at a given time. Multiple loadings were not provided for in the model. This project is an extension of the earlier study and seeks to determine how many trucks will be on the bridge simultaneously and in what lane they will be traveling.

With this information it is hoped that structural engineers will be able to obtain the loading information required to make an estimate of the fatigue caused by trucks.

The resultant model can be considered a first attempt at making a good estimate of the frequency of MTL that will occur on certain types of bridges. Further collection of data would permit refinement of the model and add more generality to its usage, but it is unlikely that the model's basic structure would be altered.

II

GENERAL PROCEDURE OF THE STUDY

The problem was to identify the variables which might influence the frequency of MTL, determine how they affected the MTL and develop a means of estimating the frequency of MTL from readily obtainable information for both existing facilities and those planned for the future.

At the onset of the project it was not known what factors were most important in determining the frequency of MTL.

Six variables were selected for preliminary study. They were:

1. Type of highway. Three types were included; two-lane two-way undivided, four-lane divided and six-lane divided.

2. Length of bridge. Seven lengths were studied: 100- to 400-ft. in 50-ft. increments.

3. Time of day. Data were collected at three times of the day: mid-day, afternoon rush hours, and night.

4. Total traffic volume. This variable included volumes of all types of vehicles for each lane observed.

5. Truck speed. This variable consisted of the speed of heary trucks, approximately 18000 lbs. and over.

6. Truck volume. This variable consisted of the volume of heavy trucks, approximately 18000 lbs and over.

The first step in the collection of data was the making of rational estimates as to the type and amount of data that was required. As more information became available the procedures were modified to meet the changing requirements.

The data were analyzed by two methods: visual inspection and statistical testing. Once the data had been processed into a useable form, visual inspection was used to provide a quick estimate of the importance of the different variables and to guide the researchers in the further collection of data. Statistical testing was employed later to determine the level of significance of the relationship between each variable and the frequency of MTL. Once the significance of each variable had been determined, a model could be developed based on those that were relevant.

A model was desired which would express the relationship between the significant variables and the frequency of MTL in a useable form. This was accomplished by fitting several linear regression curves to the data. The best fitting curve was selected as the desired model.

III

DATA COLLECTION

Data collection was started in the fall of 1971. The data were collected during periods of fair weather and with traffic flowing freely. One observer simultaneously monitored total traffic volume in each lane, truck volumes in each lane, truck speeds, truck loading situations within a specified length of roadway for each lane and all lanes together. The procedure was repeated for seven different bridge lengths for each of the three road types. A selected sample of lengths was also studied at several different times of day. By using automatic data recording equipment and spreading the data collection over time, one observer was able to handle the workload.

The observer was stationed on a highway overpass, with the exception of one site, facing the oncoming traffic. A radar meter was inconspicuously aimed upstream. Traffic volume counters were placed on the road surface downstream from the overpass; one for each lane being studied. Upstream from the overpass a specific length of roadway was delineated on the pavement through the use of marking cones and ropes stretched across the roadway. Except for the two-lane two-way undivided highway, only one direction of flow was studied. On a data sheet the observer noted the truck loading situations of each lane and the roadway as a whole within the specific study section. That is, he observed the number of trucks that were within the study section at any given moment. The number of axles on each truck were noted in order that the volume counters could later be corrected. Truck speeds were read from the radar meter and recorded. Each specific length was observed for six consecutive 15-minute counting periods coinciding with the time increments of the traffic counters. The resultant data produced the necessary information to identify the significant variables.

Selection of Study Sections

The Connecticut Department of Transportation, the sponsor of this project, recommended several highway locations that would be suitable for the study. Three different types of highways were selected to represent the most common facilities in use. All the sites had substantial truck traffic - ten per cent or more of the total traffic. The sites selected were:

Two-lane two-way undivided: Conn. Rte. 5 (Ct. 5) just south of Wallingford Tube Bending Company. Both the North and Southbound lanes were studied. The lanes were 12-ft. wide with 11-ft. shoulders on both sides of the highway. There was a slight uphill grade in the Southbound direction. There was no access control but few vehicles entered or exited the highway in the vicinity of the study area. About a quarter mile from the study area in both directions were traffic signals. The posted speed limit was 45 mph. No overpass was available so the observation point was located behing the guardrails on the Southbound side of the highway. (See Figure 1.)

Four-lane divided: the two Northbound lanes of I-91 (I-91-N) at the Depot Hill Rd. overpass near Enfield. Only the Northbound traffic was

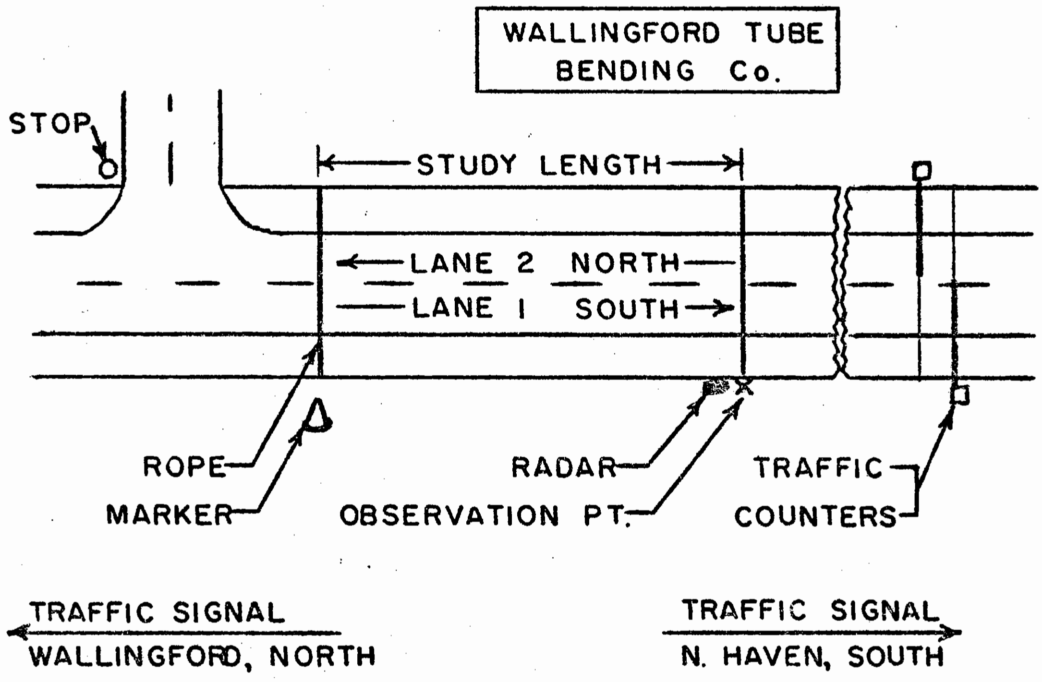


FIG. 1

CT. 5 STUDY SECTION

observed. The two lanes were 12-ft. wide and the shoulder was 10-ft. wide. The grade was level. In this report, level is defined as a site with negligible gradient. There was complete access control with no exit for entrance ramps in the vicinity of the study area. The posted speed limits were 60 miles per hour for passenger cars and 55 miles per hour for trucks. The overpass was used as the observation point. (See Figure 2.)

Six-lane divided: the three Southbound lanes of I-91 (I-91-S) at the Ct. Rte. 68 interchange near Wallingford. Only the Southbound traffic was observed. The three lanes were 12-ft. wide and the shoulder was 10-ft. wide. The grade was level. There was complete access control. Upstream of the study area was the exit ramp on the shoulder side of the highway to Ct. Rte. 68. Downstream of the study area was the entrance ramp, also on the shoulder side of the highway. Traffic on these ramps was light. The posted speed limits were 60-miles per hour for passenger cars and 55-miles per hour for trucks. Trucks were prohibited from using the median (third) lane. The overpass was used as the observation point. (See Figure 3.)

Another site a few miles South of the I-91-S site on the same Southbound lanes was also used. It was located at the Harrison Road overpass and was called I-91-Sa. The site was physically identical to I-91-S except for two factors. I-91-Sa was on a downhill grade and there was no exit or extrance ramp in the area.

Specific locations on each highway were chosen for good visibility of the road from a convenient observation point, level grade, straight alignment and the absence of any disturbances to the flow of traffic.

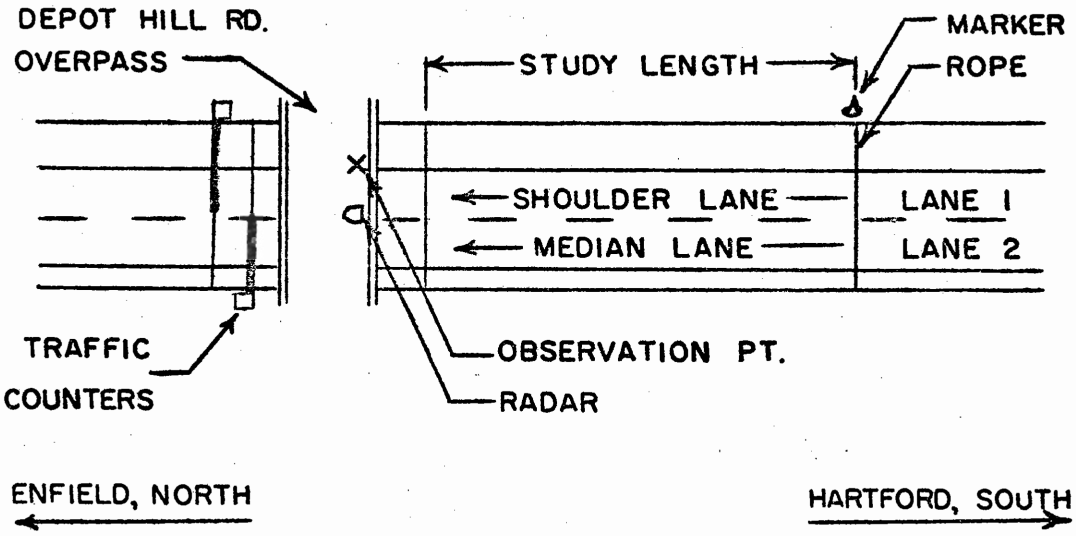


FIG 2 I-91-N STUDY SECTION

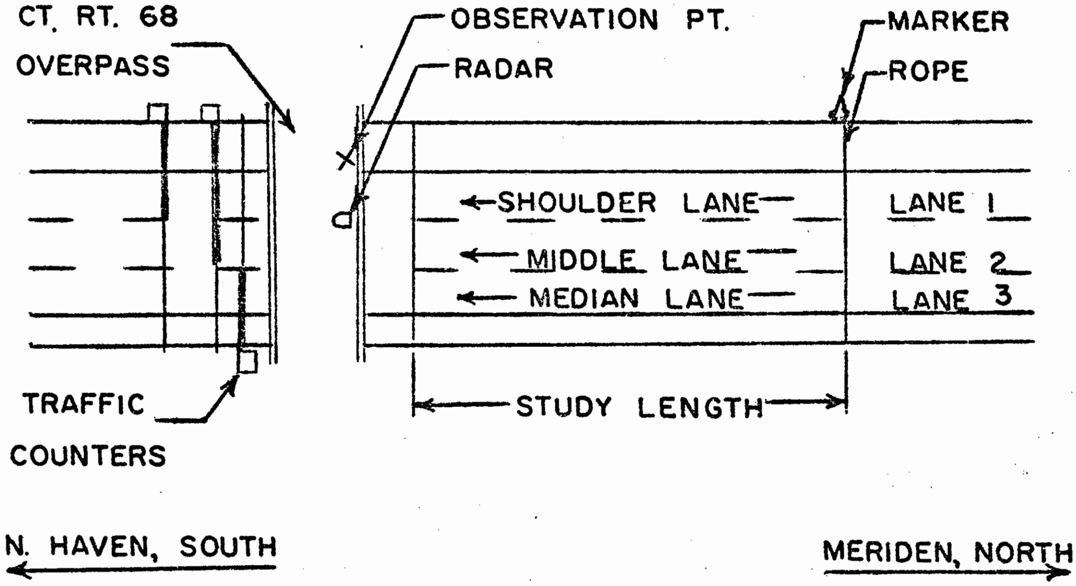


FIG 3 I-91-S STUDY SECTION

Selection of Bridge Lengths

The model was to be developed for bridges which could be approximated by one of seven specific lengths, 100- to 400-ft. in 50-ft. increments. The 50-foot increment was based on the fact that many trucks are approximately 50-feet long. The 50-foot increment allowed the bridge lengths to be increased by roughly one truck length each step. This made it possible to conduct the study for a reasonable range of bridge lengths, with a relatively small increment between the lengths.

Initially it was decided that the shortest section length investigated would be 50-feet. It soon became apparent that multiple truck loadings on a 50-foot bridge are rare. In order for two trucks to be within a 50-foot section simultaneously they must be side by side in two lanes if they are trailer trucks, or bumper-to-bumper if they are shorter trucks. Data collection on the 50-foot section was terminated and the 100-foot length was established as the shortest bridge length for the study.

Four hundred feet was the longest bridge length studies. This meant that data had to be collected for seven different lengths on each road. Data requirements were a limiting factor in the selection of the maximum number of sections to be investigated; to add more lengths would have required an excessive amount of data collection. Further, it was assumed that on longer bridges, even if the structure incorporated continuous spans, the effect of two trucks on the bridge 400-feet or more apart would be little different than loading the bridge twice with one truck each time.

Time of Day

Two bridge lengths, 150- and 250-feet, were observed at three different times of day on each highway: midday, afternoon rush hour, and night.

Collection of these data would indicate if truck traffic patterns varied at different times of the day. Only two bridge lengths were selected for study because of the length of time that would have been required to collect data for all seven lengths. The 150- and 250-foot lengths were arbitrarily selected from within the center of the bridge lengths being studies. If it were found that the frequency of MTL was different for these two lengths, data could be collected for the other lengths or an estimate could be made based on the two lengths studied.

Total Traffic Volume

Each bridge length was observed for six consecutive 15-minute counting periods. It was decided that six counting periods would be sufficient to provide meaningful data on each bridge length. The 15-minute periods coincided with the 15-minute time increments of the traffic counters. The traffic counters were used to record the total volume of traffic in each lane. One counter was needed for each lane. The clocks on all of the counters were synchronized at the beginning of each session. The date, time of the study, name of the highway, bridge length and lane were entered onto each machine's register tape after each data collection session. These counters recorded one vehicle for every two axles that actuated their mechanism. This resulted in overestimating volumes because most of the trucks had more than two axles. This error was eliminated by manually counting the number of axles on each truck and adjusting the recorded counts accordingly. It was assumed that all axles actuated the counter.

Truck Speeds

A radar speed meter was used to obtain the truck speeds. When set up on an overpass the radar picked up truck speeds only, because at that height only large vehicles returned signals strong enough to indicate a reading on the meter. Therefore, it was impossible to mistake an automobile's speed for that of a truck's. The antenna of the radar was placed so that it could detect speeds from trucks in all lanes. The set-up position was usually over the dividing line of the shoulder lane and the median lane, or in the case of the six-lane facility between the shoulder lane and the middle lane.

Not all truck speeds were recorded. The radar failed to detect and the observer failed to record some truck speeds. In the latter case, the observer was giving his full attention to the loading situations in the test section. If the loading condition in the study area were obvious, as it usually was, the observer could glance at and read the radar meter. If more than one truck was in the range of the radar, only one speed was recorded, that of the larger or closer truck: the one more likely to be reflecting the stronger signal. If two trucks sent back equally strong signals, causing the meter reading to fluctuate, the reading was not recorded.

Delineation of the Bridge Lengths

The lengths of highway being observed were delineated by the placement of orange cones or a suitable marker at the far (upstream) end of the section. All the roads used in the study were of concrete construction. Using the joints, cracks and existing painted lines, the far end of the study area could be readily recognized. In some cases for the longer sections, a rope was stretched across the road to positively locate the

the far limit. The near end was always defined as the first pavement joint visible from the overpass. With this setup one observer on the overpass looking upstream could see the entire study length without moving his head. This was essential since, with the high speeds of the trucks, many loading situations existed for only a brief period and had to be identified in one glance.

Conditions during the night time counts were somewhat different. The upstream end of the study length was identified by a kerosene lantern shielded from view of the motorists. The near end of the section was defined as the point at which the headlights disappeared from the observer's view under the bridge. Naturally there were no other visible stationary markings to aid in delineating the study section, but at night the traffic volumes were lower and the trucks were clearly identified by their lights, facilitating the observations.

Data Sheets

Typical data sheets for the fall data collection are illustrated in Figures 4 and 5. The physical characteristics of the highway location were recorded on the first data sheet (Figure 4). Multiple loading information is recorded on the second data sheet (Figure 5). The first column is used to record the time of day. Each entry indicates the beginning of a 15-minute count and all the data from this point to the beginning of the next time interval are within one 15-minute period. The total traffic volume for each lane for the 15-minute time period is recorded in the appropriate VOLUME column. The largest number, e.g. 162, is the number of vehicles initially registered by the volume counter. In each VOLUME column

SITE DATA

ROUTE NAME	I-91-N
DIRECTION OF FLOW	NORTH
LOCATION	DEPOT HILL RD
NUMBER OF LANES	2
LANE WIDTH	12', 10' SHOULDER
GRADE	LEVEL
POSTED SPEED	55-TRUCKS, 60-AUTOS
SPECIAL FEATURES	NONE
DATE	NOV. 12, 1971
TIME	1 to 4 PM
WEATHER	FAIR

DIAGRAM

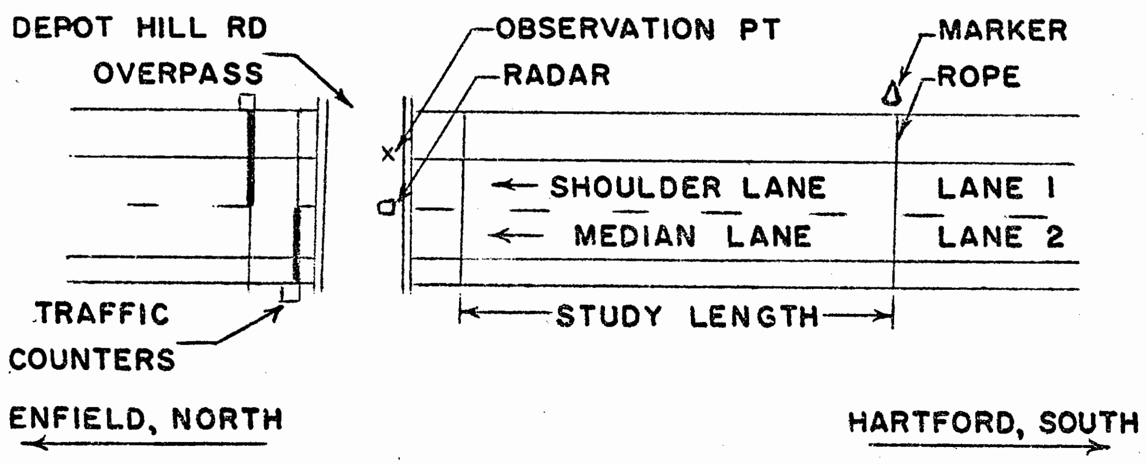


FIG 4 FALL DATA SHEET I

Route I-91-N Section 250-Ft Sheet 1

Time in 15 min Increments	Volume (15 min) Lane			Lane 1 Shoulder		Lane 2 Median		Lane 3 -		Multiple			
	1	2	3	Truck Count	Truck Speeds	Truck Count	Truck Speeds	Truck Count	Truck Speeds	1	2	3	4
1:15 PM				3, 5*	58						/		
	162	149		/		4	61			/	/		
				2	54					/			
						5				/			
				4	56					/			
				5		5					/		
				3	56					/			
				2	51					/			
	17 + 134 = 151			2, 5							/		
		5 + 138 = 143		4						/			
						3	63			/			
				5	54					/			
				2	56					/			
				2	55					/			
				3	57					/			
				4, 4**		5						/	
				2 /						/			
1:30 PM				2	59					/			
				5	58					/			

FIG 5 FALL DATA SHEET 2

there is a simple equation. The value to the left of the equal sign, e.g. 151, is the total volume of traffic which has been corrected by eliminating the error caused by trucks with three or more axles. This total traffic volume is equal to the volumes of non-heavy trucks (134) and heavy trucks (17).

Each lane was observed separately and all the lanes together equals the loading conditions on the roadway as a whole. Every horizontal line on the data sheet represents a separate loading situation. The numbers in the TRUCK COUNT column represent the number of axles on each truck. Two truck axle numbers on the same line in the same column means that two trucks were in the study length simultaneously and constitute a double loading.

If two or more axle numbers appear on the same line but in different TRUCK COUNT columns, a multiple loading situation existed for the roadway as a whole but not for any single lane. These loading situations are tabulated in the columns headed MULTIPLE LOADINGS. The first number is the sum of single loadings. The second number is the sum of double loadings, etc. The whole roadway has more MTL than the sum of the MTL on all lanes. This occurs because trucks in different lanes create a multiple loading for the roadway as a whole but not for any one lane.

Occasionally one truck was involved in two multiple truck loadings and was double counted. Because of this double counting the actual volume of trucks did not always equal the number indicated by the loading sums (number of single loadings and number of double loadings times two, etc.). To obtain correct truck volumes and to be able to check the summations, the double counted trucks were marked with asterisks. A single asterisk signifies a double count in the MULTIPLE LOADINGS column only and two asterisks signify a double count in both a TRUCK COUNT column and the MULTIPLE LOADINGS column. To prevent double counting of the truck axles, a slash line was extended from the line containing the double counted truck's axle number to the next line below where the truck is involved in a second multiple loading. An example of a typical loading situation will illustrate how the data sheet helped to simplify the task of data collection. The loading situation described in the example is also contained in the first two lines of Figure 5 and illustrated in Figures 6 through 9.

The first truck enters the study section but nothing is recorded on the data sheet because other trucks are close behind (Figure 6).

A second truck enters the section before the first truck exits. Both trucks are in the shoulder lane and their axle numbers are entered together on one line in the TRUCK COUNT column of LANE 1, indicating a double loading in that lane (Figure 7).

The first truck passes out of the section and the second truck remains alone but no new loading situation is noted on the data sheet since this truck is only the tail end of the previous double loading (Figure 8).

Before the second truck can leave the study length, a third truck enters in the median lane (Figure 9). The second truck is now the front end of a new double loading. On the data sheet (Figure 5) a slash line is extended from the axle number of the second truck to the next line below. The axle number of the third truck is entered on the same line but in the TRUCK COUNT

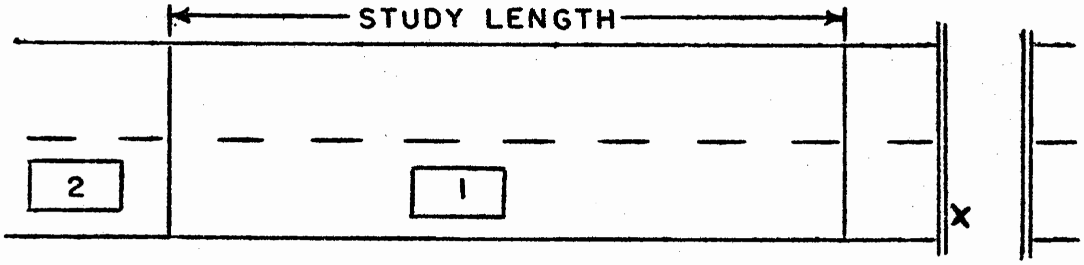


FIG 6 NO LOADING RECORDED

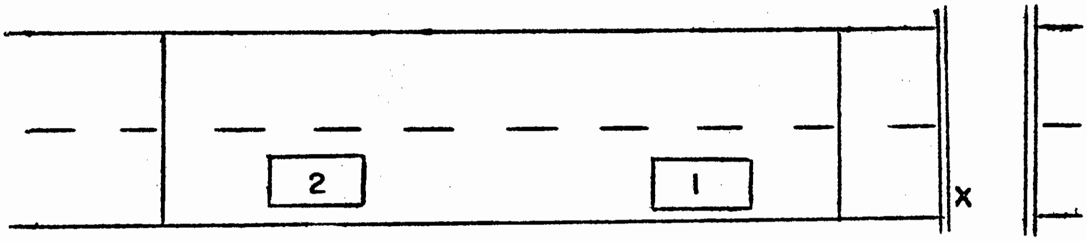


FIG 7 DOUBLE LOADING RECORDED IN LANE 1

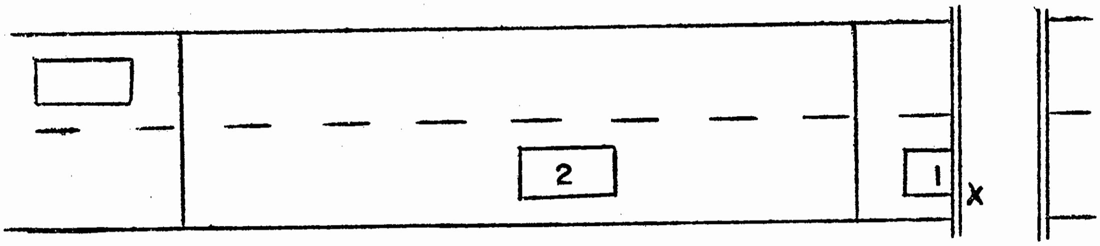


FIG 8 NO LOADING RECORDED

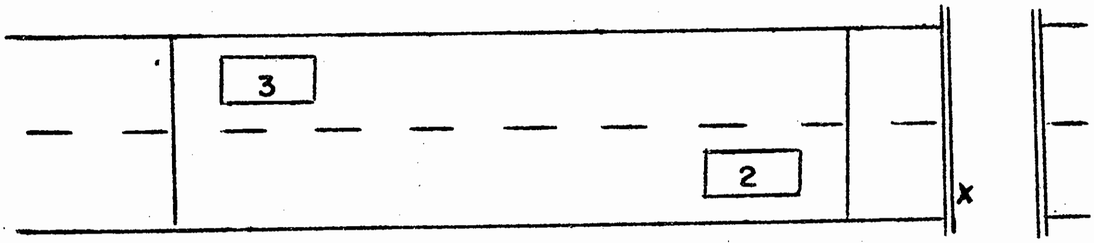


FIG 9 DOUBLE LOADING RECORDED FOR WHOLE ROADWAY

column of LANE 2. This indicated a double loading for the whole roadway but not for any one lane. The second truck was involved in two loadings and when the loadings are summed a single asterisk is placed by its axle number because the truck is double counted in the MULTIPLE LOADINGS column (Figure 5).

As a result of a preliminary analysis, which will be discussed later, additional data were collected during the spring of 1972. Data for three lengths (150, 250, and 350-ft.) were collected simultaneously at each highway location. All three lengths had the same downstream end and the longer lengths included the shorter ones (Figure 10). Simultaneous observations eliminated any variations among the three bridge lengths that could be caused if each length were observed at a different time. All traffic conditions were identical for the three lengths studied.

Additional Highway Locations Studied

In addition to the original three highways (Ct. 5, I-91-N and I-91-S), two additional sites were included in the study: I-86-W and I-91-H. Figures 10 and 11 are diagrams of the two sites. The I-86-W site is located on the two Westbound lanes of Interstate 86 at the Conn. Route 89 overpass. Except for the exit downstream from the overpass, at which few vehicles exited, the site is identical physically to the I-91-N location. However, the volumes on I-86-W were lower than those on the other Interstate highways observed. Data from this site increased the range of truck volumes recorded on the Interstate facilities.

The I-91-H site is located at the Harrison Road overpass near North Haven. It is a few miles South of the I-91-S location but is on the North-

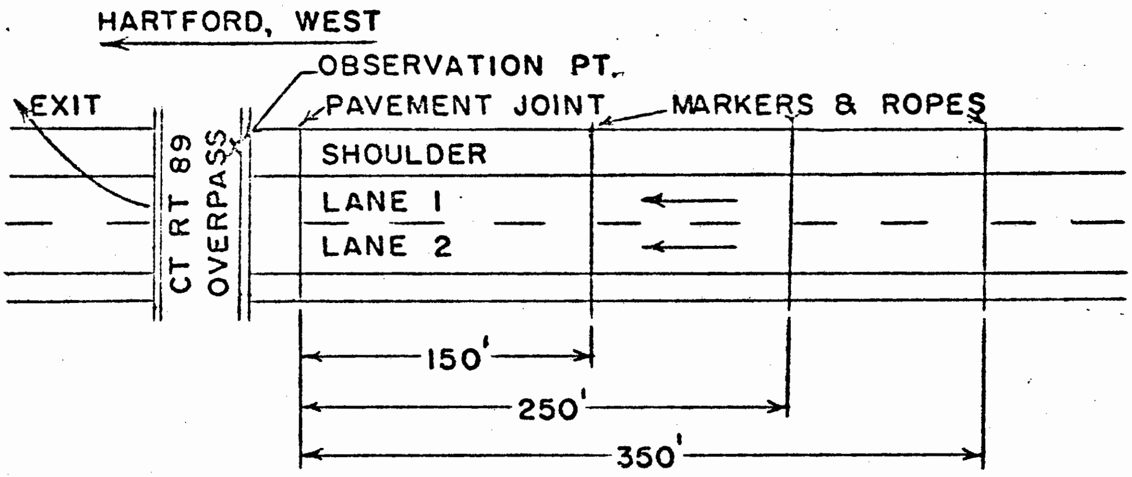


FIG 10 I-86-W STUDY SECTION

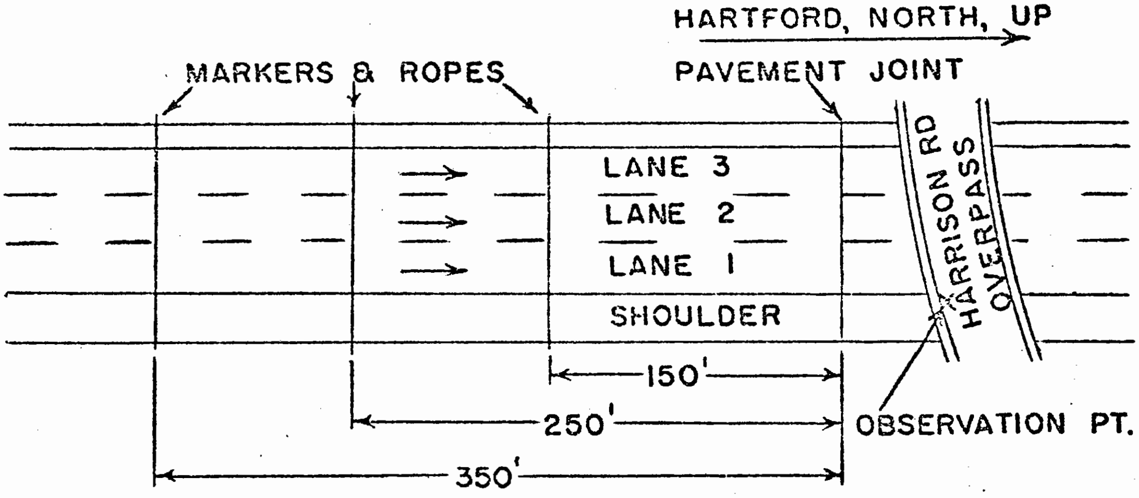


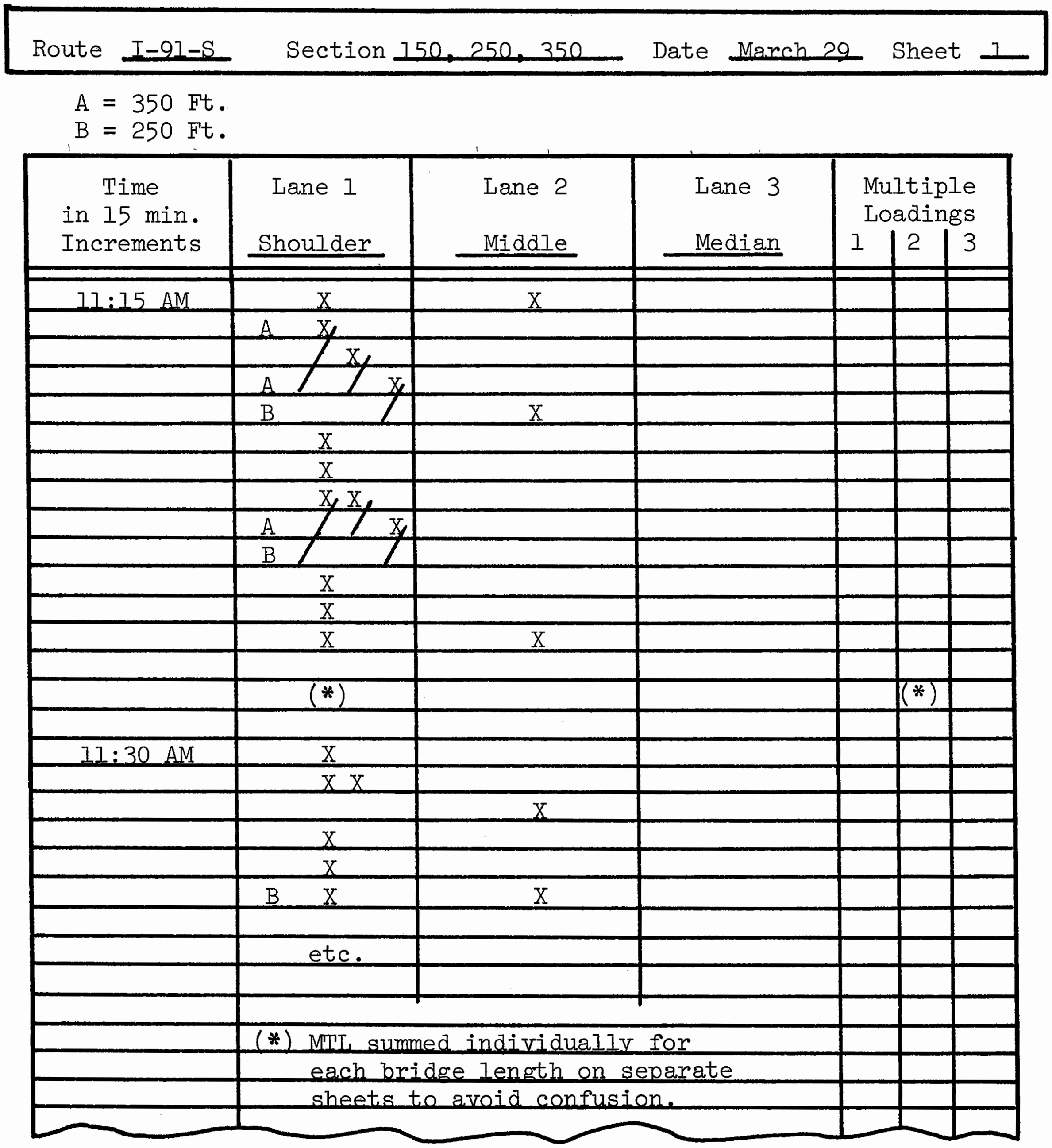
FIG 11 I-91-H STUDY SECTION

bound three lanes. The site is physically identical to I-91-S except for one feature: I-91-H is on a long moderate uphill grade.

The procedure for the spring data collection was different than that of the fall. Neither the traffic volume counters nor the radar meter were used. All the data were collected during midday, during fair weather and with no traffic restrictions. The downstream end of the three bridge lengths was the same as in the fall, the first pavement joint visible from the overpass. The three upstream ends were all delineated by a marker at the roadside and a rope stretched across the pavement. All three lengths could be monitored simultaneously by an observer stationed on the overpass. Except for a few periods of congested truck traffic, one observer was able to manage the recording process. After becoming familiarized with the setup, the observer could tell at a glance what loading situations existed by recognizing the last rope crossed by the trailing truck before the lead truck crossed the base line at the pavement joint.

The data sheet used to record the information is shown in Figure 12. It appears to be simpler than the earlier data sheet but a coding system was also used and the actual recording of the data was more complex in order to note the loading situations of three bridge lengths with a minimum of confusion.

The time column is the same as the one on the fall data sheet, recording the time of day in 15-minute increments. Because traffic count adjustments were not required, a truck could be indicated by an "x" rather than an axle number. As before, each horizontal line represents a separate loading situation. Slash marks are used to indicate individual trucks



Route I-91-S Section 150, 250, 350 Date March 29 Sheet 1

A = 350 Ft.
B = 250 Ft.

Time in 15 min. Increments	Lane 1 Shoulder	Lane 2 Middle	Lane 3 Median	Multiple Loadings 1	2	3
11:15 AM	X	X				
	A X					
	X					
	A X					
	B	X				
	X					
	X					
	X X					
	A X					
	B					
	X					
	X					
	X	X				
	(*)				(*)	
11:30 AM	X					
	X X					
		X				
	X					
	X					
	B X	X				
	etc.					

(*) MTL summed individually for each bridge length on separate sheets to avoid confusion.

FIG 12 SPRING DATA SHEET 2

involved in more than one multiple loading. Because three lengths are represented on one data sheet, the summations of the loadings were conducted separately for each length. To avoid confusion the summations are not included on the data sheet. To distinguish the loadings of one length from the others, a code was used. If no letter is entered on the line, it indicates that the loading took place entirely within the limits of the 150-foot length. These loadings occur for all three lengths since the 350- and 250-foot lengths both include the 150-foot length. Ia a "B" is entered on the same line as a double loading it means that the loading occurred outside the 150-foot limits but within the limits of the 250-foot section. These loadings are summed for both the 250- and 350-foot lengths. The entry of an "A" means that a multiple loading occurred within the 350-foot limits only and is included only in the 350-foot summation.

Because three lengths were being observed, some individual trucks were involved in different multiple loadings on two or three lengths. This occurred when there was a triple loading on either the 350- or 250-foot length.

For instance, the first two trucks of three trucks involved in a triple loading on the 350-foot length might also be involved in a double loading on the 150-foot length while the last two could also be involved in a double loading, perhaps on the 250-foot lengths. To make matters more complicated, a fourth truck and the last truck of the triple loading could create another double loading on the 350-foot lengths. Although this may seem too much for one observer to handle, the loadings did not occur instantaneously and the observer could usually anticipate what loading would take place.

Overall the data collection procedure functioned well with only a few minor problems. Information was obtained for over 1,600 trucks, in five groups on five highways. This is much less than the 5,000 trucks observed during the fall but during the spring each truck was actually observed three times, once for each bridge length.

IV

PRELIMINARY ANALYSIS OF DATA

A preliminary analysis was conducted to determine any relationships that might be obvious from a visual inspection. The results of this analysis were used to identify data deficiencies and modify data collection techniques as required. Statistical tests were conducted after all data collection was completed.

Highways

All three highways exhibited different frequency of MTL for the same bridge lengths. This was to be expected since the variables changed among the roads. One similarity, though, among all the roads, was the percentage of trucks involved in MTL. For each bridge length the percentage of trucks involved in MTL did not vary much from one road to the next, but different volumes of trucks resulted in different frequencies of MTL. Because Ct. 5 was different from the Interstates with respect to several other factors such as geometry, access control, number of lanes, operating speed, traffic controls, total volume and truck volume, it was analyzed separately from the other facilities.

The Interstate routes I-91-N and I-91-S have several factors in common; geometry, access control, operating speeds and traffic controls. They differ with respect to number of lanes, total volume and truck volume. The number of lanes may not be a significant factor when considering truck traffic alone because on I-91-S, a six-lane facility, the trucks obey the law by not traveling in the third (median) lane. When observing the roadway as a whole, the trucks are confined to two lanes on both facilities. The distribution of trucks between the lanes is approximately the same. On I-91-N, 85.2 per cent of the trucks traveled in the shoulder lane as opposed to 32.6 per cent on I-91-S. The main difference remaining between I-91-N and I-91-S are the traffic patterns. For this study the two Interstate Highways are treated as the same type of facility but with different traffic patterns.

Bridge Lengths

A visual inspection of the fall data revealed that longer bridge lengths produced more MTL than shorter ones, as would be expected. However, two factors worked together to interfere with the determination of the differences in MTL among the various bridge lengths. These factors were lack of sufficient data and lack of control over changes in other variables during different data collection sessions. The best example of this problem is illustrated by the data for the 350- and 400-foot lengths on I-91-N. For six 15-minute counting periods there were 42 MTL on the 350-foot length involving 37.7 per cent of all trucks while on the 400-foot length there were 31 MTL involving 31.1 per cent of all trucks for six counting periods but at a different time period. It was not possible to explain the differences between these two lengths or any other pair of lengths with the fall data. Either greater control over the variables or additional data might reduce or eliminate the problem. It was decided that additional data would be collected and that all the variables except bridge length would be controlled on each highway. To accomplish this additional degree of control, it was necessary to reduce the number of lengths studied.

Time of Day

Collecting data for the variable "time of day" was for the most part unsuccessful in the fall study. Equipment failures and winter weather conditions made it impossible to obtain meaningful amounts of data. The only factors that can change at different times of day are the traffic characteristics. The greatest observed changes were in total volume and truck volume. Average truck speeds, the lane distribution of trucks and the percentage of trucks involved in multiple loadings did not vary much at the different times. The main effect that different times of day have in relation to MTL is to alter the variables total volume and truck volume. Since these variables are treated separately in this study, there is no need to analyze them further under the heading of "time of day". On this basis it was decided that the model would not suffer from the elimination of the variable "time of day". Therefore, this variable was not included in the spring study.

Total Traffic Volume

In organizing the original program of data collection it was hoped that the data would contain a range of traffic volumes. For practical reasons six 15-minute counting periods were run consecutively for each length. This usually produced only small changes in the total traffic volumes among the counting periods. On a few occasions larger volume changes were recorded and for one length in particular, 150-feet on I-91-N, the volume varied more than 250 per cent.

The evidence brought out by examining this one study length verifies the relationship suspected in the rest of the data; that is, changes in total traffic volume have little effect on the frequency of MTL. Close inspection of the data for any bridge length on any highway failed to suggest that a pattern existed between the changes of total traffic volume and MTL. Repeatedly the number of MTL changed in a manner inconsistent with any changes in traffic volume, even when the traffic volume varied greatly.

The data for the 150-foot section on I-91-N indicated that even large volume changes may not alter the frequency of MTL. Data for ten counting periods were obtained for this section. For six consecutive 15-minute counts the following averages were obtained: 253 vehicles/15-minutes, including 35 trucks/15-minutes, 2.7 MTL/15-minutes, 15.2 per cent of trucks involved in MTL. For four other consecutive 15-minute counts, the corresponding averages were: 693 vehicles/15-minutes including 27 trucks/15-minutes, 2.5 MTL/15-minutes, 18.3 per cent of trucks involved in MTL.

Total vehicles in the latter group averaged 274 per cent of the former group, but truck volume dropped as did multiple loadings to a lesser degree, which the percentage of trucks involved in multiple loadings increased by 3.1 per cent. If total traffic volume were an important factor, such a large change of volume would have had a greater effect on the number of MTL than that which was observed. The 3.1 per cent change in trucks involved in multiple loadings might be due to chance alone. Even if it is not random, the 3.1 per cent is small and may not be of any consequence. No consistant relationships between total traffic volume and other variables were evident among the ten counting periods.

Truck Speed

The variations in average truck speeds among 15-minute counts of a group of consecutive counts were usually less than 5 miles per hour. Even in those cases where the variations were greater there was no correlation between truck speed and either truck volume or the number of multiple loadings. The data from one representative study section illustrate that truck speed is not an important factor in the determination of the frequency of MTL.

A total of 12 counting periods were conducted for the 100 ft. section on I-91-S. The data are divided into two groups of six periods each. One group, I-91-S, was obtained at a location with a level grade. The other group, I-91-S(a), was obtained at a site not far from I-91-S, but on a downhill grade. It can be assumed that, except for the grade and a higher total volume at the downhill site, conditions were the same at both sites. Not surprisingly, the truck speeds at the downhill location averaged higher than at the level site. The downhill trucks averaged between 59.2 and 60.9 miles per hour while the trucks on the level grade averaged between 53.4 and 57.1 miles per hour. The truck loading conditions of the 100 ft. sections were similar at both sites. At the downhill location there was an average of 53 trucks/15-minutes and 3 MTL/15-minutes, involving 12 per cent of the trucks. At the level site there was an average of 45 trucks/15-minutes, 3.2 MTL/15-minutes, involving 14.4 per cent of the trucks. It would appear that there are less MTL on the faster downhill, but the difference is so small that it does not seem important.

The downhill location provides an ideal opportunity for trucks to increase their speed, and indeed, truck speeds in excess of 70 miles per hour were observed. However, the majority of trucks increased their speed only moderately. The conclusion drawn from this finding and the bulk of the Interstate data is that truck speeds average in the mid 50's on level ground and increase four or five miles per hour on moderate downhill grades. These changes in truck speeds are not sufficient to significantly affect the frequency of MTL (the level of significance is presented in the final analysis). If speed increases do not affect the MTL on a downhill grade they are not likely to do so on level grount. If this is true, it is postulated that speed fluctuations anywhere on a particular Interstate route do not affect the frequency of MTL.

Truck Volume

As with the total traffic, the range of truck volumes was dependent on the variations that occurred during each group of six counting periods for each bridge length. The truck volumes were relatively constant on each highway limiting the changes in MTL that could occur in six 15-minute periods. Nevertheless, fluctuations were recorded. A general inspection of all the data indicated that changes in truck volume did affect the frequency of MTL; the greater the truck volume, the greater the number of MTL. This relationship is most apparent for the larger volume changes, 15 or more trucks/15-minutes and for the longer lengths. However, further data were needed encompassing a wider range of truck volumes.

Summary of Preliminary Analysis

When the study began it was not known what would be derived from the data collection. By the end of the fall data collection over 5,000 trucks had been observed during 151 15-minute periods, divided into 27 groups for three highways. This was insufficient to build a model, but inspection of the processed data began to uncover some of the relationships that existed. Based on these examinations decisions were made as to which variables were considered important, what additional data were needed and what would be a feasible course of action.

It was not feasible to develop a model for three different types of highways as originally intended. There was little variation in truck volume among the highways studied. Data were still collected on Ct. Rte. 5, but the emphasis was on the Interstates, treated as one type of facility.

The number of bridge lengths studied were reduced in order to lessen the time involved in collecting additional data and to allow more control over variables other than bridge length. The difference in the frequency of MTL between adjacent bridge lengths was small and masked by irreducible error because each bridge length had been observed at a different time.

The analysis indicated that the variable "time of day" was not a vital factor, it was eliminated from further study.

Much data were collected pertaining to total traffic volume and truck speed. Nowhere in these data could there be found a relationship between changes in these variables and changes in the number of MTL. Therefore, no additional data on total traffic volume and truck speed were collected and the variables were not used in the final model.

Truck volume emerged as the most important factor in determining the frequency of MTL for any bridge length on any highway. It was clear that increasing the truck volume increased the number of MTL. The range of truck volumes was small and more data were required to enlarge it. In further data collection, the emphasis was placed on the Interstate system since it offered more available sites suitable for data collection at different levels of truck volume.

The fall data and the preliminary analysis eliminated several variables from consideration. These variables are: time of day, total traffic volume, and truck speeds. The important variables remaining are: type of highway, bridge length, and truck volume. Additional data of a more detailed nature were required to determine the relationships needed to develop the model.

V

STATISTICAL ANALYSIS OF DATA

The objective of this analysis was to verify the findings of the preliminary analysis and to determine the significance of the individual variables in relation to the frequency of MTL. Both the fall and spring data were used in the analysis. Statistical testing was conducted to determine the significance of the variables. The method used was the Chi Square test.

Chi Square Test

The Chi Square test (X^2) was used exclusively in this study because the data were ideally suited for analysis by X^2. The X^2 test is used to determine if observed frequencies are significantly different from the frequencies that were expected to occur based on previous knowledge or assumptions made about the variables being studied. (2) The test is best suited to deal with frequencies only and not with variables that have specific units such as feet or miles per hour. The factor being tested in this study was the frequency of multiple truck loadings on bridges for varying conditions.

The basic assumption of the X^2 test is the <u>null hypothesis</u>. The hypothesis states that the two frequencies being compared, the observed and the expected, are drawn from the same population, and the only difference that might exist between the observed and exprected frequencies is caused by chance alone. The test calculates the probability that the difference that exists between the observed and expected frequencies is due only to chance. As this probability increases, approaching unity or 100 per cent, the two test frequencies are more likely to belong to the same population. As the probability decreases, approaching 0 per cent, the test frequencies are more likely to represent separate populations. For this study a probability of 0.05, five per cent or less, was considered to indicate a significant difference between the observed and expected frequencies of MTL being tested.

The most important step in the X^2 test is determining the expected value. There was no previous knowledge about the frequencies of MTL that could be used to obtain expected values for the tests. Instead, the expected values had to be derived from the data itself. A description of a typical test will explain how the expected values were determined.

By the null hypothesis it was assumed that variations in truck volume would not cause changes in the frequency of MTL. To test the hypothesis the data for the test were evenly divided into two groups, one containing high truck volumes and the other low truck volumes. The data for the two groups were divided in such a manner that no other variables except truck volume could cause a change in the frequency of MTL between the groups. Since each group contained half of the data being tested, it was assumed that each group should contain half of the total number of MTL that occurred. Any variations should be caused by chance alone. The expected value for this test is simply the average of the sum of the MTL for both groups. Throughout the analysis, similar weighted averages were used to represent the expected values. To perform the actual test, the appropriate values were inserted into the following equation: $X^2 = \frac{(O-E)^2}{E}$

Where O = observed frequency, E = expected frequency, and X^2 = calculated X^2.

For the test described above the equation would be:

$$X^2 = \frac{(O\ \text{high} - E\ \text{high})^2}{E\ \text{high}} + \frac{(O\ \text{low} - E\ \text{low})^2}{E\ \text{low}}$$

In this case E high and E low have the same value but they need not be equal in other designs.

The calculated value of X^2 is compared to a tabulated value of X^2 with the appropriate desgrees of freedom. For this study the number of degrees of freedom equals the number of observed frequencies minus one: $V = (n-1)$. In the example test there are two observed frequencies, O high and O low. The number of degrees of freedom is: $V = 2 - 1 = 1$.

The level of significance determined from the test is obtained from tabulated values. For every tabulated level of significance there is an associated tabulated X^2 value. The largest tabulated X^2 value that is less than the calculated X^2 value determines the level of significance for a particular test.

For the tests which involved only one degree of freedom a correction factor had to be used because the test values were not continuous functions. The correction was the addition of one-half (0.5) to the observed frequencies below the expected value, and the subtraction of one-half from the observed frequencies greater than the expected value. The correction results in a lower value for the calculated X^2 and indicates less difference among the test frequencies than if no correction were used. For this study, the

Table 1

X^2 Highways

150 Feet

Routes Being Compared 1	Routes Being Compared 2	Multiple Loadings 1	Multiple Loadings 2	X^2 Calculated	$X^{2(1)}$ Tabulated	Level of Significance %
Ct. 5	86W	12	13	0	-	99
Ct. 5	91N	12	24	3.36	2.71	10
Ct. 5	91S	12	43	16.35	10.83	0.1
Ct. 5	91H	12	41	14.81	10.83	0.1
86W	91N	13	24	2.70	2.71	≈ 10
86W	91S	13	43	15.00	10.83	0.1
86W	91H	13	41	13.54	10.83	0.1
91N	91S	24	43	4.84	3.84	5
91N	91H	24	41	3.94	3.84	5
91S	91H	43	41	0.01	.004	95

250 Feet

Routes Being Compared 1	Routes Being Compared 2	Multiple Loadings 1	Multiple Loadings 2	X^2 Calculated	$X^{2(1)}$ Tabulated	Level of Significance %
Ct. 5	86W	27	25	.016	.016	90
Ct. 5	91N	27	48	5.33	3.84	5
Ct. 5	91S	27	72	19.55	10.83	0.1
Ct. 5	91H	27	63	13.63	10.83	0.1
86W	91N	25	48	6.63	6.64	≈ 1
86W	91S	25	72	21.80	10.83	0.1
86W	91H	25	63	15.57	10.83	0.1
91N	91S	48	72	4.42	3.84	5
91N	91H	48	63	1.77	1.64	20
91S	91H	72	63	0.47	0.46	50

350 Feet

Routes Being Compared 1	Routes Being Compared 2	Multiple Loadings 1	Multiple Loadings 2	X^2 Calculated	$X^{2(1)}$ Tabulated	Level of Significance %
Ct. 5	86W	30	33	.064	.064	80
Ct. 5	91N	30	64	11.58	10.83	0.1
Ct. 5	91S	30	92	30.50	10.83	0.1
Ct. 5	91H	30	84	24.70	10.83	0.1
86W	91N	33	64	9.28	6.64	1
86W	91S	33	92	26.90	10.83	0.1
86W	91H	33	84	21.40	10.83	0.1
91N	91S	64	92	4.68	3.84	5
91N	91S	64	84	2.44	1.64	20
91S	91H	92	84	0.28	0.15	70

correction was conservative since significant differences were being sought. Each X^2 test is discussed separately below.

Test for Highways

The spring data were used in a series of X^2 tests to determine if the frequency of MTL differed significantly among the five highways studies. The tests are not meant to determine which individual variables affect the frequency of MTL. Rather, all the characteristics on one roadway combined, physical features and truck traffic patterns, are compared to the combined characteristics of the other roads to find any differences in MTL that result. The tests can indicate which roads are similar and which are different with respect to MTL but they cannot explain why. It is not known what combination of different features causes a change of MTL.

The X^2 test was conducted for all possible pairs of highways for each of the three bridge lengths of the spring data. The results of the tests are presented in Table 1. Generally, the number of MTL was different among the highways studied.

Two highways, Ct. 5 and I-86-W, had approximately the same frequency of MTL for 150- and 250-foot test sections. This was in spite of the fact that the two facilities had little in common with regard to physical features and truck traffic.

No model has been developed for the two-lane two-way undivided highway represented by Ct. 5 because the data from the one site provided a very narrow range of truck volumes, 14 to 26 trucks/15-minutes. However, the information that has been obtained can still be of some benefit. Since the frequency of MTL on Ct. 5 was very similar to that on I-86-W for 150-feet and 250-feet the portion of the model representing the I-86-W conditions can be used to approximate the frequency of MTL on facilities similar to Ct. 5. This is a rough approximation but with no other means of approximating MTL, even a rough approximation is better than none.

However, the test between Ct. 5 and I-86-W for 350-feet resulted in an 80 per cent level of significance. The 80 per cent level indicates neither close similarity nor distinct difference. In the 350-foot test more MTL were included than in the other two lengths. This suggests that if more data were available for 150 feet and 250 feet, the two roads might not appear as similar as they do with the actual data. This means that any use of the approximation described above should be done with caution, as it cannot be certain without further data that the approximation is a completely valid one.

Two other roads also exhibited similarities with respect to the frequency of MTL, I-91-S and I-91-H. The X^2 levels of significance were different for the three bridge lengths suggesting that there were insufficient data to estimate the true differences between the roads. The two highways were identical except for two factors: I-91-H had an uphill grade and fewer trucks than I-91-S, 397 trucks on I-91-H as opposed to 438 on I-91-S. It is believed that the uphill grade increased the frequency of MTL over that found at a level grade, while the smaller truck volume decreased the frequency of MTL. The affect of truck volume was presented earlier and will be proven later. The function that truck volume served in comparison of I-91-S and I-91-H was to mask the affects of an uphill grade. With both the truck volume and the grade varying any difference in MTL cannot be attributed to either one factor. In this comparison the two factors cancelled each other out.

There was another factor that could be used to indicate a difference in the frequency of MTL between the two highways: the percentage of trucks involved in MTL from Table 11 in the appendix. The percentage of trucks involved in MTL for I-91-S and I-91-H respectively were: 150-feet - 17.4 per cent and 20.9 per cent, 250-feet - 29.5 per cent and 31.5 per cent, and 350-feet - 38.8 per cent and 41.3 per cent. The percentages did not differ by more than 3.5 per cent but I-91-H consistently had the higher involvement rate. If 30 per cent of all trucks were involved in MTL, an increase in the involvement rate of 3 per cent of all trucks would be a 10 per cent increase of just the trucks involved in MTL. A small increase in the involvement rate would cause a greater increase in the frequency of MTL. This indicates that an uphill grade increases the frequency of MTL. But because only one uphill site was observed and the truck volumes were not the same for the two sites compared, there was insufficient data to determine the magnitude of the affect uphill grades have on the frequency of MTL. Grade has not been incorporated into the model but it is known that uphill grade increases the frequency of MTL.

The spring data consisted of simultaneous multiple truck loading frequencies for bridge lengths of 150-, 250-, and 350-feet at five different highway locations. Because all three lengths were observed at the same time, variations of truck volume, truck speeds and truck lane distribution were nonexistent. The only differences among the three observations were the bridge lengths.

A series of X^2 tests were conducted to find if each bridge length had significantly different frequency of MTL. The tests were run for each road individually. In the first test, 150-feet was compared to 250-feet. The results are presented in Table 2. There was a difference between the frequency of MTL at the five per cent level of significance or below on all the highways except I-86-W, which was significant at the 10 per cent level. The suspected reason for the 10 per cent level of significance was the small sample size. To determine if the size of the sample was the problem, the I-86-W data were combined with the Ct. 5 data and then with the I-91-H data. These two roads had the next highest percentage levels, with five per cent the cutoff value. If sample size were not the problem, the significance level of the combined data would have to be greater than five per cent. The data from I-91-N and I-91-S were not combined with the I-86-W data since they had more MTL, and a one per cent level of significance which could overshadow the I-86-W data and bring the combined significance below five per cent regardless of the reason for the ten per cent value on I-86-W.

To pool the data of different roads the sums of the MTL for the ten counting periods of 150-feet were added to the same sum from the other road. The same combination was made for 250-feet. Since only bridge lengths were being tested, pooling the data from different roads in this manner did not invalidate the X^2 test. Both of the test members contained the same amount of data from the different roads. Data from roads with different characteristics were combined, but whatever different affects these characteristics had were included in both the 150-foot test section and the 250-foot test section and since both were observed simultaneously, the affects of the different roads were self-canceling. That is, on each road, whatever affected 150-feet MTL also affected 250-feet MTL.

Table 2

X^2 Bridge Lengths

Road	Multiple Truck Loadings 150 Ft. Length	250 Ft. Length	X^2 Calculated	X^2 Tabulated	Level of Significance %
Ct. 5	12	27	5.02	3.84	5
86W	13	25	3.18	2.71	10
91N	24	48	7.36	6.64	1
91S	43	72	6.82	6.64	1
91H	41	63	4.24	3.84	5
Ct. 5-86W	25	52	8.79	6.64	1
86W-91H	54	88	7.67	6.64	1

Both of the X^2 tests on the pooled date of I-86-W and Ct. 5, and I-86-W and I-91-H resulted in a significance level of one per cent, well below the significance level on any of the individual roads. This verified the suspicion that the small sample size was the reason for the high percentage levels. The conclusion drawn from these tests was that the 150-foot bridge length has been proven to have a significantly lower frequency of MTL than the 250-foot bridge length on four of the five test sites. No difference was observed for I-86-W because of the small sample size, but tests of pooled data indicate that on I-86-W also, 150-feet has significantly fewer MTL than 250-feet.

A second series of tests were conducted comparing 250-feet to 350-feet. The results of these tests and the other combinations of lengths examined are presented in Table 3. No significant difference was found on any of the five highways individually. To find if sample size was the reason for the high percentage values, tests on pooled data were again conducted. The data were pooled as they were for the 150- and 250-foot test described earlier. All possible combinations of two highways were tested but significant differences were found for only three pairs. All possible combinations of three highways were tested and significant differences were found for seven combinations. All possible combinations of four highways had to be tested before all the tests indicated a significance level of five per cent or below.

The conclusion derived from the tests was that the 350-foot bridge length overall has a significantly higher frequency of MTL than the 250-foot length. The difference between 250- and 350-feet was not as great as that

Table 3

X^2 250 feet vs. 350 feet

Routes from which data was combined	Multiple Loadings 250 feet	Multiple Loadings 350 feet	X^2 Calculated	X^2 Tabulated	Level of Significance %
Ct. 5-86W	52	63	0.87	0.46	50
Ct. 5-91N	75	94	1.91	1.64	20
Ct. 5-91S	99	122	2.19	1.64	20
Ct. 5-91H	90	114	2.59	1.64	20
86W-91N	73	97	3.11	2.71	10
86W-91S	97	125	3.28	2.71	10
86W-91H	88	117	3.82	2.71	10
91N-91S	120	156	4.44	3.84	5
91N-91H	111	148	5.01	3.84	5
91S-91H	135	176	5.15	3.84	5
Ct. 5-86W-91N	100	127	2.98	2.71	10
Ct. 5-86W-91S	124	155	3.24	2.71	10
Ct. 5-86W-91H	115	147	3.67	2.71	10
Ct. 5-91N-91S	147	186	4.33	3.84	5
Ct. 5-91N-91H	138	178	4.81	3.84	5
Ct. 5-91S-91H	162	206	5.03	3.84	5
86W-91N-91S	145	189	5.53	3.84	5
86W-91N-91H	136	181	6.12	3.84	5
86W-91S-91H	160	209	6.24	3.84	5
91N-91S-91H	183	240	7.41	6.64	1
Ct. 5-86W-91N-91S	172	219	5.41	3.84	5
Ct. 5-86W-91N-91H	163	211	5.92	3.84	5
Ct. 5-86W-91S-91H	187	239	6.11	3.84	5
Ct. 5-91N-91S-91H	210	270	7.25	6.64	1
86W-91N-91S-91H	208	273	8.49	6.64	1

between 150- and 250-feet as it took combinations of four roads before the significant difference would emerge between 250- and 350-feet while it took only two combinations of two highways to confirm the difference between 150-feet and 250-feet. Nothing specific about the difference between 250- and 350-feet can be stated for any one highway because the tests were dependent on the combined data of several highways. No testing was needed to confirm the difference in MTL between 150-feet and 350-feet since 150-feet had significantly fewer MTL than 250-feet, which had fewer MTL than 350-feet.

Based on the information obtained from these tests a model can be developed for three bridge lengths, 150-, 250-, and 350-feet. The frequency of MTL between all the lengths has been proven to be significantly different on the individual roads for 150- and 250-feet and on an overall basis for 250- and 350-feet.

X^2 Test for Total Traffic Volume

Preliminary analysis indicated that total traffic volume was not an important factor in the determination of the frequency of MTL. Because total traffic volume might be thought of as an important variable, the X^2 test was employed to determine if total traffic volume was statistically significant. The fall data were used for the X^2 tests and the results of the tests are presented in Table 4.

For each highway the total traffic volume data for all of the bridge lengths combined were divided into two groups: high and low volume. The data were divided in such a manner that an expected value could be calculated for the X^2 test. Of the three highways, only I-91-N indicated

Table 4

X^2 Total - Volume
High vs. Low

Routes from which data was combined	Multiple Loadings High Volume	Multiple Loadings Low Volume	X^2 Calculated	X^2 Tabulated	Level of Significance %
Ct. 5	50	41	0.70	0.45	50
91N	107	80	3.62	2.71	10
91S	119	117	0	-	99
Ct. 5 - 91N	157	121	4.42	3.84	5
Ct. 5 - 91S	169	158	0.31	0.15	70
91N - 91S	226	197	186	1.64	20
Ct. 5-91N-91S	276	238	2.26	2.71	≈ 10

that total volume might be influential. To determine if the sample size was the reason for failure of the X^2 test to detect a significant difference, the data of the different roads were pooled. The low volume groups from two highways at a time were combined and tested against the combined high volume groups. The combined data of Ct. 5 and I-91-N had a five per cent level of significance indicating high total volume resulted in a high frequency of MTL. The other two pairs had higher percentages. Combining all the low volume data and testing them against all the high volume data resulted in a ten per cent level of significance, above the five per cent cutoff.

The conclusion drawn from the tests is that total traffic volume is not a useful factor in the determination of the frequency of MTL. The high volume group always had more MTL than the low volume group but overall this was only an either per cent difference, based on over 500 MTL. This was too small an affect to be of value in a model covering a wide range of MTL frequencies. The ten per cent of significance of the X^2 test for all the data combined was well above the five per cent cutoff value.

X^2 Test for Truck Speed

It was decided in the preliminary analysis that truck speed was not an important variable in the determination of the frequency of MTL. Because of the amount of data available the X^2 test could be used to prove that truck speed was not a significant factor. The fall data were used for the tests and the results of the test are presented in Table 5.

The test was conducted very similarly to the X^2 test for total traffic volume. The data of each highway were divided into a high truck speed

Table 5

X^2 Speed
High vs. Low

Routes from which data was combined	Multiple High Speed	Loadings Low Speed	X^2 Calculated	X^2 Tabulated	Level of Significance %
Ct. 5	45	46	0	-	99
91N	87	100	0.77	0.46	50
91S	153	138	0.68	0.46	50
Ct. 5 - 91N	132	146	0.61	0.46	50
Ct. 5 - 91S	198	184	0.44	-	50
91N - 91S	240	238	0	-	99
Ct. 5-91N-91S	285	284	0	-	99

group and a low truck speed group. Even when the data of all three roads were pooled, no significant difference was found. On the contrary, with all the data combined, the high and low speed groups had identical numbers of MTL, 50 per cent of the total. It is obvious that speed variations at amy one highway location have no effect on the frequency of MTL. This was to be expected since the range of truck speeds at any highway location was very narrow.

X^2 Test for Truck Volume

Truck volume was singled out in the preliminary analysis as the most important variable in determining the frequency of MTL. Before a model could be built upon the variable, it would have to be statistically proven that it was a vital factor. The spring data were analyzed by the X^2 test to validate truck volume as an important factor. The results of the X^2 test are presented in Table 6.

The X^2 tests were performed separately for each of the three bridge lengths. The ten counting periods of each bridge length were divided into two equal groups, one with high truck volume and the other with low truck volume. The sum of the MTL from the low truck volume group was tested against the sum of MTL from the high truck volume group.

The data from I-91-S were the only data that were sufficient by themselves to show that different truck volumes affected the frequency of MTL. For all three bridge lengths the level of significance was one per cent or below indicating that higher truck volumes caused more MTL. The level of significance on the other highways varied from five per cent to 50 per cent and therefore nothing can be stated about the affects of truck volume on

Table 6

X^2 Truck Volume

	Bridge Lengths								
Road	150 Feet			250 Feet			350 Feet		
	X^2 Calc.	X^2 Tab.	Signif. Level %	X^2 Calc.	X^2 Tab.	Signif. Level %	X^2 Calc.	X^2 Tab.	Signif. Level %
Ct. 5	3.00	2.71	10	3.70	2.71	10	2.70	2.71	10
86W	0.308	.148	70	0.640	0.455	50	3.03	2.71	10
91N	3.38	1.64	10	6.03	3.84	5	2.64	1.64	20
91S	7.54	6.64	1	11.70	10.83	0.1	6.79	6.64	1
91H	1.42	1.07	30	2.29	1.64	20	4.88	3.84	5
Routes from which data was combined									
Ct. 5-86W	2.56	1.64	20	4.33	3.84	5	5.32	3.84	5
Ct. 5-91N	4.97	3.84	5	3.32	2.71	10	5.63	3.84	5
Ct. 5-91S	10.50	6.64	1	16.20	10.80	0.1	10.00	6.64	1
Ct. 5-91H	3.44	2.71	10	5.87	3.84	5	8.08	6.64	1
86W-91N	2.86	2.71	10	1.12	1.07	30	5.10	3.84	5
86W-91S	7.87	6.64	1	11.90	10.80	0.1	9.40	6.64	1
86W-91H	2.08	1.64	20	3.28	2.71	10	7.48	6.64	1
91N-91S	10.40	6.64	1	10.50	6.64	1	9.76	6.64	1
91N-91H	3.82	2.71	10	2.70	1.64	20	7.90	6.64	1
91S-91H	8.38	6.64	1	13.10	10.80	0.1	12.20	10.80	0.1
Ct. 5 - 86W-91N	5.46	3.84	5	4.29	3.84	5	10.5	6.64	1
Ct. 5 - 86W-91S	10.70	6.64	1	16.30	10.80	0.1	13.2	10.80	0.1
Ct. 5 - 86W-91H	4.13	3.84	5	6.82	6.64	1	11.3	10.80	0.1
Ct. 5 - 91N-91S	13.30	10.80	0.1	14.80	10.80	0.1	12.9	10.80	0.1
Ct. 5 - 91N-91H	6.12	3.84	5	5.98	3.84	5	11.0	10.80	0.1
Ct. 5 - 91S-91H	10.90	10.80	0.1	17.30	10.80	0.1	15.4	10.80	0.1
86W - 91N-91S	10.70	6.64	1	11.20	10.80	0.1	12.3	10.80	0.1
86W 91N-91H	4.51	3.84	5	3.68	2.71	10	10.4	6.64	1
86W 91S-91H	8.91	6.64	1	13.80	10.80	0.1	14.8	10.80	0.1
91N 91S-91H	11.20	10.80	0.1	12.70	10.80	0.1	15.1	10.80	0.1

any of these highways individually. Each X^2 test compared the MTL of five collection periods against the MTL of five other periods. This was a small amount of data for the test and the probable cause of the high percentages was sample size. This suspicion was supported by the fact that the only highway for which significant levels of five per cent or below were found for all lengths also had the most data. To determine if sample size were the reason for the insignificant results of the test, the data were pooled from different highways.

For each bridge length the low truck volume groups of two highways were combined and tested against the combined high truck volume data. As with similar pooling of earlier tests, combining data from roads with different characteristics does not affect the X^2 test because the characteristics are on both sides of the test and cancel out. The data of the different bridge lengths were not pooled as in some other tests because the bridge lengths were not observed independently during the spring data collection. All possible combinations of the data from two highways at a time were tested. This pooling gave much more significant results, indicating that truck volume changes affected the MTL at the five per cent level or below for the 350-foot length for all ten pairs of highways. Small sample size was the cause for the high percentages of the individual highway tests. As an example, I-86-W and I-91-N, when tested separately, had 20 per cent levels of significance, but when their data were combined the level of significance dropped to five per cent. Similar situations existed for the other pairs. For the 150- and 250-foot lengths, about half of the combinations of each were at five per cent or below. The reason not all the combinations were below five per cent is that 150- and 250-feet had fewer MTL than 350-feet and their data were still insufficient.

The data were further tested using the pooled data of all possible combinations of three highways at a time. This involved 30 individual X^2 tests, ten for each bridge length. Of the 30 resultant levels of significance only one was above five per cent - the combined data of I-86-W, I-91-N and I-91-H for 250-feet, at ten per cent. All the 350-feet tests were one per cent or below and except for the one case cited above, all the 150- and 250-feet tests were five per cent or below.

These X^2 tests proved that higher truck volumes increase the number of MTL. Because of insufficient amounts of data, this relationship was proved on only one individual highway, I-91-S, for all three bridge lengths. Truck volume was not proved influential to MTL on the other highways on an individual basis but pooling the data in all possible combinations of three highways at a time proved that truck volume was an important factor for all but one of the test situations. Clearly truck volume is the most important factor in determining the frequency of MTL for all bridge lengths on all highways. The specific relationship between truck volume and the MTL is developed later in this report in the section on the model.

Summary of Final Data Analysis

Five variables were analyzed by the X^2 test: highways, bridge length, total traffic volume, truck speed and truck volume. (Insufficient data were available to make a meaningful test for the variable time of day, which was eliminated.) The tests confirmed all the results of the preliminary analysis. No practical relationships were found between the frequency of MTL and either of the variables total volume or truck speed. Even when all the available data were pooled for use in one X^2 test, neither variable was found to be significant. Based on these results, total traffic volume and truck speed were eliminated from use in a model.

The analysis of the data from different highways made it apparent that a model could not be developed for three types of highways as originally intended. Such a project was beyond the available resources. To obtain a range of truck volumes and MTL on one type of highway, several similar highways with different truck volumes would have to be observed. This was done for the Interstate highways, represented by I-86-W, I-91-N, and I-91-S. There was only one observation site of the two-lane two-way undivided highway used - Ct. 5. No model was developed for this facility, but the frequency of MTL on Ct. 5 was determined by the X^2 test to be very similar to the frequency on I-86-W even though the characteristics of the two roads have little in common. The frequency of MTL on facilities with physical and truck traffic characteristics similar to those observed on Ct. 5 can be approximated by the part of the model developed from I-86-W data.

Grade was also studied in the highway section. The X^2 test found no significant difference in the frequency of MTL at the two sites which are identical except for grade and truck volume. Inspection of the date indicates that an uphill grade consistently causes more MTL than a lower grade. The model may be used to develop a correction factor for grade but such a factor would be developed from observations at only one site and there is no guarantee that it will apply to all sites with grades.

The frequency of MTL was found to be significantly different among the three bridge lengths 150-, 250-, and 350-feet. The difference between 150- and 250-feet was more pronounced than the difference between 250- and 350-feet. The former comparison took much less pooling of data to obtain a level of significance below five per cent than did the latter comparison. Nonetheless, a significant difference was found among all lengths on an overall basis. The model incorporated the three bridge lengths in its structure.

With total traffic volume, truck speed and time of day eliminated only truck volume remains as a significant factor in the determination of MTL. Truck volume was proven to be statistically significant as a predictor of MTL and is the independent variable used in the model.

VI

MODEL DEVELOPMENT

The curves selected for the model are the result of examining several types of curves by the method of linear regression. The independent variable (X) was truck volume in trucks per 15 minutes, and the dependent variable (Y) was the frequency of multiple truck loadings in MTL per 15 minutes. The spring data from three Interstate routes: I-86-W, I-91-N, and I-91-S were used for the curve fitting. The three highways are similar physically with respect to truck traffic when the roadway is observed as a whole. On a lane-by-lane basis, the three highways are different and this is recognized in the lane distribution tables which are discussed later. The three roads together provided a range of truck volume not obtainable at any one highway site. Data consisting of 1,100 truck observations were used to develop the model. The following frequency of MTL were recorded for these trucks: 150-feet - 80 MTL, 250-feet - 145 MTL, and 350-feet - 189 MTL. The data were reduced to 30 plotted points for each bridge length, representing the ten counting periods for each highway.

The first equation fit to the data was a straight line of the form $Y = a + bX$. This was performed for each bridge length with the following results:

$Y = 0.155X - 3.01$ For length of 150-feet

$Y = 0.240X - 3.88$ For length of 250-feet

$Y = 0.273X - 3.69$ For length of 350-feet

The original data points and the straight lines obtained by the analysis are presented in Figures 13, 14, and 15. All three equations showed correlation with the real data at the one per cent level of significance. The standard errors of estimate for the three equations were:

± 1.70 MTL/15 minutes For length of 150-feet

± 2.22 MTL/15 minutes For length of 250-feet

± 1.85 MTL/15 minutes For length of 350-feet

The shape of the plotted data points does not appear to be linear. All three straight lines intercept the X axis between 12 and 20 trucks/15 minutes. At low truck volumes, the straight line plots were too low to provide a good estimate of the frequency of MTL. Three curvilinear plots were devloped to find a better fit.

The relationship, $Y = aX^b$, was fit for two bridge lengths, 250- and 350-feet, before it was eliminated for use in the model. The equations developed were

$Y = 0.00832X^{1.71}$ For length = 250-feet

$Y = 0.0172X^{1.68}$ For length = 350-feet

Both curves appeared to be too low when compared to the plotted data and the straight line plot. The standard errors of estimate for the equations were:

$\pm$ 2.36 MTL/15 minutes For length = 250-feet

$\pm$ 2.42 MTL/15 minutes For length = 350-feet

It was decided not to use this form of equation.

The most complex equation fit to the data was $Y = a + bX + cX^2$. It was developed only for the 150-foot bridge length, and the resultant equation was $Y = 21.60 - 1.216X + 0.01732X^2$.

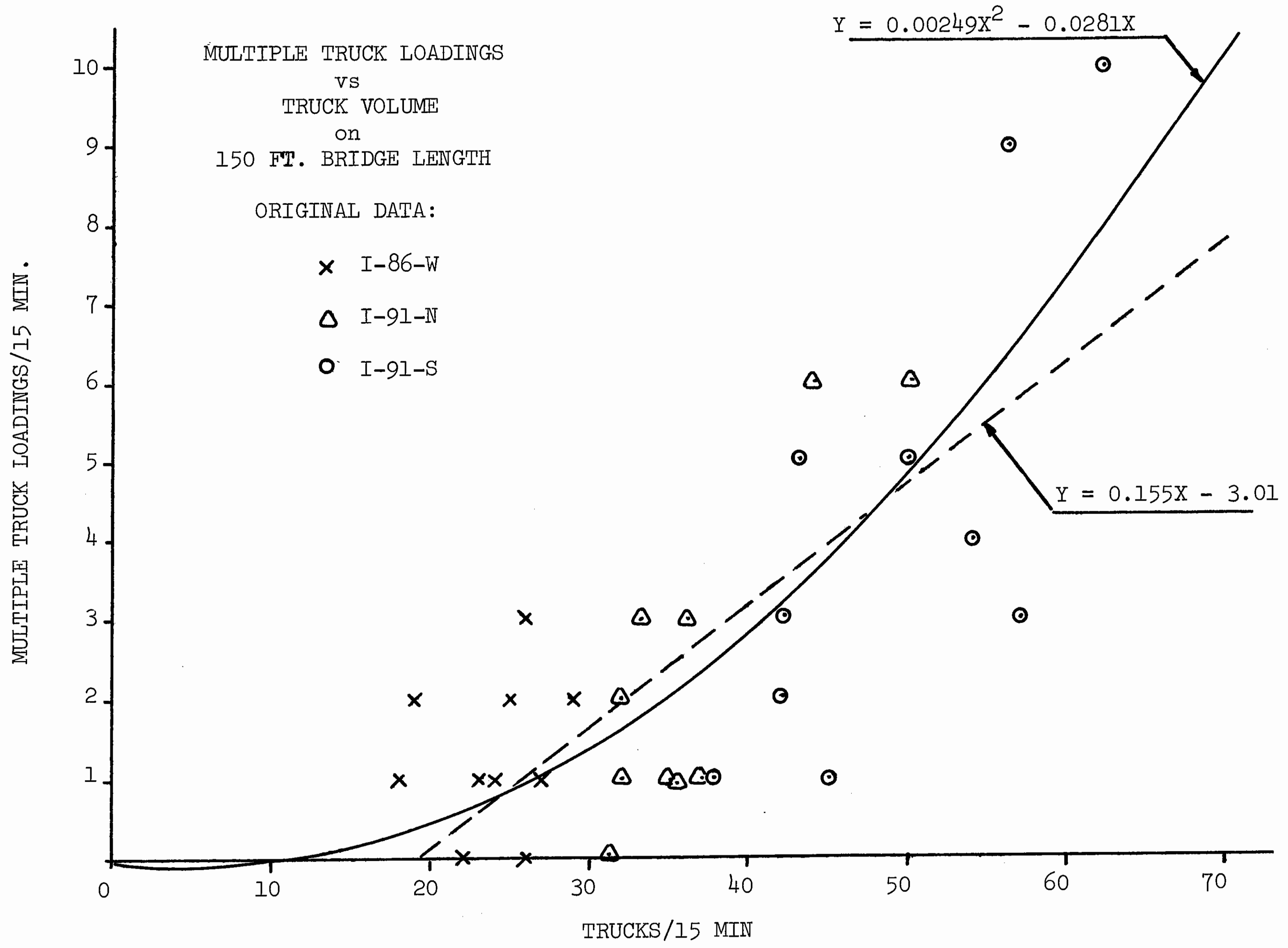


FIG 13 MTL VS TRUCK VOLUME AT 150 FT.

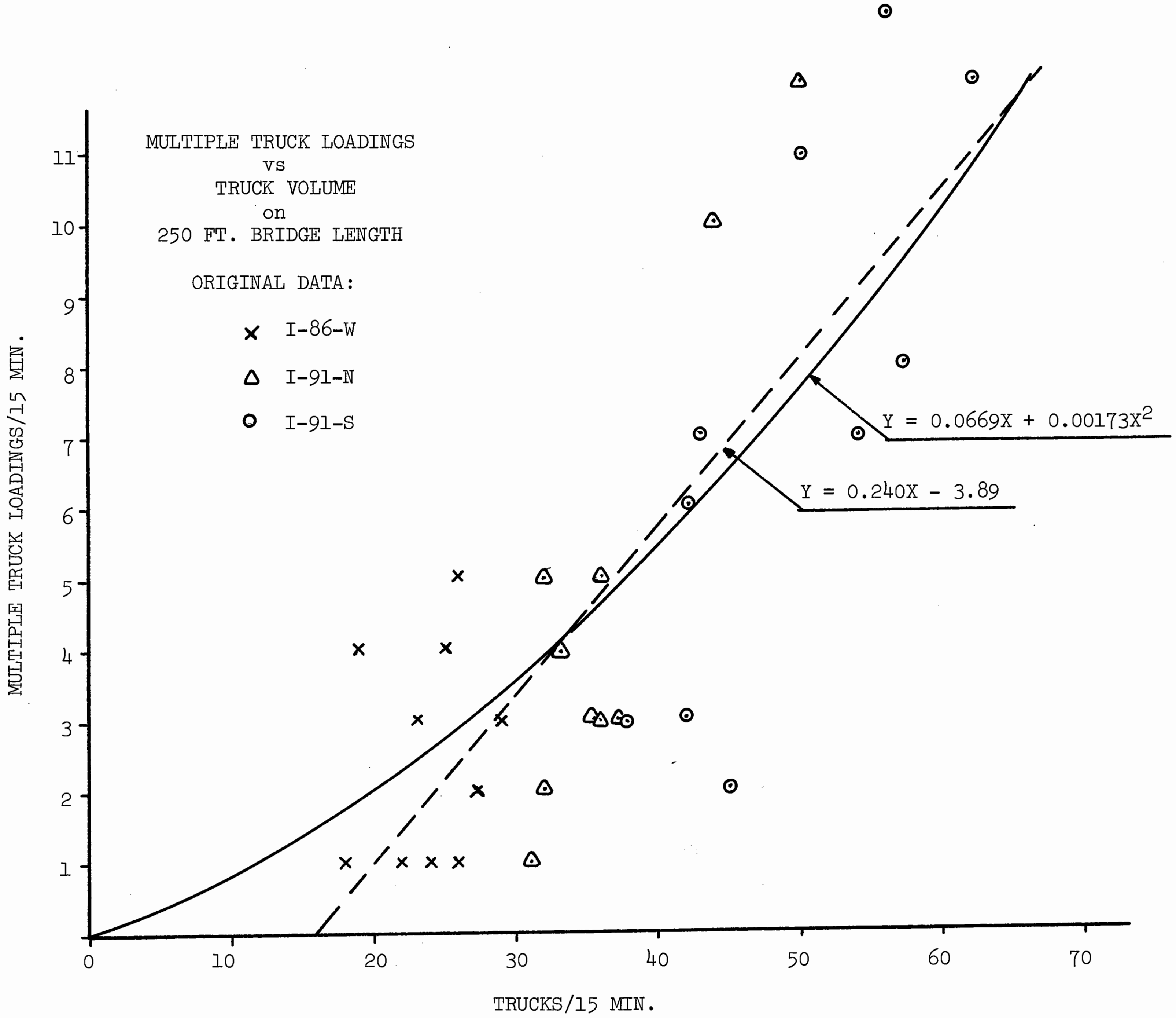


FIG 14 MTL VS TRUCK VOLUME AT 250 FT.

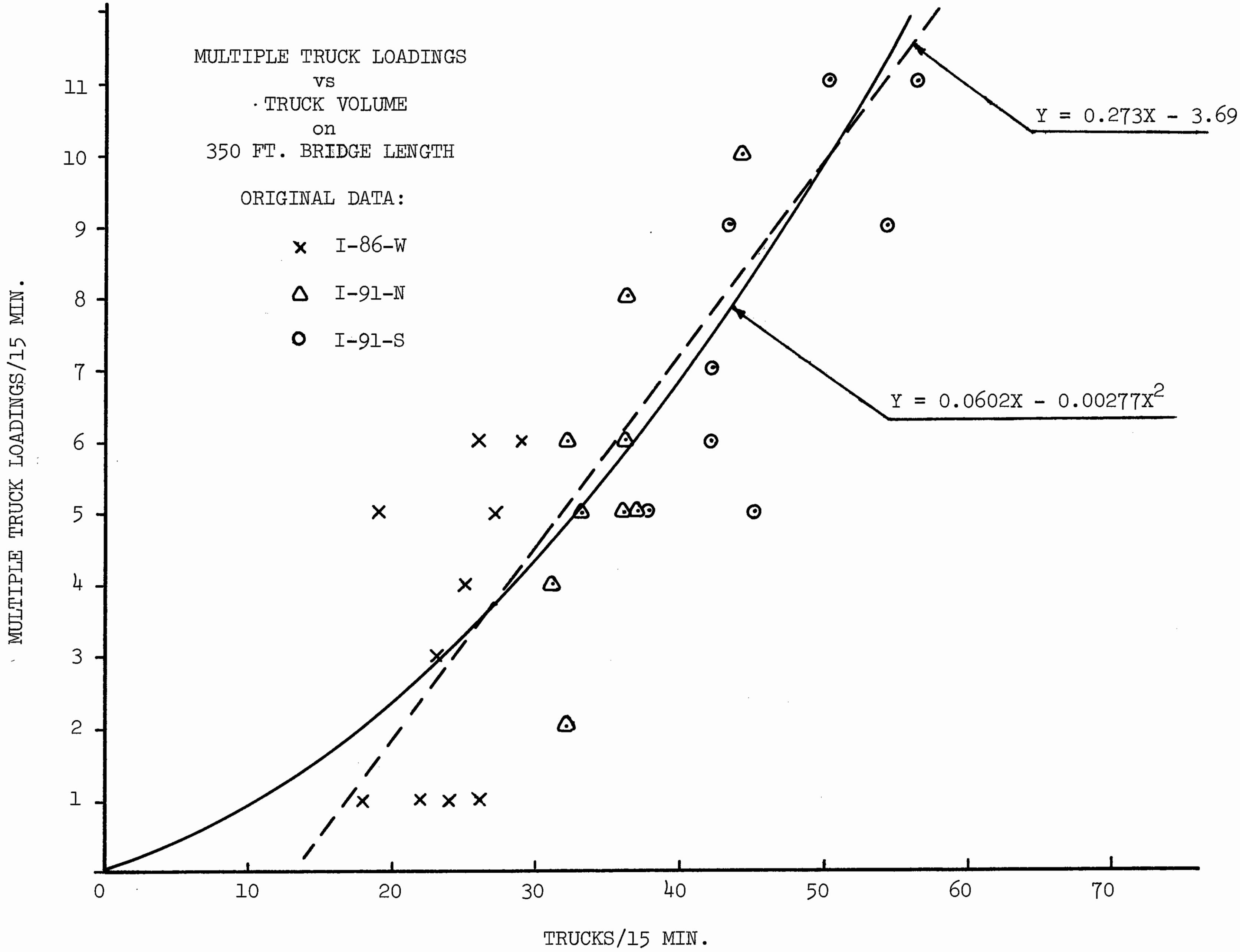


FIG 15 MTL VS TRUCK VOLUME AT 350 FT.

The curve fit the plotted data for high truck volumes but at low truck volumes the curve swung up indicating a high frequency of MTL, instead of going to the (0,0) point. Since this curve could not be used for the 150-foot length it was not developed for the other two lengths. The model was to consist of an equation for the three bridge lengths which were all of the same form.

The form $Y = aX + bX^2$ fit the plotted data for all three bridge lengths better than any of the others and on this basis it was chosen to represent the model. The three resultant equations are:

$Y = -0.0281X + 0.00249X^2$ For length = 150-feet

$Y = 0.0669X + 0.00173X^2$ For length = 250-feet

$Y = 0.0602X + 0.00277X^2$ For length = 350-feet

The curves are presented with the original data and the straight line in Figures 13, 14, and 15. The standard error of estimate for the curves were respectively:

$\pm$ 1.52 MTL/15-minutes

$\pm$ 2.13 MTL/15-minutes

$\pm$ 2.14 MTL/15-minutes

The curves fit the data well and pass through the obvious end point of (0,0). For the longer bridges the curves permit estimates of MTL frequencies at low truck volumes for which no data were collected. Negative frequencies on short spans have no significance. Clearly, these curves are the best choice for the model. A plot of the curves is presented in Figure 16. This family of curves represents the 4- and 6-lane divided highways. Two-lane two-way undivided highways can be approximated from the model

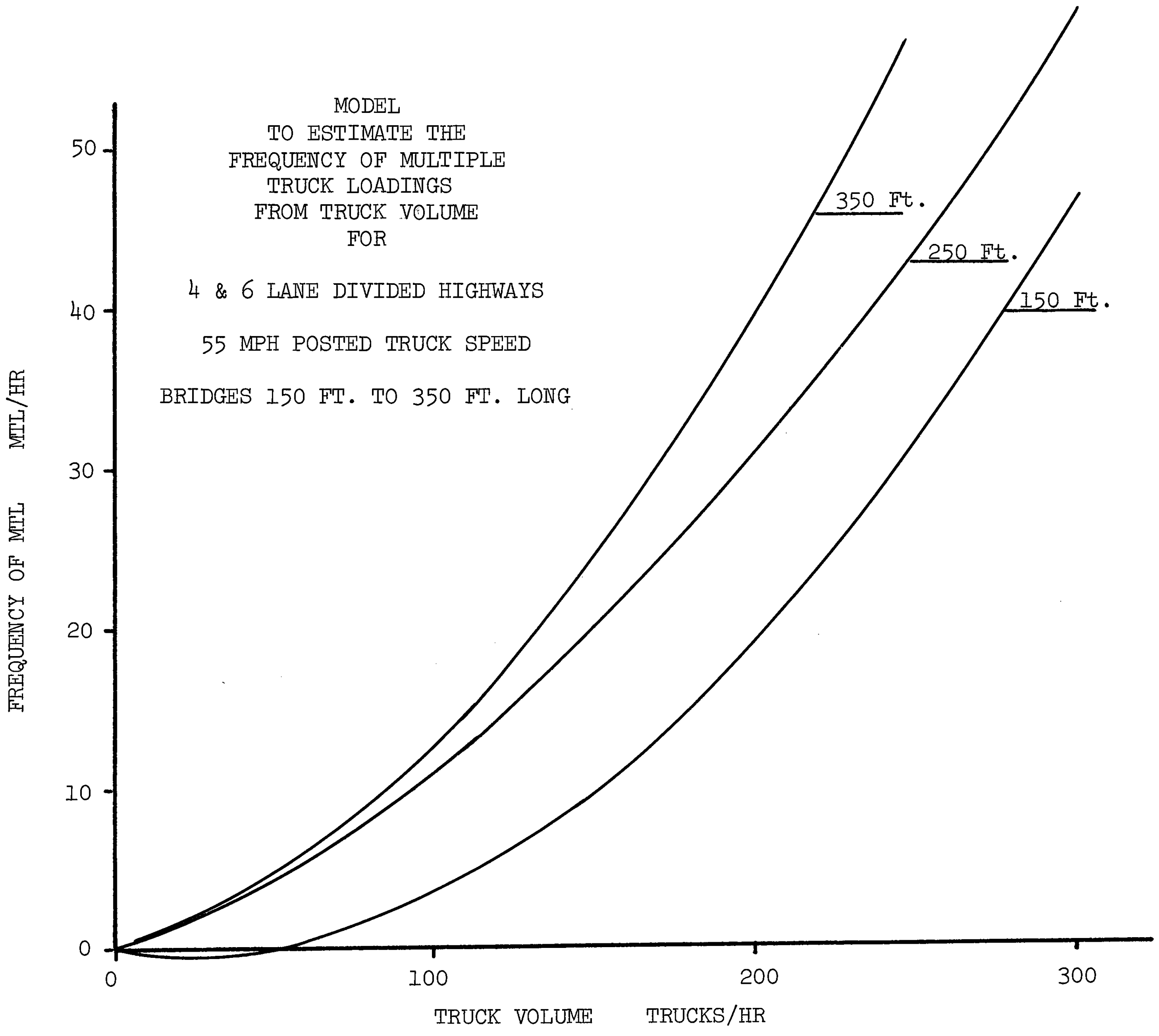


FIG 16 GRAPH FOR MODEL

when the truck volume is 0 to 75 trucks per hour. Estimates can also be made for the lane distribution of trucks, the lane distribution of MTL and the percentage of MTL that are between double or triple loadings. The values derived from the data used for the model are presented in Tables 7, 8, and 9. (The values tabulated for Ct. 5 were not used to develop the model but can be used with the model to obtain a rough approximation of the loading conditions of bridges on two-lane two-way highways.)

The lane distribution of trucks and MTL loadings were not the same on all highways. The reasons for these differences have not been studied. The lane distributions for I-91-N and I-91-S are probably close to the true averages on these facilities because they were observed during both the fall and spring data collection involving over 5,000 trucks on the two highways. The same is not true for I-86-W for which only 240 trucks were observed. Since each road had different truck volumes, the different lane distributions of trucks and MTL might be linked to this difference in truck volume. For this reason the lane distribution of all three highways are presented in addition to the average distribution of the combined data of the three highways. It is left to the individual to decide which distribution is to be used in estimates for a particular highway.

Different truck volumes could also be responsible for causing different percentages of all MTL which are triple loading, among the three highways used for the model. Since the reasons for this different breakdown of MTL have not been determined, the breakdown for each highway has been included along with the average breakdown for all three highways combined. The individual can decide which breakdown should be used in a particular estimate.

Table 7

Lane Distribution of Trucks

Road	Truck Volume All Lanes	Lane 1	Lane 2	% Trucks in Each Lane Lane 1	Lane 2
I86W	240	222	18	92.5	7.5
I91N	1985	1692	293	35.2	14.8
I91S	3193	2630	563	82.4	17.6
Combined	5418	4544	874	83.9	16.5
Ct. 5	917	464	453	50.6	49.4

Table 8

Lane Distribution of Multiple Truck Loadings

Road	Multiple Truck Loadings All Lanes	Lane 1	Lane 2	% MTL in Each Lane * Lane 1	Lane 2
I86W	33	21	1	63.7	3.0
I91N	251	129	17	51.4	6.8
I91S	393	175	18	44.6	4.6
Combined	677	325	36	48.0	5.3
Ct. 5	121	41	32	33.9	26.4

* The remaining percentages of MTL that did not occur on either lane alone occurred on two lanes together.

Table 9

Breakdown of Double and Triple MTL

150 Feet

Road	All Multiple Loadings	Double Multiple Loadings	Triple Multiple Loadings	Triple MTL as % of All MTL
I86W	13	13	0	0
I91N	50	48	2	4.0
I91S	90	87	3	3.3
Combined	153	148	5	3.3
Ct. 5	21	21	0	0

250 Feet

Road	All Multiple Loadings	Double Multiple Loadings	Triple Multiple Loadings	Triple MTL as % of All MTL
I86W	25	25	0	0
I91N	74	66	8	10.8
I91S	120	111	9	7.5
Combined	219	202	17	7.8
Ct. 5	41	41	0	0

350 Feet

Road	All Multiple Loadings	Double Multiple Loadings	Triple Multiple Loadings	Triple MTL as % of All MTL
I86W	33	31	2	6.7
I91N	106	93	13	12.3
I91S	131	111	20	15.3
Combined	270	235	35	13.0
Ct. 5	54	47	7	13.0

VII

CONCLUSIONS AND RECOMMENDATIONS

In this study a model was developed to estimate the frequency of multiple truck loadings that occur on certain highway bridges. Because only data collected specifically for the study were used, the model may not apply to all highway bridges. It should provide reasonable estimates on bridges between 150- and 350-feet long, on relatively level grades on four or six-lane divided highways with posted truck speeds of 55 mph. The only information needed to operate the model is the average hourly truck volume that travels over the bridge. Estimates are provided from the model for the hourly rate of MTL, the lane distribution of trucks and MTL, and the percentage of all MTL that are triple loadings. These estimates are meant to augment the estimates provided by Desrosier's model for the magnitude and frequency of truck loadings on bridges. Together these two models should present the structural engineer with a better estimate of the truck loadings that occur on highway bridges.

The scope of this study was narrow dealing only with MTL. This permitted the available resources to be concentrated. There was no previous knowledge about MTL to draw upon, requiring that all the data be collected and analyzed specifically for this study. Much of the data were used to eliminate variables which had little or no effect on the frequency of MTL. The variables were statistically proven to be significant or insignificant with respect to MTL. Only after the one important variable, truck volume, had been isolated could the model be developed.

The existing model is limited but it would not be a difficult task to obtain and process more data to broaden its scope. This would provide not only more information but possibly more accuracy. The spring data collection procedure could be modified so that several observers could collect data from a number of bridge lengths on two or three types of highways. The regression equations could be recalculated or new ones developed, whichever results in the smallest standard error of estimate. The model could be revised with a relatively small amount of effort. Presently the model of this study provides the best estimate of the frequency of MTL available.

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