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FEDERAL HIGHWAY ADMINISTRATION

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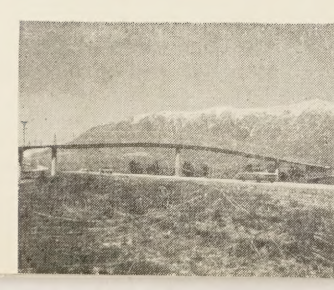

COVER

Pedestrian overpass over I–15 northwest of Ogden, Utah. (Photo courtesy of Utah State Department of Highways.)

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Use of funds for printing this publication has been approved by the Director of the Bureau of the Budget, March 23, 1971.

Bridge at St. Marys, W. Va.

Vibration Studies Relating to the Failure of the Point Pleasant Bridge

BY THE OFFICE OF RESEARCH

Reported by ROBERT F. VARNEY, Leader, Bridge Structures Group, and JOHN G. VINER, Leader, Protective Systems Group, Structures and Applied Mechanics Division

An investigation to determine the possible causes of the bridge failure was begun after a bridge across the Ohio River at Point Pleasant, W. Va., collapsed suddenly in December 1967 and claimed the lives of 46 persons. The research described in this article, representing one phase of the investigation, consists of a study of the dynamic stress amplifications and vibration responses of the bridge at St. Marys, W. Va., which also spans the Ohio River and is almost identical to the Point Pleasant Bridge. This study, conducted jointly by the Federal Highway Administration and the West Virginia State Roads Commission, was a practical attempt to gain further insight into the Point Pleasant disaster.

Introduction

FOLLOWING the failure of the eyebar chain suspension bridge over the Ohio River at Point Pleasant, W. Va., in December 1967, with a loss of 46 lives, a study of the dynamic stress amplification and vibration responses of a similar eyebar chain suspension bridge that carries Alternate U.S. Route 50 over the Ohio River at St. Marys, W. Va., was undertaken (see illustration at beginning of article).

The St. Marys Bridge, located 90 miles upstream from the site of the Point Pleasant Bridge, is part of the West Virginia State Highway System. A full-scale model is thus available for a variety of tests that may shed additional light on the cause of the Point Pleasant Bridge failure if any unusual behavior is observed.

With the concurrence of the West Virginia State Road Commission, the Federal Highway Administration's Structures and Applied Mechanics Division promptly initiated a research program to instrument the bridge and conduct a study of the static and dynamic responses to various live loadings. This group and the West Virginia State Road Commission cooperated in the endeavor. The latter organization provided on-site logistic support for conduct of the experimental study by the Federal Highway Administration.

The dual objectives of the test program were (1) to determine frequencies, mode shapes, and damping associated with the natural vibrations of the structure, and (2) to measure static and dynamic strains and displacements developed at critical points in the structure under the passage of a heavy vehicle. A judicious selection was made of locations to be gaged consistent with the available instrumentation and the expenditure of time and funds deemed appropriate for such a research effort. Many of the 35 gage points selected were suggested by failure points noted in the Point Pleasant Bridge wreckage.

It was proposed to verify the calculated natural frequencies and mode shapes by exciting the bridge with a harmonic force while the bridge was entirely free of vehicular traffic. Calculations of the theoretical natural mode shapes and frequencies indicated that the first four vertical modes would be within the range of frequencies available from the vibration generators. Low-frequency resonant vibrations in a suspension bridge may indicate susceptibility to undesirable aerodynamic excitation.

The Federal Highway Administration bridge research test vehicle (fig. 1) was used to provide a 44,300-pound, 3-axle moving load for obtaining the live-load response of the bridge under a typical heavy truck.

Figure 1.—Bridge research test vehicle.

Description of The St. Marys Bridge

The description and history of the Point Pleasant Bridge have already been well documented as a result of its disastrous failure (*1*).[1] The St. Marys Bridge superstructure was designed and built concurrently with the Point Pleasant Bridge about 40 years ago and is essentially identical except for minor differences in the approaches dictated by the difference in the sites. The St. Marys Bridge consists of a 2-lane, 27-foot truss-stiffened roadway suspended from two parallel steel eyebar chains spaced at 30-foot, 6-inch centers. The eyebar chains are anchored at each bank of the Ohio River and pass over two intermediate pier towers. The center span is 700 feet long and the two anchor spans are each 380 feet long. Short approach spans connect to the bridge at each end. Each eyebar chain consists of closely spaced parellel pairs of eyebars linked together and to adjacent pairs in the chain by a common connecting pin joining four eyebars at each joint. The eyebars vary in length from 25 to 55 feet and vary in thickness in proportion to design loading, averaging about 2 inches. The shank between eyes is 12 inches wide. The bridge design live loading consists of a uniform load of 1,400 pounds per linear foot of roadway and 42,000-pound concentrated load.

The suspension chains form the upper chords of the stiffening trusses in those panels where the chain and the truss upper chord are contiguous in both the end spans and center span. The stiffening truss members otherwise consist of steel built-up sections. Where the stiffening truss and the eyebar chain are not contiguous, vertical steel hangers connect the trusses to the eyebar chains at each panel point. Each chain passes over vertical end posts at each end of the structure. These end posts deflect the chains downward to the anchorages. The existing bridge roadway is a replacement of the original floor system and is composed of a network of stringers and floor beams supporting a 3-inch-deep concrete-filled steel grid deck.

Instrumentation

The dynamic responses were monitored by strain gages, deflectometers, and vertical and horizontal accelerometers. Strain gages on the vertical faces of upper chord members in the center span were oriented along the longitudinal axis of each member. These gages were located midway between truss panel points at approximately the ¼-, ⅜-, ½-, ⅝-, and ¾-points of the center span and served as the primary indicators of mode shape in the center span. Gages at the ⅜-, ½-, and ⅝-points were located on eyebars and the remaining two on truss channel webs.

The deflectometers used for this study each consisted of a metal cantilever beam with gages mounted near one end that was rigidly attached to the structure. The free end was then deflected more than the expected live-load deflection and held in this position by a fine steel cable anchored in the ground beneath the bridge. The live-load deflection of the structure decreased the intial deflection, and the resultant change in strain registered at the fixed end of the gage could be translated to displacement through a factor established by previous laboratory calibrations. Vertical deflectometers were located near midspan of each of the end spans.

Only four accelerometers were available for the field study. Two ±0.25 g horizontal accelerometers were attached to lower chord members of the downstream truss near midspan of the center span and of the Ohio end span. Two ±1.0 g vertical accelerometers were moved from point to poimt in the center span and the Ohio end span during different phases of the testing to determine mode shapes of the response.

All the transducers described were of the variable resistance type and were wired as Wheatstone Bridge circuits with external bridge completion resistors provided when necessary. Four-conductor grounded-shield cable in lengths up to 1,200 feet was used to connect the transducers to the signal conditioning equipment in the Federal Highway Administration research instrument van, which was located beneath the Ohio end span. Signal conditioning, amplification, bridge balancing, calibration, and attenuation for the transducer circuits were provided by instrumentation in the van. A direct-read oscillograph utilizing light-beam galvanometers was used to monitor resonances and to record the amplified transducer response signals.

Bridge Excitation and Loading Methods

The first objective of the test program called for a harmonic forced vibration input. Inertial force generators were not feasible for this purpose because of the low natural frequencies required. A method of providing an adequate low frequency harmonic energy input to the bridge with precise frequency control had to be devised. The calculations made in the process of devising such a vibration generator are given in (*2*). It was decided to use a direct cyclic pull on the underside of the Ohio end span of the bridge, which was over dry ground. Two alternative devices were provided for exerting the cyclic low-frequency pull on the underside of the bridge. In one, the drive axle torque of the bridge research test vehicle was exploited to obtain a pulsating cyclic force at frequencies as low as 20 cycles per minute. The vehicle was positioned beneath the midspan section of the end span, the left side of the drive axle

[1] Italic numbers in parentheses identify the references listed on p. 166.

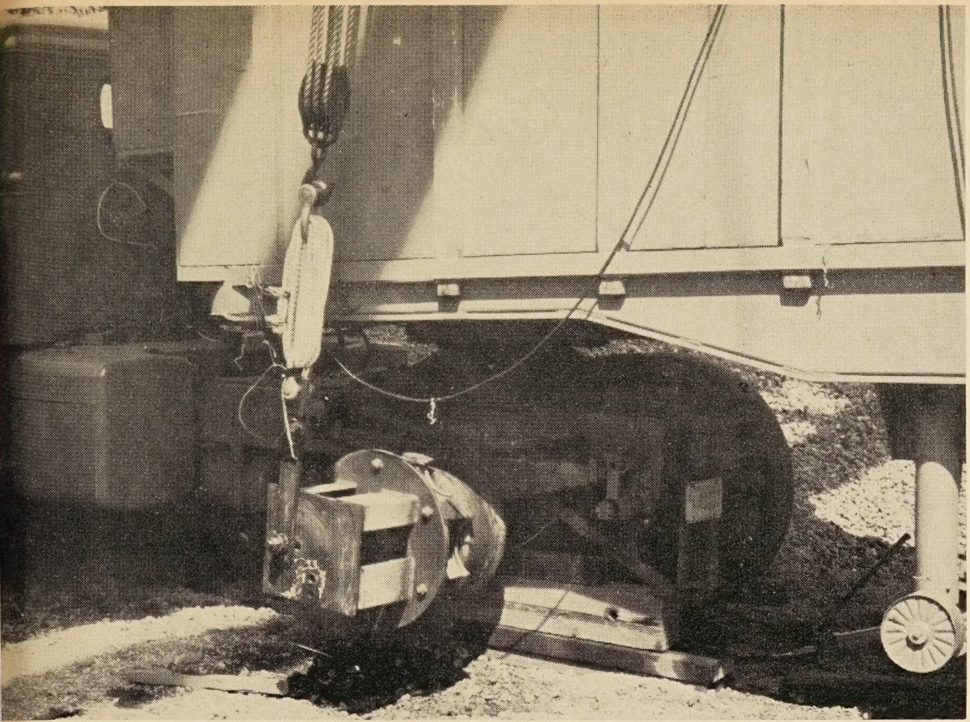


Figure 2.—Drive-axle vibration generator.

cked up and the wheels removed. A steel cture, designed to translate the rotating otion of the truck drive axle into a variable to 14-inch double amplitude vertical stroke rough a link and pin assembly, was then tached to the hub of the drive axle (fig. 2).

The reciprocating vertical force thus gen- ated by the rotation of the drive axle was en transmitted to the bridge in the following nnection sequence: First, through a 22-turn op of ⅝-inch diameter shock cord to provide sticity in the connection; then through a inch manila triple tackle to permit releasing e connection; finally, through a ⅝-inch rope nnected to an eye bolt bracket clamped to e bottom flange of the bridge floor beam at e load point. This system was capable of plying over 6,000 pounds of static pull on e bridge through the reaction of the vehicle. e resultant amplitude of bridge motion was culated to be a small fraction of the ailable vertical stroke for this level of out force even assuming the stretch in the re rope and in the triple tackle assembly be small. The shock cord loop was designed approximately 75-percent elongation. The mber of turns in the loop necessary to nsmit the maximum force was calculated m the known elasticity of the shock cord.

An alternate method of forced vibration neration consisted of a power takeoff from portable pump with a 4-inch double ampli- le reciprocating stroke. The pump was ted rigidly to the trailer bed (fig. 3) of the t vehicle and was driven by a 7.5-horse- ver gasoline engine. The frequency avail- e from this device under load ranged from 40 to 80 cycles per minute. The pump offered better frequency control but less force output than the vehicle drive axle takeoff. The connection from the pump reciprocating arm to the bridge was the same as for the vehicle drive axle takeoff, except that the loop of shock cord was eliminated.

Both methods of forced vibration were also employed in attempts to generate torsional modes of vibration in the bridge by moving the connection on the underside of the bridge to the lower chord of the truss on the downstream side of the roadway. Pure torsional modes could not be excited since the normal modes predominated even with eccentric loading. On both vibration generators, a strain gage was installed on the reciprocating link to help identify the resonant frequencies.

The second objective of the test program called for heavy vehicle passages across the bridge in the absence of other traffic. The Federal Highway Administration bridge research test vehicle was also utilized for this part of the program and was loaded with aggregate to provide a 17,800-pound load on both the driver and the trailer axles. The load on the front axle was 8,700 pounds, making a total vehicle weight of 44,300 pounds. The vehicle traversed the bridge in each direction along each normal traffic lane at speeds of 5 and 15 m.p.h. Due to the steep ascending grades on the bridge (6.8 percent) and the sharp turns and intersecting roads at the ends of the bridge, the sustained maximum speed attainable with the load being carried was slightly more than 15 m.p.h. A two-way radio permitted communication between the instrument van and the test vehicle.

Results

Natural mode shapes, natural frequencies, and associated damping values were determined from the free vibration of the bridge immediately after shutting off the vibration generator and slacking the connection to the bridge. As a slight tension remained in the attached cable after stopping the generator, the residual vibrations were not perfectly free. Figure 4 summarizes the vibration mode shapes observed during the vibration generator tests.

The first symmetric mode was obtained in test run 1 (fig. 4), using the drive axle takeoff of the truck as excitation. The frequency of vibration was 33.5 cycles per minute. The double amplitudes of vibration at the beginning of the free vibration portion of the record measured at the loading point in the end span were about 0.4 inch. The strain gages on the top chord members of the center span were all in compression at the same instant in time that the deflection gages in each end span showed upward movement, indicating that the bridge was in the fundamental vertical symmetrical mode.

Logarithmic decrements of damping were determined from the relative amplitudes between the first cycle of the free-vibration record and the nth cycle, where n was taken as large as possible without introducing measurement difficulties because of various off-resonance components in the response. For this test run, 12 cycles were used and the logarithmic decrement, δ, was 0.10. Values

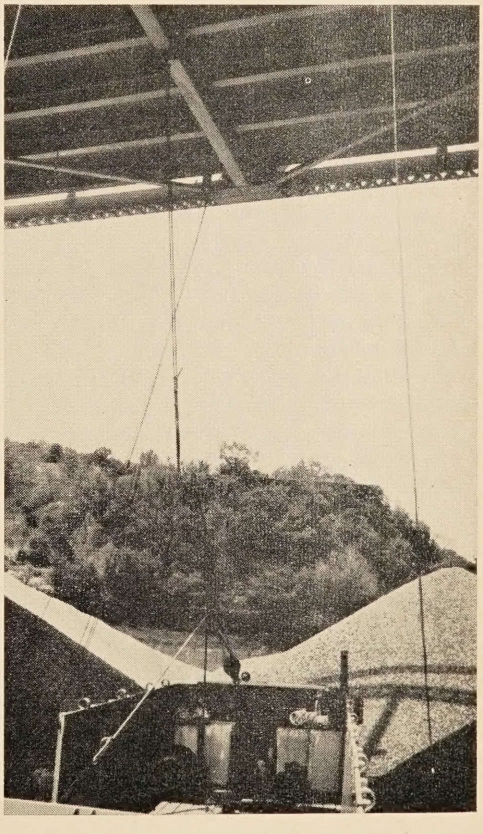


Figure 3.—Pump-drive vibration generator.

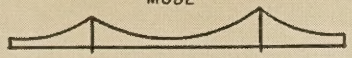
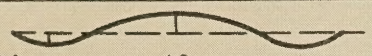
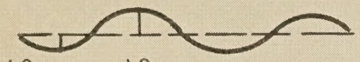
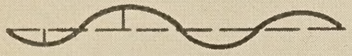
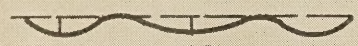
MODE 	RUN NO.	DATE	TIME	FREQUENCY (CPM)	LOGARITHMIC DECREMENT	VIBRATION GENERATOR USED
 0.4 1.0	1	5-4	11:55 A.M.	33.5	0.10	TRUCK
 1.0 1.0	2	5-6	10:58 A.M.	57.0	0.04	PUMP
	3	5-4	4:05 P.M.	54.8	0.07	PUMP
	4	5-4	11:55 A.M.	55.8	0.05	TRUCK
	5	5-4	2:45 P.M.	54.8	0.08	TRUCK
 0.5 1.0	6	5-8	8:50 A.M.	55.9	0.06	PUMP
 1.0 0.5	7	5-8	8:35 A.M.	74.2	0.04	PUMP
	8	5-4	12:05 P.M.	73.0	0.06	TRUCK
	9	5-8	8:40 A.M.	73.7	0.04	PUMP
	10	5-6	11:30 A.M.	74.0	0.04	PUMP

Figure 4.—Natural modes, frequencies, and logarithmic decrements obtained from vibration generator tests.

calculated for other runs ranged from 0.04 to 0.10, indicating a lightly damped structure.

As there were no vertical accelerometers in the center span during test run 1, the center span deflection was estimated from the strain measured in an upper chord member, assuming that the center span deflection in the first mode is a half-sine wave, the relation between the bending moment in this span and the deflection of the span is:

$$M=\frac{\pi^2}{L^2}EIy_0\sin\frac{\pi x}{L}$$

where: y_0=maximum deflection
L=span length

The midspan moment may be computed from the strain in the member, and from this the midspan deflection is determined. Using this procedure, the maximum deflection amplitude of the center span was 0.4 that of the center span.

The strain gage on the reciprocating link of the truck drive takeoff indicated that a maximum force (double amplitude) of about 6,300 pounds was applied to the bridge during this run.

Antisymmetric responses of the bridge with frequencies between 54.8 and 57.0 cycles per minute were next obtained in runs 2 through 6 (fig. 4). In run 2, the displacement at the ¼-point of the center span was derived from the response of a vertical accelerometer and was checked with the strain measured in an upper chord member by the same method used to estimate the center span deflection in the fundamental mode, except L in this test equalled one-half the span length. Reasonable agreement was obtained and the maximum end-span deflection was about 0.5 that of the center-span displacement.

In runs 2, 3, 4, and 5, there appeared to be a tendency for the natural frequency to decrease and the logarithmic decrement to increase in the afternoon runs as compared with the morning runs. This could have been a temperature effect.

A second symmetric mode with natural frequencies between 73.0 and 74.2 cycles per minute was obtained in runs 7, 8, 9, and 10. Logarithmic decrements of around 0.04 were observed in the three runs in which the pump motor provided the excitation. Run 8, in which the drive axle of the truck provided the excitation, indicated a logarithmic decrement of 0.06.

A series of records was made during forced vibration at a frequency of 72.8 cycles per minute while a vertical accelerometer was placed successively at each center-span panel point between midspan and the Ohio tower. The resultant responses have been normalized to the relative response of the deflection gage in the end span and are shown in figure 5.

When an attempt was made to excite torsional modes in the bridge with the truck driver takeoff, a single amplitude motion of about 0.06 inch in the end span was observed at frequencies of 47.7 and 49.0 cycles per minute on the two deflection gages on opposite sides of the bridge. In addition, the data indicated the presence of a beat frequency of around 4 cycles per minute. An attempt to excite torsional vibration with the pump drive resulted in a 46.7-cycle-per-minute response of the bridge with heavy beating. Vertical accelerometers at the ¼-point in the center

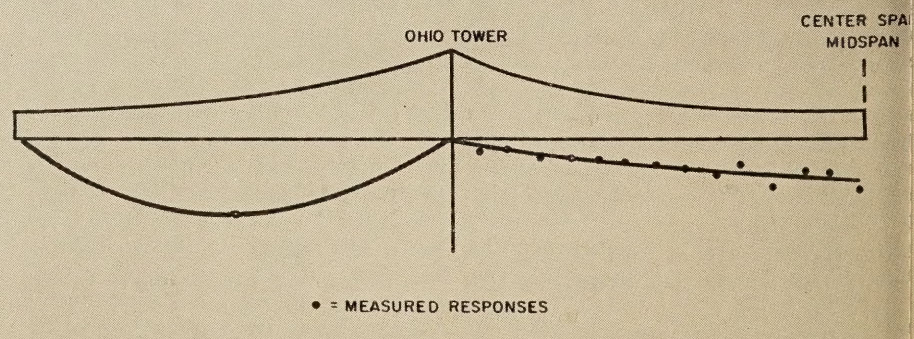


Figure 5.—Relative displacements obtained from vibration generation at 72.8 cycles per minute.

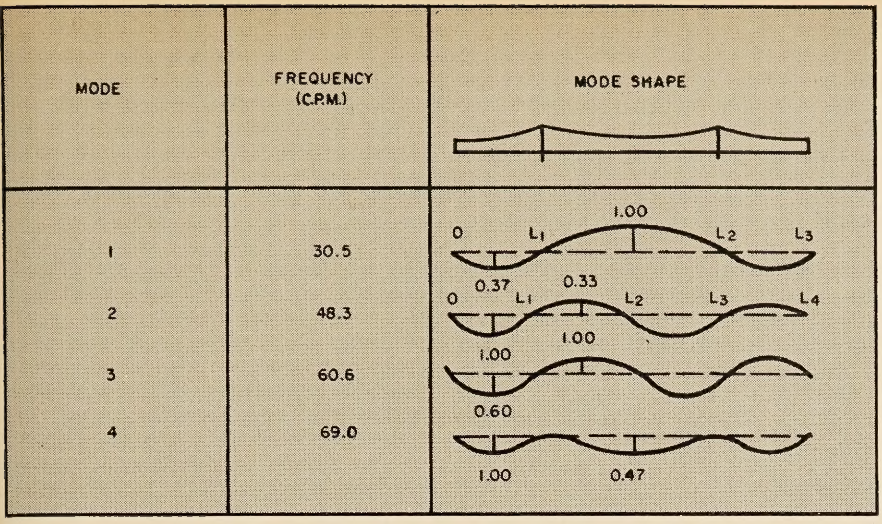


Figure 6.—Summary of computed frequencies and mode shapes.

›an indicated the torsional response at that ›oint to be out of phase with the torsional ›sponse of the midpoint of the Ohio end span. ›ther than these responses, no significant ›rsional bridge motions were noted.

Discussion of Results

The vertical mode frequencies and wave ›rms of the St. Marys Bridge, shown in ›gure 6, were computed (*3*) [2] and used to ›lculate the response of the structure for 1.0 ›). excitation at the various resonant fre-›uencies (*2*, *4*), assuming a logarithmic ›crement 0.15. Results are given in table 1. ›hese calculations were made for three ›equencies as follows: Excitation at the precise ›sonant bridge frequency; excitation at ›her 95 or 105 percent of the resonant ›equency; and excitation at either 90 or 110 ›rcent of resonance (table 1).

The mode shapes and frequencies of the ›rtical vibrations obesrved during the vibra-›n generator tests are presented in figure 4.

The calculated value of the first symmetrical ›tural frequency of 30.5 cycles per minute is reasonably good agreement with the ›perimentally determined value of 33.5 ›cles per minute. Similarly, good agreement ›tween the calculated and observed mode ›ape was obtained. The ratio of the cal-›lated value of the natural frequency the first asymmetric mode of 48.3 cycles per ›nute to the natural frequencies determined ›runs 2, 3, 4, 5, and 6 (fig. 4) is about the same the ratio of calculated to experimentally ›termined values of the fundamental sym-›etric natural frequency. The calculated first ›mmetric mode shape differed significantly ›m that observed, however. The mode shape ›tained from run 6 was rather like that of the second calculated asymmetric mode. Inasmuch as no other asymmetric modes were obtained from the test program, it is conceivable that the mode of run 6 and that of runs 2, 3, 4, and 5 may be two separate natural modes of the structure.

The ratio of the calculated second symmetric natural frequency of 69.0 cycles per minute to the measured values obtained in runs 7, 8, 9, and 10 fits into the pattern of the similar ratios in the fundamental symmetric and asymmetric modes. The calculated and measured mode shapes are in good agreement.

If the combined effects of (1) the difference between the resonant frequency of the bridge and the frequency of excitation, (2) the drift in the excitation frequency, and (3) the nonharmonic components of the forcing function are assumed to make the bridge behave as an equivalent viscous damped ideal single degree of freedom system with a sinusoidal forcing function operating at 95 percent of the fundamental resonant frequency, then the measured 6,300-pound input force corresponds to a 0.155-horsepower input. The value of the deflection of the end span (assumed as simply supported) under a concentrated load at midspan of 1,000 pounds was calculated to be 0.022 inch (*2*, *4*). Using this and the theoretical fundamental natural frequency = 30.5 cycles per minute and assuming $\delta=0.15$, the maximum end span displacement would be:

$$y=(0.4)(1.1)\sqrt{\frac{0.155}{1.0}}=0.173 \text{ inch}$$

(single amplitude)

Using the experimentally determined values of natural frequency = 33.5 cycles per minute, deflection of end span under a concentrated load of 1,000 pounds at midspan (extrapolated from truck crawl run data) = 0.0155 inch, and $\delta=0.10$, then,

$$y=0.173\sqrt{\frac{.0155}{.022}}\left(\frac{30.5}{33.5}\right)^{3/2}\sqrt{\frac{.15}{.10}}=0.160 \text{ inch}$$

(single amplitude)

In this particular case the differences between the assumed values and experimentally determined values tend to somewhat offset one another.

The measured end-span displacement at 33.5 cycles per minute was 0.18-inch single amplitude, indicating very good agreement between predicted and measured displacement for the fundamental mode.

Although the static and dynamic responses of the bridge to the moving test vehicle are the subject of a separate report, it may be pointed out here that the mean live-load stress levels determined at various points throughout the bridge during the vehicle passage were not excessive. Vibrations induced by the vehicle passage were generally of higher frequency than induced by the vibration generators and represented individual structural member vibrations in various axial and normal modes.

Summary of Results

The first two symmetric normal modes of vibration were identified in the test program. The mode shapes and frequencies were in good agreement with calculated values.

Possible existence of two separate asymmetric vertical modes, very close to one another in frequency, at around 56 cycles per minute was indicated. This observed frequency was in reasonable agreement with the calculated frequency of the first asymmetric mode. Neither experimentally determined vibration pattern was in good agreement with

Table 1.—Resonant vibration single amplitude responses for 1.0 hp. delivered input ($\delta=0.15$)

Mode	Perfect frequency control		±5% Frequency control, maximum displacement	±10% Frequency control, maximum displacement
	Maximum displacement	Maximum acceleration		
	inches	*g's*	*inches*	*inches*
1st Symmetric 30.5 c.p.m.	1.60	0.04	1.1	0.8
1st Asymmetric 48.3 do	.79	.05	.5	.4
2d Asymmetric 60.6 do	.56	.06	.4	.3
2d Symmetric 69.0 do	.44	.06	.3	.2

[2] Mode shapes and natural frequencies were computed by ›rge S. Vincent, using the numerical method described in ›rence (*3*).

the calculated first asymmetric mode shape; however, the second experimentally determined asymmetric mode shape was in reasonable agreement with the calculated second asymmetric mode shape.

Logarithmic decrements of damping determined for each experimentally determined mode of vibration indicated that the bridge was a lightly damped structure.

The calculations of bridge response for given levels of input force from the vibration generator were more than adequate for the purpose of choosing appropriate vibration generation equipment and motion sensing instrumentation.

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(1) *Eyebar Bridges and the Silver Bridge Disaster,* Engineer, publication of the Engineers Joint Council, January–February 1968.

(2) *The Dynamic Response of the Eyebar Chain Suspension Bridge over the Ohio River at St. Marys, West Virginia,* by Robert F. Varney and John G. Viner, Federal Highway Administration Staff Research Report, June 1970.

(3) *Aerodynamic Stability of Suspension Bridges with Special Reference to the Tacoma Narrows Bridge,* by Frederick C. Smith and George S. Vincent, University of Washington Experiment Station Bulletin No. 116, Part II—Mathematical Analyses, October 1950.

(4) *The Dynamic Response of a Steel Eyebar Chain Bridge over the Ohio River to Various Applied Excitations,* by R. F. Varney and J. G. Viner, Federal Highway Administration, The Shock and Vibration Bulletin, Bulletin 41 (Part 4 of 7 Parts), Naval Research Laboratory, December 1970, pp. 99–108.

New Publications

The Federal Highway Administration has recently published two documents. These publications may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, prepaid. The following paragraphs give a brief description of each publication and its purchase price.

Manual of Instructions for Construction of Roads and Bridges on Federal Highway Projects

Manual of Instructions for Construction of Roads and Bridges on Federal Highway Projects, 1970 ($3.25 a copy), provides information and guidance for employees of the Federal Highway Administration in the administration of construction contracts under the Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects, FP–69. Procedures to be followed are described and exhibits are shown to establish national uniformity in the day-to-day contacts between Government engineering forces and contractors' personnel.

Transportation Planning Data f[or] Urbanized Areas

Transportation Planning Data for Urbaniz[ed] Areas, 1970 ($9.25 a copy), is a 664-pa[ge] document in which urbanized area da[ta] tabulations present summarized informati[on] on a small area basis. The data is based on t[he] 1960 Census and is organized by urbaniz[ed] area as defined by the Bureau of the Cens[us]. The areas are subdivided into Standa[rd] Location Areas (SLA's) with each SL[A] identified by a more familiar designation— census tract, ward, etc.—for ease in locati[ng] it within the urbanized area.

Data tabulations are presented in a fo[rm] which should be useful to transportati[on] planners and others concerned with urb[an] development. The categories selected [for] presentation have proved to be useful ya[rd]sticks for measuring travel in urban are[as]. For example, both the population and t[he] number of households have a direct beari[ng] on total trip making activity within the stu[dy] area. Likewise, both median income a[nd] auto ownership can be readily translated i[nto] trip making activity at the household lev[el]. The data tabulations can therefore be us[ed] by urban transportation planners as a b[ase] from which growth can be measured. W[ith] similar information from the 1970 Census, [or] other independent sources, trends can [be] identified and rates of change can [be] established.

What would you like to read about in PUBLIC ROADS?

Dr. G. W. Cleven, the Federal Highway Administration's Associate Administrator for Research and Development, would like to know what you, the reader, would like to read about in PUBLIC ROADS.

Dr. Cleven feels that reader interest is essential in planning a more effective publication. Perhaps you need how-to-do-it information, or would like to learn what others are doing. Perhaps you would like to read brief accounts of the latest research results, like those on page 175 of this issue.

Whatever your preference, write and tell us about it. And if you like the journal in its present form, we would appreciate hearing about that too.

Please direct your comments to the Managing Editor, PUBLIC ROADS Magazine, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. 20591.

The Correlation Coefficient in Analysis of Engineering Data— Its Significance and Limitations

Reported by [1] HOWARD T. ARNI
Highway Research Engineer
Materials Division

How useful is the correlation coefficient as an effective measuring technique to determine the association between two variables? Apparently it is not as reliable as some researchers may believe and, in fact, some caution should be exercised in using it as a precise indication of the quality of a relationship between engineering measurements. Indeed, the author has compiled considerable evidence opposing the use of correlation coefficient as a true means of comparing such measurements. He is aware that it is simple to compute and gives a single statistic whose magnitude does not depend on units of variables being compared. But this very simplicity makes the correlation coefficient too popular with many researchers, and this probably leads to its overuse and evidently its misuse.

In exposing the fallacy of depending on a correlation coefficient for meaningful comparisons between measurements, the author begins by showing some basic limitations of the correlation coefficient. Then, by a review of the literature, he documents cases where the correlation coefficient has been misused to the extent of being useless or misleading. Frequently, as explained, regression analysis is the proper measuring technique to use. While it involves more computation, it still provides more information about relationships between variables.

THE correlation coefficient is often used as a measure of association between two variables. It is also frequently misused by those who disregard its limitations. The correlation coefficient is simple to compute; and the idea of having a single statistic, the magnitude of which does not depend on units of variables being compared, is attractive to many researchers.

There are, however, several reasons for avoiding the use of the correlation coefficient. First, it is frequently used when it is not applicable as a measure of association. In engineering and science, researchers are usually interested in the response of one variable to changes in one or more other controllable variables. Second, purposes served by the correlation coefficient can usually be served as well or better by a regression analysis, which involves little more computation and provides more information about relationships between variables. Third, conclusions based on the correlation coefficient can be very misleading. *Significant* correlation coefficients often are due to circumstances that are not the result of direct association or cause-and-effect relations between the two variables under study. Finally, the correlation coefficient is based on a number of assumptions about the data, which, if not met, can render the calculated correlation coefficient useless and misleading.

In their book *Engineering Statistics,* (*1*)[2] Bowker and Lieberman state, "In engineering applications, the correlation coefficient does not play a very important role." In fact, textbooks on statistics that devote much space to the correlation coefficient almost without exception devote considerable space to discussions of this statistic's limitations and of the pitfalls connected with its use and interpretation. Chapter 5 of National Bureau of Standards (NBS) Handbook 91, *Experimental Statistics* (*2*) contains a good discussion of the field of linear relations between two variables, but does not stress the correlation coefficient, *r*. When queried about this, the author of the handbook replied as follows:

"We deliberately gave (the correlation coefficient) small emphasis for various reasons. In the first place, the correlation coefficient has often been calculated and reported when the actual nature of the relationship was such that the correlation coefficient was completely inappropriate. Chapter 5 in NBS Handbook 91 describes a number of linear models for two-variable relationships, and in only one of them is the correlation coefficient appropriate (this is the so-called SI case, the case of unrestricted sampling from a bivariate normal

[1] This article contains essentially the same material that was reported in *Materials, Research and Standards,* May 1971, published by the American Society for Testing and Materials.

[2] Italic numbers in parentheses identify the references listed on page 174.

STATE LEGAL MAXIMUM DIMENSIONS AND WEIGHTS O

Prepared by the American A

Decem

Line	State	Width inches[1]	Height ft.-in.	Length-feet[2]					Number of towed units[3]			Axle load-pounds				Operating tire inflation pressure pounds per sq. in.	Pounds per engine net horsepower delivered to clutch or equivalent
				Single unit			Truck tractor semi-trailer	Other combination	Semi-trailer	Full trailer	Semi-trailer and full trailer	Single		Tandem			
				Truck	Bus	Semi-trailer or trailer						Statutory limit	Including statutory enforcement tolerance	Statutory limit	Including statutory enforcement tolerance		
1	Alabama	96	13-6	40	40	NS	55	NP	1	NP	NP	18,000	19,800	36,000	39,600	NS	NS
2	Alaska	96	13-6	40	40	[7]NR	60	65	1	1	2	20,000		34,000		NS	NS
3	Arizona	96	13-6	40	40	[7]NS	65	65	1	1	2	18,000		32,000		NS	NS
4	Arkansas	96	13-6	40	40	NS	55	65	NR	NR	NR	[8]18,000		32,000		NS	NS
5	California	96	[9]13-6	40	40	[71]40	60	65	NR	NR	NR	18,000		32,000		NS	NS
6	Colorado	[10]96	[11]13-6	35	40	NR	[22]65	[22]65	1	2	2	18,000		36,000		NS	NS
7	Connecticut	102	13-6	55	55	NR	55	NP	1	NP	NP	22,400	22,848	36,000	36,720	NS	NS
8	Delaware	96	13-6	40	42	40	55	65	1	1	NP	[63]20,000		36,000		NS	NS
9	Florida	96	13-6	[14]40	40	NS	55	55	1	1	NP	20,000	22,000	40,000	44,000	NS	NS
10	Georgia	96	13-6	55	55	NR	55	55	NR	NR	NR	18,000	20,340	36,000	40,680	NS	NS
11	Hawaii	108	13-6	40	40	NR	55	65	1	1	2	24,000		32,000		NS	NS
12	Idaho	[10]96	14-0	[18]35	[18]35	NR	[19]60	[64]65	1	1	[64]2	[20]18,000		[20]32,000		NS	[45]NS
13	Illinois	96	13-6	42	42	42	55	[24]60	1	1	2	[23]18,000		32,000		NS	NS
14	Indiana	96	13-6	36	40	NR	55	65	1	1	2	18,000	19,000	32,000	33,000	NS	NS
15	Iowa	96	13-6	35	[6]40	NR	[26]55	[26]55	1	1	2	18,000	18,540	32,000	32,960	NS	NS
16	Kansas	96	13-6	42' 6"	42' 6"	NS	55	65	1	1	2	18,000		32,000		NS	NS
17	Kentucky	96	[27]13-6	[27]35	[27]35	NR	[29]55	[65]65	1	1	2	18,000	18,900	32,000	33,600	NS	NS
18	Louisiana	96	13-6	35	[6]40	NR	60	65	1	1	NP	18,000		32,000		NS	NS
19	Maine	[28]102	[31]13-6	55	55	NR	55	55	1	1	[39]NP	22,000		[28]36,000		NS	NS
20	Maryland	[10]96	13-6	55	55	NR	55	[30]65	NR	NR	NR	22,400		[35]40,000		NS	NS
21	Massachusetts	96	13-6	35	[6]40	NR	55	NP	1	NP	NP	22,400		36,000		NS	NS
22	Michigan	96	13-6	40	40	NR	55	[25]65	1	1	2	[37]18,000		[38]32,000		NS	400
23	Minnesota	96	13-6	40	40	[66]40	55	55	1	1	NP	18,000		32,000		NS	NS
24	Mississippi	96	13-6	35	40	NR	55	55	1	1	NP	18,000		28,650	[22]32,000	NS	NS
25	Missouri	96	13-6	40	40	NR	55	[41]55	NR	NR	NR	18,000		32,000		NS	NS
26	Montana	[10]96	13-6	35	40	NR	60	60	1	1	2	18,000		32,000		NS	NS
27	Nebraska	96	13-6	40	40	[7]NR	60	65	1	1	2	20,000		34,000		NS	NS
28	Nevada	96	NR	40	40	NR	70	70	NR	NR	NR	18,000	18,900	32,000	33,600	NS	NS
29	New Hampshire	96	13-6	35	40	NR	55	55	1	1	NP	22,400		36,000		NS	NS
30	New Jersey	96	13-6	35	[42]35	[7]40	55	55	1	1	NP	22,400	23,520	32,000	33,600	NS	NS
31	New Mexico	[43]96	13-6	40	40	NR	65	65	1	1	2	21,600		34,320		NS	NS
32	New York	[10]96	13-6	35	40	NR	55	55	1	1	NP	22,400		36,000		NS	NS
33	North Carolina	96	13-6	35	[6]40	NR	55	55	1	1	NP	18,000	19,000	36,000	38,000	NS	NS
34	North Dakota	[10]96	13-6	[6]40	[6]40	NR	[24]60	[24]60	1	1	2	18,000		32,000		NS	NS
35	Ohio	96	13-6	40	[6]40	NR	55	65	1	NR	NR	19,000	19,570	[44]32,000	32,960	NS	NS
36	Oklahoma	96	13-6	40	45	NR	55	65	1	1	2	18,000		32,000		NS	NS
37	Oregon	96	[68]13-6	35	[22]40	[22]40	[21]50	[22]75	1	1	[22]2	[46]20,000		[46]34,000		NS	NS
38	Pennsylvania	96	13-6	35	40	40	55	[34]55	1	1	NP	22,400	23,072	36,000	37,080	NS	[32]450
39	Rhode Island	102	13-6	40	40	40	55	55	1	1	NP	22,400		NS		NS	NS
40	South Carolina	96	13-6	[6]40	[6]40	NR	55	[54]55	1	1	NP	20,000		[55]32,000		NS	NS
41	South Dakota	96	13-6	35	40	NR	65	65	1	1	2	18,000		32,000		NS	NS
42	Tennessee	96	13-6	40	40	NS	55	55	1	[56]1	NP	18,000		32,000		NS	NS
43	Texas	96	13-6	40	40	NR	65	65	NR	NR	NR	18,000		32,000		NS	NS
44	Utah	96	14-0	45	45	45	60	60	NR	NR	NR	18,000		33,000		NS	NS
45	Vermont	96	13-6	50	50	NS	55	55	1	1	NP	22,400	23,520	[57]36,000		NS	NS
46	Virginia	96	13-6	35	40	NS	55	55	1	1	NP	18,000		[58]32,000		NS	NS
47	Washington	96	13-6	35	40	40	[19]60	65	1	1	2	18,000		32,000		NS	NS
48	West Virginia	96	[33]12-6	35	[6]40	35	50	50	1	1	NP	18,000	18,900	32,000	33,600	NS	NS
49	Wisconsin	96	13-6	35	40	35	55	55	1	1	NP	18,000	[60]19,500	30,400	32,000	NS	NS
50	Wyoming	96	13-6	50	40	NR	65	[34]65	1	1	2	18,000		32,000	[62]36,000	NS	NS
51	District of Columbia	96	12-6	40	40	NS	55	55	1	1	NP	22,000		38,000		NS	NS
52	Puerto Rico	96	13-6	35	40	NS	50	50	1	1	NP	NS		NS		NS	NS
	AASHO Policy - 1946	96	12-6	35	40		50	60	1	1	NP	18,000		32,000		NS	NS
	Number of States: Higher	4	50	31	10		49	24	8	10		21		22			
	Number of States: Same	48	2	21	39		3	4	44	39		31		28			
	Number of States: Lower	0	0	0	3		0	24	0	3		0		2			
	AASHO Policy - 1968	102	13-6	40	40	40	55	65	1	1	2	20,000		32,000		95	400
	Number of States: Higher	1	3	9	10	42	16	2	8	10	10	14		22		[13]	
	Number of States: Same	3	47	22	39	7	33	19	44	39	19	6		28			
	Number of States: Lower	48	2	21	3	3	3	31	0	3	23	32		2			

NP—Not permitted. NR—Not restricted. NS—Not specified.

[1] Various exceptions for farm and construction equipment; public utility vehicles; house trailers; urban, suburban, and school buses; haulage of agricultural and forest products; at wheels of vehicles for safety accessories, on designated highways, and as administratively authorized.

[2] Various exceptions for utility vehicles and loads, house trailers, mobile homes and urban, suburban and school buses.

[3] When not specified, limited to number possible in practical combinations within permitted length limits; various exceptions for farm tractors, mobile homes, etc.

[4] Legally specified or established by administrative regulation.

[5] Computed under the following conditions to permit comparison on a uniform basis between States with different types of regulation:

A. Front axle load of 8,000 pounds.

B. Maximum practical wheelbase within applicable length limits:

(1) Minimum front overhang of 3 feet; minimum spacing from first to second axle of truck tractor 8 feet.

(2) In the case of a 4-axle truck-tractor semitrailer, rear overhang computed as necessary to distribute the maximum possible uniform load on the maximum permitted length of semitrailer to the single drive-axle of the tractor and to the tandem axles of the semi-trailer, within the permitted load limits of each.

(3) In the case of a combination having 5 or more axles, minimum possible combined front and rear overhang assumed to be 5 feet, with maximum practical load on maximum permitted length of semitrailer, subject to control of loading on axle groups on total wheelbase as applicable.

C. Including statutory enforcement tolerance as applicable.

[6] Less than three axles 35 feet.

[7] Trailer 35 feet in New Jersey, 40' in Nebraska, Alaska and Arizona.

[8] Steering axle 12,000 pounds.

[9] Load on vehicle may exceed 13' 6" but not exceed 14' 0".

[10] Buses 102 inches on certain highways as administratively authorized.

[11] On class AA, or designated highways, 12 ft 6 in. on other highways.

[12] On Interstate system only. 79,900 lbs. on primary and secondary highways.

[13] Not yet specified in any state law.

[14] Two-axle truck 35 feet; three-axle truck 40 feet.

[15] Formula W=500 (LN/N minus 1 plus 12N plus 36 where W=Gross Weight L=Wheelbase in feet and N=Number of Axles. The formula provides for maximum gross weight allowed on any vehicle or combination.

[16] 73,280 pounds maximum, except on roads under Rural Roads Authority 56,000 pounds maximum.

[17] 800 (L plus 40) where L is distance between first and last axle of vehicle except that 700 (L plus 40) governs for any group of 11 or more consecutive axle whose L is 13 feet or less: Alternate Load Determination by table for vehicles of 3, 4 or 5 axles for L between 19 feet and 51 feet provided single axle load limited to 18000 pounds or less: 900 (L plus 40) on highways which have no structures with span of 20 feet or over.

[18] On designated highways 40 feet.

[19] Auto transports on designated highways 65 feet in Idaho, 70 feet in Washington if equipped as specified.

[20] Special limits for vehicles hauling timber and including livestock; single axle 18,900 pounds, tandem a 66,000 pounds maximum at 21-foot axle spacing, vehicle spacing.

[21] 60 ft. in special cases: Indiana, trucks pulling h trailers on designated major routes.

[22] On designated highways only.

[23] On designated highways; 16,000 pounds on other

[24] Truck tractor semitrailer drawing one trailer or highway or any other highway designated by the Departme

[25] On designated highways only. Auto and boat tra rear of vehicle. Auto or boat transporter exceeding 60' may

[26] Auto and boat transports and three-unit combinat

[27] On state maintained highways; on other highways

[28] On Interstate System only maximum width 96 inc

[29] On state maintained highways; 30 feet on other hi

[30] On four lane highways only.

[31] Including load 14 feet; various exceptions for vehi

[32] But not less than 30 net brake horsepower.

[33] Auto transports 13 feet 6 inches; other vehicles 1

[34] Exception for poles, pilings, structural units, rowi

[35] Less than 48-inch spacing, 36,000 pounds.

[36] Subject to axle and tabular limits.

[37] Single axle spaced less than 9 feet from nearest ax

[38] On designated highways only and limited to one does not exceed 73,250 pounds; 2 tandem axle assemblies

[39] Drive away, towaway operations as defined by t exceed 3 units in contact with the surface of the highway.

[40] On Interstate System 47,500 pounds.

[41] Auto transports permitted 60 feet. Double bott therefrom and other designated routes.

[42] Or as prescribed by P.U.C.

[43] On designated highways 102 inches. Body restrict

[44] 32,000 pounds if over 4 feet but less than 8 feet feet.

[45] 98' combinations required 1 net bhp per 400 lbs.

[46] On Interstate System logging vehicles limited to 18,000 pound single axle and 32,000 pound tandem axle.

OTOR VEHICLES COMPARED WITH AASHO STANDARDS

of State Highway Officials

1970

Gross weight limit			Specified maximum gross weight-pounds[4]						Practical maximum gross weight-pounds[5]						
	Applicable to:		Truck		Truck-tractor semitrailer				Truck		Truck-tractor semitrailer				
Type of restriction	Any group of axles	Total wheelbase only	2-axle	3-axle	3-axle	4-axle	5-axle	Other combination	2-axle	3-axle	3-axle	4-axle	5-axle	Other combination	Line
le		X					73,280		27,800	47,600	47,600	67,400	73,280	NP	1
le-tire cap.		X	40,000	54,000	60,000	74,000	88,000	100,000	28,000	42,000	48,000	62,000	76.000	90,000	2
le	Under 18'	Over 18'							26,000	40,000	44,000	58,000	[72]72,000	76,800	3
., maximum			30,000	44,000	48,000	62,000	73,280	73,280	26,000	40,000	44,000	58,000	72,000	73,280	4
le	Under 18'	Over 18'							26,000	40,000	44,000	58,000	72,000	76,800	5
nula-spec. lim.		X	30,000	40,000					26,000	44,000	44,000	62,000	76,000	76,000	6
. lim.-tire cap.			32,000	53,800	53,800	67,400	73,000	NP	30,848	44,720	53,800	67,400	73,000	NP	7
le-spec. lim.	X		30,000	65,000	48,000				28,000	44,000	48,000	64,000	73,280	73,280	8
le		X							30,000	52,000	52,000	73,271	73,271	73,271	9
. max.[16]							73,280	73,280	28,340	48,680	48,680	69,110	73,280	73,280	10
nula[17]	X								32,000	40,000	56,000	64,000	72,000	80,000	11
le[20]	X								26,000	40,000	44,000	58,000	73,280	76,800	12
. lim.-tire cap.			36,000	[36]50,000	[36]50,000	[36]64,000	[36]73,280	[36]73,280	26,000	40,000	44,000	58,000	72,000	73,280	13
. lim.-tire cap.			36,000	50,000	54,000			72,000	27,000	41,000	44,000	58,000	[25]73,000	[25]73,000	14
le	X								26,540	40,960	45,080	59,500	73,280	73,280	15
le		X	[36]36,000	[36]50,000	[36]54,000	[36]72,000	[36]73,280	[36]73,280	26,000	40,000	44,000	58,000	72,000	73,280	16
. lim.-tire cap.			30,000	44,000	44,000	62,000	73,280	73,280	26,900	41,600	42,000	59,640	73,280	73,280	17
lim.-tire cap.									26,000	40,000	44,000	58,000	72,000	76,000	18
le-tire cap.	X		32,000	46,000	51,800	66,300	73,280	73,280	30,000	44,000	51,800	66,000	73,280	73,280	19
ie		X			[36]55,000	[36]65,000	[36]73,280	[36]73,280	30,400	48,000	52,800	65,000	73,280	73,280	20
le-spec. lim.		X	[36]46,000	[36]60,000	[36]67,200	[36]73,000	[36]73,000	NP	30,400	44,000	52,800	66,400	73,000	NP	21
lim.-tire cap.							73,280		26,000	40,000	44,000	58,000	72,000	138,000	22
le	X						73,280	73,280	26,000	40,000	44,000	58,000	72,000	73,280	23
ie-tire cap.	X								26,000	[22]40,000	44,000	58,000	[22]72,000	[22]73,280	24
le		X							26,000	40,000	44,000	58,000	[22]72,000	[22]73,280	25
e–formula[15]	Under 18'	Over 18'	40,000	60,000	60,000	80,000	85,500	[70]105,500	26,000	40,000	44,000	58,000	73,280	76,800	26
e	X		40,000	60,000	60,000	80,000	85,500	95,000	28,000	42,000	48,000	62,000	77,500	80,500	27
e	Under 18'	Over 18'							26,900	41,600	45,800	60,500	75,200	76,800	28
e-spec. lim.		X	33,400	[40]55,000	52,800	66,400	73,280	73,280	30,400	44,000	52,800	66,400	73,280	73,280	29
lim.-tire cap.									31,520	41,600	55,040	65,120	73,280	73,280	30
e	Under 18'	Over 18'							29,600	42,320	51,200	63,920	76,640	86,400	31
nula		X					71,000	71,000	30,400	44,000	52,800	66,400	71,000	71,000	32
. lim.			31,500	49,875	49,875	67,200	73,280	73,280	27,000	46,000	46,000	65,000	73,280	73,280	33
nula	Under 18'	Over 18'							26,000	40,000	44,000	58,000	72,000	73,280	34
nula[59]		X							27,570	40,960	46,000	58,500	71,000	78,000	35
e	X		[67]18,000	[67]32,000	[67]36,000	[67]50,000	[67]64,000	73,280	26,000	40,000	42,000	60,000	73,280	73,280	36
e[47]	18' or Under	Over 18'					[47]76,000	[47]76,000	[69]28,000	[69]42,000	[69]48,000	[69]62,000	[69]76,000	[47]76,000	37
. lim.[49]			44,000	56,000	50,000	60,000	73,280	73,280	31,072	45,080	51,500	61,800	73,280	73,280	38
. lim.			[50]36,000	[51]44,000	[52]53,800	[53]67,400	73,280	88,000	30,400	44,000	53,800	67,400	73,280	88,000	39
. lim.			35,000	46,000	50,000	65,000	73,280	73,280	28,000	40,000	48,000	60,000	72,000	73,280	40
e	X								26,000	40,000	44,000	58,000	72,000	73,280	41
. lim.		X	30,000	44,000	48,000	62,000	73,280		26,000	40,000	44,000	58,000	72,000	43,500	42
e	X								26,000	40,000	44,000	58,000	72,000	72,000	43
e	X		36,000	51,000	54,000	69,000	79,900	79,900	26,000	41,000	44,000	59,000	74,000	79,900	44
e-tire cap.	X						73,280	73,280	31,520	44,000	55,000	66,400	73,280	73,280	45
e		X	36,000	50,000	54,000	68,000	70,000	70,000	26,000	40,000	44,000	60,000	70,000	70,000	46
e	Under 18'	Over 18'	28,000	36,000	46,000	60,000	68,000	72,000	26,000	36,000	44,000	60,000	68,000	72,000	47
e	X		36,000	54,000	54,000	[66]70,000	70,000	70,000	26,900	41,600	45,800	60,500	73,280	73,280	48
e[61]	X								27,500	40,000	47,000	59,500	73,000	73,000	49
e	X								26,000	44,000	44,000	62,000	73,950	[12]73,950	50
e-tire cap.	X						70,000	70,000	30,000	46,000	52,000	68,000	70,000	70,000	51
. lim.-tire cap.															52
le	X								26,000	40,000	44,000	55,470	61,490	71,900	
									29	29	26	51	51	45	
									22	21	24	0	0	0	
									0	1	1	0	0	6	
e	X								28,000	40,000	48,000	60,000	72,000	86,500	
ula 5									15	30	15	25	26	3	
e 33	18	21							5	20	5	4	20	0	
. lim. 14									31	1	31	22	5	48	

icts, ores, concentrates, aggregates, and agricultural products
ounds, gross weight table; vehicle with 3 or 4 axles permitted
ore axles permitted 79,000 pounds maximum at 43-foot axle

and sectionalized buildings only; Oregon, truck tractor semi-

r-steered semitrailer or auto transport 65 feet. (on any 4 lane
on highways designated by Commissioner in North Dakota)
mitted 65' plus an additional 3' for load beyond the front or
on designated routes only.
d 60 feet.
h; trucks 26.5 feet and buses 30 feet long.
axle load 32,000 pounds.

orest products and construction materials.

; on designated routes.
permitted 70 feet.

13,000 pounds.
in combination; otherwise 26,000 pounds. When gross weight
tted 16,000 pounds per axle.
. may include a combination of saddlemount vehciles not to

feet on state primary and Interstate highways plus 5 miles

litional 6" for tires only.
pounds if less than 4 feet apart, 38,000 pounds if more than 8

nd single axle, 34,000 tandem axle, other vehicles limited to

[47]Governs gross weight permitted on highways designated by resolution of State highway commission.

[48]Does not apply if overall length of truck-tractor plus semitrailer does not exceed 50 feet.

[49]Single unit truck with 4-axle permitted 68,000 pounds.

[50]Axles spaced less than 6 feet 32,000 pounds; less than 12 feet 36,000 pounds; 12 feet or more gross weight governed by axle limit.

[51]Single vehicle with 3 or more axles spaced less than 16 feet 40,000 pounds; less than 20 feet 44,000 pounds; 20 feet or more governed by axle limit.

[52]Tractor semitrailer with 3 or more axles spaced less than 22 feet 46,000 pounds; not less than 27 feet 53,800 pounds.

[53]Legal limit 67,400 pounds, axle spacing 27 feet or more.

[54]House trailers, auto transports, and double saddle mounts in daylight hours, 60 feet.

[55]On Interstate System; 36,000 pounds on other roads.

[56]Limited to 3,500 pounds.

[57]Three axle truck 55,000 pounds with no restriction on tandem. On Interstate 22,400 pounds single, 36,000 pounds tandem.

[58]Vehicles registered before July 1, 1956, permitted limits in effect January 1, 1956, for life of vehicle.

[59]38,000 plus 900 L but not greater than 78,000 where L is the distance in feet from front to rear axle.

[60]Axle load 21,000 pounds on 2-axle trucks transporting milk and dairy supplies from farm to market but not over Interstate System. 21,500 pounds on single axle, 35,000 pounds for groups of axles less than 7 feet apart, and for groups of 3 or more consecutive axles more than 9 feet apart, 4000 pounds more than in Table for vehicles transporting peeled or unpeeled forest products cut crosswise.

[61]On Class A highways. All axles of a vehicle or combination—73,000 pounds maximum. Wheel, axle, axle group and gross vehicle weights on Class B Highways are 60% of weights including tolerance authorized for Class A highways.

[62]Based on ruling of Attorney General.

[63]Axle load 21,700 pounds on 3-axle trucks. Total not to exceed 65,000 pounds. Does not apply on any Interstate Route or Turnpike.

[64]Except three or four unit combinations may use up to 98 feet on certain highways designated by the Board of Highway Directors. Combination must include on semitrailer.

[65]60 feet for specially designed transports for motor vehicles, 65 feet for other combinations on designated highways by permit.

[66]45 feet for trailers or semi-trailers constructred especially to haul livestock, boats or motor vehicles.

[67]Weight shown plus front steering axle not to exceed 18,000 pounds.

[68]Auto transports 14 feet by permit on designated highways.

[69]On Interstate System—26,000; 40,000; 44,000; 58,000 and 72,000 pounds respectively.

[70]Not permitted on Interstate System.

[71]Limitation does not apply to a semitrailer being towed by truck tractor providing the distance between the kingpin and the rearmost axle does not exceed 38'. The semitrailer, exclusive of attachments, shall not extend forward of the rear of the truck cab.

[72]Five axle units having 42 to 51 feet of wheelbase may gross 73,280 lbs. not to exceed the specified axle loadings of 18,000 and 32,000 lbs.

population). Many two-variable relationships occurring in the physical sciences and engineering are cases of functional dependence and are not of the bivariate normal type. Even when the relationship is of the appropriate type, the correlation coefficient is very much affected by restrictions on the range of the variables or by deliberate choice of values for experimentation.

"It is always very difficult to interpret what a correlation coefficient really means. It has often been interpreted as expressing a causal rather than an association relationship, and a number of 'horrible examples' have been described in books like *How to Lie with Statistics*, by Darrell Huff, W. W. Horton and Company, New York, 1954."

The latest edition of Snedecor's *Statistical Methods* (*3*) states: "Over the last 40 years, investigators have tended to increase their use of regression techniques and decrease their use of correlation techniques. Several reasons can be suggested. The correlation coefficient r merely estimates the degree of closeness of linear relationship between Y and X, and the meaning of this concept is not easy to grasp. To ask whether the relation between Y and X is close or loose may be sufficient in an early stage of research. But more often the interesting questions are: How much does Y change for a given change in X? What is the shape of the curve connecting Y and X? These questions are handled by regression techniques.

"Secondly, the standard results for the distribution of r as an estimate of a non-zero ρ require random sampling from a bivariate normal population. Selection of the values of X at which Y is measured, often done intentionally or because of operational restrictions, can distort the frequency distribution of r to a marked degree.

"The correlation between two variables may be due to their common relation to other variables. The organic correlations already mentioned are examples. A big animal tends to be big all over, so that two parts are correlated because of their participation in the general size. Over a period of years, many apparently unrelated variables rise or fall together within the same country or even in different countries. There is a correlation of −0.98 between the annual birth rate in Great Britain, from 1875 to 1920, and the annual production of pig iron in the United States. The matter was discussed by Yule (*19*) as a question. 'Why do we sometimes get nonsensical correlations between time series? Social, economic, and technological changes produce the time trends that lead to such examples.' "

The linear models for two-variable relationships mentioned in NBS Handbook 91 are as follows:

- *FI relationships*—Functional relationships in which errors of measurement affect only one variable, Y.

- *FII relationships*—Functional relationships in which both variables, X and Y, are subject to errors of measurement.

- *SI relationships*—Statistical relationships in which a random sample of items is drawn from a bivariate normal population, and two characteristics are measured on each item.

- *SII relationships*—Statistical relationships in which one of the two variables, although a random variable in the population, is sampled only within a limited range or at selected preassigned values.

These relations are discussed in detail in the NBS Handbook. In the accompanying illustration, which was taken from that handbook, the essential features of the four models are summarized. The SI relationship is the *only* one to which the correlation coefficient r is applicable, and engineering problems usually involve one of the two functional relationships. With regard to engineering data, whether or not it is explicitly recognized, one of the variables that the experimenter is usually concerned with is a dependent variable, in which changes are caused by changes in the other, or independent, variable. This is the fundamental idea behind functional relationships.

A familiar example of the SI relationship is the correlation between height and weight of individuals taken at random from a population. Here the assumption is not that large weight *causes* large height, or vice versa, but only that the two are associated some way in the same individual. Also, it is assumed that for any given height there is a normal distribution of weights and for a given weight there is a normal distribution of heights. This is what is meant by a bivariate normal distribution.

Simple r is a measure of linear association between two variables. If the relationship is nonlinear, this fact is not revealed by the calculation of r. If the relationship involves more than two variables, multiple or partial correlation techniques may be used, provided the other assumptions on which correlation is based are met, but their use compounds the difficulties of interpretation.

Regression Techniques

In addition to Handbook 91, several other references (*4, 5, 6*) contain detailed discussions of regression techniques. Regression analysis shows how one variable changes with another, rather than simply the degree of association between them. Moreover, the standard error of estimate of the dependent variable, as well as standard deviations for the coefficients of the regression equation, are available in regression analyses. Relations that are not linear, or those involving more than one independent variable, all can be handled in a regression analysis; and appropriate significance tests can be used, if the data satisfy certain underlying assumptions.

Some references (*7, 8, 9*) contain examples which show misuse of the correlation coefficient. Usually these examples are from applications in economics, sociology, etc. An example in engineering, involving the development of a mathematical model to describe the amount of shrinkage of mortar and concrete specimens as a function of time, appears in the December 1967 Journal of Materials (*10*). In that study, eight laboratories tested 10 cements at each of four ages. The fact that some cements were not tested by all laboratories reduced the number of cement-laboratory combinations to 66. For each cement-laboratory combination, four replicate bars were made from each of three batches of mortar. For each of the four test ages, the 12 *replicate* measurements obtained were averaged and the mathemetical model previously deduced was applied. Sixty-six correlation coefficients were calculated by using the four selected times and the four averages of 12 shrinkage results. That the average of the 66 correlation coefficients obtained was 0.999 was cited as indicating that the mathematical model selected was "almost perfect in representing the experimental data."

Two aspects of the misuse of r are illustrated in the article (*10*). First, the correlation coefficient was used to *prove* a functional relationship; and second, the independent variable, time, was restricted in range and selected at four values: 1, 2, 3, and 4 weeks. A misleadingly high correlation coefficient can be obtained whenever one of the variables is restricted in this manner. An equally misleadingly high correlation coefficient can be obtained from an unrestricted range when one of the variables is time, because a high correlation coefficient does not imply a good functional relationship under these circumstances.

The averaging of the shrinkage data also contributed to making the correlation coefficients misleadingly high. Averaging of statistical variation among replicate measurements is a valid process in establishing a functional relationship, but the variation removed by the process is an important part of the information about how good the relationship is between two variables and of how well the mathematical model can be used in prediction. For one cement laboratory-combination in the study reported here, the calculated r was 0.999 when the four averages were used, but was 0.985 when the 48 individual measurements were used.

The authors of that paper justified their use of the correlation coefficient and treatment of the data on the grounds that the correlation coefficient "would be easier to understand by the nonstatistically trained reader" and they were "not interested in measuring the 'noise intensity' " but in "eliminating the 'background noise' so as to be able to establish better the degree of fit of the data to the mathematical model." However, the reporting of correlation coefficients of 0.999 may give the nonstatistically trained reader, who is not acquainted with the simplifying assumptions used, a wrong impression about the preciseness of the mathematical model.

No criticism of the mathematical model, of the regression techniques used, or of the conclusions stated at the end of that paper is intended. The only point at issue is the inappropriateness of the calculated correlation coefficient as an indicator of the quality of the relationship.

	Functional (F)		Statistical (S)	
	FI	FII	SI	SII
Distinctive Features and Example	x and y are linearly related by a mathematical formula, $y = \beta_0 + \beta_1 x$, or $x = \beta_0' + \beta_1' y$, which is not observed exactly because of disturbances or errors in one or both variables. Example: Determination of elastic constant of a spring which obeys Hooke's law. x = accurately-known weight applied, Y = measured value of corresponding elongation y.		X = Height Y = Weight Both measured on a random sample of individuals. X is *not* selected but "comes with" sample unit.	X = Height (preselected values) Y = Weight of individuals of preselected height X is measured beforehand; only *selected* values of X are used at which to measure Y.
Errors of Measurement	Measurement error affects Y only.	X and Y both subject to error.	Ordinarily negligible compared to variation among individuals.	Same as in SI.
Form of Line Fitted	$Y = b_0 + b_1 x$	See Paragraph 5-4.3.	$\bar{Y}_X = b_0 + b_1 X$ $\bar{X}_Y = b_0' + b_1' Y$	$\bar{Y}_X = b_0 + b_1 X$ only.
Procedure for Fitting	See Paragraphs 5-4.1, 5-4.2, and basic worksheet.	Procedure depends on what assumptions can be made. See Paragraph 5-4.3.	See Paragraph 5-5.1 and basic worksheet.	See Paragraph 5-5.2 and basic worksheet.
Correlation Coefficient	Not applicable	Not applicable	Sample estimate is $r = \frac{S_{xy}}{\sqrt{S_{xx}}\sqrt{S_{yy}}}$ See Paragraph 5-5.1.5.	Correlation may exist in the population, but r computed from *such* an experiment would provide a distorted estimate of the correlation.

Summary of four cases of linear relationships from NBS Handbook 91(2).

Use of Electronic Computers

Paradoxical as it may seem, one factor that has compounded the problem of interpretation of masses of data in this aspect, as well as in other aspects of engineering research, is the current widespread use of high-powered computing machinery. The very ease and speed with which these machines can handle large masses of data often tempts the engineer to relinquish his data to a *computer group* for a *computer analysis*, and to accept and publish the results indiscriminately on the assumption that the value of conclusions is somehow enhanced by the process. The computer can easily produce table after table containing correlation coefficients for all possible pairs of a large number of variables, and even place asterisks beside those numbers deemed *significant* because they tripped an internal switch. Experienced engineers have published results that they would never have accepted had they relied on their own engineering judgment and familiarity with their own problems, rather than depended on the computer. The trouble arises because the engineer who understands the data, abandons them to a computer specialist who, though competent in his field, has no feeling for what is reasonable or what is ridiculous in terms of what the data mean.

Another misconception that appears frequently in uses of the correlation coefficient involves the meaning of a *significant* correlation coefficient. In many texts, tables of the percentage points of the distribution of r for various numbers of measurements are given. Calculated correlation coefficients are often quoted as being *highly significant* on the basis of these tables without recognition of the fact that *significant*, in this context, merely means sufficiently large to permit rejection of the hypothesis that $\rho = 0$ in the population. In a recent report, a correlation coefficient of 0.109 was labeled *highly significant* because it was based on 713 measurements. A large number of measurements, although insuring that the calculated r is probably very close to the true ρ in the population, still does not indicate a good relationship between the two variables involved.

In summary, it seems that the engineering researcher who uses regression techniques gets much more for his time and effort, even in the infrequent situations in which the assumptions required by the correlation coefficient are known to have been met.

Significant Correlation Coefficient

Another pitfall connected with use of correlation coefficients occurs when all possible pairs of correlation coefficients for a large number of variables are computed. Often this is done and those pairs that show the largest coefficients are selected for further study. This practice ignores the fact that the significance points of the distribution of r from a population with $\rho = 0$ are points beyond which a certain percentage of calculated r's *must be expected* to occur on the average. Thus, if 100 correlation coefficients are calculated, approximately five of them will appear to be significant at the 95 percent confidence level, merely by chance, even if there are *no* correlations whatsoever between any of the pairs of variables being studied. The possible minimum correlation in the population corresponding to a *high* sample r is greatly reduced when this practice is followed (5).

There are situations in which the correlation coefficient may be used in analyzing engineering data. But in all such situations the researcher must be very careful in drawing conclusions on the basis of these deceptively simple numbers.

Quotations from Statistical Authorities Regarding the Correlation Coefficient

Kendall and Stuart (7)

pp. 278–9. "We may be interested either in the *interdependence* between a number (not necessarily all) of our variables or in the *dependence* of one or more variables on others. For example, we may be interested in whether there is a relationship between length of arm and length of leg in men; put this way, it is a problem of interdependence. But if we are interested in using leg-length measurements to convey information about arm-length, we are considering the dependence of the latter upon the former. This is a case in which either interdependence or depen-dependence may be of interest. On the other hand, there are situations when only dependence is of interest. The relationship of crop-yields and rainfall is an example in which nonstatistical considerations make it clear that there is an essential asymmetry in the situation. We say, loosely, that rainfall causes crop-yield to vary, and we are quite certain that crops do not affect the rainfall, so we measure the dependence of yield upon rainfall.

"There is no clear-cut distinction in statistical terminology for the techniques appropriate to these essentially different types of problems. . . . Nevertheless, it is true in the main that the study of *interdependence* leads to the theory of correlation . . . while the study of *dependence* leads to the theory of regression. . . ."

p. 279. "A statistical relationship, however strong and however suggestive, can never *establish* a causal connexion; our ideas on causation must come from outside statistics, ultimately from some theory or other.

"In the first flush of enthusiasm for correlation techniques, it was easy for followers of Karl Pearson and Yule to be incautious. . . . Yule (1926) frightened statisticians by adducing cases of very high correlations which were obviously not causal; e.g., the annual suicide rate was highly correlated with the membership of the Church of England. Most of these 'nonsense' correlations operate through concomitant variation in time, and they had the salutary effect of bringing home to the statistician that causation cannot be deduced from any observed co-variation, however close. Now, more than thirty years later, the reaction has perhaps gone too far; correlation analysis is very unfashionable among statisticians. Yet there are large fields of application (the social sciences and psychology, for example) where patterns of causation are not yet sufficiently well understood for correlation analysis to be replaced by more specifically 'structural' statistical methods."

Bowker and Lieberman (1)

pp. 242ff. "There are two different ways in which pairs of measurements can occur: namely when there is an underlying physical relationship and when there is a degree of association.

"In the first case, a functional relationship between y and x is assumed. Observations are made on a random variable y, whereas x is some known constant associated with this random variable. An example of such an experiment is the effect of time of aging on the strength of cement. The time corresponds to the x variate, the values of which are predetermined in the experiment. For a given value of time, the yield (corresponding to the y variate) is the random variable. Most problems which involve time usually fall into the framework above. Time can frequently be measured to a sufficient degree of accuracy so that it can be assumed to be a known constant.

"Other examples of a functional relationship are problems which involve calibration against a known standard. A series of observations may be taken by a laboratory on material whose contents are known accurately by design. The random variable y can be considered as the laboratory measurement, whereas the true composition may be regarded as the x variate. The example of calibrating a new method of determining CaO falls into this category. In each of these examples, and in the general situation, interest is centered on determining the average value of the random variable y as a function of the fixed value x. Naturally, x is never known exactly, but it is sufficient to have the error in x small compared to the variability of y.

"The degree of association case deals with observations x and y, each of which represents measurements on random variables associated with different characteristics of the same item. Interest is centered on determining the relationship between the two variables for any number of reasons. Measurements on one variable, say x, may be relatively inexpensive compared with measurements of y, thereby resulting in a monetary saving if y can be predicted from a knowledge of x. For example, determining abrasion loss is difficult, whereas measuring hardness by means of a Rockwell hardness machine is relatively simple. There exists a degree of association between abrasion loss and hardness. The example of proportional limit and tensile strength falls into this category.

"The relationship between two laboratories with respect to measurement on a certain material whose composition is not known accurately is another example where 'degree of association' is important. Each laboratory measures the sample for the quantities of the unknown characteristics and the relationship between each laboratory's results is ascertained. Measurements of both labor[a]tories may be regarded as random variable[s].

"In each of these examples, and in th[e] general situation, interest is centered on d[e]termining the average value of the rando[m] variable y as a function of a given value th[at] the random variable x takes on. Althoug[h] both of the cases presented have this pro[p]erty, the underlying assumptions are com[pletely] different. However, it turns out th[at] the methods of analysis are identical. Henc[e] once the experimenter recognizes the di[s]tinction in models, the formal mechanics ca[n] be carried out without regard to the situatio[n] that exists."

(Discussion of fitting straight lines by least squares estimates follows.)

pp. 273ff—Correlation. "In engineerin[g] problems, interest is sometimes centered [in] determining the distribution of two relate[d] variables and the degree of association betwe[en] them rather than in estimating one variab[le] from another. In earlier chapters, it wa[s] indicated that the distribution of a sing[le] variate could be characterized by its moment[s] or approximated by estimates of its moment[s]. In the case of two variables, the joint distr[i]bution of these variables is represented n[ot] only by the moments of the individual var[i]ables, but by some measure of their joi[nt] behavior. If the two variables have a bivaria[te] normal distribution, then the measure of the[ir] joint behavior is called the correlation c[o]efficient and will be denoted by ρ. . . . A[n] estimate of ρ is given by the sample correlatio[n] coefficient r. . . . The sample correlatio[n] coefficient can be derived from the slope [of] the fitted least squares line. . . . Cons[e]quently, it is clear that the sample correlatio[n] coefficient does not contain any addition[al] information. In fact, a significance test f[or] $\rho=0$ is equivalent to testing whether $B=$[0], i.e., whether or not a relationship exist[s]. These relationships indicate that correlatio[n] and fitting lines are mathematically equiv[a]lent, although these techniques are used f[or] different types of problems. In engineerin[g] applications, the correlation coefficient do[es] not play a very important role."

Freund (8)

pp. 358ff—The Interpretation of r. "W[e] already know how to interpret r when it equa[ls] 0, +1, or −1. When it is 0, the points are [so] scattered, the fit of the regression line is [so] poor, that knowledge of x does not aid in th[e] prediction of y; when it is +1 or −1, all th[e] points actually lie on a straight line and [it] stands to reason that we should be able to mak[e] excellent predictions of y by using the equ[a]tion of the line. Values of r falling betwe[en] 0 and +1 or between 0 and −1 are mo[re] difficult to explain; a person who has no know[l]edge of statistics might easily be led to th[e] *erroneous* idea that a correlation of $r=0.80$ is 'twice as good' as a correlation of $r=0.40$, or that a correlation of $r=0.75$ is 'three times as good' or 'three times as strong' as a correlation of $r=0.25$. . . .

"As a word of caution let us add that the coefficient of correlation is not only one of the most widely used, but also one of the most widely abused of statistical measures. It is abused in the sense that (1) it is often overlooked that r measures only the strength of *linear* relationships and that (2) it does not necessarily imply a cause-effect relationship.

"If r is calculated indiscriminately, for nstance, for the data of Figure 15.5 (Fig. 15.5 shows a plot of points which closely fit a concave-upward curve), a value of r close to 0 does not imply that the two variables are not related. The dashed curve of Figure 15.5 provides an excellent fit even though the straight line does not. Let us remember, therefore, that r measures only the strength of linear relationships.

"The fallacy of interpreting high values of r as implying cause-effect relationships is best explained with a few examples. One such example, which is frequently used as an illustration, is the high positive correlation one obtains for data pertaining to teachers' salaries and the consumption of liquor over the years. This is obviously not a cause-effect relationship; it results from the fact that both variables are effects of a common cause—the overall standard of living. Another classical example is the strong positive correlation obtained for the number of storks seen nesting in English villages and the number of childbirths recorded in the same communities. . . . These examples serve to illustrate that it is much safer to interpret correlation coefficients as measures of *association* rather than cauation. . . .

"It is sometimes overlooked that when r is calculated on the basis of sample data, we may get a strong (positive or negative) correlation purely by chance, even though there is actually no relationship whatsoever between the two variables under investigation." (Description of experiment involving throws of a pair of dice follows.)

"When a correlation coefficient is calculated on the basis of sample data, as in the above example, the value we obtain for r is only an *estimate* of a corresponding parameter, the *population correlation coefficient*, which we refer to as ρ (*rho*). To test the null hypothesis of no correlation, namely, the hypothesis that $\rho=0$, we shall have to make several assumptions about the distribution of the random variables whose values we observe. In *normal correlation analysis* we make the assumptions of *normal regression analysis* . . ., except that now the x's are not looked on as constants but as values of a random variable having itself a normal distribution."

Moroney (9)

pp. 246ff. "It very rarely happens that an effect is brought about by a single cause—rather do we find that a certain combination of circumstances is necessary, and the absence of even one of them is enough to prevent the occurrence of the event."

(Discussion of causes of diptheria follows.)

p. 247. "It will be appreciated that however great the difficulties, the research worker has to press on with his task of trying to piece together the whole story. Association and the theory of Dependence are at once great assets to him and dangerous pitfalls, especially when he is dealing with small samples."

pp. 248 and 249. "The significance test (tests) the *reality* of the association without telling us anything about the *intensity* of association. It will be apparent that we need two distinct things, (a) a test of significance, to be used on the data first of all, and (b) some measure of the intensity of the association, which we shall only be justified in using if the significance test confirms that the association is real. . . . In statistics when we speak of association there is always a comparison implied. . . .

"The danger of drawing the obvious conclusion from association has already been pointed out. The association between two things might be due, not to any direct causal relation between them, but to their joint association with a third factor."

pp. 303 and 304. ". . . at no point are statistical methods more of a sausage machine than in correlation analysis. The problem of interpretation is always very much more difficult to deal with than the statistical manipulations, and for this side of the work there is no substitute for detailed practical acquaintance with every aspect of the problem. The statistician can only help out the specialist in the field, not replace him. The man who plays carelessly with sharp tools is asking to be cut.

"In the fields where controlled experimentation is usually more or less impossible, such as economics or social research, it is also true, unfortunately, that in any problem under discussion we have to take account of several factors at the same time. Under these conditions we may calculate the correlation coefficient between any pair of the variables. But the obvious conclusion is not always the correct one. . . . The best advice that we can give to a man who finds a correlation and starts to say 'It's obvious,' is: Think again. Ten to one there's a catch in it. The reader has been well enough warned by now unless he is 'invincibly ignorant,' as the theologians have it. We shall therefore explain, briefly, the routine for analysis with several factors, making at once the proviso that it is usually profitless to apply the methods to cases involving more than four variables."

Dixon and Massey (11)

p. 189. "A regression problem considers the frequency distribution of one variable when another is held fixed at each of several levels. A correlation problem considers the joint variation of two measurements, neither of which is restricted by the experimenter. Examples of regression problems can be found in the study of the yields of crops grown with different amounts of fertilizer, the length of life of certain animals exposed to different amounts of radiation, the hardness of plastics which are heated for different periods of time. In these problems the variation in one measurement is studied for particular levels of the other variable selected by the experimenter. Examples of correlation problems are found in the study of the relationship between IQ and school grades, blood pressure and metabolism, height of cornstalk and yield, etc. In these examples both variables are observed as they naturally occur, neither variable being fixed at predetermined levels."

pp. 198–200. "In a correlation problem we sample from a population, observing two measurements on each individual in the sample. This contrasts with a purely regression problem, where the sample is chosen with preassigned X values. A large part of the classical study of this subject is based upon the assumption that the distribution of values (X, Y) is a 'two-variable normal' distribution. In appearance the distribution surface is bell-shaped. The distribution of Y values for any fixed X is normal, and the distribution of X values for any fixed Y is also normal. The regression curve of Y on X and the regression curve of X on Y are both straight lines with homoscedasticity (constant variance) for both X and Y variables. . . . A serious disadvantage is the rare occurrence of populations which have bivariate normal distributions i.e., populations having both the distribution of Y values for given X and the distribution of X values for given Y normal. Another disadvantage lies in the sampling procedure, which requires that neither variable be controlled."

Natrella (2)

pp. 5–1 and 5–2. "In many situations it is desirable to know something about the relationships between two characteristics of a material, product, or process. In some cases, it may be known from theoretical considerations that two properties are functionally related, and the problem is to find out more about the structure of this relationship. In other cases, there is interest in investigating whether there exists a degree of association between two properties which could be used to advantage. For example, in specifying methods of test for a material, there may be two tests available, both of which reflect performance, but one of which is cheaper, simpler, or quicker to run. If a high degree of association exists between the two tests, we might wish to run regularly only the simpler test.

"Where only two characteristics are involved, the natural first step in handling the experimental results is to plot points on graph paper. . .

"There is no substitute for a plot of the data to give some idea of the general spread and shape of the results. A pictorial indication of the probable form and sharpness of the relationship, if any, is indispensable and sometimes may save needless computing. When investigating a structural relationship, the plotted data will show whether a hypothetical linear relationship is bourne out; if not, we must consider whether there is any theoretical basis for fitting a curve of higher degree. When looking for an empirical association of two characteristics, a glance at the plot will reveal whether such association is likely or whether there is only a patternless scatter of points.

"In some cases, a plot will reveal unsuspected difficulties in the experimental setup which must be ironed out before fitting any kind of relationship (example follows). If no obvious difficulties are revealed by the plot, and the relationship appears to be linear, then a line $Y=b_0+b_1X$ ordinarily should be fitted to the data.

p. 5–3. "Before giving the detailed procedure for fitting a straight line, we discuss different physical situations which can be described by a linear relationship between two variables. The methods of description and prediction may be different, depending upon the underlying system. In general, we recognize two different and important systems which we call *Statistical* and *Functional*. It is not possible to decide which is the appropriate system from looking at the data. The distinction must be made before fitting the line—indeed, before taking the measurements."

p. 5–3.1—Functional Relationships. "In the case of a Functional Relationship, there exists an exact mathematical formula (y as a function of x) relating the two variables, and the only reason that the observations do not fit this equation exactly is because of disturbances or errors of measurement in the observed values of one or both variables. . . . Common situations that may be described by Functional Relationships include calibration lines, comparisons of analytical procedures and relationships in which time is the X variable.

pp. 5–5, 5–3.2—Statistical Relationships. "In the case of a Statistical Relationship, there is no exact mathematical relationship between X and Y; there is only a statistical association between the two variables as characteristics of individual items from some particular population. If this statistical association is of bivariate normal type . . . then the average value of the Y's associated with a particular value of X, say $\overline{Y}$, is found to depend linearly on X, i.e., $\overline{Y}_x=\beta_0+\beta_1X$; similarly, the *average* value of the X's associated with a particular value of Y, say $\overline{X}_y$, depends linearly on Y . . ., i.e., $X_y=\beta_0+\beta_1\ Y$, but—and this is important!—the two lines are *not* the same. . . ."

pp. 5–6ff. "SI Relationships. In this case, a random sample of items is drawn from some definite population (material, product, process, or people), and two characteristics are measured on each item.

"A classic example of this type is the relationship between height and weight of men. Any observant person knows that weight tends to vary with height, but also that individuals of the same height may vary widely in weight. It is obvious that the errors made in measuring height or weight are very small compared to this inherent variation between individuals. We surely would not expect to predict the exact weight of one individual from his height, but we might expect to be able to estimate the average weight of all individuals of a given height.

"The height-weight example is given as one which is universally familiar. Such examples also exist in the physical and engineering sciences, particularly in cases involving the interrelation of two test methods. In many cases there may be two tests that, strictly speaking, measure two basically different properties of a material, product, or process, but these properties are statistically related to each other in some complicated way and both are related to some performance characteristic of particular interest, one usually more directly than the other. Their interrelationship may be obscured by inherent variations among sample units (due to varying density, for example). We would be very interested in knowing whether the relationship between the two is sufficient to enable us to predict with reasonable accuracy, from a value given by one test, the average value to be expected for the other—particularly if one test is considerably simpler or cheaper than the other.

"The choice of which variable to call X and which variable to call Y is arbitrary—actually there are two regression lines. If a statistical association is found, ordinarily the variable which is easier to measure is called X. Note well that this is the only case of linear relationship in which it may be appropriate to fit two different lines, one for predicting Y from X and a different one for predicting X from Y, *and* the only case in which the sample correlation coefficient r is meaningful as an estimate of the degree of association of X and Y *in the population* as measured by the population coefficient of correlation $\rho=\sqrt{\beta_1\beta_1'}$."

pp. 5–7ff. "SII Relationships. The gene[ral] case described above (SI) is the most famili[ar] example of a statistical relationship, but w[e] also need to consider a common case [of] Statistical Relationship (SII) that must [be] treated a bit differently. In SII, one of t[he] two variables, although a random variable [in] the population, is sampled only within [a] limited range (or at selected preassign[ed] values). In the height–weight example, su[p]pose that the group of men included on[ly] those whose heights were between 5 ft. 4 i[n.] and 5 ft. 8 in. We are now able to fit a li[ne] predicting weight from height, but are u[n]able to determine the correct line for predicti[ng] height from weight. A correlation coefficie[nt] computed from such data is not a measure [of] the true correlation among height and weig[ht] in the (unrestricted) population."

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Digest of Recent Research and Development Results

Reported by the Implementation Division, Office of Development

The items reported here have been condensed from highway research and development reports, predominantly of Federally aided studies. Not necessarily endorsed or approved by the Federal Highway Administration, the items have been selected both for their relevancy to highway problems and for their potential for early effective application.

Each item is followed by source or reference information. Reports with an "NTIS" reference number are available in microfiche (microfilm) at 95 cents each or in paper facsimile at $3 each from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Va. 22151.

:MENT TREATED BASE (CTB) PERFORMANCE EVALUATION

States using or planning to use cement stabilization on base course nstruction will find the inventory of CTB performance in this study eful. Construction features indicative of improved performance in ılifornia are identified. The evaluation summary indicated that of '5 CTB projects built between 1950 and 1962, 64 percent are giving cellent service. Eleven percent rated less than fair required extensive aintenance early in their service lives. The main causes of failure ıpeared to be: (1) Insufficient cement content, (2) poor mixing of ment, (3) excessive trimming of the compacted CTB, (4) insufficient 'B thickness, (5) inadequate CTB compaction, or deficiencies in the phaltic concrete (AC) surfacing thickness or quality.

Improved performance of CTB composite pavements resulted from:) Extending the CTB at least 1 foot into the shoulder, (2) plant-mixing e CTB, (3) building in temperate weather, (4) increasing the thickness the asphaltic concrete surfacing, (5) limiting the compacted thickness any one layer of CTB to 6 inches, (6) using type II cement rather than ɔe I, (7) using a minimum CTB thickness of 6 inches, (8) providing a nimum in situ CTB compressive strength of 500 p.s.i.

nvestigation and Appraisal of the Performance of Cement-Treated Bases in Flexi- Pavements, 1968, California Division of Highways report, Study No. D-2-6. 'IS No. PB-179876.

JRFACE PROFILOMETER FOR CONSTRUCTION CONTROL

A commercially available towed pavement profilometer fostered by nt State and commercial development has demonstrated highly tisfactory performance. It yields both graphic and digital output. curacy and repeatability of graphic output compare favorably with ɔse of rod and level profiles, and correlation between graphical and gital output has been mathematically validated. The graphic results ɔvide a permanent record. The digital output can serve as a roughness dex. Texture of the surface is automatically eliminated as a component the roughness outputs. Functional features include 12 averaging ieels uniformly spaced both laterally and longitudinally for feeding ɔut into the recorder. Retractable outrigger wheels facilitate rapid ving between testing locations.

)evelopment of a Construction Control Profilograph, Texas Highway Department, port No. 49-3F. NTIS No. PB-185189.

:DUCING CRACK REFLECTANCE OF TUMINOUS OVERLAYS

According to a special study report, bituminous overlays on old con- ete pavements with widening strips develop less roughness and significantly fewer reflection cracks when the old pavement is broken and seated on the subgrade by rolling with a 59-ton pneumatic roller before resurfacing. Cost analysis indicated that beyond 5 years of service, the per mile cost of construction plus crack filling for the standard 4½-inch bituminous overlay (with no pavement breaker rolling) becomes greater than for the rolled section with 5 and 6 inches of bituminous overlay, based on rolling costs of $270 per mile and 1959 construction costs, and crack sealing practices and materials currently used in Minnesota.

Effect of Pavement Breaker Rolling on the Crack Reflectance of Bituminous Overlays, Minnesota Department of Highways, final report on Special Study No. 265, 1968.

SLOPE STABILITY ANALYSIS BY COMPUTER

Soils engineers benefit from a new computer program for solving highway slope stability problems using the method of slices developed by Fellenius and modified by Bishop. The procedure calculates the pressures due to steady-state water flow, and includes a line plotter and a drum plotter attached to an IBM 1130 computer for graphic output. However, the basic computer routine on which the analysis is based requires a larger system, the IBM S/360 Model 40.

Extension of ICES—LEASE I to Include Flow and Plotting Routines, MIT report, November 1968, Research Study R-12-4, Massachusetts Department of Public Works.

ADVANCED PHOTOGRAMMETRIC TECHNIQUES FOR INTERCHANGE DESIGN AND STAKEOUT

A comprehensive procedure, adaptable to computerization and using the least squares method, has been developed to give complete interchange design information on such alinement features as curve lengths, central angles, deflection angles, tangents, and azimuths of tangents, as well as radii, stationing, and coordinate value for various points. Provision is made for the simultaneous adjustment of critical points such as P.C., P.T., P.I., and others. For staking purposes, plane coordinates are given for any point on the adjusted road or ramp alinement, and horizontal angles can be computed. For construction, the LSM approach can be used in conjunction with photogrammetry for checking construction accuracy of interchange ramps.

Advance Photogrammetric Techniques for Interchange Geometric Design and Stakeout, Ohio Department of Highways report, Research Study RF2417.

Highway Research and Development Reports Available From National Technical Information Service

The following highway research and development reports are available from the National Technical Information Service (formerly the Clearinghouse for Federal Scientific and Technical Information), Sills Building, 5285 Port Royal Road, Springfield, Va. 22151. Paper copies are priced at $3 each and microfiche copies at 95 cents each. To order, send the stock number of each report desired and a check or money order to the National Technical Information Service. Prepayment is required.

Other highway research and development reports available from the National Technical Information Service will be announced in future issues.

Stock No.	
PB 191051	Analysis of Orthotropic Folded Plates with Eccentric Stiffeners.
PB 193453	A Systematic Cataloging and Evaluation of Plant Materials for Highway Use.
PB 193535	Analysis of Curved Folded Plate Structures.
PB 193903	Shrinkage, Creep, and Creep Recovery of Gap-Graded Versus Continuously-Graded Concrete—Report No. 5.
PB 193904	Permeability of Gap-Graded Versus Continuously-Graded Concrete—Report No. 7.
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PB 193927	Driving Ability as Affected by Age.
PB 193940	Optimum Proportioning of Gap-Graded Versus Continuously-Graded Concrete.
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PB 194159	Microtexture Measurements of Pavement Surfaces.
PB 194160	Effects of Fatigue on Skills Related to Driving.
PB 194168	The Effect of Pavement Friction and Adhesion.
PB 194170	A Study of the Factors Influencing Attraction and Retention of Engineering Talent With the Ohio Department of Highways.
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PB 194910	Prediction of Moisture Movement in Expansive Clays.
PB 194932	Analysis of Slab-Stringer-Diaphram Systems Final Report—Part III.
PB 194953	Design Procedure Compared to Full-Scale Tests of Drilled Shaft Footings.
PB 194954	A Condensation of the NCHRP 3-12 Draft—Development of Information Requirements and Transmission Techniques for Highway Users.
PB 194955	Annotated Bibliography and Summary of Research Needs of the Human Factors Aspects of Driver Visual Communications.
PB 194956	Psychophysiological Measurements as Related to the Operation of a Motor Vehicle.
PB 194957	Cost-Effectiveness Analysis of Roadway Lighting Systems.
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PB 195141	Load Partition and Ultimate Strength of Shingle Joints.
PB 195177	A Mathematical Model for Evaluating Priority Lane Operations on Freeways.
PB 195178	South Dakota Flexible Pavement Study.
PB 195179	Evaluation of Masonry Coatings.
PB 195180	Reflection Crack Sealing Study.
PB 195181	Pavement Design Methods, Literature Review-I.
PB 195182	Nuclear Measurement of Soil Properties.
PB 195189	Traffic Systems Reviews and Abstracts, October 1970 Issue.
PB 195328	Procedures for Estimating Flood Flows from Small Rural Watersheds.
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PB 195333	Comprehensive Planning For Rural Regions—A Case Study: The Slash Pine Experience.
PB 195334	A Method of Estimating Tensile Properties of Materials Tested in Indirect Tension—98-7.
PB 195335	Correlation of Tensile Properties With Stability and Cohesiometer Values for Asphalt-Treated Materials—98-6.
PB 195344	Evaluation of Traffic Control at Highway Intersections—78-1F.
PB 195345	Portland Cement Concrete Shoulders.
PB 195346	Fatigue Strength of Composite Beams With a Reduced Number of Shear Connectors in Highway Bridges.
PB 195399	Analog-To-Digital System—73-4.
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Aggregate Gradation for Highways: Simplification, Standardization, and Uniform Application, and A New Graphical Evaluation Chart (1962). 25 cents.

America's Lifelines—Federal Aid for Highways (1969). 35 cents.

Analysis and Modeling of Relationships between Accidents and the Geometric and Traffic Characteristics of the Interstate System (1969). $1.00.

A Book About Space (1968). 75 cents.

Bridge Inspector's Training Manual (1970). $2.50.

Calibrating & Testing a Gravity Model for Any Size Urban Area (1968). $1.00.

Capacity Analysis Techniques for Design of Signalized Intersections (Reprint of August and October 1967 issues of PUBLIC ROADS, a Journal of Highway Research). 45 cents.

Construction Safety Requirements, Federal Highway Projects (1967). 50 cents.

Corrugated Metal Pipe (1970). 35 cents.

Creating, Organizing, & Reporting Highway Needs Studies (Highway Planning Technical Report No. 1) (1963). 15 cents.

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Federal Laws, Regulations, and Other Material Relating to Highways (1970). $2.50.

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- Vol. 1—A Survey and Critique. 70 cents.
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1966, $1.25; 1967, $1.75; 1968, $1.75; 1969, $1.75.
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Hydraulic Design Series:
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- No. 3—Design Charts for Open-Channel Flow (1961). $1.50.
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