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16. Abstract

The need for vehicle weight data in planning and designing highway facilities has historically been satisfied by stopping selected vehicles at specially prepared roadside sites and weighing each wheel or each axle of the vehicle on either portable scales or on platform scales. This survey technique has been an expense as well as a safety hazard to both the surveying agency and the road user. A recently developed system for weighing highway vehicles in motion eliminates all user costs and reduces many of the traffic hazards and personnel expenses which have previously been inherent in weight surveys. Field tests of the in-motion weighing system indicate that accuracy comparable to that of conventional portable wheel weighing devices is feasible.

A recommended weight survey program for the State of Texas that incorporates in-motion weighing and dimensioning is described in this report. An evaluation of the required number of survey sites, the number of trucks to be weighed, and sampling techniques for detecting timewise variations in vehicle weight is presented. The potential economic advantages of using in-motion weighing in lieu of conventional static weighing for statewide surveys are also analyzed.

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TRUCK WEIGHT SURVEYS BY IN-MOTION WEIGHING

by

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C. Michael Walton

Research Report Number 181-1F

Application of In-Motion Weighing
in Planning and Design

Research Project 3-10-74-181

conducted for

Texas
State Department of Highways and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN

September 1975

PREFACE

For several decades, vehicle weight surveys have been conducted by highway agencies to obtain information needed for planning, designing, operating, and maintaining road systems. Until recently, such surveys have depended almost exclusively on the use of static weighing devices such as vehicle scales, axle-load scales, or wheel-load-weighers. To alleviate many of the problems associated with static weighing, a new in-motion vehicle weighing system has been developed through research. This study evaluates the practical applicability of in-motion weighing for truck weight surveys and recommends a plan for implementing this technique into the traffic survey program of the State Department of Highways and Public Transportation (formerly Texas Highway Department).

This report is the first and final report on Research Study No. 3-10-74-181, entitled "Application of In-Motion Weighing in Planning and Design," conducted at the Center for Highway Research, The University of Texas at Austin, as part of the Cooperative Highway Research Program with the State Department of Highways and Public Transportation and the Federal Highway Administration of the U. S. Department of Transportation. The study was supervised by Dr. Clyde E. Lee and Dr. C. Michael Walton. Randy B. Machemehl was in responsible charge of data collection and analysis and preparation of major portions of the study report. Harold H. Dalrymple, Research Engineer Associate V, assisted in the adaptation and operation of the instrument system along with Robert F. Inman, Technical Staff Assistant IV. Joe Word, Tom Ellison, Scott Goode, and Steve Golding contributed to the data reduction, computer programming, and other aspects of the study. Other staff members at the Center assisted in administrative and clerical work related to the project.

Continuous cooperation of personnel in D-10, Planning and Research Division, including Phillip L. Wilson, Engineer-Director; Charles R. Davis; W. R. Brown; and John J. Oliver, along with maintenance personnel in Districts 11, 14, and 17 made the study possible. Appreciation is expressed to these.

Implementation of research into practice depends upon the concerted efforts of many individuals. This report outlines a program for incorporating the results of two previous research studies into routine practice with the prospect of significant economy of operation and much enhanced safety for the public agencies and for the road users.

Randy B. Machemehl
Clyde E. Lee
C. Michael Walton

September 1975

ABSTRACT

The need for vehicle weight data in planning and designing highway facilities has historically been satisfied by stopping selected vehicles at specially prepared roadside sites and weighing each wheel or each axle of the vehicle on either portable scales or on platform scales. This survey technique has been an expense as well as a safety hazard to both the surveying agency and the road user. A recently developed system for weighing highway vehicles in motion eliminates all user costs and reduces many of the traffic hazards and personnel expenses which have previously been inherent in static weight surveys. Field tests of the in-motion weighing system indicate that accuracy comparable to that of conventional portable wheel weighing devices is feasible.

A recommended weight survey program for the State of Texas that incorporates in-motion weighing and dimensioning is described in this report. An evaluation of the required number of survey sites, the number of trucks to be weighed, and sampling techniques for detecting timewise variations in vehicle weight is presented. The potential economic advantages of using in-motion weighing in lieu of conventional static weighing for statewide surveys are also analyzed.

SUMMARY

Truck weight information obtained by conventional static weighing techniques between 1965 and 1973 at 21 sites in Texas was analyzed to determine whether similarities in axle weight distributions existed and whether or not fewer weighing stations could possibly be used to yield data of equal or better quality at lower cost. This study showed that the 21 existing stations could be grouped in such a way that there would be no statistically significant difference (at the 95 percent confidence level) between the mean number of equivalent 18-kip (80-kN) axles at any station in a designated group and at one of six representative stations. Thus, only six properly chosen stations are needed to obtain truck weight information that is as good as that which has, through the years, proved to be adequate for engineering practice. More stations may be necessary if weight predictive facility over the pre-1971 level is needed.

A field experiment was conducted to evaluate the accuracy with which the in-motion weighing system developed recently in Texas can be expected to estimate static weight from samples of the dynamic wheel forces sensed as vehicles move at normal road speeds. It was concluded that individual axle weights can be estimated by this means within about 11 percent and gross vehicle weights within about 6 percent with 70 percent confidence. As expected, vehicle configuration, vehicle loading condition, and speed were found to contribute to the variability. Some of the estimates of static weight were higher than those determined by vehicle (platform) scales, and some were lower. Since no pronounced bias toward higher or lower estimates of static weight was detected in the experiment, it was concluded that in-motion weighing gives a sufficiently accurate estimate of static vehicle weight for survey purposes. Recommendations for the size of sample needed to achieve defined levels of accuracy are included in the report, and a schedule for operating six in-motion weigh stations to detect significant timewise variation in truck weights is suggested.

An economic analysis shows pronounced advantages of in-motion weighing over conventional static weighing even when much larger samples are taken by in-motion weighing. The economic benefits become more pronounced as the number of weigh stations increases from the minimum of six that are recommended for current implementation. Safety benefits to road users and to the survey agency further enhance the advantages of in-motion weighing.

IMPLEMENTATION STATEMENT

This research has demonstrated that in-motion weighing can estimate static vehicle weights with accuracy comparable to that normally achieved by portable wheel-load weighers and that a recommended weighing program at only six sites instead of the twenty-one stations utilized previously is expected to give at least equal quality information at about half the cost. Implementation of the new program will require a relatively small initial investment in hardware, installation, and programmed maintenance, but manpower demands will be much less intensive. Road users will realize significant savings since no vehicle will need to stop for weighing. Since the major instrumentation system is already available, immediate adoption of in-motion weighing into practice is advocated.

NOTE

During most of the period of this study, what is now the State Department of Highways and Public Transportation was known as the Texas Highway Department. Throughout this report, especially in referring to events which occurred before the name was changed, the previous nomenclature is often used, but it should be realized that in all cases the state agency referred to is now known as the State Department of Highways and Public Transportation.

The change also affected the name of the Transportation Planning Division, which was previously named the Planning and Research Division and is frequently referred to that way in this report.

CHAPTER 1. INTRODUCTION

For over a half century, highway agencies have been conducting vehicle weight surveys to obtain information for planning and designing highway facilities. As allowable load limits for cargo vehicles have steadily increased and vehicle characteristics have changed, it has been necessary to conduct weight surveys on a continuing basis. Data obtained in these surveys has primarily been used in the design and planning process to characterize traffic loading of pavement and bridge structures. The data have also been used in several administrative analyses, including the estimation of miles of travel by vehicle type and ton-miles of cargo hauled by highway (Ref 27). The timewise accumulation of this information, therefore, has been an important input to the formulation of traffic policy.

In order to fulfill the need for vehicle weight data, most highway agencies have developed traffic survey programs that utilize a number of static weigh stations located at strategic sites on their various highway systems and occupied on a systematic basis throughout the year. Virtually all weight surveys have utilized one or both of two principal types of static weighing devices, namely, platform scales (vehicle scales), which weigh an entire vehicle at once, or wheel-load weighers, which obtain individual wheel loads.

Both weighing devices require that the subject vehicles be diverted from the main highway lanes and stopped during weighing operations. The resulting time delays, which range up to several minutes per vehicle, can represent a sizeable cost to highway users. In addition, maneuvering heavy commercial vehicles from or into a traffic stream can constitute a serious safety hazard. Survey personnel have often shown an understandable reluctance to operate static weighing equipment in adverse weather conditions, and nighttime operations have required special lighting and other safety considerations.

In an effort to minimize the costs, safety hazards, and bother of vehicle weight surveys to both highway users and the surveying agency, the Texas Highway Department, in cooperation with The University of Texas Center for

Highway Research and the Federal Highway Administration, began in 1963 the development of a system for weighing vehicles in motion. By 1971, a system which could weigh vehicles operating at highway speeds in a typical traffic stream had been developed. A field testing program indicated that it would be a practical tool for use in weight survey activities. Since this time the system has been used on a limited basis by the Department, and a considerable amount of field experience has been accumulated (Refs 2, 3, 22). The system, however, has not yet been integrated into normal vehicle weight survey activities.

Objective of Study

The objective of this study is to develop an implementation program which will incorporate the in-motion weighing system into normal traffic survey activities and take maximum advantage of the unique capabilities of the in-motion weighing (WIM) system. The system provides the capability of determining the wheel weights, speed, axle spacing and vehicle length of each vehicle operating in a moving traffic stream without interference to the subject vehicle. It provides the ability to conduct weight survey operations around-the-clock on a continuous sampling basis. This study is directed toward optimizing the use of these and other features of the WIM system, thereby reducing costs and improving safety as it is incorporated into usual survey activities.

Scope and Limitations

In order to accomplish this objective, the study was divided into the four phases described below:

(1) The ability of the in-motion weighing system to predict static vehicle loads was evaluated in a designed field experiment. This experiment provided a basis for defining the potential accuracy of the WIM system in quantitative terms. Although the system had been tested extensively in field use and its performance had been gradually established, no concise documentation of its accuracy had been produced. This experiment provided the needed documentation.

(2) Vehicle weight data previously obtained by the Texas Highway Department in routine static weighing operations were analyzed to determine the overall level of sampling effort needed to provide satisfactory estimates of vehicular weights.

(3) Timewise variations in vehicle weights were studied using data collected by the in-motion weighing system.

(4) An economic analysis comparing static and in-motion weighing was conducted.

Figure 1.1 depicts the flow of work and illustrates the relationship of these segments.

The scope of the study was limited to using loadometer data collected previously by the Texas Highway Department and a fairly extensive amount of data collected by the project staff. Personnel of the Texas Highway Department provided weight survey data collected during the years 1965 and 1966 and 1968 through 1973. In-motion weight classifying techniques were used by project personnel to collect data at two geographical locations over extended time periods. Specific limitations of these available data are noted in later sections of this report.

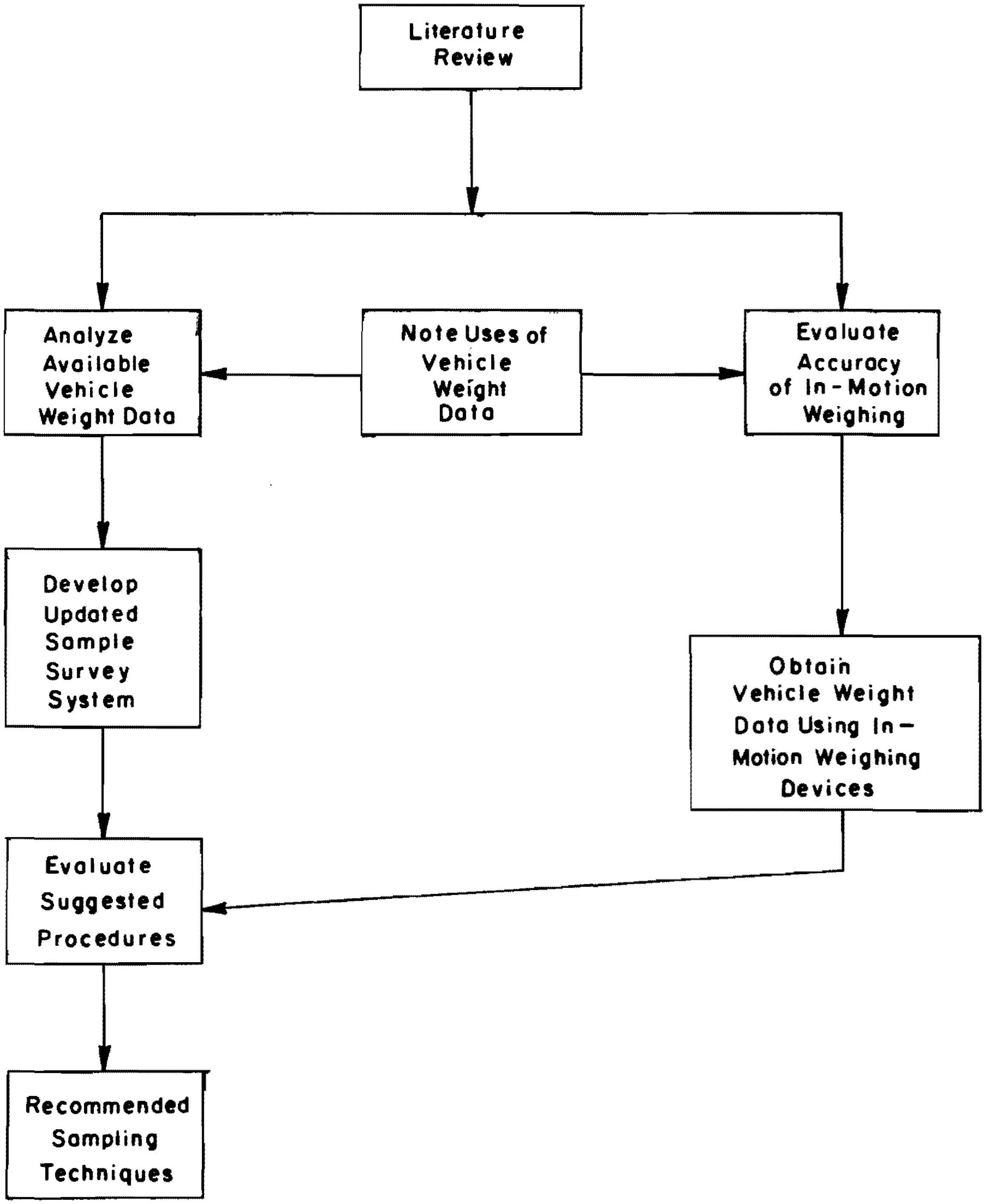


Fig 1.1. Schematic flow chart of study activities.

CHAPTER 2. VEHICLE WEIGHING IN TEXAS

Since the late 1930's, the Texas Highway Department has been conducting a systematic program of vehicle weight surveys. The following paragraphs describe this program, including equipment and techniques used, as well as a brief description of data usage.

The Weight Survey Program

Almost since the inception of the vehicle weighing program in Texas, surveys have been conducted at 21 designated sites. The locations of these sites have been slightly altered on several occasions, and, due to construction at or near some sites, operations have been suspended for short periods of time, but the original 21 sites have remained virtually unchanged through the years. Figure 2.1 illustrates the geographical locations of the original 21 survey sites.

The vehicle weight information accumulated through continuing operation for several decades at these sites forms a very large and valuable data base. This data base provides a source of information for studies of timewise trends in vehicle weights, sizes, and types. The experience gained in this weighing program provides a firm foundation upon which present and future survey activities can be based.

Due primarily to the increasing cost of operating all weighing stations and difficulty in obtaining personnel, the Texas Highway Department discontinued operation of 11 of the original 21 sites in 1971. The tabulation of comparative data which was used as the basis for selecting representative stations for continuing survey operations is included in Appendix A.

The analysis basically consisted of dividing the stations into "homogenous" groups in which the variation in vehicle weight data among stations within a group did not exceed a specific amount. One station from each of the ten groups was then chosen for continued use. The ten sites at which operations were continued after 1971 are identified in Fig 2.1 by shading.

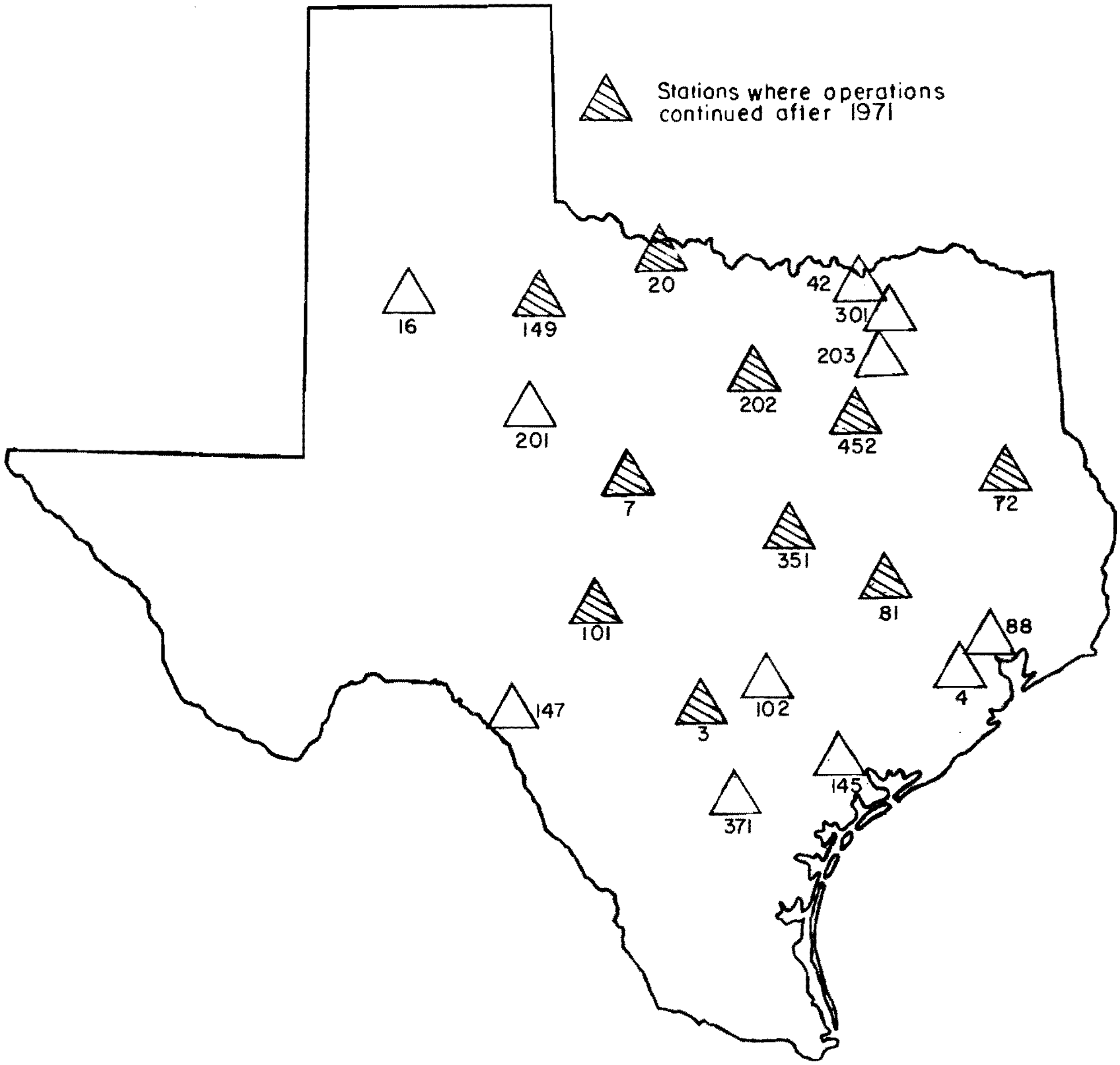


Fig 2.1. Geographical locations of weight survey stations.

Until 1967, a crew of six men was employed on a full time basis for the exclusive purpose of conducting weight surveys. This crew operated each weight station for at least 24 hours during each season of every year. The 24 hours of data acquisition operations were normally divided into three eight-hour shifts running from 6:00 a.m. to 2:00 p.m., 2:00 p.m. to 10:00 p.m., and 10:00 p.m. to 6:00 a.m. The shifts were scheduled on a systematic, though not necessarily random, basis, and no station was normally operated for more than eight consecutive hours. Each eight-hour shift was subdivided into four hours of survey activities for each direction of traffic.

In 1967, year around operations were discontinued, and, though all 21 stations were operated in the following years, activities were conducted only during the summer months. Under this modified program, data were obtained for a total of 24 hours at each station each year, but the survey period was restricted to the months of June through August.

Field Weighing Practices

Site preparation at each of the weight survey stations operated by the Texas Highway Department has consisted of paved sections of roadway parallel to the existing traffic lanes on both sides of the highway (see Fig 2.2a). Care was taken to produce a level weighing platform adjacent to a small recessed metal-lined pit in which a static wheel-load weigher was placed during survey operations (see Fig 2.2b). The pavement in advance of the weighing platform was normally constructed long enough to accommodate several waiting vehicles.

Until recently, all vehicle weighing done by the Texas Highway Department was performed using static wheel-load weighing devices. The majority of these have been manufactured by Black and Decker under the brand name "Loadometer" (see Fig 2.3). The usual practice has been to weigh only the right wheels of selected vehicles and assume that axle weight is double the respective wheel weight. The calibration of the weighing devices has been checked at least once each year using a single known weight of about 5,000 lb (22 kN) applied near the center of the weighing platen of each weighing device.

While operating any survey station, the crew attempted to weigh all commercial vehicles traveling in the particular direction being surveyed. As long as traffic volumes did not become too large, this policy was enforced,

Fig 2.2a. Site preparation for typical static weight survey station.

Fig 2.2b. Metal-lined pit for loadometer application.

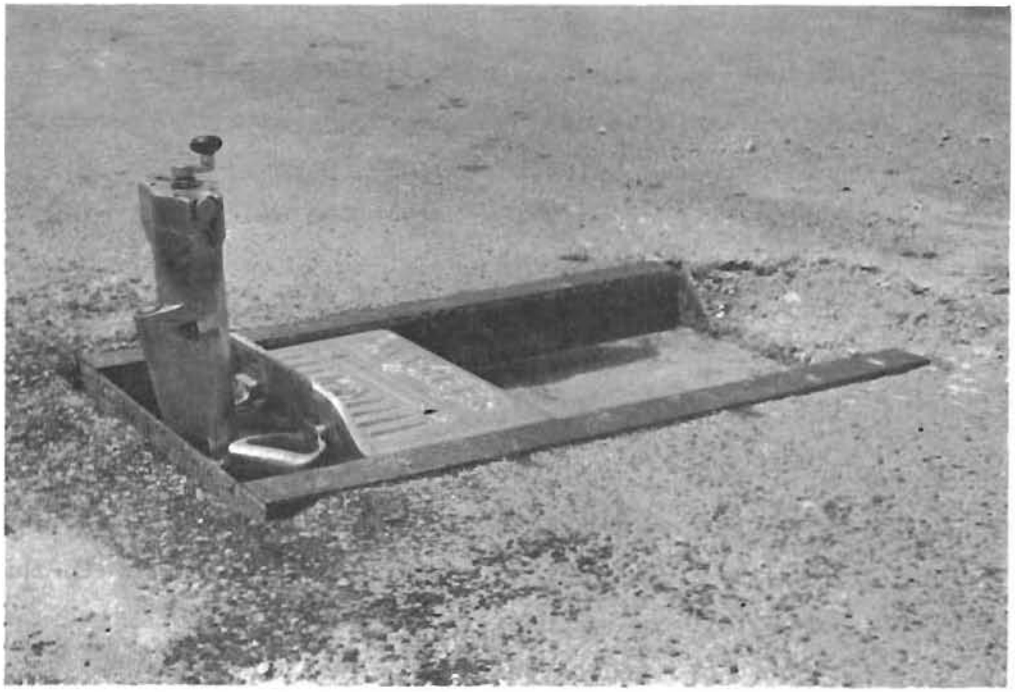


Fig 2.3a. Static wheel load weigher (loadometer).

Fig 2.3b. Static wheel load weighing operation.

but when traffic volume increased, weighing all commercial vehicles caused long waiting lines and large delays to vehicle operators. Therefore, in high truck volume situations, only selected vehicles were weighed. The process of selecting the particular vehicles which were to be weighed was left to the discretion of the flagman, who directed only chosen vehicles into the survey station so as not to create a hazardous condition. Using these techniques, about 300 to 1,000 vehicles were weighed at each station each year.

Use of Vehicle Weight Data

Processing of vehicle weight data has been performed by the Planning and Research Division of the Texas Highway Department in concert with the Division of Automation. The data were recorded in the field in a standard format and subsequently reproduced on punched cards to permit analysis and retrieval by digital computer. In recent years, they have been recorded on magnetic tape to permit more efficient storage and faster access.

Until 1969, the Planning and Research Division published summary tabulations of these data in an annual report. The report consisted of a series of tables prepared in a standard format that was specified by the Bureau of Public Roads (Federal Highway Administration). Copies of the report were made available to the Bureau, to the Divisions and Districts of the Texas Highway Department, and to others interested in such operations.

Due to changes in Federal Highway Administration requirements, since 1969 printed reports have not been prepared. Instead, the data have been forwarded on magnetic tape to the FHWA and distributed internally to Texas Highway Department users. The FHWA utilizes this information in the preparation of estimates of commodity flows, transportation system utilization, and the computation of a number of other items.

The data are usually furnished to Texas Highway Department users in the form of a standard table indicating the percentage of all axles and wheels weighed at a given station which occur in each of 50 one-kip (4.45 kN) weight classes (1 to 50 kips—4.45 to 222 kN). Table 2.1 is an example of such a table for "Loadometer" Station Number 81 at College Station, Texas.

If the selected distribution of percentages is to be used in the pavement design process, the percentage for each axle weight class can be converted to numbers of axles for each weight class. This is basically accomplished through multiplication of the percent trucks by the Average Daily Traffic and

TABLE 2.1. TYPICAL LOADOMETER DATA FORMAT

LOADOMETER STATION NO.81 IN BRAZOS COUNTY
NUMBER OF AXLES AND WHEEL LOADS ADJUSTED TO TRUCKS WEIGHED 1968 TABLE 3

GROUPS	AXLES						WEIGHT GROUPS	WHEEL LOADS					
	SINGLES	% OF TOTAL	CUMULATIVE %	TANDEM SETS	% OF TOTAL	CUMULATIVE %	(HNDS OF LBS)	SINGLES	% OF TOTAL	CUMULATIVE %	TANDEM	% OF TOTAL	CUMULATIVE %
2 KIP	1.	0.17	0.17	0.	0.0	55.46	0- 19	21.	2.52	2.52	49.	5.88	44.24
3 KIP	8.	1.39	1.56	0.	0.0	55.46	20- 29	70.	8.39	10.91	141.	16.91	61.15
4 KIP	12.	2.08	3.64	0.	0.0	55.46	30- 39	88.	10.55	21.46	65.	7.79	68.94
5 KIP	23.	3.99	7.63	0.	0.0	55.46	40- 49	84.	10.07	31.53	47.	5.64	74.58
6 KIP	47.	8.15	15.77	0.	0.0	55.46	50- 59	20.	2.40	33.93	32.	3.84	78.42
7 KIP	39.	6.76	22.53	4.	0.69	56.15	60- 69	18.	2.16	36.09	57.	6.83	85.25
8 KIP	49.	8.49	31.02	15.	2.60	58.75	70- 79	9.	1.08	37.17	72.	8.63	93.88
9 KIP	46.	7.97	38.99	25.	4.33	63.08	80- 89	6.	0.72	37.89	32.	3.84	97.72
10 KIP	38.	6.59	45.58	21.	3.64	66.72	90- 99	3.	0.36	38.25	12.	1.44	99.16
11 KIP	14.	2.43	48.01	22.	3.81	70.54	100-109	0.	0.0	38.25	3.	0.36	99.52
12 KIP	6.	1.04	49.05	12.	2.08	72.62	110-119	1.	0.12	38.37	4.	0.48	100.00
13 KIP	8.	1.39	50.43	10.	1.73	74.35	120-129	0.	0.0	38.37	0.	0.0	100.00
14 KIP	10.	1.73	52.17	11.	1.91	76.26	130-139	0.	0.0	38.37	0.	0.0	100.00
15 KIP	5.	0.87	53.03	6.	1.04	77.30	140-149	0.	0.0	38.37	0.	0.0	100.00
16 KIP	4.	0.69	53.73	4.	0.69	77.99	150-159	0.	0.0	38.37	0.	0.0	100.00
17 KIP	3.	0.52	54.25	6.	1.04	79.03	160-169	0.	0.0	38.37	0.	0.0	100.00
18 KIP	3.	0.52	54.77	5.	0.87	79.90	170-179	0.	0.0	38.37	0.	0.0	100.00
19 KIP	2.	0.35	55.11	7.	1.21	81.11	180-189	0.	0.0	38.37	0.	0.0	100.00
20 KIP	1.	0.17	55.29	3.	0.52	81.63	190-199	0.	0.0	38.37	0.	0.0	100.00
21 KIP	0.	0.0	55.29	4.	0.69	82.32	200-209	0.	0.0	38.37	0.	0.0	100.00
22 KIP	0.	0.0	55.29	3.	0.52	82.84	210-219	0.	0.0	38.37	0.	0.0	100.00
23 KIP	0.	0.0	55.29	5.	0.87	83.71	220-229	0.	0.0	38.37	0.	0.0	100.00
24 KIP	1.	0.17	55.46	2.	0.35	84.06	230-239	0.	0.0	38.37	0.	0.0	100.00
25 KIP	0.	0.0	55.46	3.	0.52	84.58	240-249	0.	0.0	38.37	0.	0.0	100.00
26 KIP	0.	0.0	55.46	8.	1.39	85.96	250-259	0.	0.0	38.37	0.	0.0	100.00
27 KIP	0.	0.0	55.46	9.	1.56	87.52	260-269	0.	0.0	38.37	0.	0.0	100.00
28 KIP	0.	0.0	55.46	10.	1.73	89.25	270-279	0.	0.0	38.37	0.	0.0	100.00
29 KIP	0.	0.0	55.46	13.	2.25	91.51	280-289	0.	0.0	38.37	0.	0.0	100.00
30 KIP	0.	0.0	55.46	6.	1.04	92.55	290-299	0.	0.0	38.37	0.	0.0	100.00
31 KIP	0.	0.0	55.46	12.	2.08	94.63	300-309	0.	0.0	38.37	0.	0.0	100.00
32 KIP	0.	0.0	55.46	9.	1.56	96.19	310-319	0.	0.0	38.37	0.	0.0	100.00
33 KIP	0.	0.0	55.46	5.	0.87	97.05	320-329	0.	0.0	38.37	0.	0.0	100.00
34 KIP	0.	0.0	55.46	2.	0.35	97.40	330-339	0.	0.0	38.37	0.	0.0	100.00
35 KIP	0.	0.0	55.46	4.	0.69	98.09	340-349	0.	0.0	38.37	0.	0.0	100.00
36 KIP	0.	0.0	55.46	2.	0.35	98.44	350-359	0.	0.0	38.37	0.	0.0	100.00
37 KIP	0.	0.0	55.46	4.	0.69	99.13	360-369	0.	0.0	38.37	0.	0.0	100.00
38 KIP	0.	0.0	55.46	0.	0.0	99.13	370-379	0.	0.0	38.37	0.	0.0	100.00
39 KIP	0.	0.0	55.46	0.	0.0	99.13	380-389	0.	0.0	38.37	0.	0.0	100.00
40 KIP	0.	0.0	55.46	2.	0.35	99.48	390-399	0.	0.0	38.37	0.	0.0	100.00
41 KIP	0.	0.0	55.46	0.	0.0	99.48	400-409	0.	0.0	38.37	0.	0.0	100.00
42 KIP	0.	0.0	55.46	1.	0.17	99.65	410-419	0.	0.0	38.37	0.	0.0	100.00
43 KIP	0.	0.0	55.46	0.	0.0	99.65	420-429	0.	0.0	38.37	0.	0.0	100.00
44 KIP	0.	0.0	55.46	0.	0.0	99.65	430-439	0.	0.0	38.37	0.	0.0	100.00
45 KIP	0.	0.0	55.46	1.	0.17	99.83	440-449	0.	0.0	38.37	0.	0.0	100.00
46 KIP	0.	0.0	55.46	1.	0.17	100.00	450-459	0.	0.0	38.37	0.	0.0	100.00
47 KIP	0.	0.0	55.46	0.	0.0	100.00	460-469	0.	0.0	38.37	0.	0.0	100.00
48 KIP	0.	0.0	55.46	0.	0.0	100.00	470-479	0.	0.0	38.37	0.	0.0	100.00
49 KIP	0.	0.0	55.46	0.	0.0	100.00	480-489	0.	0.0	38.37	0.	0.0	100.00
50 KIP	0.	0.0	55.46	0.	0.0	100.00	490-499	0.	0.0	38.37	0.	0.0	100.00
51 KIP	0.	0.0	55.46	0.	0.0	100.00	500-509	0.	0.0	38.37	0.	0.0	100.00
52 KIP	0.	0.0	55.46	0.	0.0	100.00	510-519	0.	0.0	38.37	0.	0.0	100.00
53 KIP	0.	0.0	55.46	0.	0.0	100.00	520-529	0.	0.0	38.37	0.	0.0	100.00
54 KIP	0.	0.0	55.46	0.	0.0	100.00	530-539	0.	0.0	38.37	0.	0.0	100.00
55 KIP	0.	0.0	55.46	0.	0.0	100.00	540-549	0.	0.0	38.37	0.	0.0	100.00
56 KIP	0.	0.0	55.46	0.	0.0	100.00	550-559	0.	0.0	38.37	0.	0.0	100.00

SINGLE AXLES + TANDEM SETS = 577.

1 kip = 4.45 kN

SINGLE WHEEL LOADS + TANDEM WHEEL LOADS = 834.

converting the resulting number of trucks to a number of axles using a standard conversion factor. (This conversion factor, which consists of the average number of axles per vehicle, is the subject of a later section of this study.) The resulting number of axles can be multiplied by each percentage in the weight distribution to produce an estimate of the number of axles which will occur in each weight class. This frequency distribution of axle weights is a primary input to most pavement design techniques.

In-Motion Vehicle Weighing

Since 1970, the Department has been collecting a limited amount of vehicle weight information using an in-motion weighing system that was developed especially for the Planning and Research Division through the cooperative highway research program with the Center for Highway Research. This system has the capability of measuring vehicle wheel weights while vehicles move in the normal traffic stream at highway speeds. To date, in-motion weight surveys have been conducted at three sites located near the cities of Austin, Bryan, and Lufkin. Although the system is operational, it has not yet been fully integrated into routine survey activities. A description of this system, its history, and recommended uses are the subject of the following sections of this report.

CHAPTER 3. IN-MOTION VEHICLE WEIGHING

The concept of weighing and dimensioning moving highway vehicles is not new. For several decades a number of different agencies have conducted research into the development of hardware and procedures needed for this purpose. During the 1960's General Motors, Philco-Ford, the Road Research Laboratory, the Michigan and Illinois Departments of Highways, and a number of others experimented with in-motion weighing (see Refs 3, 7, 9, 10, 3, 4, 7, 3, 6, 14). About 1963, work began in Texas on an in-motion weighing system, and by 1968 a suitable wheel-load transducer had been designed and field testing had begun. By 1971, a transportable instrumentation system had been developed and the Texas Highway Department had begun using in-motion vehicle weighing on a limited basis for weight acquisition. During the past decade, the system has been modified to take advantage of recent innovations in electronics and data processing.

The Texas In-Motion Weighing System

The in-motion weighing system described in the following paragraphs was developed through a cooperative research effort of The University of Texas Center for Highway Research, the Texas Highway Department, and the Federal Highway Administration. The components which make up the system are currently marketed commercially by two firms in Austin, Texas (see Refs 34 and 42).

The system determines and records dynamic wheel forces in each wheel path of one traffic lane, axle spacings, vehicle speed, number of axles per vehicle, and time of day (Ref 26). From these measurements, summary statistics including axle weights, gross vehicle weight, and wheel base are automatically computed. Tire forces applied normal to the pavement surface by a moving vehicle are sampled by two wheel-load transducers which are set flush with the pavement (see Fig 3.1). The transducers produce electrical signals which are proportional to the applied tire forces. Data needed for the computation of vehicle speed and axle spacing are provided by three inductance loop-type vehicle detectors located beneath the pavement surface. All in-road

Fig 3.1. Wheel load transducers.

Fig 3.2. Van housing data display and recording equipment.

hardware is beneath the pavement surface and is, therefore, non-hazardous and inconspicuous to the road user.

Analog electrical signals produced by the sensors in the road are converted to digital form, stored, and displayed by equipment housed in a van parked a safe distance off the roadway (see Fig 3.2). The operator may inspect the information immediately or record it for subsequent computer processing. The system may be operated in a fully automatic mode while recording data for all traffic in one traffic stream, or the operator can choose to manually select vehicles in the stream, or a weight threshold can be set to determine which vehicles are weighed by the system. The instrument van can be readily moved from one site to another and connected to instrumentation previously installed in the road.

Accuracy of In-Motion Weighing

Although the Texas in-motion weighing (WIM) system has been operational for several years, the accuracy with which it can estimate static vehicle loads had not been adequately documented prior to the fall of 1973. In order to provide this documentation, a field testing program was designed and conducted at the WIM site located on Interstate Highway 35 approximately 6 miles (10 km) south of Austin, Texas. The test consisted of comparing the static weight of five commercial vehicles obtained by conventional platform scales and by a pair of static wheel-load weighers with that obtained by the WIM system.

Studies conducted during the development stages of WIM indicated that the ability of the system to predict static vehicle loads could vary with vehicle configuration, vehicle speed, and vehicle loading (Refs 3 and 22). Therefore, five classes of commercial vehicles were selected for use in the test to represent a broad spectrum of vehicle configurations. These vehicles included a two-axle dump truck (2D), a three-axle single-unit van (3A), a three-axle tractor semi-trailer van (2S-1), a four-axle tractor semi-trailer (2S-2), and a five-axle tractor semi-trailer (3S-2). (See Fig 3.3.) In order to evaluate the effect of vehicle speed on the WIM estimates, vehicle speeds of 30, 45, and 60 mph (48, 72, and 97 km/hr) were employed. To assess the effect of vehicle loading, the experiment was performed twice, once when all vehicles were loaded to near capacity and once when the vehicles were empty.

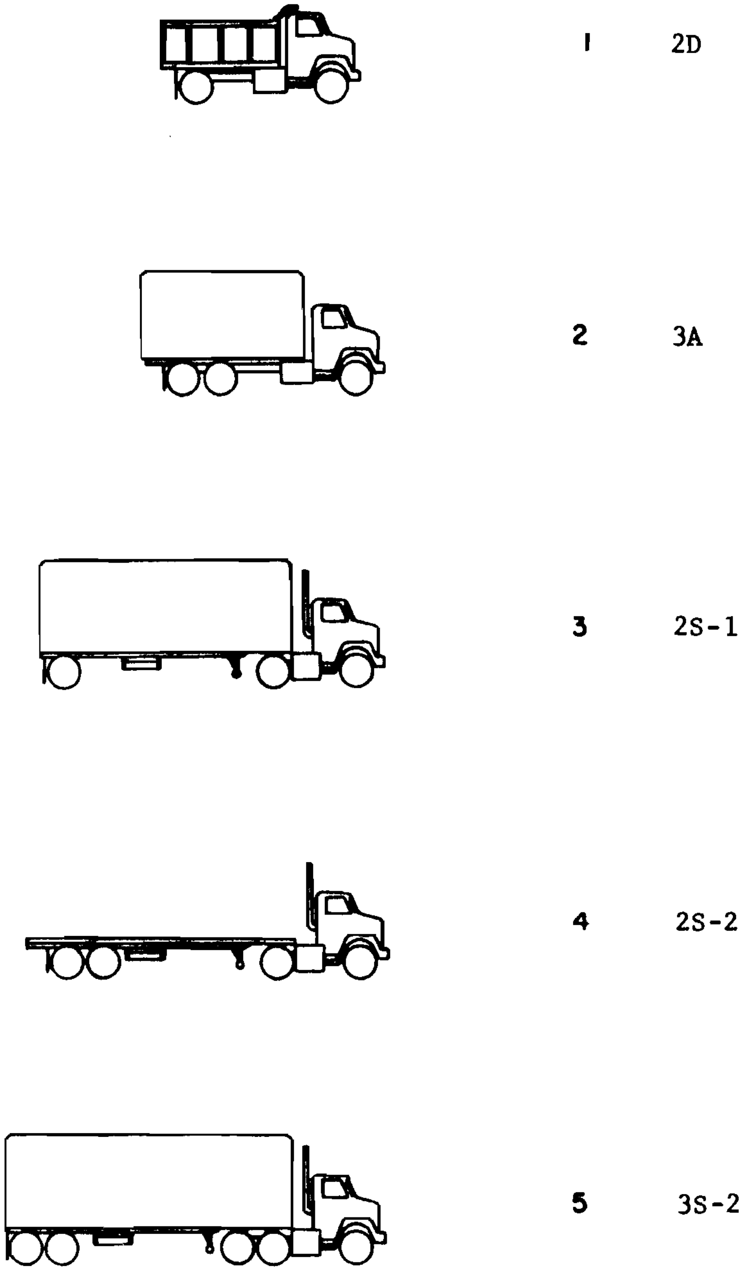


Fig 3.3. Schematic representations of test vehicles.

The field test was conducted on two successive days. On the first day, with all vehicles loaded, estimates of static weight were obtained using the platform scale, wheel-load weighers (see Ref 29 for descriptions and tolerances), and the WIM system. The following day, the entire experiment was repeated with all test vehicles completely unloaded. All measurements were replicated three times in a random sequence at the two static weigh stations while at least three replications at each of the three speed levels were obtained at the weigh-in-motion site.

The fact that the field testing could not be completed in one day was undesirable; however, due to spatial separation of the three weighing sites and the time necessary to load and unload test vehicles, it was impossible to complete the experiment in one day. There was no noticeable difference in vehicle, roadway, or environmental conditions on the two successive days.

Data Analysis

The in-motion weighing system and static wheel-load weighers measure individual wheel weights directly while platform scales (or vehicle scales) normally measure the sum of all wheel weights and indicate only gross vehicle weight. In order to provide a basis for comparing weights measured by these different devices, the approximate wheel weights measured by WIM and by the wheel-load weighers were summed to yield axle and gross vehicle weights. By successively positioning axles off the weighing platform, it was possible to compute estimates of axle weight from a series of platform scale weights. Axle and gross weight estimates could be obtained for comparing all three weighing devices, but wheel weights could be compared only between measurements from wheel-load weighers and the in-motion weighing system.

Analysis of the experimental data was conducted in two phases. In the first phase, the entire experiment was considered as a series of factorials, and analysis of variance was used to evaluate the significance of certain factors on the ability of the WIM system to predict static vehicle weights. In the second phase, a correlation analysis was performed to provide quantitative estimates of the accuracy to be expected from the in-motion weighing system.

Analysis of Variance

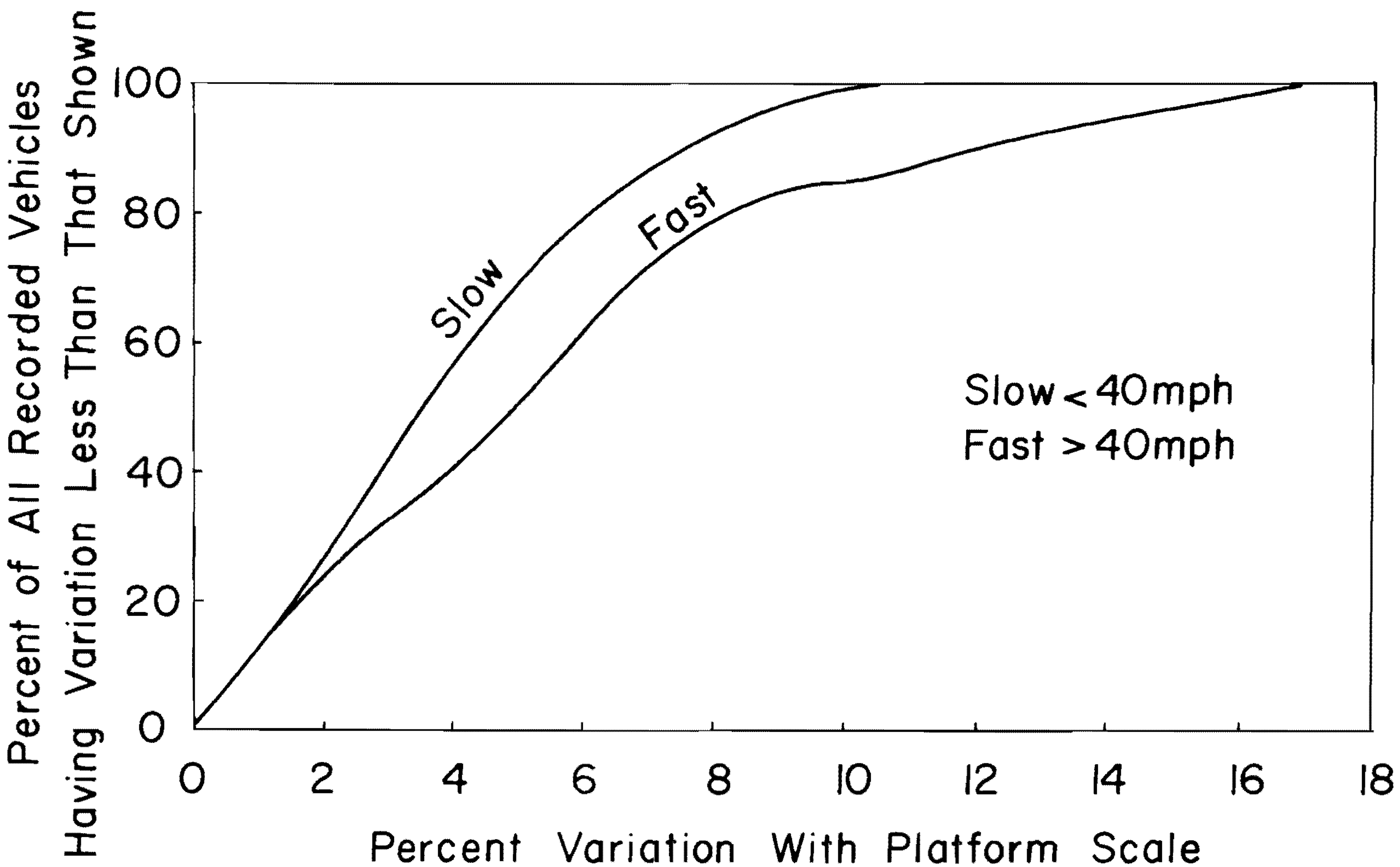
In order to determine whether or not the observed variations in WIM static weight estimates were due to chance alone or whether definable causes of variation could be identified, the WIM estimates of gross vehicle weight were analyzed in a three-way classification in which the three factors considered were (1) vehicle speed, (2) vehicle configuration, and (3) vehicle loading condition (empty or loaded). A schematic representation of the experiment design is shown in Fig 3.4. Analysis of variance indicated that the effects of each of the three factors on WIM estimates of gross vehicle weights were greater than could be attributed to chance alone 99 times out of 100; therefore, each factor contributed significantly to the variation. An illustration of the way in which vehicle speed affects WIM gross vehicle weights relative to the platform scale weights can be seen in Fig 3.5. Although vehicle speeds greater than 40 mph (64 km/hr) did not produce consistently heavier vehicle weights, higher speeds did produce vehicle weights that were consistently more scattered. For example, 60 percent of the weights observed at slow and fast vehicle speeds, respectively, had variations of less than 4.5 and 6.0 percent when compared with the platform scale.

The gross weight data obtained from the three weighing techniques described above were also analyzed in a three-way classification. The three factors studied were (1) weighing device, (2) vehicle configuration, and (3) vehicle loading condition. This factorial is illustrated in Fig 3.6. The analysis of variance performed on this classification also indicated that variations in WIM gross vehicle weights attributable to all three factors were greater than could be due to chance alone 99 times out of 100. Figure 3.7 illustrates the observed frequency of differences in gross vehicle weight obtained by static wheel load weighers and by the in-motion weighing system as compared to that obtained by the platform scale. Since the platform scale is considered to be the most accurate of the three weighing devices that were utilized, it was taken as the basis for the comparison shown in Fig 3.7. This figure indicates, for example, that 90 percent of the observations of gross weight obtained by both wheel-load weighers and by WIM were within approximately 10 percent of the values measured by the platform scale and that 60 percent of the WIM estimates of gross vehicle weight were within 5 percent of the respective platform scale weights.

Vehicle Configuration	2D						3A						2S1						2S2						3S2					
Vehicle Speed, mph	30		45		60		30		45		60		30		45		60		30		45		60		30		45		60	
Loading Condition Empty=E Loaded= L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L
Replication 1																														
2																														
3																														

1 mph = 1.6 km/hr.

Fig 3.4. Experiment design for study of factors affecting WIM estimates of static gross vehicle weight.



40 mph = 64 km/hr

Fig 3.5. Variation in gross vehicle weight measured by WIM compared with platform scale weights for slow and fast speeds.

Weighing Technique	Platform Scale										Wheel Load Weigher										WIM									
Vehicle Configuration	2D		3A		2SI		2S2		3S2		2D		3A		2SI		2S2		3S2		2D		3A		2SI		2S2		3S2	
Loading Condition Empty = E Loaded = L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L
Replication 1																														
2																														
3																														

Fig 3.6. Experiment design for comparison of weighing techniques.

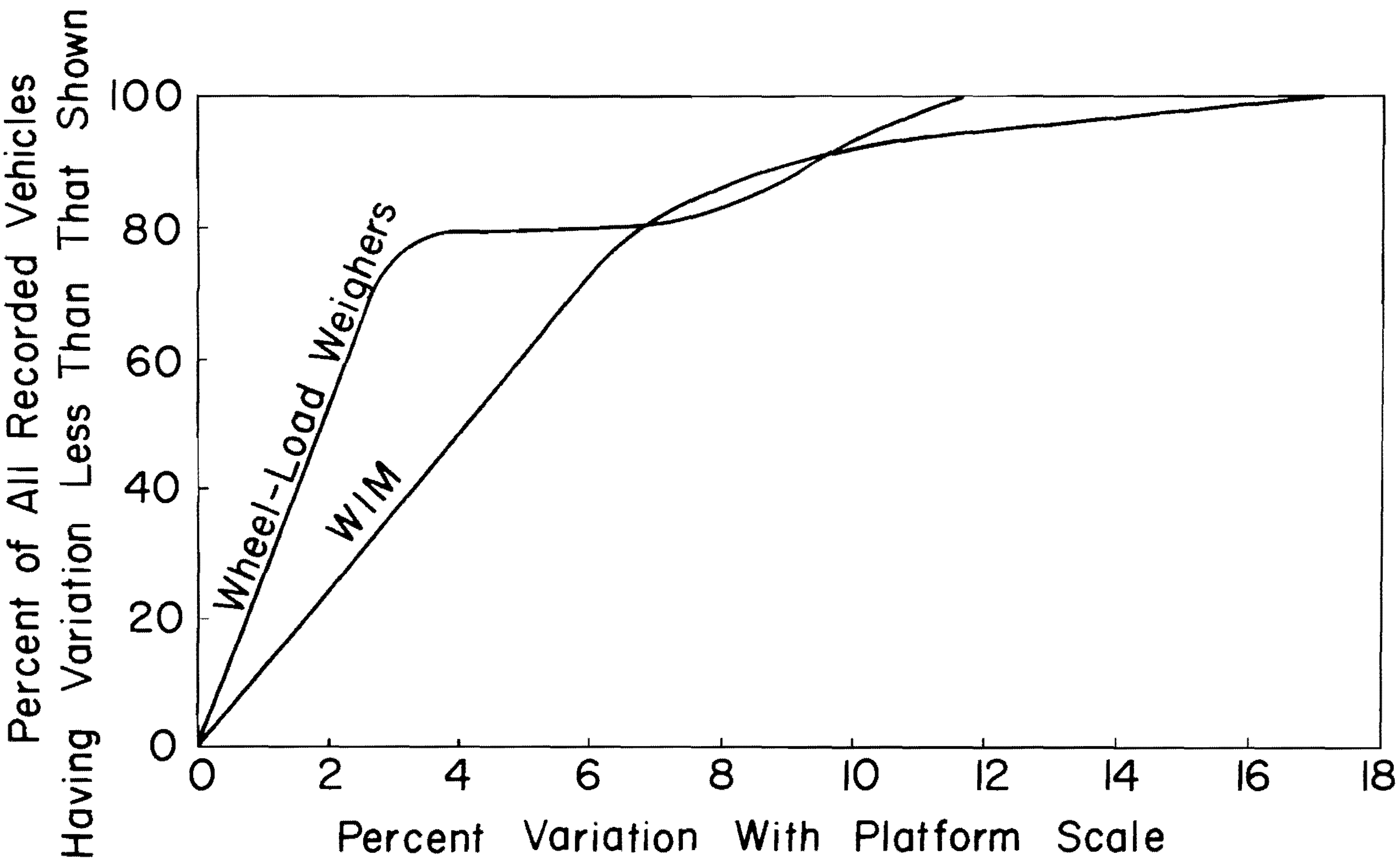


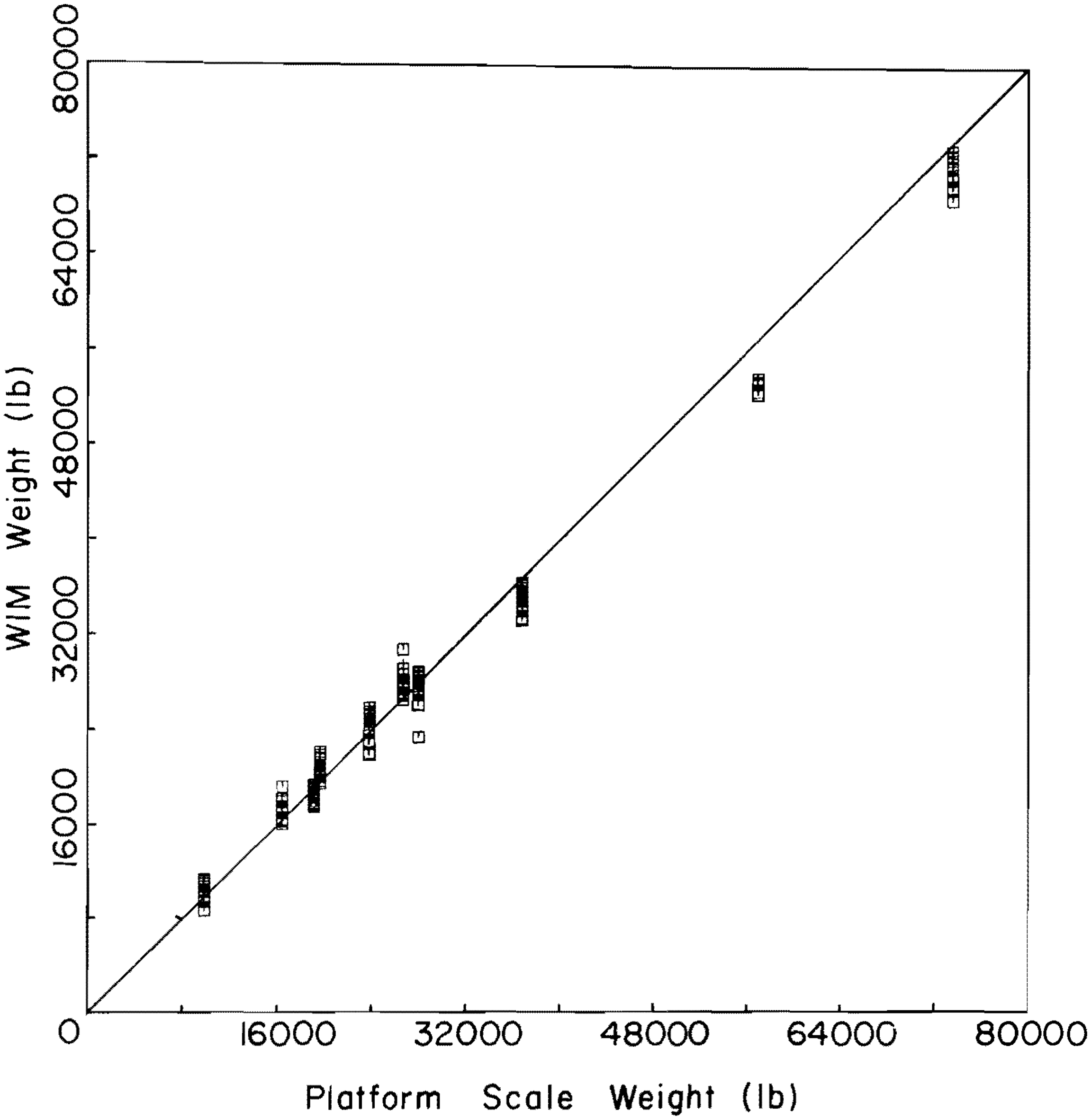
Fig 3.7. Variation in gross vehicle weight measured by wheel-load weighers compared with platform scale weights.

Correlation Analysis

Since the analysis of variance indicated that there were statistically significant differences between the estimates of static gross vehicle weight obtained using the three weighing devices, it was desirable to develop an interpretative statement about the magnitude of these differences. In order to establish a basis for such a quantitative statement, a limited correlation-regression analysis was performed. In this analysis the estimates of static gross and axle loads measured by WIM for all vehicle speeds were compared with the respective weights obtained from the platform scale. The WIM estimates of static wheel loads were, however, evaluated by comparison to the weights obtained from wheel-load weighers since it was impossible to obtain meaningful wheel load data from the platform scales.

Figure 3.8 is a scatter diagram illustrating WIM gross vehicle weight estimates versus gross vehicle weights measured by the platform scale. In developing this data, the arithmetic mean of several platform scale weighings of each vehicle were assumed to be true values. Therefore, the various WIM weight estimates (dependent variables) are plotted as y-values versus the average platform scale values which are assumed to be error-free independent (x) variables. The 45-degree line in the figure represents a line with the equation $y = x$ or perfect agreement between the variables. The standard error for the observed data about this line was computed and expressed as a coefficient of variation. This coefficient of variation was used to provide an indication of the accuracy with which the WIM system can estimate static weights. The analysis produced a coefficient of variation of ± 5.8 percent for gross vehicle weights. That is, if past experience is repeated, approximately 68 times out of 100, the in-motion weighing system can be expected to estimate gross vehicle weights within ± 5.8 percent of those measured by the platform scale.

A process analagous to that utilized for analyzing gross loads was used to study the ability of the WIM system to estimate static axle and wheel loads. This analysis indicated that, with 68 percent confidence, the WIM system can estimate static axle and wheel loads as measured by platform scales and wheel-load weighers within ± 10.8 and ± 13.6 percent, respectively.



1 lb = 4.45 N

Fig 3.8. Scatter diagram of gross vehicle weights measured by WIM versus platform scale.

Conclusions

In the series of field tests, a vehicle representative of each of five types of trucks was weighed statically, first loaded and then empty, at least three times by platform scales and by wheel-load weighers. Each vehicle was also weighed empty and loaded not less than three times while traveling at nominal speeds of 30, 45, and 60 mph (48, 72, and 97 km/hr) through the in-motion weighing system. Data from 372 static weighings and from 165 vehicle trips over the in-motion equipment were studied using standard statistical techniques to determine the expected accuracy with which samples of dynamic wheel forces from moving vehicles can be used to estimate static vehicle weights.

In recognition of the fact that no physical phenomenon can be measured with absolute precision, platform scale weights were assumed a priori to be the best basis for studying static gross vehicle weights and axle weights while wheel-load weigher weights were used as the basis for wheel weight accuracy evaluation. Accuracy on the order of 0.2 percent and 3 percent of applied load can be expected from these respective static weighing devices (Ref 29). A number of vehicle, roadway, and environmental factors cause the dynamic wheel forces produced by a moving vehicle to vary from static wheel weights of the same vehicle at rest. Samples of dynamic wheel force can be used to approximate static wheel weights under certain conditions. Since all weighing procedures for the study were conducted under representative field conditions, a comparison of the relative accuracy of static vehicle weight measurements by various methods was possible.

Statistical analysis of the observed data indicates that with approximately 68 percent confidence, the in-motion weighing system can estimate static vehicle weights with the accuracies shown in the tabulation below.

Weight	Basis for Static Weight Comparison	Expected Accuracy of WIM Estimate, %
Gross Vehicle Weight	Platform Scales	± 5.8
Axle Weight	Platform Scales	± 10.8
Wheel Weight	Wheel-Load Weighers	± 13.6

A comparative study of WIM with loadometer under field survey conditions is included in Appendix D.

CHAPTER 4. DESIGN OF A WEIGHT SURVEY PROGRAM FOR TEXAS USING IN-MOTION WEIGHING

As noted in Chapter 2, the Texas Highway Department systematically conducted year-round vehicle weight survey operations at 21 locations until 1968. As a result of increasing costs to the Department and to highway users, along with associated staffing problems, the scope of weighing operations was reduced to summer only weight surveys after 1968. In a further attempt to reduce costs, minimize staffing difficulties, and improve efficiency, the number of survey sites was reduced from 21 to ten in 1971.

The in-motion weighing system described in Chapter 3 was developed primarily to provide still further efficiency in vehicle weight surveys. The following sections describe a study which has been designed to facilitate integration of the in-motion weighing systems into routine traffic survey activities. The study is directed toward determining the kind of weight survey operations that will be necessary to maintain a quality of vehicle weight information that is at least equivalent to that which existed when the 21 original weigh stations were in year-round operation.

Number of Survey Sites

An analysis by the Texas Highway Department which led to the reduction of the number of weight survey stations from 21 to ten was based on the hypothesis that vehicle weight data from certain stations had similar characteristics and therefore certain stations possibly represented duplication of effort. For example, vehicle weight data from Stations 452, 81, 201, 202, and 203 exhibit less than 10 percent variation among any pair of the five stations. Therefore one of the five (Station 452) could be taken as an appropriate representative of the group. (This analysis is explained in detail in Appendix A.)

The study described here is based on the same general concept in that it is designed to determine which of the original 21 stations indicate significantly different weight characteristics. Realizing the significant value of data that have been accumulated through continuous study for several decades at the original 21 stations, no attempt has been made to suggest relocation of any of these sites. In view of the good geographical and highway system coverage provided by the original 21 sites, the analysis of the number of necessary sites has not been based on a theoretical statewide need for vehicle weight data.

Since 1968, 1969, and 1970 were the three most recent years in which all 21 survey stations were operated, vehicle weight data acquired in these three years were used in this study. The tabulations obtained from the Texas Highway Department were in the form of frequency distributions of wheel and axle weights for single and tandem axles. Table 2.1 is an example of the data and the format in which they were provided. The data were obtained in conventional "loadometer" surveys in which one wheel of each axle was weighed and this value doubled to yield an axle weight; therefore, the only difference between the wheel and axle weight distributions is a factor of two. Since axle weights are commonly used in pavement design procedures, axle weight distributions were chosen for use in this analysis.

The data, as presented in Table 2.1, provide a separate frequency distribution of single and of tandem axle weights for each station. For analysis purposes, these two separate distributions were brought to a common basis and combined into one axle weight distribution for each station. The common denominator of axle weight, which was utilized, was the AASHTO traffic equivalence concept. The traffic equivalence equations developed by the American Association of State Highway and Transportation Officials for flexible pavements were used to reduce both single and tandem axle weights to equivalent 18-kip (80-kN) single axle weights (see Ref 1). The equivalence factors produced by these equations relate the amount of loss in serviceability of a flexible pavement that is caused by one single or tandem axle load application to that caused by one pass of a single axle of some specified load. Since the maximum legal single axle weight in many states is 18 kips, the usually specified single axle weight is 18 kips. The equation for flexible pavement 18-kip single axle equivalencies is as follows (Ref 1):

$$\log W_{T_x}/W_{T_{18}} = 4.79 \log (18+1) - 4.79 \log (L_x + L_2) + 4.33 \log L_2 + G_T/B_x - G_T/B_{18}$$

where the ratio $W_{T_x} / W_{T_{18}}$ gives the relationship between any axle load, x , single or tandem, and an 18-kip single axle load,

L_x = weight of any axle (single or tandem), kips,

L_2 = 1 for single axles, 2 for tandems, etc.,

G_T = log (Pi - Pt) / (Pi - Px) ,

Pi = initial serviceability (assumed 4.2) (see Ref 1) ,

Px = terminal serviceability (assumed 1.5) (see Ref 1) ,

Pt = serviceability at time, t ,

$B_x = 0.40 + (0.081 (L_x + L_2)^{3.23} / (\overline{SN} + 1)^{5.19} (L_2)^{3.23}$

$B_{18} = 1094.00 / (\overline{SN} + 1)^{5.19}$

$\overline{SN}$ = mean structural number (see Ref 1) .

The Texas Highway Department normally uses this flexible pavement equivalency relationship to compute the equivalent number of 18-kip single axle applications at each loadometer station. This information, which was published annually through 1969, was based on a structural number ($\overline{SN}$) of 5.0 and a serviceability (Pt) of 2.5 ; therefore, the equivalencies computed here were also based on these same values.

The equivalency factors were used to transform the axle weight frequency distributions (see Table 2.1) into a single distribution of equivalent 18-kip single axles for each of the 21 loadometer stations. The data for 1968, 1969, and 1970 were further combined to produce for each station one frequency distribution of equivalent single axle weights for the three years. The use of data from several years instead of only one year provided a much larger sample size and, thereby, reduced the probability of adverse effects from chance variations. The mean equivalent axle data of Fig 4.1 are computed by summing the number of equivalent 18-kip single axles at each station for all three years and dividing that sum (in each case) by the number of axles observed.

The twenty-one axle weight distributions combined for the three years were analyzed using a one-way analysis of variance assuming a fixed effects model. The results of this analysis are presented in Fig 4.1, and they indicate that the F ratio is significant at more than the 99 percent confidence level. The mean equivalent axle, standard deviation, and number of observations for each station are also shown in Fig 4.1.

The analysis illustrated in Fig 4.1 indicates that there are statistically significant differences between the mean equivalent axles for the 21 stations; however, this analysis does not indicate that the mean equivalent axle for every station is different from that for every other station. That is, there is a possibility that certain stations as represented by their means are not significantly different from each other and that these means may be aggregated in homogenous groups. Testing procedures called multiple range tests are suitable for investigating this possibility (Refs 37, 45, and 14). Multiple range tests may be used in conjunction with analysis of variance to determine whether or not any "n" treatment means are significantly different from each other. Multiple range testing procedures have been developed by Duncan, Tukey, Newman-Keuls, and Fischer (Refs 12, 37, and 45). There are slight differences among these procedures and the results obtained vary slightly. In all four procedures, however, the differences between all possible pairs of treatment means are compared to a test statistic to determine whether the differences are statistically significant. Multiple range testing is applicable only if significant differences between treatment means are indicated in the analysis of variance. Duncan's, Newman-Keuls', and Fischer's tests were applied to the data shown in Fig 4.1, and the three procedures produced slightly different results. Since Duncan's test is somewhat intermediate between the liberal and conservative natures of Fischer's and Newman-Keuls', it was selected for final use in this analysis. The results of this test for a 95 percent confidence level are shown in Fig 4.2. The results are presented in a graphical format like that described in Duncan's original description of the test (Ref 12). Any two or more means underscored by the same line are not significantly different from each other at the 95 percent confidence level. The number which has been used by the

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ONE-WAY ANALYSIS OF VARIANCE
DUNCAN*S MULTIPLE RANGE TEST IS INCORPORATED
TO TEST FOR SIGNIFICANT DIFFERENCES BETWEEN GROUP MEANS
NOTE: DUNCAN*S TEST VALID ONLY IF F IS SIGNIFICANT


PROGRAM WRITTEN BY R.B.MACHEMEHL PROJ.181 CFHR


SOURCE OF VARIATION   DEGREES OF FREEDOM   SUM OF SQUARES   MEAN SQUARE


BETWEEN CLASSES                  20             88.1395          4.4070
ERROR                         70694           7443.8170           .1053
TOTAL                         70714           7531.9565


F RATIO = 41.8531)


MEANS, STD DEVIATIONS, NOS. OF OBSERVATIONS

     MEAN      STD.DEV      NO.OBS      GROUP      Station
     .100        .282        2405         1           3
     .082        .302        2152         2           4
     .127        .234        1260         3           7
     .133        .229        2774         4          16
     .175        .262        3984         5          20
     .162        .345        1108         6          42
     .183        .523        4459         7          72
     .199        .377        1762         8          81
     .287        .732        1209         9          88
     .301        .480        1176        10         101
     .155        .234        4001        11         102
     .181        .367        3418        12         145
     .126        .228         941        13         147
     .153        .234        1760        14         149
     .186        .268        5195        15         201
     .190        .304        6345        16         202
     .186        .266        6031        17         203
     .178        .307        5560        18         301
     .189        .293        5850        19         351
     .167        .280        2594        20         371
     .200        .301        6731        21         452
```

Fig 4.1. Analysis of variance of vehicle weights at 21 stations for 1968, 1969, and 1970 data.

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DUNCAN#S MULTIPLE RANGE TEST

STANDARD DEVIATION USING HARMONIC MEAN AS NO. OBS=   .006804

DUNCANS SIGNIFICANT RANGES FOR COMPARING 2 (LEFT)   THRU 21 (RIGHT) MEANS
  .019  .020  .021  .021  .021  .022  .022  .022  .022  .023  .023  .023  .023  .023  .023  .023  .023  .024  .024  .024

GROUP NOS.AND MEANS ARRANGED FROM LARGEST(LEFT) TO SMALLEST(RIGHT)
        1                                2                                3              4                 5               6
    10     9    21     8    16    19    15    17     7    12    18     5    20     6    11    14     4     3    13     1     2
  .301  .287  .200  .199  .190  .189  .186  .186  .183  .181  .178  .175  .167  .162  .155  .153  .133  .127  .126  .100  .082
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Fig 4.2. Multiple range testing of differences between mean equivalent axle weights.

Texas Highway Department to identify each of the 21 loadometer stations is shown on the line above each respective mean.

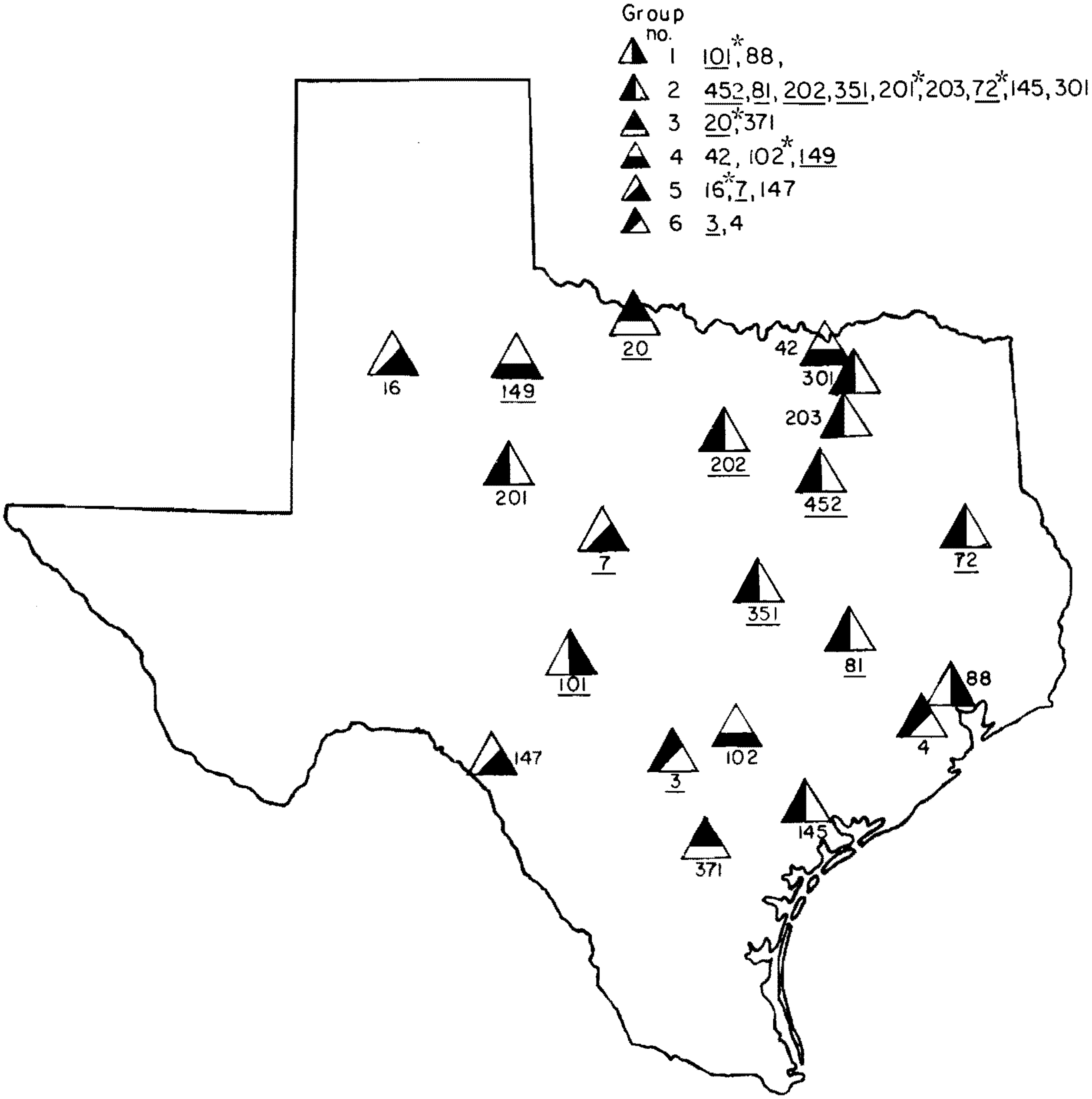
It is apparent from Fig 4.2 that several sets of groups may be formed from the original 21 stations. The particular set of groups which has been chosen here is that which yields the smallest total number of groups. It is desirable to have the smallest possible number of groups because the objective of this analysis is to minimize the total number of weight survey stations while maintaining the present quality of data. The six groups which have been chosen and the stations which compose each group are indicated in Fig 4.3.

It must be noted that the results of this analysis would vary slightly if another multiple range test or another confidence level were chosen. The test procedure, confidence level, and choice of groups which are presented here are based on engineering judgment which is in turn guided by a knowledge of data acquisition techniques and data use and by consultation with experienced personnel of the Texas Highway Department. In other words, the groups shown in Fig 4.3 do not represent the only answer to the problem, but they do represent a practical answer formulated through the use of statistical tools and tempered with judgment.

Since there is no statistically significant difference (at the 95 percent level) between the mean equivalent axles of the stations which compose a group, it is necessary to sample vehicle weights at only one station in each group. This study indicates that only six instead of 21 weighing stations are needed. The particular station in each group which is chosen as representative of all others is immaterial to the statistical analysis and should be a function of other factors.

Timewise Variation in Vehicle Weights (Seasonal Variations)

As noted in Chapter 2, until 1968, vehicle weights were sampled at all stations during all seasons of every year. In 1968 seasonal weighing was discontinued in favor of summer only operation. This change was made because of economic and staffing constraints and not necessarily because data had indicated seasonal weighing was unnecessary. Under a revised vehicle weight sampling program utilizing fewer stations and modern in-motion weighing equipment, it may be feasible to resume seasonal weighing if this is necessary.



Note: Stations at which weighing operations were continued after 1971 are underlined.

*Stations selected for initial installation of WIM 1975-76.

Fig 4.3. Groups of stations chosen to minimize the number of groups.

In order to study seasonal variations in vehicle weights, all loadometer data obtained by the Texas Highway Department in 1965 and 1966 were secured. These were the two most recent years in which seasonal sampling was conducted. The 1967 data were not available due to computer storage problems. The 1965 and 1966 data were obtained in the same general form as that shown in Table 2.1. However, in order to provide the capability of separating the data by seasons, a separate listing was obtained for every eight-hour sampling period at each station for both years. Theoretically, every station was operated for three eight-hour shifts during each season, but Table 4.1 summarizes the actual data which were available. The table indicates that no station was operated during all three shifts for all seasons for both years; five of the 21 stations were operated during the 6:00 a.m. to 2:00 p.m. and 2:00 p.m. to 10:00 p.m. shifts for all seasons for both years, and nine were operated during the 2:00 p.m. to 10:00 p.m. shift for all seasons for both years.

The seasonal variation in these data was studied using a standard method of analyzing timewise variations (see Ref 35). The method consists of first placing the data in an array in chronological order. A digital filter consisting of a simple moving average is then applied to the data array. The length of the filter or moving average is equal to the time period within which variations are being studied. The output of the filter is a new data array which lacks most of the effects of timewise variations that occur within the time period being considered. For example, if hourly data are available, and it is desirable to study the variations in hourly data that occur within a day, a 24-point moving average (24 hours per day) would be used to produce the new data array.

The differences between the original and the filtered data points are expressed as percentages of the filtered data points. The percentage values for all time periods within several replications of the major time period are averaged to produce an index of variation for each period within the major period. If hourly data were being used to study variations among the 24 hours of a day and data from several days were available, all percentage variations for each respective hour of the day would be averaged to produce one index of variation for each hour.

At least three replications of the major time period (one day in the example above) should be present. The length of the new data array produced

TABLE 4.1. SUMMARY OF VEHICLE WEIGHT DATA AVAILABLE FOR 1965 AND 1966

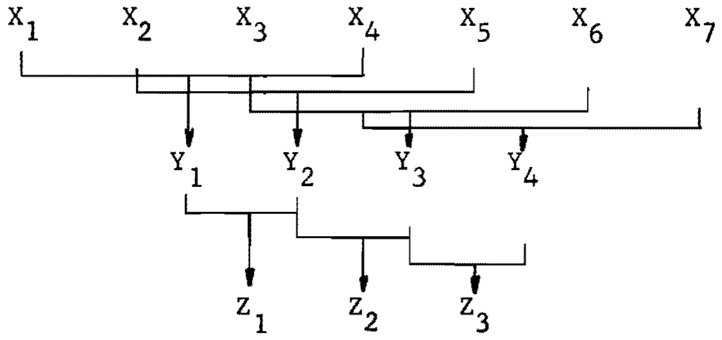
	Winter 65			Spring 65			Summer 65			Fall 65			Winter 66			Spring 66			Summer 66			Fall 66		
Station	6A-2P-10P-6A			6A-2P-10P-6A			6A-2P-10P-6A			6A-2P-10P-6A			6A-2P-10P-6A			6A-2P-10P-6A			6A-2P-10P-6A			6A-2P-10P-6A		
3	0	0	0	0	0	0	X	X	X	0	0	0	0	0	0	0	0	0	X	X	X	0	0	0
4	0	0	0	0	0	0	X	X	X	0	0	0	0	0	0	0	0	0	X	X	X	0	0	0
7	X	X	0	X	X	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	X	X	X	X
16	X	X	0	X	X	0	X	X	X	X	X	X	0	X	0	X	X	X	X	X	X	X	0	X
20	X	X	0	X	X	X	X	X	X	X	X	X	X	0	0	0	X	X	X	X	X	X	X	X
42	X	X	0	X	X	X	X	X	X	X	X	X	X	X	0	X	X	X	0	X	X	X	X	X
72	X	X	0	X	X	X	X	X	X	X	0	X	X	X	0	X	X	X	X	X	X	X	X	X
81	X	X	0	X	X	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	X	X	X	X
88	X	X	0	X	X	X	X	X	X	X	X	X	X	X	0	X	0	X	X	0	X	X	X	X
101	X	0	X	X	X	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	X	X	X	0
102	X	X	0	X	X	X	X	X	X	X	0	X	X	X	0	X	X	X	X	X	X	X	X	X
145	X	X	0	X	X	X	X	X	X	X	X	X	X	0	0	X	0	X	0	X	X	X	X	X
147	X	X	0	X	X	X	X	X	X	X	X	X	X	X	0	X	X	X	X	X	X	X	X	X
149	0	X	0	X	X	0	X	X	X	X	X	X	0	X	0	X	X	X	X	X	X	X	X	X
201	X	X	0	X	X	X	X	X	X	X	X	X	0	X	0	X	X	0	X	X	X	X	X	X
202	X	X	0	X	X	X	X	X	X	X	X	X	X	0	0	0	X	X	X	0	X	X	X	X
203	X	X	0	X	X	X	0	0	X	0	0	0	X	X	0	X	X	X	X	X	X	X	0	X
301	X	0	0	X	X	X	0	X	X	X	X	X	X	X	0	X	X	0	X	X	X	X	X	X
351	X	X	0	X	X	X	X	X	0	X	X	X	X	X	0	X	X	X	X	X	X	X	X	X
371	X	X	0	X	X	X	X	X	X	X	X	X	X	X	0	X	X	0	X	X	0	X	X	X
452	X	X	0	X	X	X	X	X	X	X	X	X	X	X	0	0	X	X	X	X	X	X	X	X

X = operated 0 = not operated

by the filtering process is equivalent to the original array minus the length of the filter (if the number of points in the filter is even). Thus, the number of values of percentage variation which may be computed is equivalent to the number of data points in the original array minus the number in the filter. Therefore, at least three replications of the major time period (day if hourly variations are being studied) must be present to provide any replication on the time periods (hours in the example) within the major period.

Before this analysis technique was utilized to study seasonal variations in vehicle weight data, the AASHTO flexible pavement equivalence factors were employed to produce a single distribution of equivalent 18-kip (80 kN) single axle weights from the single and tandem axle weight distributions described in the previous section. The resulting frequency distributions for each station and season were used to calculate a mean equivalent axle weight for each station and season. An index of weight variation for each station and season was then computed by applying a four-point moving average to the mean equivalent axle data of each station. A two-point moving average was then passed through means produced by the four-point averaging. The purpose of the two-point average was to center the computed average values on the original data points. An index of variation was then computed by finding the difference between the centered average and the corresponding original data point and expressing this difference as a percentage of the centered data point. (See Fig 4.4.) This indexing procedure was used because it provides a dimensionless measure of timewise variation which is unaffected by different overall average vehicle weights at any number of stations being compared. The technique was severely limited, however, because data from only two years were available; thus there was no replication of the values of percentage variation.

Initially, data from the nine stations which were operated during the 2:00 p.m. to 10:00 p.m. shift for all seasons of both years were analyzed using this technique. These stations along with their respective seasonal indices are tabulated in Table 4.2 and plotted (with the exception of Station 42) in Fig 4.5. The statistical significance of the seasonal trend for each station was evaluated using a two-way analysis of variance in which the two classifications were season and station. The resulting computations are shown in Fig 4.6, and they indicate that the effects of season are essentially no more than could be attributable to chance alone.



$$\frac{X_{(i + n/2)} - Z_i}{Z_i} \times 100 = \text{Index Value}$$

n = 4 (4-point moving average)

X_i = original data points

Y_i = data points produced by 4-point averaging

Z_i = data points produced by 2-point averaging (centered)

Fig 4.4. Schematic representation of moving average and index computation.

TABLE 4.2. INDICES OF SEASONAL VARIATION FOR STATIONS HAVING COMPLETE DATA FOR 2 P.M. TO 10 P.M. SHIFT

Station	Season			
	Spring	Summer	Fall	Winter
7	3.3	- 2.1	- 6.0	10.1
42	-38.7	66.8	-28.6	- 9.3
81	- 3.5	23.6	-14.8	- 4.8
147	- 1.1	- 4.1	16.6	- 3.0
149	- 0.5	1.3	20.0	-18.9
201	3.1	13.9	-10.0	10.5
351	16.5	-17.7	7.0	- 0.9
371	- 8.2	5.1	11.4	- 8.8
452	12.2	-16.2	22.1	- 2.7

TABLE 4.3. INDICES OF SEASONAL VARIATION FOR STATIONS HAVING COMPLETE DATA FOR 2 P.M. TO 10 P.M. AND 6 A.M. TO 2 P.M. SHIFTS

Station		Season		
	Spring	Summer	Fall	Winter
7	-13.6	23.0	- 3.8	-18.4
81	- 0.6	18.7	-14.3	- 3.2
147	5.3	1.6	6.9	- 4.6
351	13.2	-10.4	4.7	- 5.1
371	4.3	- 1.5	1.0	5.4

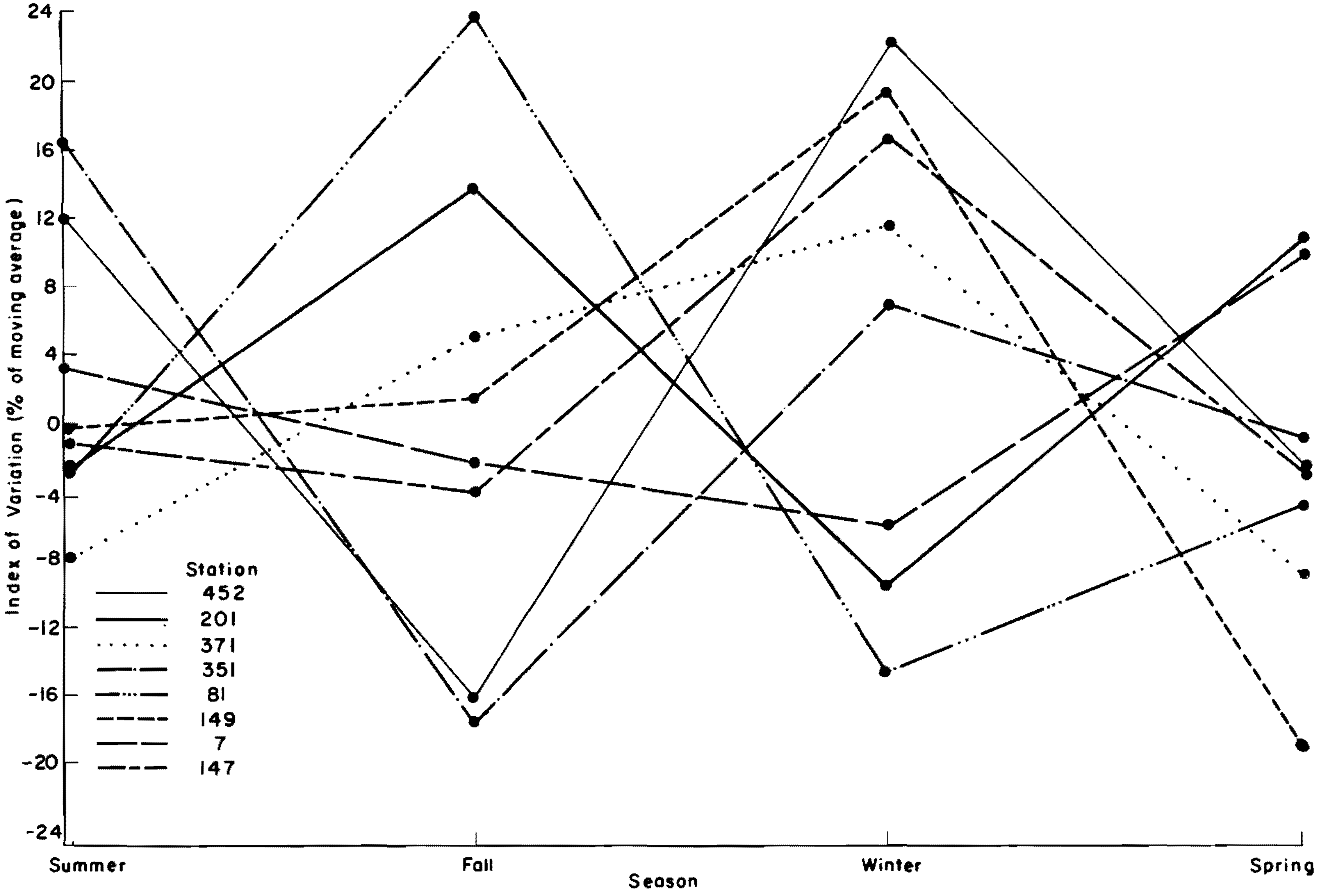


Fig 4.5. Seasonal variations for stations having 8 hours of continuous data.

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                              ANALYSIS OF VARIANCE FOR TWO-WAY  4 X  9 TABLE

SOURCE                 D.F.          SUM OF SQUARES              MEAN SQUARES             F RATIO    F PROB.

BETWEEN ROWS   SEASON   3             25.042076                  8.3473586                .239       .868
BETWEEN COLS   STATION  8            330.08956                  41.261194                1.184       .349
RESIDUALS              24            836.71028                  34.862928
TOTAL                  35           1191.8419


                                     TUKEY-S TEST FOR NON-ADDITIVITY

NON-ADDITIVITY          1             32.885249                  32.885249                .941       .342
BALANCE                23            803.82503                   34.948914
RESIDUALS              24            836.71028                   34.862928


COEFFICIENT                 ESTIMATE                STD. DEV.

GRAND MEAN                   .38847222               .98408062

ROW        1               -1.1556944               1.7044776
ROW        2                1.0263056               1.7044776
ROW        3                -.37413889              1.7044776
ROW        4                 .50352778              1.7044776

COLUMN     1               -1.7867222               2.7834003
COLUMN     2                4.5722778               2.7834003
COLUMN     3               -2.5862222               2.7834003
COLUMN     4               -4.4489722               2.7834003
COLUMN     5                 .62727778              2.7834003
COLUMN     6               -2.3409722               2.7834003
COLUMN     7                -.58722222              2.7834003
COLUMN     8                1.8142778               2.7834003
COLUMN     9                4.7362778               2.7834003

RESIDUAL                                            5.9044837
```

Fig 4.6. Analysis of variance of nine stations having data for four seasons × two years × two study periods.

This result is not entirely unexpected, however, since the seasonal index data shown in Table 4.2 exhibit a large amount of scatter. The chance variation could easily obscure the actual seasonal trends. In an attempt to overcome the effects of random variations, the sample size was increased by utilizing the data from those loadometer stations which had been operated for 16 hours (two shifts) during both seasons of both years. As noted earlier, data of this type were available from only five stations. Indices of seasonal variation were computed for these five stations using a procedure analagous to that already described and are tabulated in Table 4.3 and plotted in Fig 4.7. Stations 7, 81, and 147 are located on portions of the Federal-Aid Primary System while Stations 351 and 371 are located on the designated Interstate System. The stations which are common to each of these two systems exhibit similar characteristics (see Fig 4.7). The statistical significance of the seasonal trends for these two groups (Interstate versus Federal-Aid Primary) was then investigated using a two-way analysis of variance. The results of this investigation are indicated in Fig 4.8. The F ratio values in this table indicate that the seasonal effects are significant at the 99 percent level for stations on the Federal-Aid Primary System (Fig 4.8a) while they are not significant at even the 68 percent level for the stations on the Interstate System (Fig 4.8b).

Since these results were taken from a very small sample, only five of twenty-one stations, they cannot be used as the basis for generalizations. However, they do indicate the possibility that vehicle weight data at some stations may exhibit significant seasonal variations. Further study of seasonal trends in weight data is recommended.

Variations in Vehicle Weights Among Days

As noted earlier, due to constraints imposed by static weighing equipment, vehicle weight surveys in Texas have been conducted neither for more than eight consecutive hours nor on consecutive days at the same location. Use of in-motion weighing equipment now makes continuous operation over extended periods of time quite practical. Continuous, seven day per week operation at each site may not be necessary, however, if there is no significant variation in vehicle weights among days of the week. The following paragraphs describe an investigation of the significance of variations in vehicle weights among

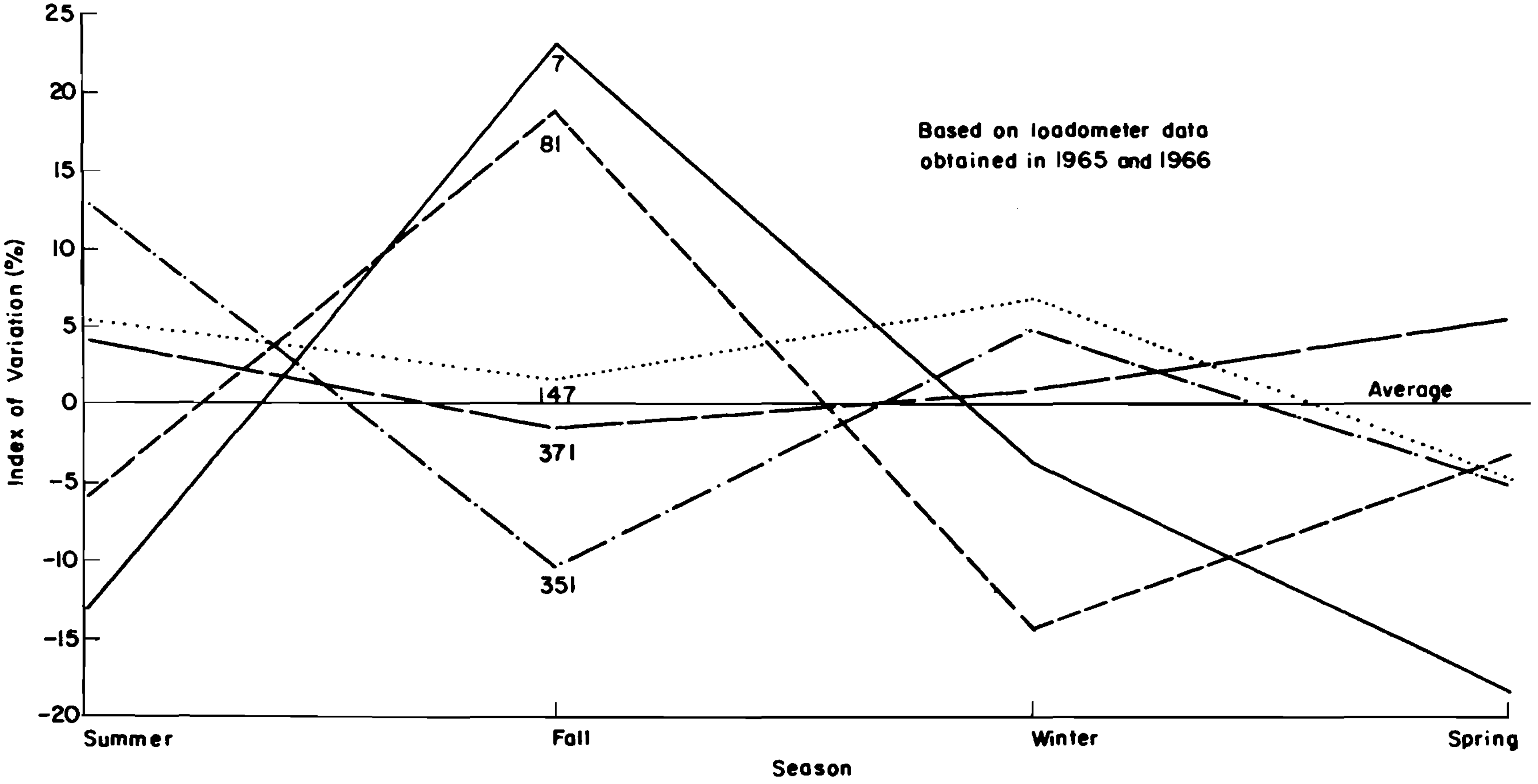

Fig 4.7. Variation of axle weights versus season of the year for five typical weight survey stations.

Analysis of Variance for Two-Way 3 × 4 Table (Stations 7, 81, 147)

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Pro
Btwn rows (stations)	2	7.3197167	3.6598583	.769	.504
Btwn cols (seasons)	3	213.10889	71.036297	14.925	.003
Residuals	6	28.557483	4.7595806		
Totals	11	248.98609			

Fig 4.8(a). Analysis of variance for non-Interstate stations.

Analysis of Variance for Two-Way 2 × 4 Table (Stations 351 and 371)

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Pro
Btwn rows (stations)	1	.020000000	.020000000	.001	.976
Btwn cols (seasons)	3	47.989300	15.996433	.880	.541
Residuals	3	54.525700	18.175233		
Totals	7	102.53500			

Fig 4.8(b). Analysis of variance for Interstate stations.

days at two survey sites and suggest a procedure which can be used to study daily variations at other survey sites.

During the months of June and July 1974, special in-motion weighing equipment was used to continuously monitor vehicle weights in the outside northbound lane of I.H. 35 south of Austin, Texas. The equipment used in this study consisted of in-road sensing devices like those described in Chapter 2, although vehicle weight, dimension, speed, and time of day information were recorded automatically on punched paper tape. The data classification and recording system utilized here had been developed in previous work (Ref 25) and was slightly modified for this application. Weight information was recorded in terms of 2,000-pound (9-kN) weight classes rather than as precise weights. The classification instrument system in use at a previously occupied site is shown in Fig 4.9a. Figure 4.9b shows another view of the system and indicates that the sensing and recording devices are quite inconspicuous to the highway user.

The system provided a continuous count of all vehicles utilizing the lane in which it was installed as well as a punched paper tape record for each vehicle having at least one wheel weight greater than a specified threshold value. Since weight surveys are normally confined to commercial type vehicles (trucks) it was deemed appropriate to obtain weight information only for these vehicles. Therefore, a wheel weight threshold of 1,600 pounds (7 kN) was used since very few passenger vehicles have wheel weights in excess of this figure. The 1,600-pound figure was derived from previous field studies conducted at this site. Time of day, which was provided by a 24-hour clock internal to the system and recorded on each tape record, provided a means of relating the weight information to days and hours of the day.

The data produced by this system were reduced using the CDC 6600-6400 computer system to the format shown in Fig 2.1. A separate weight frequency distribution was produced for each day in which data were recorded. Although the system was operated for almost two months, due to several minor environmental and technical difficulties, only 22 continuous days of acceptable data were procured.

A timewise trend analysis analogous to that used in the study of seasonal variations was performed on these data. The distribution of axle weights for each day was transformed into a total number of equivalent 18-kip (80-kN) single axles. This number was divided by the number of axles to produce an average

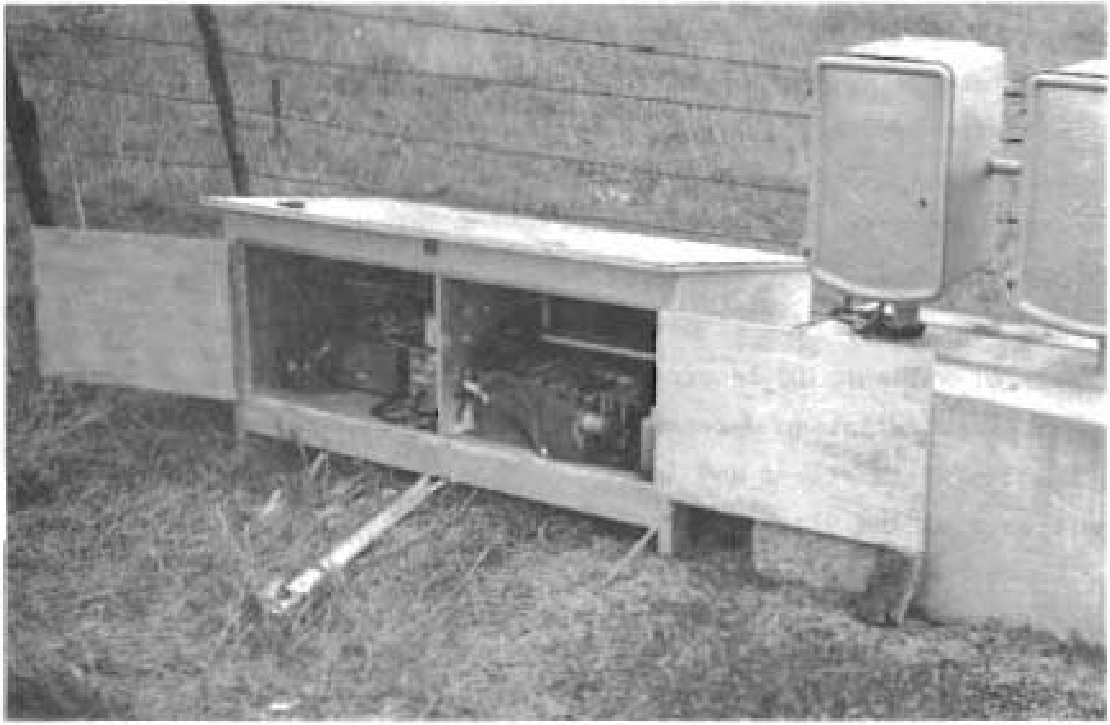

Fig 4.9a. Data classification and recording system.

Fig 4.9b. Typical field installation of classification and recording system.

number of equivalent axles for each day. Twenty days of continuous data were subjected to a 7-point moving average and the differences between the resulting 14 means and the corresponding 14 original data points were expressed as percentages of the mean values. Thus, two values for each of the seven days of the week were produced. These two values were averaged to produce an index of variation for each day. The resulting indices are plotted in Fig 4.10a.

The fourteen values of percentage variation were tested using a one-way analysis of variance to determine if the differences between the mean values of percentage variation were statistically significant. Figure 4.11 contains the results of this test and indicates that the differences among days are significant at the 97 percent level.

Duncan's multiple range test was performed on the means of the seven days to detect similarities in the computed values. The analysis that is presented in Fig 4.12 indicates that there are three possible groups. One group consists of all weekdays, another is composed of Saturday and Sunday, while the third consists of Saturday, Monday, and Friday. In general, the weekend and weekday values seem to have quite dissimilar values.

A similar study conducted for three weeks in April 1975 near College Station yielded the same general conclusion. Variation in weight index by days of the week at this site is shown in Fig 4.10b.

Variation in Vehicle Weights Among Hours of the Day

Although continuous 24-hour vehicle weighing would be practicable with in-motion weighing equipment, such operations would be unnecessary if no significant variations in vehicle weights occur during the 24 hours of a typical day. The following paragraphs use the data from I.H. 35 and techniques analogous to those of the previous section to suggest a procedure for studying and drawing limited conclusions about variations in vehicle weights among hours of the day.

Since the vehicle weight data, discussed in the previous section, had been recorded in reference to a real time base, it was easily summarized by hours. AASHTO equivalencies were again used to produce a number of equivalent 18-kip (80-kN) single axles for each hour of the 15 days used for this study. Division of the total number of equivalent 18-kip single axles for each hour by the corresponding number of axles observed produced an average equivalent axle weight for each hour.

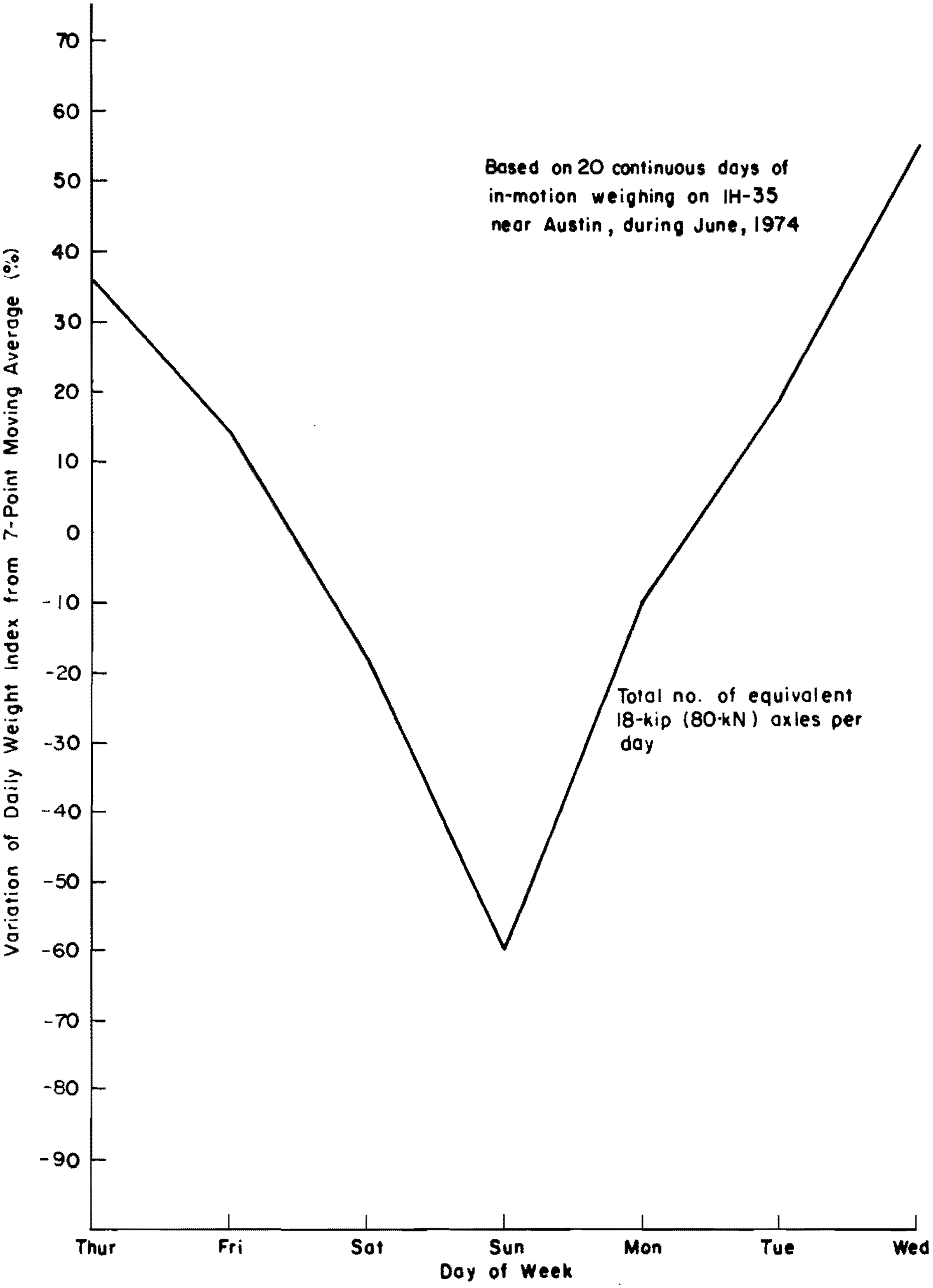

Fig 4.10a. Variation of axle weights versus day of the week, Austin.

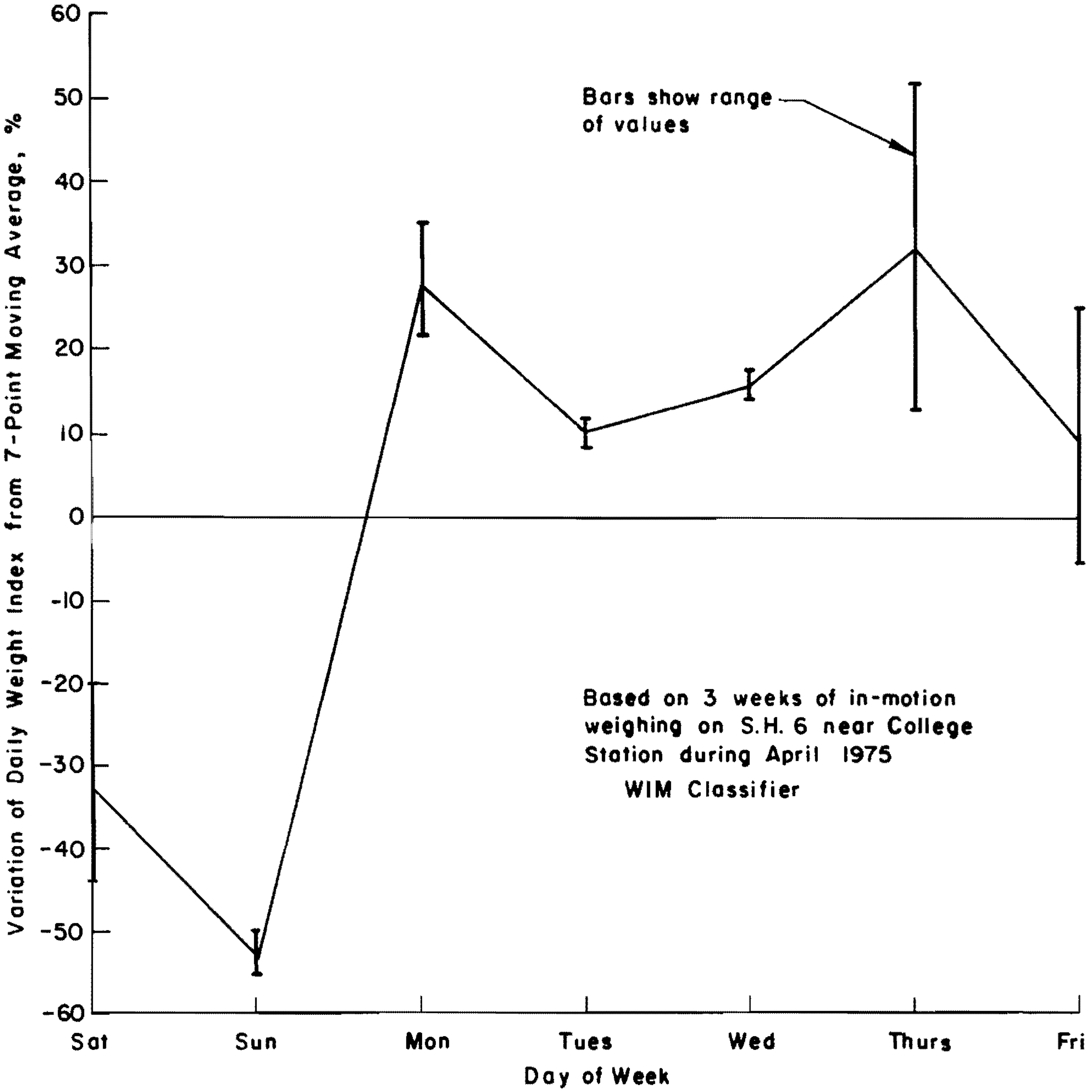

Fig 4.10b. Variation in axle weights versus day of the week, College Station.

```
                                     ANALYSIS OF VARIANCE

          SOURCE              D.F.     SUM OF SQUARES     MEAN SQUARES          F RATIO    F PROB.

          BETWEEN GROUPS        6      76.317520E+02     12.719587E+02          5.388       .022
             SLOPE                 1      55.919360E+01     55.919360E+01          .769       .410
             DEVS. ABOUT LINE      5      70.725584E+02     14.145117E+02         5.992       .005
          WITHIN GROUPS         7      16.523890E+02     23.605557E+01
          TOTAL                13      92.841410E+02

     KRUSKAL-WALLIS RANK TEST FOR DIFFERENCE BETWEEN GROUP MEANS * H =   11.600, F PROB =  .006 (APPROX.)

                                          ESTIMATES

GROUP      NO.      MEAN        WITHIN S.D.  S.D. OF MEAN     MINIMUM        MAXIMUM        S(R)    95PCT CONF INT FOR MEAN

   1        2  12.17450E+01  20.71823E-01   14.65000E-01  12.02800E+01  12.32100E+01     23.0 10.31304E+01 TO14.03596E+01
   2        2  10.55550E+01  18.17264E-01L 12.85000E-01  10.42700E+01  10.68400E+01     14.0 89.22753E+00 TO12.18825E+01
   3        2  82.34500E+00  69.93286E-01   49.45000E-01  77.40000E+00  87.29000E+00      6.0 19.51284E+00 TO14.51772E+01
   4        2  61.06000E+00L 28.24184E+00H 19.97000E+00  41.09000E+00  81.03000E+00      4.0-19.26828E+01 TO31.48028E+01
   5        2  10.31100E+01  46.24478E-01   32.70000E-01  99.84000E+00  10.63800E+01     12.0 61.56073E+00 TO14.46593E+01
   6        2  12.41350E+01  20.17376E+00   14.26500E+00  10.98700E+01  13.84000E+01     22.0-57.11894E+00 TO30.53889E+01
   7        2  13.19300E+01H 19.23330E+00   13.60000E+00  11.83300E+01  14.55300E+01     24.0-40.87432E+00 TO30.47343E+01

TOTAL      14  10.42686E+01                               41.09000E+00  14.55300E+01
      FIXED EFFECTS MODEL    15.36410E+00   41.06228E-01                                       94.55891E+00 TO11.39782E+01
      RANDOM EFFECTS MODEL   25.21863E+00   95.31746E-01                                       80.94535E+00 TO12.75918E+01
      UNGROUPED DATA         26.72386E+00   71.42252E-01                                       88.83867E+00 TO11.96985E+01

PAIRWISE MULTIPLE COMPARISON OF MEANS.  THE MEANS ARE PUT IN INCREASING ORDER IN GROUPS SEPARATED BY *****.  A MEAN IS
ADJUDGED NON-SIGNIFICANTLY DIFFERENT FROM ANY MEAN IN THE SAME GROUP AND SIGNIFICANTLY DIFFERENT AT THE .05 LEVEL FROM
ANY MEAN IN ANOTHER GROUP.  ***** ***** INDICATES ADJACENT GROUPS HAVE NO COMMON MEAN.

  NEWMAN-KEULS TECHNIQUE, HARTLEY MODIFICATION. (APPROXIMATE IF GROUP NUMBERS ARE UNEQUAL.)
  61.06000E+00,82.34500E+00,10.31100E+01,10.55550E+01,
     *****
  82.34500E+00,10.31100E+01,10.55550E+01,12.17450E+01,12.41350E+01,13.19300E+01,

  SCHEFFE TECHNIQUE.
  61.06000E+00,82.34500E+00,10.31100E+01,10.55550E+01,12.17450E+01,12.41350E+01,13.19300E+01,

TESTS FOR HOMOGENEITY OF VARIANCES.
     COCHRAN-S C = MAX. VARIANCE/SUM(VARIANCES) = .4827, P =  .335 (APPROX.)
     BARTLETT-BOX F =    1.245, P =  .298
     MAXIMUM VARIANCE / MINIMUM VARIANCE =   241.518

MODEL II - COMPONENTS OF VARIANCE.
     ESTIMATE OF BETWEEN COMPONENT 51.7951545E+01
```

Fig 4.11. Analysis of variance for testing differences in equivalent axle weights among days.

Index Values Arranged from Smallest to Largest

61.1	82.3	103.1	105.1	121.7	124.1	131.9
Sunday	Saturday	Monday	Friday	Thursday	Tuesday	Wednesday
		———	———	———	———	———
	———	———	———			
———	———					

Means underscored by same line are not significantly different at the 95 percent confidence level.

Table Values for Testing Differences Between N Means and 7 Degrees of Freedom

n	2	3	4	5	6	7
	3.35	3.47	3.54	3.58	3.60	3.61

Values of Text Statistic for Comparing N Means, 7 Degrees of Freedom and $S_{\bar{x}}=10.8$

n	2	3	4	5	6	7
	36.2	37.5	38.2	38.7	38.9	39.0

Fig 4.12. Multiple range testing of variation in vehicle weights among days of the week.

A 24-point moving average was then computed for the resulting 360 data points and the differences between the resulting 336 means and the corresponding original data points expressed as percentages of their respective means. These 336 data points represented 14 observations at each of the 24 hours of the day. A mean variation for each hour was computed and tabulated with the data in Table 4.4. Figure 4.13 illustrates graphically the resulting indices of hourly variation.

In order to test the statistical significance of these variations, one-way analysis of variance was again employed. The results of the analysis are presented in Fig 4.14 and indicate that the mean hourly variations are significantly different from each other at the 99 percent confidence level. Multiple range testing was employed to determine whether any of the means could be placed into common groups. This analysis indicated that there were essentially three groups, with the early morning hours falling into the group with the largest mean weight, the early evening falling into the group with the smallest mean equivalent axle weight, and the daylight hours belonging to the intermediate group, which most nearly approximates the overall mean weight.

Additional weight data were obtained using the Texas Highway Department's in-motion weighing system at the I.H. 35 site near Austin, at the site on S.H. 6 near College Station, Texas, and at the site on U.S. 59 near Lufkin, Texas. Two studies were performed at the I.H. 35 site, one during the summer of 1974 and the other during the fall of 1974, both of which were somewhat less than 5 days in duration. Two studies were also conducted at the College Station site, one during the fall of 1974 and the other during the spring of 1975. The first covered approximately 5 days; the second used the WIM classifier system and covered approximately 3 weeks. The study at Lufkin covered approximately 3 days. The data obtained in these studies were analyzed in a manner like that described above, and similar results were obtained. Due to the smaller sample sizes of these studies with the exception of the three-week study at College Station, the data were more scattered; however, analysis of variance again indicated highly significant differences between the mean equivalent axles for the 24 hours in all the studies. The variability in weights observed by hours of the day during the fall of 1974 at Austin and at College Station is illustrated in Fig 4.15. The indices of hourly variation for the three-week College Station study in April, 1975, are shown in Fig 4.15a. The bars show quite large variation in the observed data for some hours of the day during

TABLE 4.4. TABULATION OF HOURLY VARIATIONS

	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Hourly Average
0	184.53	200.58	109.89	239.74	95.55	146.27	137.39	221.15	110.49	88.90	128.71	170.58	138.27	174.92	153.4
1	198.88	169.24	196.30	75.84	201.67	113.73	220.30	197.11	232.01	101.43	68.86	125.01	110.69	230.86	160.1
2	185.35	134.61	298.98	123.83	205.95	189.85	167.13	297.40	123.57	76.19	159.83	71.89	77.45	141.52	161.0
3	189.71	178.86	264.74	257.58	159.80	201.41	262.71	160.37	351.56	287.91	159.44	219.41	126.59	258.93	219.9
4	93.71	101.48	19.96	141.06	84.51	188.41	150.39	160.69	323.39	119.84	218.21	134.66	112.36	184.96	145.3
5	60.87	159.85	245.37	30.34	155.40	243.79	112.64	187.97	44.92	69.08	164.57	104.12	144.83	107.74	130.8
6	93.63	93.65	128.33	178.17	129.56	60.56	113.59	31.36	38.12	31.76	101.10	76.79	82.74	72.75	88.0
7	73.54	66.21	84.71	88.32	38.43	92.21	48.30	60.88	79.06	55.37	103.37	23.27	132.39	34.89	70.1
8	49.93	104.29	88.76	201.53	50.73	39.93	86.98	72.10	55.08	38.40	97.14	87.40	104.47	13.51	77.9
9	94.27	51.20	13.51	112.58	111.53	55.24	93.15	54.42	61.03	49.01	42.23	78.24	154.44	64.03	73.9
10	117.98	67.55	71.97	79.08	69.23	29.80	89.08	78.30	73.47	93.52	77.74	72.89	71.77	148.53	81.5
11	64.98	115.17	23.38	46.05	110.32	94.17	55.71	74.84	29.10	81.73	72.54	98.73	147.71	30.79	74.7
12	74.31	88.15	13.65	106.58	96.71	72.91	72.20	56.61	59.79	107.25	166.66	125.40	173.48	26.92	88.6
13	126.51	106.28	1.87	65.54	87.10	96.33	135.64	52.93	53.74	142.59	141.03	220.58	95.01	74.79	100.0
14	36.66	32.26	72.95	162.06	121.20	103.74	67.23	91.07	29.76	53.30	95.50	111.43	69.59	81.59	80.6
15	131.67	45.31	114.40	26.50	62.85	103.56	63.16	52.02	110.65	60.34	47.24	155.83	131.41	22.27	80.5
16	30.54	81.22	78.31	59.41	45.57	44.31	41.34	97.20	82.18	110.77	91.60	104.82	118.90	37.07	73.1
17	76.57	82.68	29.62	40.74	52.61	59.25	56.96	46.05	133.06	135.95	85.58	41.82	80.01	11.00	71.8
18	29.92	18.80	64.88	22.53	59.22	30.95	28.18	27.91	114.18	30.10	66.36	61.10	22.93	11.69	42.1
19	81.47	27.87	122.62	36.85	70.02	56.78	75.67	55.70	74.02	55.46	64.22	53.25	94.09	66.93	66.8
20	72.63	39.53	78.18	77.59	71.63	29.15	52.57	36.66	102.01	11.79	45.99	57.60	28.93	21.01	51.8
21	117.57	139.45	15.68	97.19	67.74	46.85	49.25	122.91	177.14	67.68	134.02	62.31	48.81	35.94	84.5
22	78.25	91.55	143.33	151.36	87.66	87.73	100.90	75.02	99.88	17.16	100.99	62.51	84.93	4.27	84.7
23	91.88	177.45	21.44	93.27	166.17	118.25	121.54	112.16	175.54	93.36	82.56	76.34	29.05	62.40	101.5

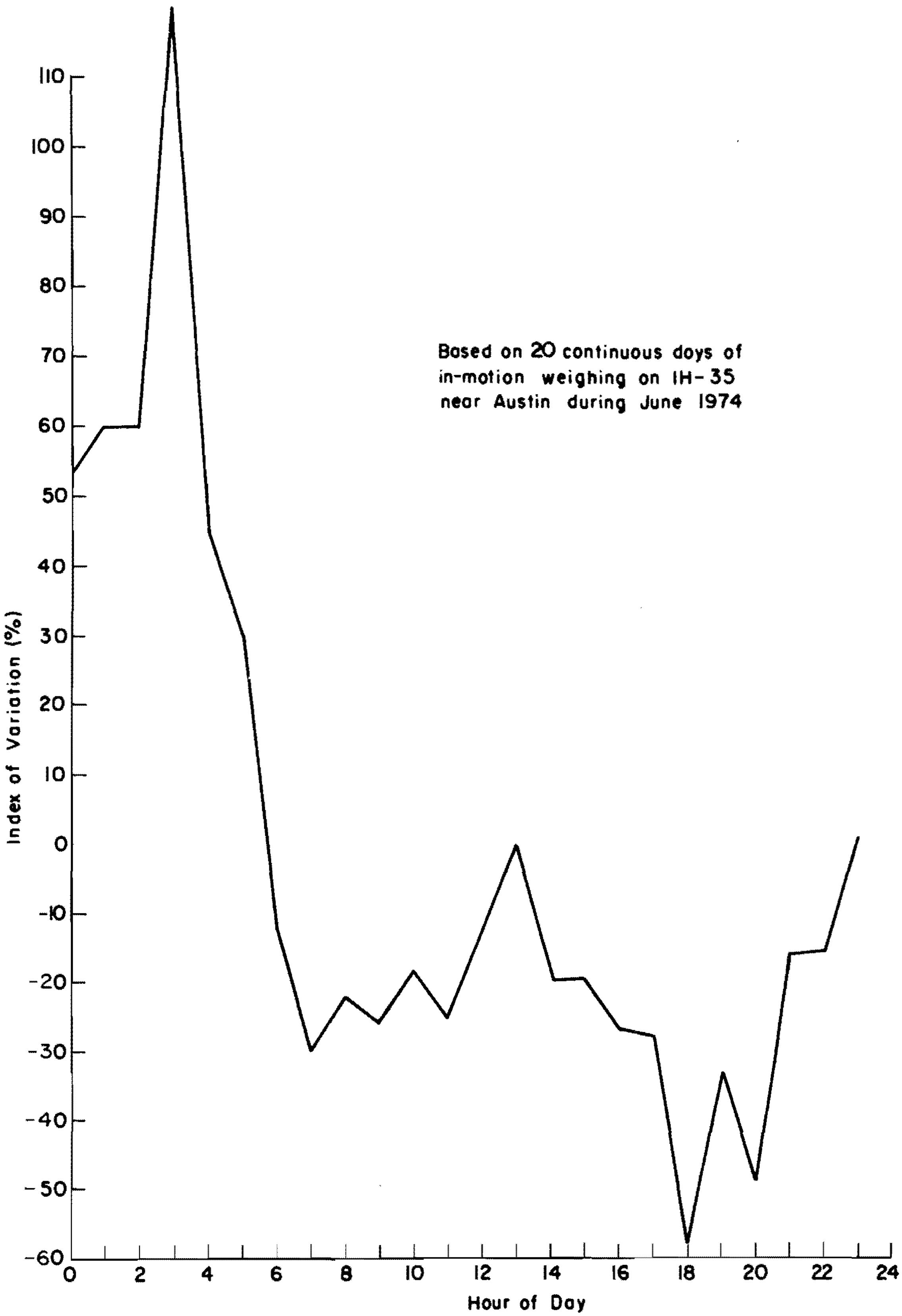

Fig 4.13 . Variation of axle weights versus hour of the day.

```
                                        ANALYSIS OF VARIANCE

          SOURCE              D.F.     SUM OF SQUARES      MEAN SQUARES          F RATIO     F PROB.

          BETWEEN GROUPS       23      56.937800E+04      24.755565E+03          11.691        .000
             SLOPE                 1      27.506239E+04      27.506239E+04        96.205       0.000
             DEVS. ABOUT LINE     22      29.431560E+04      13.377982E+03         6.318        .000
          WITHIN GROUPS       312      66.063753E+04      21.174280E+02
          TOTAL               335      12.300155E+05


      KRUSKAL-WALLIS RANK TEST FOR DIFFERENCE BETWEEN GROUP MEANS * H =  131.934, F PROB =  .000 (APPROX.)

                                             ESTIMATES

GROUP      NO.       MEAN        WITHIN S.D.  S.D. OF MEAN     MINIMUM        MAXIMUM          S(R)     95PCT CONF INT FOR MEAN

   1        14  15.33550E+01  46.72740E+00  12.48842E+00  88.90000E+00  23.97400E+01    3739.0 12.63754E+01 TO18.03346E+01
   2        14  16.01379E+01  58.49866E+00  15.63442E+00  68.86000E+00  23.20100E+01    3688.0 12.63617E+01 TO19.39140E+01
   3        14  16.09679E+01  71.84415E+00H 19.20116E+00  71.89000E+00  29.89800E+01    3620.0 11.94863E+01 TO20.24494E+01
   4        14  21.99300E+01H 62.75838E+00  16.77288E+00  12.65900E+01  35.15600E+01    4336.0 18.36944E+01 TO25.61656E+01
   5        14  14.52593E+01  71.56371E+00  19.12621E+00  19.96000E+00  32.33900E+01    3415.0 10.39396E+01 TO18.65789E+01
   6        14  13.08207E+01  67.75991E+00  18.10960E+00  30.34000E+00  24.53700E+01    3063.0 91.69731E+00 TO16.99441E+01
   7        14  88.00786E+00  41.48432E+00  11.08715E+00  31.36000E+00  17.81700E+01    2291.0 64.05552E+00 TO11.19602E+01
   8        14  70.06786E+00  29.53674E+00  78.94025E-01  23.27000E+00  13.23900E+01    1749.0 53.01385E+00 TO87.12186E+00
   9        14  77.87500E+00  45.20938E+00  12.08271E+00  13.51000E+00  20.15300E+01    1915.5 51.77188E+00 TO10.39781E+01
  10        14  73.92000E+00  36.13931E+00  96.58636E-01  13.51000E+00  15.44400E+01    1833.5 53.05379E+00 TO94.78621E+00
  11        14  81.49357E+00  26.88742E+00  71.85965E-01  29.80000E+00  14.85300E+01    2119.0 65.96924E+00 TO97.01790E+00
  12        14  74.65857E+00  36.33686E+00  97.11436E-01  23.38000E+00  14.77100E+01    1897.5 53.67829E+00 TO95.63885E+00
  13        14  88.61571E+00  45.89615E+00  12.26626E+00  13.65000E+00  17.34800E+01    2256.0 62.11607E+00 TO11.51154E+01
  14        14  99.99571E+00  52.66894E+00  14.07636E+00  18.70000E-01  22.05800E+01    2561.0 69.58558E+00 TO13.04059E+01
  15        14  80.59571E+00  37.27097E+00  99.61085E-01  29.76000E+00  16.20600E+01    2066.5 59.07610E+00 TO10.21153E+01
  16        14  80.51500E+00  42.92734E+00  11.47281E+00  22.27000E+00  15.58300E+01    2001.0 55.72950E+00 TO10.53005E+01
  17        14  73.08857E+00  29.76033E+00  79.53783E-01  30.54000E+00  11.89000E+01    1885.0 55.90547E+00 TO90.27167E+00
  18        14  66.56429E+00  35.76743E+00  95.59247E-01  11.00000E+00  13.59500E+01    1612.5 45.91279E+00 TO87.21578E+00
  19        14  42.05357E+00L 27.71697E+00  74.07672E-01  11.69000E+00  11.41800E+01     840.0 26.05027E+00 TO58.05687E+00
  20        14  66.78214E+00  23.48817E+00L 62.77478E-01  27.87000E+00  12.26200E+01    1610.0 53.22048E+00 TO80.34381E+00
  21        14  51.80500E+00  25.93162E+00  69.30517E-01  11.79000E+00  10.20100E+01    1145.5 36.83253E+00 TO66.77747E+00
  22        14  84.46714E+00  47.12358E+00  12.59431E+00  15.68000E+00  17.71400E+01    2094.0 57.25880E+00 TO11.16755E+01
  23        14  84.68143E+00  39.57711E+00  10.57743E+00  42.70000E-01  15.13600E+01    2269.0 61.83029E+00 TO10.75326E+01
  24        14  10.15293E+01  48.54342E+00  12.97377E+00  21.44000E+00  17.74500E+01    2609.0 73.50115E+00 TO12.95574E+01

TOTAL      336  98.21613E+00                              18.70000E-01  35.15600E+01
       FIXED EFFECTS MODEL     46.01552E+00  25.10352E-01                                          93.27677E+00 TO10.31555E+01
       RANDOM EFFECTS MODEL    42.05062E+00  85.83547E-01                                          80.45971E+00 TO11.59726E+01
       UNGROUPED DATA          69.59446E+00  33.05699E-01                                          91.71359E+00 TO10.47187E+01

PAIRWISE MULTIPLE COMPARISON OF MEANS.  THE MEANS ARE PUT IN INCREASING ORDER IN GROUPS SEPARATED BY *****.  A MEAN IS
ADJUDGED NON-SIGNIFICANTLY DIFFERENT FROM ANY MEAN IN THE SAME GROUP AND SIGNIFICANTLY DIFFERENT AT THE .05 LEVEL FROM
ANY MEAN IN ANOTHER GROUP.  ***** ***** INDICATES ADJACENT GROUPS HAVE NO COMMON MEAN.

  NEWMAN-KEULS TECHNIQUE, HARTLEY MODIFICATION. (APPROXIMATE IF GROUP NUMBERS ARE UNEQUAL.)
  42.05357E+00,51.80500E+00,66.56429E+00,66.78214E+00,70.06786E+00,73.08857E+00,73.92000E+00,74.65857E+00,77.87500E+00,
  80.51500E+00,80.59571E+00,81.49357E+00,84.46714E+00,84.68143E+00,88.00786E+00,88.61571E+00,99.99571E+00,10.15293E+01,
     *****
  73.08857E+00,73.92000E+00,74.65857E+00,77.87500E+00,80.51500E+00,80.59571E+00,81.49357E+00,84.46714E+00,84.68143E+00,
  88.00786E+00,88.61571E+00,99.99571E+00,10.15293E+01,13.08207E+01,
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Fig 4.14. Analysis of variance for testing variations in equivalent axles among hours of the day.

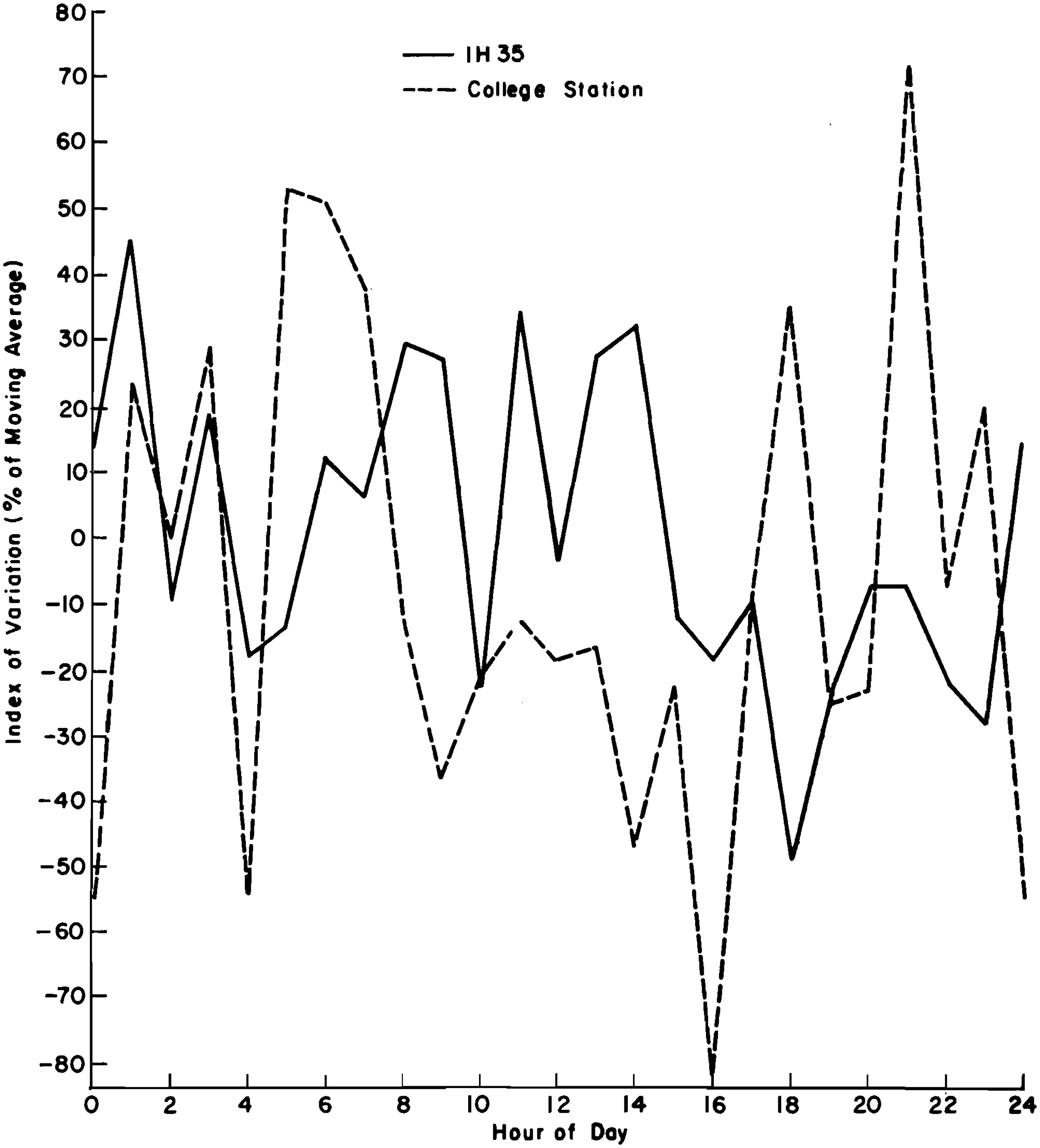


Fig 4.15a. Variation of hourly index of vehicle weight using five days' data.

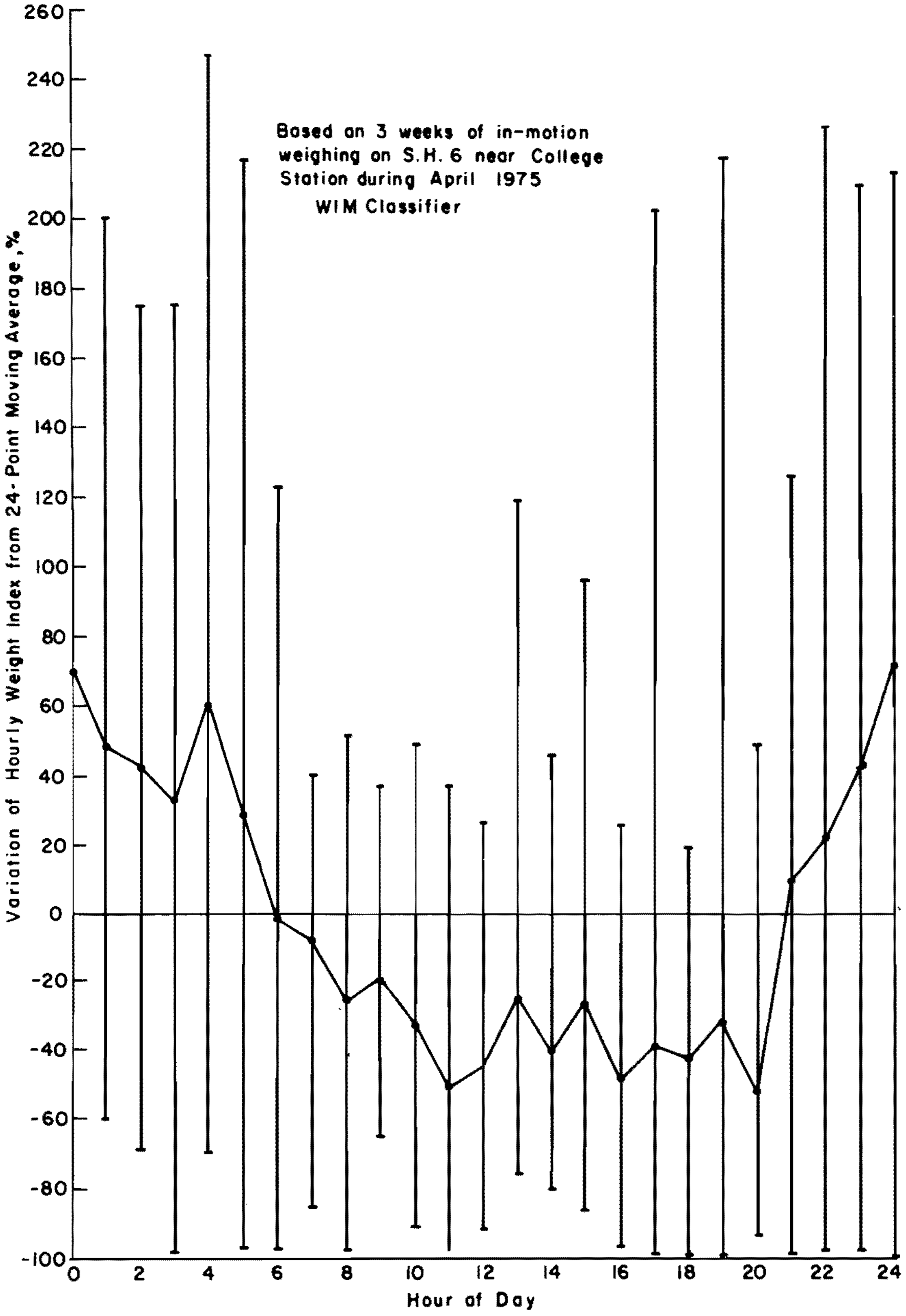


Fig 4.15b. Variation in average hourly weight index and range of the index variation.

the three-week period. The mean values show lighter loads during the daylight hours, as was observed at this station in the fall of 1974.

Sample Size

The preceding sections have dealt with several factors which could affect the design of a vehicle weight survey sampling system. However, the number of vehicles which must be surveyed in order to produce a given overall precision in the weight estimates has not been discussed. The following paragraphs describe standard statistical techniques that can be employed to determine sample size required.

The relationship used to estimate the size of simple random sample is as follows (see Ref 16):

$$n = \frac{k^2 v^2}{d^2}$$

where

n = size of simple random sample needed to obtain some specified precision in the estimate of a desired characteristic,

k = number of standard deviations which implies the degree of certainty that the sample estimate is in error by no more than a specified amount,

v = population value of the coefficient of variation of the characteristic being estimated,

d = allowable relative error expressed as a fraction of the true mean.

This relationship can be used to estimate the size of sample (n) necessary to obtain a specified level of precision (d) in the characteristic to be estimated provided a coefficient of variation (v) for that characteristic is available. The degree of certainty that the specified level of precision (d) has actually been obtained may be chosen by specifying some number of standard deviations (k). Since the population is quite large in relation to any sample which could be drawn, no finite population correction is employed.

Therefore, in order to use this relationship to estimate sample sizes, values of k and d must be chosen and v must be estimated. The value of k was chosen as 1.73 (.92 confidence level) because that value allows less than one chance in 10 that the desired level of accuracy (d) would not be obtained if the computed sample size were actually drawn. A practical value of d would probably be about 0.10 , or 10 percent; however, sample sizes were predicted for values of d of 0.05 and 0.10 in order to compare the effects on sample size of this change in desired accuracy.

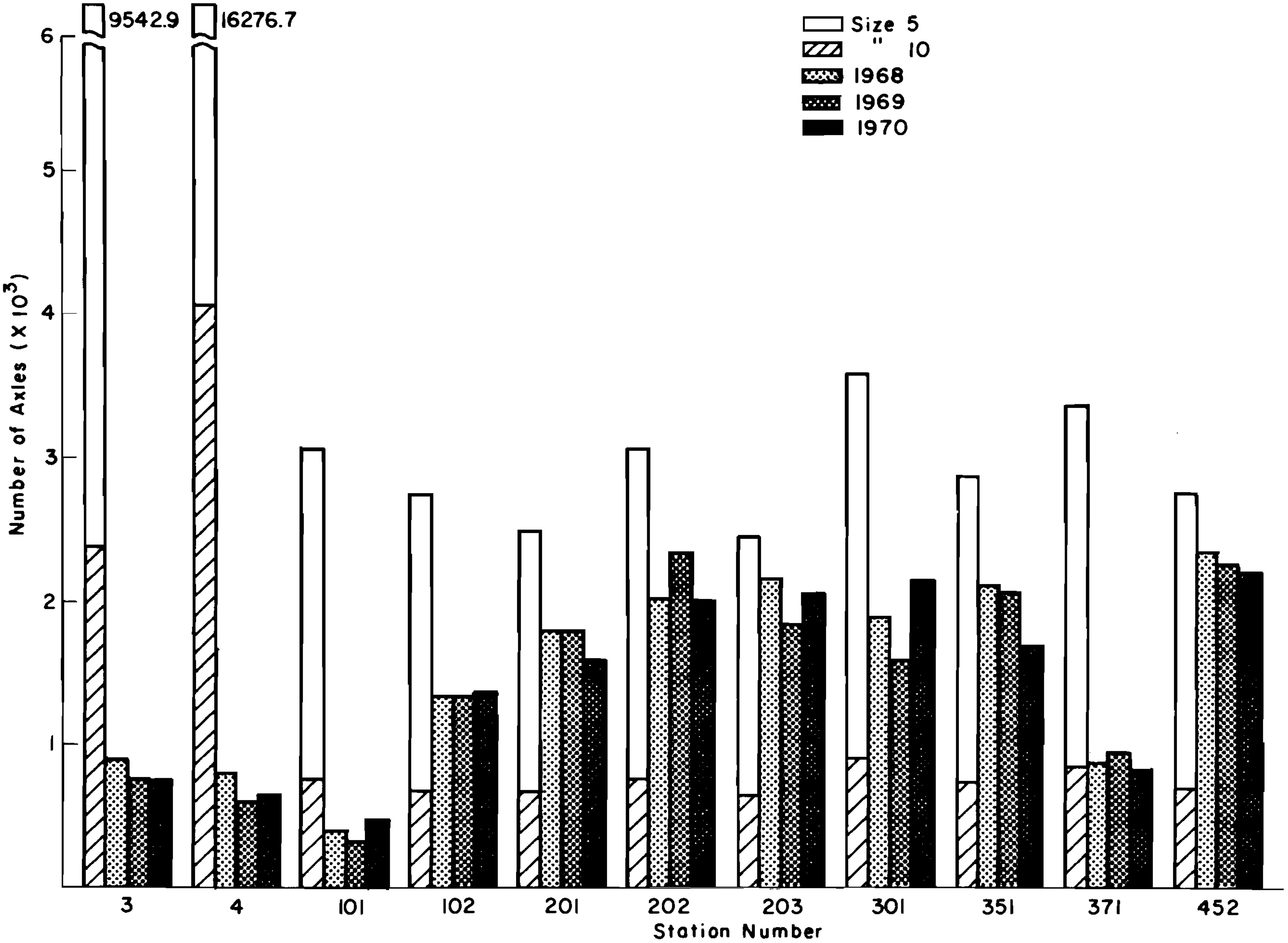
Since it is not practically possible to obtain a population value of the coefficient of variation of any component of vehicle weight, an estimate of the population value was used. This estimate was based upon loadometer data taken during 1968, 1969, and 1970. These data (as noted earlier) consist of frequency distributions of axle weights for each of the 21 survey stations and the axle weight data cannot be related to the individual vehicles from which they were obtained. Therefore, although a sample size in terms of vehicles to be weighed would be preferable, such an estimate could not be directly produced from the available coefficient of variation. Thus, the sample sizes computed using these data refer to the number of axles which must be weighed and not the number of vehicles.

The results of this analysis along with the actual number of axles weighed in 1968, 1969, and 1970 are presented graphically in Fig 4.16. The figure indicates that, at most stations, the number of axles weighed in these three years was more than sufficient to attain a level of accuracy (d) of 10 percent. The numerical values of sample size and coefficients of variation are presented in Appendix B.

Number of Axles Per Vehicle

The preceding paragraphs have provided estimates of the size of sample necessary to attain a desired level of accuracy in equivalent axle weight; however, sample sizes have been stated in terms of number of axles. Although number of axles may be a fairly practical unit, number of vehicles would be a more generally definable quantity. If the number of axles per vehicle is known, number of axles can be easily converted to number of vehicles.

Heathington (Ref 17) produced estimates of the average number of axles per vehicle weighed in Texas in 1963. His work was based on loadometer data collected in 1963 at all 21 regular static weigh stations plus a series of



(continued)

Fig 4.16. Predicted and observed sample sizes.

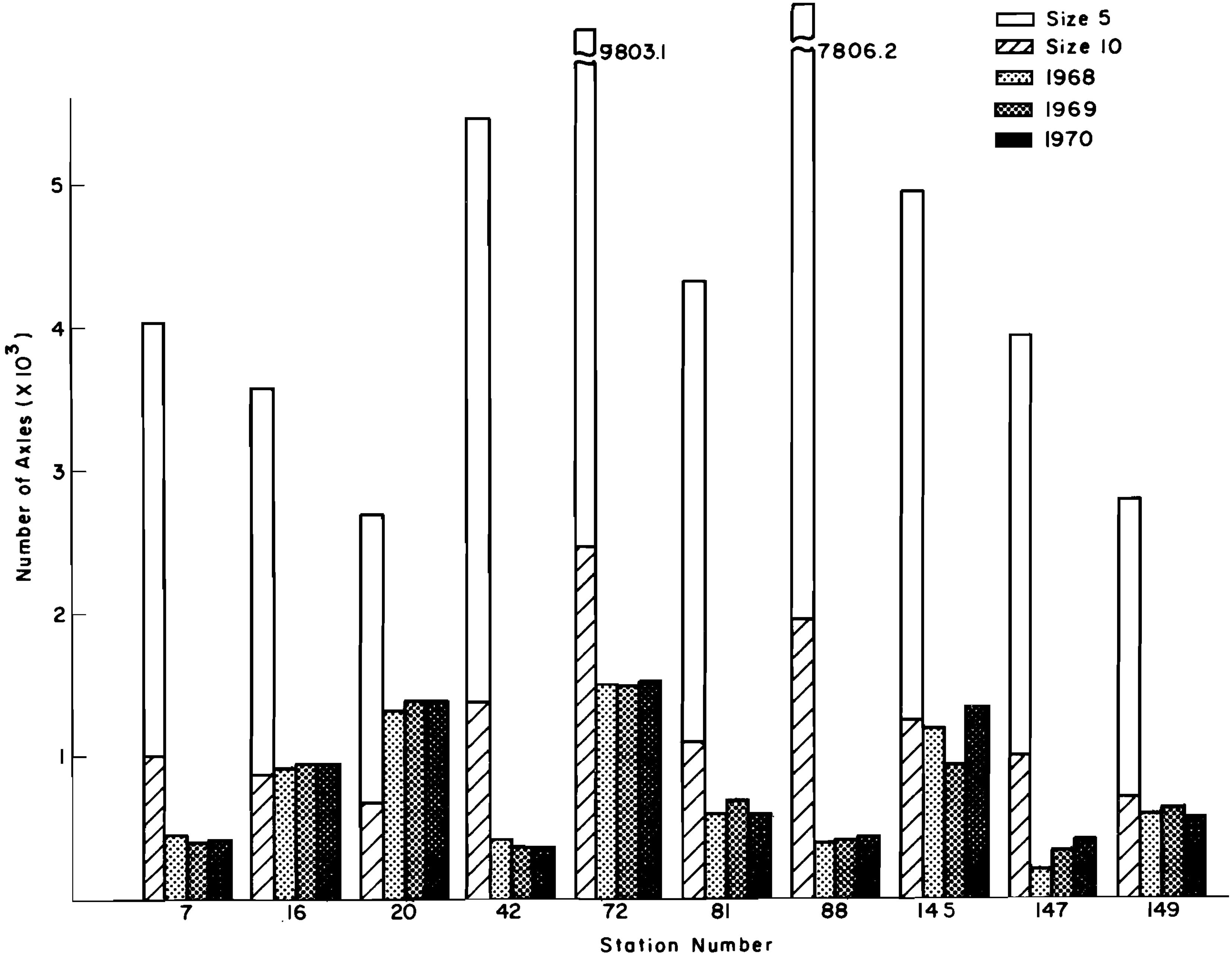


Fig 4.16. (continued)

additional stations which were operated only in that year. Using all weight data collected in 1963, Heathington estimated that, on the average, there were 2.75 axles per vehicle weighed in Texas.

In order to verify or update this estimate all weight information collected in Texas for the years 1968 through 1973 was analyzed. Using these data, two techniques were used to estimate the average number of axles per vehicle weighed in Texas. The simple ratio of axles versus vehicles was computed for all six years and all stations combined. This computation yielded a ratio of 2.70 axles per vehicle with a standard deviation of 0.024 . Since this was a ratio estimate, the standard deviation was computed using the following formula:

$$\sigma_R^2 = R^2 \left(\frac{V_x{}^2 + V_y{}^2 - 2rV_xV_y}{n} \right)$$

where

R = the ratio estimate

V_x = coefficient of variation of the numerator of the ratio

V_y = coefficient of variation of the denominator of the ratio

n = sample size

r = correlation coefficient for X and Y

Linear regression was also used to estimate this ratio because Heathington used this technique and a direct comparison with his work was considered desirable. When number of axles (dependent variable) was regressed on number of vehicles (independent variable) the following equation was produced:

$$y = -84.05 + 2.92X$$

$$R^2 = 0.978$$

Standard error = 94.39

Heathington produced a similar equation and assumed the slope (2.75 in his case) to be the ratio of axles to vehicles and suggested that the intercept be ignored. Another equation was derived which was forced through zero so that there would be no requirement for the intercept to be ignored. In this case the equation was as follows:

$$y = 0 + 2.757X$$

$$R^2 = .994$$

$$\text{Standard error} = 101.82$$

The two equations and data are shown in Fig 4.17. All three techniques tend to produce similar results and in no case do the values of axles per vehicle depart greatly from that estimated by Heathington. The most directly applicable technique, and therefore probably the most dependable, is the first in which the simple average ratio of axles per vehicle was computed. Therefore, a ratio of approximately 2.7 axles per vehicle can be assumed to be representative for all vehicles weighed in Texas for the years 1968 through 1973. Using this ratio and the sample size estimates from the previous section one can compute an approximate sample size in terms of the number of vehicles to be weighed.

Timewise Changes in Number of Axles Per Vehicle

The computation of number of axles per vehicle weighed using techniques analogous to those used by Heathington in the early 1960's indicated an increase of slightly more than 6 percent in the average number of axles per vehicle. Therefore, there seems to be a possible increase in the ratio with time. The same data for 1968 through 1973 were analyzed using linear regression to study this possibility. The ratios for all stations from 1968 through 1973 are shown plotted with the linear regression equation in Fig 4.18.

The coefficient of determination for this equation was 0.002 with a standard error of 0.283 . The standard statistical test of the hypothesis that the slope of this line was equal to zero indicated that its variation from zero was not significant at even the 50 percent confidence level.

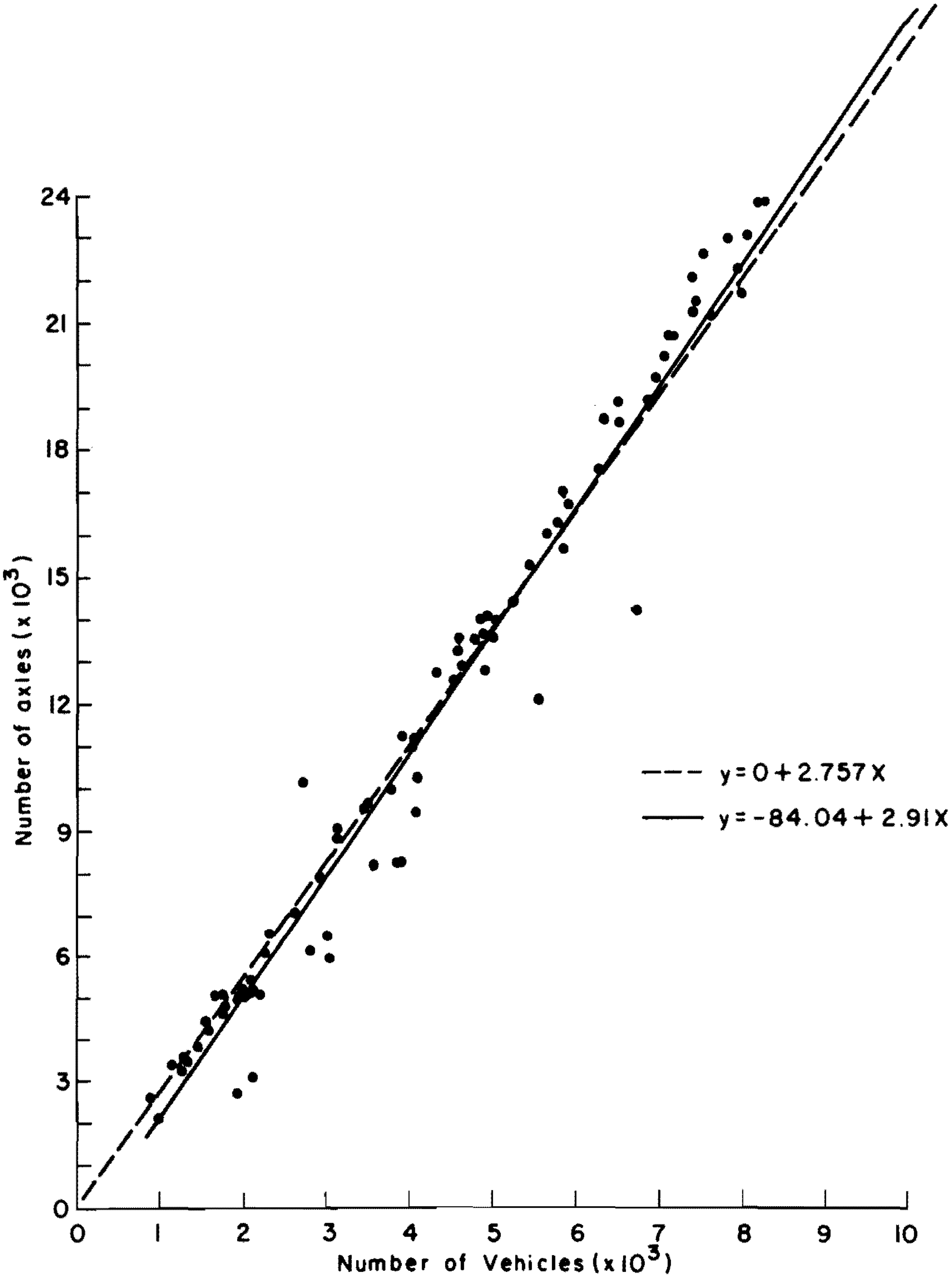


Fig 4.17. Estimation of number of axles per linear vehicle weighed using linear regression.

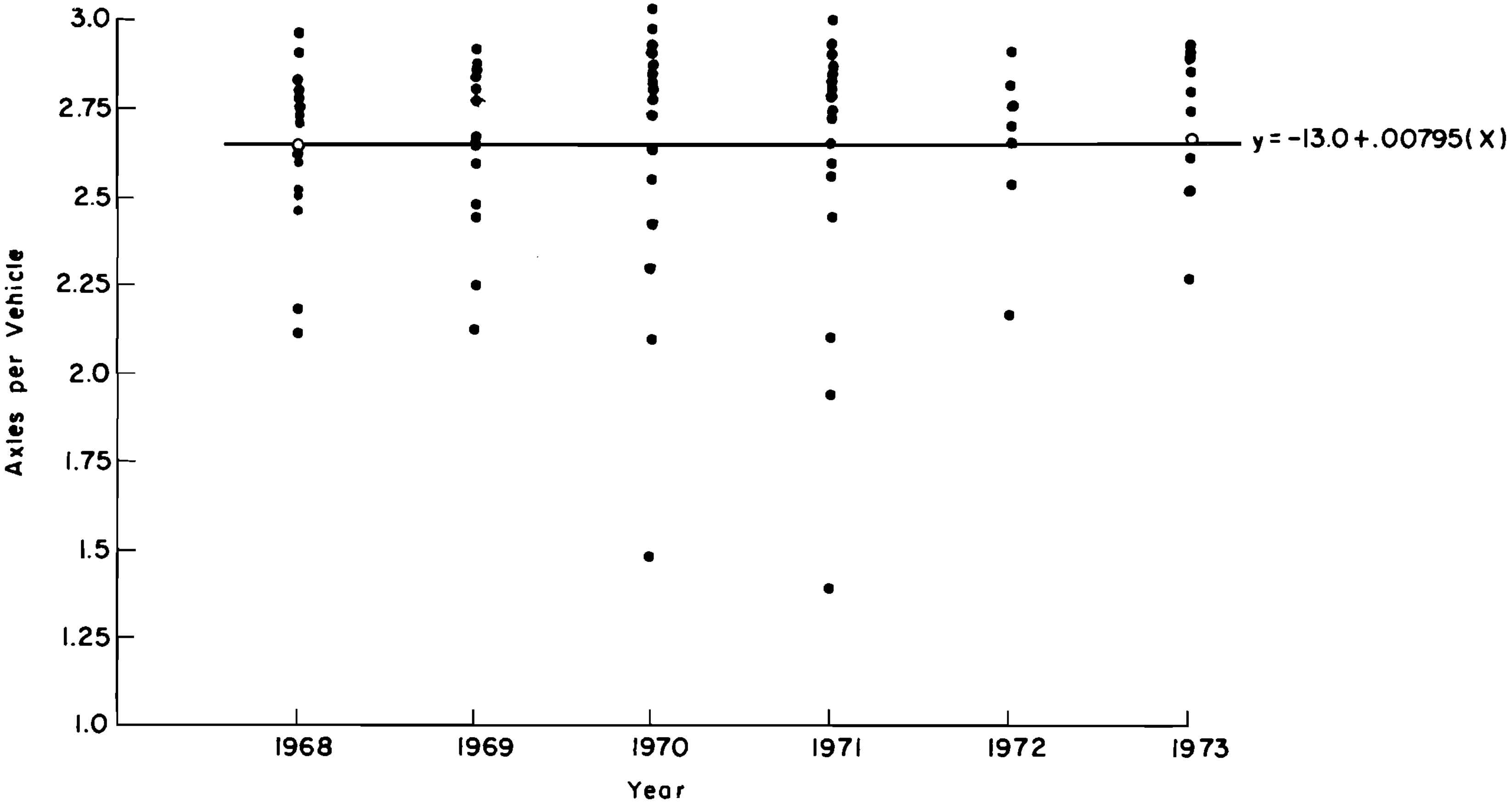


Fig 4.18. Axles per vehicle versus time.

Therefore, these data do not seem to indicate a significant linear time trend in the ratio of axles per vehicle weighed. Figure 4.18 seems to substantiate this conclusion.

However, since these data cover only six years, assumptions about long-time changes in the ratio probably are not justified.

Summary and Conclusions

The data and analyses presented in this chapter seem to warrant the following conclusions:

(1) The number of weight survey sites in Texas may be reduced from 21 to 6 without sacrificing quality of data from previous years. The analysis which led to this conclusion utilized static weight survey data from 1968 through 1970 and assumed that the choice for future site locations was to be made from the existing survey site locations. This analysis should be repeated on a systematic basis in the future to detect changes.

(2) Vehicle weight data collected on I.H. 35 near Austin, Texas, indicated that there were statistically significant variations in equivalent 18-kip (80-kN) single axle weights among hours of the day and days of the week. Although these data cannot be used to make a general statement concerning timewise variations in weights at all sites, they do indicate the possibility that such variations exist elsewhere. The analysis of seasonal variations in vehicle weights indicates such variations may be significant at non-Interstate stations.

(3) The average number of axles per vehicle weighed in Texas has been estimated using several techniques, which yielded values in the range of 2.7 to 2.75 . This ratio may be used with estimates of sample sizes (in terms of axles) to produce a meaningful estimate of the number of vehicles which must be weighed at each survey site in order to attain a specified level of sampling accuracy.

CHAPTER 5. ECONOMIC ANALYSIS

The previous chapters have dealt generally with vehicle weight surveys. In Chapter 3 the accuracy of conventional static and in-motion vehicle weighing equipment were compared. The following paragraphs compare the economic costs of static and in-motion weighing. Three standard economic analysis techniques are utilized.

Annual Cost

Table 5.1 consists of an item by item listing of costs associated with in-motion and static weighing techniques. All costs are based on six weight survey sites, the weighing of 800 vehicles per site per year, and year-round survey operations.

Since only one equipment operator per eight-hour shift and a supervisor are required for the in-motion weighing system and a six-man crew is required for every shift of static weighing, the in-motion system is much less manpower intensive. Assuming a 40-hour work week, 12 weeks per quarter (or season), and eight hours of crew travel time per week, a six-man static weighing crew can obtain 64 hours of survey data at each of the six stations per quarter. A three-man in-motion weighing crew, operating under the same work schedule, can obtain 192 hours of survey data at each site during each quarter. For a comparable amount of data, half-time operation has been assumed for the in-motion weighing crew. This is conservative because the three-man in-motion weighing crew can obtain 96 hours of data per station per quarter while the static weighing crew can obtain only 64.

Costs are divided into five categories: (1) equipment, (2) personnel, (3) data reduction, (4) travel, and (5) user costs. All costs are based upon manufacturers data, estimates by experienced supervisory personnel of the Texas Highway Department, or other references noted in Table 5.1.

All capital cost items have been transformed into annual cost items using the appropriate compound interest relationship and a 10 percent interest rate. The following basic assumptions should be noted:

TABLE 5.1. COMPARISON OF STATIC AND IN-MOTION WEIGHING USING ANNUAL COSTS

WIM			LOADOMETER		
Equipment Costs		Annual Cost	Equipment Costs		Annual Cost
Transducers			Loadometers (3) $700 each (10-yr. life)	2100	$ 342
2 complete with frames and plates $2420 ea. (4-yr. life)	(cr)4840	$ 1527	Maintenance on above	200/W	200
2 extra chasis $1500 ea. (4-yr. life)	(cr)3000	946	Generator (1) (5-yr. life)	500	132
Installation Kit (4-yr. life)	200	63			
30% salvage value for above 2 items	(stt)2352	+ 507	Maintenance on above	100/yr.	100
Installation and Maintenance 2 men 1/4 time ea. at 600/mo.	3600	3600	Paint and Flags	50/yr.	50
10 Frames with bearing pads and terminal boxes, $443 ea.	(cr)4430	1168	Site Preparation		
50% salvage value on above	(stt)2658	+ 435	$4000/each side of road/site (6 sites) (20-yr. life)	48000	5638
Maintenance on 4 Transducers	500/yr.	500	Maintenance $500/site/yr.	3000/yr.	3000
Vehicle Mounted Data Recording and Display System (8-yr. life) 5% salvage value	2175	+ 201			
Maintenance on Vehicle and DR&D System	1000	1000			
Personnel Costs			Personnel Costs		
4 men at $1000/mo. each (1/2 time)		24000	6 men at $600/mo.		43200
Per diem $22/day per man (30-day month, 1/2 time)		15840	Per diem $22/day per man		47520

(continued)

TABLE 5.1. (Continued)

WIM		LOADOMETER	
Data Reduction Costs	Annual Cost	Data Reduction Costs	Annual Cost
1 man 3 months at $600/mo.	$ 1800	1 man 3 months at $600/mo.	$ 1800
		Keypunching	500
Travel		Travel	
1000 mi/mo. using THD vehicle at $.16/mile	1920	2 privately-owned vehicles, 1000 mi/mo. at $.16/mile	3840
3 privately-owned vehicles, 1000 mi/mo. at $.16/mile	5760		
User Costs		User Costs	
No Delay to Users		Assumptions: 1) $20/hr commercial vehicle operating cost (Ref 28) 2) 800 vehicles/site/yr. weighed = 4800 vehicles/yr. 3) 1.5-minute delay during weighing 4) 5-minute slowing and waiting time Resulting Cost: 4800 × 6.5 min × $.33/min	
		5) $.3278/stop = cost of stopping (Ref 46)	10296
		Resulting Cost: 4800 × $.3278	
(1 mile = 1.6 km)		6) $.2225/hr. = cost of idling engine (Ref 46)	1573
		Resulting Cost: 4800 × 6.5 min × 0.2225/60	116
		<u>Total Cost to Users</u> ($2.50/vehicle weighed)	(11985)
TOTAL ANNUAL COST	$ 65367		$119749

(1) Presently-owned equipment and existing site preparations are ignored, and all equipment and site preparations needed for static or in-motion weighing must be purchased at current prices.

(2) No user costs are assigned to the in-motion weighing technique since it involves no interference with normal vehicle operation.

(3) User costs for static weighing are based upon 800 vehicles being weighed at each site each year. This is reasonably consistent with the sample size estimates presented in Chapter 5.

The figures in Table 5.1 show an annual cost of $119,749 for static weighing versus $65,367 for in-motion weighing. If the number of survey sites or the sample size is increased, the difference in annual costs becomes more pronounced. Increasing the sample size essentially has no effect on in-motion weighing while the additional cost is approximately $2.50 for each additional vehicle weighed by static techniques. The effect of additional survey sites is illustrated in Fig 5.1. The figure indicates that the difference in annual cost increases from about $55,000 for 6 sites to over $112,000 for 24 survey sites.

Benefit Cost

Table 5.2 illustrates the benefit-cost method of comparing economics of static and in-motion weighing. In this table, the cost figures of Table 5.1 are divided into five categories. The figures presented here are not directly comparable to those of Table 5.1 because of the following changes in assumptions:

(1) No investment cost has been assigned to site preparation or purchase of equipment for static weighing. Since static weighing is the existing procedure and sites have been prepared and equipment already purchased, these sunk costs can be ignored.

(2) Despite the fact that the Texas Highway Department already owns a sizeable amount of the necessary hardware for in-motion weighing, the full cost of all hardware has again been included in the figures of Table 5.2.

Other cost data and assumptions presented in Table 5.1, including a 10 percent interest rate, are again utilized in these computations. The figures

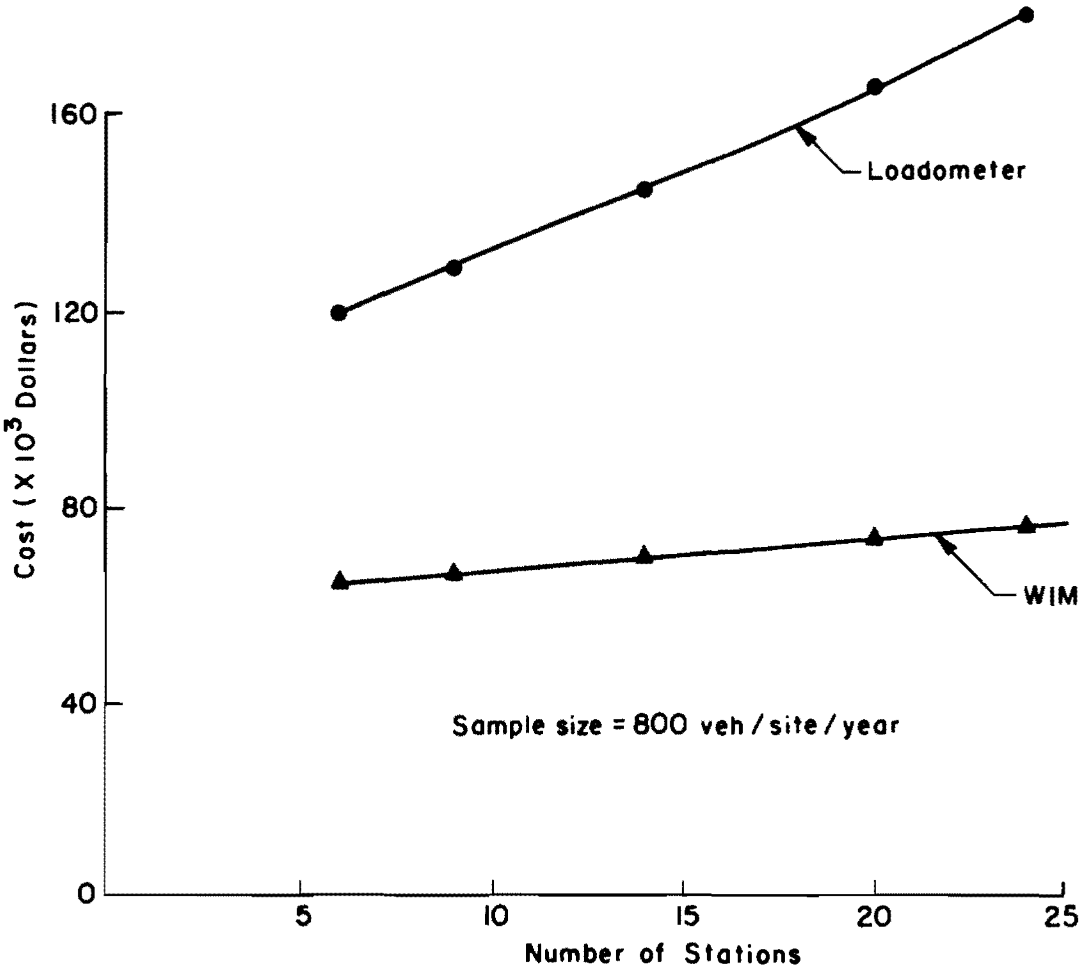


Fig 5.1. Annual cost versus number of survey stations.

TABLE 5.2. COMPUTATION OF BENEFIT-COST RATIO

Alternative	Investment	Maintenance	Personnel	Travel	User Cost
Static Weighing (1)	0 Zero investment is assumed	Service on Loadometer Generator and Site, plus supplies $850/year	Salary $45,500/yr. Per Diem 47,250/yr. $92,750	$3,840/year	$11,985
In-Motion Weighing (2)	Transducers and Data Recording and Display system $10,713/yr.	Service on Equipment and Site $5,100/yr.	Salary $25,800/yr. Per Diem 15,840/yr. $41,640	$7,680/year	0 Zero user cost
Total Annual Benefit or Cost Row 1 minus 2	$10,713 (cost)	$4,250 (cost)	$51,110 (benefit)	$3,840 (cost)	$11,985 (benefit)

Note: All figures are annual costs computed using a 10 percent interest rate.

Benefit/cost=63095/18803=3.35

indicate that in comparison to continuing existing static weighing procedures, the investment in in-motion weighing produces an overall benefit-cost ratio of 3.35 .

Rate of Return

Table 5.3 illustrates the same economic comparison using the internal rate of return technique. The assumptions and cost data are the same as those of the previous section. The analysis indicates that the investment in in-motion weighing would yield an internal rate of return of approximately 95 percent.

Conclusions

The economics of in-motion and static (loadometer) weighing have been analyzed using three common techniques. Using the annual cost method, and assuming equipment and site preparations to be capital investments, in-motion weighing annual costs are approximately half those of static weighing. Benefit-cost and internal rate of return analyses have been conducted neglecting completely any capital investment for static weighing while including the full capital cost of equipment for in-motion weighing. The computed benefit-cost ratio was 3.35 and the rate of return was approximately 95 percent. In all three cases the analysis indicates that from an economic standpoint investment in in-motion weighing would be highly desirable. Despite the assumptions which should favor static weighing in the benefit-cost and rate of return analyses, the figures nevertheless indicate in-motion weighing to be highly advantageous. The large benefit-cost ratio and rate of return indicate that an error of 50 percent or more in the calculations would not change the basic conclusion.

TABLE 5.3. COMPUTATION OF INTERNAL RATE OF RETURN

Internal Rate of Return = Interest Rate at which the investment is equal to the savings due to the investment when both the savings and investment are expressed in a common time frame.

(All figures are reduced to annual costs)

Annual Savings: $63,365

Investments:
a. All investments for static weighing are neglected
b. Transducers = $12,470 (salvage value $5010)
c. Vehicle mounted data recording system = $43,500 (salvage value $2175)

$63,095 = Transducer Cost (Capital Recovery factor / X percent / 4 yrs.) -
Transducer Salvage Value (Sinking Fund factor / X percent / 4 yrs.) +
Data Recording System Cost (Capital Recovery factor / X percent / 8 yrs.) -
Data Recording System Salvage Value (Sinking Fund factor / X percent / 8 yrs.) +
$4250 + $3840
Solving by Iteration X = 95 percent = Internal Rate of Return

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The objective of this study has been to develop an implementation program which will incorporate the in-motion weighing system into normal weight survey activities and take maximum advantage of the unique capabilities of the in-motion weighing (WIM) system. In order to accomplish this objective, the study was divided into four phases. First, the ability of the in-motion weighing system to predict static vehicle loads was evaluated in a field experiment. Second, vehicle weight data previously obtained by the Texas Highway Department in routine static weighing operations were analyzed to determine the overall level of sampling effort needed to provide satisfactory estimates of vehicular weights. Third, timewise variations in vehicle weights were studied using data collected by the in-motion weighing system. Fourth, an economic analysis comparing static and in-motion weighing was conducted. The findings of these four analysis phases appear to justify the following conclusions and recommendations.

Conclusions

(1) In-motion weighing is a useful, practical technique for obtaining vehicular weight, dimension, and speed data. The accuracy with which the system can predict static vehicle weights is summarized in Table 6.1.

TABLE 6.1. SUMMARY OF ACCURACY WITH WHICH STATIC VEHICLE WEIGHTS CAN BE ESTIMATED BY W I M

Weight	Basis for Static Weight Comparison	Expected Accuracy of WIMEstimate, %
Gross Vehicle Weight	Platform Scales	± 5.8
Axle Weight	Platform Scales	± 10.8
Wheel Weight	Wheel Load Weighers	± 13.6

The magnitude of accuracy demonstrated by weigh-in-motion appears entirely adequate for traffic survey purposes, particularly when the feasibility of taking up to 100 percent samples for extended periods of time is considered. The benefits of improved safety, reduced delay, and overall economy in data procurement all recommend adoption of the in-motion weighing system.

(2) The number of weight survey sites can be reduced from the pre-1971 level of 21 to six, provided there is no increased need for predictive capability over that of pre-1971 levels. This analysis was based on survey data for the years 1968 through 1970, the three most current years for which data from 21 stations were available.

(3) Vehicle weight data obtained on I.H. 35 near Austin, Texas, indicate that at this one site there are significant variations in vehicle weights among hours of the day and among days of the week. Although this conclusion cannot be generalized for all stations, it does suggest that such timewise variations may exist at other sites.

(4) Seasonal vehicle weight data for 1965-66 indicate that, during this two-year period, significant seasonal variations in vehicle weights existed at certain survey sites.

(5) The average number of axles per vehicle weighed in Texas appears to be about 2.70 to 2.75 . The range of this estimate reflects the results of several alternative analysis techniques all of which show very little variation from each other. There does not appear to be any significant linear time trend in this estimate.

(6) Use of in-motion as opposed to static weighing equipment appears to be highly advantageous from an economic standpoint. This analysis indicates that the annual cost of a network of six in-motion weighing stations would be approximately one-half that of six static weigh stations.

Recommendations

The following recommendations are based upon the foregoing analysis, data, and conclusions. They are intended to serve as general guidelines in establishing a revised vehicle weight survey system which will obtain the highest quantity and quality of data for each survey dollar invested.

(1) The number of survey sites should be reduced from 21 to six. The six sites chosen should consist of one from each of the six groups of Chapter 4, although the particular selections may be based on other considerations.

(2) In view of the significant timewise variations in vehicle weights detected among hours, days, and seasons, each of the six selected survey sites should initially be operated during all seasons on a 24-hour, seven-day basis. Surveys should include successive seven-day samples for each direction of traffic to detect any major differences in weight patterns that might exist. The data collected in these initial studies should be analyzed using the procedures of Chapter 4 to determine the significance of any timewise or directional variations in weights. Based upon the results of these studies, continuous directional seasonal sampling (seven-day, 24-hour) may be continued or discontinued as needed.

(3) The locations of survey sites and the number of sites should be evaluated periodically to allow future changes in vehicle weights to influence the number of survey sites and their locations.

(4) The sample size estimates of Chapter 4 should be used as general guidelines to insure acceptable levels of accuracy in vehicle weight estimates.

The foregoing analyses, conclusions and recommendations outline the framework for a redesigned vehicle weight survey program for the State of Texas. The new program will continue to provide vehicle weight and dimension data of a quality that will be at least as good as that which has been available but at reduced cost and with less hazard.

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APPENDIX A

ANALYSIS OF NUMBER OF SURVEY STATIONS CONDUCTED BY THE TEXAS HIGHWAY DEPARTMENT

APPENDIX A. ANALYSIS OF NUMBER OF SURVEY STATIONS CONDUCTED BY THE TEXAS HIGHWAY DEPARTMENT

In 1971, the magnitude of vehicle weight survey operations conducted by the Texas Highway Department was reduced by discontinuing operations at 11 of the original 21 survey stations. The analysis which led to this reduction is explained in the following sections.

All vehicle weight data from the years 1968 through 1970, along with figures on average daily traffic from each station and the AASHTO rigid pavement equivalent factors, were used to produce an estimate of the average daily number of 18-kip (80-kN) equivalent axles for each station. This term is commonly called average daily loading and is usually computed on a yearly basis for each survey station.

The values of average daily loading were compared by means of computing a percentage variation for all possible station pairs. Table A.1 illustrates these values in tabular form. From this tabulation, lists were prepared showing which stations had average daily loading values that were within a given percentage of each other. Table A.2 is an example of such a list for 10 percent or less variation. Ten stations were administratively selected from the list such that an acceptably small number of excluded stations had a percentage variation of more than 10 percent from at least one of the included stations.

TABLE A.1. PERCENTAGE VARIATION IN AVERAGE DAILY LOADING FOR ALL PAIRS OF SURVEY STATIONS

Station Numbers	L-003	L-004	L-007	L-016	L-020	L-042	L-072	L-081	L-088	L-101	L-102	L-145	L-147	L-149	L-201	L-202	L-203	L-301	L-351	L-371	L-452
L-003	-	42	39	47	108	83	90	173	231	229	95	112	63	89	128	129	134	108	108	103	150
L-004	48	-	106	118	209	171	183	304	390	388	189	214	141	180	237	238	246	213	207	201	270
L-007	28	52	-	⑥	50	32	37	96	137	136	40	52	17	36	63	64	68	52	49	46	80
L-016	32	54	⑥	-	41	24	29	85	124	123	32	44	⑩	28	54	55	59	43	41	38	70
L-020	52	68	33	29	-	12	⑧	31	59	58	⑥	②	22	⑨	⑨	⑩	12	①	0	②	20
L-042	45	23	24	20	14	-	④	49	80	80	⑦	16	11	③	24	25	28	15	13	11	36
L-072	48	65	28	23	⑨	④	-	43	73	73	①	11	15	①	19	20	23	11	⑨	⑥	31
L-081	63	75	49	56	24	37	30	-	21	21	28	22	40	31	16	16	14	23	24	25	⑧
L-088	70	80	58	54	37	45	42	18	-	0	41	36	51	43	31	31	29	36	37	39	24
L-101	70	79	58	55	37	44	42	17	0	-	41	36	51	43	31	31	29	36	37	38	24
L-102	49	65	29	25	⑦	⑥	②	40	69	69	-	9	17	③	17	17	20	⑧	⑦	④	28
L-145	53	68	34	31	②	14	10	28	56	55	⑧	-	23	11	⑦	⑧	10	①	②	④	18
L-147	39	59	14	⑨	28	13	17	67	103	102	20	30	-	16	40	40	44	30	28	25	54
L-149	47	64	26	22	⑩	③	①	44	75	74	③	12	86	-	20	21	51	12	10	6	32
L-201	56	70	39	35	⑧	19	16	20	45	45	14	⑦	29	17	-	0	③	⑦	⑨	11	⑩
L-202	56	70	39	35	⑨	20	16	19	45	44	15	⑦	29	17	0	-	②	⑧	⑨	11	⑩
L-203	57	71	40	37	11	22	18	17	41	41	17	⑨	29	19	③	②	-	10	11	13	⑦
L-301	53	68	37	30	①	13	⑩	29	57	56	⑦	①	23	10	8	8	11	-	①	④	19
L-351	52	68	30	29	⓪	12	⑧	31	59	58	⑥	②	22	⑨	⑨	⑧	12	①	-	②	20
L-371	51	67	31	27	③	⑩	⑥	34	63	62	④	④	20	⑦	12	12	15	④	②	-	23
L-452	60	73	44	41	17	27	24	⑨	32	32	22	15	35	24	⑨	⑨	⑦	16	17	19	-

TABLE A.2. SURVEY STATIONS HAVING 10 PERCENT OR LESS VARIATION IN AVERAGE DAILY LOADING

Base Station	Stations with 10% or Less Variation Compared to the Base Station
L-003*	
L-004	
L-007	L-016
L-016	L-007, L-147
L-020	L-072, L-102, L-145, L-149, L-201, L-202, L-301, L-351, L-371
L-042	L-072, L-102, L-149
L-072	L-020, L-042, L-102, L-149, L-351, L-371
L-081	
L-088	L-101
L-101	L-188
L-102	L-020, L-042, L-072, L-145, L-149, L-301, L-351, L-371
L-145	L-020, L-072, L-102, L-201, L-202, L-203, L-301, L-351, L-371
L-147	L-016
L-149	L-020, L-042, L-072, L-102, L-351, L-371
L-201	L-020, L-145, L-202, L-203, L-301, L-351, L-452
L-202	L-020, L-145, L-201, L-203, L-301, L-351, L-452
L-203	L-145, L-201, L-202, L-301, L-452
L-301	L-020, L-072, L-102, L-145, L-149, L-201, L-202, L-351, L-371
L-351	L-020, L-072, L-102, L-145, L-149, L-201, L-202, L-301, L-371
L-371	L-020, L-042, L-072, L-102, L-145, L-149, L-301, L-351
L-452	L-081, L-201, L-202, L-203

*Stations at which operations were continued are underlined.

APPENDIX B

SAMPLE SIZE ANALYSIS

APPENDIX B. SAMPLE SIZE ANALYSIS

The results of the sample size analysis of Chapter 4 are tabulated in Table B.1. The columns labeled "size 5" and "size 10" refer to the predicted necessary sample size to produce an estimate of the mean within 5 or 10 percent respectively of the true mean. The column labeled "NO. OBS" refers to the number of observations upon which the tabulated coefficients of variation are based. These numbers are the sums of all axles weighed at each respective station for the years 1969 through 1970.

TABLE B.1. TABULATED RESULTS OF SAMPLE SIZE ANALYSIS

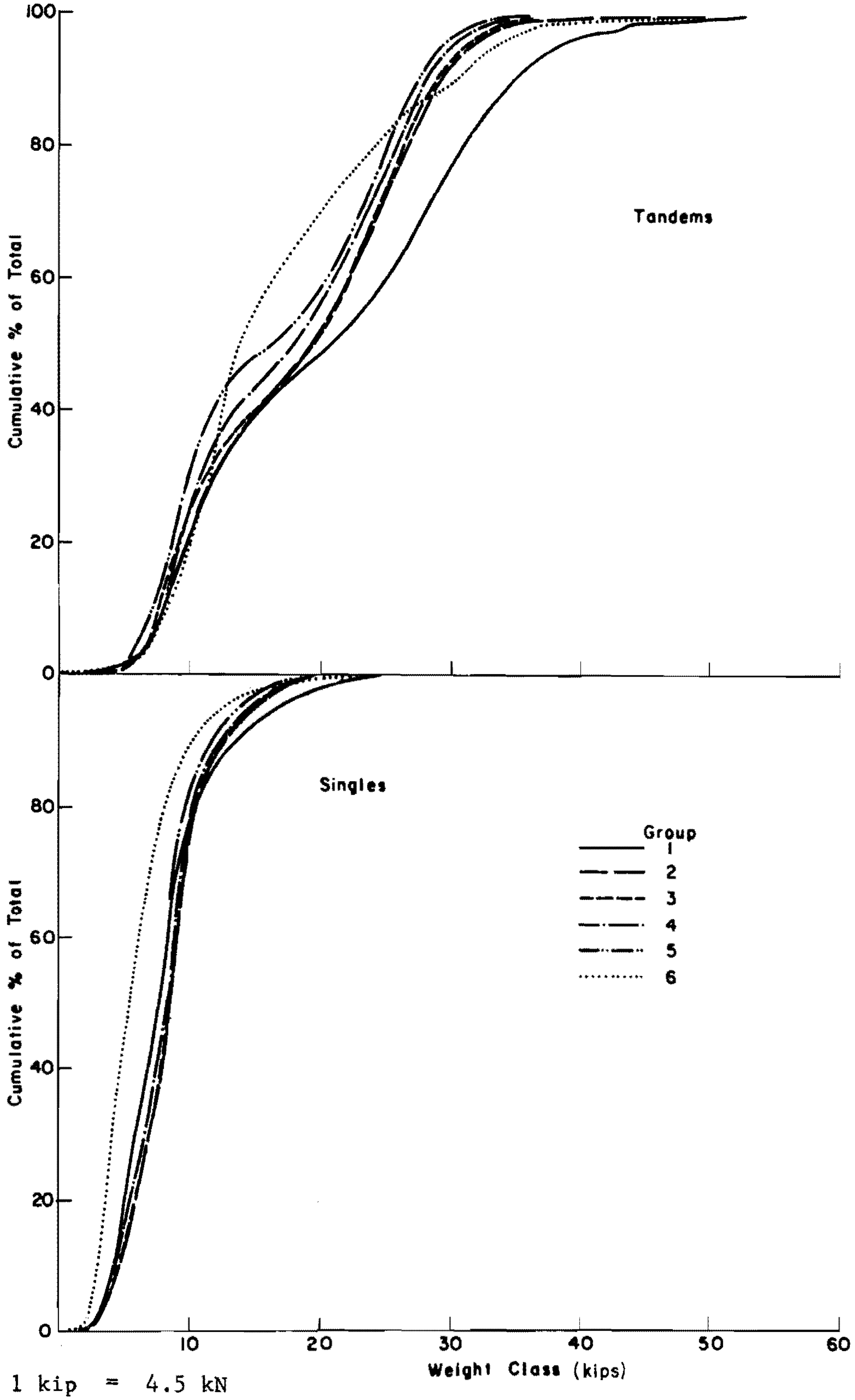
MEAN	STD.DEV	CF.VAR	SIZE10	SIZE5	NO.OBS	GROUP	STATION
.100	.282	2.820	2385.7	9542.9	2405	1	3
.082	.302	3.683	4069.2	16276.7	2152	2	4
.127	.234	1.843	1018.5	4073.9	1260	3	7
.133	.229	1.722	889.4	3557.5	2774	4	16
.175	.262	1.497	672.4	2689.7	3984	5	20
.162	.345	2.130	1360.6	5442.4	1108	6	42
.183	.523	2.858	2450.3	9801.3	4459	7	72
.199	.377	1.894	1076.7	4306.8	1762	8	81
.287	.732	2.551	1951.5	7806.2	1209	9	88
.301	.480	1.595	762.9	3051.6	1176	10	101
.155	.234	1.510	683.7	2735.0	4001	11	102
.181	.367	2.028	1233.4	4933.5	3418	12	145
.126	.228	1.810	982.3	3929.3	941	13	147
.153	.234	1.529	701.7	2806.9	1760	14	149
.186	.268	1.441	622.8	2491.3	5195	15	201
.190	.304	1.600	768.0	3072.0	6345	16	202
.186	.266	1.430	613.6	2454.2	6031	17	203
.178	.307	1.725	892.4	3569.6	5560	18	301
.189	.293	1.550	721.0	2884.0	5850	19	351
.167	.280	1.677	843.3	3373.4	2594	20	371
.200	.301	1.505	679.5	2718.0	6731	21	452

APPENDIX C

AXLE WEIGHT FREQUENCY DISTRIBUTION
FOR WEIGHT SURVEY SITES

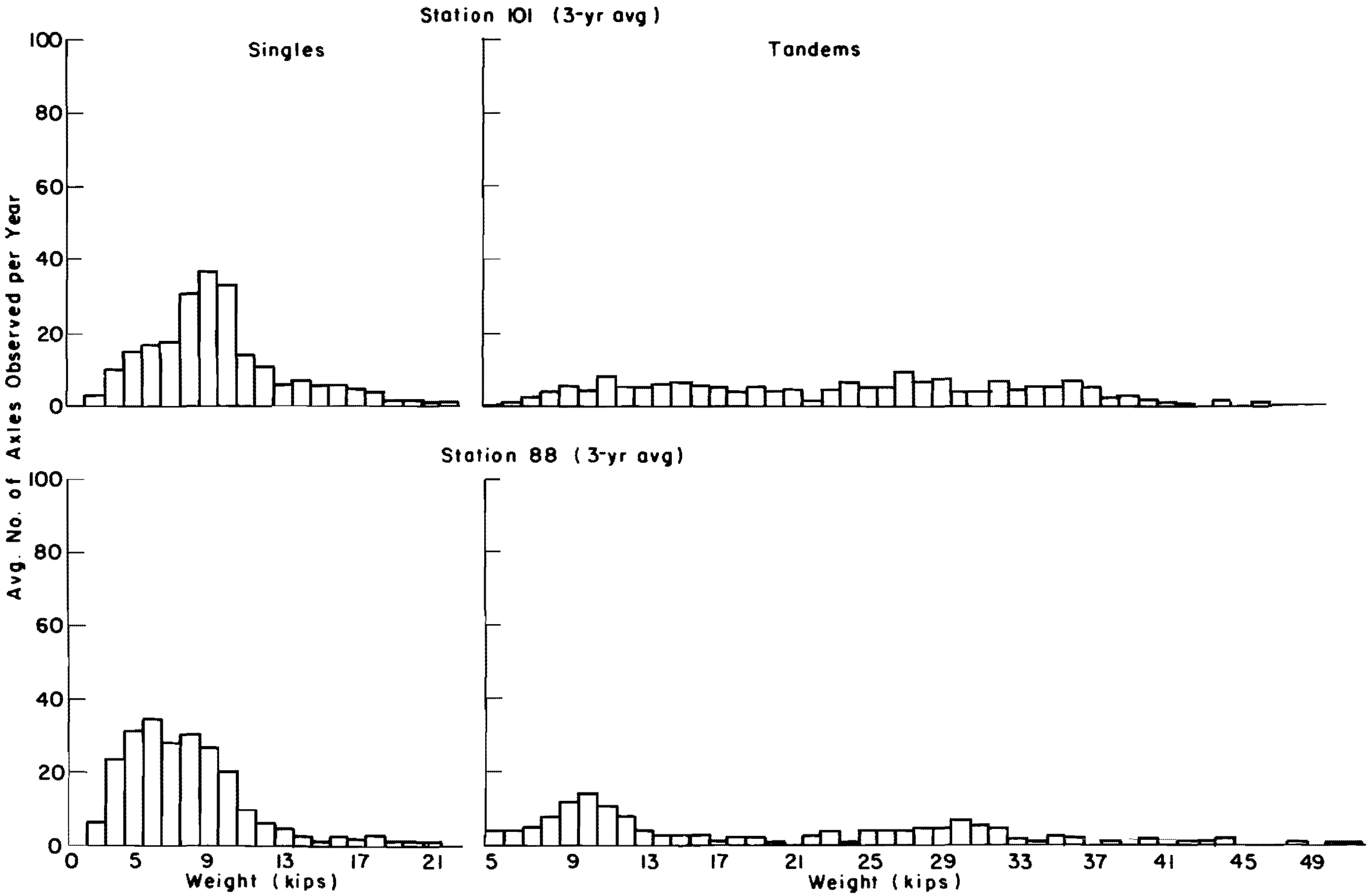
APPENDIX C. AXLE WEIGHT FREQUENCY DISTRIBUTION FOR WEIGHT SURVEY SITES

Observed axle weights at all 21 weight survey sites for the years 1968 through 1970 are presented in the form of frequency distributions in the following figures. Figure C.1 presents a comparison of the six station groups derived in Chapter 4 by means of a family of cumulative frequency curves. Figures C.2 through C.13 present frequency distributions of axle weights for each of the 21 survey sites. Data presented in these figures represent a three-year averaging of the years 1968 through 1970.



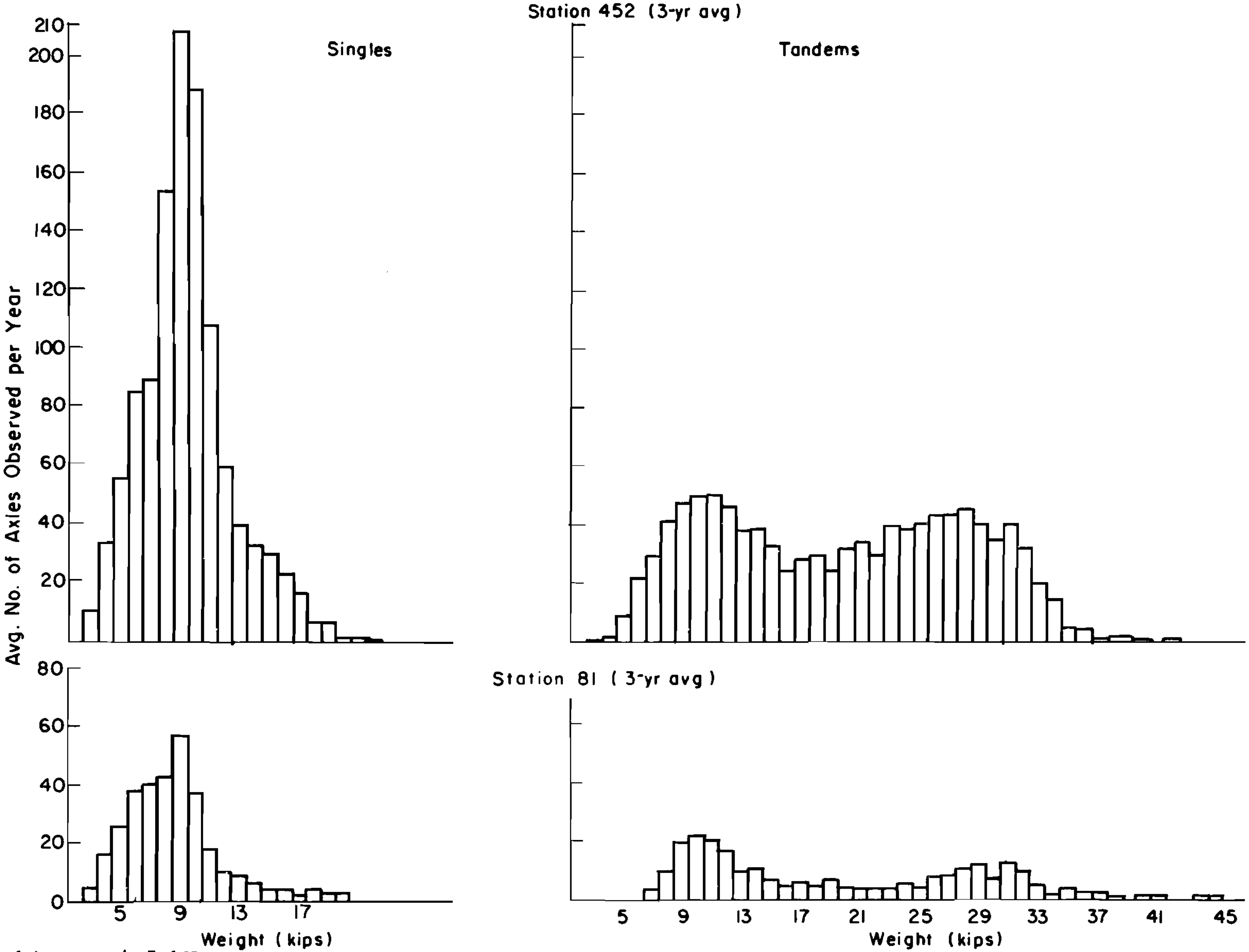
1 kip = 4.5 kN

Fig C.1. Cumulative frequency distributions for the groups of Chapter 4.



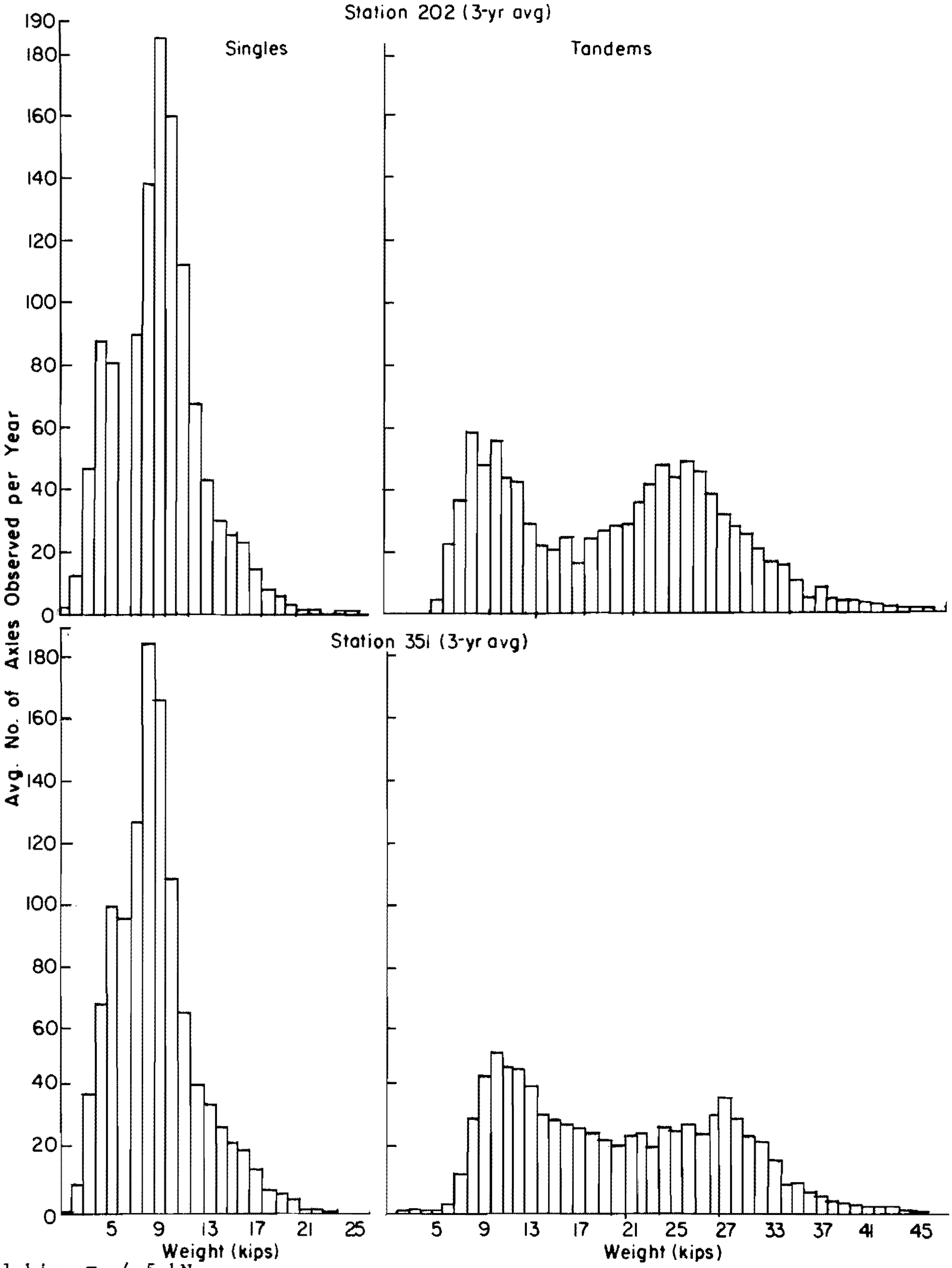
1 kip = 4.5 kN

Fig C.2. Frequency distributions for Stations 101 and 88.



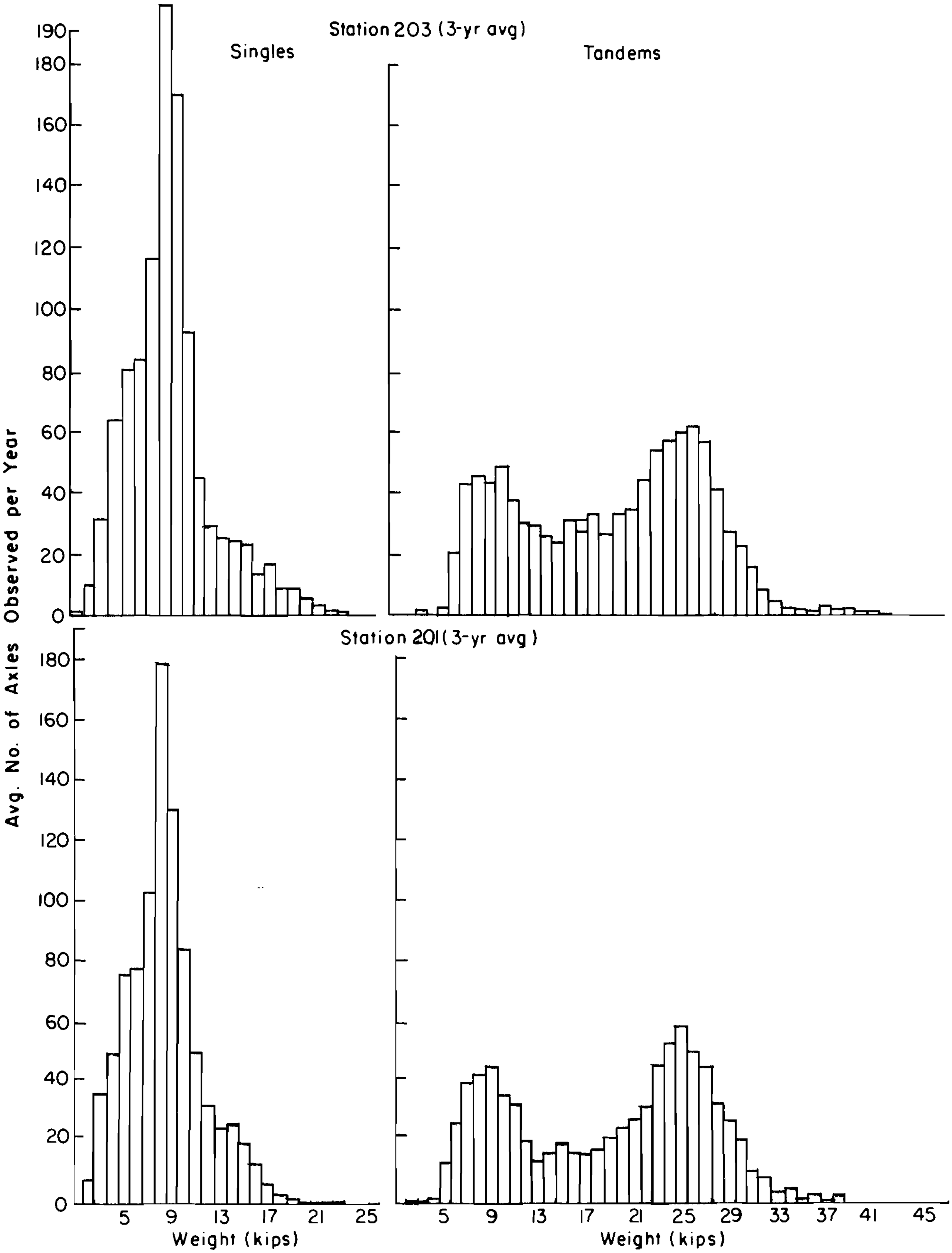
1 kip = 4.5 kN

Fig C.3. Frequency distributions for Stations 452 and 81.



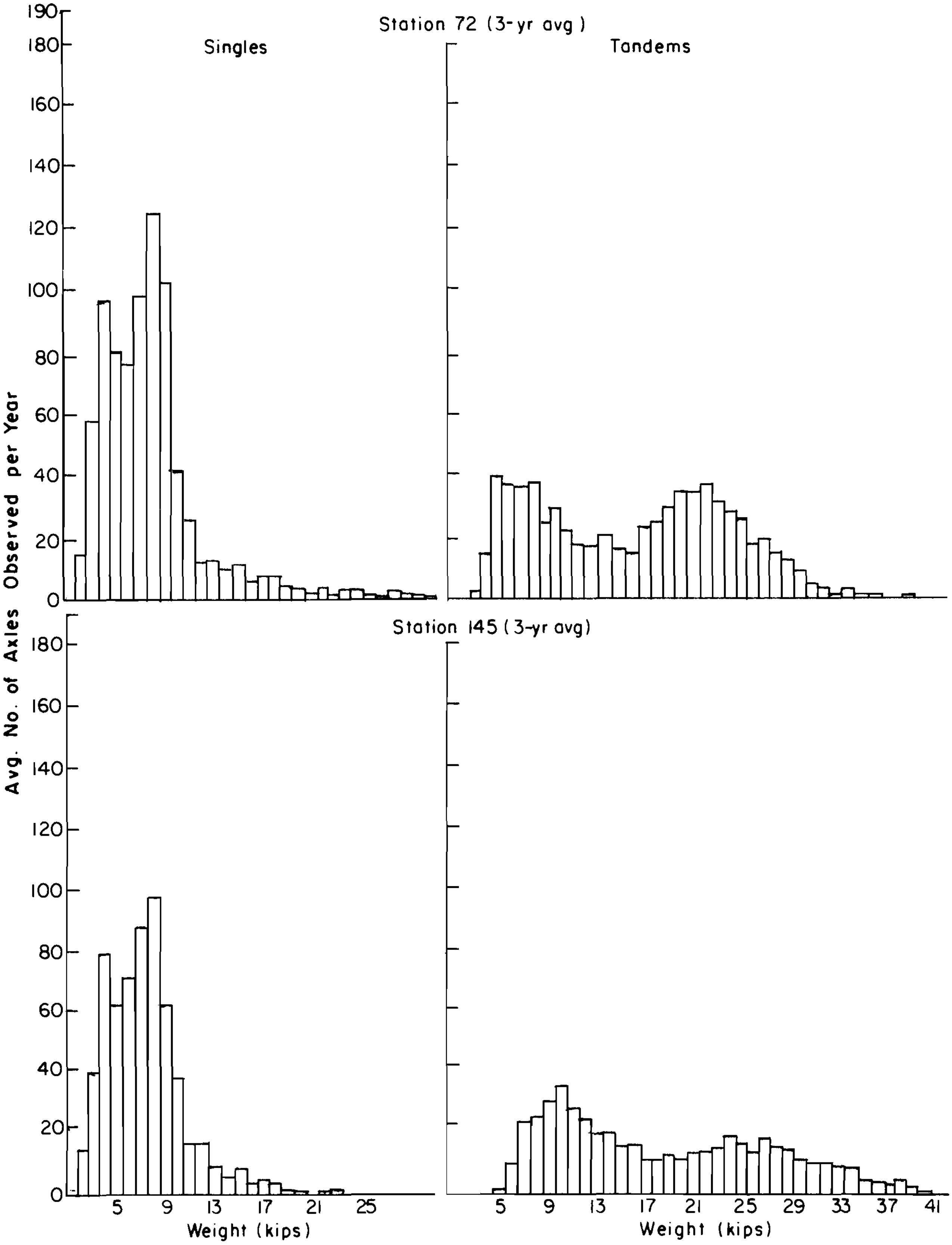
1 kip = 4.5 kN

Fig C.4. Frequency distributions for Stations 202 and 351.



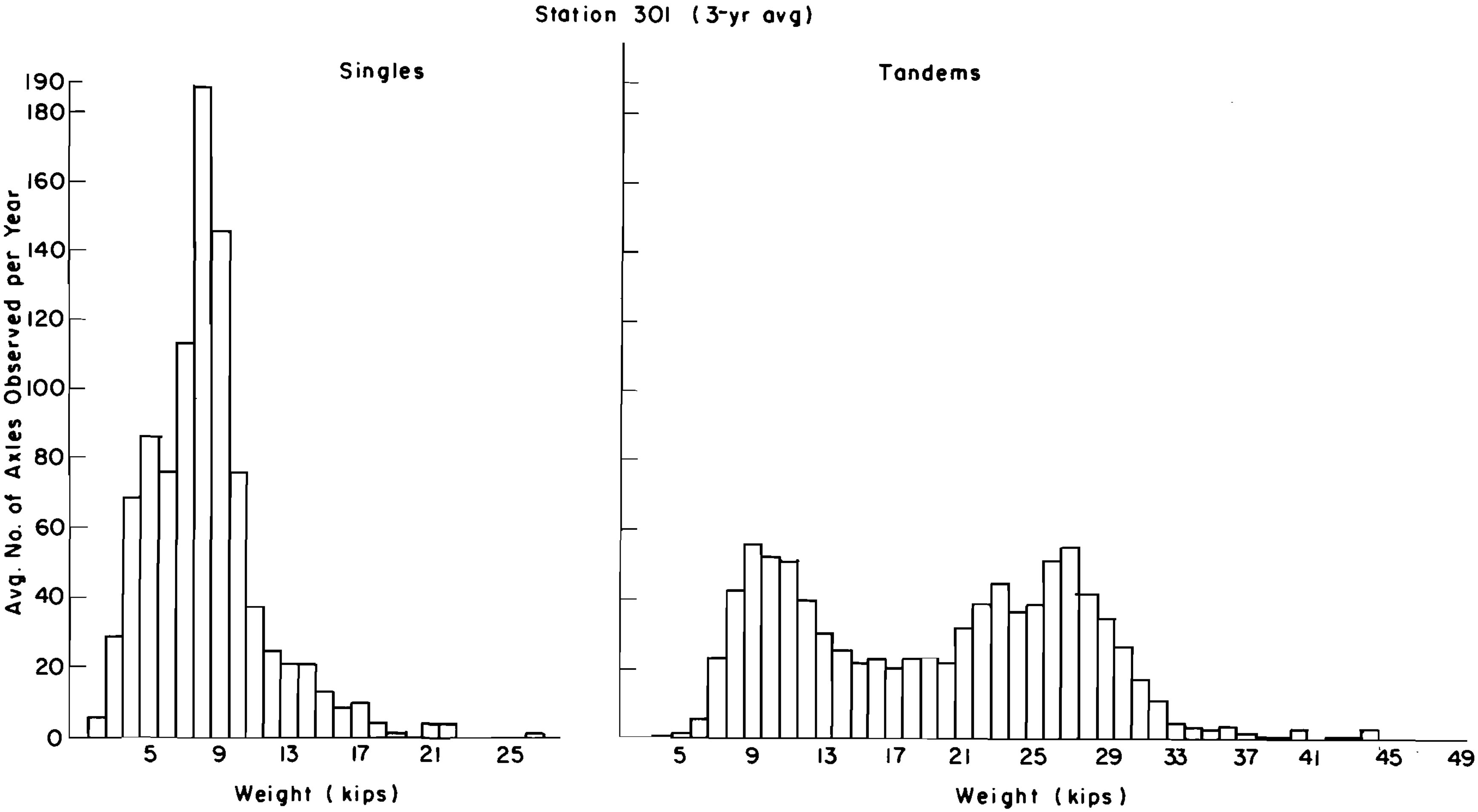
1 kip = 4.5 kN

Fig C.5. Frequency distributions for Stations 203 and 201.



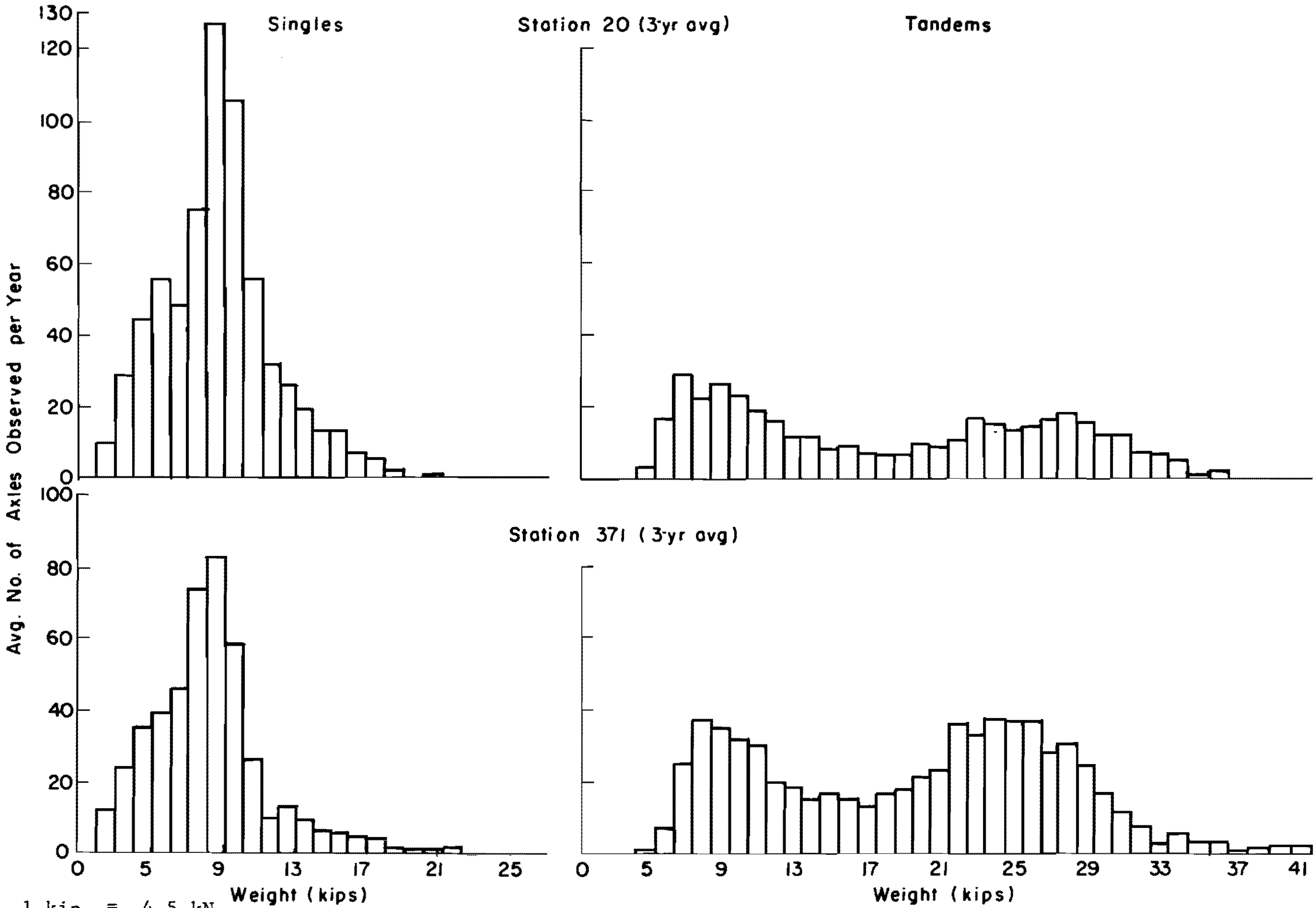
1 kip = 4.5 kN

Fig C.6. Frequency distributions for Stations 72 and 145.



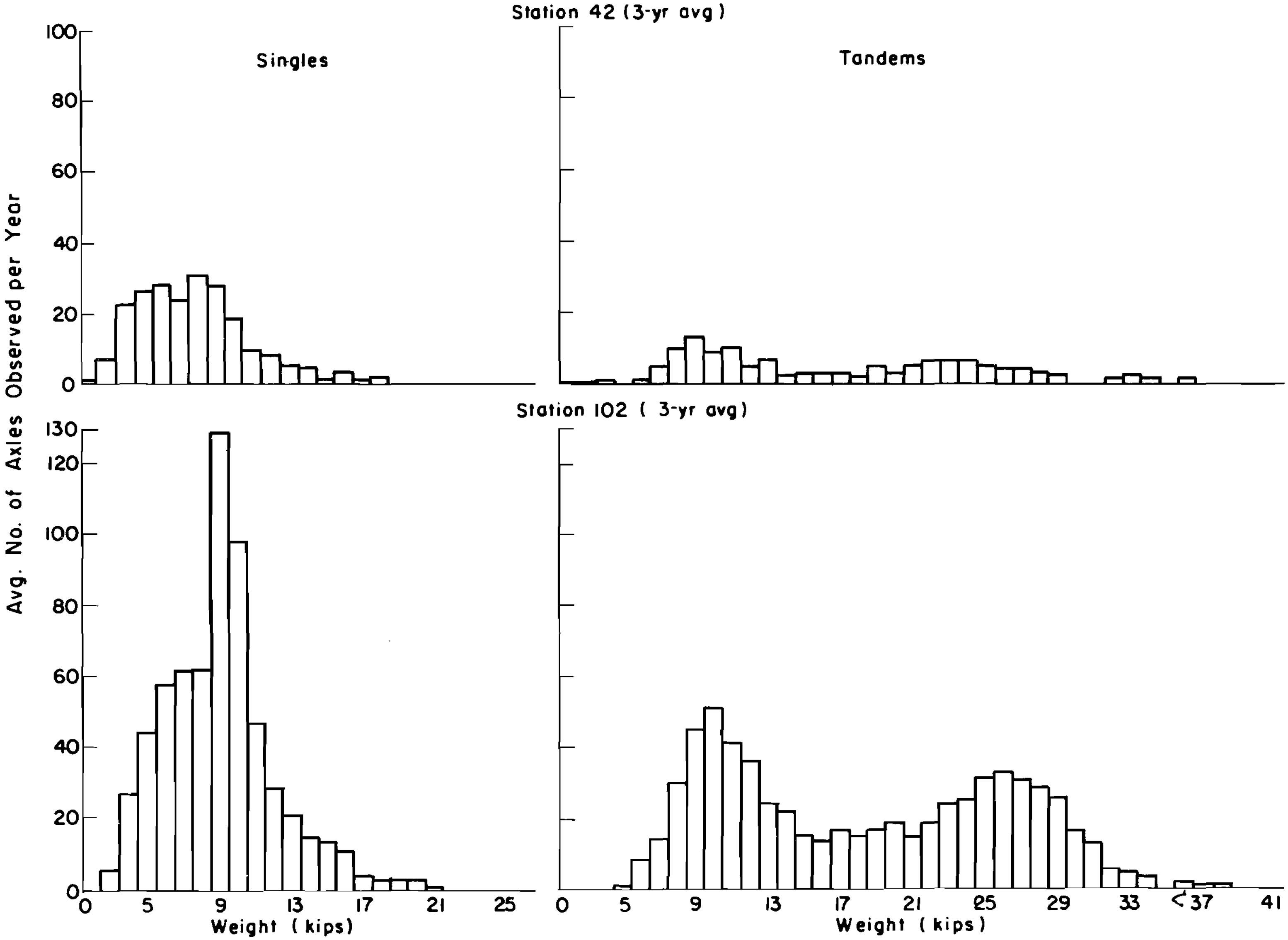
1 kip = 4.5 kN

Fig C.7. Frequency distribution for Station 301.



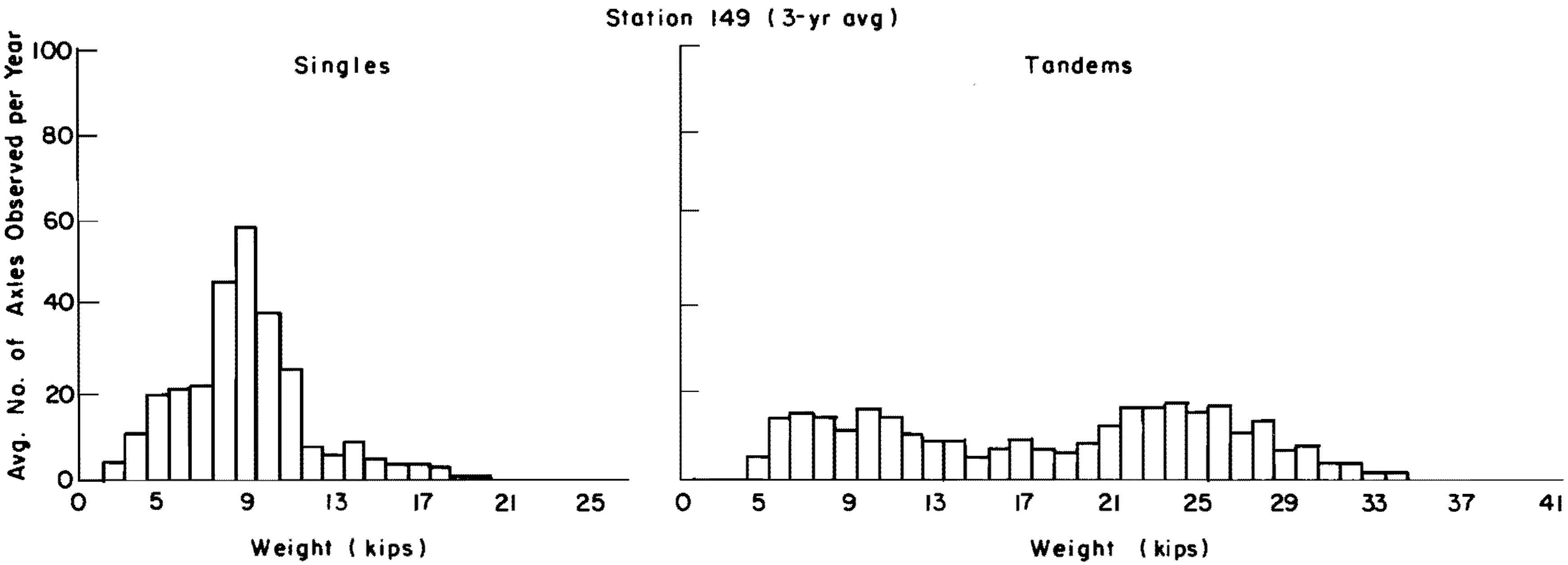
1 kip = 4.5 kN

Fig C.8. Frequency distributions for Stations 20 and 371.



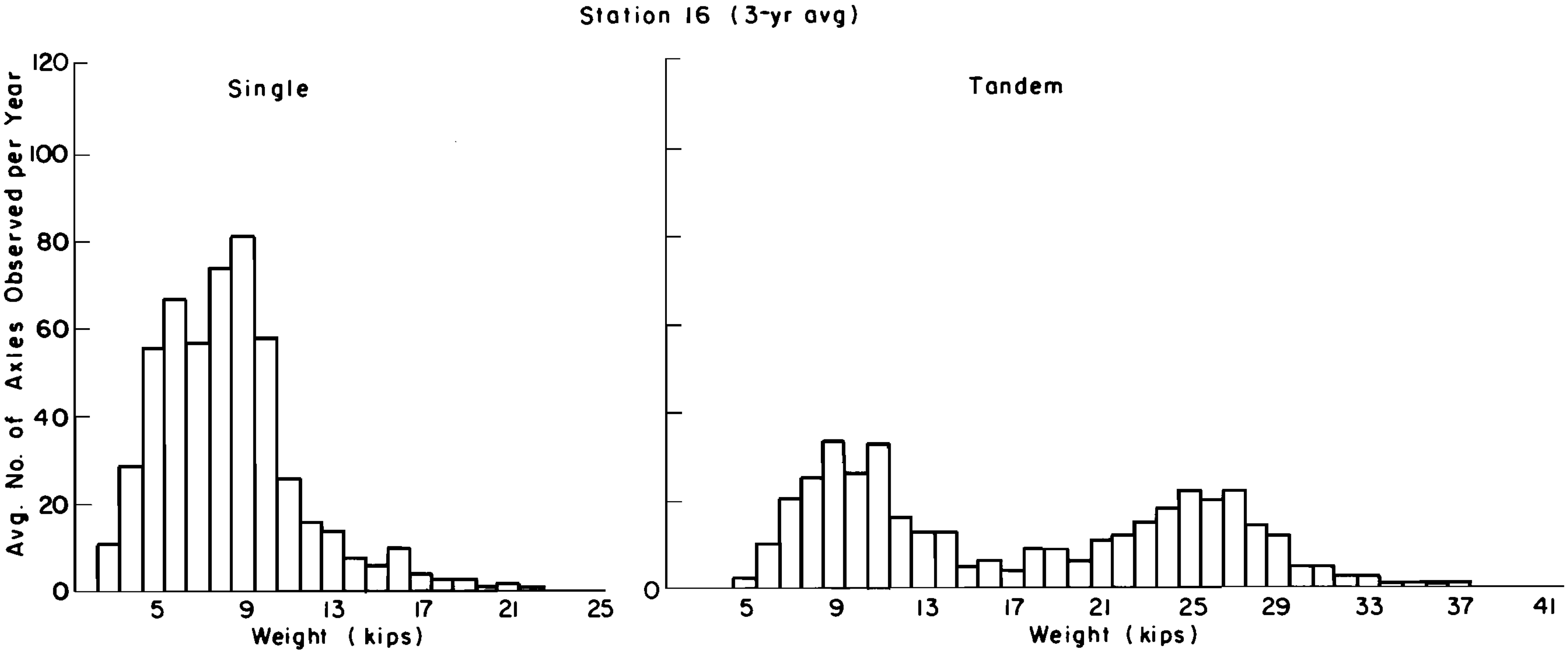
1 kip = 4.5 kN

Fig C.9. Frequency distributions for Stations 42 and 102.



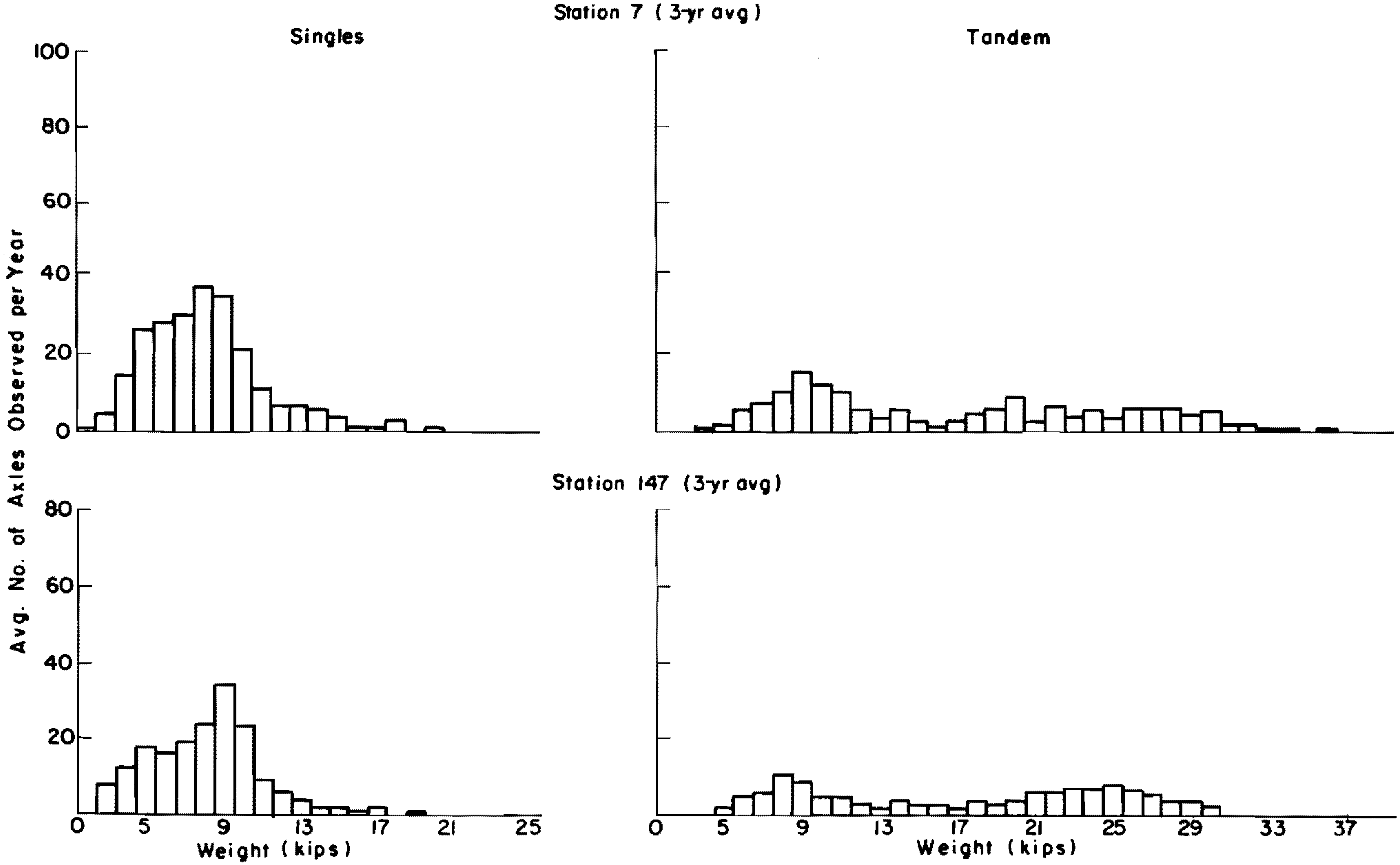
1 kip = 4.5 kN

Fig C.10. Frequency distributions for Station 149.



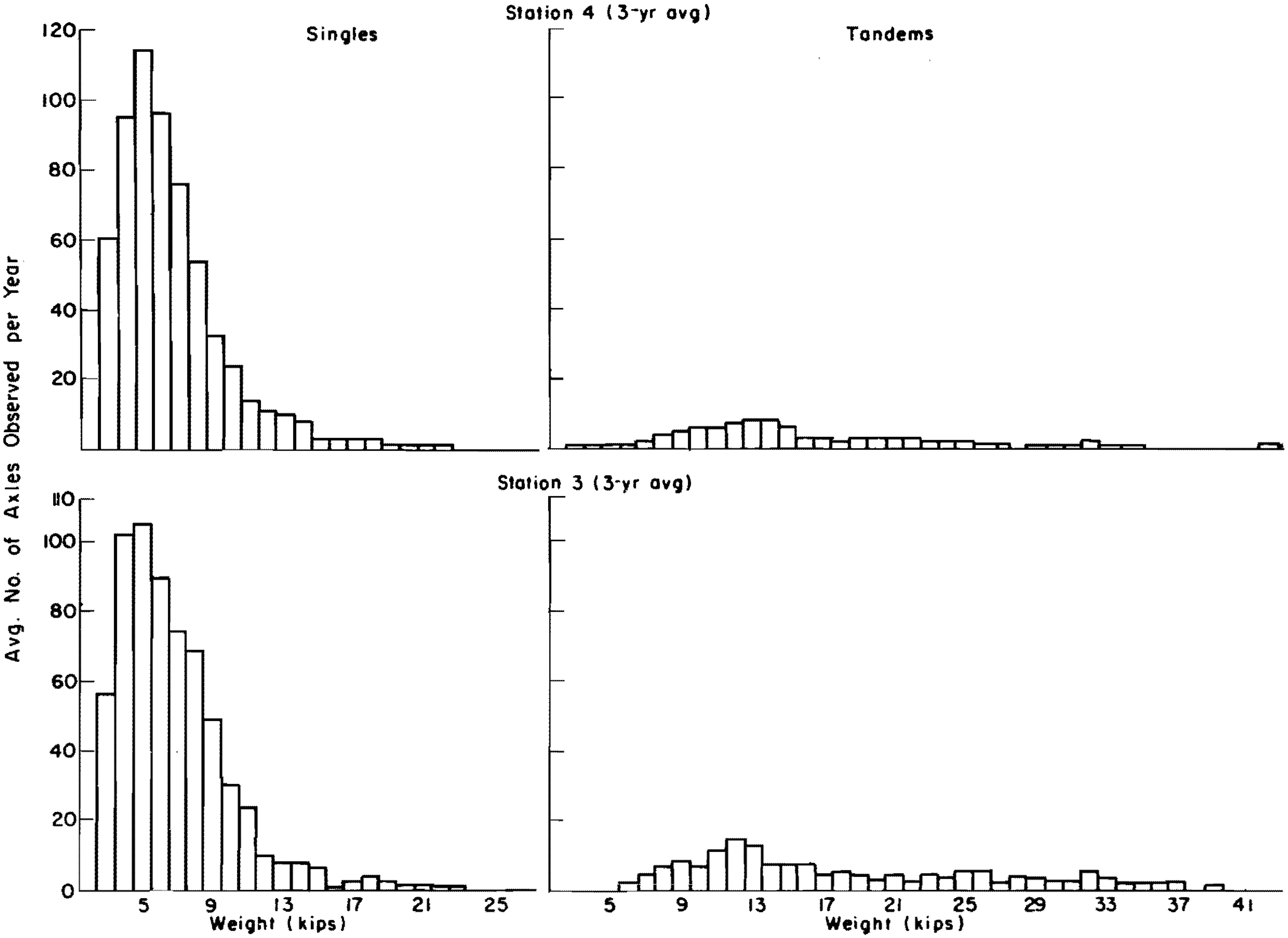
1 kip = 4.5 kN

Fig C.11. Frequency distribution for Station 16.



1 kip = 4.5 kN

Fig C.12. Frequency distributions for Stations 7 and 147.



1 kip = 4.5 kN

Fig C.13. Frequency distributions for Stations 4 and 3.

APPENDIX D

COMPARISON OF IN-MOTION WEIGHING WITH LOADOMETER SURVEY AT LUFKIN, TEXAS

APPENDIX D. COMPARISON OF IN-MOTION WEIGHING WITH LOADOMETER SURVEY AT LUFKIN, TEXAS

The truck weighing procedure which has been used by the Texas Highway Department for nearly forty years is described in Chapter 2, pp 5-10. In field operations, each wheel on the right side of every truck that is stopped during a survey is positioned for weighing so that the outboard tire rests on a wheel-load weigher, the platen of which is set approximately flush with the surface of the surrounding level pavement. Axle weight is assumed to be twice the right wheel weight and gross vehicle weight to be the sum of all axle weights. Length, width, axle spacing, and commodity carried are also determined while the vehicle is standing. By this technique, consistent weight and dimension data upon which to base planning and design decisions have been obtained, and an extensive file of loadometer survey information has been accumulated through the years. A more effective and less costly means of obtaining these data has been the objective of research studies in recent years.

The weigh-in-motion (WIM) system that is described in Chapter 3, pp 13-15, has been developed for this purpose. It utilizes a pair of specially designed wheel force transducers set flush with the smooth surface of a normal traffic lane to sample the dynamic forces imposed by each wheel as a vehicle passes over at high speed. The average dynamic force detected while a wheel is fully supported by a transducer is an estimate of the static wheel weight. Axle weight is the sum of the individually measured wheel weights, and the gross vehicle weight is the sum of all wheel weights. Speed, axle spacing, time of day, and other information are determined automatically by the system, also. Because vehicles are not required to stop, this weighing and dimensioning technique is much more efficient than conventional static weight survey procedures; therefore, it is proposed as a replacement method. It is obviously not possible to determine commodity information with the WIM system, but other survey techniques can be used for sampling this statistic.

Comparative Study

In order to determine whether the new WIM system can obtain adequate truck weight and dimension data under field operating conditions, a comparison was made with data from a routine loadometer survey during a four-hour sampling period. The study was conducted at the weighing site on U.S. 59 in Nacogdoches County north of Lufkin, Texas, on June 23, 1975. The scheduled loadometer survey was made from 6 to 10 A.M. for northbound traffic and from 10 A.M. through 2 P.M. for southbound trucks by the regular Texas Highway Department loadometer personnel. The weigh-in-motion (WIM) system was operated also by Texas Highway Department personnel during the latter period at a previously installed site approximately 0.5 mile (0.8 km) upstream from the loadometer station. Observers equipped with two-way radios were stationed at each location to identify and match individual truck license numbers with the recorded data obtained by each survey technique.

Trucks traveling in the right southbound lane of the four-lane divided highway were processed without interference by the WIM system, a record number was automatically assigned, and this number along with the license number and other visual identification was transmitted by radio to the downstream loadometer station. If the queue of waiting trucks at the loadometer site was not excessively long, every southbound truck was stopped for weighing; otherwise, trucks were flagged past the loadometer until the queue shortened. During the four-hour survey period, 73 trucks from the normal traffic stream were identified and weighed at both sites. Of these, approximately 60 percent were type 3S-2 (5-axle semi-trailer), about 20 percent were type 2D (2-axle single unit, dual rear tires), and some 13 percent were type 2S-2 (single-axles on tractor and a tandem axle trailer).

It is important to note that the loadometer that was used in the study had been previously verified in the Center for Highway Research laboratory against a National Bureau of Standards certified load cell. This loadometer was found to be accurate within approximately 2 percent of the applied load for various load positions on the weighing platen. At the Lufkin loadometer site, the paved area surrounding the metal-lined wheel-load weigher pit had recently received a seal coat, and the resulting elevation of the weighing platen during the study was about 3/4 inch (20 mm) lower than the pavement surface rather than even with the surface as intended. The WIM system was calibrated on-site for the study in the usual manner by using a vehicle of known weight crossing the transducers near the estimated running speed of trucks at the location.

Truck

A 2-axle dump truck loaded with premixed asphalt material was used as a test vehicle in the comparative study. It was weighed on three different commercial vehicle (platform) scales in Nacogdoches, and the following gross vehicle weights were obtained.

Scale No. 1	Scale No. 2	Scale No. 3
24,200 lb	24,160 lb	24,180 lb

(1 lb = 4.45 N)

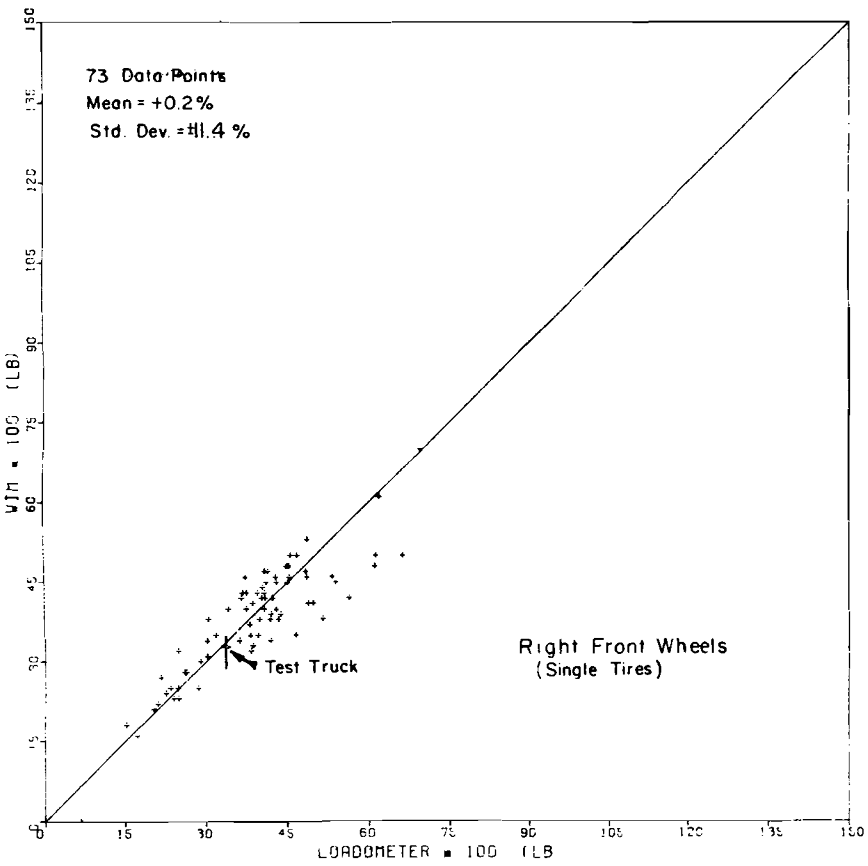
The test truck passed through the WIM system 16 times and over the loadometer 8 times during the four-hour period. Analysis of the gross vehicle weight data obtained by the two techniques as compared with an assumed true gross weight of 24,200 lbs (108 kN) gave the following values.

	Loadometer	WIM
Mean Difference, %	- 4.0	- 0.5
Standard Deviation, %	1.9	1.6

This indicated that the loadometer weights were consistently lower than the vehicle scale weight and that the WIM weights were nearly equal to the vehicle scale weight of the test truck. The mean weights and the range of observed weights of the test truck are presented graphically in Figs D.1 through D.6. Only a small difference was found in the mean weight of the single-tired front wheel as determined by the two methods, but a somewhat larger difference existed between the mean weights of the dual-tired rear wheel (see Fig D.5) of the two-axle vehicle.

Data Analysis

Measured wheel weights as well as calculated axle weights and gross vehicle weights for the 73 trucks that were weighed by loadometer and by WIM are shown in Figs D.1 through D.9 along with standard statistical measures of central tendency and dispersion in the data. If there were perfect agreement



1 lb = 4.45 N

Fig D.1. Loadometer vs WIM weights of the right front wheel of 73 trucks.

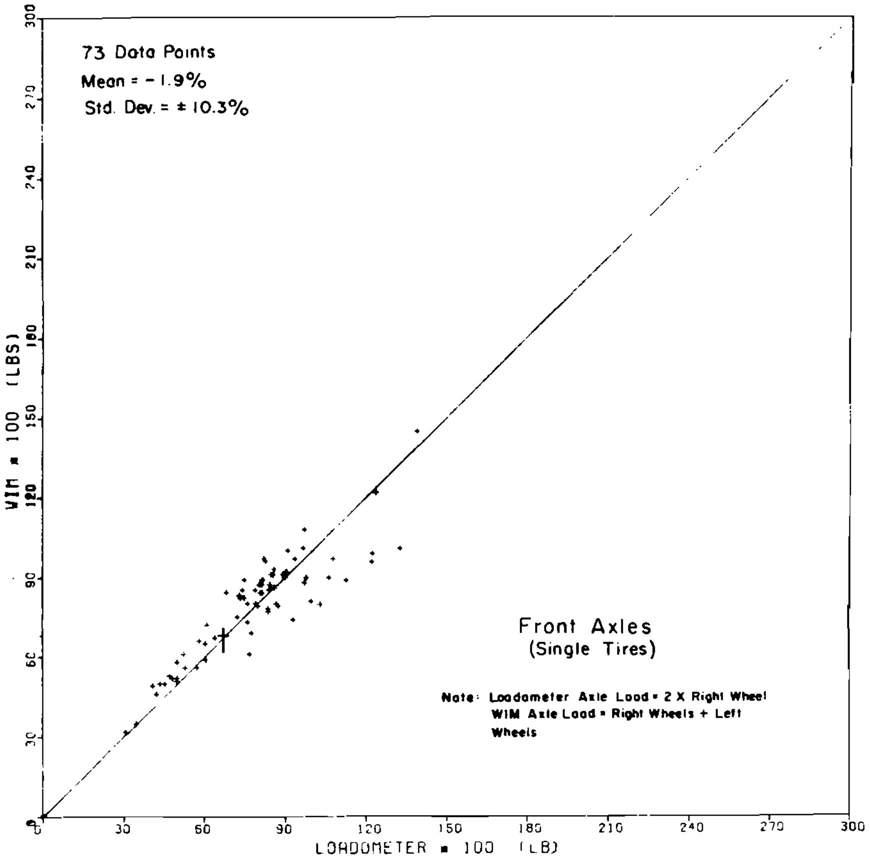
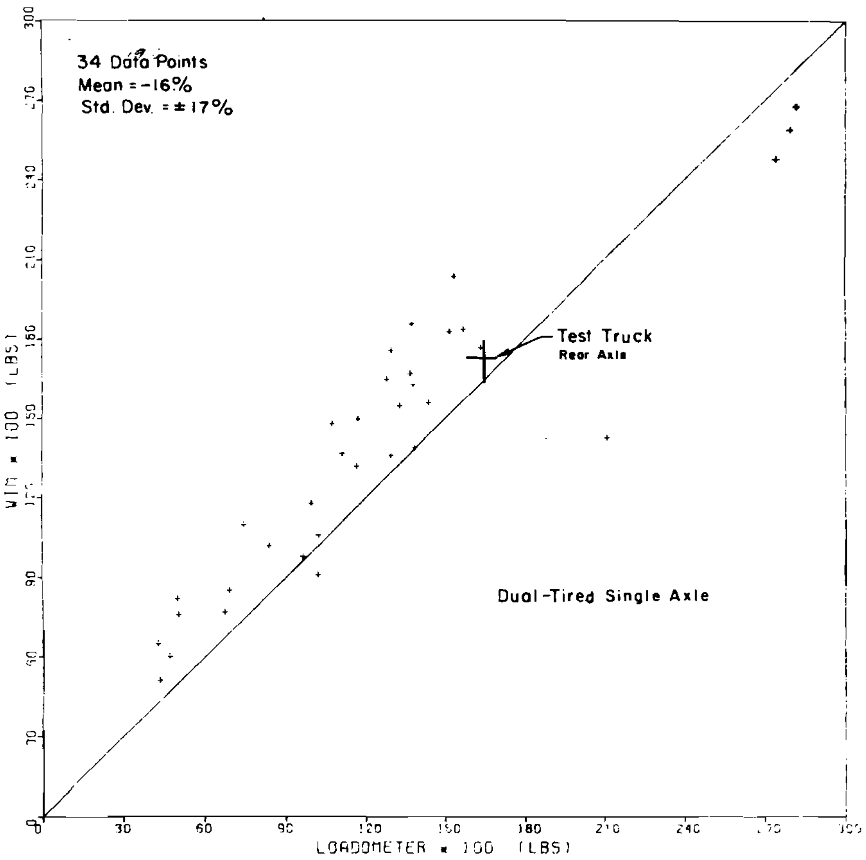


Fig D.2. Weights of front axle of 73 trucks estimated from Loadometer and WIM.



1 lb = 4.45 N

Fig D.3. Loadometer vs WIM weights for 34 dual-tired single axles.

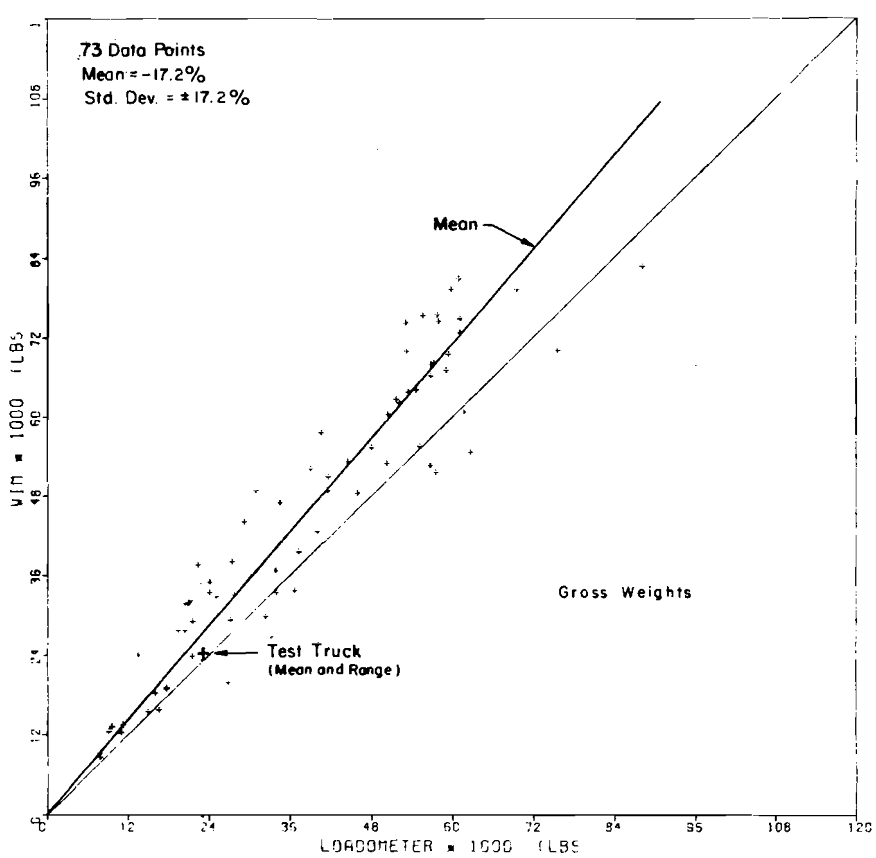
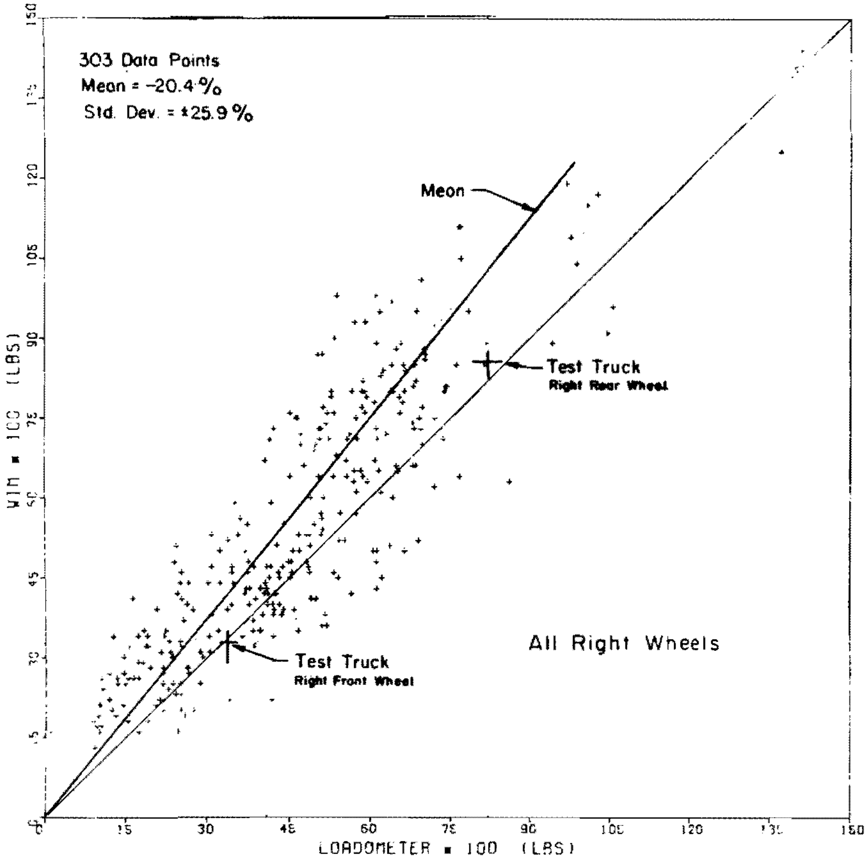


Fig D.4. Estimated gross vehicle weights of 73 trucks by Loadometer and by WIM.



1 lb = 4.45 N

Fig D.5. Loadometer vs WIM weights of all right wheels on 73 trucks.

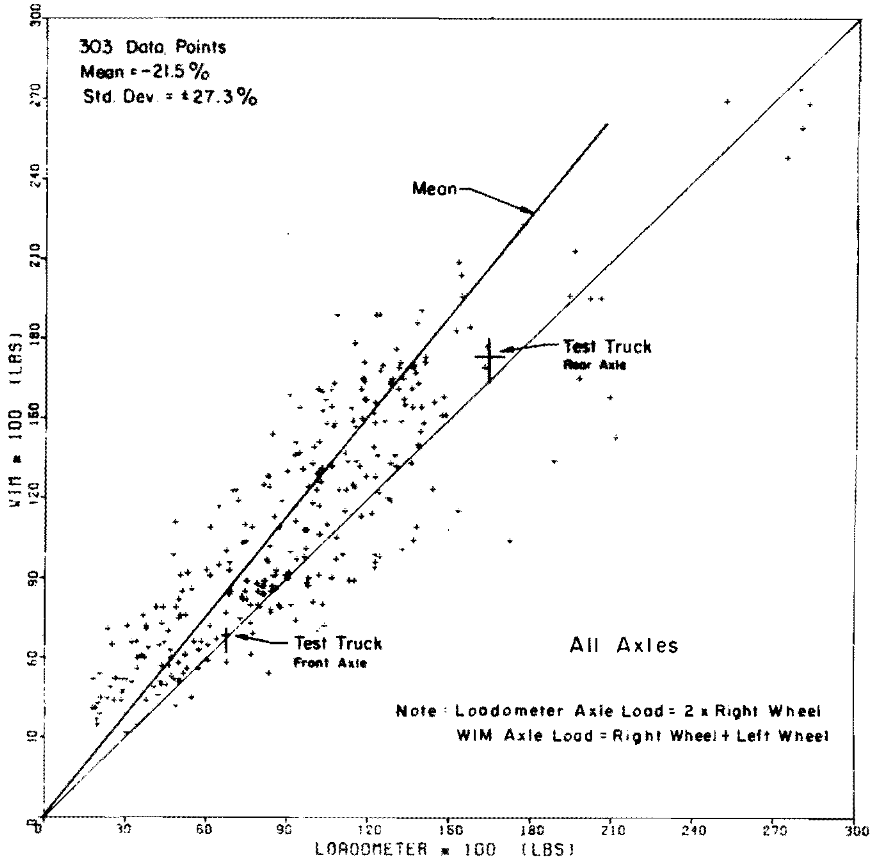
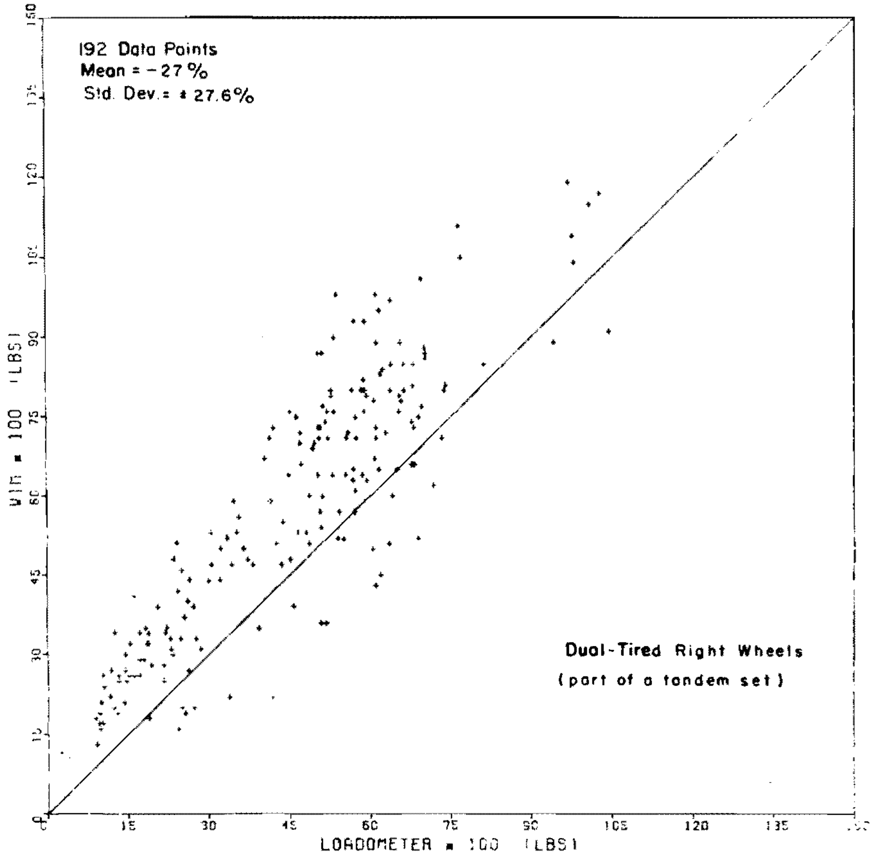
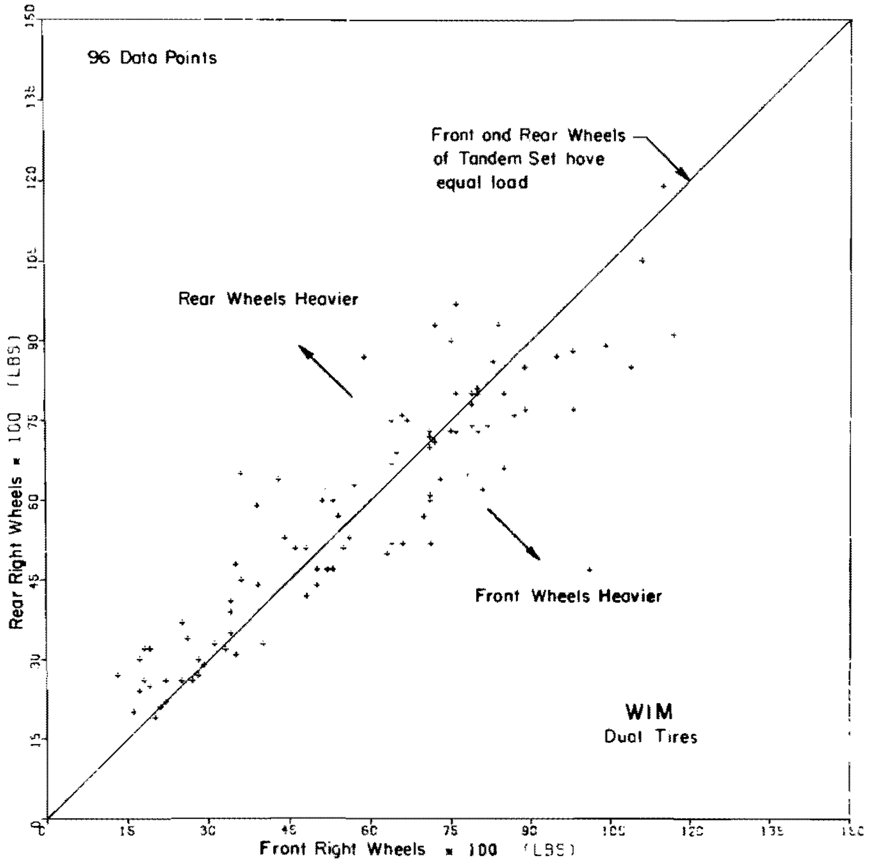


Fig D.6. Estimated axle weights of 73 trucks by Loadometer and by WIM.



1 lb = 4.45 N

Fig D.7. Loadometer vs WIM weights of 192 dual-tired right wheels that were part of a tandem set.



1 lb = 4.45 N

Fig D.8. Weights of front vs rear dual-tired right wheels of tandem sets by WIM.

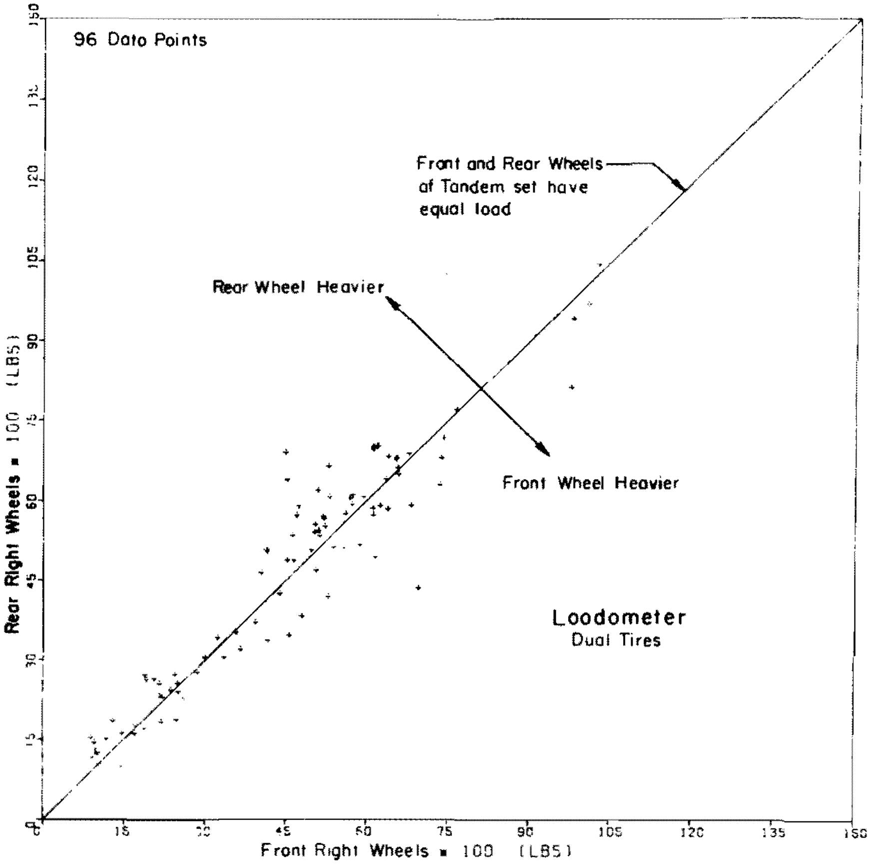


Fig D.9. Weights of front vs rear dual-tired right wheels of tandem sets by Loadometer.

in the two sets of corresponding weights that are plotted in these figures, all data points would lie on the diagonal line, but differences existed between the values determined by the two measuring techniques. Points that are plotted below the diagonal line in Figs D.1 through D.7 indicate that WIM weights were lower than corresponding loadometer weights, and points above the line indicate that loadometer values were lower than WIM values. These figures provide a convenient means of evaluating the differences in weight values when portions of the data are considered separately or when observed weights are combined in various ways.

A cursory glance at Figs D.1 through D.7 reveals that loadometer weights were generally lower than WIM weights. This is not the case, however, when the front axle of all the observed vehicles is analyzed separately (see Figs D.1 and D.2). The single-tired right front wheel of each truck was weighed directly by both WIM and loadometer, and the points plotted in Fig D.1 show scatter approximately equally distributed about the line of weight equality. The mean value of the difference in measured weight for these wheels indicates that loadometer weights averaged only 0.2 percent heavier than WIM weights. Approximately 68 percent of the values were within ± 11.4 percent of the mean. Axle weights determined as noted in Fig D.2 were likewise scattered evenly about the diagonal line of equality with perhaps a slight bias toward lower loadometer axle weights (mean loadometer weight 1.9 percent lower than WIM).

Variations of this magnitude in front wheel and front axle weights are anticipated and can be understood when the limitations of each weighing technique are recognized. The loadometer platen is designed to accept only a single tire, and the maintenance tolerance for wheel-load weighers as recommended by the National Bureau of Standards is ±3 percent. Small differences in the elevation of the platen from a surrounding level plane surface during the study probably did not result in a large weight transfer among the wheels of a vehicle when the front axle was being weighed since single tires were always used on the front axle and the spring rate of the front suspension was relatively low (estimated at about 1000 - 2000 lb/in. - 175 - 350 N/mm). Loadometer weights of the single-tired front axles were probably within about 3 percent of true values. Comparable WIM weight estimates based on samples of the dynamic wheel might, however, have varied from true static weight somewhat more than this because of the effects of road surface roughness, vehicle speed, tire and suspension system condition, wind, and other factors. But since a uniform scatter in the observed front axle weights indicates no pronounced tendency toward either higher or lower weights for WIM compared to loadometer, the mean value of front axle weight determined by WIM can be taken as an unbiased estimate of the true mean static front axle weight. There was generally good agreement between WIM and loadometer weights for the front wheels of the 73 vehicles observed with 68 percent of the loadometer weights differing less than about 11 percent from the observed WIM weights. This kind of variability in an unbiased sample is acceptable for traffic survey purposes.

The axle weight data for 34 dual-tired single axles that were included in the comparative study indicate that loadometer weights were nearly always lower than corresponding WIM values (see Fig D.3). Load transferred from the wheel that was being weighed by the loadometer to other wheels of the vehicle could account qualitatively for at least part of this difference. Redistribution of the total weight of the vehicle among the wheels no doubt occurred as the outside dual tire rolled from the level pavement surface onto the small loadometer platen (which was 3/4 inch - 20 mm - below the surrounding surface) and thereby received the full wheel load that had previously been shared by the two tires of the dual set. Since truck tire stiffness is generally on the order of 4,000 pounds per inch (700 N/mm) of deflection and suspension stiffness is usually about 4,000 to 6,000 pounds per inch (700 - 1050 N/mm) of deflection, considerable weight could conceivably have been shifted to other wheels when the right wheel was lowered more than an inch (25 mm) due to additional deflection in the outside dual tire and the low position of the loadometer platen. Weight registered by the loadometer under these circumstances would have been less than the true load carried by the dual-tired wheel on a level surface. Average loadometer weights for the 34 dual-tired single axles that were weighed were 16 percent less than average WIM axle weights for these same axles. It should be noted that any error in loadometer wheel weight is doubled in axle weight since axle weight is assumed to be twice the right wheel weight.

Gross weights of the 73 vehicles included in the study are shown in Fig D.4. The mean value determined by loadometer weighing of all right wheels was 17 percent less than the mean weight estimated by summing individually measured WIM wheel weights. It is pertinent to realize that less than 1/4 of the wheels weighed in the study were single-tired and that over 60 percent of the axles weighed were dual-tired and part of a tandem set. The preceding discussion of weight transfer during loadometer weighing of dual-tired single axles is recalled and note is taken of the fact that the effect of lowering an axle onto the loadometer platen is even more pronounced when a nearby tandem axle is involved. The gross weights shown in this figure are constituted of the appropriately summed wheel weights of all types of axles.

There were 303 axles on the 73 vehicles that were weighed. The weights of all right wheels as determined by the two different weighing techniques are plotted in Fig D.5 along with test truck weights. As might be expected, the data are scattered more than in previous figures and the difference in mean wheel weight for the two methods is greater (loadometer 20 percent lower than WIM) since a large percentage of tandem axles is included. When axle weights are estimated in the usual way, the mean difference in weight is somewhat greater as shown in Fig D.6. The scatter in the data can be attributed to inherent variability in both weighing techniques, especially WIM, but the bias is apparently related mostly to weight transfer associated with loadometer weighing of dual-tired axles.

Figure D.7 shows observed data for dual-tired right wheels that were part of a tandem set. Loadometer weights, on the average, were 27 percent lower than WIM weights. This difference might well be due to the fact that the adjacent axle of the tandem set could readily pick up part of the weight from the axle that had the right wheel lowered onto the loadometer platen. This was especially true for trucks with a four-spring tandem suspension since each wheel is in effect independently sprung.

The data in Figs D.8 and D.9 show that there was little difference in the weight carried by either axle of a tandem set. Both weighing techniques reflect this fact. The consistency in the pattern of data in the two figures as well as the magnitude of the weights shown supports the concept that load was transferred to adjacent wheels during loadometer weighing. There is somewhat less scatter in the loadometer data than in the WIM data.

Follow-Up Study (Austin)

Because there was some concern about the difference in loadometer and WIM weights in the Lufkin study, another series of tests was conducted at the Austin WIM site on IH-35 on 10 July 1975. In the Lufkin study, both weighing techniques had produced highly satisfactory results for the 2D type test truck with reference to static weights obtained by three different vehicle scales in Nacogdoches, but average differences on the order of 25 percent had been observed between loadometer and WIM weights for trucks with dual-tired tandem axles sampled from the normal traffic stream. A further check of WIM against a vehicle scale (NBS maintenance tolerance 0.2 percent of applied load) was deemed desirable.

Arrangements were made for two test trucks: one was a 2D type loaded to a gross weight of 24,610 pounds (110 kN), and the other was a 3S-2 semitrailer van with a gross weight of 63,680 pounds (283 kN) weighed on a commercial vehicle scale near the Austin WIM location. The WIM system was calibrated on-site in the usual way, and the two trucks were driven over the transducers at a nominal speed of 55 mph.(88 km/hr). The 2D made 14 trips and the 3S-2 made 10 trips. Percent difference between observed WIM gross vehicle weight and the vehicle scale weight are shown in the tabulation below along with computed means and standard deviations.

Difference in WIM and Vehicle Scale Weight

	2D Truck	3S-2 Truck
	+ 0.77%	+ 3.17%
	+ 0.37	+ 1.92
	+ 0.37	+ 4.90
	+ 1.58	- 1.54
	- 1.67	- 0.13
	+ 0.77	- 8.13 *
	- 2.07	+ 5.06
	+ 2.80	+ 6.35
	+ 2.80	+ 1.76
	- 0.45	+ 2.23
	+ 0.37	
	+ 1.18	
	- 4.10	
Mean =	+ 0.28%	+ 1.6 %
Standard Deviation =	± 1.9 %	± 4.2 %

*If this maximum variation is excluded, the mean is +2.6% and the standard deviation is ± 2.5%.

These test results, which are consistent with those from previous studies, showed no pronounced tendency toward WIM estimates of gross vehicle weight being predominately higher or lower than true static weight, and scatter in the data was not greatly different for either type of vehicle. The deduction that loadometer weights of dual-tired wheels obtained in the Lufkin comparative study were lighter than true wheel weights and that WIM weight estimates were varied but unbiased was substantiated by this follow-up study in Austin. No loadometer weighing was attempted in the Austin study.

Summary

The vehicle-by-vehicle comparative study of in-motion weighing with loadometer weighing of 73 trucks at Lufkin, Texas, can be summarized as follows:

(1) Both techniques gave good estimates of the gross weight of a loaded single-unit two-axle test truck that was weighed several times. Loadometer weights averaged 4 percent lighter than true weight (measured on three different vehicle scales) and mean WIM weights were only 0.5 percent lighter.

(2) Front wheel weights of 73 trucks from the normal traffic stream determined by loadometer and by WIM agreed, on the average, within 0.2 percent, and front axle weights were within 1.9 percent.

(3) Loadometer weights of dual-tired single axles averaged 16 percent lower than comparable WIM weights, and dual-tired axles that were part of a tandem set had mean loadometer weights that were 27 percent less than WIM estimates.

(4) Gross vehicle weights for the 73 trucks showed loadometer weights that were 17 percent lower than WIM values.

(5) At least part of the difference in dual-tired wheel weights can be explained by the fact that weight was transferred from the wheel being weighed on the loadometer to adjacent wheels when the outside tire deflected as it received the total wheel load when positioned on the small loadometer platen. Additionally, since the platen was 3/4 inch (20 mm) below the surrounding pavement during the study, more load was shifted.

(6) A follow-up study in Austin indicated that WIM estimates of the gross weight of a 2D type single-unit truck and a 3S-2 semi-trailer truck differed on the average by only + 0.28 percent and + 1.6 percent respectively from vehicle scale weights.

(7) The WIM estimate of static weight for an individual wheel may vary from the true value, but there seems to be no consistent bias toward either higher or lower estimates. Therefore, with

an adequately large sample, the WIM system can give acceptable vehicle weight and dimension data for traffic survey purposes. Quality of the data can be at least equal to, and perhaps better than, that obtained by conventional loadometer weighing techniques.