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16. Abstract

The objective of this study has been to develop relationships between pavement roughness and weigh-in-motion (WIM) system measurement error for individual axles, tandem axles, gross weight and axle spacing. The dynamic weight measured by a WIM scale is determined by the dynamic response of the vehicle system to the pavement roughness. A dynamic simulation model was formulated and used to study the important parameters which affect tire/pavement dynamic force. A series of tests were conducted at three inservice WIM sites in Nevada to determine the relationship between WIM measurement error and vehicle factors including (1) cab type, (2) trailer type, (3) configuration, (4) suspension system type, (5) speed, and (6) roughness. A second series of tests were conducted using two vehicles and instrumented to measure dynamic tire/pavement force. An empirical relationship has been developed to predict axle and gross weight weighing error as a function of pavement roughness. A procedure is outlined to calculate pavement smoothness requirements for WIM installations to achieve specified accuracy levels. An example is included.

The other volume in this two-volume series is Publication No. FHWA-RD-88-129, "Calibration of Weigh-In-Motion (WIM) Systems, Volume II: Final Report."

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

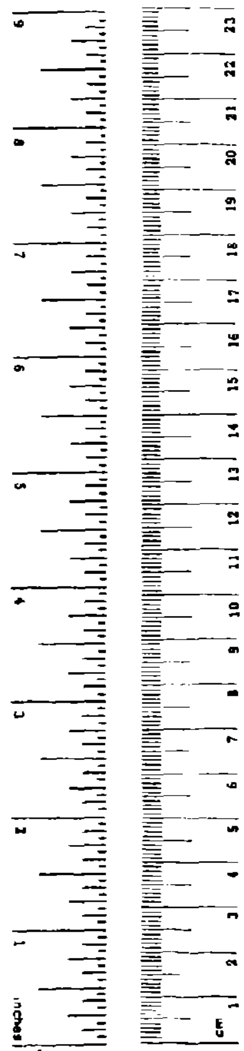
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements

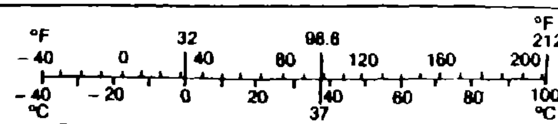


APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Calibration of Weigh-In-Motion Systems

Volume I: Summary and Recommendations

Publication No. FHWA-RD-88-128

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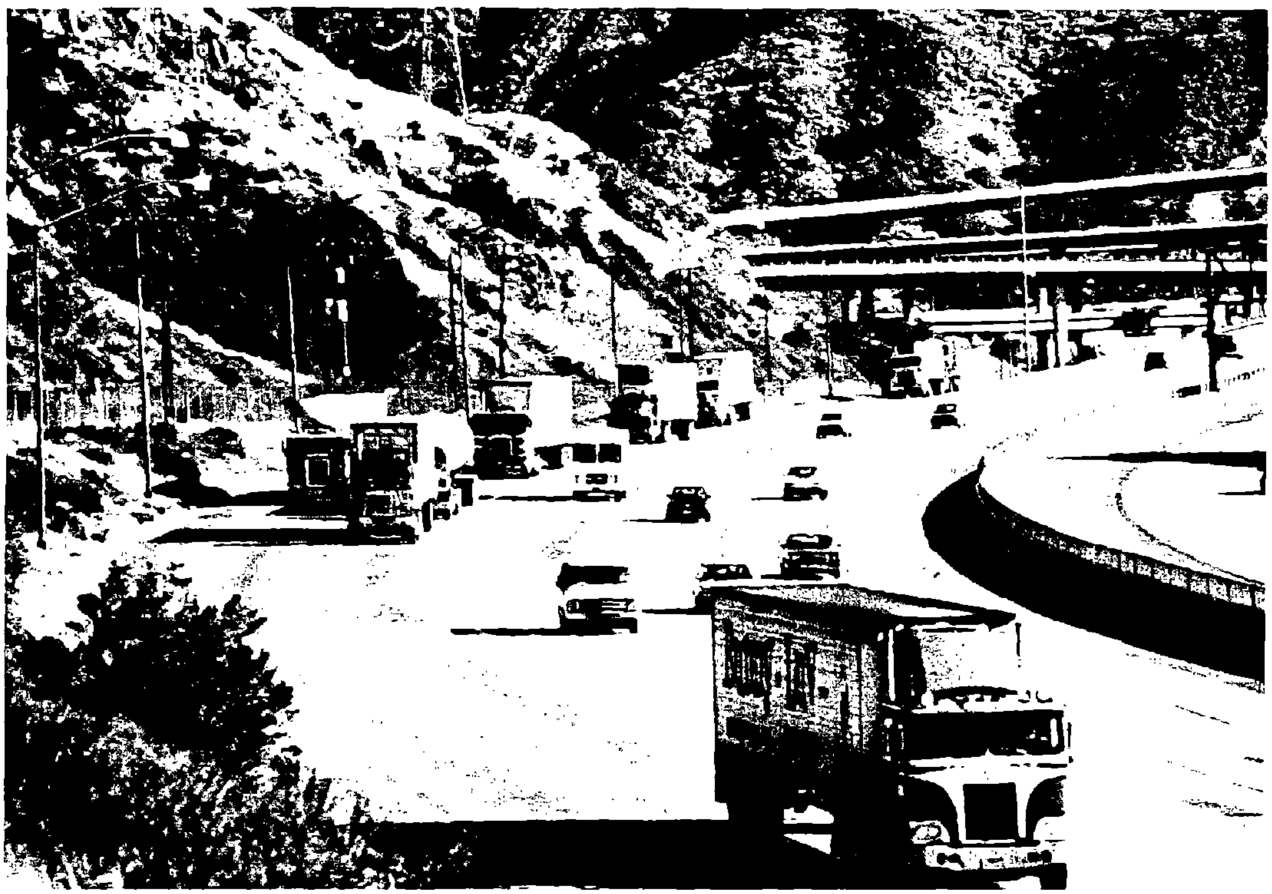

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FOREWORD

This report documents a study to determine the length and smoothness of an approach section of pavement which is required to provide acceptable WIM measurement accuracy. The report summarizes the results of a combination analytical and experimental study designed to meet the objectives. The study consisted of two sets of field studies to collect the data: (1) statistical comparisons of WIM and static axle weights, and (2) tire-pavement force measurement experiments using specially instrumented vehicles. An empirical relationship has been developed to predict axle and gross weighing error as a function of pavement roughness. Also, there is a procedure used to calculate pavement smoothness requirements for WIM installations to achieve the specified accuracy levels. The report should be of interest to State personnel dealing with truck weight data for planning and pavement design purposes.

Research on WIM is included in the Nationally Coordinated Program of Highway Research, Development, and Technology as Program Area A.4, "Special Highway Users;" Project A.4.a, "Large Trucks." Justin True is the Program Manager.

R. J. Betsold, Director
Office of Safety and Traffic
Operations R&D

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The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

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CHAPTER 1 INTRODUCTION

Truck weight data have been obtained for many years for a wide variety of reasons. These data have been obtained by making static weight measurements using single draft or individual wheel scales. However, development of weigh-in-motion (WIM) technology, over the past 10 years, has produced equipment which is effective in measuring the total wheel loads (dynamic plus static load) of vehicles in motion at highway speeds.

The need to effectively monitor and control truck weights is well established. The most recent FHWA Truck Characteristic Report indicates that not only are truck volumes increasing, but there is a shift toward heavier vehicles.(1) Skinner gives some insight into the estimated pavement damage which occurs as a result of the heavier vehicles:(2)

- One 5-axle truck loaded to 80,000 lbs does equivalent damage to the pavement as 9,600 two-thousand lb cars.

- One 20,000 lb axle does equivalent damage as 4,000 cars, but one 26,000 lb axle does equivalent damage as 12,000 cars.

The above data highlight two important facts. First, heavy trucks cause significantly greater pavement damage than cars. Second, incremental increases in single axle loads cause amplified pavement damage. It is clear that there is a need not only to monitor truck weights, but to enforce truck weight laws to the maximum extent.

Truck weight data provide input to the following activities: pavement design, monitoring, and research; bridge design, monitoring, and research; size and weight enforcement; legislation and regulation; and administration and planning. Pavement design and planning require weight data to provide current estimates and trends of the characteristics of axle loads which must be accommodated by pavements. These data are statistically based and are often organized by weight classes, truck configuration and type.

The use of these data require that large quantities of truck weight data be collected in an efficient and safe manner. The statistical nature of the data preclude concern about the weight of specific individual vehicles; however, the distribution must be established within specified accuracy and confidence levels. In general, these accuracy levels are $\pm$ 10 percent for individual axles, and $\pm$ 5 percent for gross weight.

Size and weight enforcement requires truck weight data to support several levels of activity; assessment of the magnitude of the overweight vehicle problem; weighing of individual trucks to determine compliance; and monitoring the traffic stream to determine whether enforcement efforts are effective.

The use of these data require accurate weighing of individual vehicles in a safe and efficient manner. Enforcement weighing requires more stringent accuracy requirements. According to the National Bureau of Standards, individual wheel load weighters must be certified at 1 percent and maintained at $\pm$ 2 percent.(3)

WIM technology has been applied to both the gathering of design/planning data and to size and weight enforcement. The advantages of WIM technology include high vehicle processing rate; improved safety to both trucks and the driving public; increasing coverage; minimized scale avoidance; reduced unit cost for trucks weighed; and availability of dynamic loading information. The major disadvantage of WIM systems is the uncertainty of using WIM output to compute single axle and gross vehicle weights.

In-motion-weighing of a highway vehicle approximates the weight of a vehicle, a wheel, an axle, or a group of axles, by measuring the vertical component of the total force applied to the pavement surface by successive tires. The total force is, in general, different from the static weight due to the vertical motion of the vehicle system. This vertical motion generates a dynamic force component which is dictated by the amplitude and frequency spectrum of the pavement surface. Therefore, the accuracy of a WIM system is dependent upon the dynamic coupling of the roadway and the vehicle.

In response to these issues, the FHWA sponsored this research program to address the issue of WIM system accuracy. The objectives of this program are:

- Determine the accuracy of WIM systems when installed on pavements of various roughness including both older as well as newly resurfaced pavements. The accuracies to be obtained are:

    a. ±10 percent on axle weights.

    b. ±5 percent on gross weight.

    c. ±6 inches on the determination of axle spacing and total wheel base length.

- Determine the length and smoothness of an approach section of pavement which is required to provide acceptable WIM measurement accuracy in those pavements with roughness which would otherwise result in accuracies poorer than listed above.

This report summarizes the results of a combination analytical and experimental project designed to meet the objectives listed above. The project consisted of two sets of field studies to collect the data to meet the objectives: (1) statistical comparisons of WIM and static axle weights, and (2) tire-pavement force measurement experiments using specially instrumented vehicles. The test planning activity was supported by a review of the most current pertinent literature, and a survey of current State WIM experience and practices. In addition, a dynamic simulation model was developed and utilized to identify the key influential vehicle, roadway, and operational parameters to guide the experimental design. Chapter 2 contains a summary of States' experiences and practices, summarizes the results of dynamic simulation analysis and describes the two field study programs performed. Recommendations are contained in Chapter 3.

CHAPTER 2 BACKGROUND

SUMMARY OF STATES EXPERIENCES AND PRACTICES

The results of the literature review indicated that most current research related to WIM system applications was being conducted as part of WIM system acceptance testing performed by the various States. In order to compile the most current data relevant to the objectives of the study, a series of discussions with various State planning officials was conducted in October of 1985. Table 1 is a compilation of the current use of WIM equipment by State. These data were compiled from Cunagin and Kent.[4,5]

For project purposes, it was desired to identify those States which have active WIM data collection activities using inservice traffic lanes. These States are listed below:

- Alabama
- Arizona
- California
- Florida
- Idaho
- Louisiana
- Minnesota
- Nevada
- New Mexico
- Texas
- Washington

The cognizant planning department personnel in each of the States listed above, were contacted and asked to supply information related to their experiences with WIM equipment. The specific information solicited is listed below:

- Type of WIM system(s) in use.
- Number of WIM sites and type of pavement at each site.
- Number of sites used to collect statistical data.
- Number of sites used for enforcement only.
- Criteria for WIM site selection.

Table 1. WIM traffic lane installations.

STATE	RADIAN	IRD	PAT	STREETER RICHARDSON	GOLDEN RIVER
ALABAMA	●				
ARIZONA					●
CALIFORNIA			●	●	
FLORIDA	●	●			●
IDAHO	●		●		
ILLINOIS				●	
KENTUCKY	●				
LOUISIANA	●				
MAINE		●			
MASSACHUSETTS			●		
MINNESOTA		●			
NEVADA	●				
NEW MEXICO	●				
OREGON		●			
PENNSYLVANIA			●	●	
TEXAS	●			●	●
WASHINGTON			●		

- Special site preparations made prior to installation.
- Criteria for length of smooth WIM approach.
- Calibration procedure(s).
- Accuracy levels.
- Special research activities:
  - portable/permanent comparisons.
  - multiple pad installations.

The results of compiling the information obtained from the States is given in table 2. Several conclusions can be drawn from these results:

- Five of 10 States collecting travel-lane data use RADIAN systems.
- 75 percent of the travel-lane WIM sites are in flexible pavement.
- No special site preparations are routinely performed on flexible sites.
- Grinding of rigid pavements is routinely performed.
- Although most States have a criterion for the length of smooth approach to a WIM device, this length varies from 100 ft to 900 ft.
- Although most States have a criterion for the length of smooth pavement required downstream of the WIM device, the respondents appeared uncertain about the genesis and application of this requirement.
- Most States identify WIM sites by selecting visually smooth pavement sections.
- Most States use one of two calibration procedures:
  - use a standard-weight State vehicle at several speeds.
  - select a random sample of vehicles from the traffic stream.

Table 2. Summary of State WIM experience.

STATE		AZ	FL	LA	NM	WA	GA	ME	CA	AL	NV	MI
TYPE OF EQUIPMENT		GOLDEN RIVER	RADIAN	RADIAN	RADIAN	PAT(S)	STREETER-AMET	IRD	PAT	RADIAN	RADIAN	IRD
NO. OF SITES	RIGID			2	6		13	1	2	1	3	1
	FLEXIBLE		20		6					12	9	2
INSTALLATION	TRAVEL LANES		20	2	12			1	2	13	12	1
	ENFORCEMENT						13					
SPECIAL SITE PREPARATIONS			NONE	NONE	NONE	NONE	INSTALL IN CONCRETE PADS	INSTALL IN CONCRETE PLANNED PAD	INSTALL IN CONCRETE GROUND PAD	RESURFACE AS REQ'D.	NONE	GRIND & RESURFACE AS REQ'D.
LENGTH OF SMOOTH PAVEMENT	UPSTREAM		900		MANU. RECOMM.	100	600	200	200	500		100
	DOWNSTREAM		100		MANU. RECOMM.	100	50	50	75			
CRITERIA FOR SELECTION			VISUALLY SMOOTH	CHOOSE SMOOTH CONCRETE	VISUALLY SMOOTH	VISUALLY SMOOTH		VISUALLY SMOOTH		VISUALLY SMOOTH	VISUAL & ROAD METER	VISUALLY SMOOTH
CALIBRATION PROCEDURES	MANUFACTURER			•								
	STD VEHICLE		•		•	•	•	•		•	•	•
	TRAFFIC SAMPLE			•		•		•	• (100)	•	•	•
PORTABLE/PERMANENT RESEARCH		NONE	PRELIM. STUDY BEING COMPL.	NONE	NONE	NONE			NONE	NONE	LIMITED STUDY OF AZ	NONE
MULTIPLE PADS RESEARCH		NONE	NONE	NONE	NONE	NONE			NONE	NONE	NONE	NONE

Accuracy of Operational WIM Systems

As previously discussed, the ability of a WIM device to accurately measure static weight is dependent upon the dynamic coupling of the pavement and the vehicle system. The intended use of the weight data determines the level of accuracy required.

Weight data for planning or pavement design may be collected on a statistical basis. Frequency distributions may be obtained for axle, tandem, and gross weights. These may be categorized by weight range, vehicle type, etc., in addition to summaries of the numbers and characteristics of overweight vehicles. In this context, accuracy relates to the distribution of error in assigning vehicles to specific weight categories.

Cunagin reports that aggregate gross weight and tandem weights within ± 10 percent of static weight at the 95 percent confidence level is acceptable for most WIM equipment.[4] However, some States find that aggregate gross weight within ± 5 percent of the static weight at the 95 percent confidence level is desirable.

Table 3 summarizes the information obtained from those States employing WIM equipment for statistical data collection. These data agree, in general, with the accuracy bounds reported above.

WIM Operational Calibrations

Based upon information received from the various States operating WIM equipment for statistical data collection, it appears that there are two calibration schemes which are widely used for operational WIM systems. Both schemes require sampling the dynamic force measurements and comparing them with weight measurements obtained at static weighing sites.

Table 3. WIM accuracy experience.

STATE	SYSTEM	AXLE		GROSS		WHEEL BASE	
		ERROR	CONF.	ERROR	CONF.	ERROR	CONF.
ALABAMA	RADIAN	±2		±2			
CALIFORNIA	PAT	±5		±1		0.1 ft	
FLORIDA	RADIAN	±10		±10			
GEORGIA	STREETER-AMET	±5	90	±10	75	±5	90
IDAHO	PAT	±5		±5	75		
ILLINOIS	STREETER-RICHARDSON	±10	80	±7	90		
MINN.	IRD	±12	90	±8	90		
NEVADA	RADIAN	±5	90	±2	90		
PENN.	PAT(S)	±4		±4			
WASHINGTON	PAT(S)	±10		±5			
MANUFACTURERS:	GOLDEN RIVER	±10	95	±10	95		
	IRD	±5	90	±5	90		
	RADIAN	±10	90	±5	90		
	STREETER-RICHARDSON	±5	90	±5	90		
	STREETER-RICHARDSON(S)	±10	95	±10	95		

Single Vehicle Calibration

The single-vehicle calibration technique is the most widely used according to information received from the States. This technique involves operating a standard heavy vehicle, of known weight, over the WIM device at several speeds.

The dynamic weight, as measured by the WIM, is compared with the known static axle and gross weight of the vehicle. Calibration is accomplished by minimizing this error through repeated trials.

A major factor in this technique is ensuring an adequate number of trials (i.e., sample size) appropriate to the level of confidence and error in the calibration. The information reported by the States indicates typical sample sizes of five repetitions. However, the appropriate sample size can be calculated for specified confidence levels and tolerable error, e, by determining the dispersion of the weighing error distribution.

An estimate of σ has been made from dynamic loading data in reference.[6] Table 4 shows the required sample sizes as a function of confidence level and tolerable error assuming the measurement error to be Gaussian.

Table 4. Initial sample size requirements for single vehicle calibration.

Replications	Confidence Level		
error	90 percent	95 percent	99 percent
1 percent	22	31	54
3 percent	3	4	6
5 percent	1	2	3
10 percent	1	1	1

Random Sample Calibration

The random sample calibration scheme consists of selecting a sample of inservice heavy trucks operating on a WIM installed roadway and comparing the dynamic force measured by the WIM with static weights measured adjacent to the site. Vehicle selection criteria are usually established to reflect the relative frequency of occurrence of each configuration type in the general population.

The same statistical considerations apply as for the single-vehicle calibration scheme. Estimates of the standard deviation of a sample of vehicles operating on a WIM were taken from Chow.[7] A value of $\sigma = 5.7$ percent for single axles was used to produce the sample size requirements shown in table 5.

Table 5. Initial sample size requirements for random sample calibration (95 percent level).

Error, (e)	Sample Size
1 percent	125
3 percent	14
5 percent	5
10 percent	2

DYNAMIC PAVEMENT LOADING

Overview

A literature survey was performed to provide insight into the important vehicle parameters affecting the magnitude of the dynamic wheel load. Since only a limited number of vehicle configurations could be included in the experimental phase, a rationale was formulated which enabled the "worst case(s)" to be selected. However, the vast majority of relevant information from the literature focused on the ride quality of tractor-trailers and did not address the wheel/pavement interaction and damping distance problems. The problem of selecting the most important factors is compounded by the non-linear relationship between the road roughness and many other factors which contribute to the dynamic wheel load. For example, several factors which are less significant on a rough road become more significant on a smooth road (e.g., wheel unbalance). A dynamic simulation model was developed and used to identify the most significant roadway, vehicle, operational, and environmental factors by performing a set of parametric sensitivity analyses. The results of the simulation analyses, and the literature review were used to identify the most significant factors. Almost without exception the factors identified are coupled, although for ease of presentation only the most important interactions are discussed.

The best example of the importance of these interactions, and, probably the single most important factor influencing wheel dynamic loading, is tuning of the road roughness with vehicle dynamic characteristics. The frequency of significant road roughness can range from less than 1.5 to greater than 20 Hz depending on vehicle speed. There are an abundance of tractor/trailer rigid body, structural and axle natural frequencies also in this frequency range (see table 6).[8] A summary of the factors affecting vehicle dynamics are presented in table 7. These factors are organized into four categories previously listed, and are prioritized depending on how important each factor is to the dynamic response.

Pavement factors

Road roughness is often described as a combination of random amplitudes having a Gaussian distribution which can be statistically represented by a power spectral density (PSD). Random road roughness is differentiated from discrete pavement damage such as patches, rutting, cracking, spalling and raveling or damage to the pavement substructure such as subsurface shifting and road-bed deterioration. The power spectral density (PSD) quantifies the intensity of road profile amplitudes as a function of spatial or temporal frequency through the velocity.

Table 6. Vibration modes of a tractor van-trailer combination.

Mode Description	Frequency (Hz)
Rigid body lateral translation	1.45
Rigid body fore/aft translation	1.4-1.5
Vehicle yaw	2.1-2.3
Front end lateral/trailer yaw*	2.7-3.0
Vehicle vertical translation	3.2-3.6
Front end torsion	3.8-4.1
Tractor pitch/trailer bounce	4.0-4.3
Tractor pitch/trailer pitch	4.4-4.9
Complex mode*	4.9-5.2
Tractor roll/cab motion at mounts*	6.1-6.2
Exhaust stack fore/aft	6.9
Tractor vertical bending	6.5-7.0
Battery box and fuel tank lateral*	7.3**
Complex fuel tank mode*	7.6**
Lateral bending of tractor	7.9
Tractor tandem yaw mode	8.9
Tractor torsional mode*	9.7**
Exhaust stack fore/aft	9.9-10.0
Tractor tandem lateral/exhaust active	9.8-10.3
Radiator pitch	10.1
Tractor second torsional mode	11.6-13.1
Tandem bounce (axles out-of-phase)	11.7-12.7
Battery box/fuel tanks/exhaust stack*	12.6
Battery box/fuel tanks mode*	12.6-12.8
Engine/transmission bounce at rear	14.7
Shift tower/battery box	14.9
Cab bounce at rear/fuel tank vertical	15.2
Front axle roll mode	15.3
Tandem roll (axles out-of-phase)	15.8-17.0
Complex mode*	16.0**
Tandem bounce (axles in-phase)	16.5-17.1
Radiator lateral mode	17.3
Cab and engine/transmission pitch	18.4**
Trailer tandem bounce (out-of-phase)	18.6
Tractor tandem roll (axles in-phase)	18.7
Front axle bounce	20.4

*Complex modes not readily recognizable as a basic mode

**Not observed experimentally on-the-road

Table 7. Factors affecting vehicle dynamic response.

	Road Conditions	Vehicle Configurations	Operational Conditions	Atmospheric Conditions
First Order	Pavement roughness	Type of suspension	Speed	Wind Gusting
	WIM stiffness, damping, geometry	Suspension stiffness & damping characteristics	Vehicle Load	
	Jointed concrete	Tire pressure		
		Unsprung mass		
		Tire & wheel unbalance		
		Tandem axles		
		Number of axles		
		Frame beaming		
Second Order	Transverse roughness variations	Suspension maintenance (friction)	Vehicle acceleration & deceleration	Wind resistance
		Tire stiffness variation	Drive torque reaction	
		Suspension geometry		
		Tandem axles load transfer		
	WIM stiffness, damping, geometry	Cab mounting		Wind
	Crown in road			
	Pavement type (rigid, flexible overlay	Suspension geometry		
		Tire age		
		Radial or bias tire		

Three conclusions can be derived from the typical pavement PSD shown in figure 1 :

- There is significant energy up to about 20 Hz.
- There is significantly greater energy at the lower frequencies (i.e., 1.5-4 Hz) than at the higher frequencies (i.e., 10-20 Hz).
- A greater intensity derives from a higher vehicle velocity for the same frequency.

The implication of the first point is that sufficient energy is available to excite truck rigid body, structural and axle modes (i.e., frequencies ranging from 1.5 to 20 Hz). The second point suggests that the principal source of dynamic response should derive from the vehicle rigid body modes, assuming the same amount of modal damping is available for rigid body, structural and axle modes. This assumption is vehicle configuration dependent. Lastly, it can be inferred from the third point that greater vehicle dynamic response is expected at higher vehicle velocities and that unsprung mass modes will become more important for higher vehicle velocities.[6]

Discrete pavement damage is also of concern. A single 1/4 in step input can induce significant dynamic wheel loads (see figure 2). Some finite time and distance, dependent on the vehicle configuration, is required for these dynamic loads to decay to acceptable levels. The dynamic response data in figure 2 indicates that 0.5 - 1.0 seconds of damping time is required for the 1/4 in step excitation to decay to a few percent of the peak dynamic wheel load.

The presence of the weigh-in-motion scales in the pavement can also induce dynamic wheel loads, thus increasing the propensity of WIM errors. The geometry of the scales (i.e., whether flush with the pavement) is the predominant effect; however, compliance of the scales in the vertical direction can effectively induce a bump.[7]

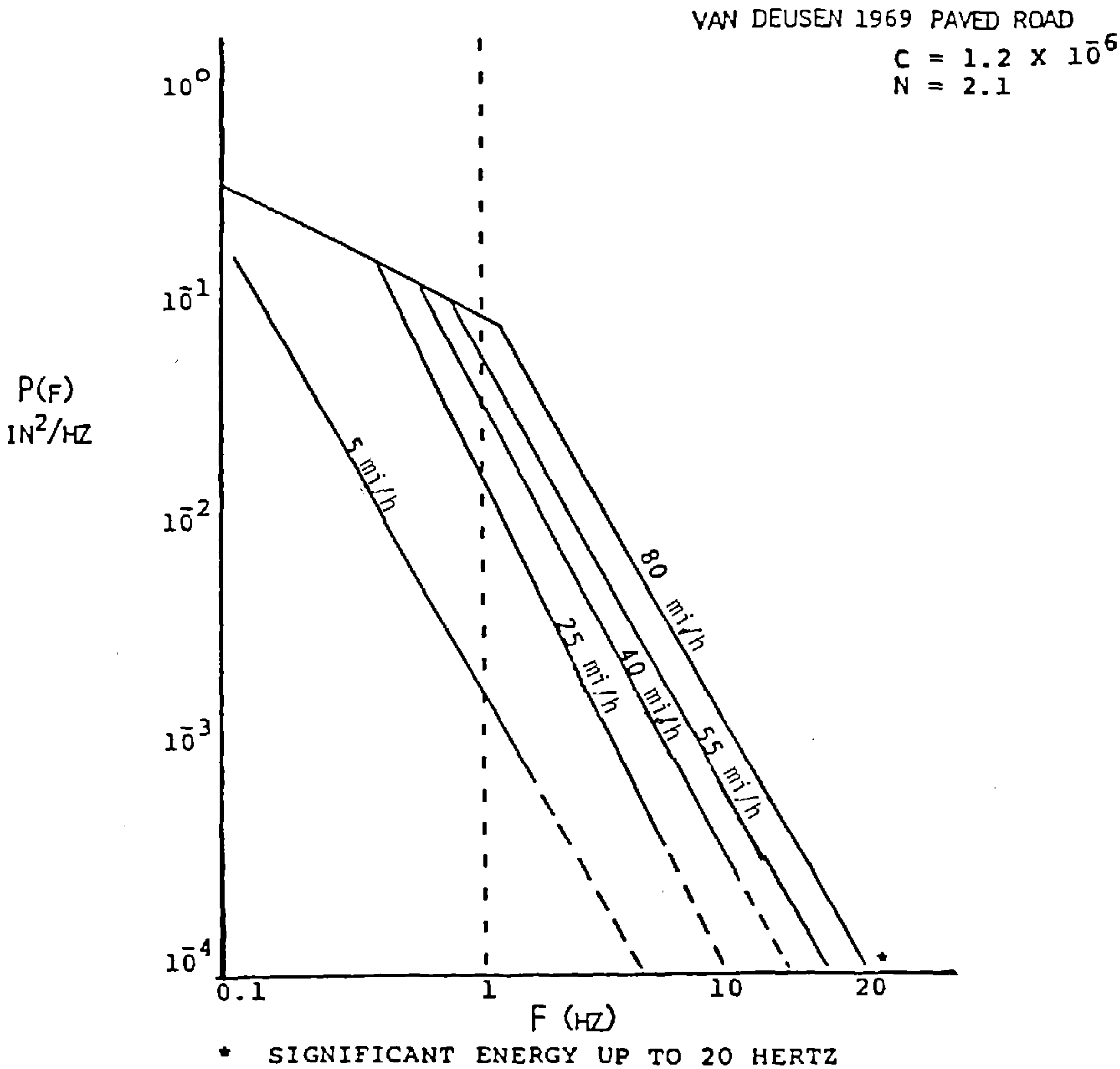

Figure 1. PSD representation of typical terrain.

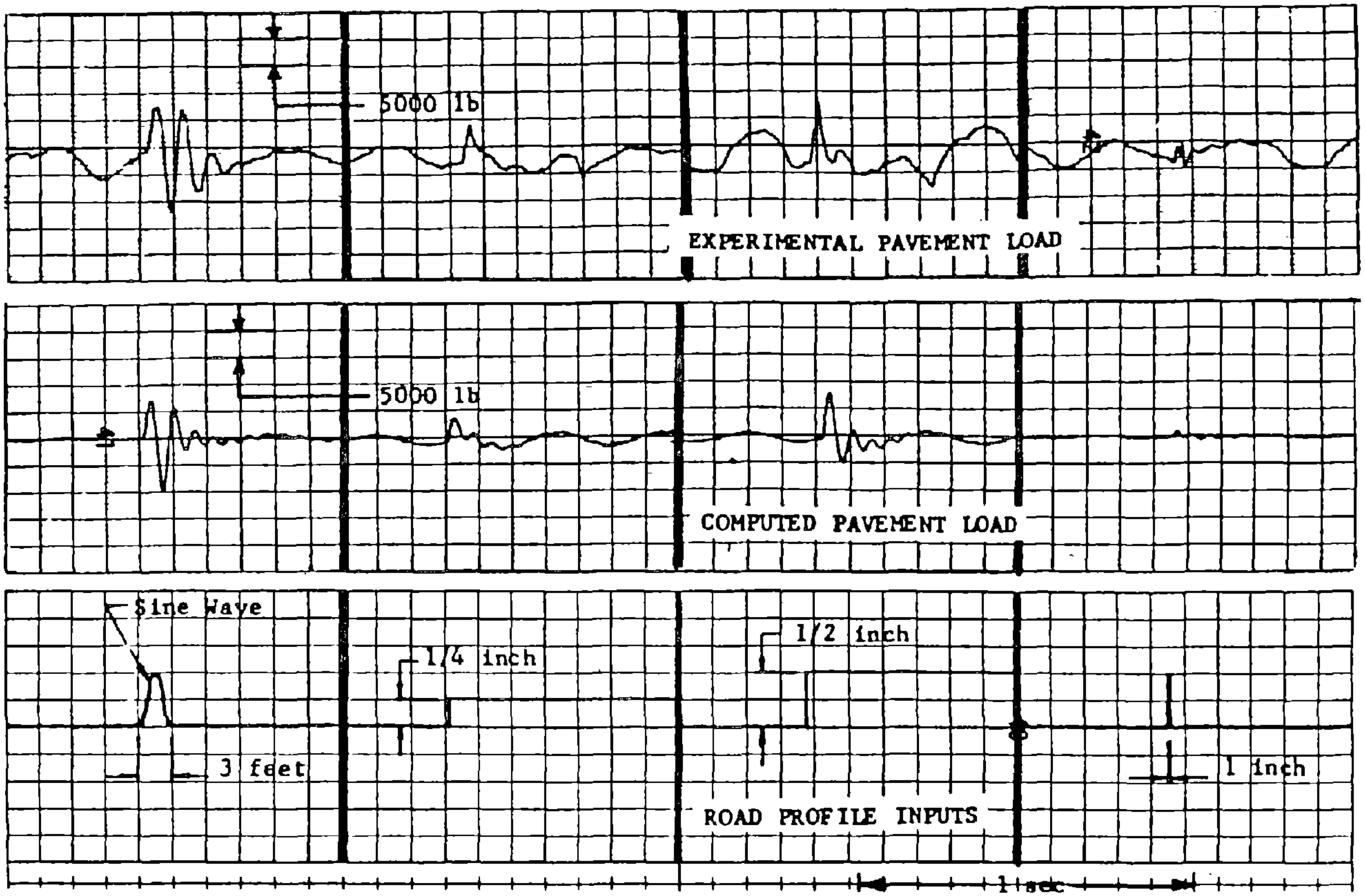

Figure 2. Computed and experimental load for deterministic inputs.
Vehicle speed: 34 mi/h[6], static load = 9,400 lbs.

The third item identified under road conditions is jointed concrete. While road roughness is commonly evaluated as a random event, the excitations from jointed concrete are considered deterministic (i.e., the excitation occurs at regular intervals). The frequency of excitation is dependent on the spacing of the joints, the spacing between axles and the vehicle speed. Significant wheel dynamic loads will occur if the excitation frequency coincides with one of several rigid body, structural and/or unsprung mass modes. The interference diagram in figure 3 shows that an imbalance in a 42 in diameter wheel could potentially excite any of several body and axle modes for a vehicle traveling above 5 mi/h.

Vehicle factors

The dynamic simulation analysis results identified suspension system factors, tire pressure, coupling, and axle and vehicle configuration as key factors which influence dynamic load. These factors are discussed below.

Suspension system

Four leaf spring, walking beam, torsion spring, air and rubber-block suspensions were identified. Representative single, tandem, four leaf, torsion, and air suspension system types are presented in figure 4. Information from several industry sources indicate that the largest number of spring types is four leaf (approaching 80 percent). Other data indicate that the four leaf spring suspension is responsible for some of the largest dynamic wheel loads only surpassed by the walking beam.[9,11] The torsion and air suspensions represent the smallest percentage of the population and result in relatively smaller dynamic wheel loads.

The results indicate that unsprung mass is a first order effect. Three values of unsprung mass ranging from 0.67 to 1.5 of nominal were analyzed in the simulation model. For example, increasing the unsprung mass by a factor of 2.25 from 0.67 to 1.5 of nominal, increases the

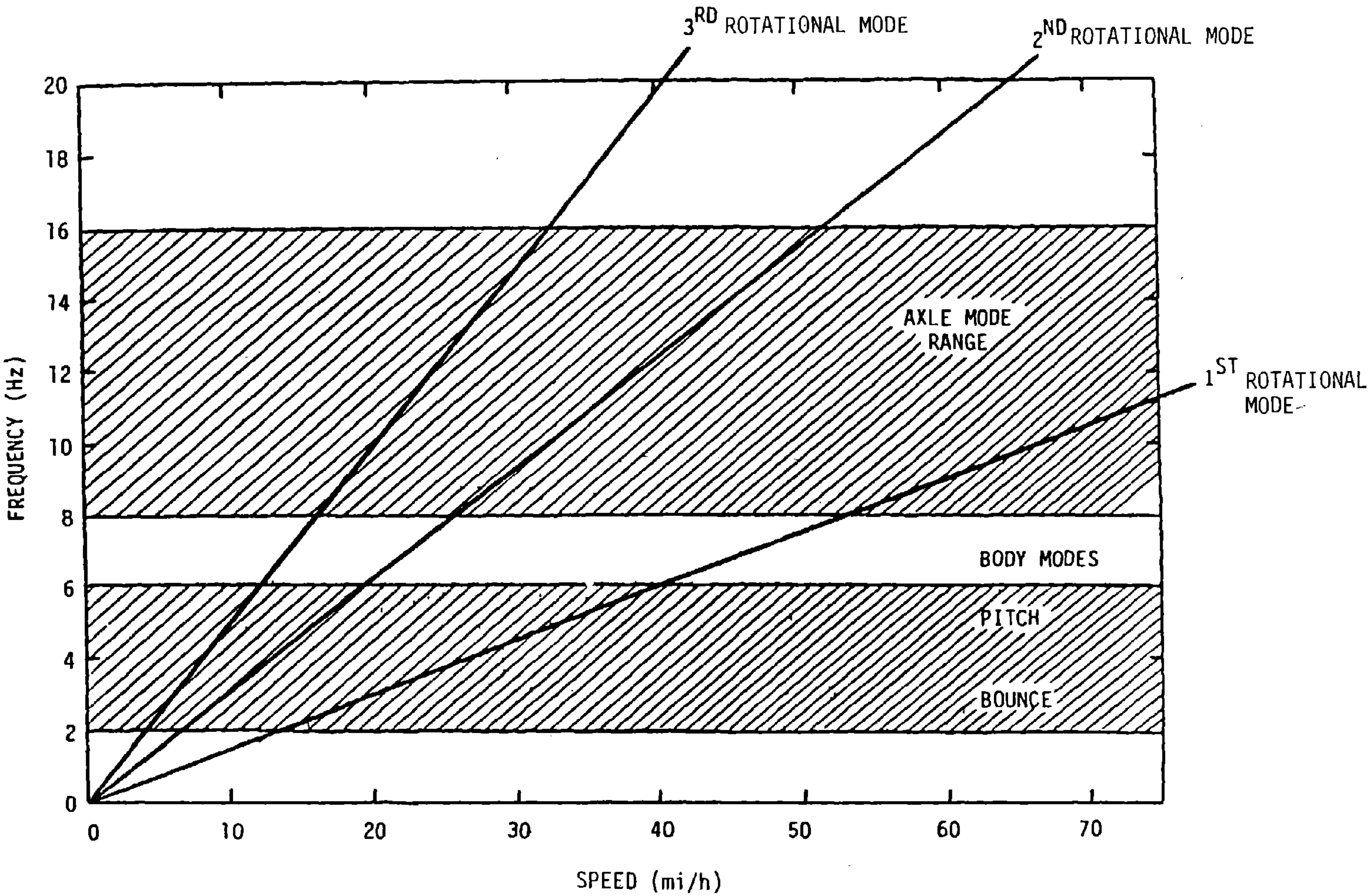

Figure 3. Truck wheel rotation interference diagram.

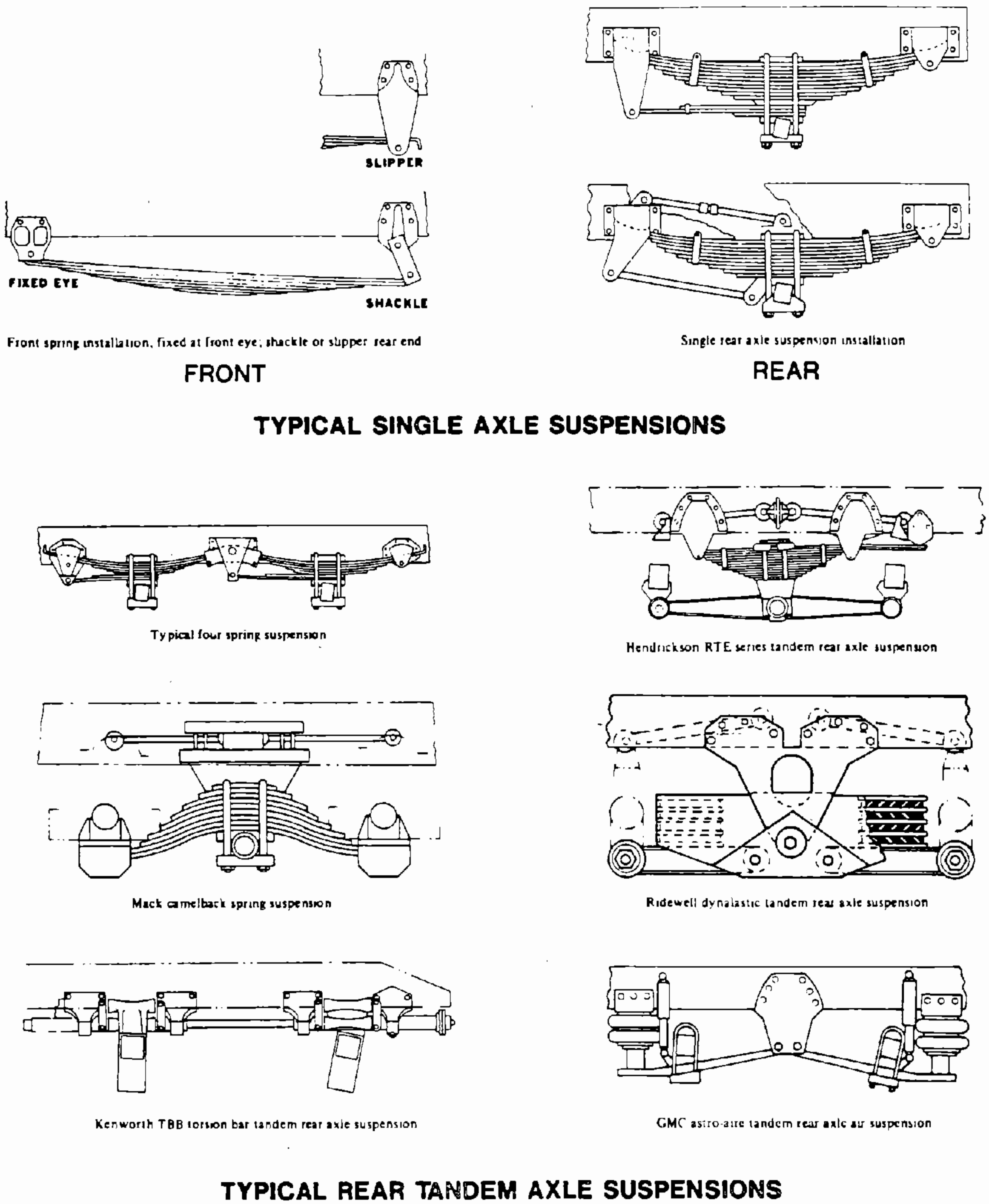

Figure 4. Typical suspensions used on heavy trucks.(8)

pavement dynamic wheel loads by 2.50. It could be inferred that larger gross axle load requirements, which usually mean larger axle designs, will result in larger dynamic wheel loads.

Speed

An increase in vehicle speed results in an increase in the frequency of road roughness with respect to the vehicle and therefore, the intensity of the input to the vehicle suspension system (see figure 1). For example, tuning of the vehicle dynamics with the road roughness or wheel unbalance may result in high dynamic wheel loads at a lower velocity.

Simulation analyses were performed to determine the sensitivity of dynamic wheel load and damping distance to a number of configuration variations for a five axle tractor-trailer vehicle. These analytical results were used in combination with information from the literature survey to select the "worst case(s)" vehicle configurations and subcomponents to be used in the experimental phase of the program.

The "worst case(s)" are defined as those configurations which: (1) result in dynamically active vehicles, and (2) represent a sizable portion of the population. Parameters varied in the analyses include the unsprung mass and inertia properties, tire pressure, primary suspension stiffness and damping, number of axles and tractor inertia. The influence of coupling between axles in a tandem and between tractor and trailer axles was examined and correlated with damping distance (i.e., length of smooth pavement necessary for the dynamic wheel load to decay to 10 percent of the peak levels).

Tire Pressure

Tire pressure was found from the analyses to be a very important parameter potentially affecting WIM accuracy for two reasons. First the peak pavement loads were found to be directly proportional to the tire pressure, and second fairly large variations in tire pressure are anticipated in the field. A recent survey in Texas revealed average pressures of 95 psi with extremes in excess of 135 psi reference.[10] The 95 psi average is significantly higher than the 70-75 psi assumed by most researchers. These findings were confirmed by data collected as part of the field test program where average "hot" tire pressures exceeded 95 psi with the range 90 to 100 psi.

Coupling

The force coupling between axles in the same tandem group and the coupling between the drive and trailer tandem were examined using a 3/8-in bump excitation in the simulation model. The degree of coupling between axles in the same tandem and between the drive and trailer tandems, in the context of dynamic wheel load, is dependent upon the vehicle speed, vehicle suspension geometry and inertia properties. The small mass of the tractor relative to the loaded trailer (i.e., ratio of four to five) results in little transfer of energy from the tractor to the trailer. In contrast, the trailer response does tend to drive the dynamic wheel loads in the steering axle. Analyses revealed that the trailer mass can excite the tractor steering axle wheel loads to levels of about 25 percent of the trailer levels, thus effectively increasing the damping distance.

A second coupling analysis was performed to examine axles in the same tandem. The results indicate that coupling between axles in the same tandem does not affect the damping distance, that the peak of the dynamic wheel load is not increased.

Single Versus Tandem Axle

The objective of these analyses was to determine if the ratio of dynamic wheel load to static wheel load is larger for a single or tandem suspension. The baseline static tandem axle load is 17 kips (34 kips per tandem) for the trailer suspension. The static axle load for the single axle system analyzed is 20 kips. All other elements of the system (e.g., percent of critical damping and suspension stiffness) were equal for the two configurations. The magnitude of the peak loads was found to be about the same for both suspensions, but the smaller static axle load on the tandem axle results in the ratio of dynamic to static axle load a few percent higher for the tandem system.

COE Versus Conventional Cab

The first order effect of tractor inertia on dynamic wheel load was examined using the simulation model by varying the pitch inertia of the tractor by factors of 5 and 10 while keeping all other mass, stiffness, damping, and geometric properties constant. The results indicate that conventional tractors have lower dynamic wheel loads on the steering axle and higher dynamic wheel loads on the driver axles than COE configurations.

CHAPTER 3 WIM DATA COLLECTION PROGRAM

A two part program of field experiments was conducted to collect data which could be used to relate WIM error to pavement roughness attributes. The first part of the program utilized inservice WIM sites in Nevada to gain an understanding of how WIM weighing and spacing error is related to vehicle parameters. This program was accomplished by comparing WIM generated weight and spacing data with static data for a large sample of inservice vehicles. The second part of the program utilized several instrumented vehicles to develop specific data to relate pavement roughness attributes to measured dynamic wheel force.

WIM Field Tests

The objective of these field tests was to characterize WIM error by making direct comparisons of WIM generated axle and gross weight, and axle spacing with static measurements made on the same vehicle. A series of such surveys were conducted at four inservice WIM sites in the State of Nevada.

Table 8 shows the actual number of vehicles for which usable WIM static data were collected for various configurations at each test site. In this table, COE refers to CAB-over-engine; CON refers to conventional CAB; and the other designations follow established usage.

The 3S-2 truck configuration is the most widely used truck configuration nationally and the data collected as shown in the tables reflects this fact with 65 percent of the sample in this class. To draw any conclusions for the other truck configurations, a smaller confidence level would have to be used, thereby increasing the chance of concluding that the WIM error is not significant when it is significant. Therefore, most of the analysis concentrated on the 3S-2 configuration.

Table 8. Field test sample sizes.

Truck Configuration								
Test Site	3S2 COE	3S2 CON	3S2 TOTAL	2S1	2SD	2S1-2	2S1-2-2
US95	33	39	72	6	27	15	0
APEX	42	43	85	1	11	21	18
SLOAN	56	58	114	3	4	37	1
TOTAL	131	140	271	10	42	73	19

Test Methodology

The selected measures for determining the accuracy of WIM systems is the calculation of gross weight, single and tandem axle weighing errors, and the spacing errors. Radian WIM scales were used to measure the axle and gross weights, axle spacing, and speeds for numerous truck configuration traveling along the highway. These scales were deployed, calibrated, and operated by the Nevada Department of Transportation (NDOT) personnel. A short distance down the highway, the same vehicles were flagged down by NDOT and weighed on static scales at inservice static weigh sites. Documentation for each test vehicle included such information as tractor and trailer type, type of commodity, number of axles, type of suspensions, wheel-base, tire pressure, etc. The WIM and static weight data were then analyzed to determine the WIM error which derives primarily from dynamic wheel load.

Prior to the collection of data, pavement profiles were measured using Pentax model GT-4B surveying equipment. Measurements were taken every 6 in for 200 ft upstream of the WIM scales and 80 ft downstream. These profiles were then analyzed to determine appropriate measures to rate WIM performance.

A procedure was developed by which individual inservice tractor trailers or single unit vehicles could be selected from the traffic stream and weighed statically and then dynamically using a Radian WIM system operated by NDOT.

Test Results

A total of 657 vehicles were sampled at three test sites in southern Nevada from which 486 usable data records were obtained. Analyses were conducted to determine the distribution of weighing error and spacing error stratified to the lowest level where statistically reliable results could be obtained. In each case WIM measured data were compared with static data. Error was defined as the difference between the static quantity and the WIM quantity and expressed as a percentage of the static quantity.

$$\text{Weighing errors} = \frac{\text{Static weight - WIM weight}}{\text{Static weight}} \times 100 \text{ (percent)}$$

$$\text{Spacing error} = \text{Static spacing - WIM spacing (in)}$$

Table 9 summarizes these results for 3S-2 axle weights and gives the percentage of vehicles falling within $\pm$ 10 percent of the static weight. Note should be made that it was not possible to measure individual axle weights in a tandem or tridem combination due to equipment limitations, therefore, the driver axle and trailer axle errors are tandem axle weighing errors. Table 10 lists the mean error and standard deviation for the 3S-2 sample for all sites combined stratified by configuration and suspension type.

Several observations can be made based upon the results given in table 10: (1) the steering axle error is highest when a leaf spring driver axle is used (the most prevalent in the sample); (2) the standard deviation is approximately the same for the steering axle and the driver but, 20 percent higher for the trailer tandem axle; (3) leaf spring suspensions produce higher errors than air ride suspensions; and (4) COE

Table 9. Percentage of axle weights within ± 10 percent of static weight (3S-2).

SITE	COE			CON			ALL		
	STEER	DRIVER	TRAILER	STEER	DRIVER	TRAILER	STEER	DRIVER	TRAILER
APEX	71.4	33.3	46.5	70.4	33.3	40.1	81.4	88.5	88.2
US95	65.8	85.3	55.9	79.3	40.0	78.0	74.7	90.5	68.0
SLOAN	54.1	84.6	73.1	74.7	92.9	73.2	65.1	89.0	73.4

Table 10. Distribution of axle weighing error statistics (3S-2).

		CONVENTIONAL			COE			ALL
		ALL	LEAF	AIR	ALL	LEAF	AIR	
STEER	MEAN	3.00	6.07	1.63	5.86	7.49	4.82	4.35
	SIGMA	7.23	4.41	7.62	8.71	8.34	6.04	8.09
DRIVER	MEAN	1.12	-1.89	2.47	1.36	1.53	0.44	1.23
	SIGMA	7.64	8.11	5.35	8.44	9.48	6.33	8.02
TRAILER	MEAN	0.01	0.03	-0.17	4.49	4.71	4.12	2.12
	SIGMA	8.85	10.82	5.83	10.20	11.45	6.73	9.77

configurations have generally higher errors than conventional configurations, this as a result of the higher pitching moment.

Table 11 summarizes the gross weight error results for all 3S-2 vehicles. This table gives the percentage of vehicles falling within the ± 5 percent error criterion. Several observations can be made: (1) generally fewer vehicles fall within the gross weight criterion than the single axle criterion; and (2) the conventional configuration has less error than the COE configuration, consistent with the single axle data.

Table 12 summarizes the axle spacing error results for 3S-2 vehicles. This table gives the percentage of vehicles which fall within ± 6 in of the static spacing. It can be noted from the table that, apparently, a small percentage of vehicles meet the spacing error criterion. However, a review of the procedures for measuring the static spacing indicate a high degree of measurement error for the longer span measurements. This is confirmed by noting the high percentage of agreement for the tandem axles. Therefore, only the tandem axle error results should be used.

In addition to these results, the data for all sites combined were utilized to draw general conclusions regarding the effect of vehicle configuration and type and suspension system type. The conventional configuration falls within the ± 10 percent criterion more often than the COE, however (91.5 percent vs. 83.8 percent) there are no statistically significant differences between the mean and standard deviations of the distributions. Similar results were obtained for the steering axle however the mean error for the COE case is significantly higher than for the conventional configuration. This confirms the results of the dynamic simulation analyses.

Additional data showed that the air ride performs significantly better than the leaf spring suspension. These results are confirmed by driver interviews conducted during the field data collection activity

Table 11. Percentage of gross weights within ± 5 percent of static weight (3S-2).

SITE	3S-2 TRACTOR			ALL VEHICLES	ALL	
	COE	CON	TOTAL	TOTAL	DRIVER	TRAILER
APEX	83.3	74.3	78.8	65.0	88.5	88.2
US95	69.7	74.3	72.2	65.9	90.5	68.0
SLOAN	54.1	84.6	62.9	61.1	89.0	73.4
ALL	62.9	72.5	68.3	61.1		

Table 12. Percentage of vehicles within ± 6 inches axle spacing (3S-2).

SITE	STEERING			DRIVER TANDEM	INTER TANDEM	TRAILER TANDEM
	CON	COE	TOTAL			
APEX	30.8	51.3	42.7	84.9	44.3	88.1
US95	18.2	34.3	26.5	77.6	16.7	86.3
SLOAN	22.5	26.8	24.7	58.8	30.6	60.7
ALL			31.3	71.9	44.8	80.6

wherein the drivers reported significantly better riding comfort with air ride compared with leaf springs.

The results of the dynamic simulation analysis raised questions regarding the degree of dynamic coupling between adjacent trailers in a double or triple combination. The means and standard deviation for the distributions were calculated with the result that no significant differences were determined within the limits imposed by the difference in sample size. Therefore, it appears that any vertical force coupling between adjacent trailers is insignificant.

Although sufficient data was not obtained at each site to evaluate the performance of the 2SD configuration, the data were combined for all sites and indicate considerably poorer performance of the driver axle in meeting the error criterion than the steering axle. Although this result is contrary to the result for the tractor trailers, it is consistent with the expected performance of a nonarticulated single unit vehicle. In addition, comparisons of the steering axle weighing error performance with the 3S-2 results indicate consistent agreement where a high percentage of vehicles fall within the error criterion.

A comparison between vehicle weighing error and pavement roughness was made. Figure 5 shows a plot of the percentage of vehicles meeting the weighing error criterion (either tandem axle or gross weight) versus the RMS profile height. The RMS profile height is the average RMS profile height obtained from the right and left wheel tracks. This figure clearly indicates the effect of the pavement in statistical weighing accuracy. Similarly figure 6 shows the same weighing error data plotted against Quarter Car Index which was obtained directly from the pavement profile by averaging the values from the right and left wheel tracks. A similar trend is evident as would be expected.

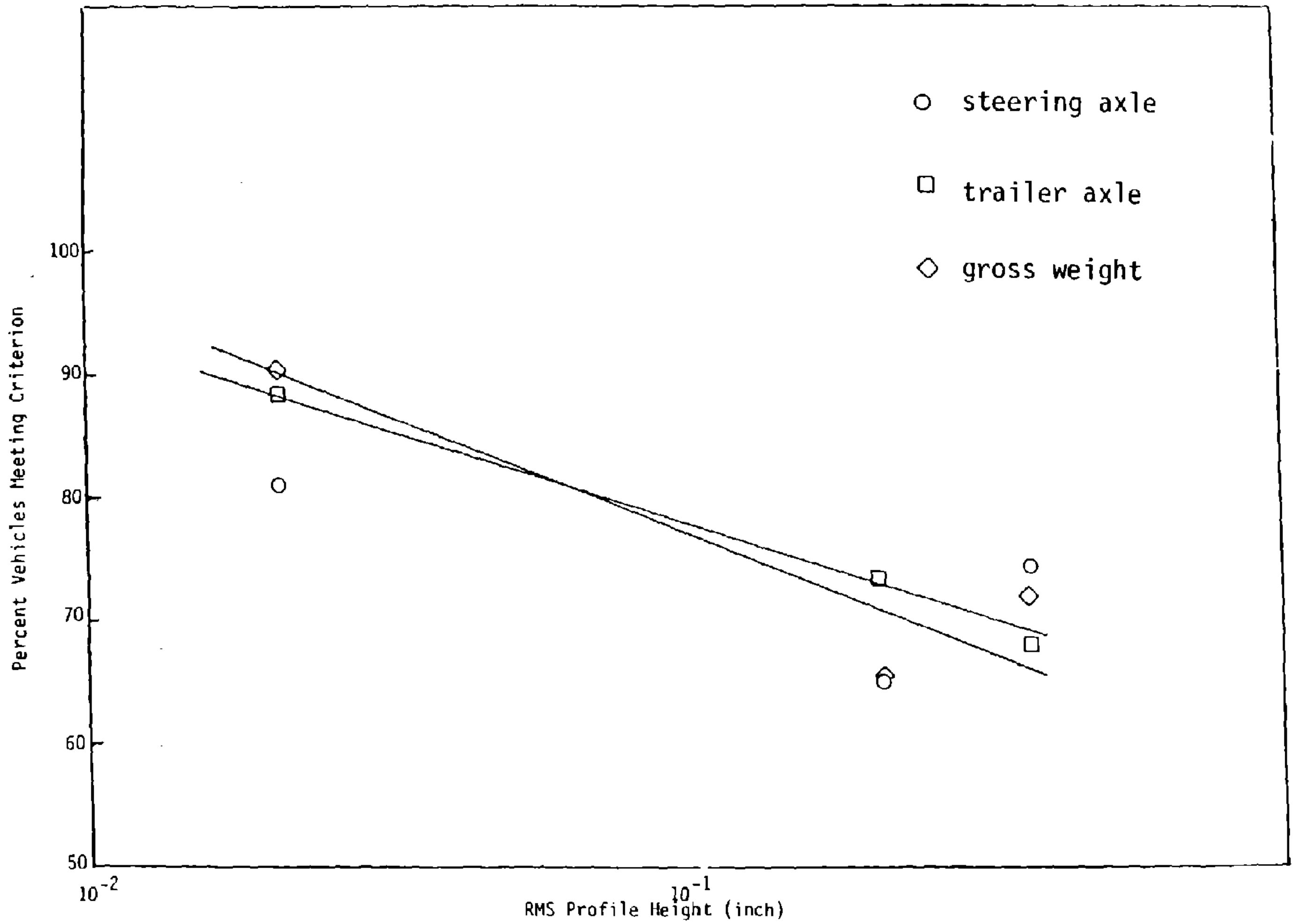

Figure 5. Percentage of vehicles which meet weighing error criteria (3S2).

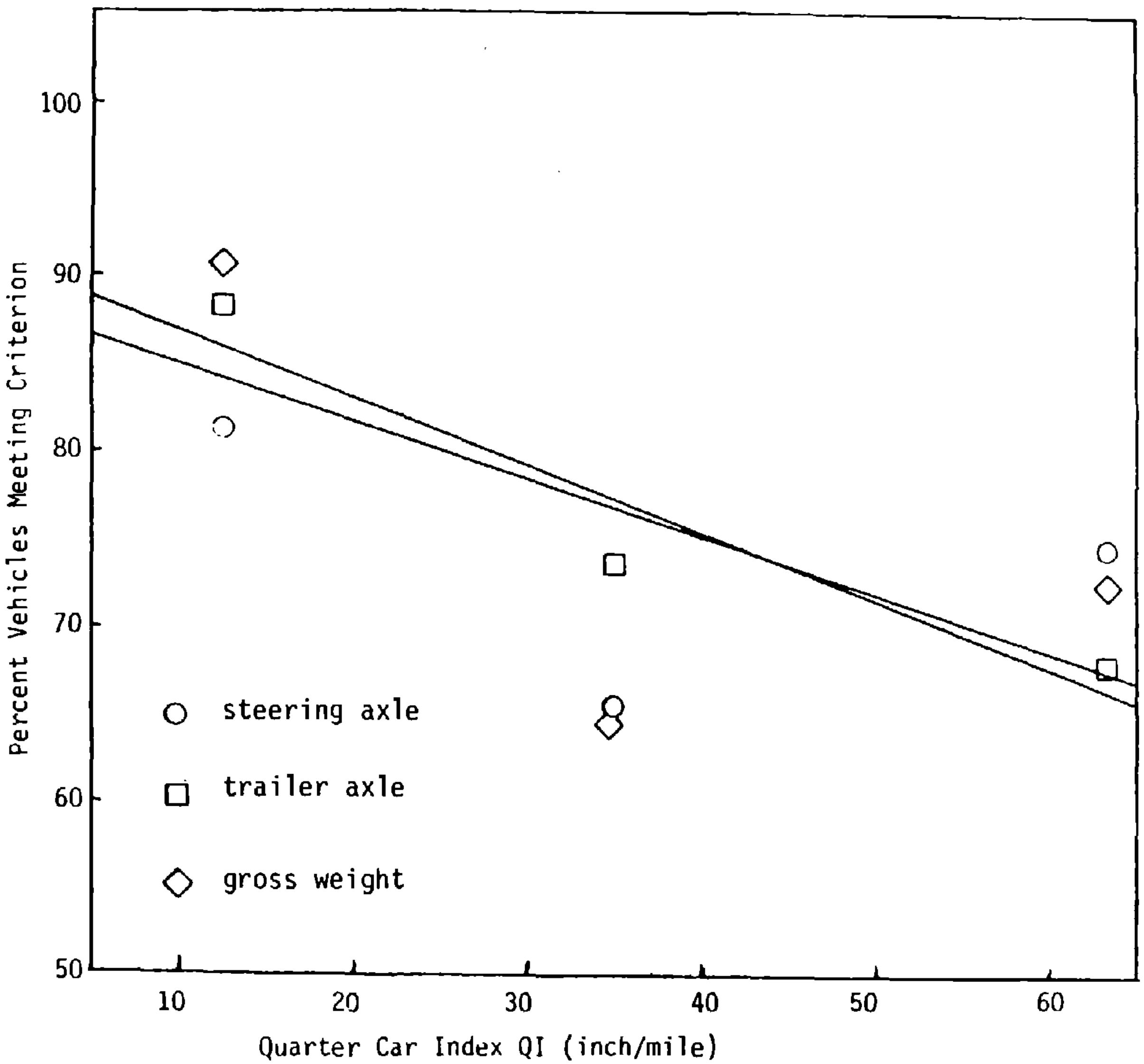

Figure 6. Percentage of vehicles which meet weighing error criteria (3S2).

Dynamic loading tests

The objective of these tests is to generate a data base of dynamic wheel load and damping distance data for a range of pavement roughness. The test series was conducted using two vehicle configurations, a 3S-2 COE and a 2SD vehicle. Three flexible and one rigid pavement section, shown in table 13, were selected to provide a range of roughness from smooth to levels which would result in dynamic wheel loads in excess of 20 percent of the static wheel loads.

The objective of the tests was to develop a data base of dynamic wheel load and road roughness, where the road roughness, as an independent variable, was stratified into the four levels mentioned. The road profile data was reduced and analyzed using power spectral density (PSD) analysis as discussed in the previous section so that simple criteria could be formulated from the dynamic wheel load and road profile relationships.

Test Methodology

The dynamic loading tests consist of a series of controlled tests wherein the tire-pavement force time history is measured for specific vehicles operating over test sections whose wheel track profiles have been measured using rod and level techniques. Tire-pavement force history is measured using a wheel hub force transducer/accelerometer system designed for this purpose.

Pavement Measurements

Both wheel track pavement profile for each pavement section was measured using a rod and level technique at 6 in intervals. Figure 7 is the PSD representation for the pavement profiles. As discussed earlier, a speed of 60 mi/h was chosen to convert the profiles from a spatial representation to a frequency representation. This value was chosen to

Table 13. Test site characteristics.

Site	Location	Description	Condition	Roughness	
				QI (inch/mile)	RMS (in)
A	Torey Pines Road	Concrete	Smooth/deteriorated	166.5	$0.586X10^{-2}$
B	US 101 (MP 10.0)	Flexible	Rough	178.4	0.191
C	Mira Mesa Boulevard	Flexible	Smooth/new	14.9	$3.77X10^{-2}$
D	US 101 (MP 7.5)	Flexible	Worn	109	0.126

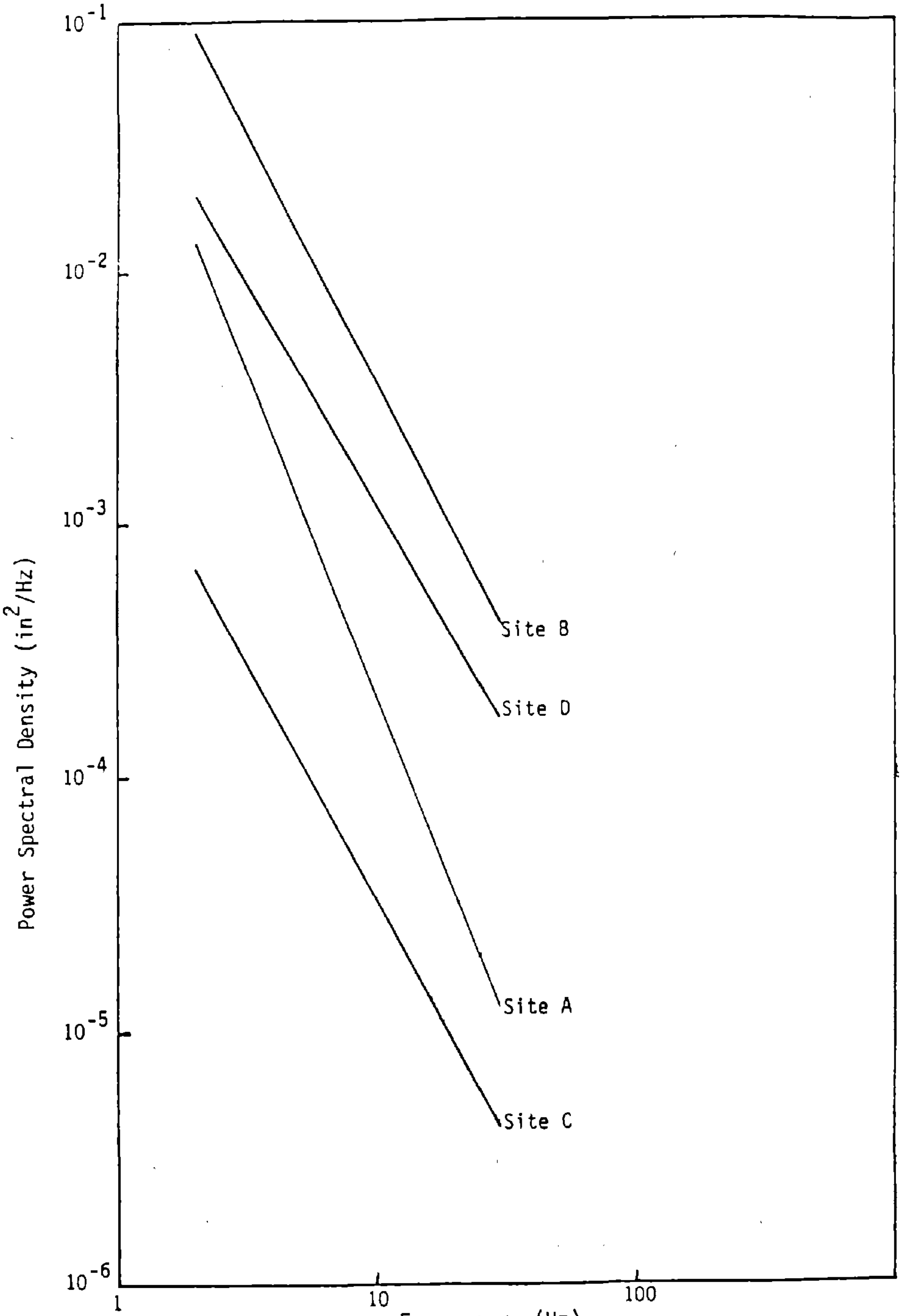

Figure 7. PSD of pavement profiles.

represent the typical operational speeds observed for in traffic WIM weighing during the field test activity.

Test Results

A total of 93 dynamic pavement loading tests were performed to collect data to develop simple criteria for pavement roughness to meet specified WIM accuracy limits. As previously discussed, these tests were limited to two vehicle configurations tested at three speeds on four pavement sections selected to represent a significant range in dynamic response.

Although it would be useful to attempt to investigate relationships between the spectral content of the pavement profile and that of the response, it was determined that such relationships would not provide implementable guidelines for users who would not be able to characterize such spectral properties. Therefore, as with the statistical data, a relationship between macroscopic measurable pavement properties and weighing error was developed.

Figures 8 and 9 summarize the results by comparing the Weighing Index with the Quarter Car Index (QCI) and the RMS profile height computed from the RMS average of the actual profile. The QCI and RMS profile height are averages of the left and right wheel tracks. The Weighing Index is defined as the probability that the dynamic force is within ± 10 percent of the static force. Therefore, a larger value of Weighing Index indicates less dynamic effect.

In addition to determining the influence of pavement roughness on dynamic loads, several tests were performed to determine the distance required to damp the dynamic force response to levels which would meet the ± 10 percent criterion. These tests were conducted at 60 mi/h at Site A where approximate 0.21 in pavement discontinuity exists. Figure 10 is the calculated dynamic force response. This figure, which gives dynamic force as a percentage of static force, shows that approximately

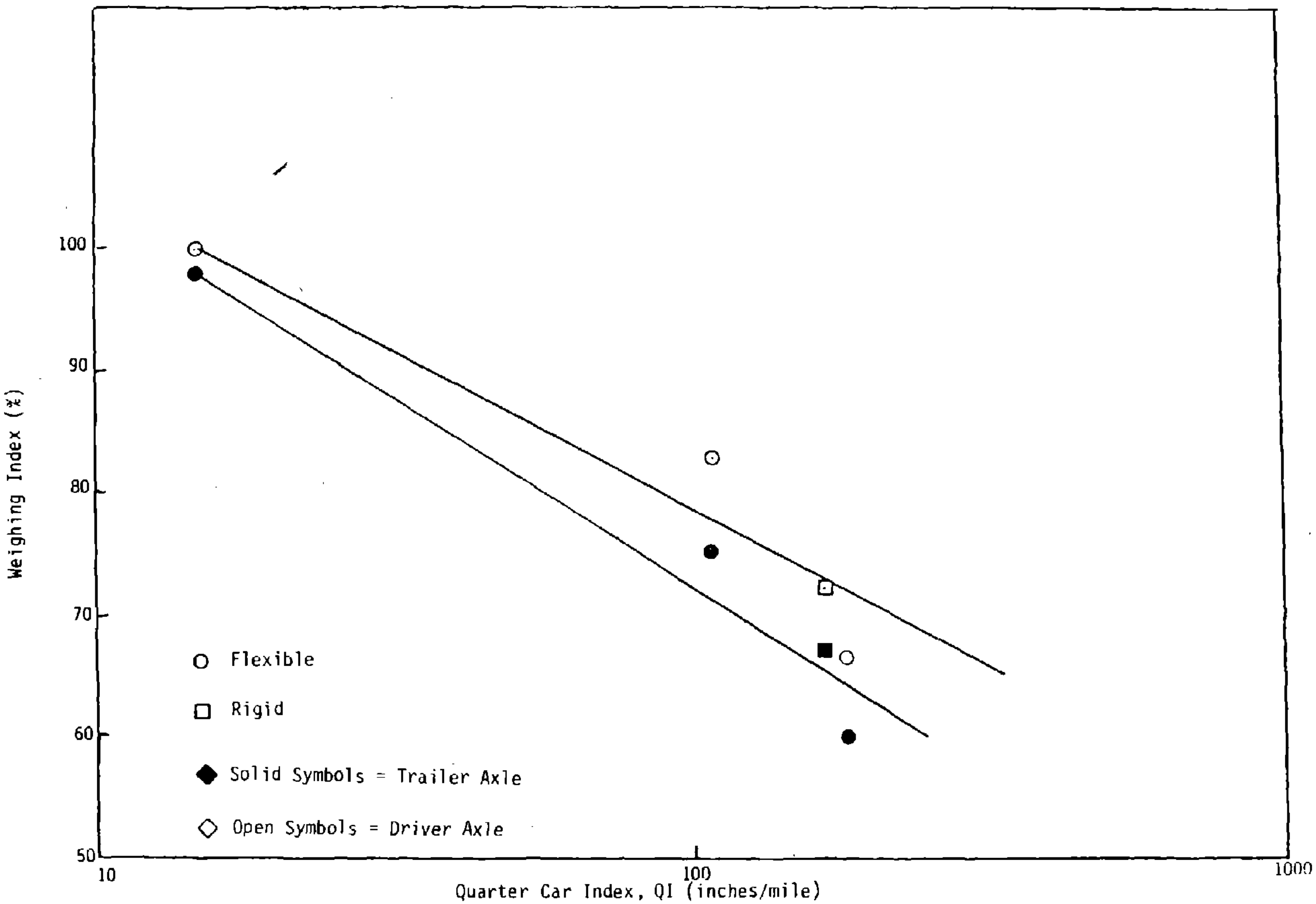

Figure 8. Relationship between weighing index and QCI.

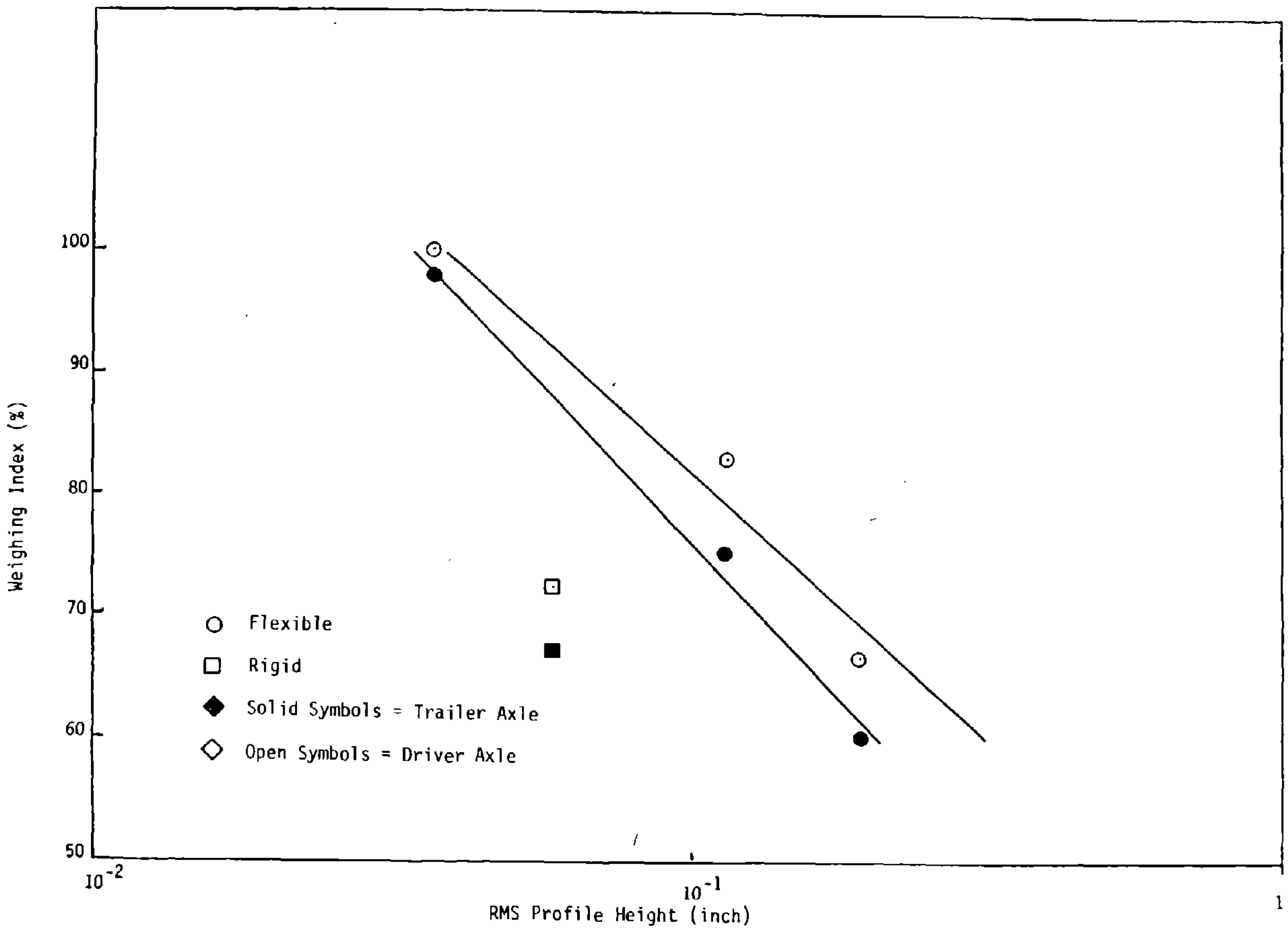

Figure 9. Relationship between weighing index and RMS profile height.

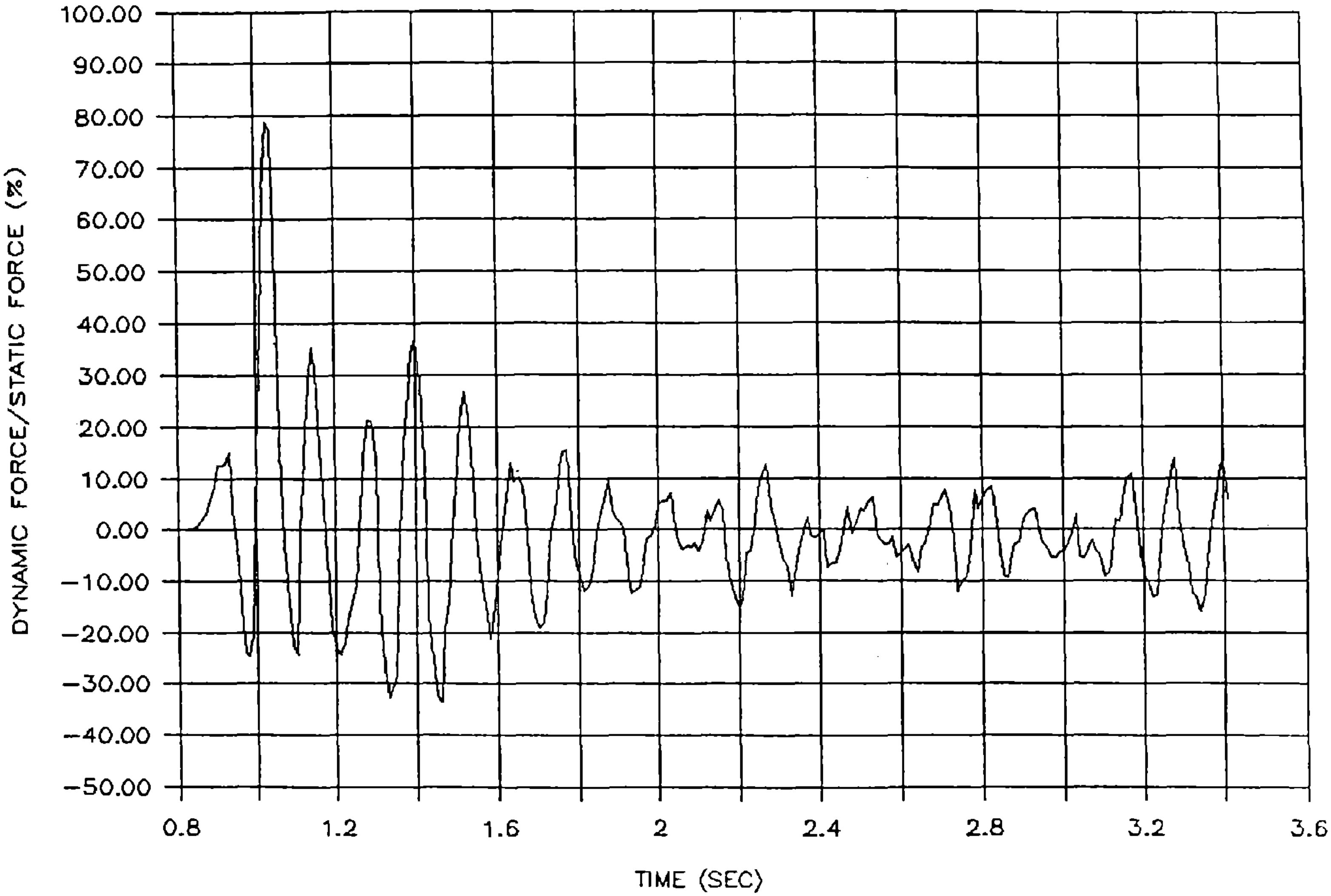

Figure 10. Force time history 3S2 driver axle site A 60 mi/h.

0.9 second (80 ft) is required for sufficient damping. This result is considered a worst case since no WIM site would be selected with such a large visible pavement discontinuity. Therefore, it appears that a minimum distance in excess of 80 ft will provide a sufficiently smooth WIM approach.

CHAPTER 4 RECOMMENDATIONS

Recommendations as to the level of pavement roughness and length of approach section to achieve specific levels of WIM measurement accuracy have been developed from the results of the two field study programs described in chapter 2. The recommendations are based, in part, upon statistical data and therefore represent the results which might derive from an "average vehicle." Since the largest proportion of the vehicle fleet consists of the 3S-2 configuration and the testing focussed on this configuration, the recommendations are based primarily on this vehicle configuration.

Figure 11 shows the weighing error as a function of pavement roughness (in/mi) for the driver tandem, trailer axle, and the vehicle gross weight. This figure was developed with the assumption that the pavement roughness upstream of the WIM scale would be homogenous with the roughness value indicated. The figure does not account for specially prepared smooth pavement sections upstream of the WIM scale.

Figure 12 gives adjustment factors to account for provision of smooth pavement upstream of the WIM scale. The adjustment factor computed is multiplied by the roughness level to yield an adjusted roughness for application to figure 11. The damping time (t) is the length of smooth pavement associated with the vehicle speed and is interpreted as the damping time required to achieve a level of smoothness desired. The total damping time (t_T) includes a speed adjustment factor (t^*) which was based upon parametric studies covering a range of vehicle speeds and pavement roughness.

Application to a particular site is accomplished as follows:

1. Measure the pavement roughness of the site (in/mi) over a section of at least 100 ft upstream of the potential location.

2. Check the anticipated weighing error on figure 11. If the error is unacceptable, then surface preparation is required.

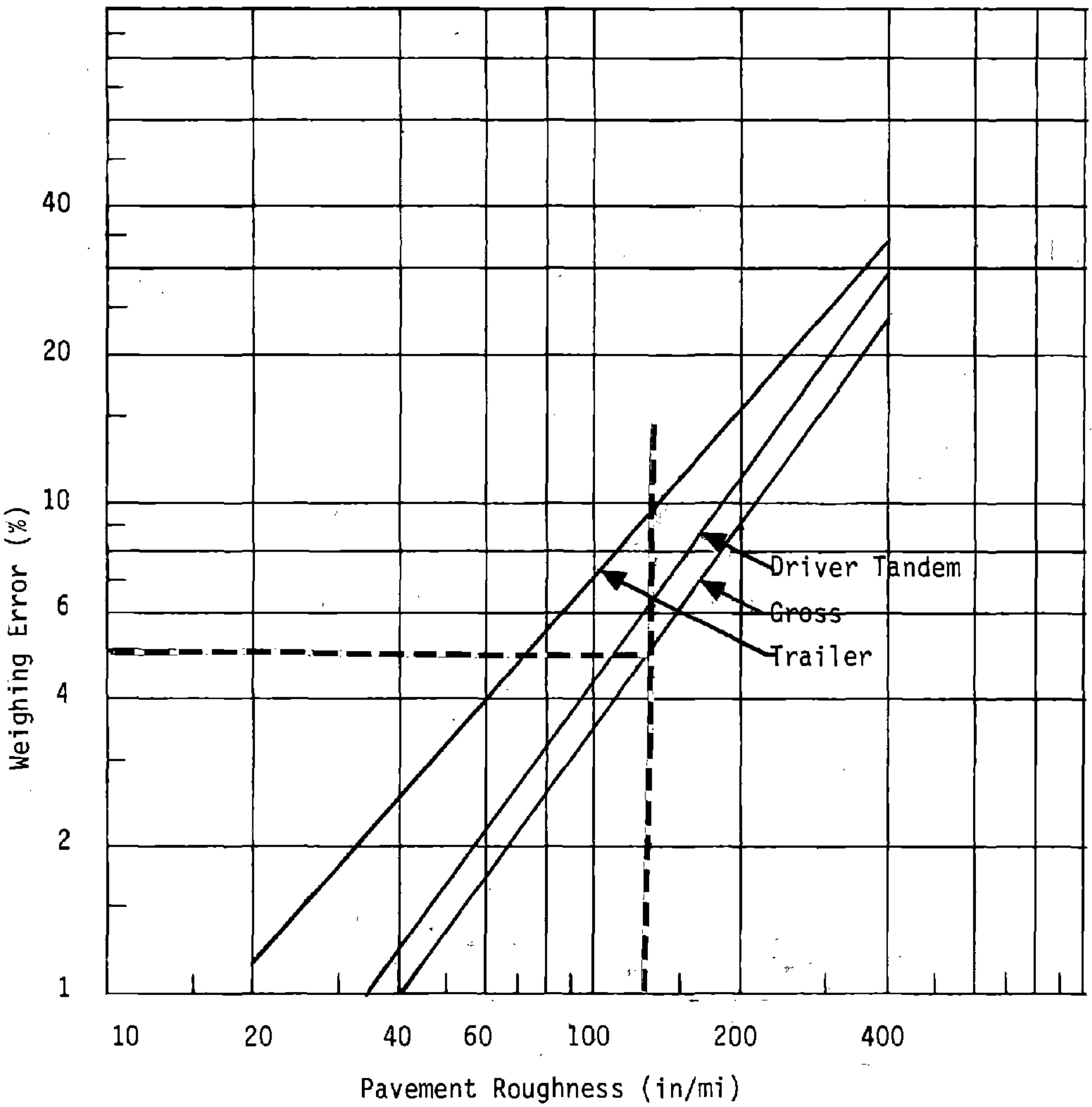

Figure 11. The effects of pavement roughness on weighing error.

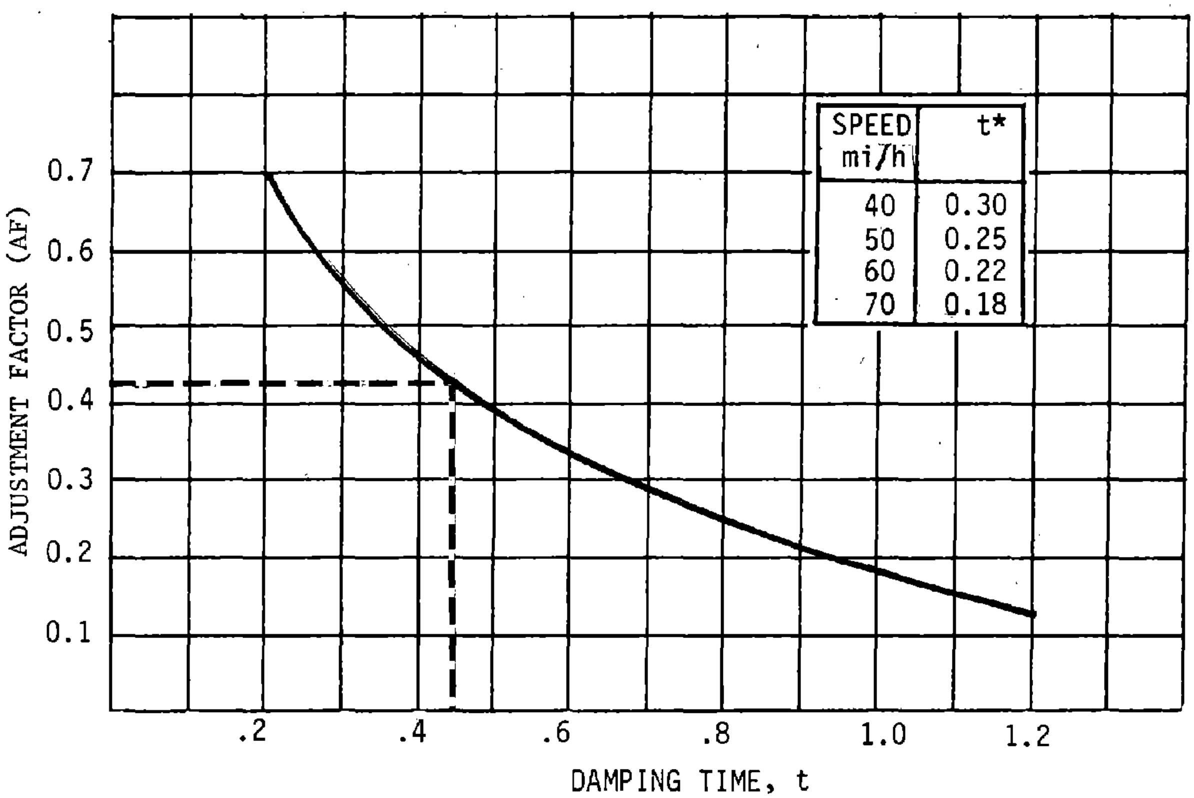

Figure 12. Weighing error adjustment factor as a function of damping time.

3. Determine the level of acceptable error and use figure 11 to determine the associated roughness valued.

4. Calculate the necessary adjustment factor (AF) as follows

$$AF = \frac{\text{desired roughness}}{\text{actual roughness}}$$

5. Utilize figure 12 to associate the necessary AF with a damping time, t.

6. Using the speed adjustment factor (t*) from the table in figure 12, calculate the total damping time t_T as follows:

$$t_T = t + t^*$$

7. Based upon the design/operating speeds expected at the site, calculate a minimum smooth pavement length, L(min) as follows:

$$L(min) = speed(ft/sec) \times t_T$$

8. Calculate the smooth pavement length required by including the vehicle factor, VF, which accounts for the range of vehicle suspension system response properties:

$$L = L(min) \times VF$$

Based upon the results of literature reviews and dynamic simulation analyses, a value of VF = 2.5 has been used.

Example

If 5 percent is the maximum acceptable error for gross weight, figure 11, indicates a maximum roughness of approximately 130 in/mi as shown. This value has associated with it approximately 6 percent and 9 percent error for the tandem driver axle and tandem trailer axle, respectively.

However, if the roughness at the site is 300 in/mi, for example, then the errors appear to be unacceptable and a section of smooth approach pavement is required. In order to determine the length of smooth pavement required, the adjustment factor, AF is calculated from step 4 above. AF = $\frac{130}{300}$ = 0.43 which from figure 12 yields an approximate value of **t** = 0.43. The total damping time, t_T, is calculated from step 6. Then the minimum pavement length required for specific speeds is calculated using step 7. Step 8 is used to adjust the minimum requirements to account for vehicle variations. Sample calculations for this example are given in the table below for VF = 2.5.

	Smooth Pavement Length, (ft)	
Speed (mi/h)	L(min)	L(min)xVF)
40	44	100
50	51	130
60	59	150
70	65	165

REFERENCES

1. 1975-1978 National Truck Characteristic Report, Federal Highway Administration, June 1981.

2. Skinner, Harry, "Why Size and Weight Legislation", Paper presented at the National Weigh-in-Motion Conference, Denver, CO, 1983.

3. National Bureau of Standards. Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices. U.S. Department of Commerce: Washington, D.C., 1983.

4. Cunagin, Wiley, D., "Synthesis of the Use of Weigh-in-Motion Equipment for Data Collection and Enforcement", Draft Report for Project NCHRP 20-5/16-02, July 1985.

5. Personal communication with Perry M. Kent, FHWA.

6. Whittemore, A.P., J.R. Wiley, P.C. Schultz, D.E. Pollock, "Dynamic Pavement Loads of Heavy Highway Vehicles", National Cooperative Highway Research Program Report 105, 1970.

7. Chow, William, "Evaluation of the PAT and Streeter-Amet Weigh-in-Motion Systems" California Department of Transportation, Report FHWA/CA/TL-82/08, July 1982.

8. Gillespie, L.D., "Heavy Truck Ride", University of Michigan Transportation Research Institute, SP-607, 1985.

9. Sayers, M., T. Gillespie, University of Michigan, "Dynamic Pavement/Wheel Loading for Trucks with Tandem Suspensions", University of Michigan Transportation Research Institute.

10. Roberts, F.R. and R.L. Lytton, "Summary of Findings from Texas Studies of Tire Pressures", Texas Transportation Institute, Texas AM University.

11. Sayers. M, T. Gillespie, "Dynamic Pavement/Wheel Loading for Trucks with Tandem Suspensions", Transportation Research Institute, University of Michigan, Ann Arbor, Michigan.