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Department of Transportation

Urban Mass Transportation Administration

Proceedings: Direct Fixation Fastener Workshop

Transportation Systems Center
Cambridge MA 02142

June 1985
Final Report

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16. Abstract

This report is a collection of papers and discussion transcripts from a workshop on direct fixation fastener systems (DFFS) that are increasingly being used in the construction of modern rail transit systems and system extensions. Preservice testing, specification development and revision, and in-service experience with DFFS are discussed. The preliminary results of field tests are also presented, as well as industry practices and problems, current laboratory procedures, and noise/vibration reduction.

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PREFACE

Direct fixation of rail to concrete slabs in tunnels, on aerial structures, and at-grade has become increasingly employed in the construction of modern rail transit systems and system extensions. As the use of the direct fixation fastener (here defined as a device anchored to the slab with a thick pad of elastomeric material bonded to a top-- and sometimes bottom-- metallic plate to which the rail is affixed by means of either bolts or resilient clips) has increased, problems have begun to appear with the fasteners in service. These problems are indicative of specifications for pre-service testing that are not representative of the actual fastener load environments under traffic.

Responding to a need expressed by many systems to develop guidelines for fastener acceptance based on realistic load values, the Urban Rail Division of the Urban Mass Transportation Administration (UMTA) Office of Systems Engineering has sponsored research to provide the data necessary in formulating these guidelines. The workshop on which these proceedings are based was sponsored by UMTA to provide a forum for transit industry representatives to describe their experiences with direct fixation fasteners, voice their concerns with present specifications, and view the preliminary results of field tests in this area.

This report contains papers which have surveyed the industry's practices and problems; describe current laboratory test procedures; present a manufacturer's perspective; discuss the noise reduction aspects of fastener design; document the experience of the Bay Area Rapid Transit System (San Francisco), the Washington Metropolitan Area Transit Authority, the Massachusetts Bay Transportation Authority, and the Mass Transit Administration (Baltimore); and document the results of vehicle and track tests on the Washington Metro.

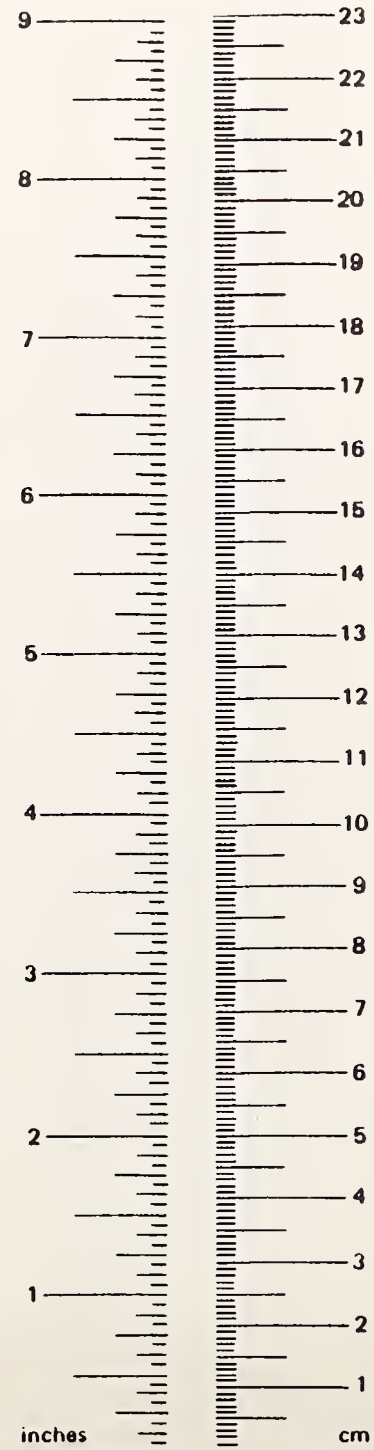
These proceedings include the original papers and resulting discussion and include a transcript of a panel discussion with audience participation on the subject of "Direct Fixation Fasteners- Problems and Potential Solutions." Presentation and discussion were edited by Andrew Sluz, while discussions were transcribed from audio tapes by Melodie A. Esterberg and Jon F. Pietrak.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

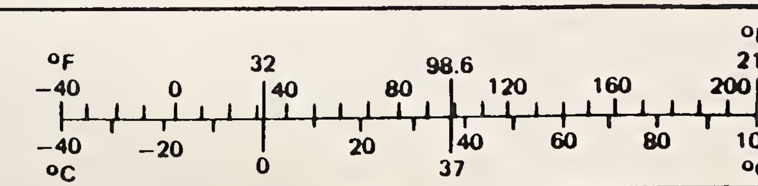
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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DFF SPECIFICATIONS AND DESIGN

A Survey of Direct Fixation Fasteners Systems in North America: Existing Types and Associated Problems

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EXECUTIVE SUMMARY

Detailed data relating to the experiences of U.S. and Canadian transit properties with direct fixation fastening systems (DFFS) have been collected by the Transportation Systems Center (TSC) as part of a research and development program in this area of study. This effort was under the sponsorship of the Office of Systems Engineering, Urban Mass Transportation Administration (UMTA) of the U.S. Department of Transportation, and is a major area of concentration in TSC's Urban Rail Construction and Rehabilitation Program.

The primary objective was to describe the types of DFFS used by North American transit properties and the problems that have been encountered. This effort included a survey of literature including manufacturers' descriptions of products, trade publications, and technical papers on the subject; a detailed mail-in survey of U.S. and Canadian transit properties; and site visits to the properties to inspect the installations, examine failed specimens, and interact with system personnel. Additionally, personal and telephone contacts were made with industry sources including suppliers, systems consultants, and engineers. The work spanned a period of ten months from October 1980 to July 1981.

The major observation from the study is that problems exist to varying degrees with the early applications of DFFS on North American transit properties. The problems common to most transit properties include failures of anchorage systems, most likely due to poor construction practices and lack of quality control during installation of anchor bolts, and corrosion of DFFS components due to wet conditions and/or lack of corrosion protection. Other types of problems have been reported but are usually unique to those individual transit systems. It is concluded that the application of DFFS can be successful if all track requirements unique to a given transit system are carefully analyzed and accounted for in specifying not only a product but, especially, all aspects relating to its installation, operation and upkeep.

INTRODUCTION

Background

For more than 100 years, the railroad and transit track structure has remained fundamentally unchanged.[1] The wooden crosstie was introduced in about 1840 and additions such as tie plates and rail anchors were made subsequently, along with larger rail sizes and better materials and methods of maintenance. Still the basic track structural design has remained the same.

Continuing efforts to improve track structures in the United States have resulted in the development of steel and concrete crossties, mechanical fasteners with and without resilient elements, and slab track with direct fixation fastening systems (DFFS). These items have been employed with varying degrees of success. In North America, increasing activity in the development of urban rail transportation--mass transit and commuter railways --has accelerated the development of ballastless track, especially in subway tunnels and on elevated structures. This, in turn, has brought about technological advancement in terms not only of the track structure but also track components, as in the case of DFFS. Furthermore, increasing environmental sensitivities, followed by regulatory requirements, have also placed considerable emphasis on advancing the technology toward minimizing noise and vibration through the use of noise-abating track components as well as improved track structure design, installation, and maintenance practices. When viewed in light of construction, maintenance, and structural integrity considerations, the technical advantages of ballastless track are obvious. Although more expensive than the conventional tie/ballast structure, this type of construction reduces required maintenance while providing improved geometry retention and lateral restraint.

For these reasons, the use of ballastless track on North American transit systems is increasing in both new construction and track rehabilitation. Primary applications to date have been on steel and concrete-deck elevated structures, in subway tunnels, and in the vicinity of station platforms, all of which afford limited access for maintenance operations.

Design Concepts

Because of the variety of functions it must perform, the DFFS is one of the most critical elements in any ballastless track system. Early history of the development of direct fixation fasteners can be traced to the need for securing rails directly to a concrete base or a steel girder in tunnels and bridges. Fundamentally, the mechanics of the fastener design should provide for elastic connection between the rail and the track base (i.e., concrete slab), to distribute the loads from passing trains, and avoid damaging impact on the concrete. A rail on a series of elastic fasteners is analogous to a beam on elastic supports, and the relative movement between the rail and the slab may be described by motion in a six-degree-of-freedom system, i.e., translation in three orthogonal directions and rotation in three orthogonal planes. These six modes of relative displacement must be taken into account in designing elastic resistance into a fastening system.

The primary considerations underlying the design of direct fixation fastening systems include:

- elastic restraint in all modes of deformation
- damping considerations for vibration and noise abatement
- operational factors, i.e., adjustability during installation and later maintenance; electrical insulation, etc.

The various DFFS designs available in the North American market accommodate these design considerations through two fundamental concepts. These two concepts may be categorized as: (1) screw-type fasteners, in which the rail is fastened to a plate with rigid, bolted clamps; and (2) spring clip-type fasteners, in which the rail is held on to the plate by elastic clips. While some of the manufacturers produce only fasteners with the spring clip arrangement, others make both types of fasteners. In the case of the latter, their original product lines were the screw-type systems, with the spring clip type added on, perhaps in response to market demands.

Objective

The objective of this paper is to report on the types of DFFS manufactured in North America and used by North American transit properties. Also, problems being encountered by these transit properties with DFFS and remedial measures that have been undertaken to correct the problems will be discussed.

DATA COLLECTION

WYLE Laboratories of Colorado collected detailed data relating to the experiences of U.S. and Canadian transit authorities with DFFS. [2] The effort included a survey of literature including manufacturers' descriptions of products, trade publications, and technical papers on the subject; a detailed mail-in survey of U.S. and Canadian transit properties; and site visits to the properties to inspect the installations, examine failed specimens, and interact with system personnel. Additionally, personal and telephone contacts were made with industry sources including suppliers, systems consultants, and engineers. Results of this work pertinent to this paper are discussed in the following sections.

DFFS Types Available

A survey of the presently available types of DFFS in the United States and Canada was conducted which included a search of information published in trade magazines; direct contact with manufacturers, transit authorities, and consultants; and a computer search of the engineering index. As a result, several types of DFFS were identified and are listed in Table 1. The list developed was based on the best information available at the time of the survey and is not intended to be a fully exhaustive listing. Other types of DFFS are manufactured and used around the world which are not included in this paper.

TABLE 1. LIST OF AVAILABLE TYPES OF DFFS

MANUFACTURER	MODEL IDENTIFICATION	RAIL BASE ATTACHMENT	ELASTOMERIC ELEMENT(S)
LANDIS RAIL FASTENING SYSTEMS (Los Altos, California)	LANDIS MODEL 2000	Screw type--rigid toe clamp	Rubber compound bonded between parallel base plates
	LANDIS MODEL 2010	Boltless formed spring clip of bending-torsion type (Pandrol 602-A)	Rubber compound bonded between parallel base plates
	LANDIS-PANDROL MODEL 5202 & 5301	Boltless formed spring clip of bending-torsion type (Pandrol, 601-A)	Rubber compound inserted between base plate and slab
LORD KINEMATICS, LORD CORPORATION (Erie, Pennsylvania)	N/A	Screw type-rigid toe clamp	Rubber compound bonded between parallel base plates
PORTEC, INC., RAILROAD PRODUCTS DIVISION (Oak Brook, Illinois)	SIDEWINDER SERIES 100 & 500	Boltless formed spring clip of bending-torsion type	Rubber compound inserted between rail base and slab. Additional elastomer between spring clip and rail base
RAILROAD RUBBER PRODUCTS (Ashtabula, Ohio)	N/A	Encapsulation of rail base in preformed rubber boot	Rubber compound surrounding rail base

TABLE 1. LIST OF AVAILABLE TYPES OF DFFS (CONTINUED)

MANUFACTURER	MODEL IDENTIFICATION	RAIL BASE ATTACHMENT	ELASTOMERIC ELEMENT(S)
STEDEF, INC. (Falls Church, Virginia)	AP STEDEF	Bolted flat leaf spring	Rubber compound inserted between rail base and crosstie. Additional elastomer between spring clip and rail base
TRANSIT PRODUCTS COMPANY, INC. (College Park, Georgia)	HIXSON H-10	Screw type - rigid toe clamp	Rubber compound bonded to lower side of fastener base plate
	HIXSON H-12	Screw type - rigid toe clamp	Rubber compound bonded between parallel base plates
	HIXSON H-15A	Boltless flat leaf spring	Rubber compound bonded between parallel base plates
	HIXSON H-17	Screw type - rigid toe clamp	Rubber compound bonded between parallel base plates
UNIT-D.E. (Chicago, Illinois)	UNIT-D.E.	Boltless formed spring clip of bending type	Rubber compound inserted between base plate and slab
N/A	TORONTO/TTC STANDARD	Bolted formed spring clip	Rubber compound inserted between tie plate and slab

North American Transit Users of DFFS

Through information on North American transit systems gathered from available literature, government and industry sources, and with the assistance of the American Public Transit Association (APTA), a list of existing, future, and potential users of DFFS was developed (see Table 2). Table 3 lists 12 of the 13 transit properties opting to participate in the data collection survey performed along with the types of DFFS in use. Miami, at the time of this program, was still undecided on which DFFS type to procure and is not included in Table 3.

TABLE 2. NORTH AMERICAN TRANSIT SYSTEM USE OF DFFS

TRANSIT PROPERTY	DFFS STATUS	SERVICE TYPE
Atlanta (MARTA)	In Use	HR
Baltimore (MTA)	Under Construction	HR
Boston (MBTA)	In Use	HR
New York (NYCTA)	In Use	HR
Buffalo (NFTA)	Under Procurement	LRRT
Camden (PATCO)	In Use	HR
Chicago (CTA)	In Use	HR
New York (LIRR)	In Use	HR, FRT
Miami Dade County (MDCTA)	Under Procurement	HR
New York/New Jersey (PATH)	In Use	HR
Oakland/San Francisco (BART)	In Use	HR
Philadelphia (SEPTA)	In Use	HR, LR
Pittsburgh (PAT)	Planned (Future)	LR
San Francisco (MUNI)	In Use	LR
Washington (WMATA)	In Use	HR
Calgary (Alberta, Canada)	In Use	LR
Edmonton (Alberta, Canada)	In Use	LRRT
Toronto (TTC) (Ontario, Canada)	In Use	HR

HR = Heavy Rail LRRT = Light Rail Rapid Transit

LR = Light Rail FRT = Freight Service

TABLE 3. DFFS IN NORTH AMERICAN SERVICE

TRANSIT PROPERTY	TYPES OF DFFS IN USE
Atlanta (MARTA)	Hixson H-10 plate
	AP Stedef ballastless track
Baltimore (MTA)	Hixson H-15A
	Hixson 009x-2 ballastless track
New York (NYCTA)	Landis-2000 plate
	Type VIII Track (including in-house designed D-L, B, D-J and D-B plates)
Camden (PATCO)	Type V & V-1 (Toronto types)
	Landis-Pandrol 5301
Chicago (CTA)	Railroad Rubber Products
	Landis 2000 plate
New York/New Jersey (PATH)	Toronto TTC Standard
	Landis 2000 plate
Oakland/San Francisco (BART)	Landis
Philadelphia (SEPTA)	Landis 2000 plate
	Landis 2010 plate
	Landis-Pandrol 5301
	Toronto TTC standard
	In-house design
San Francisco (MUNI)	Hixson
Washington (WMATA)	Landis 2000 plate
	Hixson H-12 plate
	Hixson H-17 plate
	Lord plate
Edmonton (Alberta, Canada)	Landis-Pandrol 5301
Toronto (TTC) (Ontario, Canada)	TTC-Standard

SITE VISIT DOCUMENTATION

Site visits were made to 12 transit authorities to gather information supplementing that reported in the letter survey and to obtain photographic documentation of the various DFFS installations. Observations centered on conditions of DFFS installation and maintenance as evidenced by the overall track condition. Particular attention was paid to failure details and the corrective actions taken. The effects of environmental factors, such as water in subway tunnels, were considered if they were believed contributory to fastener failure.

The following sections summarize observations made during site visits to the above-mentioned 12 transit properties. It has been attempted to report objectively the conditions as they were observed. Consideration of comparison between transit properties forms the basis for many of the findings discussed later.

Metropolitan Atlanta Rapid Transit Authority (MARTA)

MARTA employs two types of DFFS, the Hixson H-10 plate and the Stedef ballastless track with the AP Stedef rail fastening.

Track Structure

Hixson H-10

- Single-plate resilient base with screw-type, rigid toe clamp rail attachment
- Employed on tunnel and elevated deck slab
- Attached to slab by 7/8 inch carriage bolts inserted in formed steel plate with cast-in-place inserts
- Spacing: 30 inches
- Rail: 115 RE (CWR)
- Gauge: 56-1/2 inches

Stedef

- Two-block, rubber booted concrete crossties grouted in invert
- Bolted flat leaf spring rail attachment with separate elastomeric elements

Service Conditions

- Subway inverts dry and free of debris, grease, etc.
- Elevated slabs free of debris, grease, etc.
- Little evidence of corrosion

Problems and Remedies

1. Loosening of carriage anchor bolts; rounding of square shank beneath head and widening of insert keyslot preventing retightening, primarily in areas of rail corregation	Remove bolt and build up shank width with weld to prevent rotation; re-install and re-torque; schedule periodic grinding of rail corregations
2. Cracking of square washers that resist uplift loads	Replace fasteners affected; torque bolts to manufacturer's specifications
3. Distortion and rotation of square washers that react uplift loads (see Figures 1 and 2)	Leave fasteners in place; prevent washer contact with rail base by further bending adjacent corner as necessary

Mass Transit Adminstration (Baltimore)

All DFFS on the Baltimore system will employ a single configuration of the Hixson boltless flat leaf spring rail attachment. Fasteners utilized are the Hixson H-15A plate and the Stedef ballastless track with Hixson 009X-2 fasteners attached.

Track Structure

Hixson H-15A

- Single-plate resilient base with boltlesss flat leaf spring rail attachment (see Figure 3)
- Employed on tunnel and elevated deck slabs
- Attached to slab by 7/8-inch carriage bolts inserted in formed steel plate with cast-in-place inserts
- Spacing: 36 inches maximum
- Rail: 115 RE (CWR)
- Gauge: 56-1/4 inches, $\pm$ 1/8 inch on tangents

Stedef/Hixson 009X-2

- Two-block, rubber-booted concrete crosstie grouted in invert
- Boltless flat leaf spring rail attachment with separate elastomeric elements

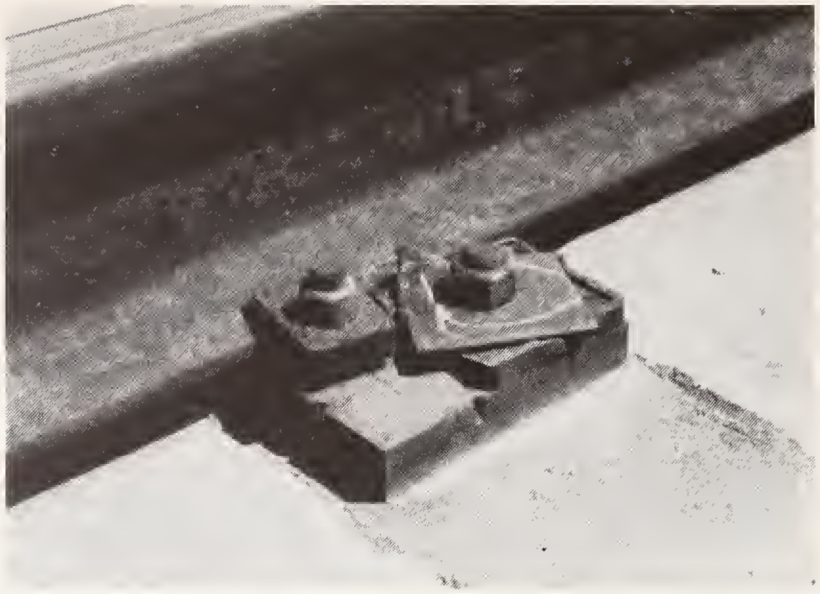

FIGURE 1. INSTALLATION OF HIXSON H-10 FASTENER SHOWING DEFORMATION AND ROTATION OF TOP WASHERS

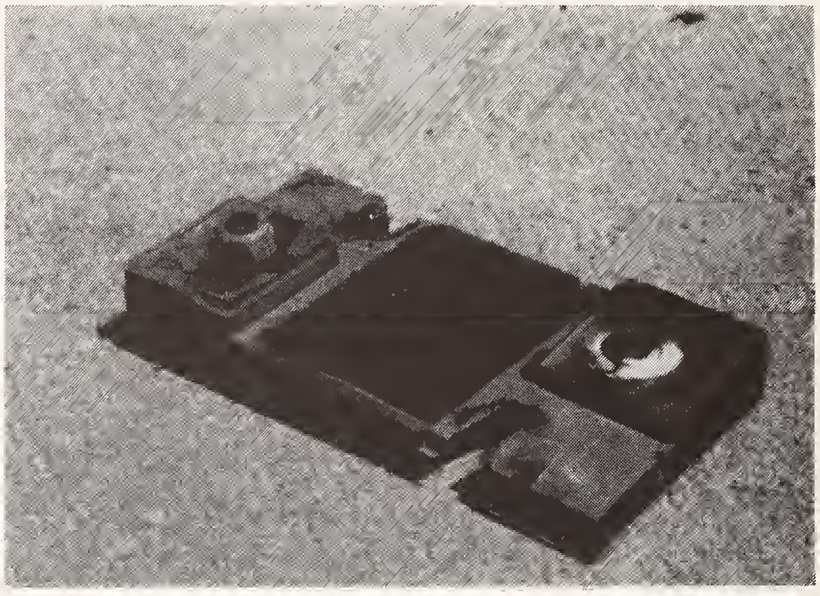

FIGURE 2. FAILED MARTA HIXSON H-10 FASTENER BASE WITH DEFORMATION AND MISSING TOP WASHERS

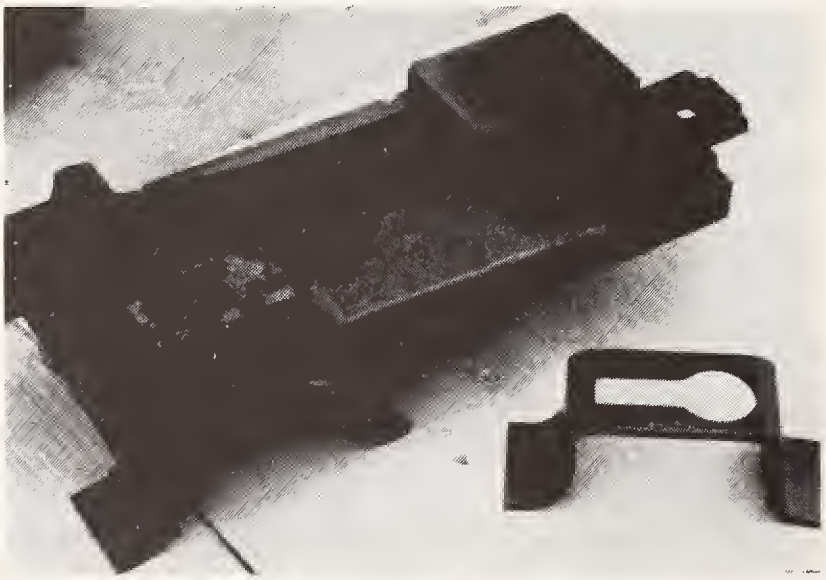

FIGURE 3. BALTIMORE HIXSON H-15A FASTENER AND FORMED STEEL PLATE BOLTS

- Employed in subway
- Spacing: 30 inches
- Rail: 115 RE (CWR)

Service Condition

- Not yet in service

Problems and Remedies

- None - system not yet operational

New York City Transit Authority (NYCTA)

Aside from a single installation of Landis plate fasteners, NYCTA employs in-house designs for direct fixation, which are utilized in short test sections throughout the system.

Track Structure

Landis 2000

- Double-plate resilient base with screw-type, rigid toe clamp rail attachment
- Attached to individual pads in tunnel invert using 7/8-inch bolts and cast-in-place threaded inserts
- Spacing: 22 inches
- Rail: 100 RE
- Gauge: 56-1/2 inches

Type VII and Modified Type VIII Track (in-house designs)

- Based on standard tie plates or encapsulation of rail base by preformed rubber supported in rigid base container
- Bracing against railhead for radius less then 1500-feet
- Used on tunnel slab
- Attached to slab by concrete "U" bolts or anchor bolts threaded into epoxied studs with sleeve nuts
- Spacing: 18-19 inches at joints; 24-29-1/2 inches otherwise
- Rail: 100 RE (jointed)
- Gauge: 56-1/2 and 56-3/4 inches

Service Conditions

o Subway invert subject to water, grease, debris and other contaminants

o Evidence of corrosion or failures in rails, fasteners and anchors exposed to contaminants

Problems and Remedies

1.	Anchor bolts break or loosen in concrete	Tighten/replace anchor bolts as required
2.	Concrete failure due to water condition in invert	Monthly gang maintenance
3.	Rail base corrosion, concrete failure of Type VIII track in water susceptible area	Replace rails every 3 years and fasteners every 10 years as required

Port Authority Transit Corporation (PATCO)

PATCO employs DFFS only on three slab-decked viaducts. The primary fastener is based on the Toronto TTC standard design and referrred to as Type "V" (132 RE rail) and Type "V-1" (100 AS rail). Intermediate Landis-Pandrol fasteners are installed on one viaduct.

Track Structure

Type "V" and "V-1"

o Modified AREA tie plate supported on separate resilient pad

o Bolted formed spring clip rail attachment

o Attached to slab by 7/8-inch bolts and lead cinch anchors with spring washer under nut

o Spacing: 24 to 30 inches

o Rail: 132 RE and 100 AS (CWR)

o Gauge: 56-1/4 and 57 inches

Landis-Pandrol

o Formed flat plate supported on separate resilient pad

o Boltless formed bending-torsion spring clip rail attachment

o Attached to slab (6" thick) by 3/4-inch thru-bolts and nuts between existing Type "V-1" fasteners

o Spacing: 24 inches

- Rail: 100 AS (CWR)
- Gauge: 57 inches

Service Conditions

- Viaduct slabs free of debris, grease, etc.
- Evidence of weather-related deterioration of exposed grout surfaces
- No evidence of excessive corrosion of exposed fastener elements

Problems and Remedies

1.	Delamination of paper phenolic insulation sleeve around Type "V" and "V-1" fastener anchor bolts degrading insulating properties	Replace with canvas phenolic insulating sleeve
2.	Disintegration of grout pads, loose anchor bolts on Type "V" and "V-1" fasteners (see Figure 4)	Tighten or re-install anchor bolts as required
3.	Failure of anchor bolts on Type "V-1" fasteners	Install Landis-Pandrol fasteners between Type "V-1" fasteners (see Figure 5)

Chicago Transit Authority (CTA)

The CTA use of DFFS is limited to elevated structures and truss bridge decks where timber ties cannot be used for electrical isolation of the running rails. The two types of DFFS used are the Landis plate and the Railroad Rubber Products wrap-around tie plates.

Track Structure

Landis 2000

- Double plate resilient base with screw-type, rigid toe clamp rail attachment
- Attached to steel deck beams with 7/8-inch bolts (see Figure 6)
- Spacing: 24 inches
- Rail: 90 AS (jointed) and 100 RA (jointed)
- Gauge: 56-1/2 inches

FIGURE 4. PATCO TYPE V FASTENER SHOWING EVIDENCE OF LOOSE ANCHOR BOLTS

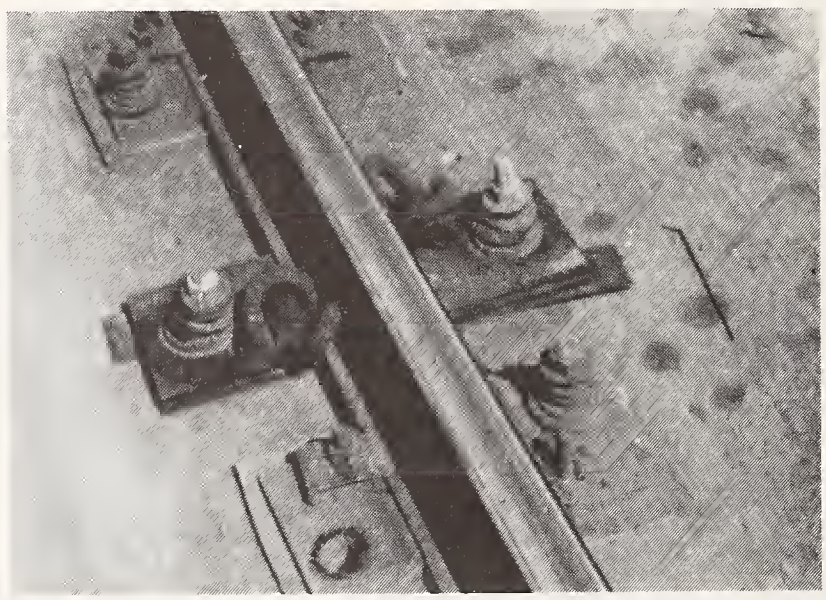

FIGURE 5. FAILED PATCO TYPE V-1 FASTENER WITH INTERMEDIATE LANDIS-PANDROL FASTENER INSTALLED

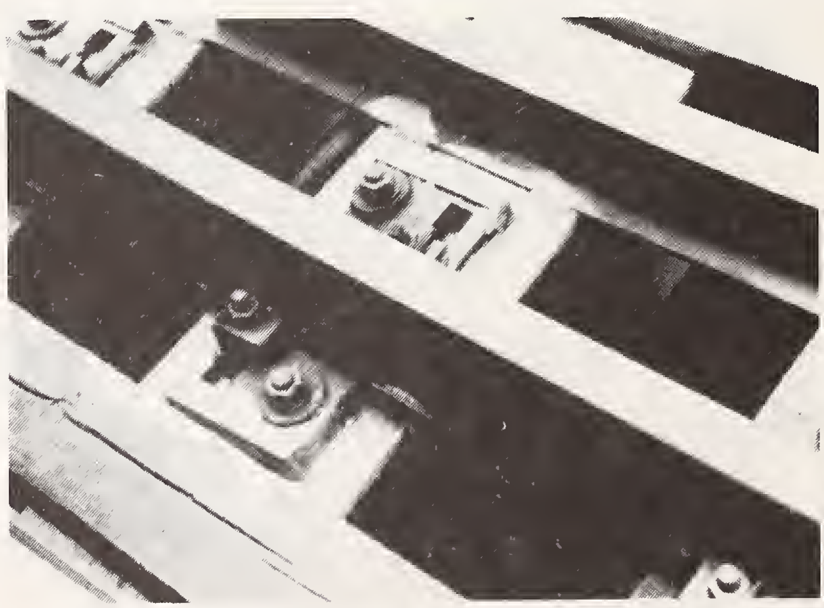

FIGURE 6. CTA INSTALLATION OF LANDIS FASTENER BOLTED TO TRANSVERSE DECK MEMBER

Railroad Rubber Products

- o Encapsulation of rail base by pre-formed rubber supported laterally by bolted formed washer plates
- o Attached with four 3/4-inch bolts to transverse deck beams or to plates welded to deck beams or spanning adjacent beams (see Figure 7)
- o Spacing: 24, 30 and 36 inches
- o Rail: 90 AS (jointed)
- o Gauge: 56-1/2 inches

Service Conditions

- o Elevated and truss bridge structures subject to water and air-borne contaminants
- o Presence of grease and debris noted
- o No evidence of excessive corrosion of exposed fastener elements

Problems and Remedies

1. Bulging of washer plates on Railroad Rubber Products fastener	No action taken; does not affect function of fastener

Metropolitan Dade County Transportation Administration (Miami)

Miami is in the process of DFFS and direct fixation track construction procurements. Comments below are from field observations and procurement specifications.

Track Structure

- o Single plate resilient base with boltless spring clip rail attachment
- o Employed on elevated slab, approach slab and in maintenance buildings
- o Attached to reinforced concrete plinth pad by 7/8-inch bolts and cast-in-place or grouted threaded inserts
- o Spacing: 30 inches
- o Rail: 15 RE (CWR and jointed)
- o Gauge: 56-1/4 to 56-1/2 inches

Service Conditions

- o Subject to salt environment

Problems and Remedies

- Not applicable

Port Authority Trans-Hudson Corporation (PATH)

PATH employes two types of DFFS, the Toronto TTC standard design on station platform slabs and the Landis 2000 plate on station platform and tunnel invert slabs.

Track Structure

TTC Standard

- Modified AREA tie plate supported on separate resilient pad
- Bolted formed spring clip rail attachment
- Attached to slab by 7/8-inch bolts and lead cinch anchors with spring washer under nut
- Mounted on individual grout pads
- Spacing: 19-3/4 inches
- Rail: 100 RB (CWR)
- Gauge: 56-1/2 inches

Landis 2000

- Double plate resilient base with screw-type, rigid toe clamp rail attachment
- Attached to precast concrete blocks by 7/8-inch bolts
- Blocks concreted in slab
- Spacing: 24 inches
- Rail: 100 RB (CWR)

Service Conditions

- Tunnel invert has water condition
- Evidence of corrosion on exposed fastener elements

Problems and Remedies

1. Corrosion of threaded and spring fastener elements	Maintain cleanliness; apply anti-corrosion compound

2. Loosening of Landis clip bolts; rotation of clip damaging serrations	Re-tighten clip bolts every 2-4 weeks; replace clip, bolts and nuts as required; restore serrations if possible

Bay Area Rapid Transit District (BART)

BART employs the Landis plate DFFS on 44.2 miles of elevated subway and tunnel slab. Although not so identified, this fastener appears identical to the current Landis 2000 plate.

Track Structure

- o Double-plate resilient base with screw-type, rigid toe clamp rail attachment
- o Attached to discontinuous reinforced concrete slab by 7/8-inch bolts and cast-in-place threaded inserts (see Figure 8)
- o Polyethylene pad between fastener and slab for height adjustment
- o Spacing: 36 inches on tangents; 30 inches on curves
- o Rail: 119 RE (CWR)
- o Gauge: 66 inches

Service Conditions

- o Subway and tunnel inverts and aerial slabs dry and free of debris, grease, etc.
- o Elevated slabs subject to salt environment
- o Some evidence of corrosion of fastener elements (see Figure 9)

Problems and Remedies

1. Failure of clip bolts shortly after start of revenue service	Shim each Landis pad to correct height

Southeastern Pennsylvania Transit Authority (SEPTA)

SEPTA employs four types of DFFS in rapid transit applications and a single, in-house design for streetcar subway use. On rapid transit elevated structures, the Landis-Pandrol and Landis 2000 are used, with the Landis 2000 being converted to the Landis 2010 configuration by installation of adaptors for the Pandrol clip. The Toronto type fastener is employed in a rapid transit subway installation.

FIGURE 7. CTA INSTALLATION OF RAILROAD RUBBER PRODUCTS WRAP-AROUND TIE PLATE

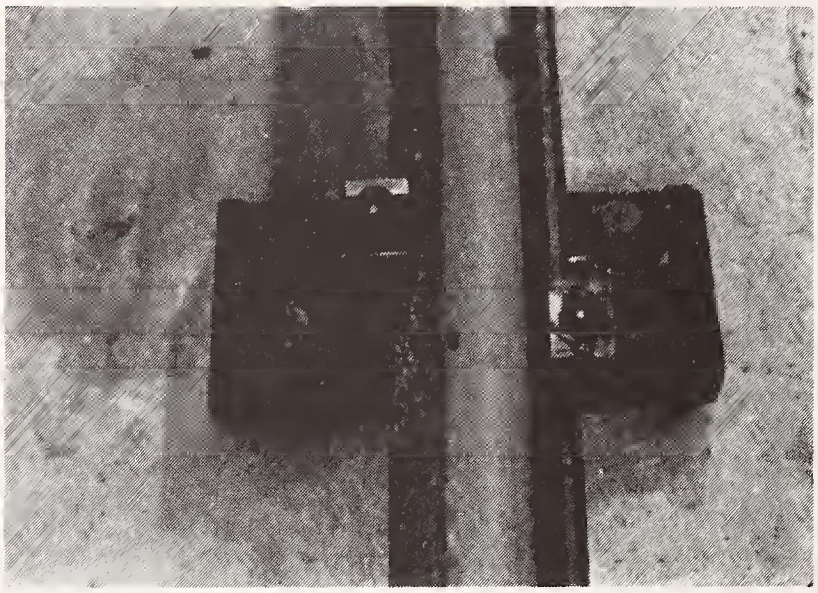

FIGURE 8. BART SUBWAY INSTALLATION OF LANDIS FASTENER

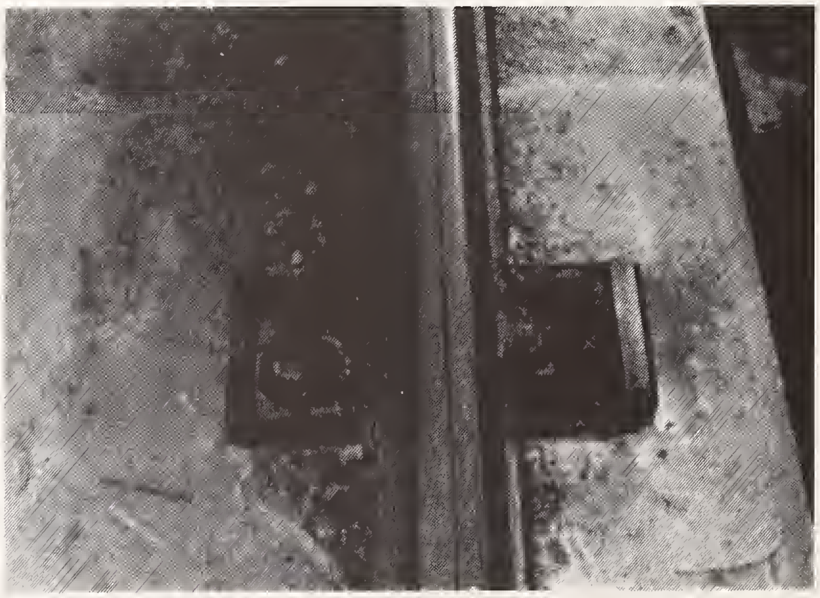

FIGURE 9. LANDIS FASTENER IN BART SUBWAY SHOWING RESULTS OF CORROSION

Track Structure

Landis-Pandrol

- Formed flat plate supported on separate resilient pad
- Boltless formed bending-torsion spring clip rail attachment
- Attached to elevated slab by anchor bolts grouted in concrete (see Figure 10)
- Spacing: 24 inches
- Rail 115 RE (CWR)
- Gauge: 62-1/2 inches

Landis 2000

- Double plate resilient base with screw-type, rigid toe clamp rail attachment
- Attached to elevated slab with 7/8-inch anchor bolts and cast-in-place inserts in pads beneath each fastener
- Spacing: 24 inches
- Rail: 115 RE (CWR)
- Gauge: 62-1/4 inches

Landis 2010

- Double plate resilient base with special adaptor for boltless formed bending-torsion spring clip rail attachment
- Attached to elevated slab with 7/8-inch anchor bolts and cast-in-place inserts in pads beneath each fastener (see Figure 11)
- Spacing: 24 inches
- Rail: 115 RE (CWR)
- Gauge: 62-1/4 inches

Toronto

- Modified AREA tie plate supported on separate resilient pad
- Bolted formed spring clip rail attachment
- Attached to continuous, reinforced concrete slab by anchor bolts and cast-in-place inserts

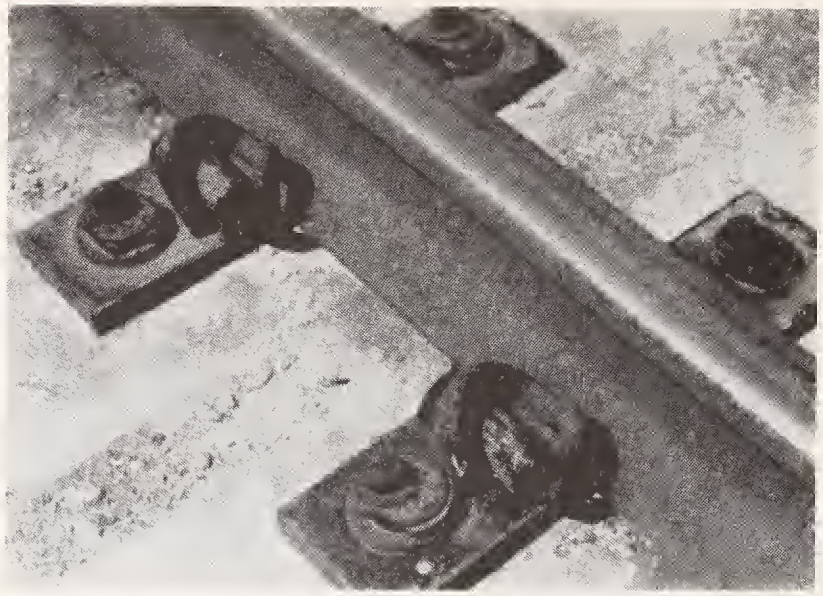

FIGURE 10. SEPTA INSTALLATION OF LANDIS-PANDROL ON ELEVATED DECK

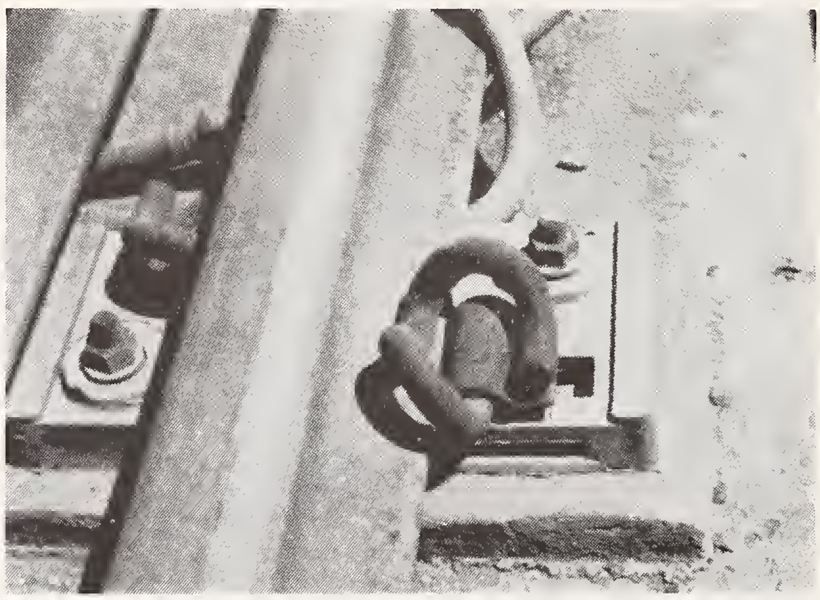

FIGURE 11. SEPTA INSTALLATION OF LANDIS FASTENER WITH RETROFIT PANDROL ADAPTOR

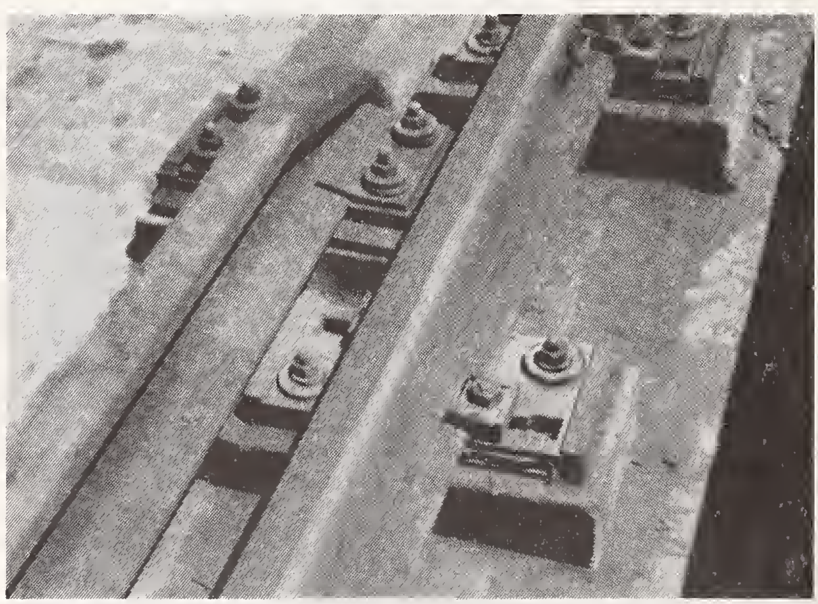

FIGURE 12. LANDIS FASTENERS ON SEPTA VIADUCT SHOWING RAIL CLAMP ROTATION

In-House Design

- o Rail supported on plate and separate resilient pad
- o Bolted formed spring clip rail attachment bolted to slab by anchor bolts and cast-in-place inserts
- o Spacing: 24 inches
- o Rail: 100 AS (CWR)
- o Gauge: 62-1/4 inches

Service Conditions

- o Elevated structures relatively free of debris, grease, etc.
- o No evidence of excessive corrosion of exposed fasteners elements on elevated structure installations
- o Subway installation subject to water seepage

Problems and Remedies

1. Loosening of Landis clip bolts; rotation of clip (see Figure 12)	Re-tighten as required; replace bolted clip with adaptor for Pandrol clip
2. Loosening of Landis-Pandrol anchor bolts in elevated slab due to grout failures (see Figure 13)	Re-install anchor bolts and ensure proper mixing of two-part epoxy
3. Electrical breakdown of Toronto fasteners in subway due to water seepage and contamination	Steam clean as required

Washington Metropolitan Area Transit Authority (WMATA)

WMATA has employed DFFS in four phases of track construction on elevated and tunnel slab. The Landis 2000 plate fasteners were installed in Phase I. Phase II, III and IV installations employed the Hixson H-12 plates. The current Phases V (A,C) and VI employ the Lord plate. Phase V (L) will install Hixson H-17 plate and Lord plate fasteners in 1983.

Track Structure

- o Double plate resilient base with the screw type, rigid toe clamp rail attachment
- o Employed on tunnel slab and elevated slab
- o Attached to slab by 7/8-inch anchor studs epoxied in drilled holes

FIGURE 13. SEPTA LANDIS-PANDROL INSTALLATION SHOWING ANCHOR BOLT FAILURES

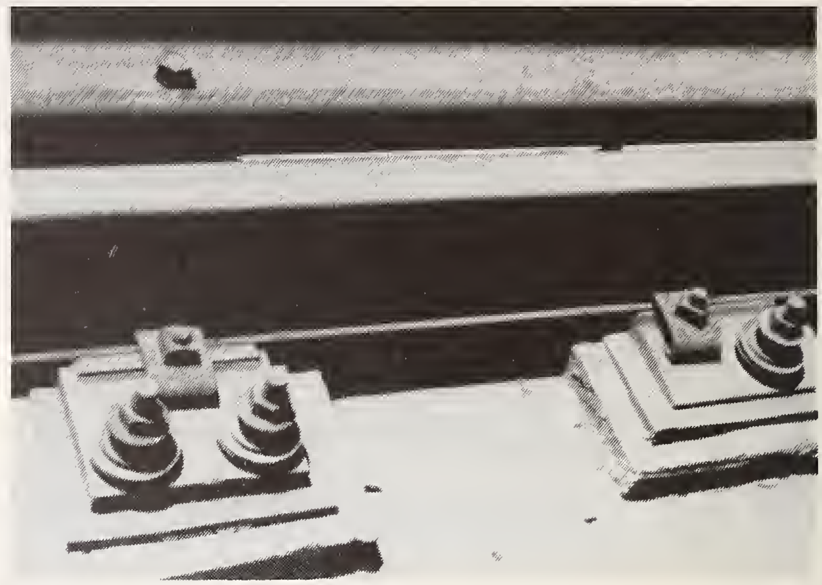

FIGURE 14. STANDARD AND RESTRAINING RAIL SUPPORT TORONTO FASTENERS AT TTC

FIGURE 15. SPECIAL TRACK AND SCISSORS EXPANSION JOINT ON TTC ELEVATED STRUCTURE

- Spacing: 30 inches
- Rail: 115 RE (CWR)
- Gauge: 56-1/4 inches

Service Conditions

- Subway inverts subject to water, grease, and other contaminants
- Evidence of corrosion on fasteners and anchors exposed to water conditions

Problems and Remedies

1. Failure of Hixson H-12 Plate connection stud at weld in lower plate causing fastener to separate	Install wood braces in track as required for safety; replace fasteners with Lord fasteners
2. Loosening of fastener anchor studs	Apply lock washer and re-torque
3. Failure of anchor studs in epoxy	Re-install using improved installation procedures

Edmonton Transit System

The Edmonton Transit System employs the Landis-Pandrol fastener for direct fixation applications in tunnels and under bridges.

Track Structure

- Formed flat plate supported on separate resilient pad
- Boltless formed bending-torsion spring clip
- Attached to slab by epoxied studs
- Spacing: 24 inches
- Rail: 100 RA
- Gauge: 56-1/2 inches

Service Conditions

- Tunnels clean except for some water intrusion

Problems and Remedies

1. Failure of fastener base plates near bend for Pandrol clip	Add shims and install new fasteners at proper elevation

Toronto Transit Commission (TTC)

TTC employs the Toronto TTC standard fastener in all tunnel and underground structures and on 75 percent of elevated structures. Variations are required for support of restraining rail.

Track Structures

- Modified AISC tie plate supported on separate resilient pad
- Bolted formed spring clip rail attachment
- Attached to slab by 7/8-inch bolts, epoxied or by use of cinch anchors (see Figure 14)
- Spacing: 23 to 25 inches
- Rail: 100 RA and 115 RE
- Gauge: 58-7/8 inches
- Modified form-bolt fasteners used for special trackwork (see Figure 15)

Service Conditions

- Aerial structures clean, free of debris
- No evidence of excessive corrosion of exposed fastener elements
- Wet areas exist in tunnels
- Fiber insulation components subject to environmental degradation

Problems and Remedies

1.	Degradation of fiber insulation components in wet areas	Install new insulating materials to prevent failures

SUMMARY AND CONCLUSIONS

Experience to date shows that problems exist to varying degrees with the early applications of DFFS on North American transit properties. Problems such as loosening of anchorage systems, electrical leakage, and inadequate performance of DFFS components have occurred with only partial conclusions on the reasons for them. What was expected of DFFS regarding their track performance has not yet been fully realized by any North American transit authority.

The amount of information reported by the individual transit properties varied during the data collection program, as was expected, since the experience of each property was unique to its own conditions in terms of length of service, operating environment, and maintenance practices. Therefore, engineering judgement has to be exercised in evaluating the reported information so as to arrive at generalized statements of problems being experienced with DFFS.

The problems common to most transit properties are failures of anchorage systems, most likely due to poor construction practices and lack of quality control during installation of anchor bolts; and the rapid corrosion of DFFS components due to wet conditions and/or lack of corrosion protection. Transit systems using screw-type DFFS have been experiencing problems with loose hold-down clips which have resulted in damaged serrations used for adjusting track gauge. Also, damaged serrations, resulting from either loose hold-down clips or corrosion, make it practically impossible to re-tighten and seat the hold-down clips properly and have resulted in their replacement with a new DFFS of the same type. In some cases, the screw-type DFFS have been replaced with the spring clip-type utilizing eccentric bushings for lateral track adjustment.

On the basis of facts presented in this paper, the following general conclusions are made:

1. Minimizing the number of fastener components is desirable for ease of installation and maintenance, and improved performance reliability.

2. DFFS must be protected from contamination and exposure to water in subway environments. Subway inverts must be designed with this in mind.

3. Precision mounting surfaces and proper alignment betweeen adjacent mounting surfaces are design prerequisites for track structure life. It is extremely difficult to perform good in-service installation of DFFS.

4. Extensive cleaning and preventive maintenance practices are essential to DFFS life.

5. DFFS must be designed and tested to loads consistent with service applications.

6. Extreme care must be taken in the installation of anchor bolts to achieve consistent and specified results.

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[2] RamaChandran, P. V., and Gadden, E. C., "Direct Fixation Fastening Systems-Deployment and Experience on American Transit Systems," WYLE Laboratories Report for Transportation Systems Center, Contract Number DTRS57-80-C-00174, July 1981.

Evaluation of Direct Fixation Fasteners By Laboratory Tests

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INTRODUCTION

Direct fixation fasteners are used by U.S. transit systems to secure rails to concrete in tunnels and on elevated structures. These fasteners utilize elastomeric pads, steel plates, insulating components, and anchoring devices.

Direct fixation fasteners fulfill five primary functions. They maintain gage, maintain alignment, control longitudinal rail movements, provide resilience, and assure electrical insulation. To maintain these functions during their service life, direct fixation fasteners should be capable of withstanding repeated traffic loads and environmental effects with a minimum of deterioration or damage. Therefore, engineering specifications set forth minimum performance requirements as a guide for the design and manufacture of fasteners. Compliance with these specifications is evaluated by laboratory tests.

WHY LABORATORY TESTS?

The ability of direct fixation rail fasteners to fulfill their intended functions may be evaluated by mathematical analysis, laboratory tests, or field measurements. An accurate analysis of rail fasteners cannot be performed easily. Field testing under normal operating conditions requires a long time, often years, and a large investment. However laboratory tests provide information on fastener performance in a relatively short time period at low cost. In addition, laboratory tests serve the following purposes:

1. Identify and reject inappropriate materials and products without conducting expensive and time-consuming track tests
2. Compare properties of alternative materials and components
3. Evaluate properties for quality control during production
4. Help in development of products for a specific use
5. Evaluate product compliance with specification requirements

LABORATORY TESTS

To assure the ability of direct fixation rail fasteners to provide their intended functions, specifications give minimum performance requirements. These requirements are utilized as a guide for the design and manufacture of rail fasteners. Compliance with specification requirements is evaluated by laboratory tests. In these tests, fastener performance is evaluated under specified loads or in a specified environment. This is accomplished by comparing fastener response to acceptance criteria set forth in specifications.

No nationally acceptable standard or recommended practice has yet been developed for fastener evaluation. Therefore, specifications have been developed for individual projects in the United States and Canada. Although test procedures and acceptance criteria vary, specifications generally include tests on complete fastening assemblies to evaluate the fastener's ability to perform the following functions:

1. Resist uplift forces without damage to fastening components
2. Control longitudinal rail movements
3. Restrain lateral rail movement and hold proper gage
4. Resist repeated vertical and lateral loads without damage to fastening components
5. Provide adequate electrical insulation

Direct fixation fastener tests include static, dynamic, and repeated load tests. Static tests evaluate fastener response to statically applied loads. Dynamic tests evaluate fastener response to dynamically applied or short-term cyclic loads. Repeated load tests evaluate the durability of fastener components. Examples of static tests include vertical load, lateral load, lateral restraint, and longitudinal restraint tests. Dynamic tests include vertical uplift and dynamic to static stiffness ratio tests. Vertical and repeated load, uplift repeated load, and push-pull tests are examples of repeated load tests.

Procedures and acceptance criteria for tests have been specified in recent procurements, including those for the following projects:

1. Trackwork-8 on Washington Metropolitan Area Transit Authority [1]
2. Mass Transit Administration's Baltimore Region Rapid Transit System [2]
3. Metropolitan Dade County Stage I Rapid Transit System [3]
4. O'Hare Extension on Chicago Transit Authority [4]
5. Niagara Frontier Transportation Authority's Buffalo Light Rail Transit Project [5]
6. Advanced Light Rail Rapid Transit System for Vancouver, British Columbia [6]

Vertical Load Test

A vertical load test evaluates the effect of vertical loads on rail vertical deflection. In this test, shown in Fig. 1, a downward vertical load is applied to the head of a rail secured to a concrete block using a complete fastening assembly. Rail vertical deflection is measured at increments of load. A maximum vertical load ranging from 15,000 lb [1,5,6] to 18,000 lb [2,4] has been specified for this test.

To pass the vertical load test, specifications stipulate five requirements:

1. Load versus deflection data should lie within a specified envelope
2. Fastener spring rate calculated from load and deflection data should be within a certain range. The acceptable spring rate varies from a minimum of 80,000 to 120,000 lb/in. [3] to a high of 140,000 to 300,000 lb/in. [6]
3. The maximum deflection should not exceed a certain value, generally expressed as a percentage of the elastomer thickness.

The acceptable value ranges from 20% [2,4] to 25%.[3,5,6]

4. Fastener should return to within 0.005 in. of its initial position within one minute after load removal.
5. None of the faster components should exhibit signs of failure during the test.

Lateral Load Test

A lateral load test evaluates the effect of lateral load on rail head lateral deflection when a vertical load is applied. In this test, shown in Fig. 2, a downward vertical load is applied to the head of a rail secured to a concrete block. A complete fastening assembly is used. In addition, a lateral load is applied to the rail head at the gage point. Rail head lateral deflection is measured at increments of the lateral load. Combinations of lateral and vertical loads specified for this test have included 10,000 and 13,500 lb. [1,5,6] 9,000 and 16,200 lb [2], and 12,000 and 16,200 lb. [3,4]

To pass the lateral load test, specifications stipulate three requirements:

1. Maximum rail head lateral deflection should not exceed 0.30 in.
2. Rail head lateral deflection after load removal should not exceed 0.062 in.
3. None of the fastener components should exhibit signs of failure during the test.

Lateral Restraint Test

A lateral restraint test evaluates the effect of lateral shear applied to the rail base on rail lateral displacement. In this test, shown in Fig. 3, the lateral loads are applied simultaneously to the base of a rail secured to a concrete block using a complete fastening assembly. Rail lateral deflection is measured at increments of lateral load. A maximum lateral shear of 5,000 lb [1,5,6] or 6,000 lb [2,3,4] has been specified for this test.

To pass the lateral restraint test, specifications stipulate three requirements:

1. Maximum rail lateral deflection should not exceed 0.125 in.
2. Rail lateral deflection after load removal should not exceed 0.062 in.
3. None of the fastener components should exhibit signs of failure during the test.

Longitudinal Restraint Test

A fastening longitudinal restraint test evaluates the effect of longitudinal forces on rail longitudinal movement. In this test, shown in Fig. 4, longitudinal force is applied to the centroid of a short piece of rail. The rail is secured to a concrete block using a complete fastening assembly. Longitudinal rail displacement is measured at increments of load. A maximum longitudinal force to produce 0.6 in. rail movement, but not to exceed 10,000 lb, has been

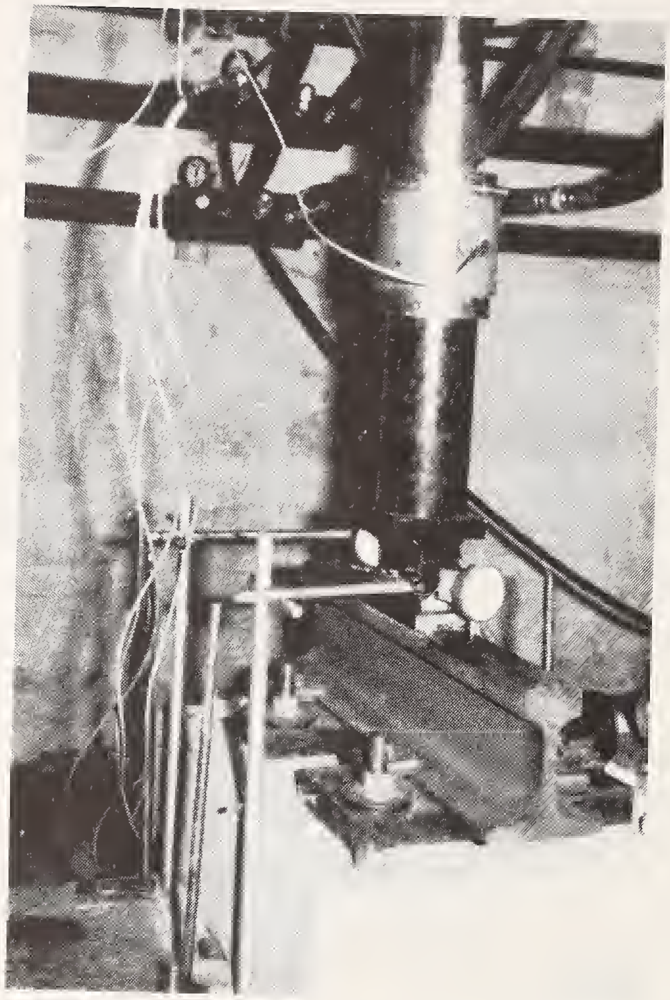

FIGURE 1. VERTICAL LOAD TEST

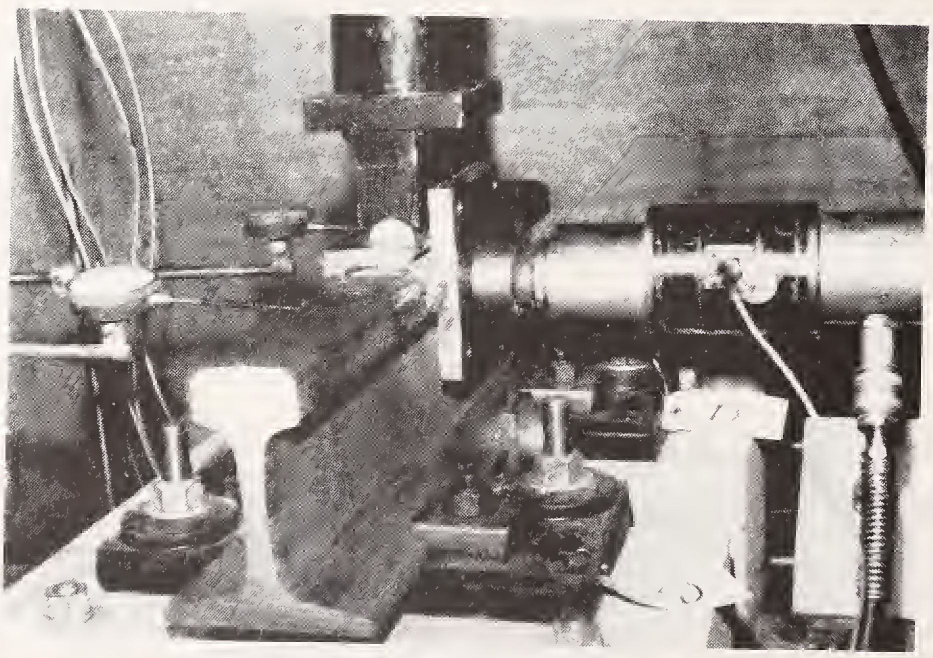

FIGURE 2. LATERAL LOAD TEST

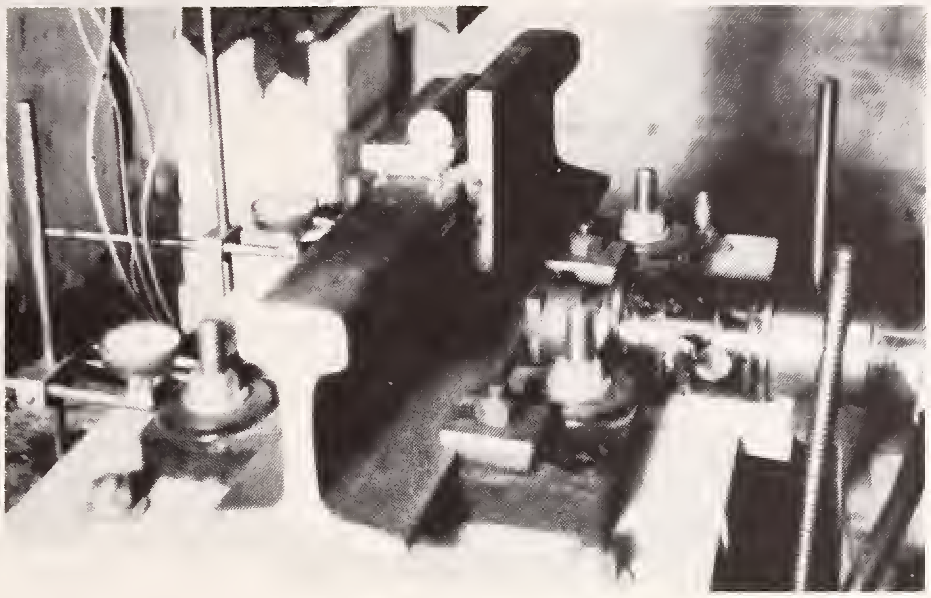

FIGURE 3. LATERAL RESTRAINT TEST

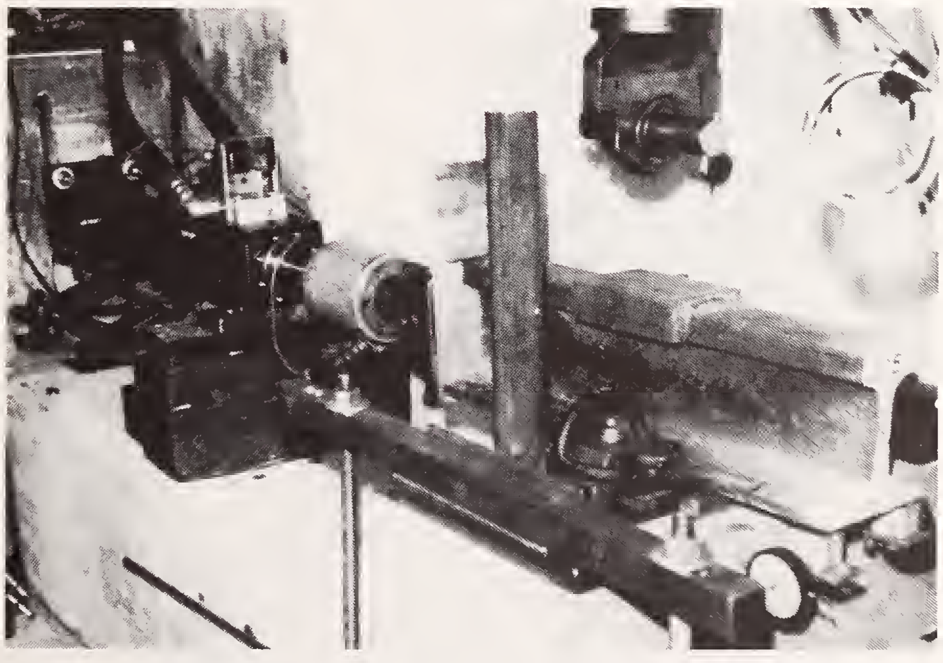

FIGURE 4. LONGITUDINAL RESTRAINT TEST

specified in one project for subway fasteners. [5] For aerial structures, the maximum load was specified as that required to produce 0.6 in. rail movement [3,6], but not to exceed 4,000 lb. [6]

To pass the longitudinal restraint test, specifications stipulate three requirements:

1. Load versus deflection data should lie within a specified envelope.
2. Rail movement after load removal should not exceed rail slippage by more than 0.125 in.
3. None of the fastener components should exhibit signs of failure during the test.

Vertical Uplift Test

A vertical uplift test evaluates the effect of alternating downward-upward vertical loads on rail vertical deflection. In this test, shown in Fig. 5, downward-upward cyclic vertical load is applied to the head of a rail secured to a concrete block using a complete fastening assembly. The load versus rail vertical deflection is continuously recorded during the test. Alternating loads ranging from + 2,000 lb [1,3] to + 3,600 lb [5,6] have been specified for this test.

To pass the vertical uplift test, specifications stipulate four requirements:

1. The upward to downward deflection ratio should be within a certain range. The acceptable range varies from a minimum of 0.8 to 1.5 [1,3] to a high of 1.05 to 2.05. [5,6] In some cases, no acceptable range is specified. [2,4]
2. Load versus deflection data should indicate that neither backlash nor freeplay exists when deflection changes direction.
3. Fasteners should return to within 0.005 in. of its initial position after load removal.
4. None of the fastener components should exhibit signs of failure during the test.

Dynamic to Static Stiffness Ratio Test

The purpose of a dynamic to static stiffness ratio test, specified for more recent projects [5,6], is to compare the fastener's dynamic and static stiffness values. This is accomplished by the application of static and dynamic vertical loads to the head of a rail secured to a concrete block using a complete fastening assembly.

In this test, shown in Fig. 6, static and dynamic loads are applied to deflect the fastener over a certain range. The ratio of dynamic to static stiffness is calculated from applied loads and deflections. Specifications require that loads be applied to deflect the fastener from 0.05 to 0.10 in. [5,6] Dynamic loads are applied at a frequency of 10 to 20 cycles per second.

To pass the dynamic to static stiffness ratio test, specifications require that the dynamic to static stiffness ratio does not exceed a specified value, generally 1.5. [5,6]

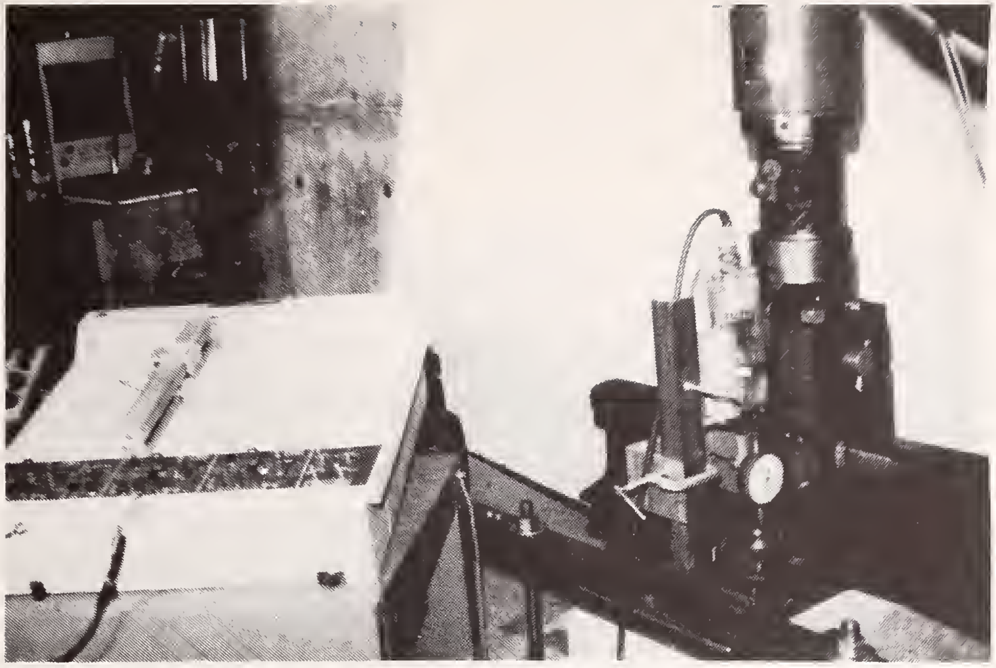

FIGURE 5. VERTICAL UPLIFT TEST

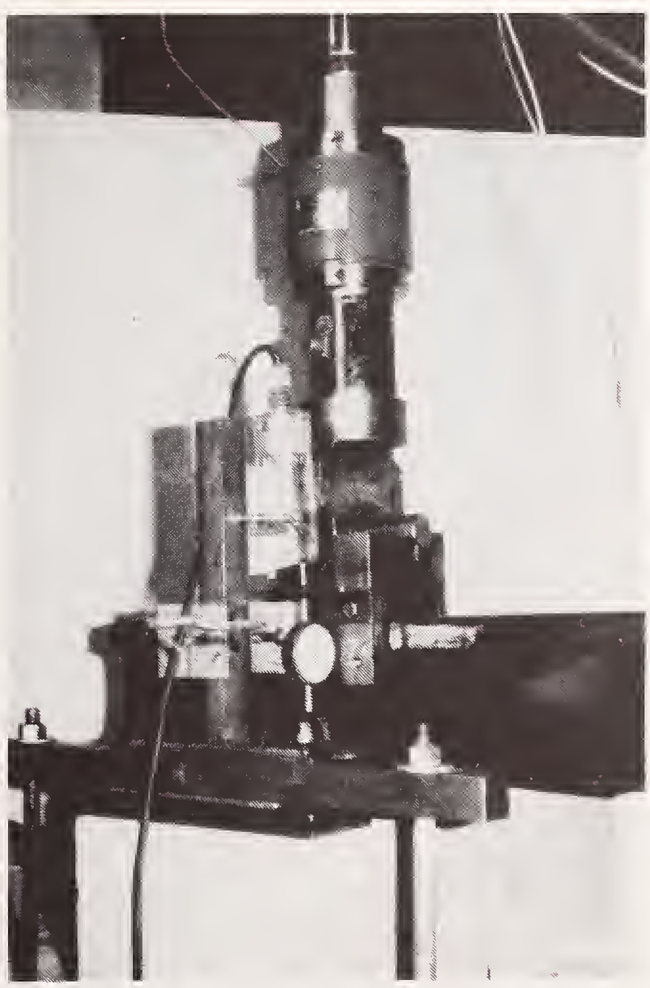

FIGURE 6. DYNAMIC TO STATIC STIFFNESS RATIO TEST

Vertical and Lateral Repeated Load Test

The purpose of a vertical and a lateral repeated load test is to evaluate the effects of repeated loads on fastening components. This is accomplished by application of repeated vertical and lateral loads to the head of a rail secured to a concrete block using a complete fastening assembly.

During the repeated load test, shown in Fig. 7, vertical and lateral forces are applied simultaneously to the rail. Generally, only downward vertical loads are applied for this test. The lateral load, however, varies from a push to a pull force. The application of these lateral forces are alternated such that a vertical load is combined with each application of a push or pull lateral load. Load combinations specified for this test include a 13,500-lb vertical load combined with a 3,900-lb lateral push or a 2,700-lb lateral pull load, [1,5,6] and a 16,200-lb vertical load combined with a 4,700-lb lateral push or a 3,200-lb lateral pull load. [2,3,4] Test loads are applied for three million cycles.

To pass the vertical and lateral repeated load test, specifications require that fastener components survive the test without signs of failure.

Upon completion of the vertical and lateral repeated load test, specifications require continuation of the test, with gage side anchoring device removed, for an additional 15,000 load cycles. For acceptance, fastener components should withstand this test without signs of failure.

Uplift Repeated Test

The purpose of an uplift repeated load test is to evaluate the effect of repeated uplift forces on fastening components. This is accomplished by the application of repeated vertical loads to the head of a rail secured to a concrete block. A complete fastening assembly is used.

During the uplift repeated load test, shown in Fig. 8, a cyclic vertical force is applied to the rail head. The force changes from a large downward load to a small upward load. Vertical loads varying from 12,000 lb downward to 2,000 lb upward [1,5,6] and from 14,400 lb downward to 2,400 lb upward [2,3,4] have been specified for this test. Test loads are applied for 1.5 million cycles. In addition, most specifications [2,3,4,5,6] require that during a portion of the last 500,000 load cycles, a 600-lb longitudinal load is recorded at increments of the longitudinal load.

To pass the uplift repeated load test, specifications stipulate the following requirements:

1. None of the fastener components should exhibit signs of failure during the test.
2. No rail slippage should occur during the test.

Push-Pull Test

The purpose of a push-pull test is to calculate the effect of cyclic push-pull longitudinal loads or displacements on fastener components. This is accomplished by the application of cyclic push-pull longitudinal loads to the

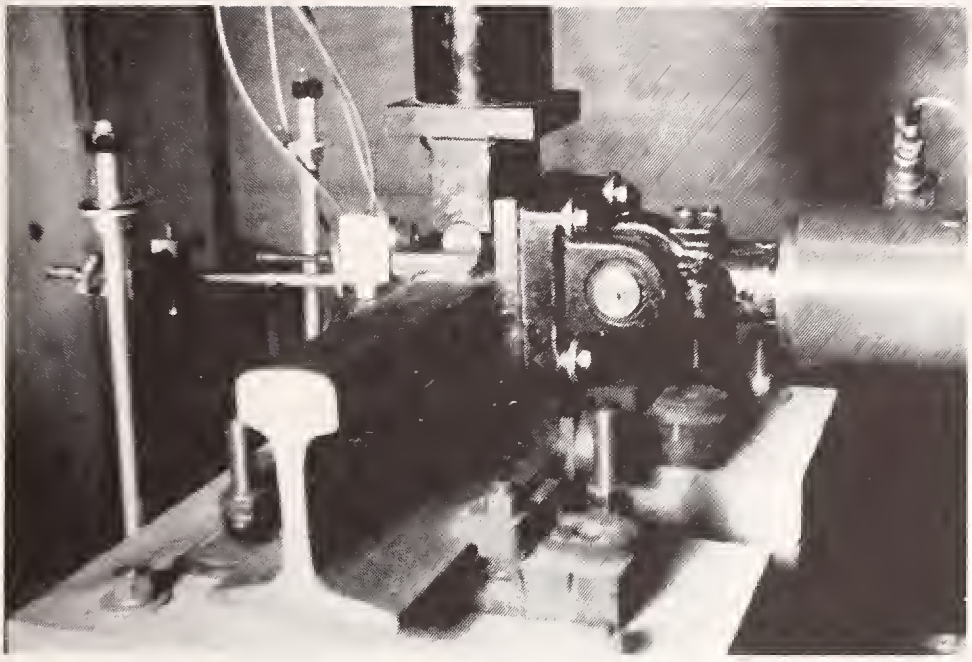

FIGURE 7. VERTICAL AND LATERAL REPEATED LOAD TEST

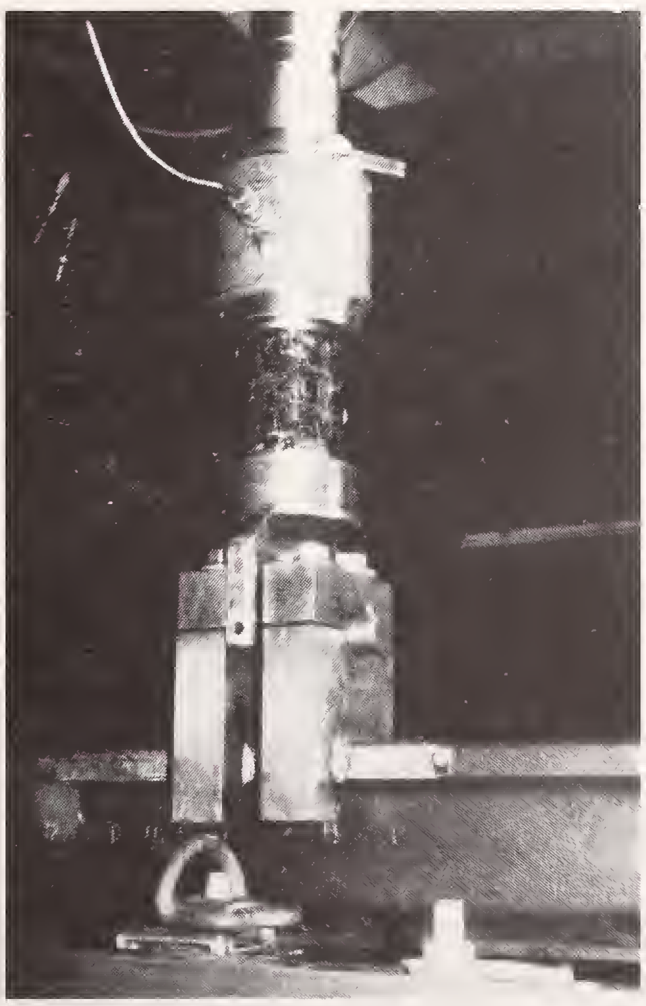

FIGURE 8. UPLIFT REPEATED LOAD TEST

centroid of a rail secured to a concrete block. A complete fastening assembly is used.

For this test, specifications generally require that applied loads be controlled to produce a specified equal longitudinal rail movement in both directions. This movement varies from + 1/8 in. [1,3] to + 1/2 in. [2,4,6] Also, a constant cyclic load of + 4,000 lb has been specified. [5] Test duration varies from 25,000 cycles [2,4,6] to one million cycles. [3]

To pass the push-pull test, specifications require that fastener components survive the test without sign of failure and that the test rail should exhibit no evidence of wear or grooving that would contribute to its failure.

CONCLUDING REMARKS

Laboratory tests are used to evaluate fastener performance. These tests when combined with proper evaluation criteria can be used to evaluate the ability of a fastening system to withstand loading and environmental conditions during its intended service life. Evaluation criteria as well as test methods and conditions are set forth in specifications.

It should be pointed out that in many cases specifications do not utilize test loads and conditions that closely simulate track environment. Therefore, data obtained can be used to compare characteristics of different fastenings but not to predict fastening performance in track. To develop more meaningful specifications, the following items should be considered:

1. Selection of representative load magnitudes for use in tests: Loads in track include maximum loads that occur on only a few occasions, largest loads that occur frequently, and average loads that occur regularly. Maximum loads should be used for safety evaluation in static tests. Largest loads should be used in durability and fatigue evaluation in repeated load tests. Average loads should be used for statistical evaluations.

2. Selection of representative test duration: A 25-year service life has been intended for fastener components. During this life, more than 30 million load cycles would occur on a track with moderate traffic volume. Therefore, consideration should be given to traffic volume and anticipated service life in selecting an appropriate number of load cycles for durability evaluation of fastener components.

3. Selection of representative test conditions: Track vibration and environmental conditions occuring in track affect fastener performance. Therefore, loading frequency and test environment should be selected to produce effects similar to those encountered in track.

4. Selection of appropriate acceptance criteria: Acceptance values should be stringent enough to assure good performance in track. However, they should not require excessively over-designed systems with unneeded superior characteristics.

Finally, it should be recognized that information generated from laboratory fastener tests is considered to have worth only to the extent that tests correspond to service conditions. Therefore, field data and results of laboratory investigations should be utilized to establish these loads. Laboratory tests provide data on fastener response for a wide range of vertical and lateral loads. Field tests determine rail deflections due to service loads. These results can be used to establish loads required to produce deflections in a laboratory test setup that simulate those obtained from field tests.

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Soft Direct Fixation Fastener: A Manufacturer's Perspective of Design and Specifications

Robert Gildenston
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Lord Corporation

GENERAL TYPES OF FASTENERS

Many types of rail fastening systems used on concrete surfaces have been generically called direct fixation fasteners. While all of the systems hold the rails to their correct gauge, the function of some direct fixation fasteners goes significantly beyond that.

This writer has chosen to divide direct fixation fasteners into two major groups as follows:

1. Thin pad fasteners with the rail resting directly on a 1/2" or less elastomeric element with flexible clips and rigid embedded shoulders providing no or limited vertical and lateral adjustment.

2. Thick pad fasteners with a top steel plate bonded to an elastomeric element of 5/8" thickness or greater, and either rigid or flexible clips, usually providing vertical or lateral adjustment and compliance.

The basic reason for the distinction between these two major groups is not a mechanical design feature or type of clip, but rather the vertical stiffness that each major generic style gives to the total rail/car system. It is this stiffness that has major impact upon the vibration and shock transmission from the rail through the fasteners to any surrounding structure or personnel.

Stiff Thin Pad Direct Fixation Fasteners

Stiff thin pad systems with the rail resting directly upon the elastomeric pad have vertical stiffnesses in the range of 800,000 lbs./inch to 2,000,000 lbs./inch. It appears from published material that any stiffness characteristics significantly below the lower range for this generic type of fasteners, generally involve difficulties with either the breakdown of the elastomeric pad or problems associated with the spring clip. There are inherent design limitations to reducing vertical stiffness significantly within this generic type of fastener concept. This type of design also allows a direct path for noise and shock transmission from the rail flange edge through the imbedded shoulder arrangement. While this path can be broken by the introduction of plastic insulating elements, it offers little in vibration isolation or attenuation. It is sufficient to say that this generic design using stiff thin elastomeric pad construction is not within the scope of the fasteners being discussed within this paper.

Soft Thick Pad Direct Fixation Fasteners

It is this second group of direct fixation fasteners utilizing a top plate with a soft, thick elastomeric pad, which we are discussing today. This is a basic design concept whereby the rail, instead of resting on the elastomeric pad directly, rests upon a top metallic plate with a thick elastomer directly beneath it. Either rigid or elastic clips can be used to hold the rail to the top plate to give lateral and longitudinal stability. Its distinguishing characteristic is the fact that its vertical stiffness is approximately 100,000 to 180,000 lbs./inch. With its softer vertical stiffness, a maximum reduction in shock or vibration transmission to any attached structure is possible, compared to the thin pad fastener. This reduction of primary vibration transmission also reduces the possibility of secondary excitation occurring in adjacent structures.

Rigid and Flexible Clips

There exists a certain amount of misunderstanding and confusion about the application of elastic (or spring) clips as opposed to rigid fastening elements. The rigid or flexible clips are merely utilized as a method of fastening the rail to the top plate of the fastener. The direct fixation fastener manufacturer has the ability to utilize any type of clip based on specifications from the authority calling for such a design feature. The type of clip used has little or no effect on the vibration or noise reduction characteristics of soft direct fixation fasteners. It should be noted, however, that the choice of clip utilized does have major impact on the design of the fastener and the required testing specifications.

It is highly probable that three or more completely different specifications are required to cover the procurement and testing of different generic styles of soft fastener systems now being used at transit authorities. Gross changes to vertical stiffness, rigid to flexible clips or other basic design points, force reconsideration of all specification parameters for each combination of design features.

Extension of Specifications for Noise, Shock and Vibration

Since soft thick pad direct fixation fasteners are used for shock, vibration and noise reduction, it is highly desirable that further statements on these requirements be included in the specifications. Presently, the only portion of existing specification recognizing these critical points, is a callout for a vertical stiffness of the fastener. In some few cases, a specification requires a dynamic to static stiffness ratio test. Further enhanced requirements, to optimize fastener design and configuration, on noise, shock and vibration control, should be considered in the specifications. Here some recognition should be given to the difference between groundborne vibration reduction and the matter of radiated noise reduction from the rail and support structure. Published works by Bolt, Beranek and Newman and Wilson Ihrig and Associates highlight both the difference and the mutual interrelationship of these two areas. Awareness on the part of the authorities as to the relationship of these problems within the trackwork system design, should allow the specification and subsequent testing to be adjusted to address them in the correct manner, so that desired characteristics can be designed into the fasteners.

Vertical and Horizontal Stiffness Relationship

When discussing future considerations for the reduction of groundborne shock and vibration in soft thick pad direct fixation fasteners, it should be noted that while the fasteners are soft vertically, they do at present, by authority specification design requirements, exhibit high stiffnesses laterally. Therefore, some of the shock and vibration generated by wheel/rail dynamics, is not significantly reduced when passing laterally through the direct fixation fastener. Since this lateral stiffness has direct relationship on maintaining rail head movement, the problem becomes more difficult to approach from a design standpoint. A lower lateral stiffness through the introduction of more elastomer would improve noise, shock and vibration isolation. In addition, it would cause an increased lateral movement of the rail head under both qualification tests and actual vehicle loads. One study done by the Department of Transportation at WMATA indicates that lower amounts of lateral or horizontal stiffness on the part of soft thick pad direct fixation fasteners can reduce lateral loads into the fasteners. Also, a fastener softer in the lateral direction may provide some benefit in wheel and rail wear. Further study is suggested to determine the exact maximum lateral softness allowable in a fastener that still can provide required rail head control.

Truck Influences on Fastener Lateral Stiffness Requirements

In discussing lateral stiffness requirements, it should be mentioned that one of the more significant generators of high lateral loads is a truck's journal box when high lateral stiffness elements are employed. Some trucks, having these high stiffness elements, force significantly higher lateral loads into the fastener system especially in curved track areas. Fastener difficulties experienced at WMATA and other authorities using this type of truck suspension compared to authorities using a soft primary suspension, appear to confirm this point. These same laterally stiff trucks are usually also stiff in the vertical direction. The effect of the high vertical stiffness characteristic, coupled with the mass of the truck and wheel track irregularities, generates far greater input vibration levels to the track system. The present direct fixation fastening systems cannot be expected to compensate for undesireable wheel/rail forces generated by stiff trucks.

Noise Attenuation

Looking towards specification modification to address attenuation of noise, a paper being presented today by Bolt, Beranek and Newman goes into considerable detail on how to achieve maximum reduction. It is sufficient to say that material damping, quarter wave resonant frequency, base plate mass and stiffness of the fastener assembly have major impact on these characteristics. Present specifications do not address these needs. These noise reduction characteristics have major potential impact where fasteners are being applied to old existing steel elevated structures. Specifically designed, high damped fasteners used in newer concrete elevated structures may have less dramatic noise reduction, however, they could have impact on that portion of noise radiated by the rail itself.

General Fastener Specifications

In discussing specifications in general, it could be agreed that not all fasteners procured have been successful in service. Recognition by the authorities that different generic styles of direct fixation fasteners do require significantly different procurement documents can improve this condition. The use of performance oriented specifications, improved elastomers and more freedom for the manufacturer in design can result in more practical and cost effective methods of fastener manufacture.

Material Specification

In going through a typical specification, one of the first callouts is the materials to be used for the construction of thick pad direct fixation fasteners. While most specifications indicate that either neoprene or natural rubber or various blends can be utilized, the tests required within the material specifications preclude the use of any material other than neoprene. Why this occurs within the specification is probably lost in history; however, it may be that neoprene at one time was a preferred material because of the use of fuel oil on diesel locomotive power sources. Specifically, the callouts for the oil emersion test within the material specifications, force the manufacturer to use only a neoprene for fastener construction. These callouts are too severe and performed in such a manner that has no relationship to the actual system operation. The test specimens of the elastomer are literally boiled in oil for extended periods of time at very high temperatures. Changes to these tests must be made to allow the use of natural rubber and other modern synthetic elastomers. The major advantage of going to natural rubber and blends is the dramatic increase in the fatigue life of the elastomeric components of a direct fixation fastener. Secondly, from a noise and vibration standpoint, natural rubber and other elastomers exhibit far lower dynamic to static stiffness ratios which, in turn, will lead to increased levels of groundborne vibration attenuation and noise reduction for the entire trackwork system. A call for re-evaluation of the material portion of all specifications is a necessity.

Fastener Anchorages

Most authorities are now requiring a fastener be furnished with the anchorage system as part of the overall fastener package. In addition, qualification testing of the fastener assembly is now being required with the actual anchorages embedded in a concrete test block. This is logical and desirable from a total trackwork system standpoint and will help prevent any discrepancies, interferences or conflicts between all of the various portions of the total fastening system.

In requiring a direct fixation fastener manufacturer to furnish or specify either male or female style anchorages, the male style stud is the least expensive on a first cost basis; however, it would appear that the female style insert embedded in concrete has more desirable characteristics from the maintenance and total life cycle cost standpoint. Using the male style stud, significantly more fasteners must be detached and the rail raised to a higher elevation to permit any fastener replacement. There is also an inherent design difference affecting life cycle costs between male and female style anchorage systems.

When a fastener is tightened to the concrete structure using a male style anchorage arrangement, the nut at the top of the fastener produces a constant upward shear at the boundary surface between the male style insert and the epoxy or epoxy grout mixture being used to hold it in place. Where less than optimum materials are used, this constant shear can result in creep or failure of the compound being used to hold the male style insert in place. The resultant fall-off in anchor bolt tension and possible loosening of the fastener body assembly can accelerate destruction of the male style anchorage and cause failure of the fastener system.

With the use of a female style anchorage, when the anchor bolt is tightened through the pad and into the female insert, no shear tension is experienced by the boundary surface between the insert and the epoxy or epoxy grout mixture. This is because the male bolt of a female insert assembly, passing through the fastener body pulls the anchor insert into direct contact with the bottom plate and the rigid steel internal sleeving mechanism of the direct fixation fasteners. Therefore, with no constant shear on the boundary surface, the female style anchorage should experience no creep of the epoxy. While we are seeing female style anchorages being specified at most authorities, where it is not specifically called out and the procurement is done through a lowest cost bid, the manufacturer is forced into bidding a male style stud arrangement. Recognition that the male style stud anchorage has lower first cost advantage in the bidding process should not preclude the use of female style anchorages which would appear to have a lower total life cycle cost.

Insert Coatings

One question is the effect of requiring coating on either male or female style anchor inserts. Some authorities utilizing male style anchorages do not require the coating of the male stud itself. This is apparently because one or two part epoxy is normally used in securing the male style anchorage into drilled holes, apparently it is felt that this provides sufficient corrosion protection. Since female style anchorages are usually cast directly into grout or concrete mixture while wet, the question of coating this type of insert for corrosion protection is more apparent.

We see, however, that when coated male or female style anchorages are indicated within the fastener specification, an option is still left open to the installation contractor concerning his method of installation. It has been suggested by anchor manufacturers that there exists a possible incompatibility between the coating of the inserts and possible epoxy mixtures used to hold the inserts in place. Compatibility of the insert coating and any epoxy materials required to hold it in place should be verified by the authority prior to bid procedures and more specific instructions given to the installing contractor.

It should be noted that the coating or non-coating of anchorage inserts has very little to do with the electrical isolation of the running rails from any ground potential. Electrical isolation is achieved through design features within the body of the direct fixation fastener that isolates the running rail from any ground potential of the anchor insert. If, for some reason, the fastener top plate and rail would become shorted to the top of the anchor area, a direct path is available for the current through the bottom plate that is not altered by a coating of the anchor insert.

Fastener Vertical Adjustment

Where a fastener shim is procured outside the designs recommended by the fastener manufacturer, problems with the direct fixation fastener itself may occur. This is particularly critical where male style anchorage studs are being used because the shims provide less than a full bearing support area. When female anchorages are used, a shim providing full bearing support area can be simply provided. Plastic shims are not recommended since they exhibit some characteristics of set and creep and, therefore, can result in loss of anchor bolt tension and cause subsequent loosening of the fastener. The use of metallic shims provides definite known characteristics and should require no subsequent maintenance or retightening of the anchor assembly. The proposition that plastic shims provide some type of additional electrical isolation to the fastener body is not valid. Since an alternate electrical path exists through the anchor insert assembly, the use of insulating materials for shims has little or no effect on the fastener system isolation from ground.

TESTING MACHINES

There are significant differences between test results obtained at various testing laboratories. This is the result of the differences in the testing equipment, set up, procedures and data collection. The result is that depending on the testing laboratory chosen, it is possible that a fastener of faulty design or low quality may pass qualification tests. Conversely, a well designed, quality fastener can fail when tested at a different laboratory. Clearly what is needed is the development of an industry-wide standard covering the test equipment design. At present, there is no reliable correlation between testing data obtained from one testing laboratory as opposed to the data obtained from testing the same part at a different laboratory. If the testing labs cannot mutually agree upon suitable comparative methods, it may be necessary that the government or some other body set the standards for the industry.

General Static and Dynamic Testing

In general, all testing, whether qualification or production, can be divided into two major categories. Static tests, which are: vertical load test, lateral load test, lateral restraint test, voltage withstand test and electrical resistance and impedance test; and dynamic tests: dynamic to static stiffness test, push-pull test, the uplift repeated load test and vertical and lateral repeated load test. Noting specifications for designs using flexible clips on soft thick pad direct fixation fasteners, the testing portions of the specifications must be changed so as to agree with what can be achieved.

The difficulty arises in the testing standpoint, that not only does the thick pad direct fixation fastener body deflect and act as a spring, but also the flexible (or spring) clip under lateral loads will also deflect and act as a spring in series to give larger rail head deflections. The maximum allowable rail head deflections or proposed reductions of the applied lateral loads in qualification testing requires further study and analysis.

Here we would like to point out that there is a difference between the way in which the flexible clip on a soft thick pad direct fixation fastener behaves within laboratory testing as opposed to its behavior within an actual trackwork installation. Since all laboratory testing is only performed on one or two fasteners attached to a short section of rail, it does not duplicate the entire rail fastener assembly system. From a practical standpoint, it would appear to be very costly and highly impractical trying to use long lengths of rail with large numbers of fasteners for qualification testing. Even then, the entire question of wheel/rail dynamics and their applied forces might make the results of such a large scale test arrangement invalid. What is needed is a practical method by which one or two fasteners with flexible clips can be tested with a short section of rail in the qualification testing.

The fastener manufacturer has little control over various tolerances that become involved within qualification and production testing. As an example, the longitudinal slip characteristic of any fastener design is dependent upon the variations within the toe load pressure of a flexible clip, bolt torque tolerance, and rail surface condition. Therefore, tightening of specifications in longitudinal slip envelopes has not proved to be practical. It merely increases cost without improving fastener performance. This further forcing of tighter and tighter tolerances and specification in many of the tests has no positive result in actual trackwork improvement or in the quality of the fasteners being procurred by authorities.

Vertical Load Test

In the vertical load test few difficulties are perceived in meeting the requirements. A related question that arises periodically is, "Can the voids be eliminated so as to allow installation contractors certain construction techniques?" Voids must be placed at the bottom of the fasteners so as to produce the correct vertical spring rate and meet other design and manufacturing parameters. Within the scope of the specifications and other dictated factors of good elastomeric design, it is required voids be placed in the undersides of most soft compression style fasteners. While it might be possible to totally eliminate these voids, it is not possible within the present size, limitations and other specification restrictions. It is also highly probable that voidless fasteners would be of a higher cost than existing designs when considered from the total trackwork requirements.

Lateral Load Test

In the lateral load test, difficulties within the testing procedures occur when flexible clips are used on the fastener body as opposed to rigid clamps. Lateral load values derived from older specifications, when rigid clips were required, will cause failure of the flexible clips. A failure of the spring clip during this test does not provide any worthwhile information as to the value of the fastener system. The point of the lateral load test is to prove both the body of the fastener and the clip attachment method in conjunction with each other. A complete rethinking of what is attempting to be provided by the lateral load test and lateral load values is required when utilizing flexible clips. The direct fixation fastener manufacturer has no control over the amount of rail head deflection or failure of the clip when excessive loads, beyond the spring clips ability to resist, are required during testing procedures. The usual method of test failure occurs when lateral loads are being applied at too great a value and the rail flange lifts from the top plate of the fastener body. Beyond a certain lateral load value, a permanent deformation or failure of the clip occurs. Stressing of clips beyond their design in this test proves nothing about the fastener system concept or the fastener body itself.

Longitudinal Restraint Test

In a longitudinal restraint test, it should be understood that, in general, rigid clips give higher longitudinal restraint characteristics than flexible clips applied to the same soft thick pad direct fixation fastener body. Typically, rigid clamp specifications call for a longitudinal slip characteristic someplace between 5,000 to 10,000 lbs. Laboratory testing indicates that standard rigid clamps cannot be utilized where longitudinal slip characteristics are requried below the 3,000 lb. level. Where flexible clips are utilized on soft thick pad direct fixation fasteners, the longitudinal slip characteristic is governed by the type of clip being utilized. This slip characteristic is a direct function of the toe load pressure as set by the spring clip manufacturer. As previously indicated, it is not within the ability of the direct fixation fastener manufacturer to change this toe load pressure beyond certain controlled limits.

Electrical Testing

Pertaining to electrical requirements in specifications, it can be stated that with a good design and the proper elastomers, little if any difficulties are experienced in meeting qualification testing requirements. However, certain physical design characteristics of some fasteners will allow the build-up of debris, within fastener body voids and openings, that can result in the degradation of electrical isolation properties and subsequent signal loss. Some authorities have recognized this, but are at a disadvantage because their specifications do not address this point. The use of unbonded fasteners can also result in less than desirable electrical characteristics and signal loss. Build-up of debris and rail grindings along the unbonded surfaces can short the electrical isolation of the fastener. Because of the manner in which qualification tests are performed, potential defects cannot not be discovered during the qualification testing. A governmental report on one authority using unbonded fasteners for subway application, indicates the necessity of steam cleaning these fasteners to prevent electrical breakdown due to debris. This same report also indicates difficulties at the same authority and others with the mechanical breakdown due to wear of the insulating sleeve within the anchorage area. It is recommended that more stringent testing specifications be required for unbonded fasteners recognizing these difficulties.

Dynamic to Static Testing

In discussing the dynamic to static tests, we would again refer you to changes within the elastomeric callouts so as to permit the use of a material other than neoprene for fastener use. Since the dynamic stiffness is the condition within which the rail system operates, it recognizes no difference between any elastomer being used and only recognizes what is the dynamic stiffness. Specifications should call for one dynamic to static stiffness ratio number rather than some present callouts which allow for two different ratios to be applied dependent upon the elastomer used. Since the train/track system generates no noise or vibration when in a static condition or sitting still, the value of a callout for only the static stiffness is somewhat misleading. Major importance should be placed upon the dynamic stiffness characteristics of the direct fixation fasteners since this is the environment within which it operates. A fastener manufactured in natural rubber as compared to neoprene could have as much as a 40% difference in vertical dynamic stiffness and, therefore, dramatic differences in noise, shock and vibration reduction could be achieved.

Push-Pull Testing

In the rail push-pull testing now required, again large differences exist between the effect of rigid clamps and spring clips. Rail movements through the fastener due to thermal expansion and contraction and rail movement due to car passage are a fact. Some difficulties have been perceived in laboratory testing of rigid clamp designs as opposed to flexible clip designs undergoing push-pull testing. It is suggested that a re-evaluation be done of the push-pull test to determine what the purpose of the test is and what components are being tested. From this re-evaluation, a more comprehensive and valid testing requirement can be proposed.

Repeated Uplift Test

As regards the repeated uplift test, there should be few difficulties experienced by the direct fixation fastener manufacturer in meeting these tests with a bonded fastener. A bonded fastener utilizes three modes of resisting vertical uplift. First the fastener body elastomer is placed in tension at any point between the top plate and any bottom plate arrangement. Secondly, a portion of the elastomer in the anchorage area is placed into compression under the washer arrangements specified by most manufacturers. Third, a small amount of shear is introduced at the interface between the top plate and anchor assembly. These three elements make for smooth and uniform loading of the anchorage assembly and prevent metal to metal contact and large shock forces from being introduced into the anchorage element. Unbonded designs do require the introduction of coil spring washers and other necessary components in the fastener anchorage assembly so as to eliminate the direct metal to metal to metal contact in an uplift mode.

Vertical Lateral Repeated Load Test

In the vertical lateral repeated load test we again run into the inherent problems of the differences between rigid clamp and elastic clip designs. Specification callouts for high lateral loads within this test preclude the fastener manufacturers in some cases from meeting qualification test requirements when using spring clips. In the past where only rigid clamp designs were utilized, few difficulties were observed, even when the testing loads for both the field and gauge side were increased beyond in-track measured levels. This is due to the fact that with a rigid clamp, the rail flange is held tightly to the top plate of the fastener body and only small deflections occur within that portion of the fastener system.

Since larger and larger lateral loads are now being used in qualification testing, inherent difficulties are experienced with spring clip arrangements in being able to meet the qualification criteria. If a fastener fails the qualification testing due to large imposed lateral loads on the spring clips, the entire point of why the fastener is being tested becomes irrelevant. Recognition within the vertical lateral repeated load test, as to the deflection of the spring clips, is required to get a true and valid representation of the complete fastener system. Performing the vertical lateral repeated load test with higher loads than can be met by the spring clips only proves the point that the spring clips are destined to fail. A true representation of the quality of the fastener body becomes lost within the test failure. It is not within the direct fixation fastener manufacturers' ability to force the flexible clips to perform beyond designed limitations. As stated, the direct fixation fastener manufacturer does not have control over the pass/fail conditions of qualification testing when the spring clip fails. That responsibility has to lie with the authority that requires the application of the spring clip to the soft thick pad direct fixation fastener and the loads applied for testing.

Testing Acceptance Criteria

In discussing acceptance criteria for both static and dynamic tests, it should be understood that this testing represents some period of use applied to the fastener. The fasteners, after being thoroughly tested, cannot be expected to resemble a fastener that has just been manufactured. We see subjective evaluations, in acceptance criteria, concerning cracks within the elastomeric element as being a failure mode. It should be understood that minor cracking within the elastomer after dynamic testing is typical of elastomeric materials and does not indicate a failure of the part as long as it can perform its intended function. Acceptance of the elastomer within a fastener should be based on its ability to pass some other criteria, such as passing the static tests as a last qualification test criteria in performing its design function. Where cracks occur in the metal components of a fastener, rejection of the fastener should apply.

INTERRELATIONSHIP OF THE FASTENER SYSTEM

It is vitally important that all points called out by a specification maintain an interrelationship to each other. Failure to maintain this interrelationship results in confusing and conflicting indications to the manufacturer. The result in many cases is costly redesign and/or inability to meet the specifications as stated. Specification documents by their nature are difficult and time consuming to produce. Requests on the part of various parties to include particular features or requirements, in many cases, cause a conflict within the specifications when a full review of all of the documents is not done. There is not only the interrelationship within the fastener procurement document to be considered, but also the interrelationship of the specifications and instructions given to the contractors. What is required is an early basic determination on the part of the authority of certain factors such as clip style, installation method and longitudinal restraint. From these and other major points, specifications and direction to both the fastener manufacturer and the installation contractor can be drawn up to accurately portray those relationships. With these predetermined factors, the successful manufacturing and application of soft thick pad direct fixation fasteners can result.

PRE-BID CONSIDERATIONS

Most direct fixation fasteners are procured within the U.S. under a standard bidding procedure. This can either be a bid to the authority or to an installation contractor. This entire procedure can be improved within the existing framework so as to allow designs at a lower cost and better quality to be furnished. One such method might be the use of technical pre-bid submissions from the various manufacturers. Included within such proposals would be detailed drawings of the fastener and its components in sufficient detail to show the relationship of all parts and the sufficienty of its design. Other inclusions might be certification from the manufacturer that all points of the design portion of the specifications have been met without deviation or exception. A review of the fastener manufacturer, his program management proposal and list of all subcomponent supplier company names and locations would also seem to be a reasonable request. Finally, the fastener manufacturer should outline his production quality control plan. A preapproval of the manufacturing facility to be used may be in order to assure maintenance of product quality throughout the production run. This technical pre-bid method, however, requires that enough time be allotted prior to the actual fastener purchase so as to make it a workable procedure.

In discussing time limitations, it should be noted that no authority has ever had the ability to reject non-complying soft pad direct fixation fasteners. This has been due to time constraints imposed by the system. If the authorities would recognize this and allow more time for qualification of a second qualified bidder, fewer exceptions and deviations from specifications would be forced upon the authorities. A second method might be to allow both the lowest and second lowest manufacturer submitting the bids to both enter into the qualification procedure. Under this method, qualification performance tradeoffs could be made against the two different fasteners. Where direct fixation fasteners are being bid directly to installation contractors, even greater delays for qualification have been experienced. Since there is no such thing as a standard direct fixation fastener "off the shelf", the installation contractor has only one avenue open to him upon the failure of the fastener to pass qualification tests. He must concur with his selected fastener manufacturer in any deviations or exceptions required by the sub-contractor, or face delay of contract penalties. The installation contractor cannot procure anything other than his first chosen lowest bid fastener due to the time constraints in his contract.

INDUSTRY SUGGESTIONS

From the long range standpoint, the following points should be considered by all involved parties:

1. Establishment of standard specifications for the different generic types of direct fixation fasteners.

2. Re-evaluation of testing procedures and acceptance criteria based on the type of fastener being procured.

3. Specifications based on performance rather than design criteria.

4. Inclusion of significant tests concerning the noise, shock and

vibration features of soft thick pad fasteners.

5. Requirement of technical pre-bid submissions for evaluation by the authority to eliminate faulty and non-conforming designs.

6. More time in the procurement process for rejection of non-qualifying fasteners.

7. Enforcement of the specifications as written.

Design of a Resilient Rail Fastener for Minimizing Noise From an Open Wood-Tie Deck, Steel Plate Stringer Elevated Structure

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INTRODUCTION

Background and Objective

About 400,000 people in their homes are affected by the noise from U.S. rapid transit trains passing on elevated structures.[3] One type of structure, consisting of an open wood-tie deck supported on steel plate stringers, constitutes about 50% of the mileage of all U.S. elevated structures and accounts for 90% of the noise impact. This type of structure has been the subject of much research in recent years.[1, 2, 4]

One test program involved measurements in New York City to evaluate the effectiveness of a resilient fastener in reducing the noise near these structures [4]. Figure 1 shows the standard tie saver pad used on the New York City Transit Authority (NYCTA) elevated structures; Figure 2 shows the resilient fastener used in the tests; and Figure 3 shows the results of the noise measurements. The resilient fastener provided 3 to 5 dBA of noise reduction compared to the structure with standard tie saver pads.

Based on these results and additional study of the NYCTA resilient fasteners [2], it was concluded that these fasteners were providing more noise reduction than could be explained by representing their actions as a simple spring (even with internal damping). As part of the work performed by Bolt, Beranek and Newman, Inc. (BBN), an analytical model was developed to explain the performance of the NYCTA resilient fastener and to assess the noise reduction achievable on the open-tie deck elevated structure through the use of various noise control treatments. [2] Preliminary results of that study indicated the possibility of achieving significantly greater noise reduction, through appropriately designed rail fasteners, than the 3 to 5 dBA provided by the existing NYCTA resilient rail fastener.

The objective of the work summarized in this report was to develop design concepts for a resilient fastener which would maximize noise reduction when used on open wood-tie deck, steel plate stringer elevated structures. It is important to remember, in reading this report, that a fastener designed to reduce elevated structure noise as not necessarily similar to one which is intended to minimize groundborne noise and vibration. The important frequency range for elevated structure noise is 250 to 2000 Hz, while that for groundborne noise is 16 to 200 Hz. It is also essential to remember that the recommendations included in this report for fastener design parameters (to reduce noise) are based entirely on an analytical model which has only partially been validated. Any new fastener design will have to be fully evaluated in the field to verify its acoustical performance.

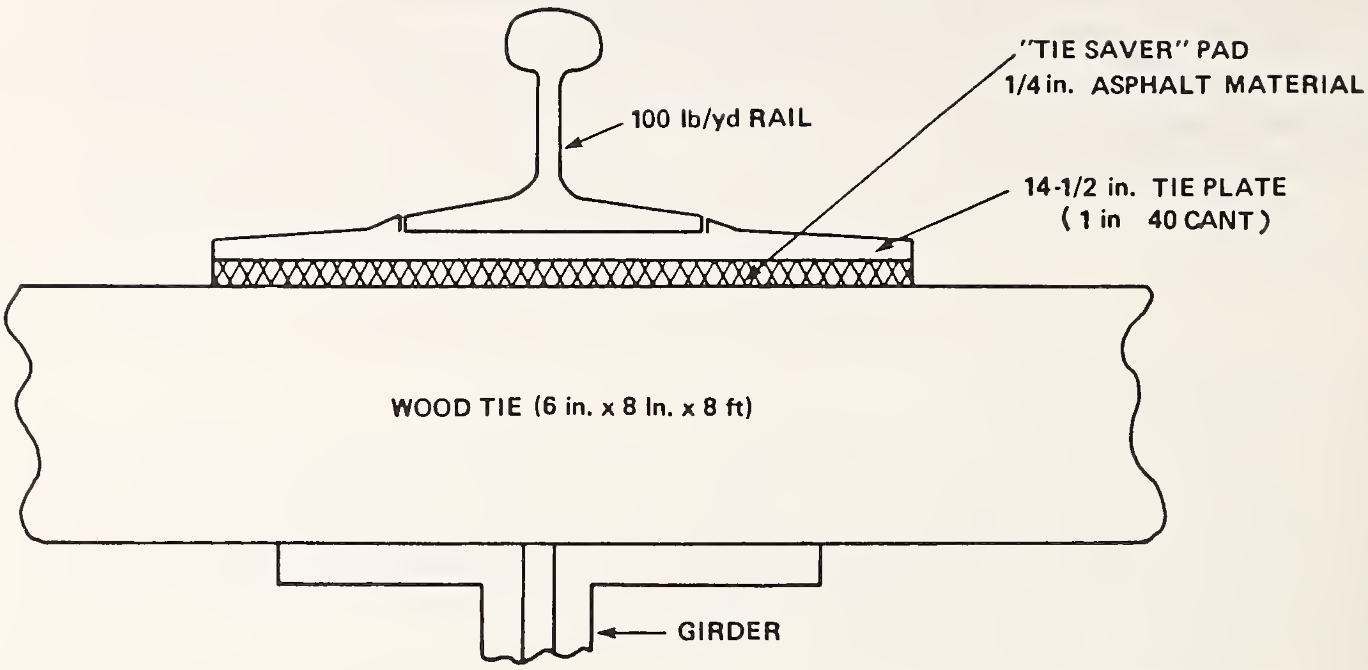

FIGURE 1. TYPICAL ELEVATED STRUCTURE RAIL SUPPORT SYSTEM ON THE NYCTA

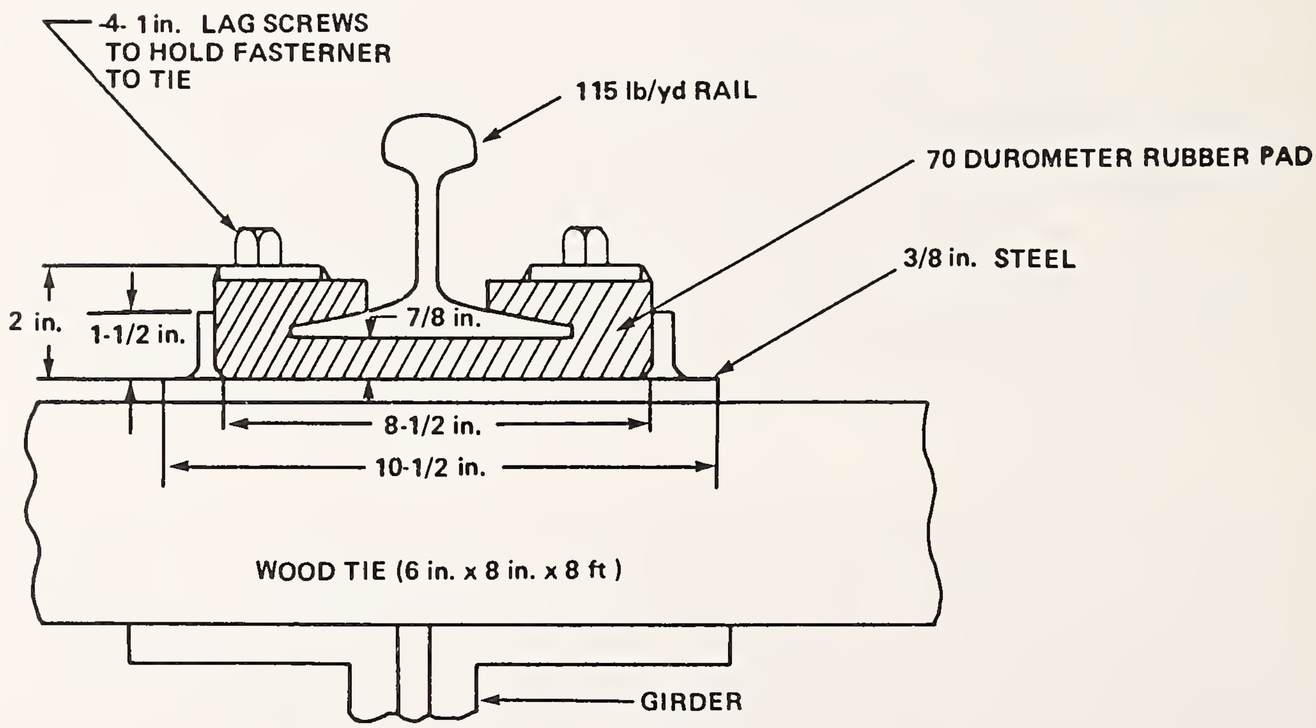

FIGURE 2. RESILIENT FASTENER USED ON THE 10TH AVENUE NYCTA ELEVATED STRUCTURE

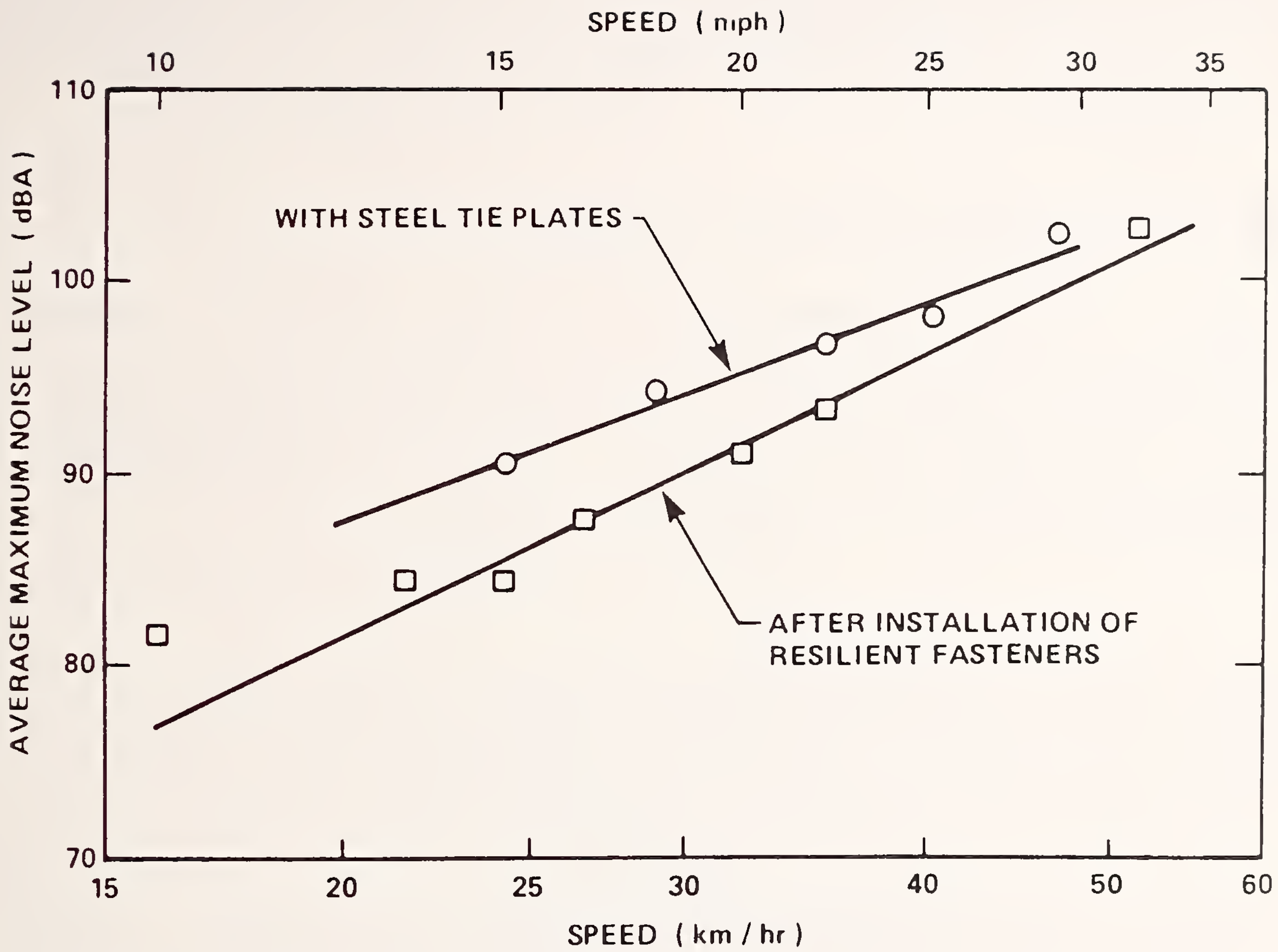

FIGURE 3. EFFECT OF RESILIENT FASTENERS ON WAYSIDE NOISE AT 25 FT FROM NYCTA ELEVATED STRUCTURE

Organization of the Report

Section 2 of this report describes the fastener parameters which control its acoustic (noise reduction) performance and presents the results of a parametric study to quantify the effect of each parameter on the noise radiated by the elevated structure. Section 3 summarizes the information collected during visits to the NYCTA and the Chicago Transit Authority (CTA) regarding their requirements for resilient fasteners on elevated structures. Section 4 presents a brief survey of the resilient rail fasteners in use in the U.S., along with estimates of their relevant properties. Section 5 presents several approaches for designing a resilient fastener with improved noise reduction characteristics. Finally, Section 6 presents a summary of the study and provides recommendations for pursuing development of a fastener for quieting elevated structures.

EFFECT OF FASTENER DESIGN ON ACOUSTIC PERFORMANCE

Figure 4 is an idealized sketch of a rail fastener showing the components which affect its acoustic (noise reduction) properties for use on a wood tie deck, steel plate stringer elevated structure. The specific parameters which affect its performance include the mass of the base plate (M_{BP}), and the loss factor (η_f), low frequency dynamic stiffness (K_f) and quarter-wave thickness resonance frequency ($f_{1/4}$) of the elastomer -- the latter two of which are defined as follows:

$$K_f = \frac{E_c A}{t} \tag{1}$$

$$f_{1/4} = \frac{\sqrt{E_o/\rho}}{4t} \tag{2}$$

where E_o = Dynamic Young's Modulus

E_c = Dynamic Compression Modulus (Proportional to E_o and Shape Factor)

ρ = Density of Elastomer

A = Loaded Area of Elastomer

t = Thickness of Elastomer

The thickness resonance comes about because, within the frequency range of interest, the vibration wavelength in the elastomer is on the order of the thickness of the elastomer. The quarter-wave resonance frequency is that frequency at which the elastomer thickness equals 1/4 of the vibration wavelength.

An analytical model previously developed under this program [2] provided a means for evaluating the effect of varying the parameters related to the elastomer. This model was modified to incorporate the effect of the base plate mass on the noise radiated from the elevated structure.

In order to exercise the analytical model, a complete set of parameters describing the elevated structure was developed to simulate a typical NYCTA open wood-tie deck steel plate stringer structure. The basic properties of the elevated structure are given in Table 1. A computer model was used to investigate the effect, on the average noise level during a train passby, of varying the four parameters which describe the resilient fastener. The values of the parameters used as input to the program are given in Table 2.

The results of the sensitivity runs are given in Figures 5 through 8. The noise levels represent the average noise (32 sec averaging time) 25 ft from a ten-car train passing at 25 mph. All of the combinations of parameters listed in Table 2 are represented in these figures except for the combinations involving $f_{1/4}$ = 3000 Hz. The results for this value of the thickness resonant frequency are the same (within 1 dB) as those for $f_{1/4}$ = 1500 Hz.

In order to more clearly illustrate the effects of each of the parameters on noise, some of the results in Figures 5 through 8 have been replotted in Figures 9 through 12.

Figure 9 illustrates the effect of the fastener loss factor on the noise from the elevated structure. Increasing η_f results in a decrease in noise, as can be seen in Figures 5 through 8.

Figure 10 illustrates the effect of the base plate mass on wayside noise. For most of the cases looked at, increasing the mass of the base plate reduces the wayside noise. A more detailed look at the computer output indicates that increasing base plate mass had little or no effect on the noise coming from the wheels and rails, but did result in reduced noise radiation from the ties and stringers.

Figure 11 illustrates the effect of the fastener quarter-wave resonant frequency on the wayside noise. Typically, reducing $f_{1/4}$ results in reduced noise, although for low values of K_f, varying $f_{1/4}$ has very little effect.

Figure 12 illustrates the effect of fastener stiffness on noise. As seen from this figure and Figures 5 through 8, the effect of K_f on noise depends primarily on the value of $f_{1/4}$. For, $f_{1/4} \ll\sim$ 400 Hz, increasing K_f tends to slightly decrease or have little effect on the wayside noise. For large values of $f_{1/4}$, increasing K_f tends to increase the noise. Insight as to the effect of K_f on noise can be obtained by looking at the changes in the noise radiated from each of the major components as K_f is varied. This is shown in Figure 13 for one set of the other three parameters. From this figure, it is seen that increasing K_f reduces the noise radiated from the rails while increasing the noise from the ties and stringers. The net effect on the overall wayside noise depends on whether the change in the noise from the rails is greater than or less than the change in the noise from the ties and stringers.

Figure 14 shows the predicted noise spectrum for a structure with the standard NYCTA tie saver pads under the rails. The parameters used to approximate the tie saver pads are:

TABLE 1. DESCRIPTION OF ELEVATED STRUCTURE

Rails:		100 lb/yd
Ties:		6 in. high x 8 in. wide x 8-1/2 ft long creosoted wooden ties, spaced 1.5 ft apart, Stiffness of tie under fastener base plate = 175,000 lb/in.
Stringers:	Web:	3/8 in. thick x 5 ft. high
	Flange:	2 - 6 in. x 6 in. x 9/16 in. L's back to back, riveted to the top and bottom of the web.
	Web Stiffeners:	2 - 3-1/2 in. x 3-1/2 in. x 3/8 in. L's back to back, 8 per 50 ft span.

TABLE 2. VALUES OF RESILIENT FASTENER PARAMETERS USED FOR SENSITIVITY ANALYSIS

Fastener Parameter	Values
Base Plate Mass, M_{BP}	0, 10, 20, 40, lb
Loss Factor, η_f	0.01, 0.25, 0.5
Fastener Stiffness, K_f	50, 100, 200, 400, 800 Kips/in.
Thickness Resonant Frequency, $f_{1/4}$	200, 400, 800, 1500, 3000 Hz

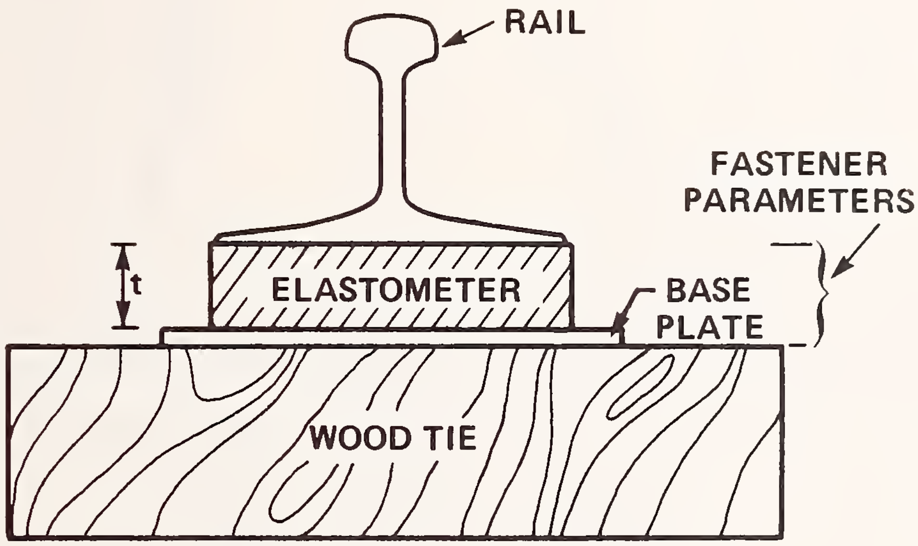

FIGURE 4. SCHEMATIC OF RESILIENT FASTENER COMPONENTS WHICH AFFECT ACOUSTIC PERFORMANCE

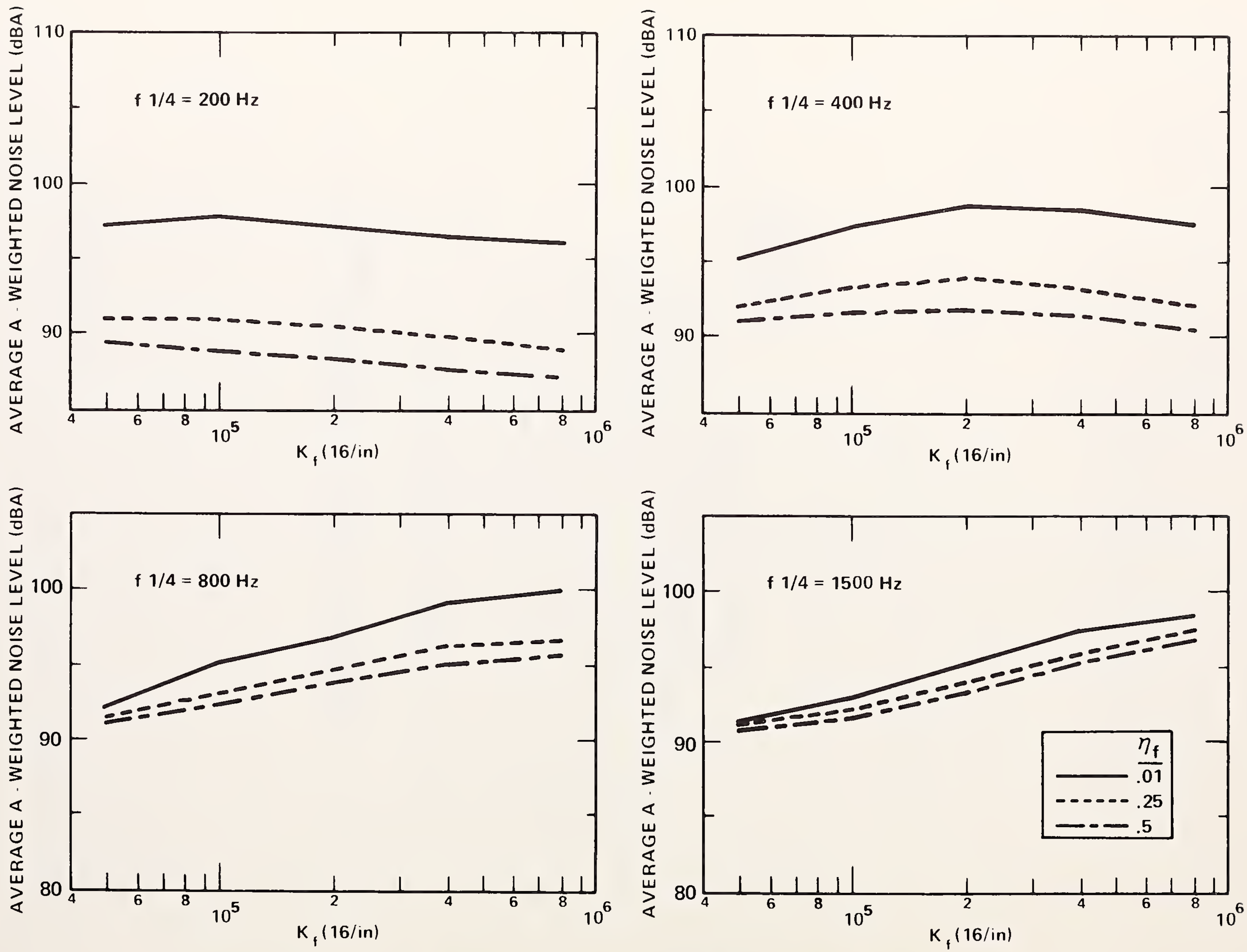

FIGURE 5. AVERAGE NOISE LEVEL 25 FT FROM THE TRACK CENTERLINE FOR THE PASSAGE OF A 10-CAR TRAIN AT 25 MPH (32 SEC AVERAGING TIME) AS A FUNCTION OF RESILIENT FASTENER PARAMETERS (BASE PLATE MASS = 0 LBS)

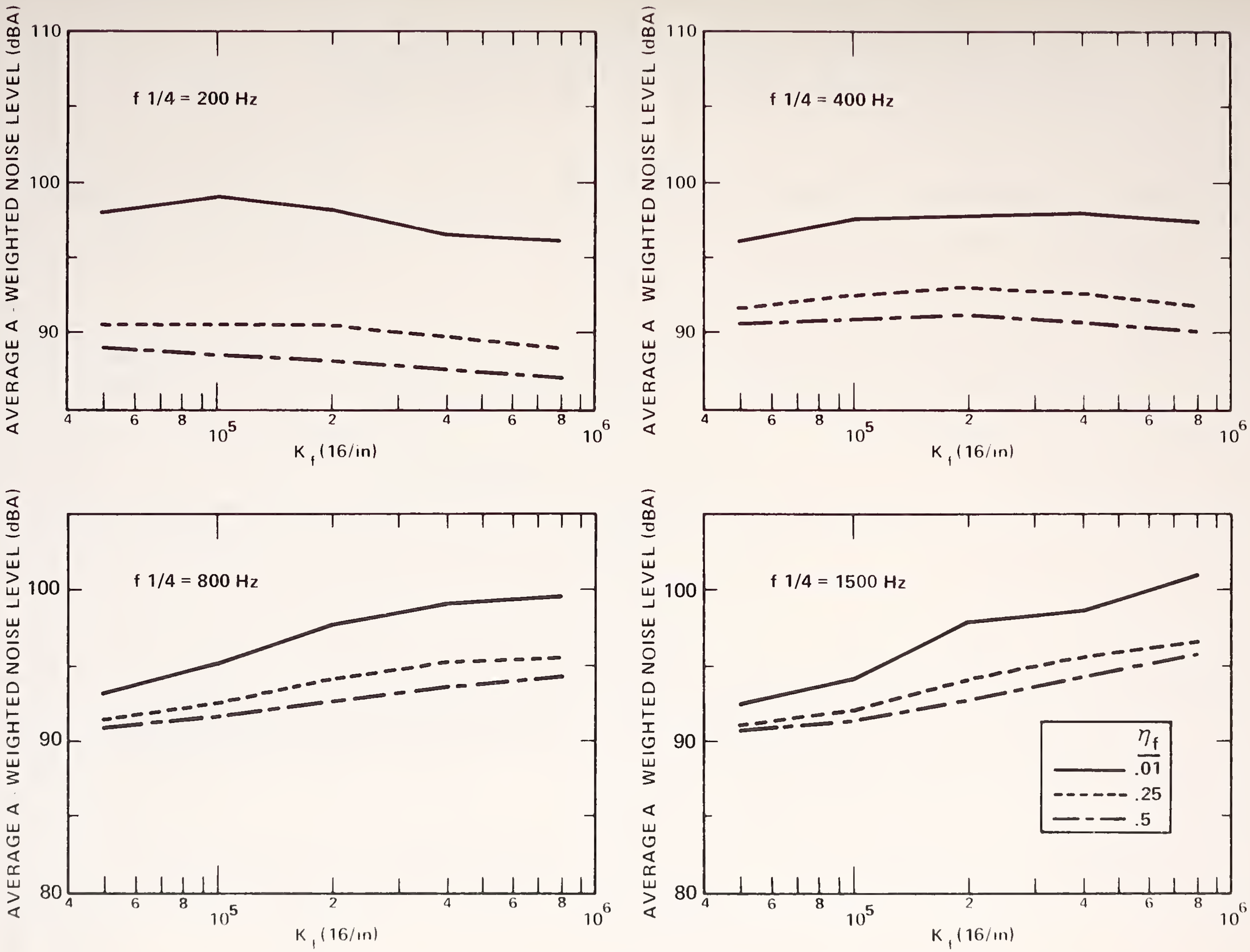

FIGURE 6. AVERAGE NOISE LEVEL 25 FT FROM THE TRACK CENTERLINE FOR THE PASSAGE OF A 10-CAR TRAIN AT 25 MPH (32 SEC AVERAGING TIME) AS A FUNCTION OF RESILIENT FASTENER PARAMETERS (BASE PLATE MASS = 10 LBS)

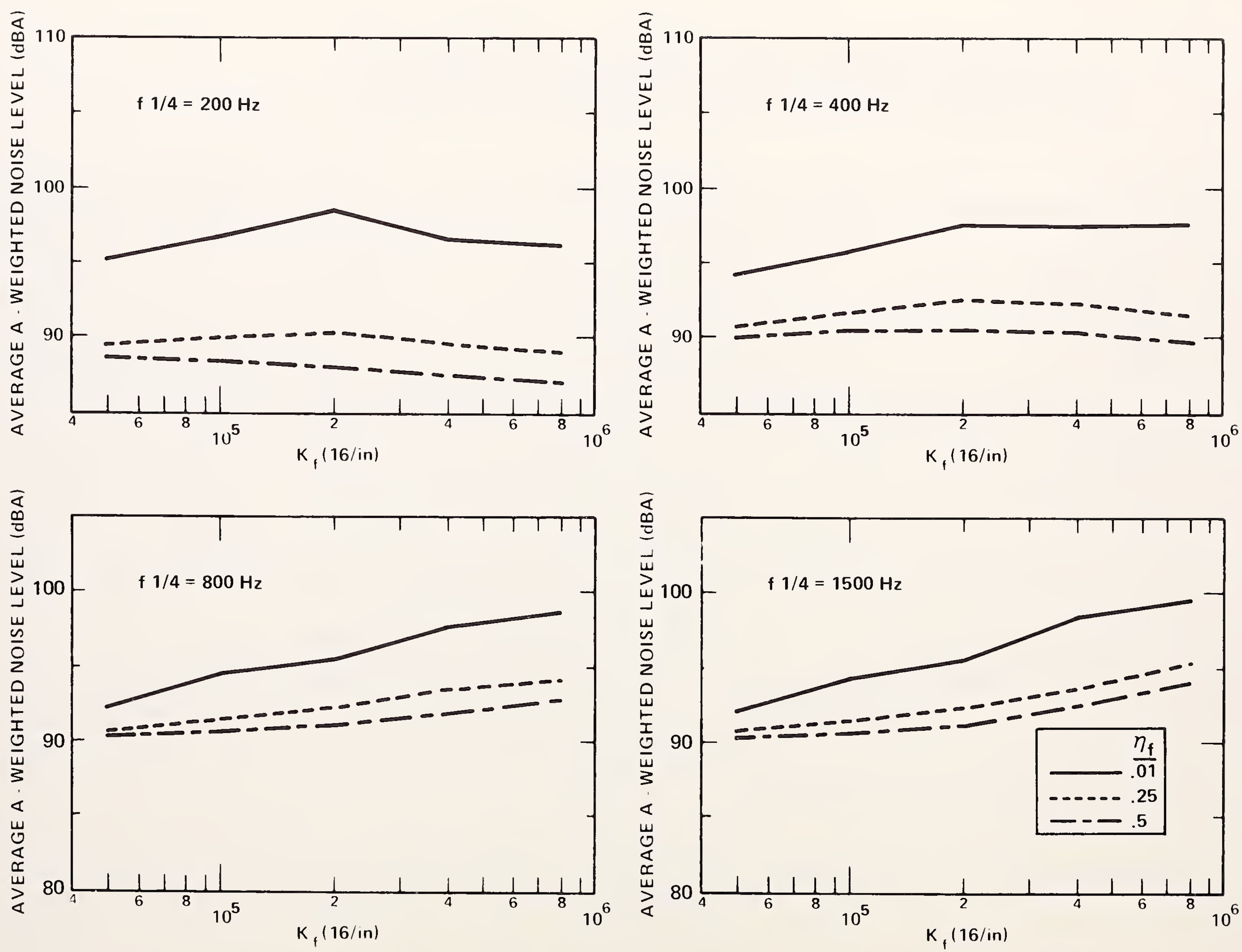

FIGURE 7. AVERAGE NOISE LEVEL 25 FT FROM THE TRACK CENTERLINE FOR THE PASSAGE OF A 10-CAR TRAIN AT 25 MPH (32 SEC AVERAGING TIME) AS A FUNCTION OF RESILIENT FASTENER PARAMETERS (BASE PLATE MASS = 20 LBS)

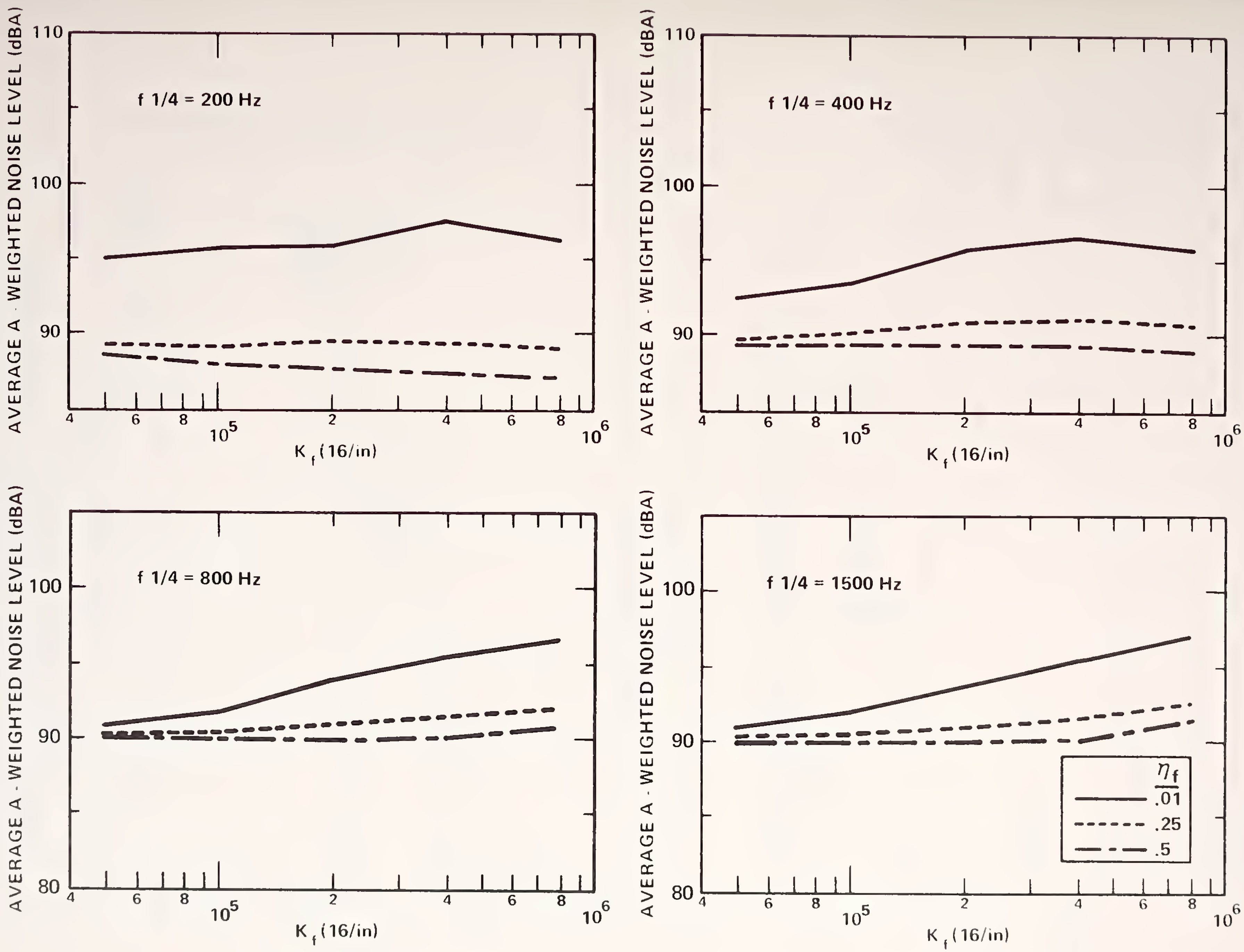

FIGURE 8. AVERAGE NOISE LEVEL 25 FT FROM THE TRACK CENTERLINE FOR THE PASSAGE OF A 10-CAR TRAIN AT 25 MPH (32 SEC AVERAGING TIME) AS A FUNCTION OF RESILIENT FASTENER PARAMETERS (BASE PLATE MASS = 40 LBS)

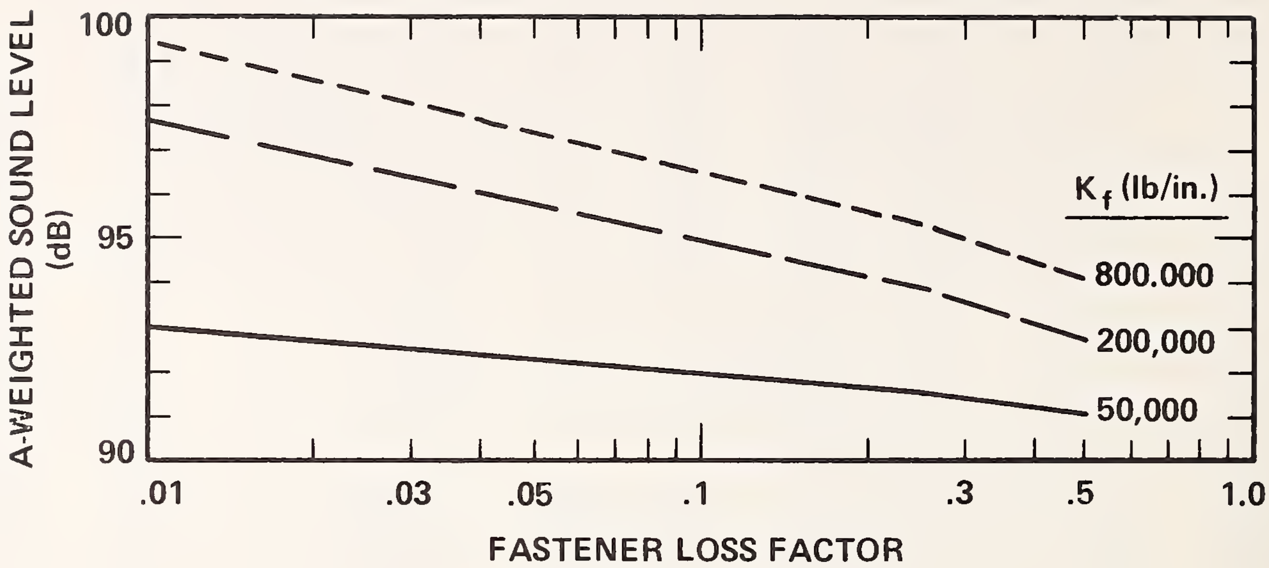

FIGURE 9. EFFECT OF FASTENER LOSS FACTOR ON NOISE ($f_{1/4}$ = 800 HZ, M_{BP} = 10 LBS)

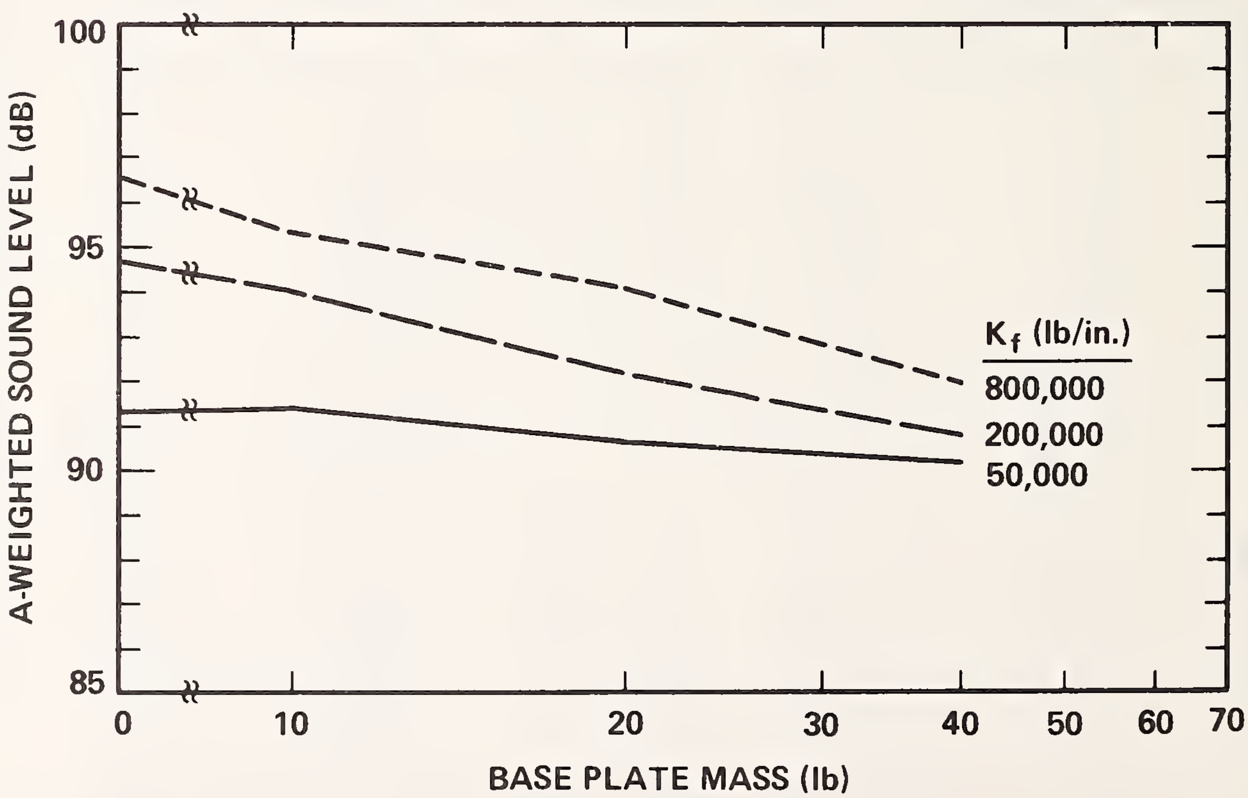

FIGURE 10. EFFECT OF BASE PLATE MASS ON NOISE ($f_{1/4}$ = 800 HZ, η_f = .25)

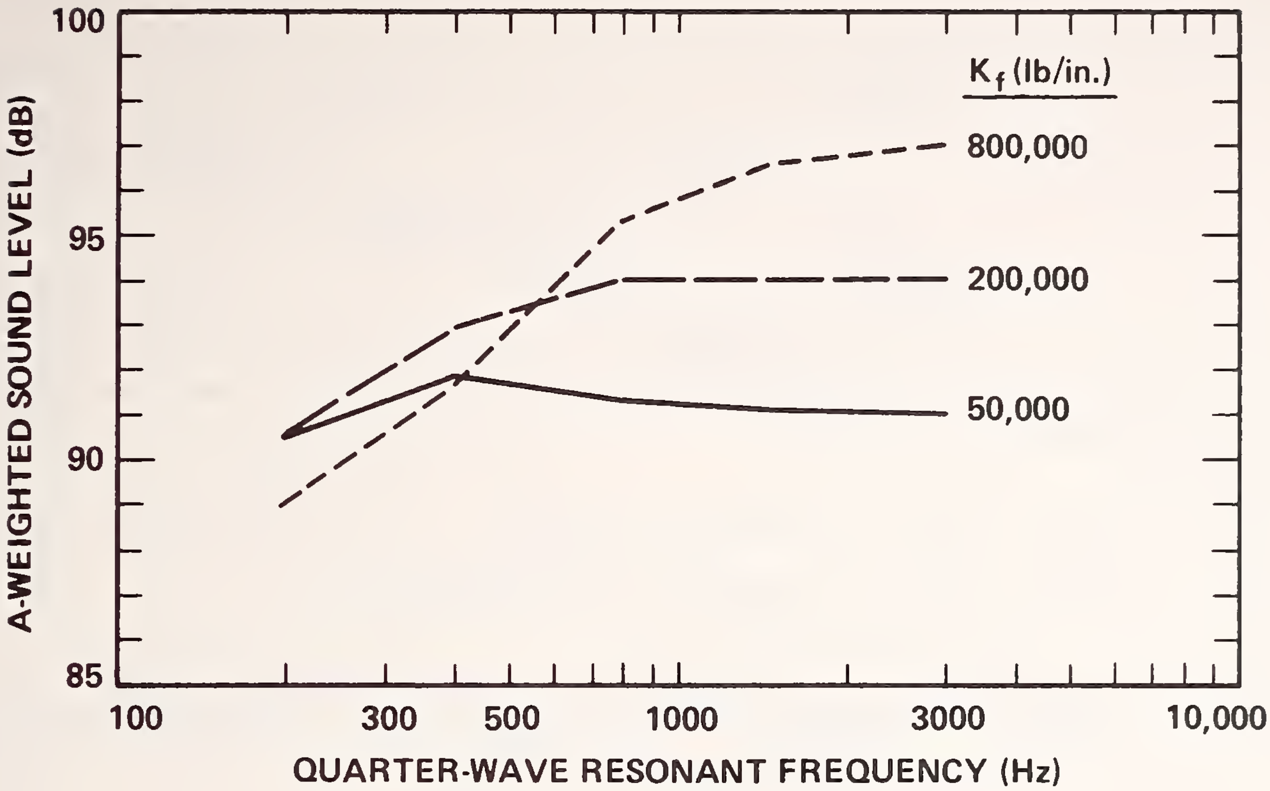

FIGURE 11. EFFECT OF FASTENER THICKNESS RESONANCE ON NOISE
(η_f = 0.25, M_{BP} = 10 LBS)

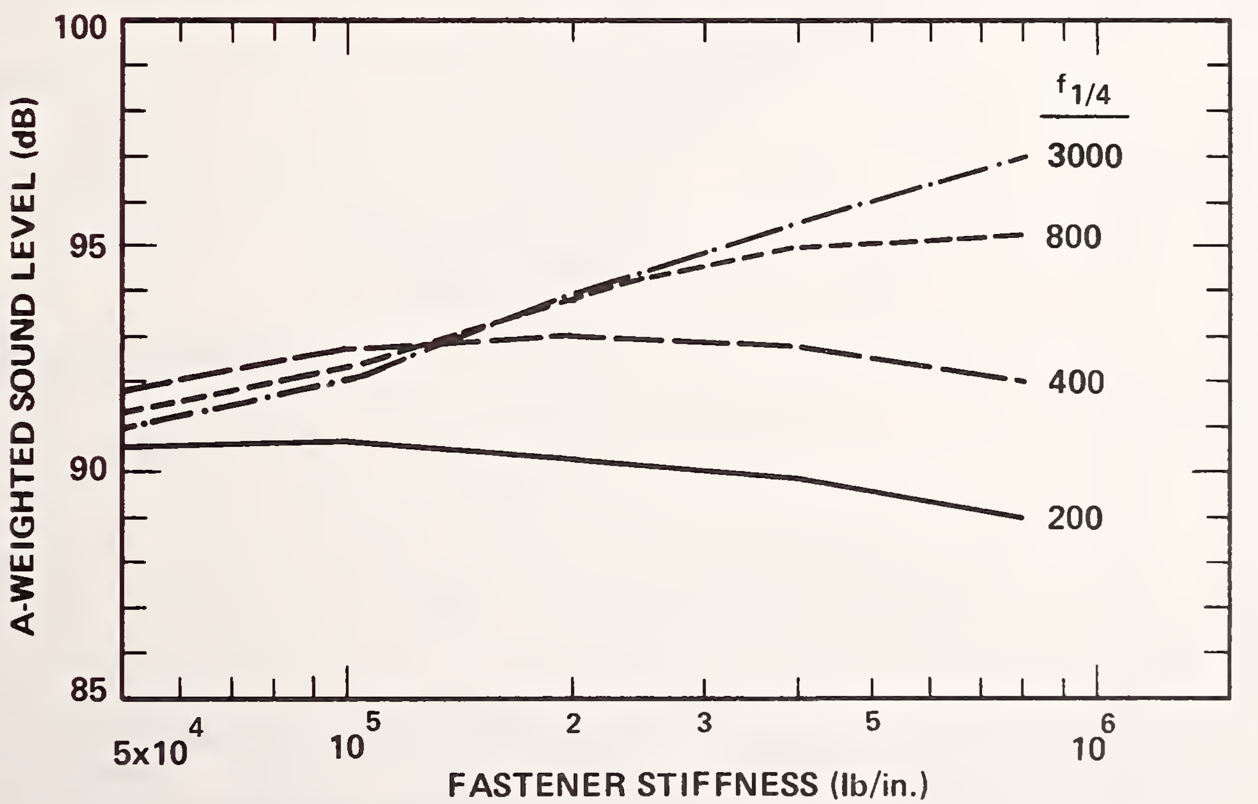

FIGURE 12. EFFECT OF FASTENER STIFFNESS ON NOISE
(η_f = 0.25, M_{BP} = 10 LBS)

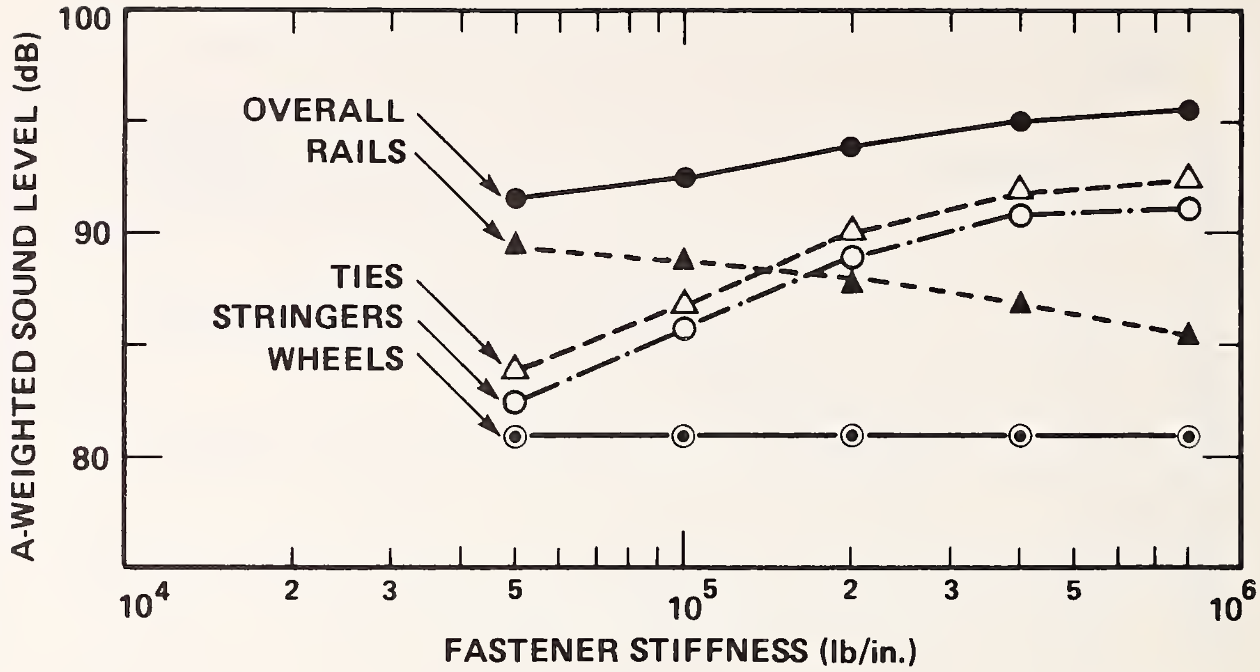

FIGURE 13. EFFECT OF FASTENER STIFFNESS ON NOISE FROM EACH COMPONENT ($f_{1/4}$ = 800 HZ, η_f=0.25, M_{BP} = 10 LBS)

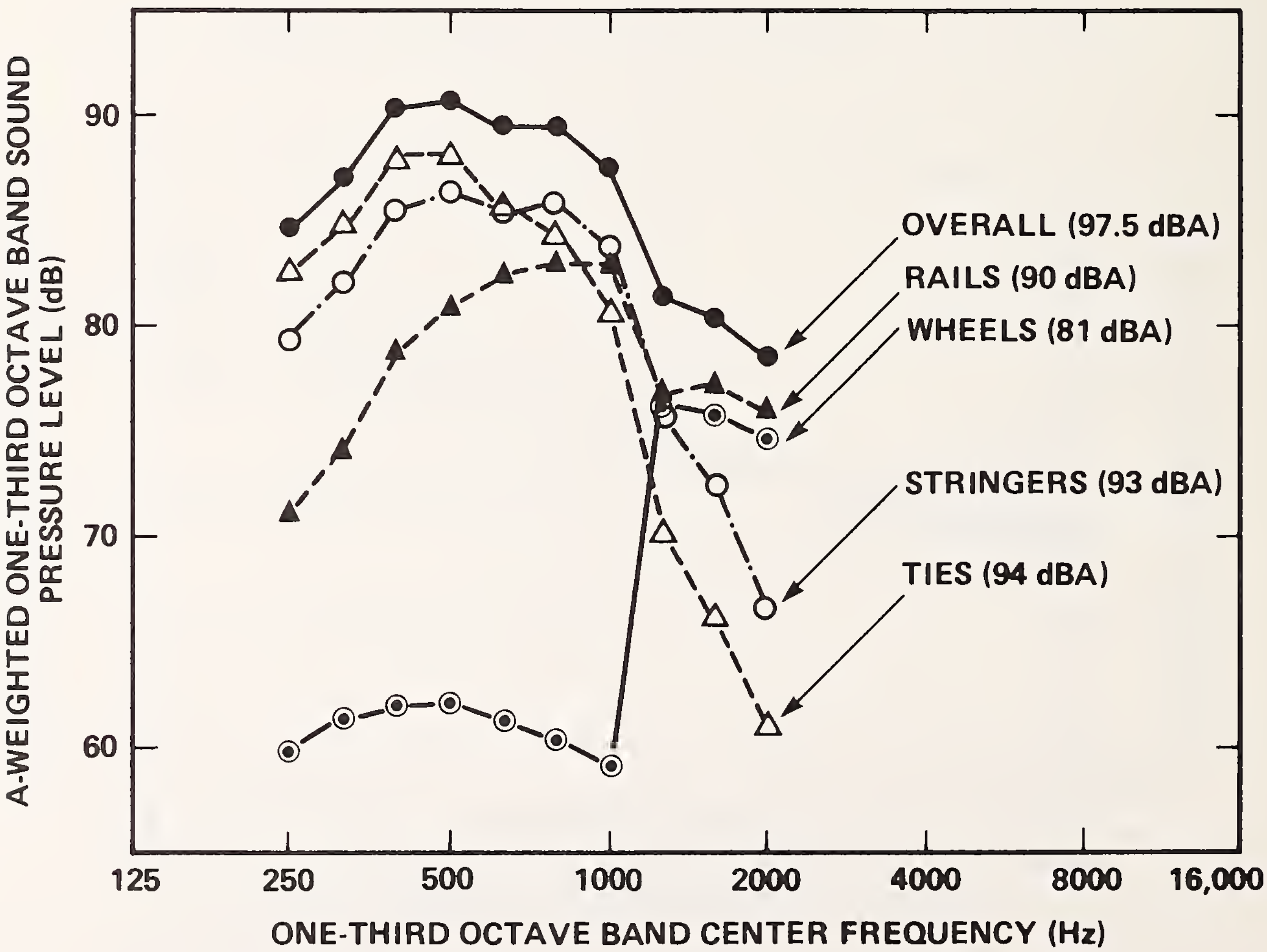

FIGURE 14. PREDICTED COMPONENT NOISE SPECTRA AT 25 FT (TIE SAVER PADS, 25 MPH)

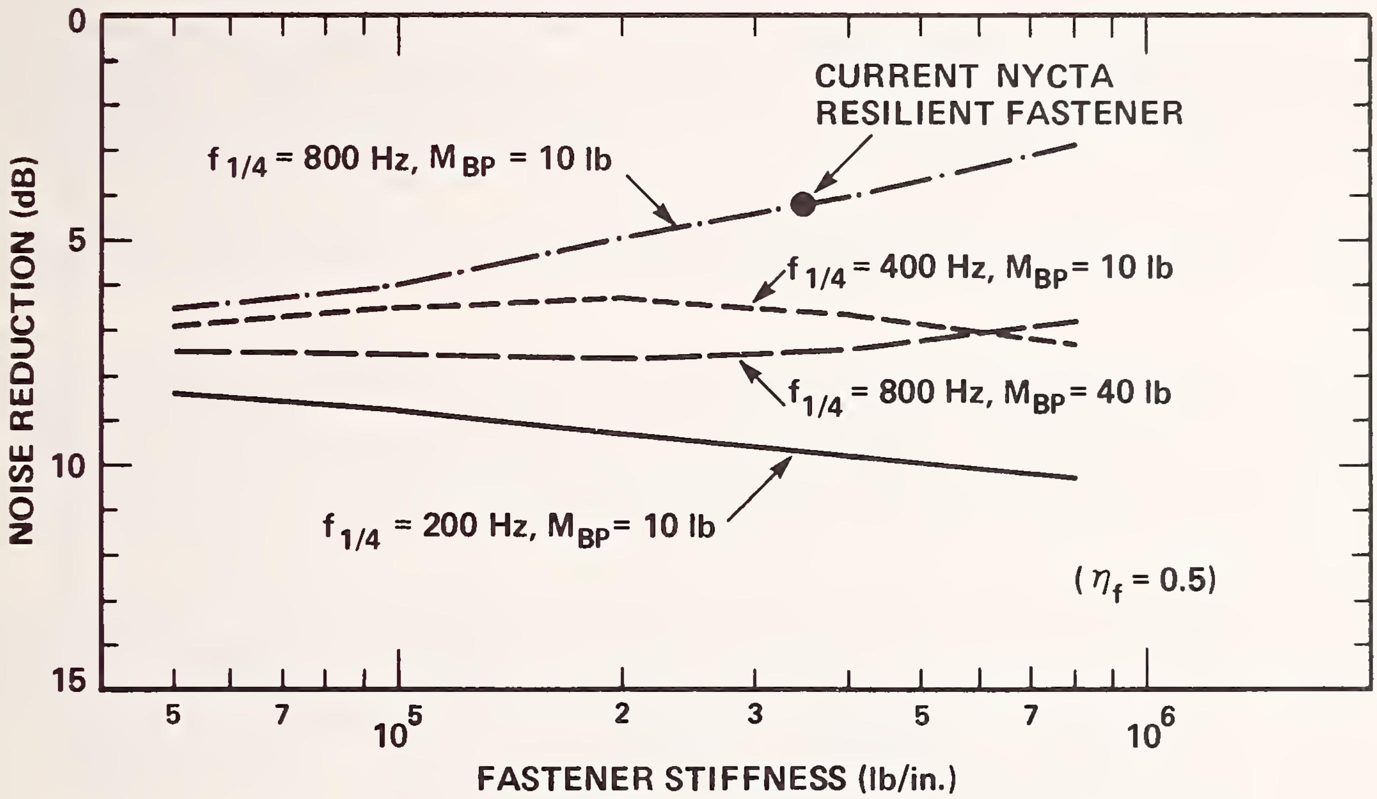

FIGURE 15. ESTIMATED NOISE REDUCTION OF VARIOUS FASTENERS COMPARED TO NYCTA TIE SAVER PAD

K_f = 10 lb/in

η_f = .01

M_{BP} = 0 lb

$f_{1/4}$ = 96,000 Hz (arbitrarily high value).

The average A-weighted noise from a train passby on the structure with the tie saver pads is 97.5 dBA.

This noise level can be compared to the levels in Figures 5 through 13 to estimate the noise reduction achievable by use of various resilient fasteners relative to the standard structure. One such set of results is shown in Figure 15. The point marked "current NYCTA resilient fastener" represents the predicted noise reduction (4 dBA) obtainable by using the NYCTA modified Type VIII fastener with 70 durometer rubber K_f = 350,000 lb/in, η_f = .475, $f_{1/4}$ = 867 Hz, M_{BP}, = 11 lbs). This result agrees well with the 3 to 5 dBA noise reduction measured for this fastener in actual field tests.[4]

It is interesting to look at what improvement in acoustic performance could be achieved with the NYCTA fastener, if it were modified. By increasing the base plate mass from about 10 lbs to 20 lbs, the wayside noise would be reduced by another 1.5 dB (i.e., a total of 5.5 dB relative to the tie saver pad). Keeping the base plate mass at 11 lbs and K_f = 350,000 lb/in, decreasing $f_{1/4}$ from about 800 to about 400 Hz would result in an additional 2.5 dB of noise reduction, or a total of 6.5 dB relative to the tie saver pad. More substantial reductions could be achieved by other fastener design concepts which would allow one either to significantly reduce the vertical fastener stiffness (to about 100,000 lb/in) or to reduce the quarter-wave resonant frequency to 200 to 300 Hz. For example (referring to Figure 15), if $f_{1/4}$ = 200 Hz could be achieved, with a vertical stiffness of about 150,000 lb/in, 9 dB of noise reduction could be achieved relative to the tie saver pad.

NON-ACOUSTIC FASTENER DESIGN CONSIDERATIONS

A series of visits were made to both the Chicago Transit Authority (CTA) and the New York City Transit Authority (NYCTA) to identify characteristics and specifications required for the use of resilient rail fasteners on open wood-tie deck, steel-plate stringer elevated structures.

To determine the necessary physical trackwork parameters that would be required for any highly damped resilient rail fastener for use on this type of elevated structure, a list of questions was prepared and discussed with each authority.

Information received from both authorities is summarized below.

1. The wood tie size was 6" x 8" x 8' (CTA) and 6" x 8" x 8-1/2' (NYCTA).

2. Spacing of the ties was 21" at CTA and 18" at NYCTA.

3. Both authorities use guard rail in all portions of the elevated structure, with similar spacings between running and guard rails. It should be noted that most of the resilient rail fasteners now in use are not designed for application on an elevated structure with a guard rail.

4. Both authorities utilize restraining rail in curved sections. NYCTA uses a vertical restraining rail while CTA utilizes a horizontal restraining rail. This particular point will have to be considered during fastener design.

5. CTA will be utilizing 115/119 lb/yd rail with 5-1/2" railbase. At present, NYCTA utilizes 100 lb/yd rail and has a rail base of 5-9/64". The design concept for the special fastener will have to accommodate both dimensions.

6. It was determined that at present both authorities utilize bolted rails and are likely to continue their use on the old elevated structures.

7. Both systems have track oilers in some portions of curved track and also utilize some type of ice and snow removal chemical, basically of an ethylene glycol solution nature. Consideration of these two factors will have to be made in the selection of the elastomer to be used in the special fastener.

8. Presently a discrepancy exists between the two styles of screw spikes used at the two authorities. The Chicago Transit Authority utilizes a 3/4" specially designed lag screw with its tie plate. New York City is utilizing a 1" diameter lag screw in those instances where a direct fixation fastener is being applied to a wood tie. This apparent discrepancy is due to the fact that the NYCTA must provide a heavier lag screw when used within the direct fixation fastener assembly. This point will be considered within the design parameters of any proposed highly damped fastener.

9. Contact rail height would have to be raised to match any raise in height of the running rail due to increased fastener thickness. This does not seem to be an insurmountable problem since NYCTA has already done this at an earlier demonstration section where fasteners were installed. One of the problems that could occur, however, is the possibility of having to raise platform heights where direct fixation fasteners are used. However, until such a time as the actual physical design parameters of the fastener are known, this and other height problems cannot be determined.

10. The question of longitudinal restraint for any proposed fastener was addressed at meetings of both authorities. The importance of this question is that in dealing with an older structure, any buildup of forces due to rail restraint might have detrimental effect on either the structure or the wood tie position. It should be recognized that with standard tie arrangements and cut spikes or lag bolts, the amount of longitudinal restraint on any

TABLE 3. SURVEY OF EXISTING RESILIENT FASTENERS AND THEIR CHARACTERISTICS

FASTENER IDENTIFICATION	MANUFACTURER	RAIL FLANGE ATTACHMENT	ELASTOMERIC ELEMENT	ELASTOMERIC ELEMENT THICKNESS 't'	COMPRESSION STIFFNESS	1/4 WAVE FREQ. f(1/4)"hz	DAMPING LOSS FACTOR	BASE PLATE WEIGHT	REMARKS
Pandrol Assembly using Pandrol Clips & rubber pad under rail base	Pandrol (USA)	Pandrol Clips	Synthetic rubber; Not bonded	5mm (.19")	900,000 #/in at 1800# 1.9 x 10^6#/in at 2800#	1400	.18	None	No adjustment
Pact System	Pandrol (England)	Pandrol Spring Clip	Cork-Rubber; Not bonded	10mm (.39")	Est 750,000 to 1,000,000#/in	1300	.20	None	No adjustment
Unit - D.E.	Unit O.E. (Chicago)	Spring Clip of Bending Tie	Cork-Rubber; Not bonded 2 pads top & bottom	2 x 4.5mm (.18")	Est 1,000,000#/in		.20	None	
Landis Model 2000	Landis Rail Fastening Systems (Los Altos, CA)	Rigid Toe Clamp	Neoprene Bonded	.75"	125,000 mean	700	.15	7.25#	With adjustment
Landis-Pandrol Model 5202 & 5301	Landis Rail Fastening Systems (Los Altos, CA)	Pandrol Spring Clip	Neoprene Bonded	.62"	125,000 mean	830	.12	None	Cam-type adjustment
Sidewinder Series 100-500	Portec, Inc. RR Prod. Div. (Oakbrook, IL)	Sidewinder Spring Clip	Polyurethane pad; Not bonded	.19"	Est 1,000,000#/in Min	3140	.13	None	No adjustment
A. P. Stedef	Stedef, Inc. (Falls Church, VA)	Bolted Flat Leaf Spring	Neoprene Pad & Rubber Booted Concrete Ties	.18" (4.5mm)	Est 750,000#/in pad only Total stiffness with boot not available	3200	.20	None	Not suitable for elevated structure
Toronto TTC	Toronto Transit Commission buys components & assembles.	Bolted Formed Spring Clip	Neoprene pad; Not bonded	.62"	Est 500,000#/in.	960	.15	None	No adjustment
Hixson H-10	Transit Product Co. (College Park, GA)	Screw type - Rigid Toe Clamp	Neoprene rubber; Bonded	.75"	125,000#/in	700	.15/.18	1.00#*	With adjustment
Hixson H-15A	Transit Product Co. (College Park, GA)	Boltless - Flat Lead Spring	Neoprene rubber; Bonded	.75"	150,000#/in	800	.15/.18	1.75#*	With adjustment
NYCTA	Railroad Rubber Products (Ashtabula, OH)	Bolted	Butyl; Not Bonded	.875"	Est 500,000#/in Est250,000#/in	850 525	.30/.35 .2/.27	12#	70 duro butyl 50 duro butyl
Lord Fastener	Lord Corporation Erie, PA	Screw Type- Rigid Toe Clamp	Neoprene Bonded	.75"	125,000#/in	700	.15/.18	5.75#	With adjustment
Cologne Egg	Clouth, Germany	Spring Clip	Bonded		70,000#/in (Static) 98,000#/in (Dynamic)	300 (App.)	.12	26#	No adjustment in lateral direction

* Anchor holes end metal pads.

elevated rail system is minimal. This is true even when rail anchors are used. Most rail anchors, as seen in actual operation, become displaced away from the tie and, therefore, provide little, consistent longitudinal restraint to the rail. Further information on this characteristic was requested from both authorities due to the critical nature of this parameter. This point may have dramatic impact on the basic design concept that must be utilized for the special fastener.

11. No particular preference was shown by the CTA for any arrangements similar to existing fasteners which might provide the desired characteristics. NYCTA voiced opinion that their present resilient rail fasteners, currently in use in subways and at one location on steel elevated track, were highly desirable from their standpoint, because of their experience with that fastener. Since it was not within the intent of these meetings to come up with a design concept, no decisions were reached concerning basic design concepts of the special highly damped resilient rail fasteners.

In viewing the overall information, nothing was discovered that would preclude the use of a specially designed fastener at either participating authority. The area of physical trackwork requirements may cause the most difficulty in designing a fastener to meet the necessary parameters of both CTA and NYCTA.

SURVEY OF EXISTING RESILIENT RAIL FASTENERS

Prior to concept development, a survey was taken of existing resilient rail fasteners. This information was derived from various published sources and information from the manufacturers. Further, the values of the noise-related parameters not readily available were estimated based on available technical information. For the most part, the fasteners surveyed were those in current use in the United States. Insufficient time and information were available on most other fasteners to compile a list of their relevant properties within the scope of this project. It should be noted, however, that most of the foreign fasteners resemble, in whole or part, one of the fasteners now available in the United States. One notable exception to this is the Cologne Egg resilient rail fastener, which is currently being tested on the Massachusetts Bay Transportation Authority (MBTA). This fastener utilizes rubber in shear to achieve a very low vertical stiffness.

The survey results are summarized in Table 3. Note that only the Cologne Egg comes close to achieving a quarter-wave resonant frequency below about 300 Hz, and this is based on the shear wave length in the elastomer. Because the Cologne Egg is fundamentally different from the idealized fastener model developed for the analysis described in Section 2, it is not clear at this time if it would provide the degree of noise reduction expected from the analysis.

All the fasteners listed in Table 3 fall into two generic design concepts. The first incorporates an elastomeric pad, placed immediately below and adjacent to the rail base; the elastomeric pad, in turn, rests directly on the supporting structure or on a part of the fastener itself. In the second type of fastener system, the rail flange sits directly on a steel plate with the elastomer beneath that steel plate; the elastomer, in turn, rests directly upon the support structure or on a part of the fastener itself.

In the first type of system where the rail sits directly on an elastomeric pad, the pads are normally of ten millimeters or less in thickness. In addition, they generally incorporate a flexible clip which presses upon the rail flange and follows the rail as it moves downward and upward. None of the direct fixation fasteners of this type included in the survey utilize one inch or thicker elastomeric pads.

The second fastener style utilizes a variety of rail hold-down devices, such as rigid clamps, constant pressure clamps and flexible clips. Since the rail flange base is seated directly on a steel plate, no deflections occur in this area and all relative movements and deflections occur below the clamp/clip plate area.

After evaluating the properties of the fasteners included in the survey, it was concluded that none of these fasteners provide both the desired physical characteristics (to meet trackwork requirements) and the necessary acoustical properties (to minimize wayside noise) defined in Sections 2 and 3, although the Cologne Egg may come close.

FASTENER DESIGNS FOR MINIMIZING ELEVATED STRUCTURE NOISE

General Approaches

Based on the results presented in Section 2, there are two basic approaches to achieving significantly improved noise reduction compared to existing fasteners:

1. Design or maximum damping:

η_f	as high as possible (>.3)
$f_{1/4}$	as low as possible (<300 Hz)
K_f and M_{BP}	can be whatever is practical since for $f_{1/4}$ <300 Hz, K_f and M_{MP} have little effect on the overall wayside noise.

2. Design for maximum vibration isolation:

K_f	as low as possible (<125,000 lb/in)
M_{BP}	as high as practical
η_f	>.25
$f_{1/4}$	has little effect when K_f is very low unless it gets below about 300 Hz.

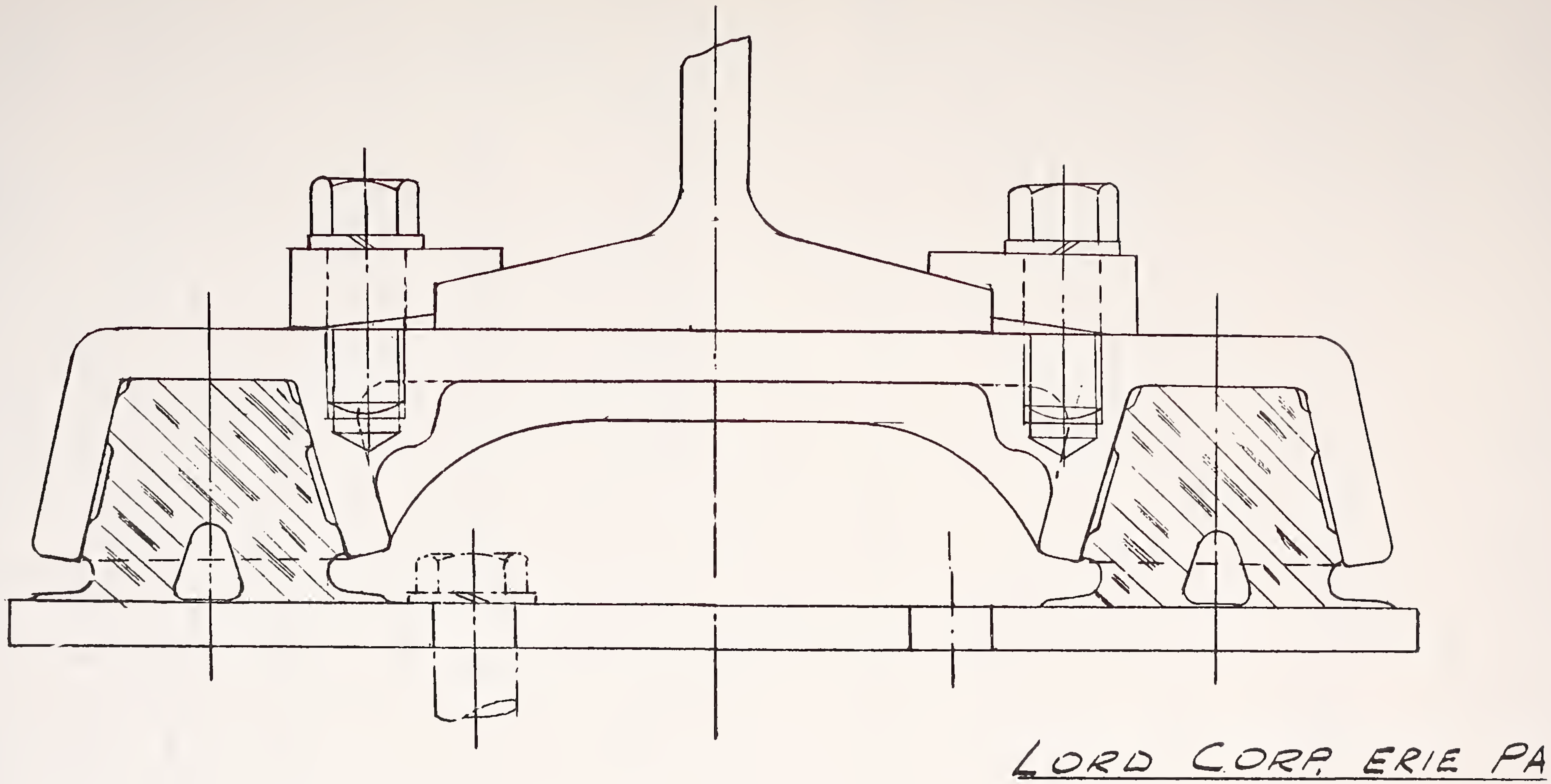

FIGURE 16. CONCEPT FOR FASTENER TO ACHIEVE A QUARTER WAVE RESONANT FREQUENCY < 300 HZ

Optimization of the NYCTA-Type Resilient Fastener

The properties of the NYCTA resilient rail fastener in use on their elevated structures fall in the following ranges:

$$K_f = 350{,}000 - 450{,}000 \text{ lb/in.}$$

$$\eta_f = .3 - .5$$

$$f_{1/4} = 800 - 900 \text{ Hz}$$

$$M_{BP} = 11 \text{ lbs.}$$

The only readily available method for improving its noise reduction performance while maintaining the design configuration is to increase the base plate mass to a practical limit of about 20 lbs. This would provide an additional estimated noise reduction of about 1.5 dBA. With the present NYCTA design concept, it appears that there is no practical way of increasing rubber thickness to reduce quarter wave resonance while still maintaining rail head control. In order to improve rail head control with increased elastomer thickness below the rail, there would have to be significant physical changes to rail hold down features. One method might be the removal of the top portion of the elastomer and metal plate and the introduction of different style of clamping device. As noted in Section 2, if the quarter-wave resonant frequency could be reduced to about 400 Hz, an additional 2 to 3 dBA of noise reduction could be obtained.

Design Concept for Optimized Noise Control

A generic fastener design is shown in Figure 16 which has an elastomeric section arranged to accept vertical loading in combined compression and shear. This provides adequate stability during loading cycles. The elastomer is of sufficient thickness to meet a quarter-wave resonant frequency of just under 300 Hz.

Polybutadiene appears to be the best choice for the elastomer. It can be compounded to provide desired characteristics for the fastener such as:

(i) The damping loss factor ranges from .2 to .35.

(ii) It is more economical than silicone and butyl rubber.

(iii) The compression set and drift characteristics are superior to those of butyl rubber.

(iv) Polybutadiene does not stiffen as rapidly as butyl rubber does at low temperature.

(v) Polybutadiene fatigue characteristics as applied to the fastener are superior to that of butyl rubber.

(vi) The resulting dynamic to static stiffness ratio, in the frequency range 250 - 2000 Hz, will typically be between 2 and 3.

For an elastomer with a loss factor of about η_f = .3, this type of fastener could provide about 7 dBA of noise reduction compared to the standard tie saver pad.

SUMMARY AND RECOMMENDATIONS

This study looked at the design parameters for resilient rail fasteners which affect the noise reduction potential when used on open wood-tie deck, steel-plate stringer elevated structures. It was found that by capitalizing on the "wave-bearing" properties of the elastomer in the fastener, noise reductions on the order of 7 dBA may be possible. Alternately, by utilizing the isolating effect of a low vertical fastener stiffness and a large base plate mass, it may also be possible to achieve about 7 dBA of noise reduction. The existing rail fasteners were surveyed to determine if any had properties suitable for minimizing the noise from elevated structures. The Cologne Egg appears to have the necessary acoustical properties, although its unusual design makes the application of our anaylsis suspect. In their present form, none of the available fasteners have both the acoustic and physical parameters needed. The physical trackwork requirements for the fasteners were established by site visits to the CTA and the NYCTA.

Several steps are needed before the results of this study can be applied with confidence.

1. The trends predicted by the analytical model should be verified by laboratory test. For example, a test could be developed in which the rate of vibration attenuation down the rail could be measured in a laboratory set-up with a 39 ft section of rail resting on simple elastomeric pads which, in turn, rest on wooden ties. Metal plates could be installed between the pads and the ties to simulate fastener base plates. The thickness of the pads and the base plate mass could be changed to determine whether the expected change in vibration damping in the rail is achieved. If the ties, in turn, were supported on concrete (very stiff) blocks over an area representative of the upper flange of the longitudinal stringers, the effect on tie vibration (and hence noise radiated by the ties) of varying the properties of the elastomeric pads and base plates could be compared with the theory. The tests described above are only an example of the types of testing that could be performed. A careful test design is necessary to assure that all the important parameters which govern the performance of the resilient fasteners were properly simulated in order to verify the analytical model. If the trends differ significantly from those predicted by the model, a determination will need to be made regarding whether the model is in error or whether the test simulation is incomplete. If the former is believed to be the case, the test set-up itself can be used to evaluate alternative fastener designs.

2. Based on the results of the above tests, one or more prototype fasteners should be designed and fabricated. This should be done in coordination with a cooperating transit authority to assure that the designs are compatible with use on their structures.

3. The mechanical and acoustical properties of the prototype fasteners should be verified by laboratory test on individual fasteners. One design should be selected and a sufficient number of prototypes fabricated to support a 39 ft section of rail. Tests similar to those described in 1 above should be repeated and final design changes made if necessary.

4. After review and acceptance of the final design by the cooperating transit authority, a sufficient number of the optimized design fasteners should be fabricated to test on an actual elevated structure. A detailed in-service test plan should be developed and, after approval, carried out.

5. Finally, the results of the development and test program should be presented to the transit industry. This communication should ideally be done in an on-going manner during the developing and testing phases so that industry feedback can be incorporated into the fastener design and test program.

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ACKNOWLEDGEMENT

This report presents the results of the final phase of a project dealing with the reduction of noise from elevated structures in use in U.S. rail rapid transit systems. Here we focus on defining the design parameters of a resilient rail fastener for minimizing noise on an elevated structure with an open wood-tie deck supported on steel-plate stringers.

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Inputs covering non-acoustic design considerations, as well as the conceptual design shown in Figure 16, were provided by the Lord Corporation under subcontract to BBN. In particular, Mr. Robert Gildenston and Mr. Kenneth Siwek of the Lord Corporation provided the material covered in Sections 3, 4 and parts of 5.

We are grateful to the New York City Transit Authority (NYCTA) and to the Chicago Transit Authority (CTA) for their time and efforts in meeting with us and providing us with a definition of their requirements for a resilient fastener suitable for use on their elevated structures. In particular, Mr. William Jehle of the NYCTA and Messrs. Chris Kalogeras and Steve Martin of the CTA were instrumental in assuring that the necessary personnel were present at the meetings and that subsequent information was provided as necessary.

The author also is indebted to Dr. Paul J. Remington of BBN for his assistance in extending the analytical model for predicting the performance of the resilient fastener.

Question: There seems to be a strong coupling between the girders and the ties on an elevated structure. Is there any research that has been performed on damping between the tie and girders?

Kurzweil: Yes, there were tests conducted in Stockholm where pads were put in between the ties and girders; and, in fact, some noise reduction was achieved. The current thinking, both in Stockholm, and here, is isolation introduced between the rail and tie is more effective with noise from both the ties and stringers reduced. Tests in Stockholm, indicated the noise originating from the stringers was reduced, having little effect on noise stemming from the ties and rail.

Question: Have you studied the effect of bonded versus non-bonded fasteners as related to noise and vibration?

Kurzweil: No. My general impression is that the reason for going to bonded fasteners has no specific relevance to the vibration effectiveness of the fastener. If you can design a bonded fastener with the same vertical stiffness as an unbonded fastener you will have the same vibration reduction effectiveness. There may be other reasons for using a bonded fastener that someone else may want to address.

Gildenston: I have seen only one specification that has recognized unbonded fasteners will exhibit greater changes in vertical stiffness, relative to bonded fasteners, where the surfaces are lubricated, i.e., by water or rain.

Wilson: The performance of the TTC (Toronto) unbonded fastener can be altered by changing the stiffness of the pad. There is a basic difference in the vibration isolation provided by bonded and unbonded fasteners; that it is not due to the bonding, it is due to the design of the fasteners. You have better control over the end product with a bonded device when you know what the interface is going to do. Another aspect is the number of pieces to contend with during handling and installation.

Gildenston: The anchorage area has mechanical wear problems and electrical problems. With fully bonded fastener, whether the anchorage area is fully encapsulated or bonded, the elastomeric interface between the top steel plate and the insulating element (regardless of plastic sleeves, or molded plastic, etc.) prevents the introduction of water in that area. It also forms a barrier to the mechanical action of the top plate against the insulator. A top steel plate wearing against the hard insulative sleeve will eventually result in a mechanical breakdown. When rail grinding is performed, and "debris" is formed, there is a greater opportunity for the "debris" to introduce itself along unbonded surfaces with a resultant loss of signal. The TSC report (see presentation by Mr. Witkiewicz) discussed Toronto steam cleaning the fasteners but did not mention the electrical breakdown of the unbonded fasteners.

Anon: No one seems to realize why fasteners were originally bonded. Originally rigid clips were used and the bonding provided shear resistance against longitudinal loads. With the introduction of elastic clips (i.e., with a positive hold down) there is no longer the need. Now it depends on what you are anchoring the spring clip with, as opposed to what you're anchoring the rigid fasteners with. If you are anchoring both of them separate from the base, you would still need to depend on the bonding.

Gildenston: I think the question of whether it is a rigid or flexible clip has nothing to do with bonding the way the present anchorage is designed. If you have a rigid clip that holds the rail, the only thing that allows the rail to move in relation to the ground is the bonded shear pad.

McEwen: I would like to go back to this predictability of long term longitudinal load restraint. Without having some established loading condition or actual retention through the fastener, I don't see how predictable results can be maintained over a long period of time. I'm looking for a predictable load transfer from the rail to the structure and it is the fastener that carries the load through it. We have to develop a performance level in this area that is going to be predictable, so that it will function, not only on day one, but five years hence.

Anon: We are talking about clips and fasteners. Clips being a resilient or rigid device to hold the rail to some type of sub-structure. The fastener provides the base, to which the rail is attached by the clip. We ought to keep these two things separated.

Hanna: Let's deal with the system as a whole, regardless of whether its clips are rigid, or resilient. With respect to the question on longitudinal restraint, in this regard the repeated push-pull test is intended to give an idea of long term longitudinal restraint.

McEwen: I agree that is its purpose; how reliable it is we are not really sure yet.

Wilson: I think the bonded fastener does provide a more predictable restraint. In the case of the unbonded fastener, the anchor bolt and sleeve hold the top plate in place and slippage occurs between the resilient clip and the rail and that is much less predictable and more subject to the conditions Mr. Gildenston brought up. The bonded fastener can be made to have a much more predictable response.

Anon: Once the spring clip slips, restoring force has been lost. With the bond, you always have restoring force.

Hanna: Once the bolts loosen on a rigid clip, restoring force is lost as well. That was the reason for replacing all rigid clips on the Long Island Railroad. With the wire clip, they can look and see if the clip is there providing a known force. With the rigid clip, the hold down force is unknown.

Anon: I've never seen any reports that document the longevity of the holding force of the spring clip. I'm sure several of the good companies here could provide that data. The only advantage of an unbonded fastener is that it is relatively cheap. Where do we go from there? Do we solve the same problem with the same configuration? Do we get the same fatigue life and load distribution?

Tillman: Mr. Gildenston, I understood you to say that there was a place for more performance requirements and specifications in place of testing. Is that true?

Gildenston: No. What I meant to say is that many specifications grew out of a desire to avoid certain design problems. In that respect they can't be faulted. When a particular specification comes to a manufacturer, one line in the specification may make the manufacturer alter his design. We feel hemmed in. The elastomeric callout, for example, limits the elastomer to be made of neoprene. Are there any authorities that use something other than neoprene for an elastomer?

Anon: BART, SEPTA, WMATA as a blend on TW-1.

Tillman: In the past we have been too restrictive in design and need to go to performance elements in our specifications. But, I would like to ask Dr. Hanna, does he feel that a set of parameters can be defined which will actually reflect in field performance? These are what we really need; but that is where the difficulty begins, because designers all come up with different parameters for testing.

Hanna: Yes, but it has to be done in conjunction with field testing, because it is by that means that the data required for a performance evaluation is derived.

Gildenston: One factor is that in three million cycles of testing, with one exception, the test is carried out on a dry fastener. Who can tell me where it doesn't rain? Secondly, surface debris, from rail grinding and such is never introduced. How do we handle this?

Hanna: Vancouver introduces moisture in the repeated load test for the last one-half million or one million cycles. Moisture is not introduced on a continuous basis, however.

Sluz: Related to the response (of Mr. Gildenston) concerning changes in design specifications that cause manufacturers to redesign their products: How much redesign is actually done. If specifications were all uniform how much cost savings would there be in a one-size-fits-all fastener?

McEwen: There are so many different vehicle systems and so many different structural requirements for fasteners, it is not possible to get a one-size-fits-all fastener from the structural standpoint.

Sluz: I agree; Dr. Hanna had a slide up (Dr. Hanna's presentation figure) which showed several specifications from many transit systems. One could notice that several systems had identical specifications but employed vehicles with greatly dissimilar wheel loads and suspension systems. It appears that specification parameters can be quite arbitrary. In addition, on the same system, much different loading conditions exist on tangent track than on curves, on well maintained track than on poorly maintained track. The same fasteners are still used.

Anon: In some instances you don't have the opportunity to know what kind of load will be encountered. For example, we had to write a specification before we knew which vehicle was to be selected.

Gildenston: There are clauses written into design specifications that literally cause major design changes and there are other clauses which give us less severe problems. One of the specifications for the WMATA fastener, requiring a minimum lateral stiffness seems to be written backwards according to the TSC tests. Current specifications seem to force us to make a stiffer fastener when TSC results seem to indicate that laterally softer fasteners can better distribute loads.

Weinstock: Along those lines, what is sought is a specification that describes what a fastener is supposed to accomplish. A fastener is supposed to distribute load from the rail to the supports and to attenuate ground vibration; nothing in the specification is doing that now. What is needed is a consensus on what kinds of things should be put into the specifications to address ground vibration. These should include maximum compliances and load distribution properties.

Hanna: What Dr. Kurzweil showed earlier can be related to the stiffness characteristics, and so, is an easy way to arrive at those numbers.

Wilson: We have tried to incorporate performance in the fastener specification indirectly through the stiffness specification and other requirements on the fastener. How does one perform a noise and vibration performance test on a fastener in a laboratory?

Gildenston: Our greatest fear as a manufacturer is that someone will devise an exotic test that will be difficult to perform in a reasonably well-equipped laboratory. Specifications could be divided into two categories. One that addresses what I will call rail head control, or keeping the train on the tracks; the other that goes beyond vertical stiffness or perhaps the dynamic to static ratio to address the other thing a fastener is supposed to do.

Phillips: It is not quite that simple because as the TSC-WMATA tests show, more factors are involved that just noise and vibration control, e.g., rail, wheel wear and ride quality.

Anon: Another important aspect of the qualification test is to determine a projected life, which is a tough problem. Here, the matter of restrictions on neoprene and natural rubber enter. The requirements for boiling the elastomer in oil is an extended life test. Perhaps that is a reasonable test.

Gildenston: How much No. 1 and No. 3 fuel oil is on board a rapid transit train? The attack of the petroleum distillate on an elastomer falls off with the square of time. There is only a very small area that is subject to attack.

Anon: That is only for a bonded fastener.

Gildenston: The test specimen is free to be attacked on all sides. Why not very slow, especially at normal operating temperatures. If you put grease onto a fastener and leave it there for 10,000 years, it may penetrate one quarter to one half an inch; which would only be on that small portion where it touched.

Anon: While we are talking about elastomer tests, we are talking about ASTM tests performed on dumbbell samples. Even if we assume No. 1 and No. 3 oil tests do simulate elastomeric aging, it should be tested on a fastener. We should look at ASTM requirements and model the acceptance tests we have done to show about 300% swell.

Gildenston: No, it's 100%.

Anon: Usually it swells about 300%. Where we have done this, the attack is on the surface and can apparently be scraped away with a penknife. What effect this has on fastener life is probably minimal or none at all.

Anon: We have seen a specification recently that called for the oil test, then continued to state that if you use a particular type of elastomer, that part of the specification does not apply. It was written that way to cover both natural rubber and neoprene.

Gildenston: Within the specification for the material, the callout for testing natural rubber one way and neoprene another makes no sense.

Anon: There are blends that provide oil resistance, perhaps not to the same degree as neoprene, but certainly to a high degree.

Sluz: An important question related to accelerated life tests is: How many tests are enough? What is a fair sample? A bonded fastener is tested as a unit, perhaps an unbonded fastener shouldn't be. It may be better to test each component of an unbonded fastener individually.

Hanna: First, it is very difficult to establish a test sample; however, most specifications now require three or four fasteners to be tested statically. Static testing is not of major concern, however; of more concern is the repeated load and durability testing. One must consider the cost of the program to minimize the cost to the transit authority, manufacturer, or whomever is sponsoring the work. My personal view is to take the two fasteners with the most extreme behavior based on static tests, i.e., the fasteners with the minimum and maximum range of whatever is being tested, and use these for repeated load testing.

Anon: We ought to recognize statistically the sample is abysmal; but the problem is that when the tests go on for a month, and require fairly expensive machinery, one can't afford too many tests.

Sluz: If the test is not going to give a representative indication of performance, why do it at all?

Anon: Statistically speaking, it is a lot better than zero.

Hanna: In some cases, it could be to the disadvantage of the manufacturer to accept the results of a single test, if it happens you are testing a sample on the low end of performance. On the other hand, if it is on the high end, the manufacturer could benefit.

Sluz: What you propose is to vary the number of static tests according to the range of characteristics. The wider the gap between minimum and maximum characteristics, the more tests that would need to be run. The two fasteners with extreme characteristics would be tested under repeated load.

Hanna: That is correct.

THE TRANSIT EXPERIENCE WITH DFF'S

BART's Experience with Direct Fixation Fasteners

Vincent P. Mahon
Manager, Power and Way Maintenance Division
Bay Area Rapid Transit District

The Bay Areas Rapid Transit (BART), a high speed rail transit system servicing the San Francisco Area with a mainline of approximately 150 track miles is divided almost equally between "at grade," "subway" and "aerial" distances. The subway and aerial portion represent 100 track slab miles or 200 miles of continuous welded rail anchored on 36 inch centers, requiring 352,000 direct fixation fasteners. The material value of the fasteners alone represents an investment of over $13,000,000 today.

The direct fixation fasteners installed by the construction contractors, shown in Figure 1, are the combination serrated plate and clip type with two clip bolts and two anchor bolts. The serrated plate provides for positive clip attachment while allowing for two inches of alignment adjustment. Guard-rail fasteners, shown in Figure 2, are similar except the plate is elongated and the guardrail saddle added. Prior to acceptance for installation the supplier was required to submit test results to insure the fasteners met BART specifications. These specifications required three test methods: base line; dynamic and heat aging. Testing was performed by the Association of American Railroads Research Department.

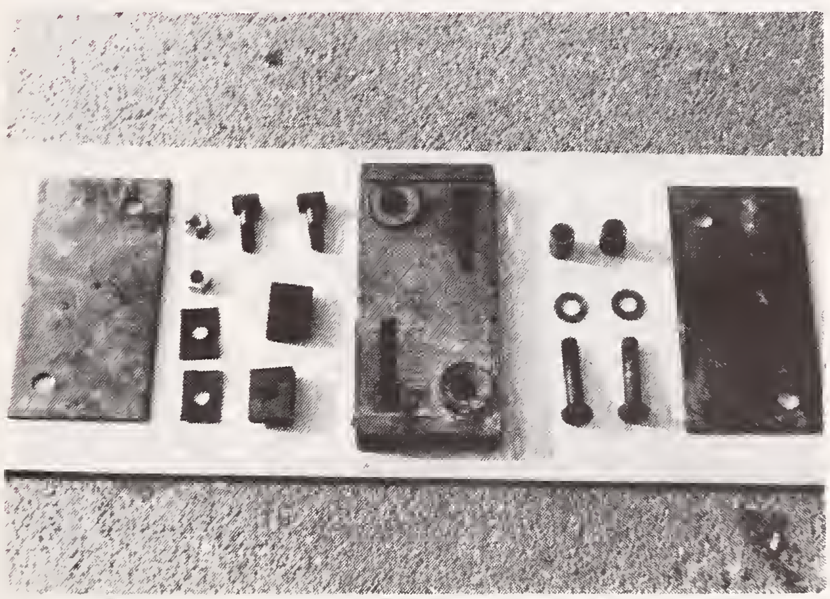

FIGURE 1. DETAIL OF DFF USED BY BART

Base line testing was a three part test: longitudinal deflection, shown in Figure 3, to 0.10 inches required a 3,700 pound load on end of one rail and a 3,500 pound load on the end of the second rail. Lateral deflection, shown in Figure 4, using a 3,000 pound load applied to the side of head of rail resulted in 0.156 inches and 0.105 inches for two fasteners tested. Insulation resistance using a 500 volt tester was "infinity" for both fasteners.

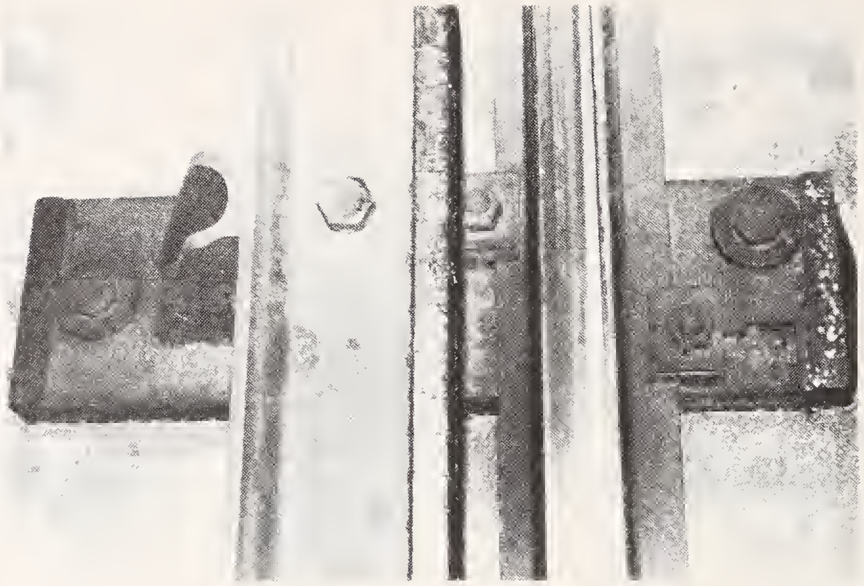

FIGURE 2. GUARDRAIL FASTENER

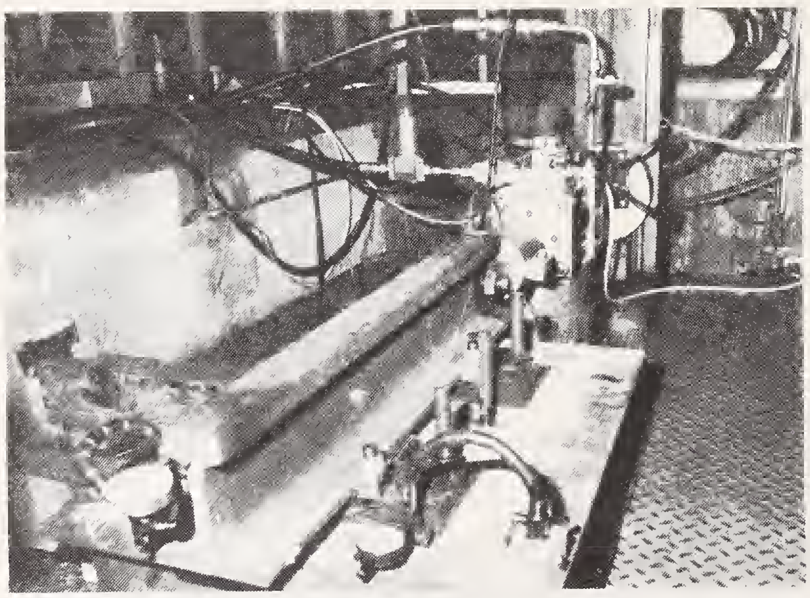

FIGURE 3. DFF LONGITUDINAL DEFLECTION TEST

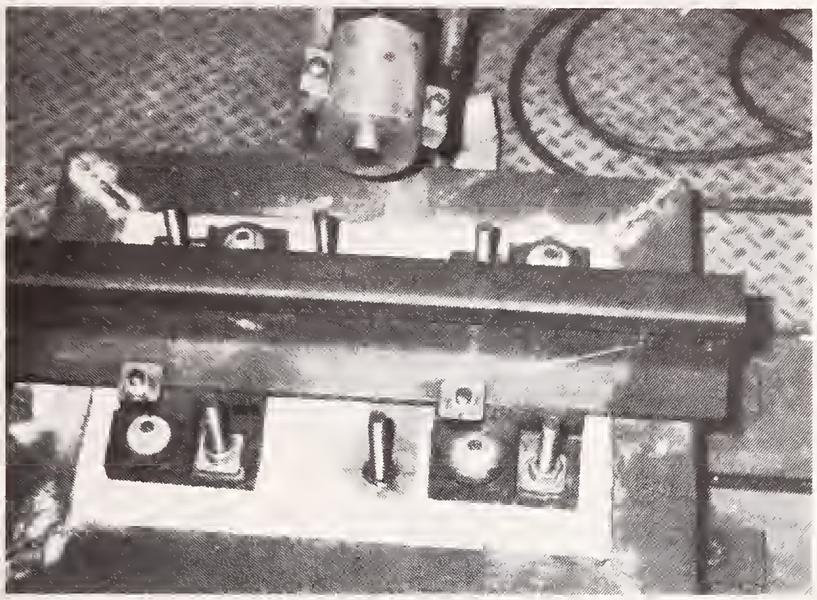

FIGURE 4. PREPARING FOR DFF LATERAL DEFLECTION TEST

Dynamic testing, again using the same fasteners on the "push-pull" completed 1.5 million cycles each without failure. No change or loss of torque in anchor or clip bolts was noted. "Tie wear," shown in Figure 5, the second portion of dynamic testing showed the fasteners completed 3,000,000 cycles without failure in the tie wear machine. The final dynamic test consisted of an extra 10,000 cycles of tie wear machine testing with the gauge anchor bolt removed, again without failure. No reduction in torque on clip bolts was noted, reduction from 200 foot pounds to 170 foot pounds torque was noted on the field anchor bolt of one fastener.

Heat aging for 70 hours at 212°F was the final principal test. Longitudinal deflection of 0.10 inches was reached with a 3,500 pound longitudinal load on end of rail for one fastener and a 3,750 pound load on the second. Lateral deflection with a 3,000 pound load applied to side of head of rail was 0.092 inches on one and 0.073 inches on the second. Again, insulation resistance with a 500 volt tester was infinity.

Further testing and comparisons were made. All results were within BART's specifications and the offered fasteners were accepted and installed.

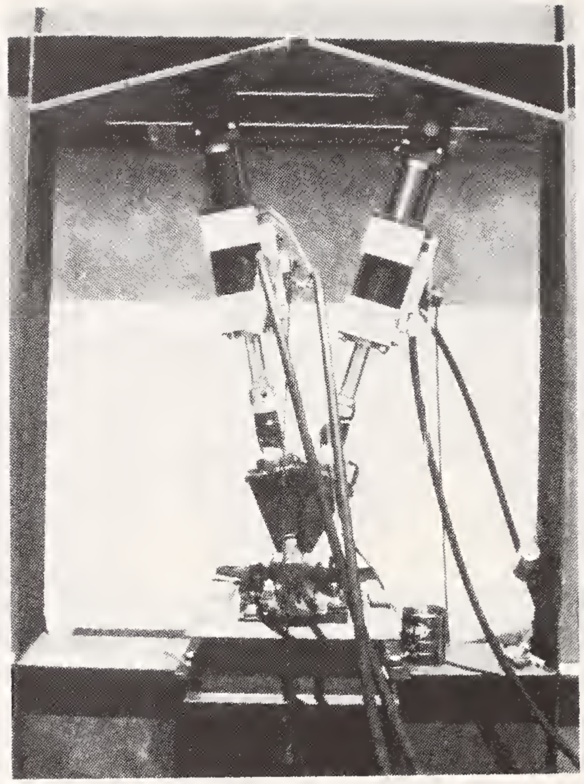

FIGURE 5. DFF TIE WEAR TEST

The success of the direct fixation fasteners in passing their initial testing has been proven in field use. In 10 years of service, with 9 million wheel passes, shown in Figure 6, carrying over 355 million passengers and 97 million track tons, there have been no failures of the fasteners. Not only have the fasteners passed the daily operating load test but unplanned stress tests: fire and flood. To review these stress tests briefly, during the period between construction acceptance and prior to train operation a portion of one tunnel was exposed to a high, prolonged external ground water pressure resulting in water flow through concrete walls. Drains containing concrete wash retarded water removal for a period. During this period and before stopping the water flow with grout the high humidity accelerated ferrous oxidation. Prior to commencement of revenue operations, these fasteners were removed, sand blasted and an epoxy coating was applied. The fasteners were reinstalled and have performed without incident since.

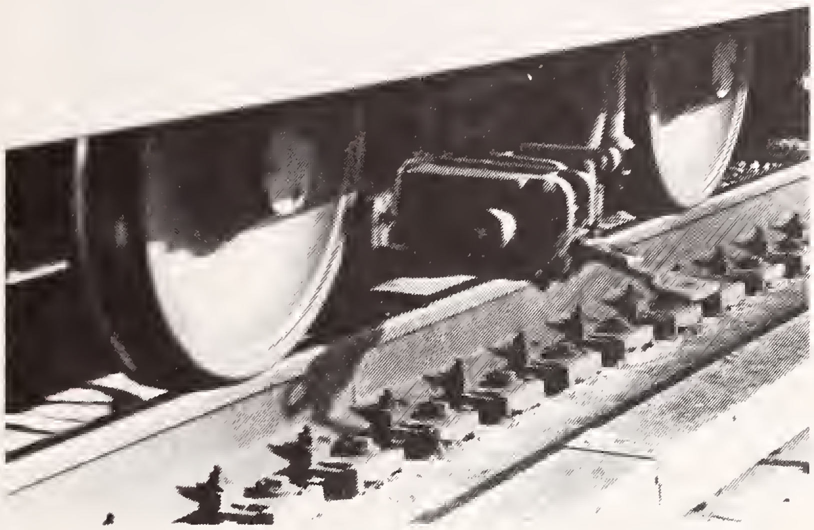

FIGURE 6. OVER 9 MILLION WHEEL PASSES WITHOUT DFF FAILURE

The second operational stress test was the transbay tube train fire in which three transit cars were destroyed. Temperatures at the tube crown were estimated at above 600°F for over three hours. The concrete crown spawlled to a depth of two inches and metal skin on the vehicles was totally consumed. A survey of the running rail indicated the fasteners held firmly. Neither alignment, surfacing nor torquing was required in the fire area.

Maintenance on the direct fixation fasteners used by BART is not imaginative nor complex, rather, it's a straightforward operation. Long range, cyclical maintenance is planned and scheduled. Maintenance is dictated when a given number of bolts are loose within a given distance. Experience has shown this to be approximately each 12 months. In order to hold proper gauge and alignment, we do not allow the number of loose or broken clip bolts to exceed 25% of the total in a distance of 39 feet. Bolt torquing is the base program of the direct fixation fastener maintenance. In this, two maintenance workers proceed down the track with a penetrating lubricant thinned 5 to 1 with diesel oil, lubricating each bolt. Following them are two bolt torquing machines for each rail, shown in Figure 7. One machine torques the anchor bolt to 200 foot pounds while the other torques the clip bolt to 150 foot pounds. BART's minimum standards require a combined torque of 250 foot pounds. Depending on track availability, a bolt torquing crew can torque up to three quarters of a mile of track per shift.

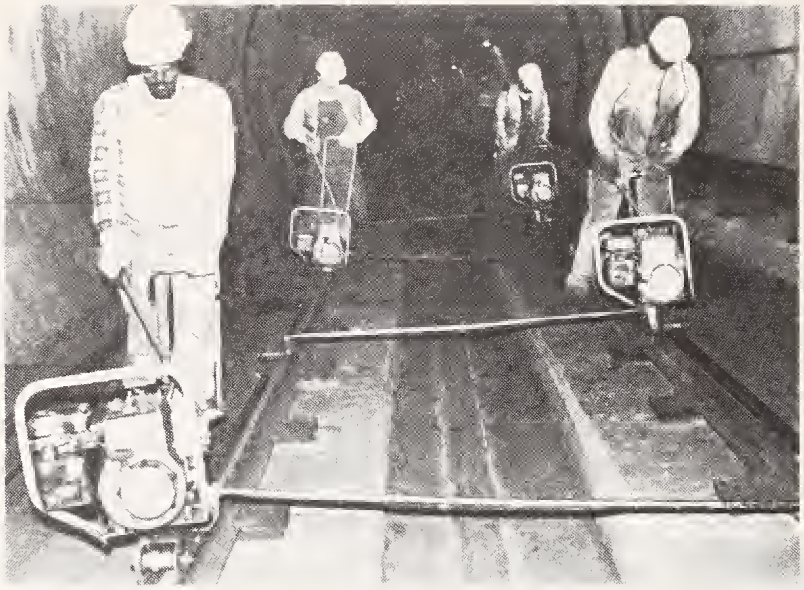

FIGURE 7. TORQUING DFF ANCHOR AND CLIP BOLTS

Another track maintenance program which does not directly contact the direct fixation fasteners nevertheless greatly increases their life expectancy and the ability of the bolts to hold their torque. This program is rail grinding. Through meticulous adherence to a precision rail grinding program irregularities in rail surface and rail head sides are eliminated; thus wheel impact thrust to fasteners is minimal. Additionally, the swing factor is substantially reduced, lessening the chance for anchor and clip bolts to work loose or shear from stress.

BART's geometry vehicle, recently placed in operation, will afford track crews the opportunity to further reduce stress on fastener clips and bolts. The geometry vehicle's ability to precisely measure gauge will allow track crews to readily regauge track in areas of need, reducing the potential of train imposed loadings against the side of the rail head due to track gauge deviation which culminates in thrust against the clips and bolts.

These and other maintenance actions which bear directly or indirectly on the holding ability of the direct fixation fasteners increases BART's safety factor for patrons and employees. This is really the final direction of all our maintenance efforts.

In 1978, Scientific Service, Inc., of Redwood City, California, was commissioned to test a sampling of in-service BART fasteners. This would further assure track safety attributable to the direct fixation fastener performance ability, verify our maintenance programs and if necessary, allow for the procurement of replacement fasteners and associated expense. The following is taken from Scientific Service, Inc., "Test Report of the BART/ Landis Fastener," dated June, 1978.

SSI TEST

A test program was conducted on the BART/Landis track fasteners to determine the amount of wear that has occurred in service to date, and to furnish data to allow estimation of their useful life. Six fasteners were evaluated: two removed from a curved section of track; two removed from a tangent section of track; and, for comparison, two unused fasteners taken from the BART warehouse.

All the fasteners were subjected to a series of base line static tests which duplicated the tests performed for the original qualification of these fasteners. The results showed that the in-service fasteners had not measurably deteriorated in over five years of service. The tangent track fasteners were subjected to a dynamic Tie Wear Test, as shown in Figures 5 and 7 (also part of the original qualification tests) and again, no measureable deterioration was noted. The curved track fasteners and the unused fasteners were subjected to a new American Railway Engineering Association test -- the Inclined Vertical Repeated Load Test -- which was designed to more closely approximate the behavior of train-imposed loadings on curves. During this test, failure of two fasteners occurred. Further analysis of these failures, however, and a computer analysis of the actual service loads indicated that this test, as performed, was excessively severe.

FIGURE 8. TIE WEAR TESTING OF DFF AFTER 5 YEARS OF SERVICE

The overall conclusion from the program, therefore, is that the BART/Landis fasteners are entirely adequate for the job. From the results of the static and dynamic tests that are directly relatable to the BART system and from the computer analysis of the loads on the fasteners as related to fatigue, it appears that a fastener's life approaches infinity -- that is, the useful life of a BART fastener will in all likelihood not be a factor of the loads on the rail system under normal service conditions and may well depend on other conditions, such as environmental deterioration, heat, ozone, sunlight, or some unknown type of failure. However, from visual inspection and from the electrical tests, none of these factors has caused significant harm to these fasteners to date.

A time saving benefit has been developed using the direct fixation fastener in an unintended way. BART's subways have several 500 to 900 foot radius curves with no restraining rail. This requires transposition or renewal every three years due to gauge wear. Because of the distance to the curves from staging sites, restricted working areas and short track time availability, each minute is invaluable. When performing transposition or renewal we reverse the rail clip on each third fastener. This allows maintaining proper gauge and alignment for replacement rail by providing a reference point for seating the base of the rail on the plate. Using this technique rail is automatically positioned, expediting the renewal program and saving hours. This use was not incorporated into the fastener design but the method was discovered while experimenting in time-saving methods. The procedure is not limited to curves but may be used on any trackway location where regauging or realignment may present a problem. This feature should be given consideration in any future design of fasteners.

SUMMARY

For ground-borne noise and vibration testing purposes, one thousand feet of modified, low stiffness direct fixation fasteners were installed in a circular, steel encased subway. It is generally believed "soft" fasteners would transmit less ground-borne noise and vibrations than those having greater stiffness. The modified fasteners were designed to have one fourth the stiffness of standard fasteners. Without discussing documented test detail, suffice it to say the results were unexpected and contrary to those anticipated. The "soft" fasteners produced about the same level of ground-borne noise and vibrations as the standard fasteners. Possibility of grout filling spaces or voids in the modified fasteners was advanced as a reason for the similar test results. Based on these tests, it is suggested that for ground-borne noise reduction purposes, intensive testing be performed on direct fixation fasteners and their relation to design, elastomers, the various construction practices used in areas of mounting and other related materials. Guidelines and/or standards should be established for anticipating ground-borne noise and vibrations.

After 10 years of operation we are well satisfied with the service quality, life expectancy and BART's maintenance program of the direct fixation fasteners which hold the rail to slab beds. The one unsatisfactory factor in the whole area is the direct maintenance cost attributable to the fasteners due to the required torquing and lubrication program. For BART this cost equals $2,112 per track mile or $211,200 per year or $0.60 per fastener. If in 1968 when BART track specifications were being prepared workshops such as this were advanced to the state which they are today, spring type clips, as shown in Figure 9, or other bolt locking devices could have been added to the direct fixation fastener. This, I am convinced, would have greatly reduced our maintenance torquing efforts and costs. It is my recommendation that spring type clips or their equivalent be made a part of the trackway for all future high speed heavy and/or lightweight rail transit systems. They will provide increased safety, long life, less maintenance and lower the maintenance cost per mile for those future rail transit systems.

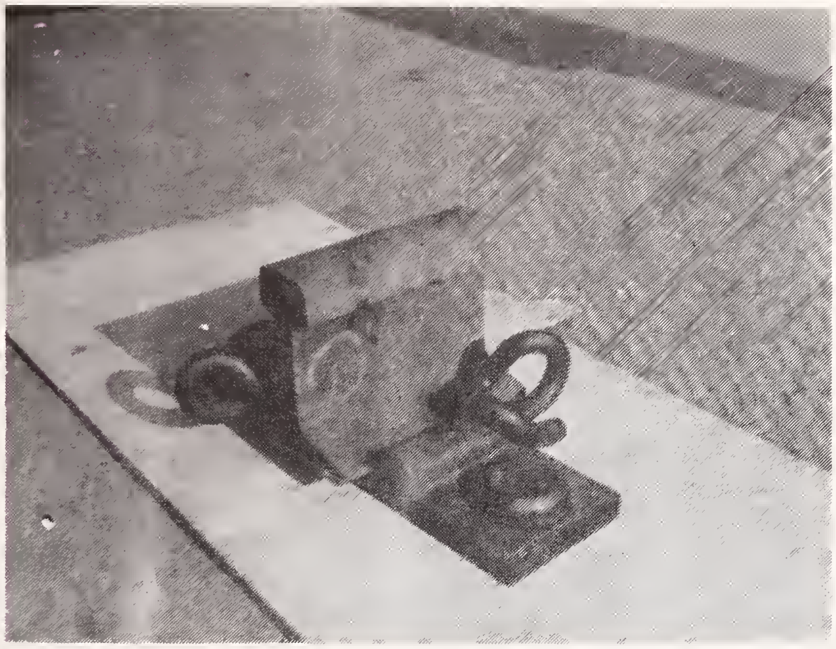

FIGURE 9. MOUNTED SPRING CLIP DIRECT FIXATION FASTENER

Track Fasteners on the WMATA Metrorail System

Arthur Keffler
Chief Trackwork Engineer
DeLeuw, Cather & Company

INTRODUCTION

The purpose of this report is to summarize the history of direct fixation fasteners used on Metro, to describe the problems incurred and the remedies proposed.

In the context of today's technology, a direct fixation fastener is a device featuring an elastomer pad, steel plate(s), and various anchoring and insulating components used to attach the rail directly to a concrete invert.

Of the projected 101-mile Metro system, approximately 58 miles are underground or on aerial structures, requiring approximately 490,000 direct fixation fasteners. The balance will be installed at-grade using tie-and-ballast construction. To date, 340,000 direct fixation fasteners have been placed under contract; 224,000 are in service on the system; while the other 116,000 are in various stages of installation. About 150,000 fasteners remain to be purchased.

The fastener must provide vertical, lateral, and longitudinal stability to the rail and the vehicles. It must dampen vibrations from passing trains and isolate the rails electrically from each other and from the ground. It must fulfill these requirements and, at the same time, it must offer adequate service life, simplicity, interchangeability and maintainability. This report will discuss how the performance parameters of Metro's direct fixation fasteners were determined, how the problems encountered to date relate to those parameters and how they are being resolved.

BACKGROUND

In 1969, when the first Metro fastener procurement documents were initiated, the Toronto Transit Commission, Delaware River Port Authority and San Francisco Bay Area Rapid Transit District (BARTD) were using direct fixation fasteners. These systems were investigated and evaluated. Philadelphia was in the process of introducing theirs on the South Broad Street Subway. Of the three systems with experience, only BARTD had gone through a series of system demonstration tests verifying performance type specifications and including qualification as well as acceptance criteria. The other fasteners, all similar in concept, were procured using specifications for individual materials, some requiring tests, but without an overall fastener system testing program. Assumptions used in developing the Metro fastener specification were considered state-of-art in 1968.

Since the WMATA fastener criteria were developed, Atlanta, Baltimore and Buffalo have procured fasteners utilizing similar performance specifications. They were derived from the WMATA and BARTD performance specifications to meet the specific vehicle and trackbed requirements of those properties.

WMATA, BART, MARTA (Atlanta), MTA (Baltimore) and NFTA (Buffalo) utilize similar fasteners while Toronto and the Delaware River Port Authority fasteners are quite different. The WMATA, BARTD and NFTA fasteners utilize two steel plates, top and bottom, with the elastomer bonded between them.

These are installed at 30-inch or greater spacings and bolted rigidly to the concrete invert. The Toronto system uses mostly unbonded components fastened to the invert 24 inches apart, in a fashion which compresses the elastomeric pad and uses a double coil spring washer to make the fastener resilient in the uplift mode. MARTA and MTA feature only one steel plate on top with the elastomer bonded to it. The Toronto fastener does not have lateral adjustment capability, all the others do; some use the anchor bolts, other use the rail hold-down device for lateral adjustment.

TRACK ANALYSIS

The analysis of Metro track, which led to the formulation of performance specifications for its fasteners is described in detail in De Leuw, Cather's "Trackwork Study," Volume II (second edition) published in July 1969. It was based upon:

1. Vertical and lateral wheel loads of 30 kips and 8 kips, respectively, representing expected vehicle weight, dynamic factors as well as projected track and vehicle conditions.

2. The configuration of the wheel loads, as determined by recommended axle and truck spacings (7 feet 6 inches and 52 feet, respectively).

3. Lateral and longitudinal fastener loads resulting from thermal rail forces.

4. 115 RE rail section and its mechanical properties.

5. A desirable vertical rail support modulus, selected to reduce noise and vibration transmission, of 3,000 lbs/in/in.

6. Allowable lateral rail deflection to minimize gauge widening of 1/8 inch nom. and 3/10 inch max.

7. A fourth order ordinary differential equation which mathematically models an infinite beam on a uniform continuous elastic foundation.

An economical design goal was set of providing for the largest possible fastener spacing commensurate with the above design parameters and with good engineering judgment.

The mathematical model used in De Leuw, Cather's studies reflects the characteristics of an infinite beam supported by a continuous uniform elastic foundation. While not actually representative of a rapid transit track, where fasteners represent discrete points supporting the rail, the use of the model was justified by the assumption that at each discrete point, the fastener would act as if it would support the rail uniformly over the entire fastener spacing, and the support modulus was considered equal to the fastener spring rate divided by the fastener spacing. The variation introduced by this assumption was not considered significant, provided the fastener spacing ultimately selected was less than the value computed from the solution of the mathematical model. This method of calculation had the advantage of introducing parameters for fastener spring rate and fastener spacing into the analysis.

From the above parameters and the solution of the mathematical model, the vertical and lateral fastener loads as well as the rail bending moment were computed. After checking whether the rail bending stresses were within the allowable range, the corresponding fastener loads were stipulated in the performance specifications and related test criteria.

A fastener must prevent the rail from "running" under the tractive effort of the vehicle or under the effects of thermal expansion which can cause buckling or tension failures as well as misalignment of special trackwork. On the other hand, it is desirable that the rail slide on the fastener before the device or its anchor bolts fail. On aerial structures, the problem is compounded by large interactive forces between rail and structure caused by ambient temperature changes. The analysis of this phenomenon is complex due to the large number of structural redundancies. A discussion of the problem is found in De Leuw, Cather's report prepared for WMATA entitled, "Feasibility of Direct Fixation on Unballasted Structures, Appendix A: Interaction Between Rail and Structure on Unballasted Aerial Structures."

On aerial structures, standard fasteners having substantial longitudinal restraint capability are used to control rail gap in the event of a rail break. They are placed at locations where there is minimum potential for thermal interaction. At all other locations, an aerial direct fixation fastener with small longitudinal restraint characteristics is used to minimize thermal interaction while still providing sufficient restraint of the rail to dampen noise and vibrations.

The fasteners must also provide the electrical isolation necessary to ensure reliability of signal circuits and to minimize stray current corrosion. The requirements are based on the results of investigation performed by the Association of American Railroads (AAR) and the American Committee on Electrolysis.

Ease of construction, inspection, and maintenance requires minimizing the number of parts in a fastener. Interchangeability requires that all fasteners have consistent dimensions such as width, length, thickness, and anchor bolt location. Several of these parameters were added to the specifications after the first procurement in order to standardize the system.

To permit accurate gauging of track during construction and regauging to compensate for rail wear, the fastener has a lateral adjustment range of one inch.

Laboratory repetitive loading tests were required to provide an indication of future service life, the number of cycles being limited by the schedule and financial constraints. In 1969, an accelerated three million cycle load test cost approximately $25,000 and required approximately four weeks. To date, repeated load tests have been limited to three million cycles, under the assumption that any possible fatigue failure would occur before that exposure.

(Today, fatigue test costs have been reduced to about $1,500 to $2,000 per million cycles.)

PROCUREMENT HISTORY

In order to insure the highest possible ride quality, noise and vibration control, electrical insulation, rail creep prevention, gauge holding capability, ease of maintenance and longevity; a comprehensive series of stringent acceptance and quality control tests were developed and specified by De Leuw, Cather. They have governed the procurement of direct fixation fasteners since the inception of the project.

The non-proprietary performance specifications prepared for Metro do not include detailed designs but consist of performance tests with acceptance criteria and a minimum of dimensional constraints to insure interchangeability as well as economy and ease of maintenance. They also stipulate the sampling and minimum quality control tests required. It has been left to the manufacturer to design the fastener that will fulfill the requirements of the specifications and to submit shop drawings including a detailed description of installation procedures for the approval of the Engineer. Upon approval of the shop drawings, selected samples of the fastener are tested by an independent testing laboratory under contract to the supplier in accordance with the acceptance criteria specified.

After the sample fasteners pass the qualification tests, no change in design or manufacturing process is permitted without review and approval of the Engineer. Further testing may be required. Production fasteners are grouped in lots, each of which must satisfy a quality control program before being accepted by the Engineer. The quality control program includes static and repeated load tests. Furthermore, a standard warranty clause requires the contractor/supplier to replace any item found to be defective.

Theoretically, at least, this approach had the merit of providing the necessary incentive for the industry to develop a competitive product and thus fulfill UMTA's objective of procurement from multiple, non-proprietary sources.

In practice, however, the results have been mixed. As illustrated in Table 1, a maximum of three bids was received for two of the seven contracts let. Two generated two bids each and the remainder were either supplied directly by the track installation contractor or through a sole bidder. For each individual contract, a different type of fastener had to go through the series of acceptance tests at significant costs, with delays incurred in the process. Several variances from the specifications had to be granted to the manufacturers in order to keep the construction on schedule. During the Metro construction, various changes were made to the performance specifications originally stipulated for the first trackwork installation contract (TW-1):

1. Beginning with TW-2, aerial fasteners were specified.
2. Beginning with TW-2, the thickness (1-1/2 inch), width (7 inches), length (14 inches) and anchor bolt location of the fastener were standardized to permit interchangeability.

3. Prior to TW-3, bonded or unbonded fasteners were allowed; with TW-3 only bonded fasteners were allowed.

4. In TW-1 and TW-2, direct fixation fasteners were both procured and installed by the trackwork contractor. Beginning with TW-3, fasteners were procured separately by WMATA and supplied to the track contractor for installation. Prior to this modification, the fastener tests included the anchor bolt installation system. After the modification, special tests were added, requiring the installation contractor to qualify acceptable materials and procedures for installing grout pads and anchor bolts.

5. Beginning with TW-5, a 500,000-cycle repeated load test became part of the minimum requirements for the quality control program.

6. Beginning with TW-8, the lateral adjustment feature was restricted from being designed as part of the anchor bolt assembly. This was intended to eliminate welded stud problems characteristic of the TW-2, 3 and 4 fasteners as well as problems related to releasing and tightening the nuts on the studs.

7. While not part of the fastener itself, beginning with TW-7 which will soon be awarded, female threaded anchor inserts will replace the threaded studs used to anchor fasteners to the invert.

EXPERIENCE

The fastener type, quantity procured for each trackwork contract, and procurement status of each contract, are shown in Table 2.

Metro has approximately seven years of operating experience with TW-1 direct fixation fasteners. In TW-1, 27,000 fasteners were installed (Figure 1 illustrates its configuration). Significant problems requiring replacements have not been encountered with the fastener although some have been replaced due to excessive corrosion.

A total of 178,000 Hixson fasteners, illustrated in Figure 2, were installed in TW-2, 3, and 4. After approximately five years of operations with 92,000 fasteners installed in TW-2, two significant problems have become evident:

1. Many stud welds have failed, apparently as a result of fatigue. (This problem is discussed in greater detail further in this paper.) The remedial action to date has been to install a different type of fastener in replacement.

2. Anchor bolts have lost their bond to the invert due to epoxy failures. This is attributed to improper installation procedures (incorrect proportioning of components, poor mixing or use of soiled containers) or improper installation preparation (dirty bolts, dirty or wet holes), or both.

In TW-5 and 6, 104,000 fasteners (illustrated in Figure 3) have been installed, about 18,000 of which have been in service for a year. Approximately 7,000 fasteners were bought as an addition to the TW-5 and 6 procurement for installation in TW-7. Approximately 36,000 fasteners have also been installed by maintenance forces as replacements for failed fasteners at various locations. With up to two years of service on some of these fasteners no major service problems have been identified although an installation problem did develop. The anchor bolt assembly deformed when torqued, resulting in cracked insulators. The deformation appears to be precipitated by a non-uniform bearing condition between the grout pad and the bottom plate of the fastener. This condition has been eliminated by ensuring uniform bearing is provided in the area around the anchor bolt.

The last fastener procurement was for TW-8 and included 21,000 units. The configuration of this fastener is shown in Figure 4. There is no in-service experience to date although the fasteners have been installed.

MAJOR PROBLEM DISCUSSION

Background

The failed fastener replacement program has so far focused on the high rail of curves with radii less than 2,000 feet which have had five and one-half years of service. Table 2 gives the number of curves and the number of fasteners on the high rail for curves with radii shorter than 1000 feet and between 1000 and 2000 feet. Due to the complexity of replacing fasteners, the maintenance force replaces all fasteners in an area once failures have been identified.

Table 3 was developed from maintenance records and shows the progression of replacement of failed fasteners from May 1980 to December 1982. The first replacements began in late 1979, about two years after beginning service. To date 97 percent of the fasteners on the high rail of curves of less than 1000 foot radius have been replaced with lesser percentages on the flatter curves, tangents and low rails of all curves. A total of 21 percent of all fasteners have been replaced thus far.

Possible Causes

The stud failures plaguing the TW-2, 3 and 4 fasteners are a major maintenance problem for the Authority. At the request of the Authority, the Engineer called upon the Artech Corporation to investigate the welds of the fasteners. Artech's conclusions were that cyclic lateral displacement of the rivet resulted in a fatigue failure at the weld joining the rivet to the bottom plate and that design characteristics of the fastener, together with the quality of the weld, were definite contributing factors. The configuration of the stud of the TW-2 fastener was modified for TW-3 and 4. (See Figures 2 and 5.) This has not had any significant effect on the fatigue resistance of the weld.

Evaluation of the problem led to the deduction that two major possibilities existed: (1) the quality of the prototypes subjected to acceptance tests was substantially superior to the subsequent production-run fasteners; or (2) the prototype acceptance tests specified were not severe enough in (a) duration of test or (b) magnitude of load, to insure longevity under normal operations.

Answering the first possibility was accomplished by comparing production fasteners with the prototype fasteners. The comparison program, as originally conceived, called for completely retesting the prototypes along with testing the production fasteners.

Unfortunately, the prototype fasteners could not be found. As a result, the comparison of the prototype with the specification, shop drawings and production fasteners and any additional testing on the prototypes had to be deleted from the program.

For the remaining testing, De Leuw, Cather & Co. contracted with Scientific Service, Incorporated (SSI). SSI was chosen because they did the original qualification testing and because of their transit industry experience in testing direct fixation fasteners. They had both the personnel responsible and the test equipment used for TW-2, 3 and 4 testing and therefore were best able to accomplish the objective of duplicating the prototype testing on the production fasteners.

The SSI scope of work included:

- o Randomly selecting TW-2, 3 and 4 fasteners, 8 each, and marking them for identification.
- o Examining the welds, both before and after testing, in a manner that would permit qualitative comparisons.
- o Perform all qualification testing on TW-2, 3 and 4 production fasteners in accordance with their corresponding specifications and in a manner as nearly duplicating the original testing as possible.

The major findings of the investigation were (1) nearly every weld contained defects and (2) none of the fasteners were able to complete the three million cycle repeated load test. The welds failed at less than one million cycles.

Answering the possibility that the acceptance tests were of insufficient duration involved a review of the adequacy of the three million cycles of repeated loads used in the Vertical and Lateral Repeated Load Test.

The fastener should be designed so that the fatigue life is equal to or greater than the design life. One approach to this problem would be to analyze and design the fastener for stress levels that meet standard (AISC, AASHTO, etc.) allowable stress values for fatigue design. A second approach would be to produce fasteners and to test them to the number of cycles anticipated during the design life of the fastener. A third method, which is similar to the second, is to stop the cycling when "runout" is reached. Runout means that if fatigue has not occurred by a certain number of cycles, then the stress is less than the fatigue (or endurance) limit and it is not likely that fatigue will occur.

In order to apply any of these approaches, it is necessary to know the load environment. Assuming the design load is known, the first approach should be used by the fastener designer. However, because of the complexities (configuration and materials) of a fastener, it is not easily analyzed. Many assumptions have to be made. A finite element analysis could be made to obtain a more accurate picture but the analysis would still use numerous assumptions. To accept a fastener as having sufficient fatigue strength based upon calculations alone would not be prudent.

Assuming that the load environment is well known, the second approach would provide the most assurance. The time provided for testing would have to be lengthy and the testing cost may be significant. However, the time and cost may well be justified if premature failures are thereby prevented.

The third approach attempts to provide a degree of assurance similar to the second approach but with a reduced testing schedule and cost. It is based upon knowing the number of cycles for runout of the fastener. Because the fastener is made of many components, the runout for each component has to be known. The longest runout should be used for testing. For standard grade steels, 2 million cycles is the most common value found in references; however, 8.5 million cycles and a statement saying that there is no fatigue limit can also be found.

No data have been found on runout for elastomer, but the consensus of manufacturers is that there is none. The quality of the elastomer and therefore fatigue resistance can be controlled by the compounding. A manufacture could compound for a quality that would meet the 3 million cycle requirement but would deteriorate soon thereafter. The specification requires high quality elastomer, which may be responsible for the fact that there have been no elastomer fatigue problems on the operating system.

At the time of the development of the fastener specification, 3 million cycles was quite conservative compared to the generally accepted runout of 2 million for steel. However, with more recent findings concerning fatigue of steels, the characteristics of elastomer fatigue and the reduced costs today of fatigue testing, it would be prudent to increase the number of cycles to at least 10 million or, even better, to 25 million (based on the number of truck passages using the present operating schedule for the WMATA Blue/Orange line over a 25-year design life period).

Answering the possibility that the acceptance test loads were not severe enough to replicate the service environment has resulted in two test programs at WMATA:

1. The In-Service Direct Fixation Environment measurements performed by Wilson, Ihrig and Associates in cooperation with De Leuw, Cather & Company, and

2. The UMTA sponsored WMATA Fastener and Truck Test Program, Phase II performed by TSC and their subcontractors.

Each of these programs will be explained in detail in a separate presentation during this workshop.

The results of these measurements indicate that the load environment is interdependent of the fastener installed. Thus, while present test loads and acceptance criteria have been developed analytically and from limited empirical state-of-the-art data, the ideal procedure would be to determine a fastener's characteristics through in-service dynamic measurements. This would require installing a test section of each fastener to be considered.

CONCLUSIONS

Our experience at Metro, both the problems and the successes, have brought us to some conclusions in our search for the perfect fastener. During the year (1983), De Leuw, Cather & Company will be developing an updated fastener procurement specification. Our approach will be to make use of actual vehicle, track and structure as much as possible in the development of a new fastener procurement.

The first step will be to establish the fastener configuration. In this area, we will probably relax our present configuration requirements. While we intend to retain the interchangeability of fasteners, some relaxation of the dimensional requirements is possible. Even the thickness may be allowed to vary although this will require shims under thinner fasteners if new, thicker fasteners are intermixed with older fasteners.

Other characteristics will be reviewed as well. Either bolted rail clips or elastic clips may be permitted. Our concern will center on system results, not on geometrics or components. Since we have had no problems with the elastomer, that portion of the specifications will probably not be changed although it will be reviewed. The need for greater corrosion resistance will also be reviewed. While a number of fasteners at WMATA have been replaced due to corrosion, this has occurred at locations where there has been water intrusion in the tunnels. Overall, stopping the leaks may be a more economical alternative since all steel components are affected, not just the fasteners; however, where economical, corrosion-resistant features will be specified.

The heart of the changes to the specifications will be the load determination for fastener test and acceptance criteria. Ideally, since a fastener appears to influence its own load environment, as will be seen in subsequent presentations, each prototype fastener should be installed in a service environment and the resultant loads on it determined by field measurement. It would be desirable to have installations on both flat and sharp curves.

Subsequent to the determination of the appropriate loads for each type of fastener at each location, accelerated aging or fatigue tests will be run. Using the loads determined by the in-service test installation, a sampling of fasteners will be tested through at least 10 million cycles to evaluate its expected service life.

Finally, once a fastener has been selected from the prototypes tested, a carefully developed quality control program must be initiated will provide a high degree of assurance that production fasteners are manufactured of materials and by processes that result in fasteners of the same quality as the prototypes. The emphasis will be on the duplication of the product and less on the replication of the qualification tests.

Possible cost effective alternatives to procuring one fastener design that will withstand cycling to design life are: 1) have two fasteners - one for sharp radius curves and one for tangent and flatter curves; 2) have one fastener, designed for less than the worst curves, and a planned fastener replacement-program for the worst curves. Also assuming fastener spacing affects fastener load, which affects strength requirements, which in turn affects procurement cost, then an economic analysis should be performed to determine whether it is more cost effective to use less expensive fasteners at smaller spacing or more expensive fasteners at greater spacing.

The above process involves considerable time and effort, by both supplier and purchaser. Simultaneously with the development of the technical specifications, a procurement plan must be developed. This plan will seek ways of reducing costs and risks. Factors to be evaluated include combining procurements to spread the development costs over larger quantities, use of requests for proposals with technical data evaluation before award to improve coordination between supplier and purchaser, and separate testing contracts to limit supplier costs and improve communications between purchaser and tester.

TABLE 1. HISTORY OF FASTENER BIDS ON METRO

CONTRACT	DATE OF BID	QUANTITY	FASTENER UNIT		OTHER BIDDERS			
			SUPPLIER	PRICE	NAME	PRICE	NAME	PRICE
TW-1	2/24/71	27,120±	Landis	Unknown	Fastener furnished by Construction Contractor: Metro Track Constructors			
TW-2	11/28/73	91,820±	Hixson TW-2	Unknown	Fastener furnished by Construction Contractor: Metro Track Constructors			
TW-3	8/18/75	11,340 STD. 15,360 AER.	Hixson TW-3	\$22.35 \$24.20	No other bidders			
TW-4	12/8/76	64,300 STD. 5,300 AER.	Hixson TW-4	\$24.50 \$30.00	Lord Corp.	\$26.31 \$27.91	Transit-Track	\$27.00 \$28.00
TW-5,6	11/29/78	99,650 STD. 11,900 AER.	Lord	\$23.67 \$24.79	Transit Products	\$26.18 \$34.25		
TW-8	2/13/80	21,100 STD.	Hixson H-17	\$32.20	Lord Kinematics	\$33.70	Mimsco Steel	\$39.97

NOTES: Hixson = Transit Products
STD. = Standard Fastener
AER. = Aerial Structure Fastener

TABLE 2. STATUS OF METRO MAINLINE DIRECT FIXATION FASTENERS

TRACKWORK INSTALLATION & PROCUREMENT CONTRACTS	METRO PHASE	FASTENER TYPE	STATUS	TOTAL QUANTITY OF FASTENERS	CURVES With $r \leq 1000$ ft.		CURVES With $1000 \text{ ft.} < r \leq 2000$ ft.	
					NO. OF CURVES	NO. OF FASTENERS ON HIGH RAIL	NO. OF CURVES	NO. OF FASTENERS ON HIGH RAIL
TW-1	I	LANDIS FOR WMATA	IN SERVICE OPERATION	27,120	7	2,720	7	1,990
TW-2	IA, II	HIXSON FOR WMATA TW-2	IN SERVICE OPERATION	91,820	29	10,890	16	6,930
TW-3	IIA, III	HIXSON FOR WMATA TW-3	IN SERVICE OPERATION	23,840	2	560	11	4,820
TW-4	IV, IVA	HIXSON FOR WMATA TW-4	IN SERVICE OPERATION	62,720	10	3,560	2	360
TW-5	V(A)	LORD J-16281-2	IN SERVICE	17,520	1	650	2	830
	V(C)	J-16281-3	INSTALLED	16,180	3	670	3	470
TW-6*	VI	LORD J-16281-2 J-16281-3	INSTALLED	69,920	2	1,000	1	290
TW-7*	VII	LORD J-16281-2 J-16281-3	PROCURED BUT NOT YET INSTALLED	7,120	0	0	2	860
TW-8	V(L)	HIXSON STANDARD NO. H-17	INSTALLED, NOT IN SERVICE	20,560	4	1,120**	3	970**

* PROCURED AT PART OF TW-5 PROCUREMENT, INSTALLED IN TW-6, TW-7

** LORD FASTENERS WERE SUBSTITUTED FOR HIXSON ON BOTH RAILS OF CURVES R 2000 FT.

TABLE 3. REPLACEMENT STATUS OF TW-2, 3, 8, 4 HIXSON FASTENERS ON METRO MAINLINE

	CURVE CATEGORIES				TOTAL
	R<1000 HIGH RAIL	1000<R<2000 HIGH RAIL	2000<R HIGH RAIL	TANGENT AND LOW RAIL OF CURVES	
ORIGINAL QUANTITY INSTALLED	15,010	12,110	12,600	138,660	178,380
HIXSONS REPLACED BY LORDS AS OF MAY 1980	1672 / 11%	1677 / 14%	338 / 3%	0 / 0	3687 / 2%
HIXSONS REPLACED BY LORDS AS OF MARCH 1981	4398 / 29%	2771 / 23%	765 / 6%	1150 / 1%	9084 / 5%
HIXSONS REPLACED BY LORDS AS OF DECEMBER 1982	14500 / 97%	6000 / 50%	2500 / 20%	13700 / 10%	36700 / 21%

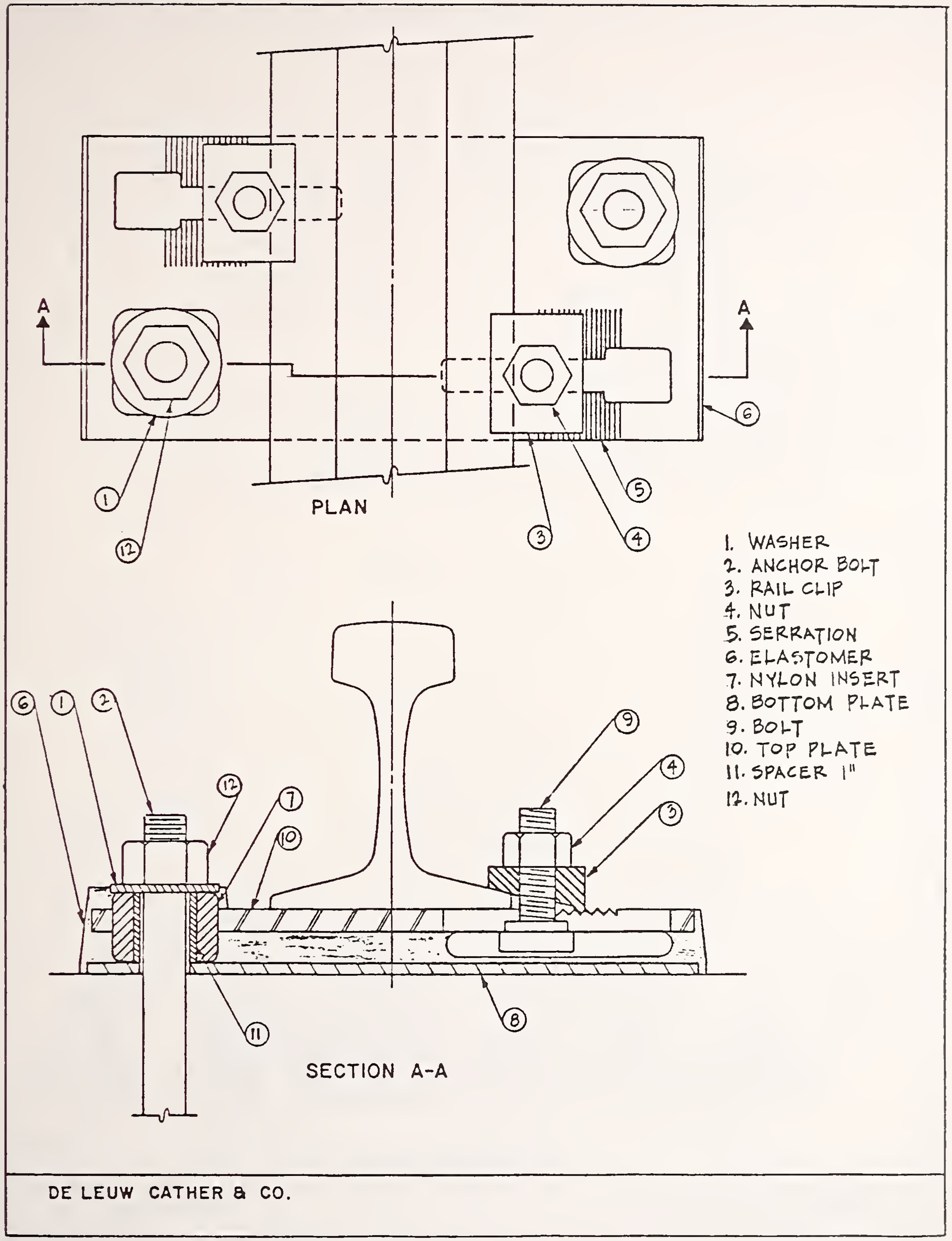

FIGURE 1. LANDIS FASTENER TW-1

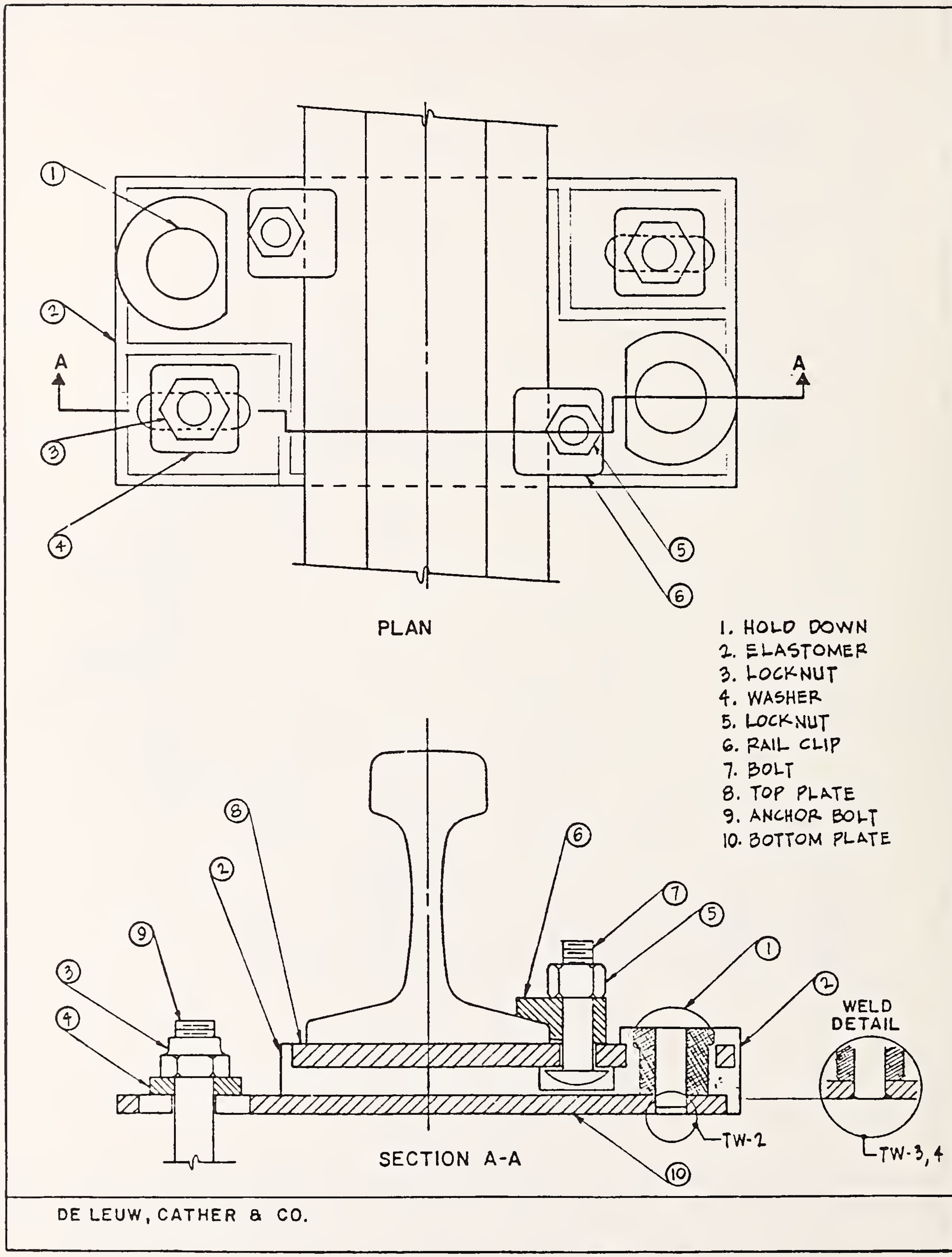

FIGURE 2. HIXSON FASTENER TW-2, 384

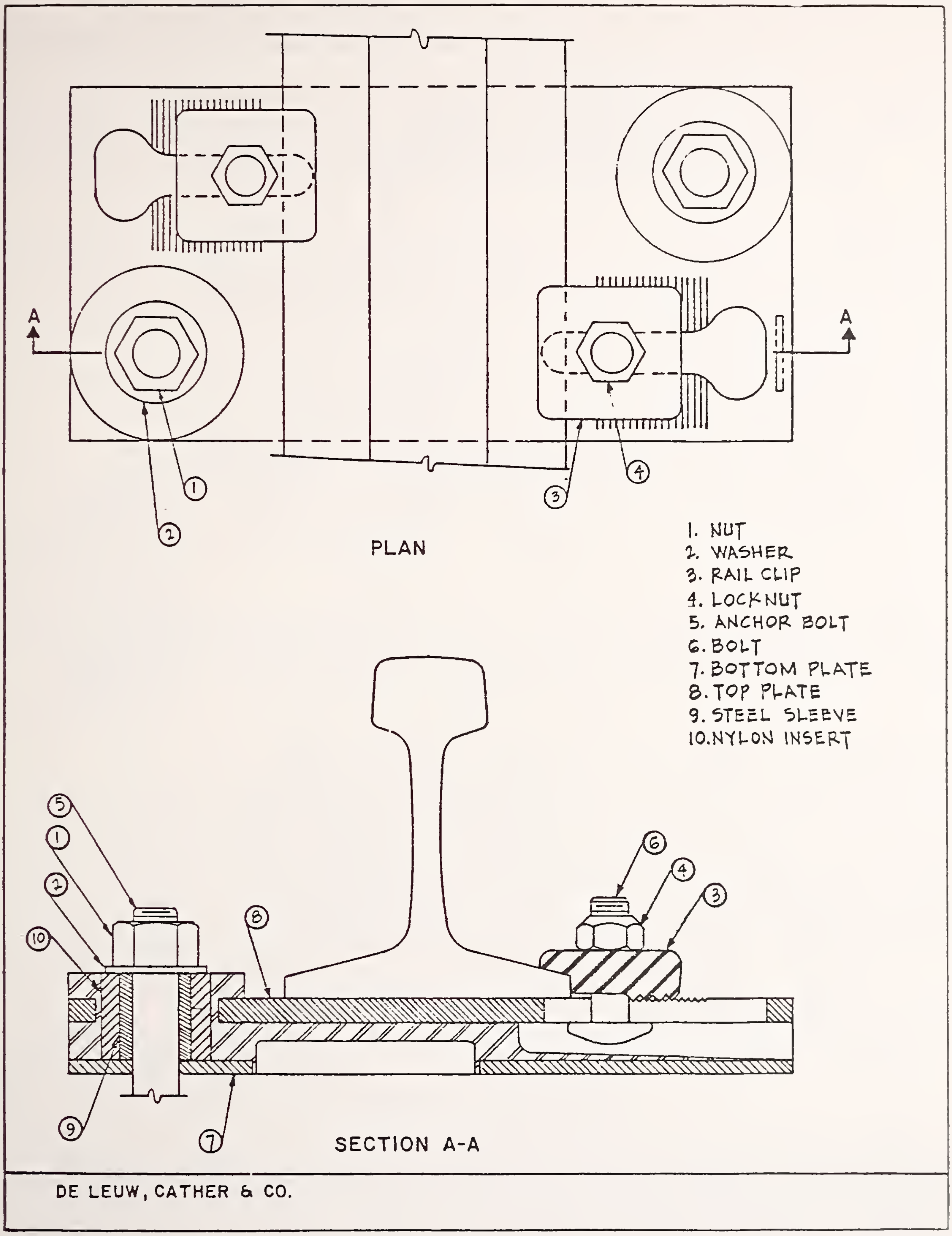

FIGURE 3. LORD FASTENER TW-586

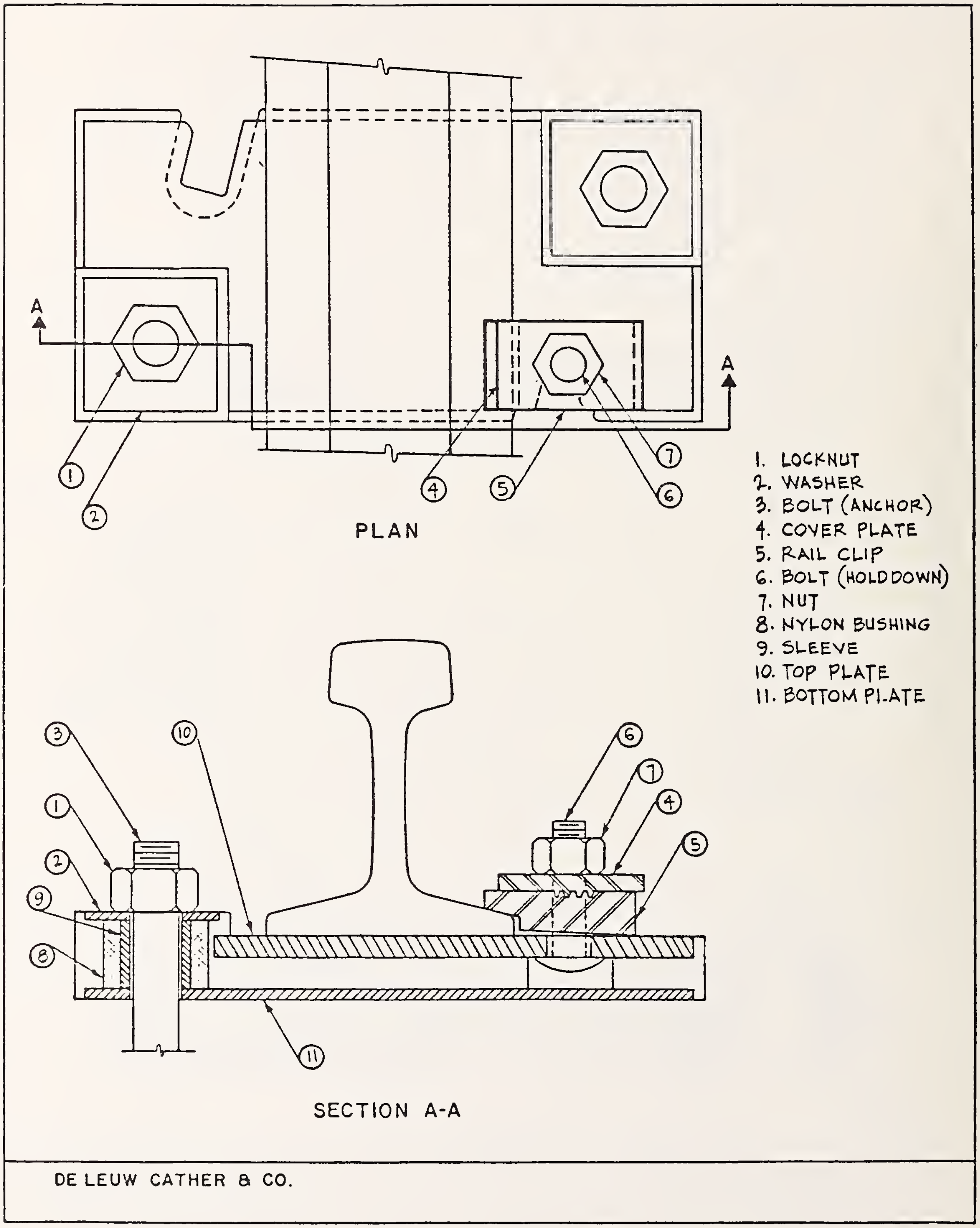

FIGURE 4. HIXSON FASTENER TW-8

Direct Fixation Track on the MBTA

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PAST EXPERIENCE WITH DIRECT FIXATION

Tie and ballast track has been the standard used by the MBTA and its predecessors for track in tunnels and at grade. The Red Line South Shore extension, opened in 1971, used two-block concrete ties, and recent track improvement projects have made extensive use of monoblock pre-stressed concrete ties.

The South Shore project did use direct fixation on two bridge structures: the Neponset River Bridge and Savin Hill Flyover (a railroad grade separation). The total length of structure was several thousand feet, long enough to enjoy the savings from reduction of dead load on the structure made possible by elimination of ballast. The "Liberty" or New York type fastener was used as it was about the only one in production when these structures were being designed. Each fastener uses four bolts to clamp both the rail and the resilient fastener elements to the slab. The second pour method was used for installation, and a special adjustable jig was used to hold the fastener in place while the concrete was poured. This incorporated a leave-in-place cement-asbestos block under the rail seat which held the anchor bolt assemblies at their proper location. Unfortunately, some of these blocks deteriorated after only a few years service, forcing us to retrofit Pandrol shoulders and clips with new elastomer rail supporting pads at a number of locations.

We have also found that the bolts used on this fastener and those used to secure the rail to the two-block ties are now rusting to the point that when we have to replace rail, we can't unscrew the nuts. This, plus experience of others, has led us to favor screwless and bolt-less spring clip fastener systems for new work.

Several years ago, we reconstructed a short concrete viaduct on our Mattapan light rail line. To reduce weight, we used direct fixation incorporating an early version of the Landis Pandrol fastener, installed in drilled holes in a second pour slab. We have had a few problems with this installation. The contractor did a poor job finishing the surface of the slab so that extensive use of shims was needed. Some of these, which were of plastic, have failed. A few of the grouted anchor bolt assemblies have pulled out. The grout did not bond to the slab, probably because of moisture in the drilled hole or improper mixing of the epoxy.

Though this fastener had a lateral adjustment feature, we did not need it as we were able to drill the holes and set the fasteners to precise location due to good survey and layout work, accurate drilling, and use of "slop" in the slightly oversized holes when setting the anchor bolts.

Another factor which we felt was responsible for pull-out of the anchor bolts was the basic design of the fastener anchorage. The base plate on its resilient pad would deflect under load, then rebound to place against a hard stop which was part of the anchorage system. This hard stop also provides a handy shortcut for vibration. We are aware that the newest version of this fastener, which will be installed in Miami, incorporates a resilient pad in the anchorage assembly to soften the rebound of the baseplate and improve its vibration isolating capabilities. We are currently looking at a variation in the design of this fastener which would eliminate the threaded anchor bolts and lateral adjustment feature.

RECOMMENDED DIRECT FIXATION SYSTEM

During the late 1970s while design of the MBTA's 3.5 mile Red Line Northwest Extension and 4.0 mile Orange Line Southwest relocation project were underway, it was decided that the rapid transit track would be installed by a direct fixation system. Noise and vibration studies indicated that most of the Northwest project and about 1/4 of the Southwest project would have to utilize floating slab construction to achieve adequate reduction of groundborne noise and vibration. Experience in Toronto with their design of the discontinuous "double-tie" precast floating slabs showed that this was a good approach to use in Boston, where an improvement over tie and ballast and conventional direct fixation fasteners was required to meet environmental requirements.

The bulk of the Southwest project which did not require floating slab vibration isolation was to be in a massive reinforced concrete boat section, passing through areas where residential development was some distance from the right-of-way. This meant that a sophisticated track fastener system was not really needed. The Southwest project also accommodates three railroad tracks used by commuter rail and Amtrak Northeast Corridor in addition to the two rapid transit tracks, but, because of the lack of experience in this country with direct fixation track for high speed, relatively heavy locomotive hauled passenger trains, the railroad will use concrete tie and ballast construction.

In addition to the need for floating slabs which require some form of direct fixation of the rails, there were other good reasons for use of direct fixation. Both Northwest and Southwest lines have a considerable amount of curved track and stations at relatively close spacing. Maintaining proper profile, alignment, cross-level and superelevation is critical at these locations. Direct fixation would eliminate the problems of settlement or shifting track that are inherent in tie and ballast construction. Both lines have a restricted right-of-way in subway, or open cut with walls, which makes trackwork such as tie or rail replacement, and ballast cleaning difficult to do, in the case of conventional track. Also, trackwork can only be done during the few nighttime hours when there is no service, so that an easily maintained, "fit and forget" track structure is clearly needed.

The floating slab, with its large soft rubber support pads, does the real work of attenuating groundborne noise and vibration. Thus the track fastener can be fairly simple. As the Southwest non-floating slab sections do not require an elaborate track fastener either, we decided that a single, simple fastening system should be used for both Northwest and Southwest projects. In all cases, the rails would be fastened down on a second pour slab, applied to the floating slabs or the fixed invert. Thus we were able to proceed with design of the inverts and floating slabs even though we had not yet chosen a particular track fastening system.

We reviewed a number of the track fasteners in use in other cities, as well as the limited installations on our own system. While this was going on, we were installing new track on our Green Line light rail system using spring clip fasteners of the Pandrol design on both timber and concrete ties. We were impressed with the features of the spring clip rail fastener -- ease of installation, elimination of separate rail anchors, and freedom from worry about proper tension and corrosion which are problems with bolted fasteners. We were aware of many of the problems with track fasteners that were plaguing other properties and wished to avoid them. Our investigations led us to the choice of a direct fixation system, as described below.

The MBTA's recommended direct fixation system supports the rail with a continuous resilient elastomer pad, and holds the rail in place with steel spring clips which engage malleable iron shoulders embedded in the second pour track slab. Plastic insulators isolate the rail from the clips and shoulders.

The system is based on that developed by British Rail Research and Development Division in conjunction with McGregor (Paving) Ltd. and Pandrol as the method for securing rail to slab track constructed by the slip form process, known as the PACT system. The fastening hardware is similar to that used on concrete ties. The PACT system has been thoroughly tested since the initial trial installation in 1969, and as of 1982 over 100 miles of track are in service utilizing this method of direct fixation construction. In addition, thousands of miles of track using this fastener hardware on concrete or wood ties are now in service, including 25 track miles on our own system.

The recommended direct fixation system is being applied to the following project:

a) Northwest Project - all double-tie floating slab track, for a length of 3-1/4 miles.

b) Southwest Corridor - all double-tie floating slab track, for a length of 3/4 miles.

c) Southwest Corridor - all fixed invert slab track (except South Cove Tunnel) for a length of 3 miles.

GENERAL DESCRIPTION OF THE BASIC ELEMENTS

Concrete Track Slab

The track slab is applied as a second pour over the fixed invert, or floating slab units. The top surface is finished to accurate line and grade and is contoured to provide the 1:40 rail cant and to drain water away from the rails. The slab is reinforced and is bonded to the base slab with the aid of reinforcing bar hoops embedded in the base slab. The second pour slab may be installed by conventional means with fixed forms or by use of the continuous slip form paving method, the choice of installation method being left to the track contractor.

The Northwest application, located in bored circular tunnels and box section structures, uses double-tie floating slabs for all track except special work and non-revenue track. The slabs are about 10' wide and 5' long. Each rail is supported by an individual second pour slab, about 2'6" wide by 4' long by 8" deep. Indentations about 5" deep are left in the precast slab to receive the second pour slabs. In the bored tunnel segment it was relatively easy to rotate the entire moveable form used to cast the concrete liner to provide superelevation of the invert slab on curves. To allow use of the same precast floating slabs throughout the project, the invert in the box section is also superelevated.

In the fixed invert application on Southwest, the second pour slab will be 9'0" wide and nominally 10" thick at the rail. In the double-tie floating slab application in Southwest, the second pour slab will be about 7'0" wide and about 7" thick at the rail, on tangent track. On superelevated curves the slab thickness will increase the high rail, as the invert slab is not superelevated. The slab thickness will also vary to make up for irregularities in line and grade of the invert slab.

Resilient Pad

The pad used in this system supports the rail continuously, except where interrupted to provide lateral drainage of the track slab, or at the joints between floating slab elements. The pad is harder than those used in most resilient fasteners to better resist lateral and overturning forces, and to reduce vertical deflection and uplift of the rail under load. The pad as specified has been used on transit applications with axle loads of 12 tons and speed of 50 mph -- similar to our requirement, and on main line railroads with axle loads of 25 tons and speeds over 100 mph. The pad absorbs some vibration (see below) and transmits the load from the smooth bottom of the rail to the relatively rough surface of the slab.

The pad is 3/8" thick and is 3/8" narrower than the base of the rail. With 115 lb R.E. rail the pad will be 5-1/8" wide. The pad may be composed of a natural rubber/cork formulation, or a synthetic rubber. In addition to supporting the rail, the pad electrically isolates the rail from the slab, as required by the signal and traction power negative return systems.

The pad is glued to the invert slab to hold it in place during the rail laying process. Once the rail is in place, the pad is confined by the embedded shoulders and by the clamping action of the rail, which is preloaded by the spring clips.

The pad should have a spring rate of approximately 1 million lbs/in., a Shore A hardness of 66-76, and minimum tensile strength of 1800 p.s.i.

Spring Clips

The spring clips are applied parallel to the rail. Pandrol or Portec Sidewinder clips may be used. Each clip provides a vertical clamping force or toe load of about 2000 lbs. This results in a force to resist longitudinal movement of about 2400 lbs per pair of clips. The clips are spaced 30" o.c.

The clips and pad work together allowing the rail to flex vertically to accommodate the wave motion imparted in the rail by the moving load. The rail can deflect downward under the wheel and upward in front of and behind the wheel. This is similar to rail on tie and ballast, but the magnitude of movement is considerably less.

The spring clip provides the proper longitudinal anchoring force automatically and does not depend upon the skill of the installer, as in the case of systems which require tensioning of bolts.

Embedded Shoulders

The shoulders are placed on each side of the rail and spaced along the track nominally at 30" o.c. The shoulders maintain line and gauge largely by working in shear. There is only enough tension in the shoulder to counteract the toe load of the spring clips -- about 2000 lbs. This is a fraction of the load on bolts used by other fastener systems which rely on bolts in tension to maintain the rail in line and gauge.

A hole in the shoulder receives the spring clip which is driven into place parallel to the rail. The stem of the shoulder is round in cross-section with an irregular surface. It may be cast in place or embedded in a drilled hole in the slab with epoxy or polyester resin. The shoulder is cast malleable iron to resist corrosion. The stem should be approximately 6" long with a maximum diameter of about 1-1/2" and minimum of 1-1/8".

This concept does not permit lateral adjustment of the rail once the shoulders are permanently embedded in the slab. Experience has shown us that it is possible to install the shoulders to the desired level of accuracy by several methods, which can include the use of the running rails as a guide for setting the shoulders to line. Some will argue that lateral adjustment is needed to allow for future regauging of the rail. In many cases, regauging is necessary with conventional track when spike-killed timber ties have allowed the rails to move laterally. We use premium rail and restraining rail on sharper curves to reduce rail wear and can transpose the rail if necessary. As concrete ties and many European track fasteners do not have the capability of gauge adjustment, we felt that this could be given up in order to simplify and improve the reliability of the fastening system.

Insulators

Plastic insulators are required to electrically isolate the rail from the clip and shoulder. The shoulders are normally located to allow for a small amount of play between the rail, insulator, and shoulder. The insulators may be all-plastic or a combination of plastic and steel elements or elastomer and steel elements.

COMPATIBILITY WITH RESTRAINING RAIL

This direct fixation system can easily accommodate our new standard restraining rail configuration which utilizes a 132 lb vertical restraining rail with 115 lb running rail. The exact same fastening hardware as on plain track is used. The shoulders are spaced to accommodate both rails side-by-side. An additional pad is added to support the restraining rail, or, a single wide pad may be used to support both rails. Special insulators can be used to allow adjustment of the restraining rail to make up for wear. This concept is identical to that used on our concrete and timber tie restraining rail installation.

ACOUSTIC PERFORMANCE

A harder pad, as used in this application, provides somewhat less attenuation of groundborne noise and vibration than softer pads or fastener systems, but, in the locations proposed on our system, this is not an issue. In the Southwest Corridor, where the fixed slab installation will be on the massive invert slab in the open boat sections, the airborne noise will predominate over groundborne noise, according to our acoustic consultant. British Rail tests of the PACT system showed groundborne noise and vibration levels similar to tie and ballast construction over much of the frequency spectrum. According to British Rail engineers, the massive invert in our multi-track installation will provide for better attenuation vibration than their application which was a light single track slab on grade.

In the sensitive areas of both Southwest and Northwest projects, we are already committed to use of the double tie floating slabs. With this application, the heavy slab mounted on relatively soft elastomer pads does virtually all of the groundborne noise and vibration attenuation. On floating slab, the pad between rail and slab is needed mainly to provide electrical isolation and to provide sufficient resiliency to allow for deflection of the rail and slabs under a moving load.

In terms of airborne noise, the recommended fastening system should be superior to systems using softer fasteners or pads. The spring clips and harder pad restrain the rail, damping out vibrations which radiate airborne noise. Softer fasteners would allow more vibration resulting in higher noise levels.

COMPARISON WITH OTHER FASTENER SYSTEMS

This method of direct fixation is simple and robust. The most critical elements are visible, making inspection easy and avoiding surprises from hidden failures that have plagued other, more elaborate track fasteners. The mass and composition of the metal elements is sufficient to resist corrosion and stand up under derailments. Bonded elastomer steel elements, which can fail without being seen, are not required.

Screws and bolts to attach the rail to the fastener, or the fastener to the slab, are not required. Failure of these elements in other fastening systems have created serious problems. Bolts, because of their shape, are particularly susceptible to corrosion. Those systems that need a high bolt tension to keep the rail in line and gauge have had to put excessive loads on the epoxy material used to bond the bolt to the slab.

The recommended system is "forgiving" in nature. The spring clip and resilient pad allow the rail to move, in a controlled manner. There are no elements which "bottom-out" under load, which can create impacts on fastener elements that eventually lead to fatigue.

The recommended system is less complex, having fewer, less expensive parts than the other track fastener designs. This means there is less hardware to buy initially, and less to take care of in the long run. The quality of finish needed for the second pour slab is no different with this system than that needed for other fasteners.

As the recommended system is easily adapted to handle restraining rail, we avoid the problem of using untried special fasteners at these locations. Currently, there are no resilient track fasteners known to be in production which can accomodate our restraining rail configuration.

SPECIAL TRACKWORK

The MBTA is staying with timber ties for special trackwork. In the case of the Northwest project, crossovers in floating slab territory are made up with timber ties and ballast resting on a cast-in-place floating slab. In the Southwest project, most of the crossovers will be made up with timber ties set in concrete. Ribbed rubber pads attached to the bottom and sides of the ties will provide some resilience, along with elastomer pads located between the plates and ties.

Our main reasons for choosing this method of construction is that the plates and related hardware are all compatible with that used elsewhere on the system and that timber ties are more "forgiving" than direct fixation, giving us more freedom to make field adjustments.

COMMENTS ON THE NORTHWEST TRACK INSTALLATION PROCEDURE

The plans and specifications gave the contractor some latitude in choice of track fastener hardware and method of installation. There was considerable interest in the job, which was a total package that included the supply and installation of the floating slabs, supply of the fasteners, and installation of these elements and the Authority supplied rail. Six contractors bid and four of these were well below the engineer's estimate.

The Perini Corporation was low bidder and has applied considerable ingenuity to the method of track installation. They made several mock-ups using both Pandrol and Portec fasteners and chose the latter for this project. Minor changes were made to the configuration of the embedded shoulder to ease installation.

Perini wanted an installation method which minimized use of skilled labor. They chose to set the shoulders directly into the second pour slab when it was cast, as they felt it was less costly and more reliable than drilling holes and setting shoulders in grout. The running rails (in the form of long welded strings) are set to their final line and grade with the aid of special temporary supporting beams. These are inverted Tee sections placed at the open space between floating slabs. They are spaced 25' o.c. on tangent and somewhat closer on curves. The rails are clamped to the beams, which are easily adapted to handle restraining rail, and gauge widening on curves. The rails are held at proper gauge, line, elevation, and cant. The beams are outfitted with bolts which may be screwed in or out to make these adjustments. Standard gauge bars ("Cooper-rods") are used in between the beams to hold gauge.

At each floating slab a 3/8" thick steel plate (the same thickness as the rail support pad) is clamped to the underside of the rail. This plate serves as a jig to hold two pair of shoulders at their proper position and to serve as a form for the rail seat area of the second pour slab. Rectangular wooden forms make up the four sides of each track slab. Reinforcing bars are tied to stirrups which were cast into the precast floating slabs. Concrete is poured, vibrated, and hand finished with a wood float, with the top of the slab flush with the bottom of the jig plate.

After the concrete has set, the rails are jacked up several inches to release the plates (which were coated with form oil so that they would would not bond to the concrete) and any "rat-holes" are filled with grout. Later the 42" long rail support pad is glued to the slab, the rail is lowered to place, and the insulators and spring clips installed. The temporary support beams and gauge bars are removed prior to final fastening of the rails.

Where restraining rail is used, the restraining rail and adjacent running rail are drilled to receive the bolts which tie them together on 30" spacing, midway between the shoulders which are at the same spacing. This can be done at any stage in the process once the rails are aligned in their proper place. The field welds used to join the strings of CWR are made after the rail has been anchored.

The actual production rate has been in line with the expected schedule. The installation of floating slabs averages 170 L.F. per work day and the placing of the second pour and installation of the rail is done at a rate of 155 L.F. per work day. The total bid price for the track contract including floating slabs, track, and specialwork installation (including a short section of three tail tracks at the terminal using tie and ballast construction) is $12,977,000 for 3.5 miles of double track.

SOUTH COVE TUNNEL

This is a small portion of the Orange Line Southwest Corridor project, roughly 2000' long, which connects the existing subway with the new surface alignment. This tunnel was completed some years in advance of the rest of the project to coordinate with urban renewal projects on the surface. The box section cut and cover tunnel with one station passes under a hospital complex, a high school, and several apartment buildings. It was designed, and the bulk of it constructed, before the day of the floating slab. It was originally intended to use direct fixation track with a second pour track slab and fasteners such as those used at BART.

Because of advances in the state-of-the-art of groundborne noise control, we decided that we should use a higher performance fastener in this project. There was not enough space to install floating slab, but, by making a slight change in profile, the Köln (Cologne) Egg fastener could be installed on this project. With the aid of an UMTA Technology Deployment grant, we are in the process of installing a short test section of the Köln Egg fasteners in the existing subway at the junction with the new line. We will compare the performance of this fastener with the New York type fastener installed some years ago on steel beams used to support the track during reconstruction of the tunnel. Later, we will test a "home made" fastener made up of Pandrol plates on a resilient pad, which is anchored to the base slab by a second set of Pandrol clips attached to embedded shoulders. This fastener, the "Pan-Plate" was developed while we were searching for a fastening system for the Northwest and Southwest projects.

However, it proved to be a more elaborate fastener than what we really needed for these projects.

TRACK IMPROVEMENT PROGRAM

This program is intended to replace and upgrade track over much of the existing rapid transit and light rail system. We investigated direct fixation for the subway portions of these lines, but found that it was not possible to install direct fixation track and keep the lines in operation every day. We plan to reconstruct track by shutting down service in the late evening and early morning hours in order to extend our normal 4 to 5 hour shutdown to 7 or 8 hours. This gives us one full shift to remove and replace track. Weekend shutdowns will be used for special work replacement. These limited periods of time are just not long enough to allow use of direct fixation methods which require time for precise installation of fasteners and rail, and curing time for concrete.

The only direct fixation system that might have had a chance was the resiliently supported STEDEF tie track which could be installed on blocking and grouted later. However, this tie cannot accept restraining rail, which is used extensively in the subway, and it uses bolts to secure the rails, which we consider to be inferior to the spring clip systems.

CONCLUSION

It is our opinion that the recommended fastening system for Northwest and Southwest projects will meet our requirements far better than any other system we know of. We have done extensive research over several years, which has included site visits, interviews with transit operators and suppliers, and collection of a vast amount of literature on the subject. We have had extensive discussions with consultants but have found that often we have told them more than they could tell us.

While the system described in this report is for installations on the Southwest fixed invert slab and on Southwest and Northwest floating slab track, there may be other portions of the transit system where this design could be used. If we install floating slab elsewhere, the recommended system would be used. In other areas where vibration could be a problem but floating slab is not justified or is infeasible, an acoustically higher performance fastener such as the Köln Egg may be a better solution.

We believe that the fastening system used on the Southwest and Northwest projects will be less costly and more reliable than any other system. It is the only system which can boast of many years of proven trouble-free service in conditions far more severe than our proposed application.

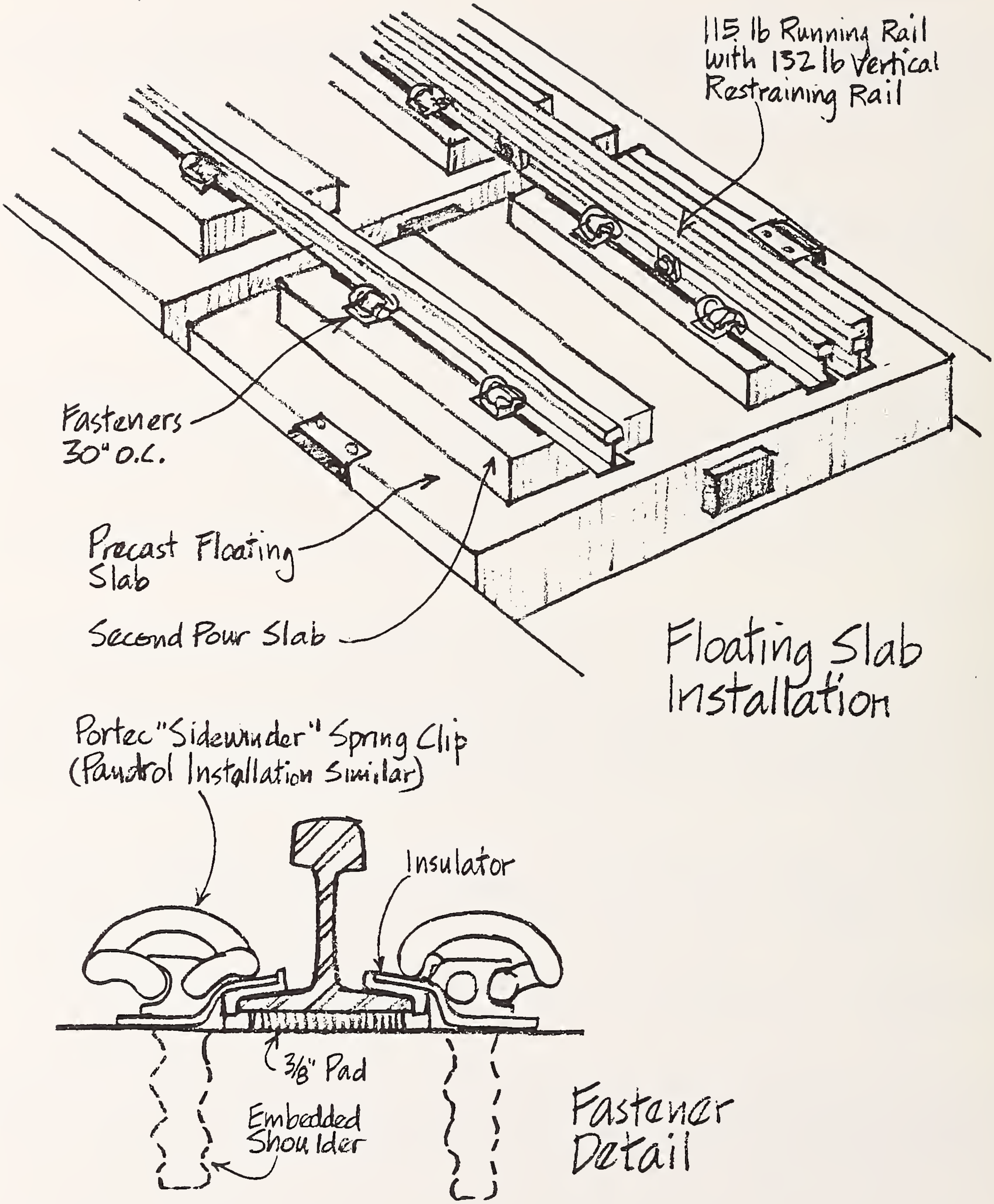

FIGURE 1. MBTA DIRECT FIXATION TRACK

Development of Criteria for the Baltimore Metro

Robert Hampton
Director, Facilities Engineering
Maryland Mass Transit Administration

INTRODUCTION

The present Baltimore (Phase I) system is made up of Section A* with:

1. 4 1/2 miles of subway with six (6) cut-and-cover stations,
2. 2 1/2 miles of aerial with three (3) stations,
3. 1 mile of at-grade track with storage yard and shop;

and also, Section B - a six-mile extension to Owings Mills in Baltimore County. This section is being constructed at-grade with bridge crossings over streams, highways, and the Western Maryland Railway. Three (3) stations are located along this extension.

Pre-revenue vehicle testing is presently underway throughout the at-grade and aerial sections.

Construction work on Section B began last year. Four (4) miles of the line, located within the median of the Northwest Expressway, is being constructed by joint contract with the Maryland State Highway Administration. Work on the MTA (only) portion will begin this year.

DESIGN CRITERIA

The stated goal of MTA is to:

> "Design and construct a track system within the present state of the art that will provide adequate strength, safety, maximum uniformity and simplicity, and ease of maintenance."

The resource documents for these criteria are:

> The American Railway Engineering Association's "Manual for Railway Engineering" and "Portfolio of Trackwork Plans."

The Baltimore criteria were developed with attention to current practices within the industry. The design recommendations established by the "noise and vibration" consultant were implemented to the fullest extent possible (Wilson, Ihrig & Associates).

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* Construction work on Section A is nearly complete.

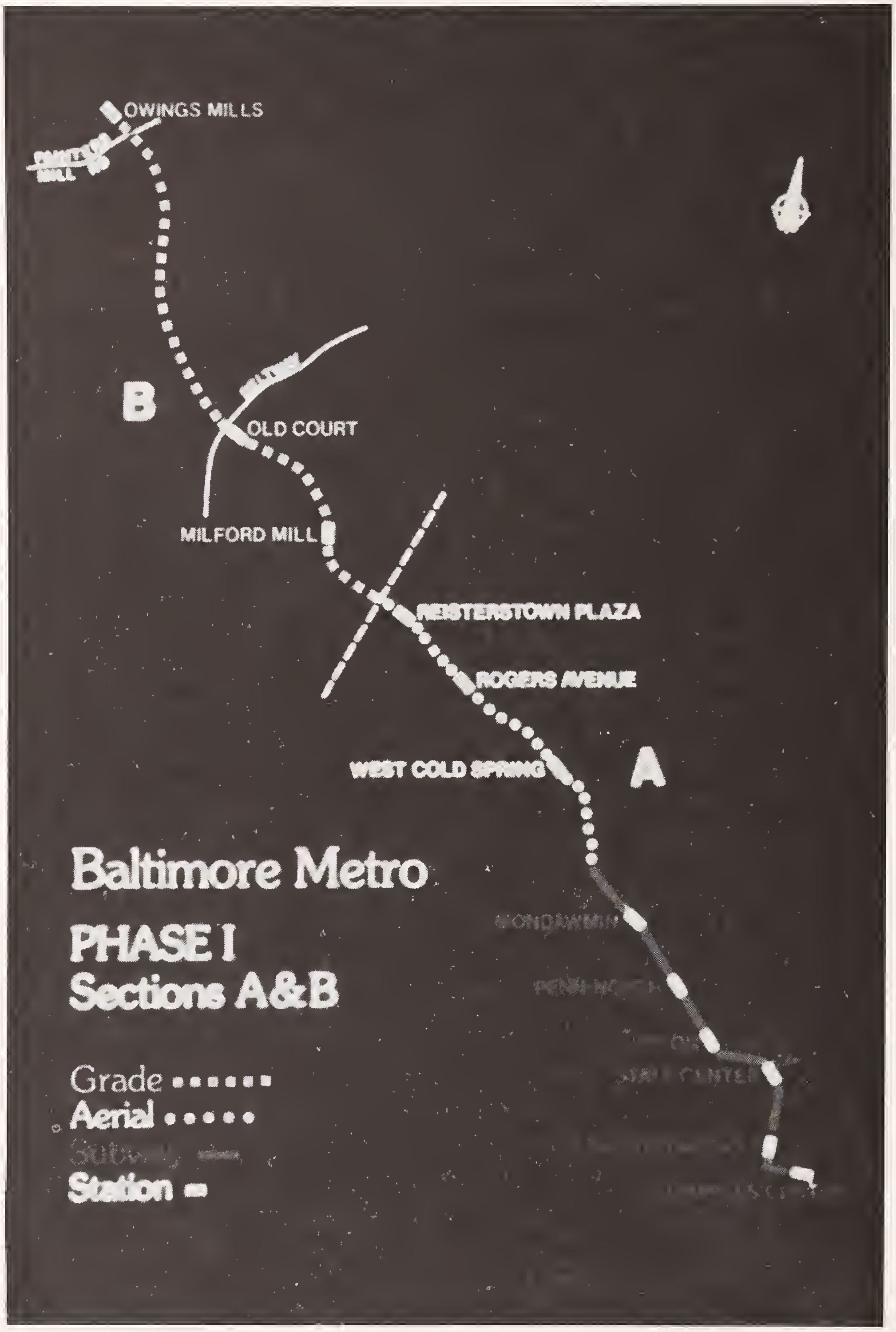

FIGURE 1. THE PRESENT BALTIMORE PHASE I SYSTEM

a. Running Rail

115 RE rail was selected for use throughout the system because of its adequate strength and availability. The rail is continuously welded with bonded joints at most gaps. Rail design assumed temperatures ranging from 0° to 140°F with zero-stress at 90°F in the aerial and at-grade segment and 70°F in the underground. On curves of less than 3,000 ft. radius, both rails are fully heat treated. The minimum radius of curve is 755' throughout mainline track.

b. Types of Track in System

Ballasted with wood and mono-block concrete ties,

Direct fixation,

Resiliently supported, and

Floating stab and two-block concrete ties.

Instead of discussing the above systems, I have chosen a series of slides that illustrate the actual application and installation of these track systems into the Baltimore Metro.

Direct fixation in the underground -- 2-2' - 7" x 4" continuous blockouts in invert slab (Figure 2)

The installation procedure (Hixson fastener) (Figures 3 through 7)

Completed underground installation (Figure 8)

Transition between DFF and STDEF resiliently supported tie blocks (Figure 9)

STEDEF installation procedure (Figure 10)

Completed installation of two-block ties in portal from underground (Figure 11)

Aerial girder deck (Figures 12, 13)

Aerial track installation procedure with Hixson fastener (Figures 14 through 21)

Aerial section, completed installation (Figure 22)

Mono-block tie and spring clip fastening (Figure 23)

FIGURE 2. DIRECT FIXATION IN THE UNDERGROUND

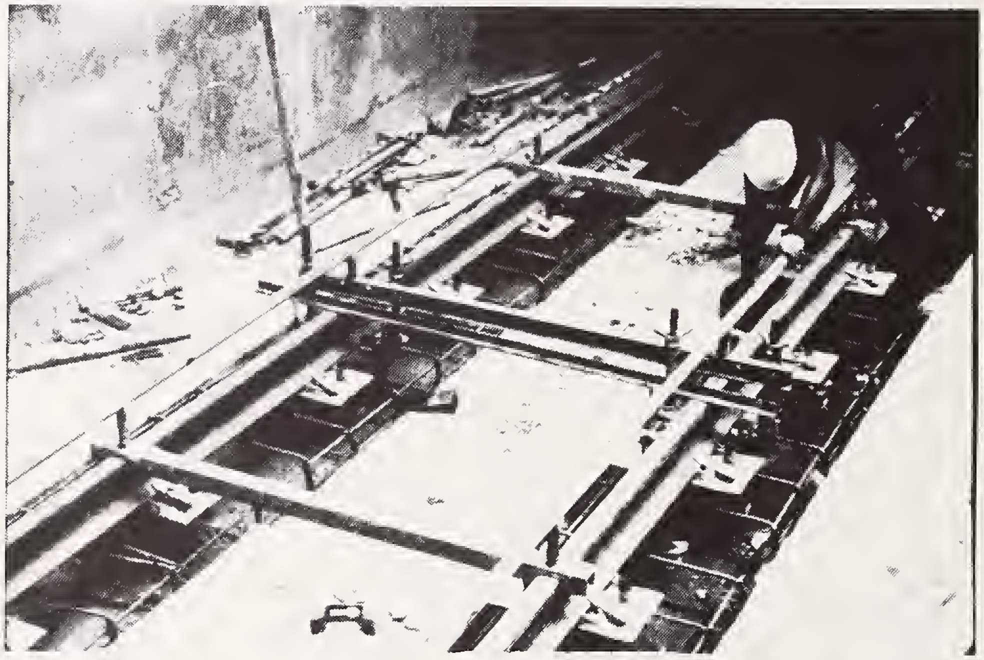

FIGURE 3.

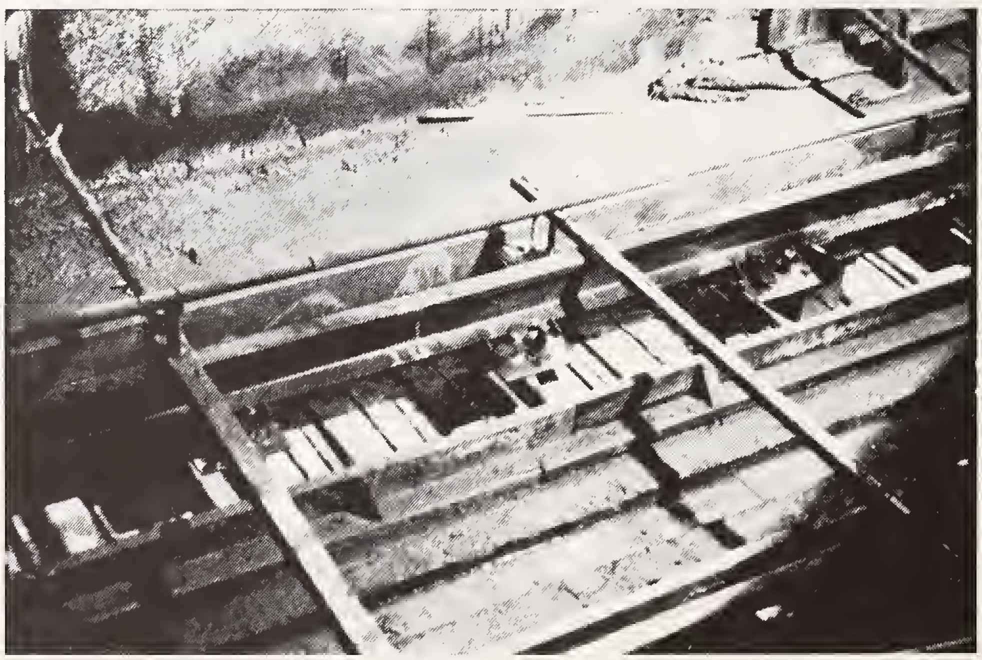

FIGURE 4. THE INSTALLATION PROCEDURE (HIXSON FASTENER)

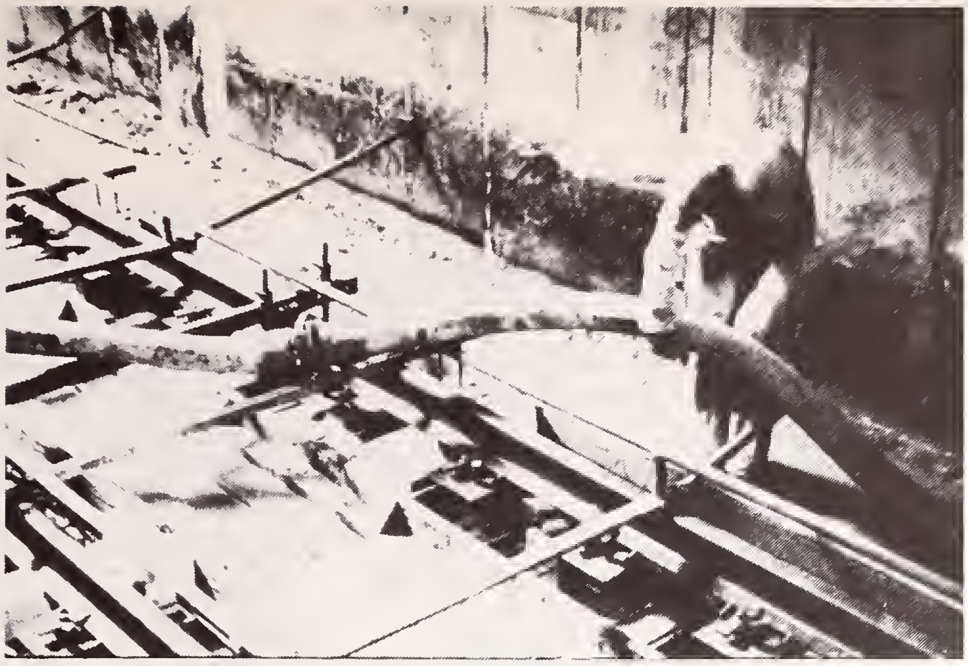

FIGURE 5.

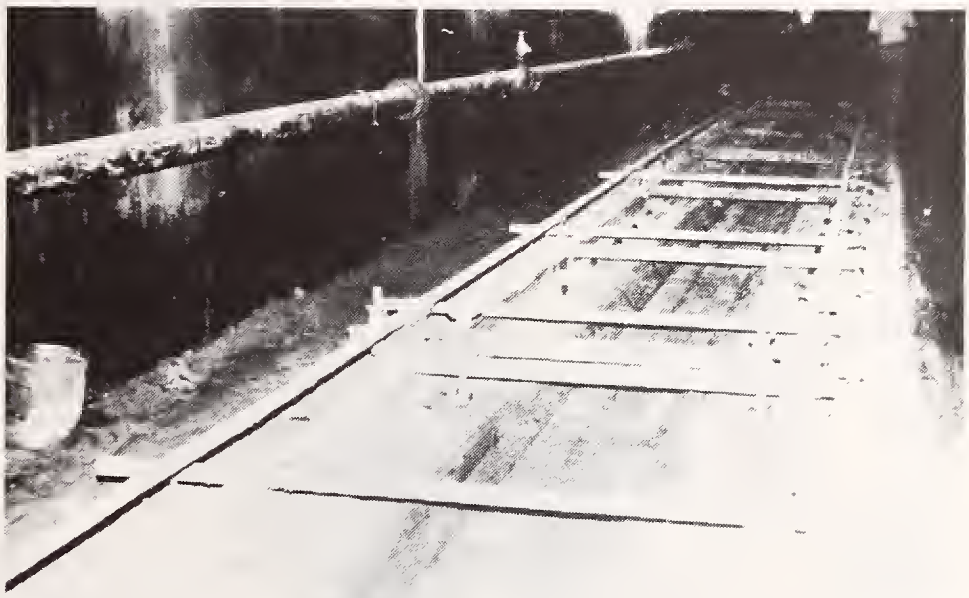

FIGURE 6.

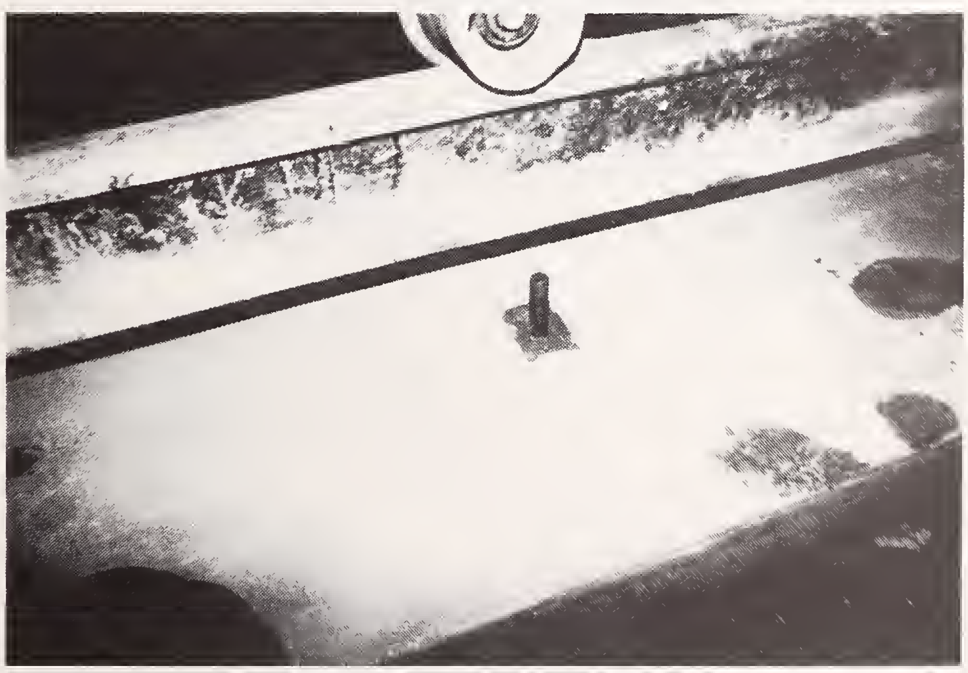

FIGURE 7. THE INSTALLATION PROCEDURE (HIXSON FASTENER)

FIGURE 8. COMPLETED UNDERGROUND INSTALLATION

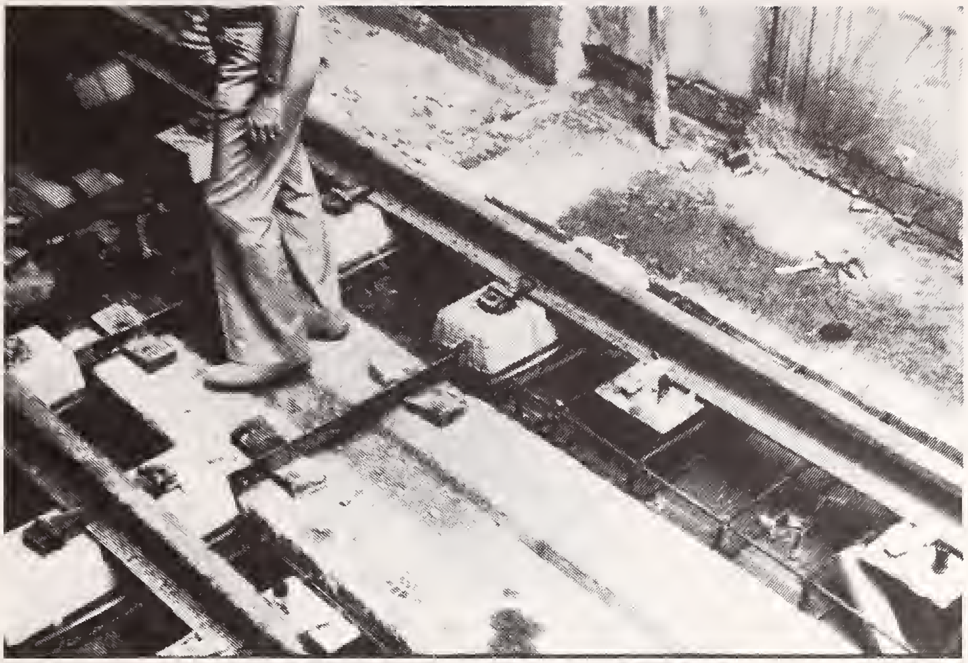

FIGURE 9. TRANSITION BETWEEN DFF AND STEDEF RESILIENTLY SUPPORTED TIE BLOCKS

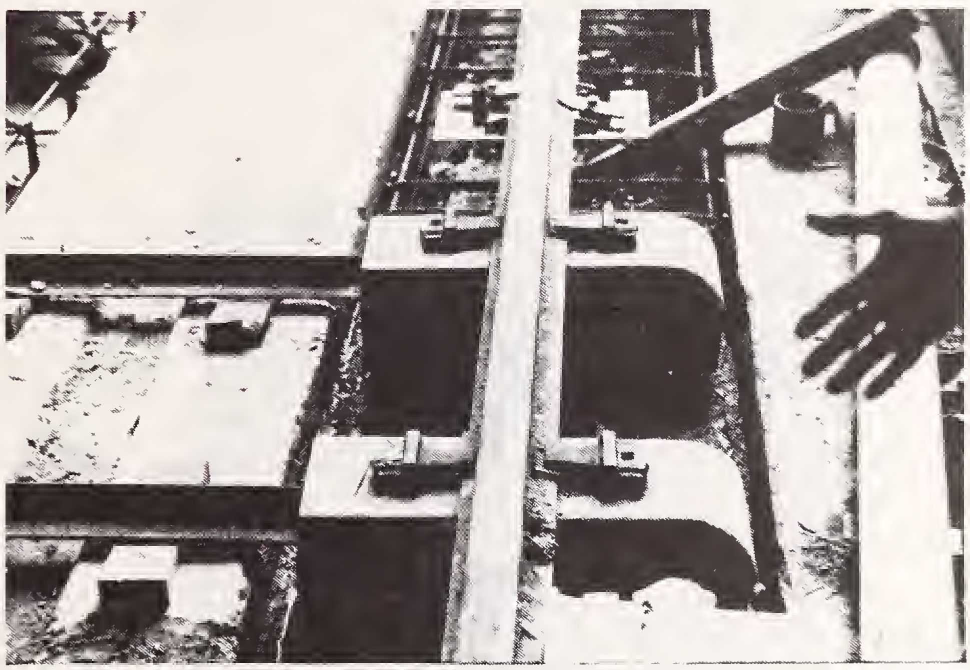

FIGURE 10. STEDEF INSTALLATION PROCEDURE

FIGURE 11. COMPLETED INSTALLATION OF TWO-BLOCK TIES IN PORTAL FROM UNDERGROUND

FIGURE 12. AERIAL GIRDER DECK

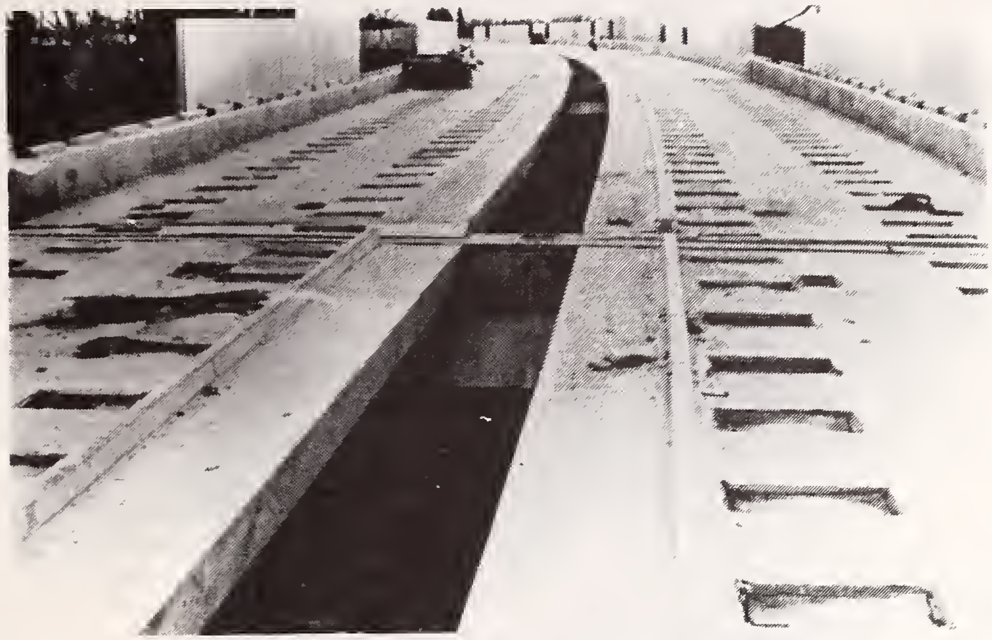

FIGURE 13. AERIAL GIRDER DECK

FIGURE 14. AERIAL TRACK INSTALLATION WITH HIXSON FASTENER

FIGURE 15.

FIGURE 16. AERIAL TRACK INSTALLATION WITH HIXSON FASTENER

FIGURE 17.

FIGURE 18. AERIAL TRACK INSTALLATION WITH HIXSON FASTENER

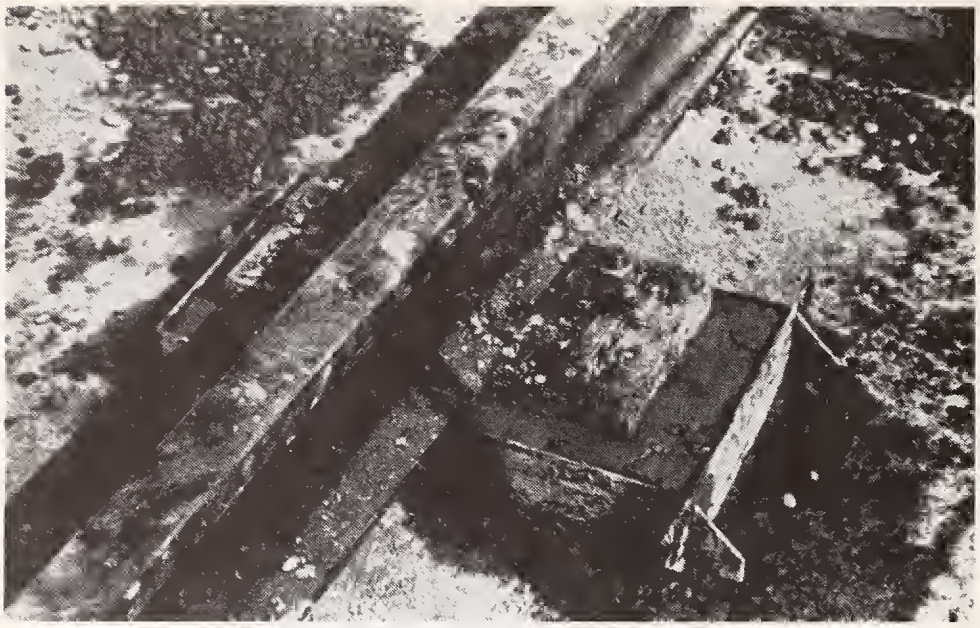

FIGURE 19.

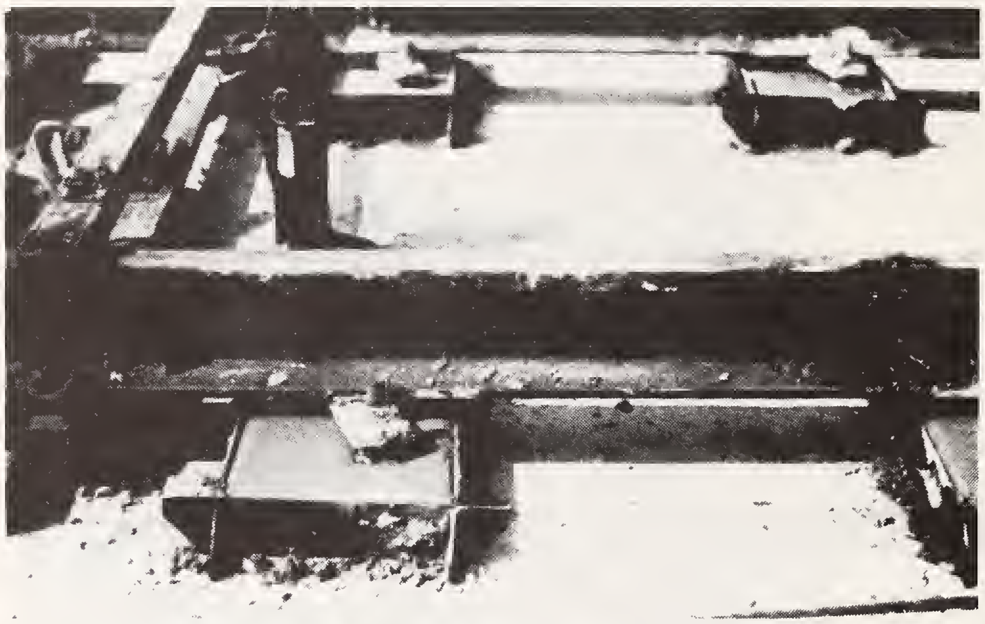

FIGURE 20.

FIGURE 21. AERIAL TRACK INSTALLATION WITH HIXSON FASTENER

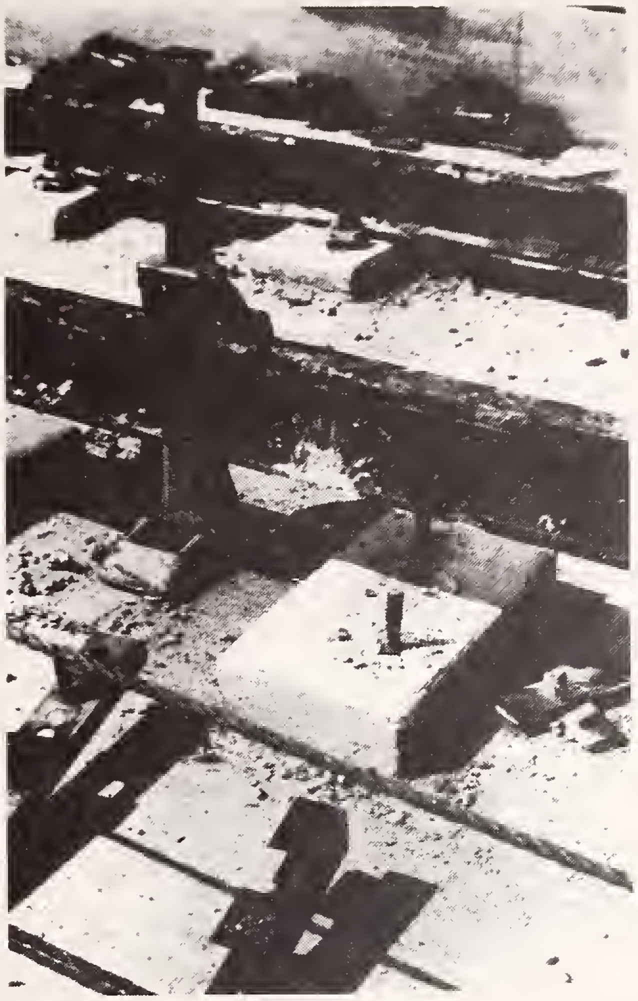

FIGURE 22. AERIAL SECTION, COMPLETED INSTALLATION

FIGURE 23. MONO-BLOCK TIE AND SPRING CLIP FASTENING

Track design criteria for the "Section B" extension that is currently under construction remain very similar to the "Section A" criteria. Some lessons have been learned, and minor modifications are being studied.

Experience from the completed aerial and subway direct fixation installations have demonstrated the simplicity and versatility of the continuous beam construction system as used in the underground section. This system has been modified and adopted as the standard for direct fixation at all structures in the at-grade Section B extension.

The modifications include a revised blockout in the concrete deck to 27" wide and 2" deep. The continuous beam is reinforced and attached to the structural deck slab with reinforcing dowel.

Although this detail results in some additional cost for concrete and reinforcing steel, it is our opinion that the benefits from this simplified construction detail should more than balance out the added costs in construction material.

Question: AMTRAK has experienced some problems with malleable shoulder inserts breaking out of the concrete ties, could this occur on your invert slab? If so how would you eliminate the problem?

Williams: The loading on the MBTA is probably less than half the worse case load on AMTRAK. Speeds are probably half the speed or less. The insert is probably twice as big and twice as heavy. We have reinforcing bars all around the inserts. I think the combination of all these factors hopefully will help us avoid that problem. We've had pretty good experience on our own concrete ties with the inserts. I think I've seen one tie that was broken and I think that was not service related. The tie was skewed at 25°, so the contractor probably stuck a straight bar in the hole of the insert and tried to straighten it out. It just twisted the insert which is a different shape and it caused the tie to split.

Question: What will happen to these during derailment?

Williams: I would say the best example of a derailment situation that I have seen was down on the Northeast corridor south of Boston where I think someone dragged a passenger car for about 10 miles and it had a broken axle. The wheelset was just bouncing over the thing and I saw one or 2 Pandrol shoulders that had maybe a little nick where you saw a little fresh metal. The clips themselves self-destruct. They broke up. It was a very hot day, but the track didn't lose gage. What I think was happening was the spring clips were taking the brunt of the impact from the wheelset and were gracefully self-destructing and absorbing a lot of energy. I saw no broken ties, no problems.

Question (to Charles Pelton): Did you say that the spacing on your fastener was 36 inches?

Pelton: Yes.

O'Donnell (to Charles Pelton): How often do you torque fasteners in your maintenance program? How many times a year do you torque your bolts?

Pelton: About every 11 or 12 months. About once a year we'll do our cyclical maintenance.

O'Donnell: Your grinding program no doubt is what is helping reduce the need for more frequent maintenance?

Pelton: We believe it is.

O'Donnell: I think the grinding program that BART has, has helped on the frequency of torqueing. On the Washington Metro bolts that needed tightening up to four times a year, after grinding needed torqueing less often. So I'm pretty sure that's what's helped you quite a bit.

Pelton: We have done some experimentation on one curve coming out of a station with about a 600° radius without a restraining rail. It is one of the areas where we experienced a lot of corrugation. We have upgraded our grinding program in that area and it's one of the areas where we would consistently pick up loose bolts. Since upgrading the grinding in those areas we've eliminated the problem.

Question (for Art Keffler): At one point in time you excluded the unbonded fastener in your procurement program. Would you please explain the rationale for this action at some time.

Keffler: Between the TW-2 & 3 or the 3 & 4 we excluded non-bonded fasteners. Up until that time we had allowed either and we had ended up with all bonded fasteners. The Landis and the Hixson fasteners are both bonded fasteners. I think our main concern at that point was having gotten the bonded fastener and having been successful with respect to its electrical isolation characteristics, we did not want to go back to a system where we could have water intrusion and intrusion of iron filings and whatnot into the fastener. We do have some electrical leakage problems and we don't want to make them any worse. We consider the bonding worth the expense in our case.

Hanna: Would you please read the first question again?

The question was that AMTRAK has experienced some problems with malleable shoulder inserts breaking out the concrete ties, could this occur in your invert slab?

Hanna: I would like to make a comment on that. There are a few problems with the concrete ties on AMTRAK, but they are very, very minimal.

McQueen: I think it's true to say that the insert's pull-out is not part of the problem. This occurrence is usually related to rail or other anomalies. The test value for those shoulders in the concrete ties is 12 kips, their ultimate value is on the order of 14 to 16 kips. Bob Gildenston made the point that it's very important not to expect to take care of other problems in the design of fastening systems and I think that's a case where you see a problem being mentioned which is stemming from something else.

Question: One question for two people. The question is for John Williams and Bob Hampton. What is the cost of the floating slab that you showed in your slides?

Williams: I think the contract was for about 3-1/2 miles of double track including everything but the rail and it was for around $12 million.

Hampton: Our break out was separate, but I don't know the exact figure.

Williams: The precast slabs included all the hardware, all the rubber units and of course the installation costs included the 2nd course. There's a lot of messy concrete work in there too, even with the precast slabs. It's in someways very similar to what Baltimore was doing.

Question: John, did I understand from your presentation that those precast slabs that you had were very similar to the Toronto design?

Williams: They're similar in that they're probably about the same width and the same length. They are thicker. Another area where I made a change from the Toronto slabs, the corners are sort of cut-out and we eliminated that corner cut-out. I think that was done in Toronto so that in theory you could jack up a slab; maybe replace one of the elastic supporting elements. We found those holes to be great places to fall and step into, lose dead cats and things down there so we did away with them. The other thing is I think Toronto has a very minimal grout pad underneath their fastener and our grout pad is deep - it's about 8 inches thick. So they started out being similar but I think as time went on they became less similar. They're heavier and more massive so we're hoping that they'll work.

Wilson: I think Mr. William's point was that the rubber components are exactly identical to Toronto, the slab itself is not.

I'm sure most or many of you probably have seen or at least know that up in Toronto on their Spadina line all of the underground portion of the Spadina line uses that same concept even though it may be somewhat different.

Question: Art, you mentioned that you are looking at changing the specifications for your fastener and in your presentation you also said that you had no problems with the fasteners in your TW-1, right?

Keffler: That's correct.

Question: Then why do you want to reinvent the wheel and go for another fastener when you have one that's working in your track? Can you answer that? Is it not going to be costly to develop them?

Keffler: I'm sure that a cost is involved; but we think that we're not so much reinventing the wheel as making some improvements on something that's a bit more complicated than the concept of the wheel and with the problems that have ensued with the development of fasteners. We think that there is a great deal of opportunity for improvements to be made. The test programs that have been performed at WMATA give us indications that there are areas where we could make a better fastener than the fasteners we are now using that may cost less. We could get better vibration reduction, better maintenance performance, better corrosion resistance, less problems with anchor bolts, and still not spend as much money as we're presently spending.

Question: Art, do you feel in your experience with the various fastener suppliers that they really understand the mechanism of the load transfer between all the components in the fasteners.

Keffler: Well, since I'm not sure that we understand it that well, no.

Question: Could the components be tested rather than the unit? Is it possible that one component is maybe 10 or 20 times more adequate that it should be?

Keffler: It's a matter of engineering judgement as I said at one point in my presentation, a finite element analysis could be made of every component of the fastening systems. At least at the present time it looks like that would involve a great many assumptions that tend to detract from the expected accuracy of the analysis. What we're interested in (at least at WMATA) is the fastener as a whole, as a system performing it's function, and we like to keep our performance specifications on that level rather than going to individual component testing.

Question: Yes, this one's for John, when you were putting in that floating slab did you have any areas where you had any special work?

Williams: I forgot to mention the special work. We took the coward's way out on the special work for the floating slab in that we did what Toronto had done. We put in a continuous floating slab on elastic elements and then put in the tie and ballast. The one thing we learned from Toronto was to divide that big slab up into sections. We have a set of universal cross-overs and we have a big diamond cross-over all on a huge floating slab. Now if anything goes wrong with the elastomeric elements down under the middle of that slab we're dead; but we've got a million of them in there so it should be alright.

Question: Did you use the same hold down system?

Williams: No, on the special work with the wood ties we're just using standard plates and cut spikes. All out of the AREA track book. We save a lot of money that way.

Question: In Baltimore when you went to the 90°F ambient laying temperature, did you consider going to a lower temperature because you are using direct fixation fasteners?

Hampton: No, due to the possibility of a track buckle we just used the neutral temperature.

WMATA TEST DATA

Wheel/Rail Force Measurements at the Washington Metropolitan Area Transit Authority

Charles Phillips
U.S. Department of Transportation
Transportation Systems Center

INTRODUCTION

In support of the Office of Systems Engineering of the Urban Mass Transportation Adminstration (UMTA), the Transportation Systems Center (TSC) is conducting analytical and experimental studies to relate transit truck design characteristics, wheel/rail forces and wheel/rail wear rates, in order to provide options to transit properties to minimize life cycle costs of vehicle and track components, while maintaining or improving equipment performance.

As part of this work, TSC planned and implemented a measurement program at the Washington Metropolitan Area Transit Authority (WMATA) to obtain data to quantify the wheel/rail load environment as it related to wheel/rail and direct fixation fastener failures on that system. These measurements were conducted in two phases, the first in August 1979, and the second from August through November 1981. Along with the data reduction and preliminary analysis these measurements have been described in the following reports and papers.

"Wheel/Rail Force Measurements at the Washington Metropolitan Area Transit Authority"
Vol. I. Analysis Report, Report No. UMTA-MA-06-0025-80-6
Vol. II. Test Report, Report No. UMTA-MA-06-0025-80-7

"Wheel/Rail Force Measurements at the Washington Metropolitan Area Transit Authority Phase II"
Vol. I. Analysis Report, Report No. UMTA-06-0025-82-28
Vol. II. Test Report, Report No. UMTA-MA-06-0025-83-1

"The Effect of Two Point Contact on The Curving Behavior of Railroad Vehicles"
ASME Paper No. 82-WA/DSC-13, J.A. Elkins and H. Weinstock

This presentation reviews the work described in the referenced reports and presents new results of ongoing analysis of the extensive data that was collected.

TABLE 1. WMATA TRUCK TEST PROGRAM (PHASE 2)

BACKGROUND

HIGH RATES OF WEAR EXPERIENCED IN SHARP CURVES AT WMATA

PRINCIPAL FACTORS AFFECTING WEAR IDENTIFIED/EVALUATED IN PHASE 1 TESTS:

- WHEEL TAPER
- GAGE WIDENING IN CURVES
- RAIL LUBRICATION
- TRUCK PRIMARY SUSPENSION

PRINCIPAL RESULTS, PHASE 1 TESTS:

- INCREASING WHEEL TAPER REDUCED WHEEL/RAIL FORCES
- FORCES RELATIVELY INSENSITIVE TO OPERATING CONDITION
- REDUCING TRUCK STIFFNESS SHOULD REDUCE CURVING FORCES
- MUST EVALUATE EFFECTS OF TRUCK MODIFICATIONS ON STABILITY

OBJECTIVES

EVALUATE EFFECTS OF INCREASED WHEEL TAPER AND SOFTENED TRUCK PRIMARY SUSPENSION ON VEHICLE AND TRUCK

- CURVING PERFORMANCE
- STABLE SPEED RANGE
- RIDE VIBRATION

Figure 1 plots the stiffness of various transit trucks in current use on US transit properties and relates them to truck curving performance and stability. The curving performance is indicated by the angular curvature in degrees that the truck can negotiate without hard flanging producing high wheel and rail wear. The stability is indicated by a single critical speed of 150 mph above which hunting and instability would occur. As a comparison, the CTA Wegmann truck with a relatively soft suspension can negotiate a 5° curve without hard flanging and be stable at a speed less than 150 mph but safely above the CTA operating speed of 55 mph. The PATCO Budd truck with a stiff suspension can negotiate a less than 1.8° curve without hard flanging and has a critical speed well above 150 mph as compared with a maximum operating speed on PATCO of 75 mph.

This information is intended to be qualitative to display a comparison and tradeoff potential. It does not include the effects of varying wheel profile and wheel rail adhesion coefficients. Hard flanging is not defined. A more practical wear index based on the work performed is described later. Conventional trucks discussed here fall below the diagonal line. Steerable trucks with inter-axle connecting linkings allow greater freedom for performance tradeoffs and can occur above as well as below the line.

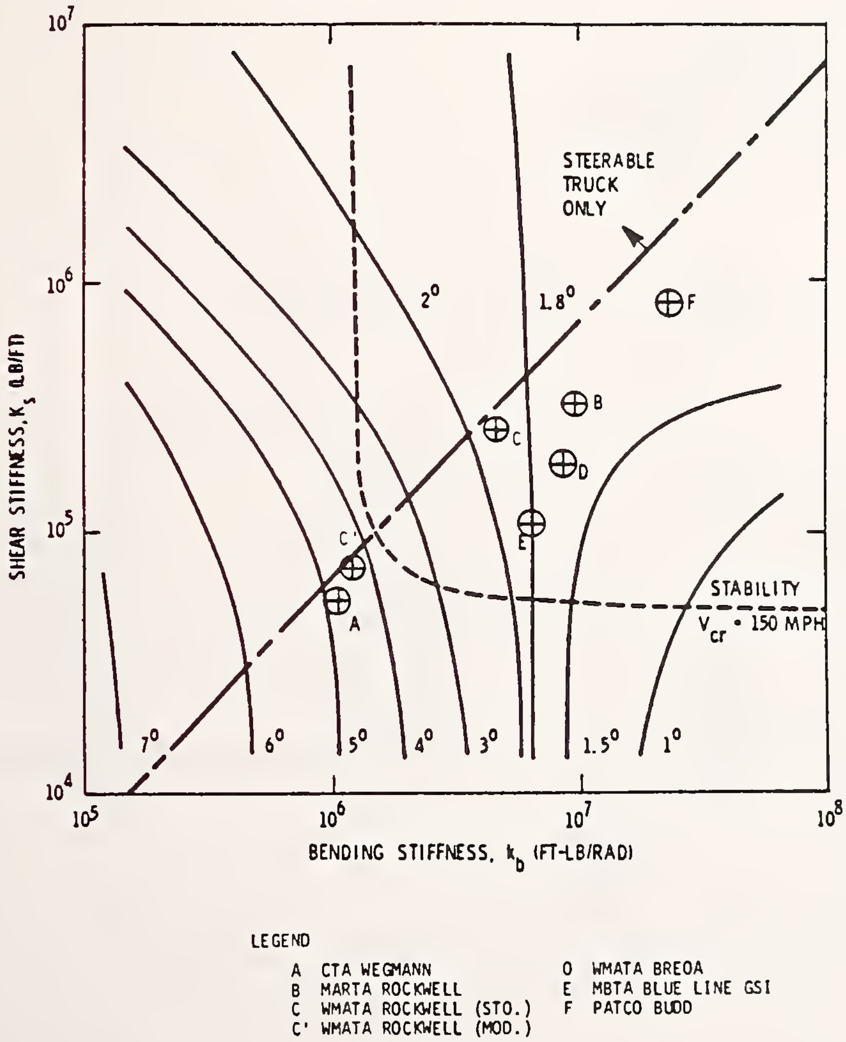

FIGURE 1. WHEEL/RAIL DYNAMICS PROGRAM TRUCK CURVING AND STABILITY VS BENDING AND SHEAR STIFFNESS (PRELIMINARY)

Tables 2, 3, and 4, and Figure 2 describe the test program conducted with an instrumented wheelset at WMATA to measure wheel rail forces for a variety of truck configurations and over a number of different curves and track conditions. The reports previously identified describe the tests in detail.

TABLE 2. TEST PROGRAM - OUTLINE

- TEST CONSIST:
  - LEAD CAR, INSTRUMENTED
  - TRAILING CAR, STANDARD VEHICLE
- PRINCIPAL TEST VARIABLES:
  - WHEEL TAPER
  - PRIMARY SUSPENSION STIFFNESS
  - OPERATING CONDITIONS
  - TRACK CURVATURE
- INSTRUMENTATION:
  - VERTICAL AND LATERAL WHEEL/RAIL FORCES
  - VEHICLE/TRUCK/AXLE KINEMATICS
  - CARBODY/TRACTION MOTOR ACCELERATIONS
- TYPES OF TESTS:
  - STABILITY
  - STEADY CURVING
  - ROUTE EVALUATION
  - RIDE VIBRATION

TABLE 3. TRUCK TEST SCHEDULE

DYNAMIC TEST SERIES	TAPER	TRUCK		PLANNED	ACTUAL
A	CYL	STD		8/29, 8/30	8/22, 8/27
B	1/20	STD		9/10, 9/11, 9/12	9/10, 9/12
C	1/10	STD		9/19, 9/20	9/19, 9/20
D	1/5	STD		9/26, 9/27	CANCELLED
E	1/y	STD		10/1, 10/2, 10/3	CANCELLED
F	1/10	SOFT		10/17, 10/18	10/17
G	1/20	SOFT		10/24, 10/25	10/25
H	1/a	SOFT		10/31, 11/1	REPLACED WITH J
I	1/20	STD	TEST SERIES ADDED		10/31
J	CYL	SOFT	REPLACED TEST SERIES H		11/7
WMATA SYS. EVALUATION	CYL	STD			8/29
	1/20	SOFT			10/24
STATIC		STD		10/5-10/9	10/5-10/9
		SOFT		10/12-10/16	10/12-10/16

TABLE 4. TEST SPECIFICATIONS

NO.	LENGTH	RADIUS	CURVATURE	S.E.	SERVICE SPEED
3	490'	1200'	4.8^0	4"	50 MPH
311	430'	956'	6.0^0	4"	40 MPH
37	780'	755'	7.6^0	4"	40 MPH
43	220'	1750'	3.3^0	6"	65 MPH
49	310'	800'	7.2^0	6"	45 MPH
157	680'	2508'	2.3^0	6"	70 MPH

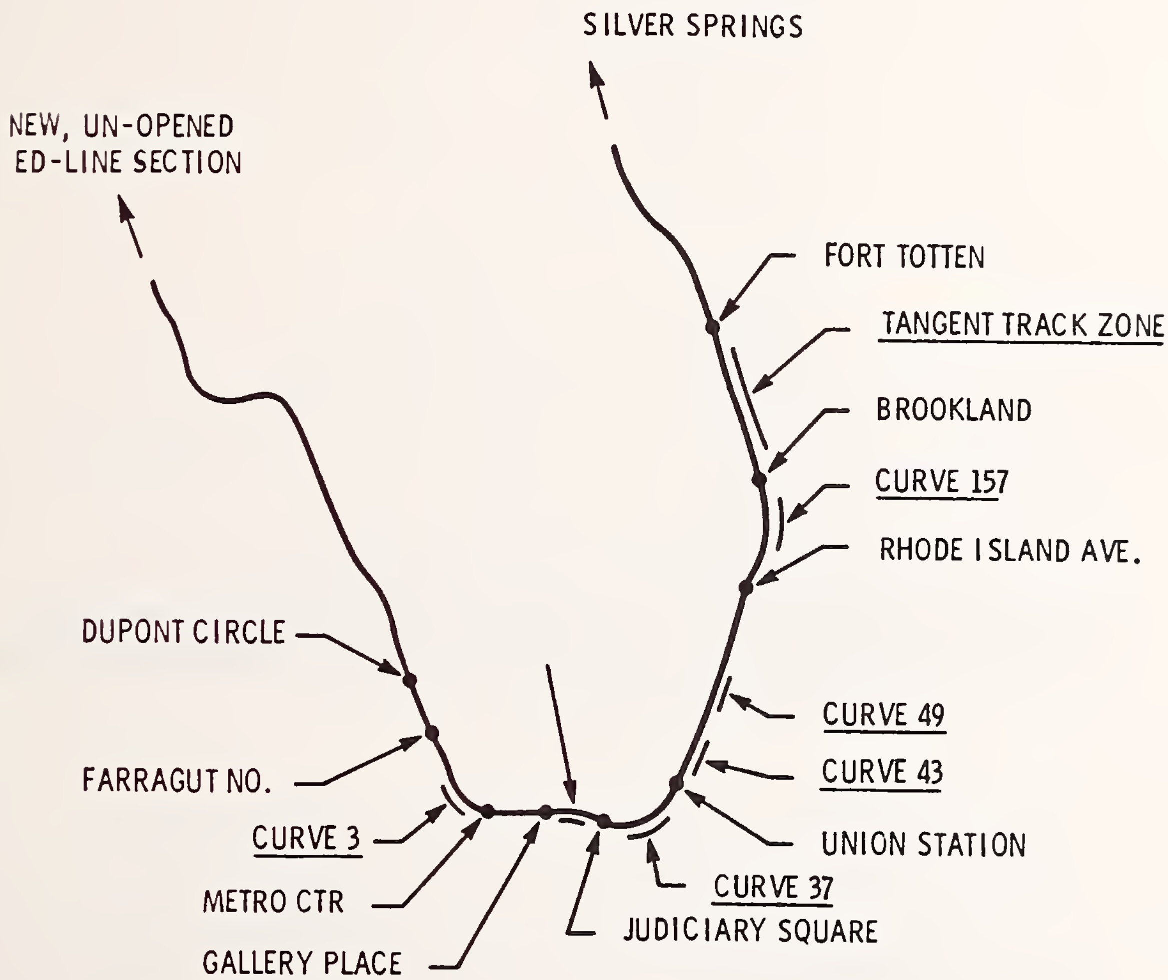

FIGURE 2. ROUTE DESCRIPTION AND CURVE DATA

Figures 3 and 4 present a summary of the lateral wheel/rail force measured outbound on the WMATA Red Line. In the first case the forces are presented for both the left and right rails as a function of distance over the entire line as generated by the conventional stiff primary suspension truck with cylindrical wheels. In the second case the forces are presented for the right rail as a histogram of occurrence frequency of the forces for both the cylindrical profile stiff suspension truck and the 1:20 profile soft suspension truck.

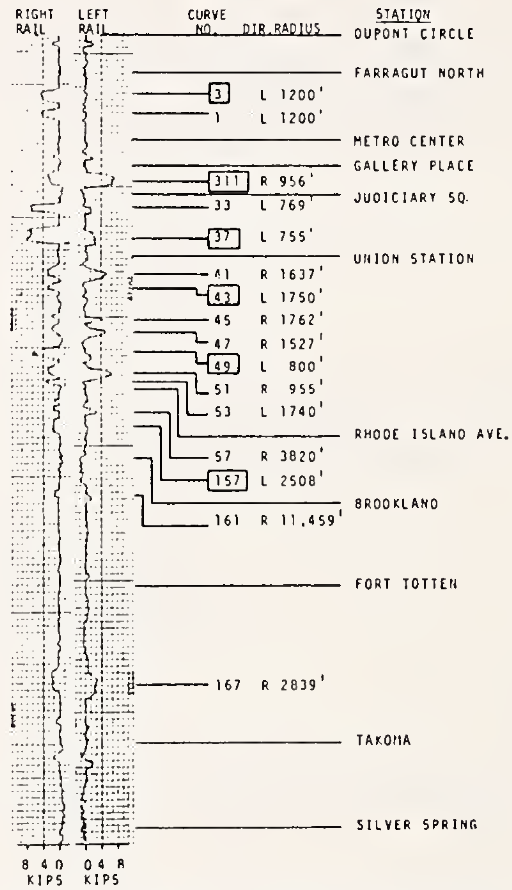

FIGURE 3. WMATA RED LINE LATERAL WHEEL/RAIL FORCE SURVEY, CYLINDRICAL WHEEL PROFILE, STIFF PRIMARY SUSPENSION

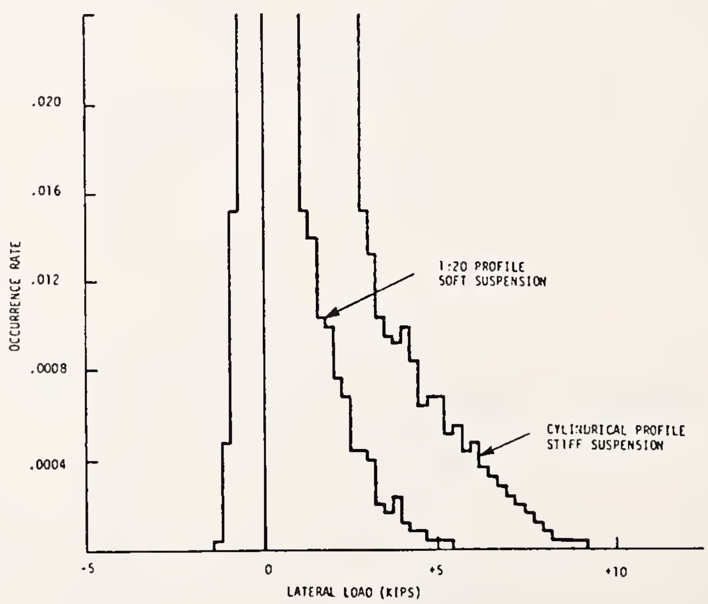

FIGURE 4. INSTRUMENTED WHEEL SET FREQUENCY HISTOGRAM OF LATERAL RAIL LOADS ON WMATA TEST LINE

Figures 5 through 13 present detailed wheel/rail lateral force measurement for curve 37 as a function of distance through the curve and for various test configurations. In addition, each sheet presents a histogram of the forces and the power spectral density of the frequency of the fluctuations as determined by a Fast Fourier Transform of the data. Figure 5 shows the close relationship between the forces and the gage face wear of the rail on the high rail. Figure 6 through 9 compare the forces on the high and low rail for high and low speeds showing a relative insenstivity to speed because of the forces being generated by friction rather than centrifugal effects. Figures 10 through 13 present the same comparision for the tapered profile, soft primary suspension configuration showing the reduction in average force for that configuration but the lack of change in the frequency fluctuations.

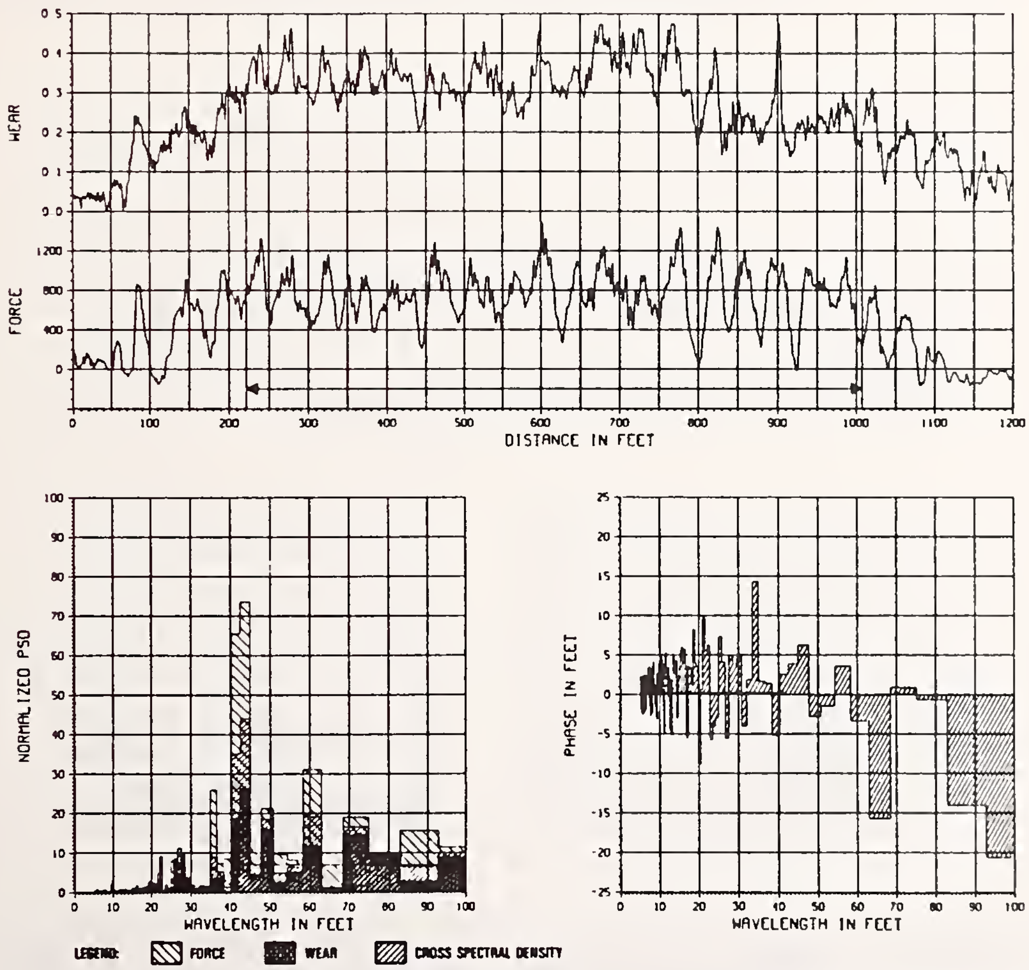

FIGURE 5. COMPARISON OF LATERAL WHEEL/RAIL FORCES VS GAGE FACE WEAR, CURVE 37, HI RAIL TAPERED WHEEL, STIFF SUSPENSION - 40 MPH

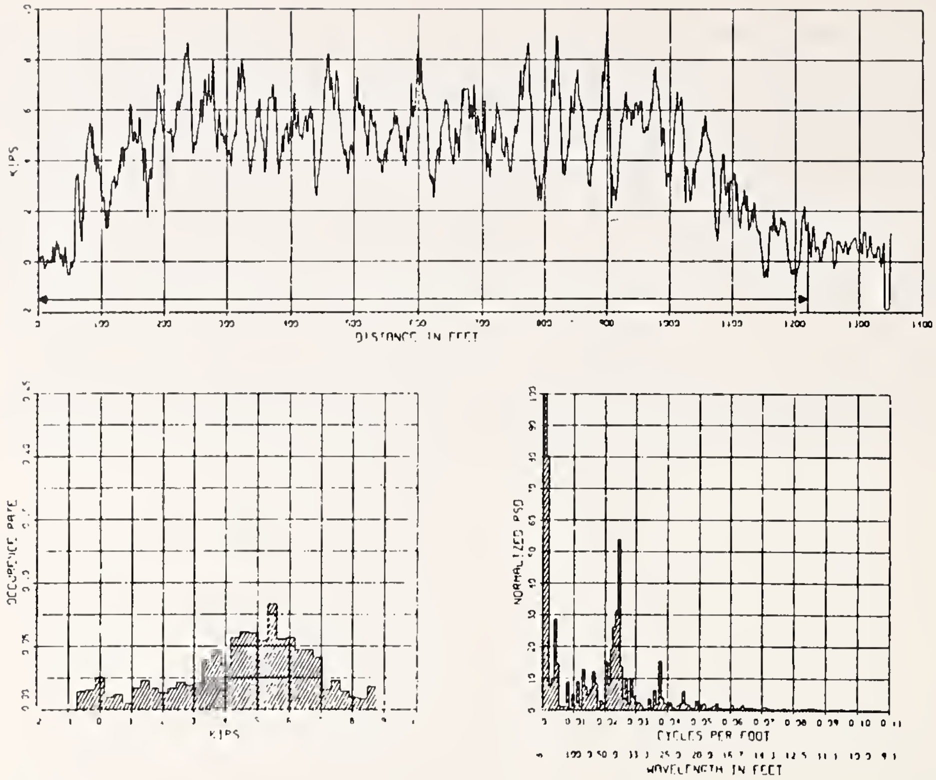

FIGURE 6. CURVE 37 HI RAIL LATERAL WHEEL/RAIL FORCES.
CYLINDRICAL WHEEL, STIFF SUSPENSION - 37 MPH

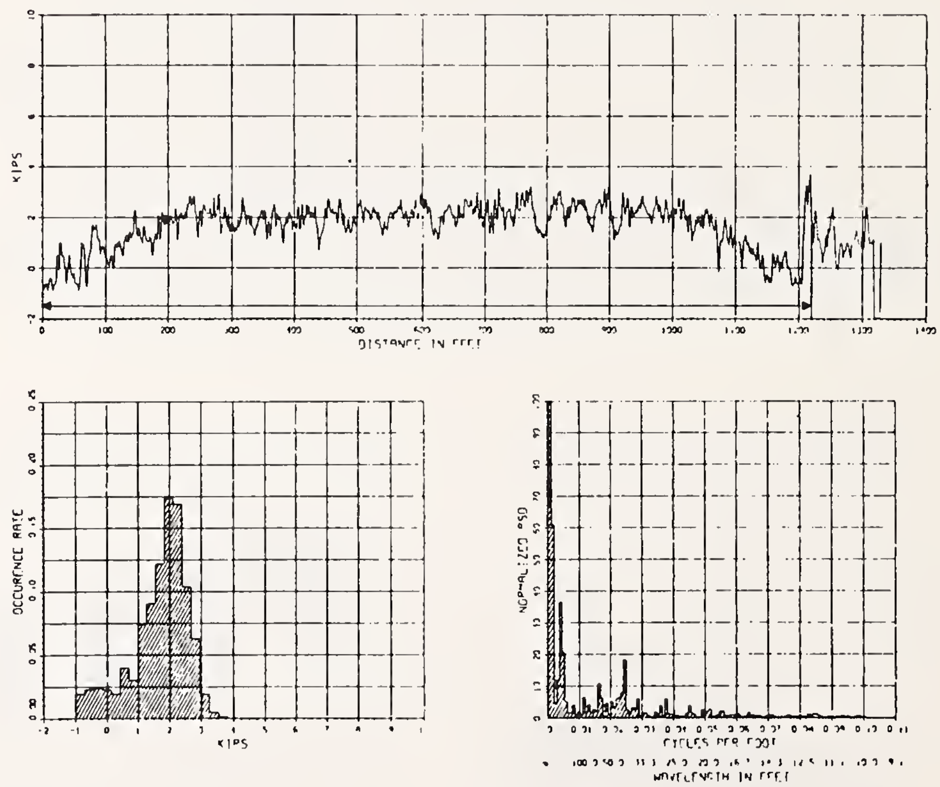

FIGURE 7. CURVE 37 LO RAIL LATERAL WHEEL/RAIL FORCES,
CYLINDRICAL WHEEL, STIFF SUSPENSION - 37 MPH

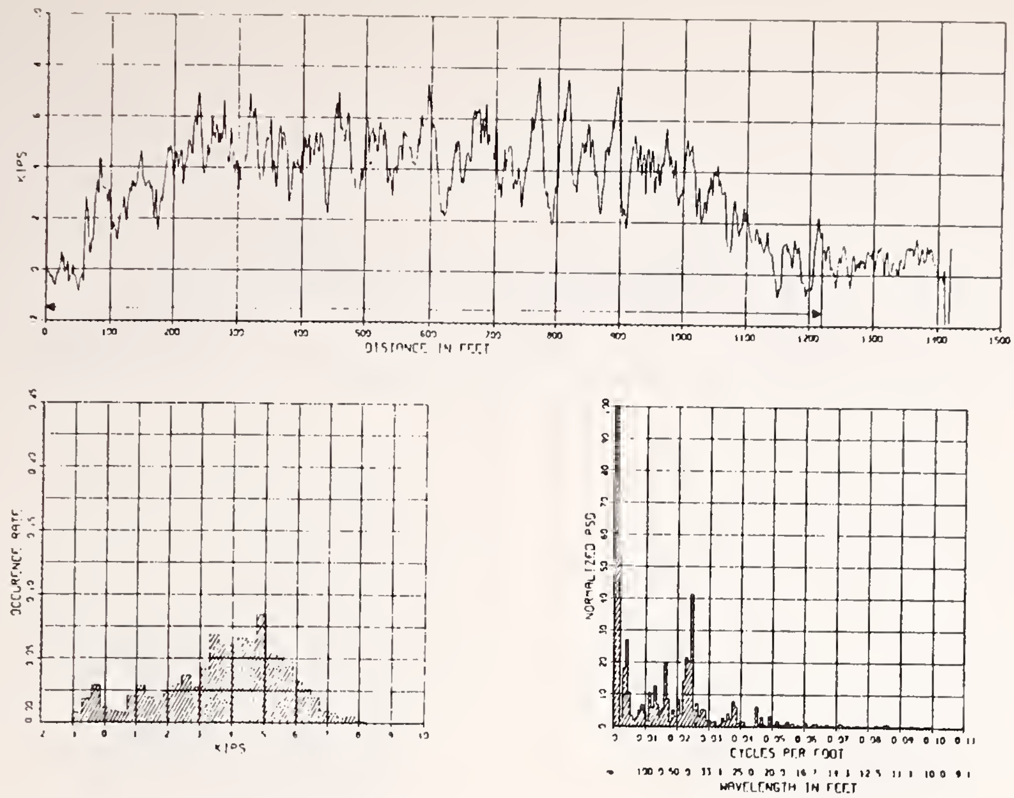

FIGURE 8. CURVE 37 HI RAIL LATERAL WHEEL/RAIL FORCES,
CYLINDRICAL WHEEL, STIFF SUSPENSION - 10 MPH

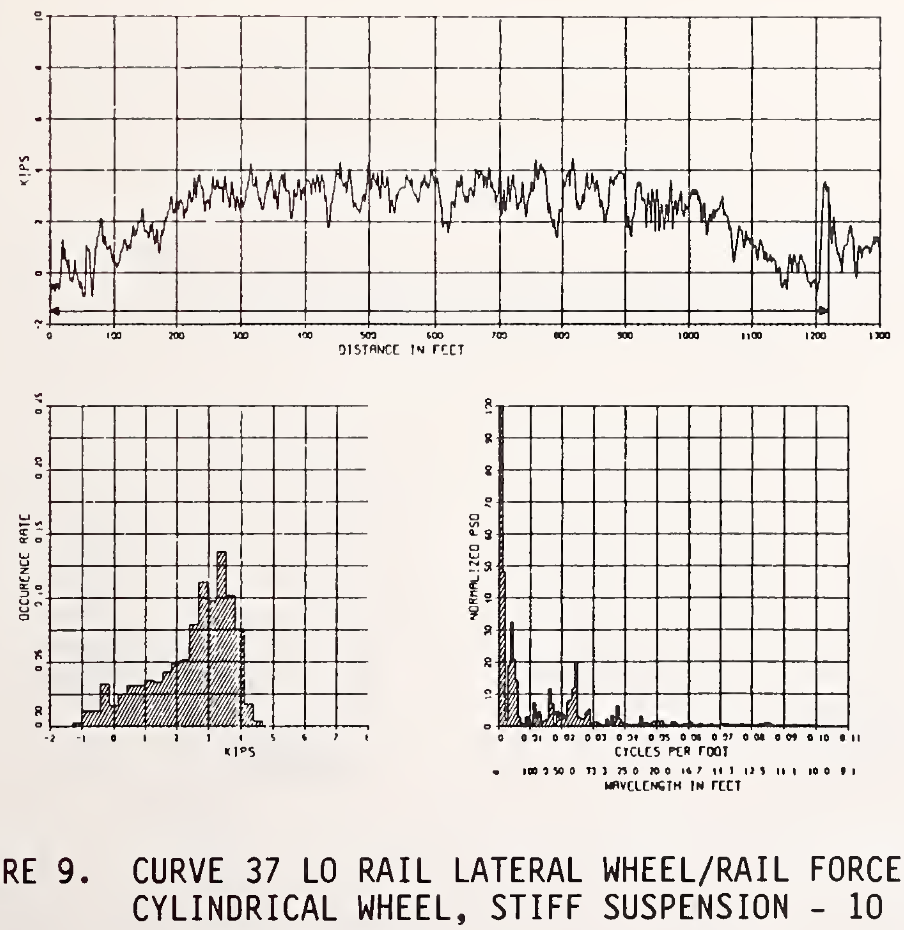

FIGURE 9. CURVE 37 LO RAIL LATERAL WHEEL/RAIL FORCES,
CYLINDRICAL WHEEL, STIFF SUSPENSION - 10 MPH

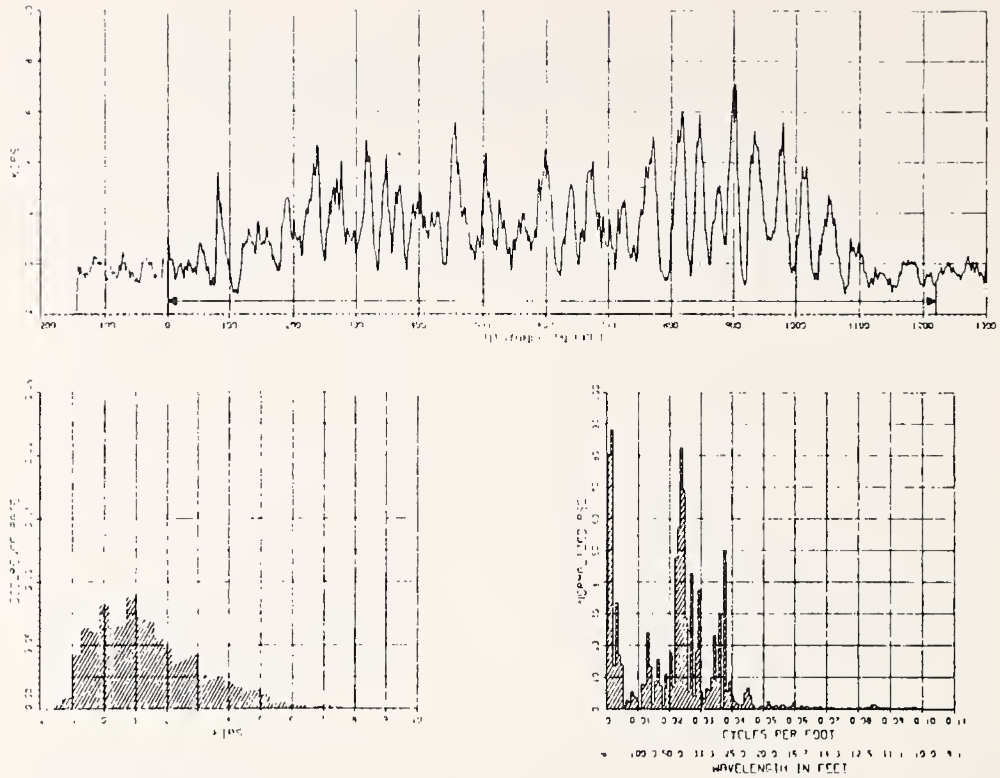

FIGURE 10. CURVE 37 HI RAIL LATERAL WHEEL/RAIL FORCES, TAPERED WHEEL, SOFT SUSPENSION - 40 MPH

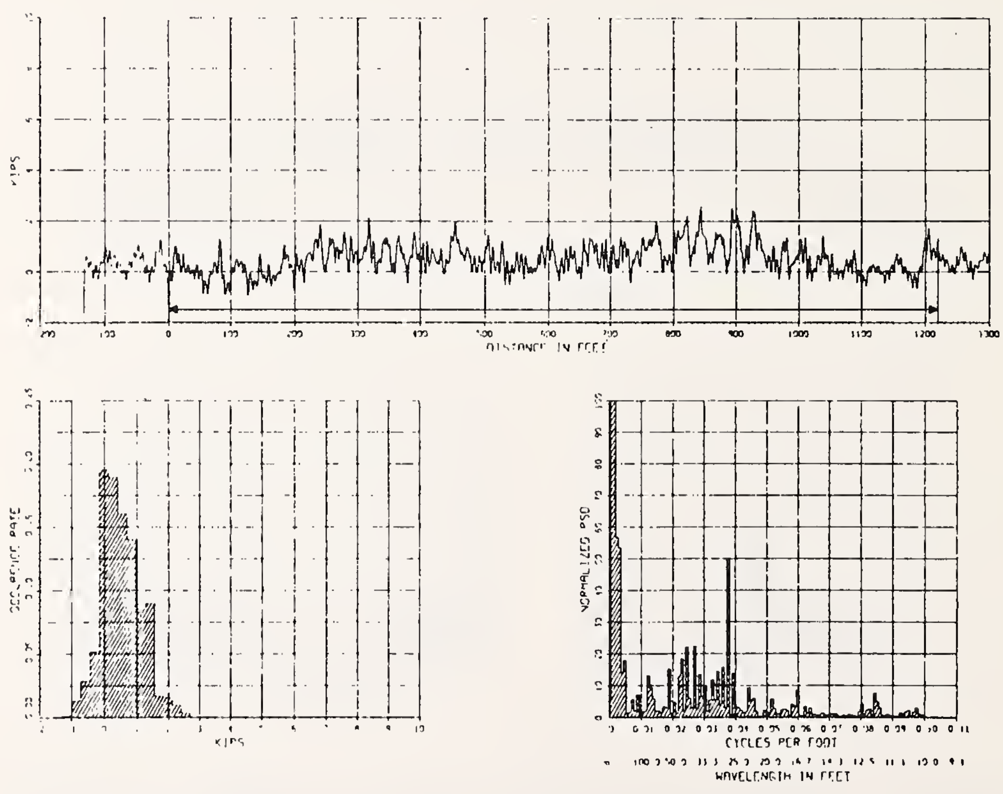

FIGURE 11. CURVE 37 LO RAIL LATERAL WHEEL/RAIL FORCES, TAPERED WHEEL, SOFT SUSPENSION - 40 MPH

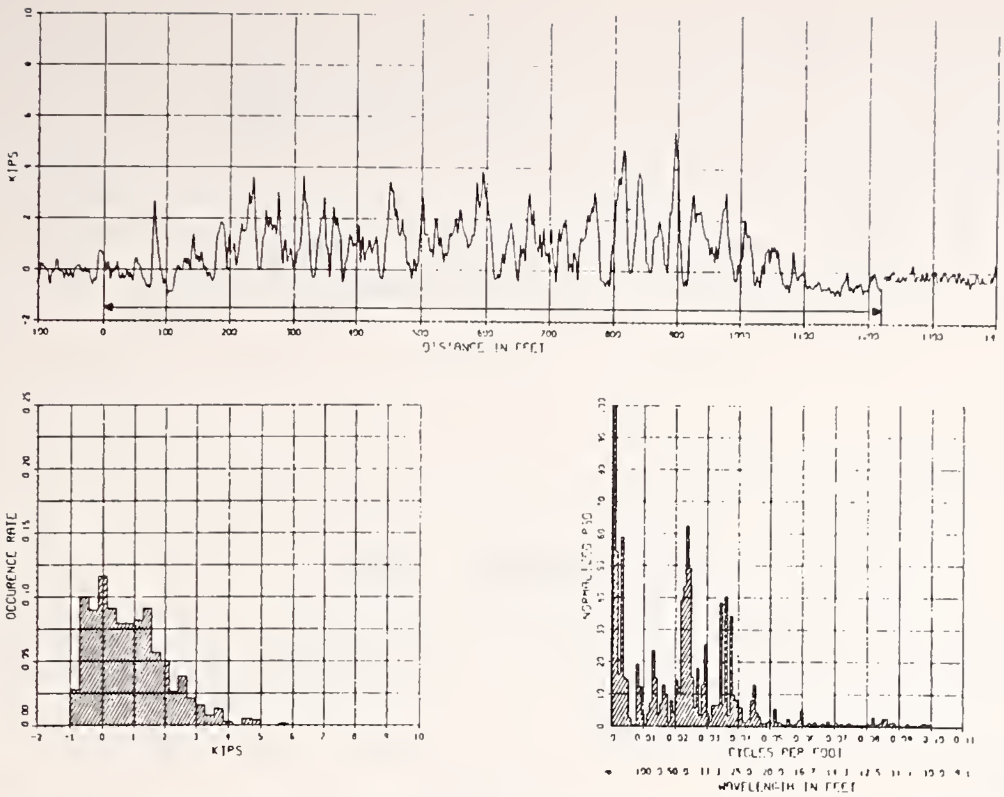

FIGURE 12. CURVE 37 HI RAIL LATERAL WHEEL/RAIL FORCES, TAPERED WHEEL, SOFT SUSPENSION - 14 MPH

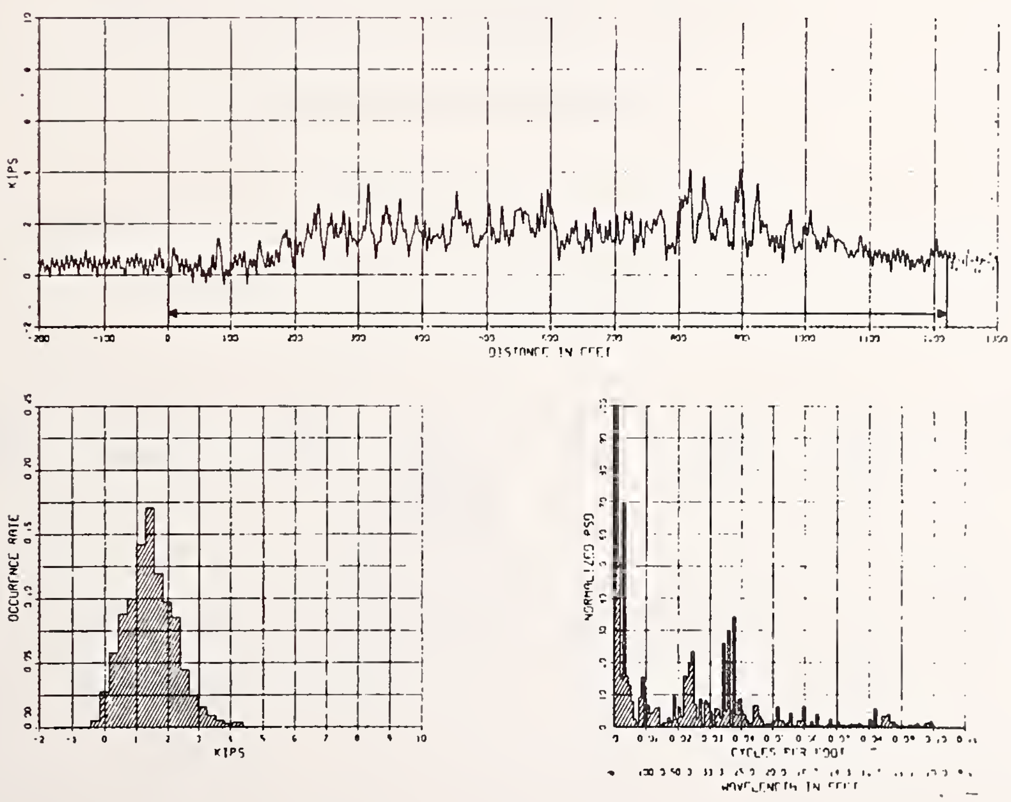

FIGURE 13. CURVE 37 LO RAIL LATERAL WHEEL/RAIL FORCES, TAPERED WHEEL, SOFT SUSPENSION - 14 MPH

Figures 14 and 15 present the peak and average forces on curve 37 as a function of speed for the four combinations of suspension stiffness and wheel profile. Figure 16 summarizes the average force at balance speed as a function of radius for the six selected test curves. This plot shows a general trend of increasing forces for decreasing radius with the exception of curve 311. The higher forces on this curve are explained by the direction of curvature of curve 311 being opposite from the other curves. It is assumed that because of very small axle misalignments the truck generates lower forces on the other curves and higher forces on curve 311.

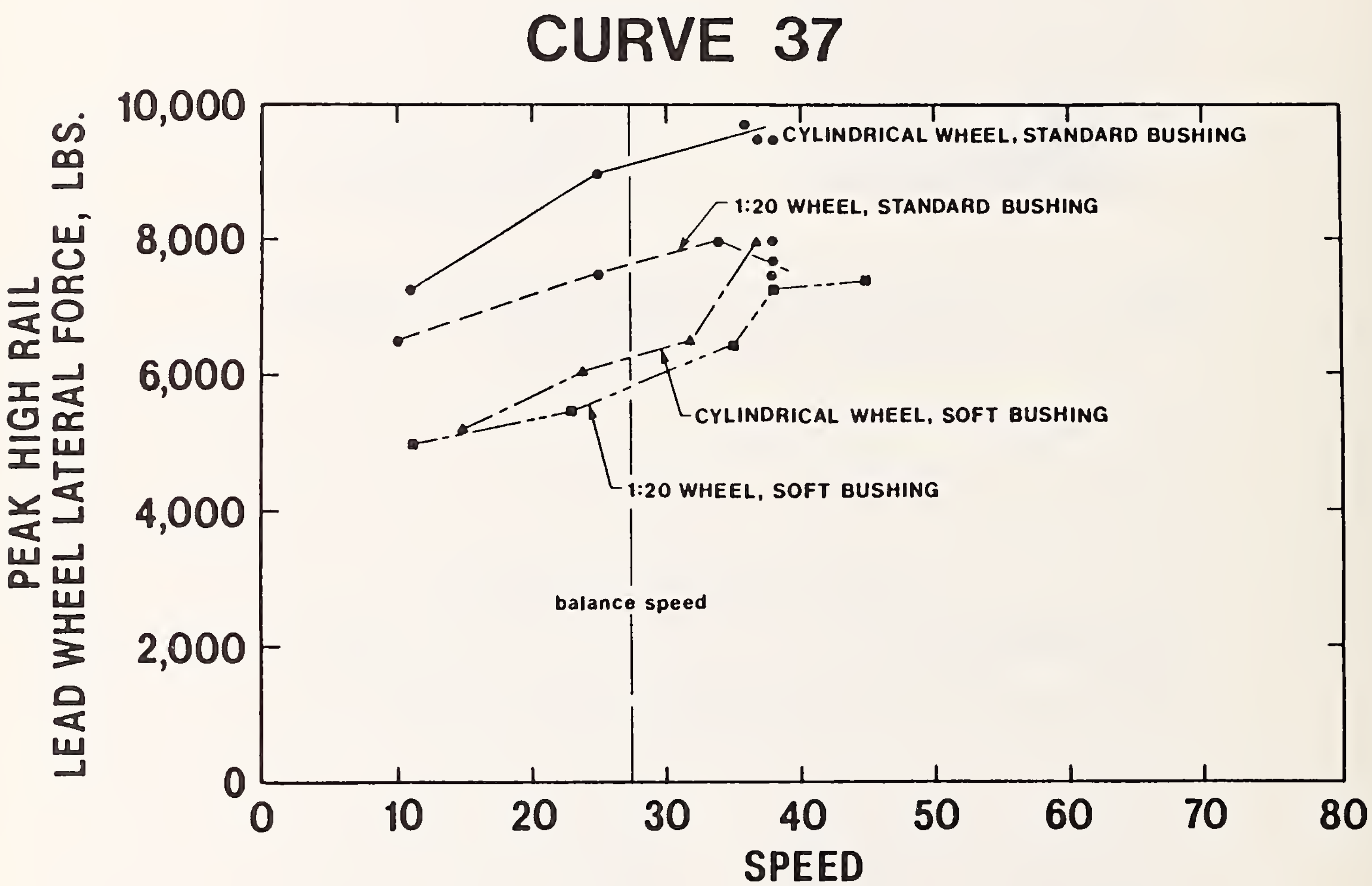

FIGURE 14. PEAK FORCES

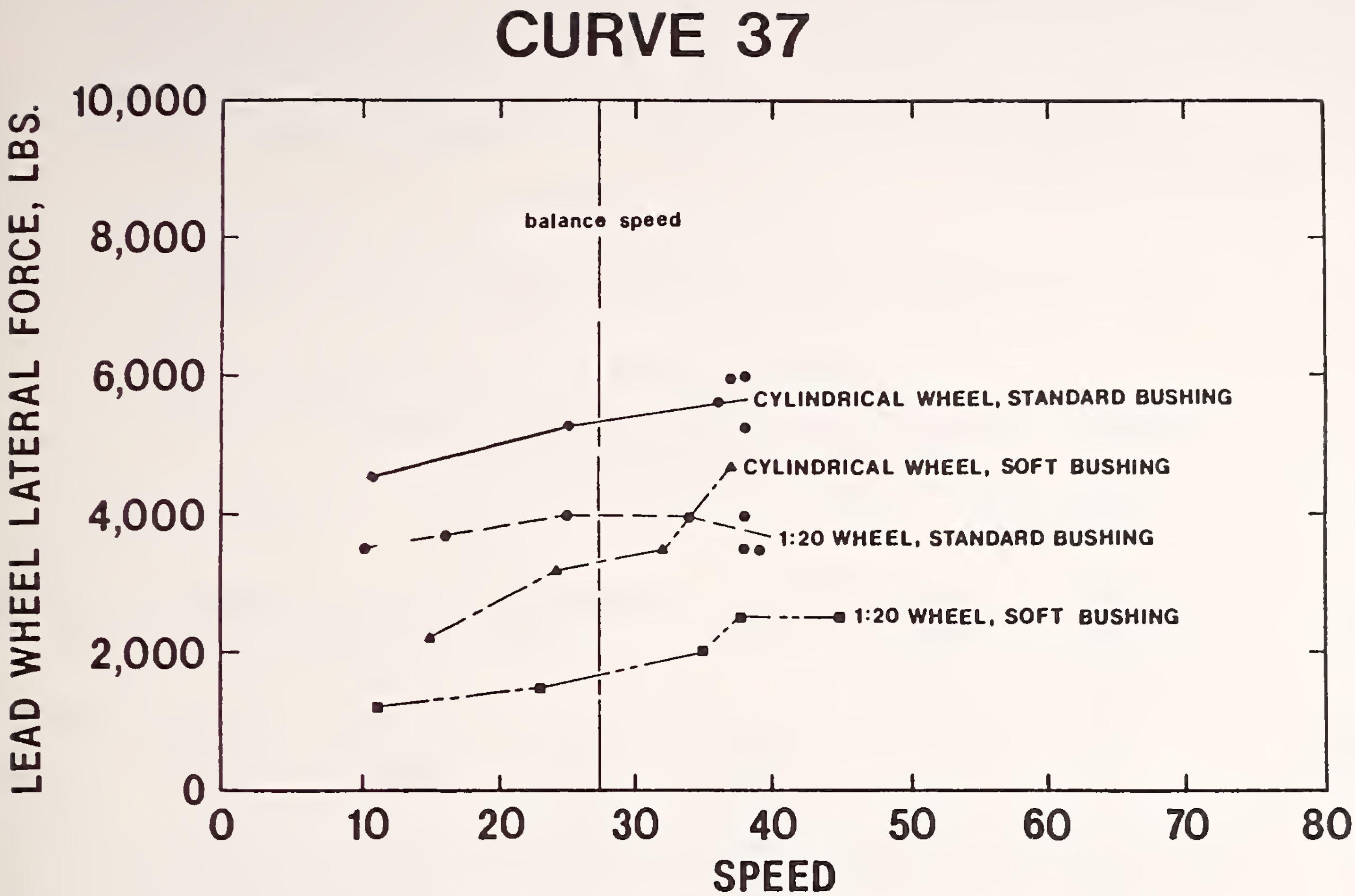

FIGURE 15. AVERAGE FORCES

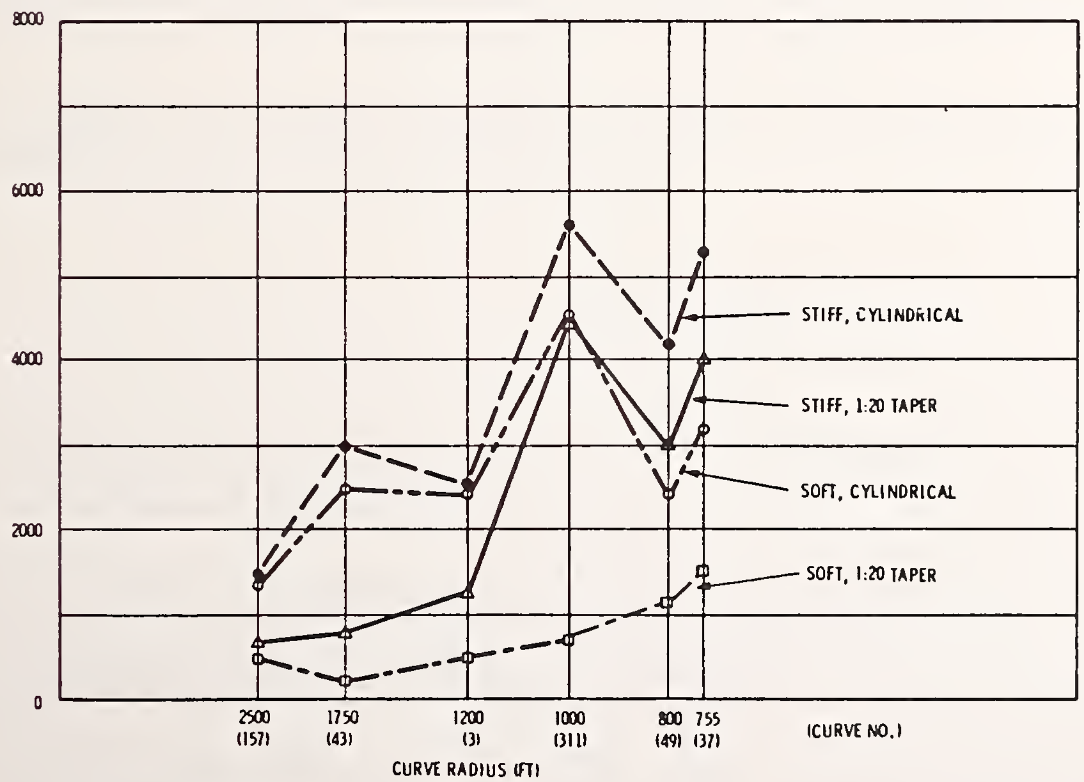

FIGURE 16. SUMMARY OF RESULTS FROM WMATA TRUCK TEST PROJECT (FOR BALANCE SPEED CONDITIONS)

Table 5 presents the preliminary findings for the lateral wheel rail forces on curve 37 as they were effected by reducing suspension stiffness and increasing wheel taper. A maximum reduction of 72% was realized for a soft primary suspension and a 1:20 worn wheel taper versus a stiff primary suspension and a cylindrical wheel taper. This force reduction if implemented over the entire WMATA fleet would result in significant reduction in wheel and rail wear and fastener failure on curves.

TABLE 5. PRELIMINARY FINDINGS, CURVE 37 UNION STATION, LATERAL WHEEL/RAIL FORCES (KIPS)

TAPER	SUSP.	PEAK	(Δ%)	AVERAGE	(Δ%)	MODEL	(Δ%)
CYL.	STD.	9.3		5.4		5.2	
1:20 (BR)	STD	7.8	(16%)	4.0	(26%)	4.8	(8%)
1:10	STD	6.5	(30%)	3.4	(37%)	4.5	(13%)
1:10	SOFT	5.1	(45%)	1.3	(76%)	1.8%	(65%)
1:20	SOFT	5.8	(37%)	1.5	(72%)	1.6	(69%)

TABLE 6A. PRELIMINARY FINDINGS, WMATA TRUCK TEST

PEAK LATERAL W/R FORCES, 10-11 KIPS

LARGE FLUCTUATIONS OF FORCES DURING CURVING

LOCATION OF FORCE PEAKS REPEATABLE, INDEPENDENT OF SPEED

FORCE PEAKS OCCUR APPROX. EVERY 40 FT

FORCE FLUCTUATIONS ARE SMALLER ON NEW TRACK THAN ON OLD

AXLE MISALIGNMENT INFLUENCES W/R FORCES

TABLE 6B. PRELIMINARY CONCLUSIONS, WMATA TRUCK TESTS

FLUCTUATIONS IN LATERAL W/R FORCES ARE RELATED TO IRREGULAR WEAR IN CURVES

IRREGULAR WEAR IN CURVES IS RELATED TO RAIL WELDS AND FASTENER VARIATIONS

HIGH RATES OF WEAR ARE DUE TO STIFF PRIMARY SUSPENSION, AXLE MISALIGNMENT, AND POSSIBLY WHEEL RAIL IMPACT ASSOCIATED WITH IRREGULAR WEAR

SOFTENING THE PRIMARY SUSPENSION RESULTS IN 72% REDUCTION IN AVERAGE W/R FORCES AND REDUCES EFFECTS OF MISALIGNMENT

SOFTENING THE PRIMARY SUSPENSION RESULTED IN NO SIGNS OF HUNTING WITH A 1:10 TAPER AT 75 MPH

TABLE 6C. RECOMMENDATIONS

- EVALUATE SOFTENED SUSPENSION BUSHES FOR ADEQUATE LIFE AND STABILITY AS A POSSIBLE FLEET RETROFIT
- CONTINUE WITH INTRODUCTION OF 1:20 B.R. TAPERED WHEELS
- CONTINUE INVESTIGATION INTO WEAR MECHANISM
- CONTINUE ANALYSIS OF W/R FORCE TEST DATA

The In-Service Dynamic Fastener Environment Measurement Program

Arthur Lohrmann
Senior Trackwork Engineer
DeLeuw, Cather & Company

INTRODUCTION

During session two yesterday, Arthur Keffler described the nature and extent of the direct fixation fastener problems at WMATA. In order to identify the cause of the problems, to find solutions applicable to the existing operating system and to take steps to preclude the problem from future segments, a measurement program was performed. The program was titled "The In-Service Dynamic Fastener Environment (ISDFE) Measurement Program". This paper discusses the approach, field equipment and procedures, test plan, data reduction, and laboratory procedures used, and the results and conclusions from the program.

The fastener environment (see Figure 1) was to be defined by vertical and lateral loads and a roll moment. The longitudinal load and pitch and yaw moments were dispensed with as being relatively too small to be significant in the study. The loads and moments were to be determined as transients for the real world operating condition.

The measured fastener environment would be compared with the performance test requirements in the WMATA procurement specifications and could be used to simulate the in-service environment in a laboratory in order to determine a mechanical fatigue life.

APPROACH

It was desired to use a measurement technique that required minimum site preparation, minimum intrusion onto or modification of track, and no disturbance of either rail alignment or fastener. In this manner, it would be possible to collect data at several fastener locations at each site in minimum time and without the large cost of track crews to make track modifications. The experimental advantages are:

- o The measurements are in-situ and there is no need to be concerned about introducing either a geometric or mechanical irregularity.

- o Additional data collection locations at a site will account for spatial effects.

The approach devised was to record in-situ time deflection data that characterizes the vertical, lateral and roll movement of the top plate of the fastener, remove the fastener from track, and then determine the vertical and lateral transient forces while replicating the time deflection data in the laboratory.

FIELD EQUIPMENT

Wilson Ihrig and Associates (WIA), acoustical consultants on the Washington

Metro project, designed and built fixtures that could be positioned by hand and secured with a screwdriver to the top and bottom steel plates of a fastener. The fixtures were provided with attachment points for Linear Variable Differential Transducers (LVDTs). Four LVDTs were used to instrument a fastener (see Figures 2A & 2B). Two were oriented vertical to the fastener and located diagonally and symmetric to the vertical centerline of the fastener. These were referenced to the field and gage sides. The average of the data from the two points is the vertical deflection of the fastener. The difference indicates the roll. It was assumed that the effect of pitch would be small or nil when roll is of the most interest. Also, the top plate fixture was attached at points beneath the edges of the base of the rail so that rotation measured would also be the rail rotation. With this feature,rail head displacement could be calculated.

The third LVDT was oriented parallel to the top plate and perpendicular to the rail, and located at a corner of the fixture. This LVDT measured the lateral deflection of the top plate relative to the bottom plate where it was assumed that the effect of yaw would be small or nil when the lateral movement is of the most interest.

The fourth LVDT was used to monitor the lateral movement of the bottom plate of the fastener to the invert. Although this information was not necessary to determine the fastener load in the laboratory, it was necessary to verify that the fastener was anchored to the invert as the design assumes. If it was not anchored tightly, the effective lateral stiffness in the track would be less than when rigidly anchored. It would be expected that a fastener with reduced effective lateral stiffness will participate less in supporting the rail and carry a smaller load. If loosely anchored fasteners were not identified and accounted for, then the results could be flawed with low fastener loads.

Two sets of fixtures with LVDTs were used so that both the high rail and opposite low rail fasteners could be instrumented and measured simultaneously. An eight channel graphic recorder was used to record the data.

FIELD PROCEDURES, TEST PLAN AND DATA REDUCTION

Instrumented fasteners were located on curves that were chosen by horizontal curvature. Other parameters, such as superelevation, speed, mode of operation (acceleration, braking, and coasting), grade and vehicle were considered. However, superelevation is nearly the same on most curves on the operating system with direct fixation fasteners, which makes it a single value parameter. Since UMTA's Phase I Wheel/Rail Force Study performed at WMATA in August 1979 concluded there was no pronounced pattern relating forces to velocity, accelerating, coasting or braking conditions, the speed and mode of operation parameters were not further considered. It was further assumed that the vector component of the weight of a vehicle in the direction of the profile grade would be similar to an acceleration or braking vector. Therefore, it was assumed that grade would have a similar effect as mode of operation, that is, little. Presently, there is only one vehicle type in use.

Four sites were chosen as shown in Table 1. The table also shows the number of fastener pairs instrumented, a total number of vehicle passes during data collection and the number of vehicle passes for which the data were reduced.

TABLE 1. TEST SPECIFICATION SUMMARY

Radius	Number of Fastener Pairs	Number of Vehicles Recorded	Number of Vehicles for Which the Data was Reduced
Tangent	2	--	41
2500 ft.	--	--	--
1600 ft.	1	--	33
755 ft.	3	--	116
		TOTAL 312	

After a preliminary review of the data, it was decided that data from the 2500-ft. radius curve would not enhance the study further so it was dropped from the plan.

Figure 3 is a sample of the strip chart data recorded for instrumented fasteners on the 755-ft. radius curve. There are four channels for the high rail fastener and four for the opposite low rail fastener.

Each channel is labeled to correspond to the LVDT orientation and location as discussed earlier. For the vertical data, a downward deflection is indicated and for the lateral data, a deflection toward the field side is shown. The deflection scale for each channel is shown. The time scale is shown and time increases from left to right. The sample shows the deflection resulting from the passage of the second truck of a car followed by the first truck of the next car. The axle spacing can be approximately located by the peaks in the vertical traces.

The lateral top plate trace dramatically shows that the maximum and primary lateral deflection occurs at the lead axle of a truck and the location of the truck in the vehicle has little effect on the data. The trailing axle causes less than a third of the deflection of the lead. When the trailing axle is at the instrumented fastener, the lead axle is still influencing the deflection at the fastener. The dotted lines are assumed contributions of the two axles.

As expected, the difference in the vertical deflections on the field and gage side is largest with the lead axle at the fastener. This shows maximum roll. At the trailing axle where lateral deflection is small, the difference in the vertical deflections are small, indicating little roll, the traces also show that the patterns found at a high rail fastener are also found at a low rail fastener. The lateral deflection toward the field side is approximately one half that for the high rail fastener.

Figures 4 and 5 are examples of traces for the 1600-ft. radius curve and the tangent sites.

The data for each track curvature were reduced in the following manner:

1. Observing the peak lateral deflection caused by any of the four axles on a vehicle.

2. Observing the two vertical deflections at the instant of maximum lateral deflection.

3. Recording in a table the two vertical, the average of the two vertical, and lateral deflection values.

4. Repeating for each vehicle for which the data is to be reduced.

5. Plotting the peak lateral and the average vertical deflections per vehicle on distribution curves. (See Figures 6, 7, 8, 9, 10, and 11.)

6. Computing the mean values (Table 2). Since the deflection environment is significantly more severe for the 755-ft. radius than the 1600-ft or tangent curvature, the rest of the program concentrated on the 755-ft. data.

7. Identifying field and gage side vertical deflections from a trace that satisfied the mean average vertical and mean peak lateral deflections. The traces were also used to identify the transient characteristic for each deflection. This deflection data (Table 3), and the transient curves became the "goals" to duplicate in the laboratory phase of the program.

TABLE 2. MEAN VALUE COMPUTATION

Radius of Track Curvature	Number of Vehicles	Mean Peak Lateral Deflection (in.)	Mean Average Vertical Deflection (in.)
755 ft.	116	.058	.035
1600 ft.	33	.016	.025
Tangent	41	.006	.024

TABLE 3. FIELD AND GAGE SIDE DEFLECTION DATA

	Vertical Deflection		Lateral
	Field (in.)	Gage (in.)	Deflection (in.)
GOAL	.058	.016	.058

LABORATORY PROCEDURES

WIA designed a test rig that could apply both vertical and lateral transient loads to a short section of rail mounted on a fastener. The vertical load was applied at the center of the rail head similar to the requirements in the WMATA procurement specifications. The test rig was designed so that the height of the lateral load could be adjusted (see Figure 12A).

Three fasteners were used in the laboratory. Two were the same fasteners that had been instrumented on the high rail of the 755-foot radius curve. The third was a spare fastener that belonged to WIA. They were mounted in the test rig so that the loading and deflection would be in the same orientation as it had been in the track.

The fastener in the test rig was instrumented with the same equipment, in the same orientation that was used during the field data collection with one exception. As stated earlier, in the field it was assumed that yaw rotation would be nil when the lateral deflection was most significant. This was due to the continuous structural system. However, in the test rig, the structure was not continuous and the fastener stood alone and was potentially unstable. As a result, yaw could occur. In order to determine that yaw was also small during the laboratory replication the bottom lateral LVDT, which is not needed in the test rig, was used as a second instrument to monitor the top plate rotation for yaw (see Figure 12B).

During the trial and error process of replicating the two vertical and one lateral transient deflections, it was necessary to adjust the vertical and lateral transient loads and the height at which the lateral load was applied. The strip chart data of successfully replicated deflections and the associated loads are shown in Figures 13, 14 and 15 for the three fasteners. The data are shown in Table 4 .

TABLE 4. TRANSIENT DEFLECTION DATA

Fastener	Vertical Deflection (in.)		Lateral Deflection (in.)	Force (Pounds)		Height Above Rail Base (in.)
	Field	Gage		Vertical	Lateral	
GOAL	.058	.016	.058			
#7	.056	.016	.057	4600	5700	3-1/4
#11	.054	.018	.057	5000	6700	2-7/16
WIA Spare	.051	.016	.057	4110	6200	1-7/8
			Average	4570	6200	

DISCUSSION OF RESULTS

The number of fasteners instrumented was limited so that the spatial effects might not have been adequately accounted for. By observation, there did not appear to be any geometric or mechanical irregularities which would have influenced the results at the sites instrumented.

Table 5 compares the ISDFE results with the test requirements specified in WMATA's procurement contract for direct fixation fasteners. The load data for the 1600-foot and tangent sites were determined from the laboratory loads for the 755-foot site, assuming the loads would be in the same proportion as the deflections in Table 2.

TABLE 5. ISDFE RESULTS AND REQUIREMENTS

		Vertical Load (kips)	Lateral Load (kips)	Rolling Moment About Bottom of Top Plate (in.-kips)	Horizontal Stability (As Determined by Rail Head Deflection) (in.)	Load Cycle Pulse Length (secs)
Lateral Load Test	1st Criteria	13.5	4	27	0.125	Static
	2nd Criteria	13.5	10	67.5	0.30	Static
Repeated Load Test		13.5	3.9	26.3	Unspecified	0.25
ISDFE	755*	4.57	6.2	20.15	0.09	0.25
	1600**	3.26	1.7			
	TAN**	3.13	0.6			

* High rail
** Determined by proportioning

The table shows:

- o The vertical load used in the Lateral Load Test and the Vertical and Lateral Repeated Load Test is about three times the measured field condition at a 755-foot curve.

- o For the first criteria limit of the Lateral Load Test, the average lateral shear force measured on the 755-foot curve exceeds the capacity tested by 50 percent. However, the roll moment of the fastener is tested to a capacity 34 percent greater than the field condition.

- o The second criteria limit in the Lateral Load Test had provided a safety factor of 2.5 for lateral shear. With the measured higher average shear load on the 755-foot curve the safety factor is reduced to 1.6. Only 30 percent of the rolling moment capacity and only 30 percent of the allowable rail head deflection are used in the field.

- o The Vertical and Lateral Repeated Load Test, which demonstrates the mechanical fatigue resistance of the fastener, when compared to the average field condition measured for the 755-foot curve, severely punishes the fastener vertically and in bending (rolling) but is not severe enough with respect to lateral shear.

- o The lateral rail head deflection in the field on the 755-foot curve does not exceed the design values.

The ISDFE results can also be compared with a previous UMTA study on WMATA during 1979 and 1980. That program measured the wheel/rail forces and was performed at a site that was essentially identical to the ISDFE 755-foot site except that it was ballast track construction. (The design radius was 800 feet instead of 755 feet.) Table 5 in the UMTA report titled, "Measurement of Wheel/Rail Forces at the Washington Metropolitan Area Transit Authority Volume 1," shows an average lateral wheel/rail force of 4550 pounds. The wheel/rail force that causes the averge 6200-pound fastener force measured in the ISDFE data must be at least this value. It can be hypothesized that the track structure may play a significant role in determining the track forces on curves of small radius.

The ISDFE results were plotted as shown in Figure 16. The three data points were connected with straight lines. The 3900-pound load used in the Vertical and Lateral Repeated Load Test is shown. Non-vehicle factors account for 600 pounds of that load, which is why 3300 pounds are also shown. The straight line graph intersects the 3300 pound load at about 1200 feet. From this, it was concluded that minimally acceptable fastener designs would be susceptible to failure on curves with radius less than 1200 feet.

A second line was plotted for fastener spacing of 15 inches, which is one half of the WMATA standard spacing of 30 inches. It intersects the 3300-pound line at about 850-foot radius. From this it was concluded that minimally acceptable fasteners, which are installed at 15-inch spacing, would be susceptible to fatigue failure on curves with radius less than 850 feet.

However, the plot was based upon the assumptions shown on the graph. The third assumption is significant in light of the above hypothesis that the track structure may play an important role in determining track forces. If a stiffer track, which is the consequence of reducing fastener spacing, does increase the wheel/rail forces then the benefits of doubling the number of fasteners would be reduced.

Table 6 shows the geometric design and the in-service operating characteristics at the three test sites. Unbalanced superelevation (Eu) is twice as large at the 755-foot site than at the 1600 foot site. A simple centripetal acceleration analysis that only considers the vehicles as a two dimensional plane with a point mass would indicate that when Eu is doubled, the lateral load is approximately doubled. Assuming the dynamic characteristics of the track structure are not significantly different under the conditions when Eu is doubled, it would be expected that the fastener's lateral deflections would be doubled.

However, as shown earlier in Table 2, the lateral deflection is 3.5 times greater at the 755-foot site. This discrepancy suggests that some other factor such as tread creep plays a significant role in generating lateral forces on small radius curves at WMATA. A clue to this phenomenon can be seen in Figure 3, which shows the displacement of the low rail fastener was approximately one half of that on the high rail side and was towards the inside of the curve, the opposite direction than would be expected from a centripetal analysis when travelling at a speed with positive unbalanced superelevation.

TABLE 6. OPERATING CHARACTERISTICS

	DESIGN		OPERATION	
	RADIUS (FT.)	SUPER-ELEVATION (IN.)	UNBALANCED SUPER-ELEVATION (IN.)	SPEED (MPH)
Tangent	Infinite	0	0	45
1600 ft.	1600	4	2.27	50
755 ft.	755	4	4.5	40

CONCLUSIONS AND RECOMMENDATIONS

1. Spatial effects might not have been adequately accounted for. Several similar curves and several sites on each curve should be instrumented so that there would be better confidence with the results.

2. Assuming the stiffness requirements for future WMATA fasteners which are to be used on 755-foot curves is unchanged, then:

   o The lateral load condition in the Vertical and Lateral Repeated Load Test in the procurement specification should be increased to be in line with the ISDFE results.

   o Also, the vertical load and roll moment test condition should be reduced as indicated by the ISDFE results.

3. However, because

   o A comparison of the UMTA, Phase I and ISDFE results (which were performed on ballast and direct fixation track, respectively) indicate that the lateral force on direct fixation is greater than on ballast track, and

   o The ISDFE measured rail head deflection (vertical and lateral) were less than anticipated, then a reduction in the vertical, lateral and roll stiffness requirements in the procurement specification should be considered. A reduction in the stiffness is anticipated to have a positive consequence of reducing the loads measured in the ISDFE program.

4. The ISDFE results indicate that a fastener which is designed to minimally pass the Vertical and Lateral Repeated Load Test would be susceptible to fatigue failures on curves with radius less than 1200 feet. Also, if the increased stiffness due to cutting the fastener spacing one half does not result in increased wheel/rail forces, then it is anticipated that minimally acceptable fasteners, spaced at 15 inches, would be susceptible to fatigue failure on curves with radii less than 850 feet.

5. The lateral loads measured in the ISDFE program on small radius curves cannot be explained only by centripetal considerations. It appears the vehicle characteristics have to be considered in the analysis.

6. Assuming a verified dynamic analytical model that considers both track and vehicle characteristics is not available, then a fastener proposed for use with stiffness characteristics different from those used in the ISDFE program should be installed, instrumented and measured for deflections and loads in test sections. The results should be used to determine the test requirements for the Vertical and Lateral Repeated Load Test used to qualify the proposed fastener.

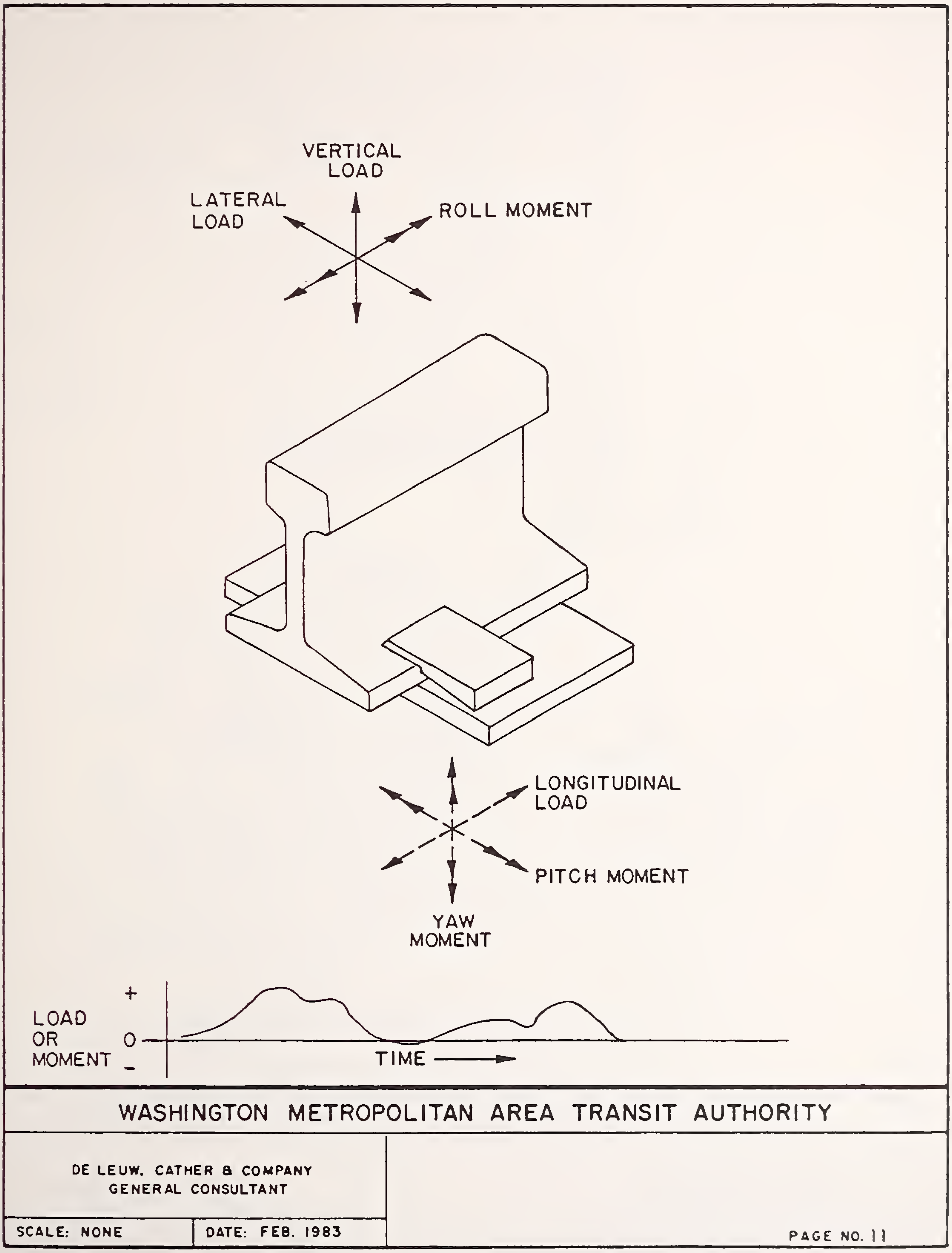

FIGURE 1. ISDFE ENVIRONMENT

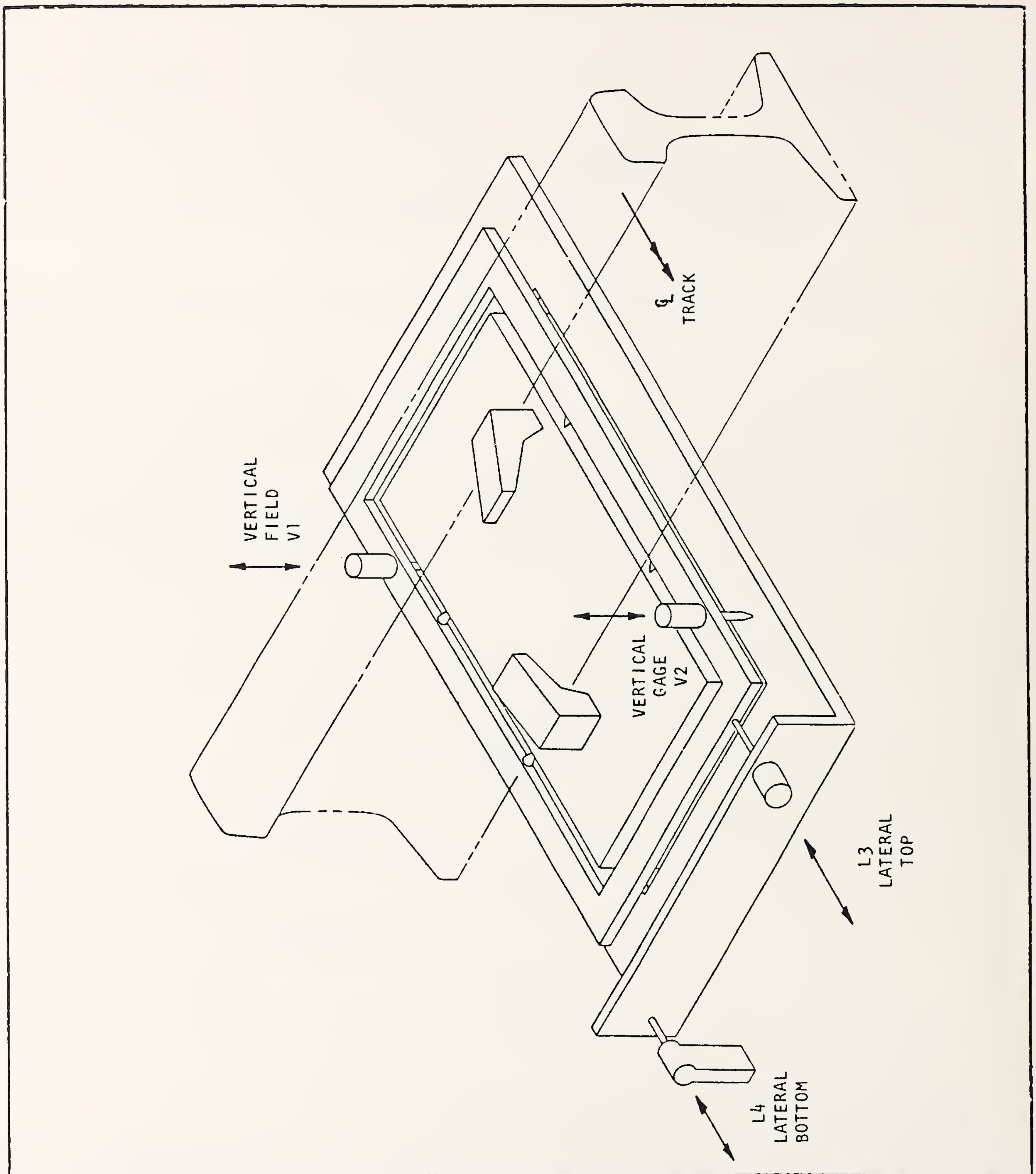

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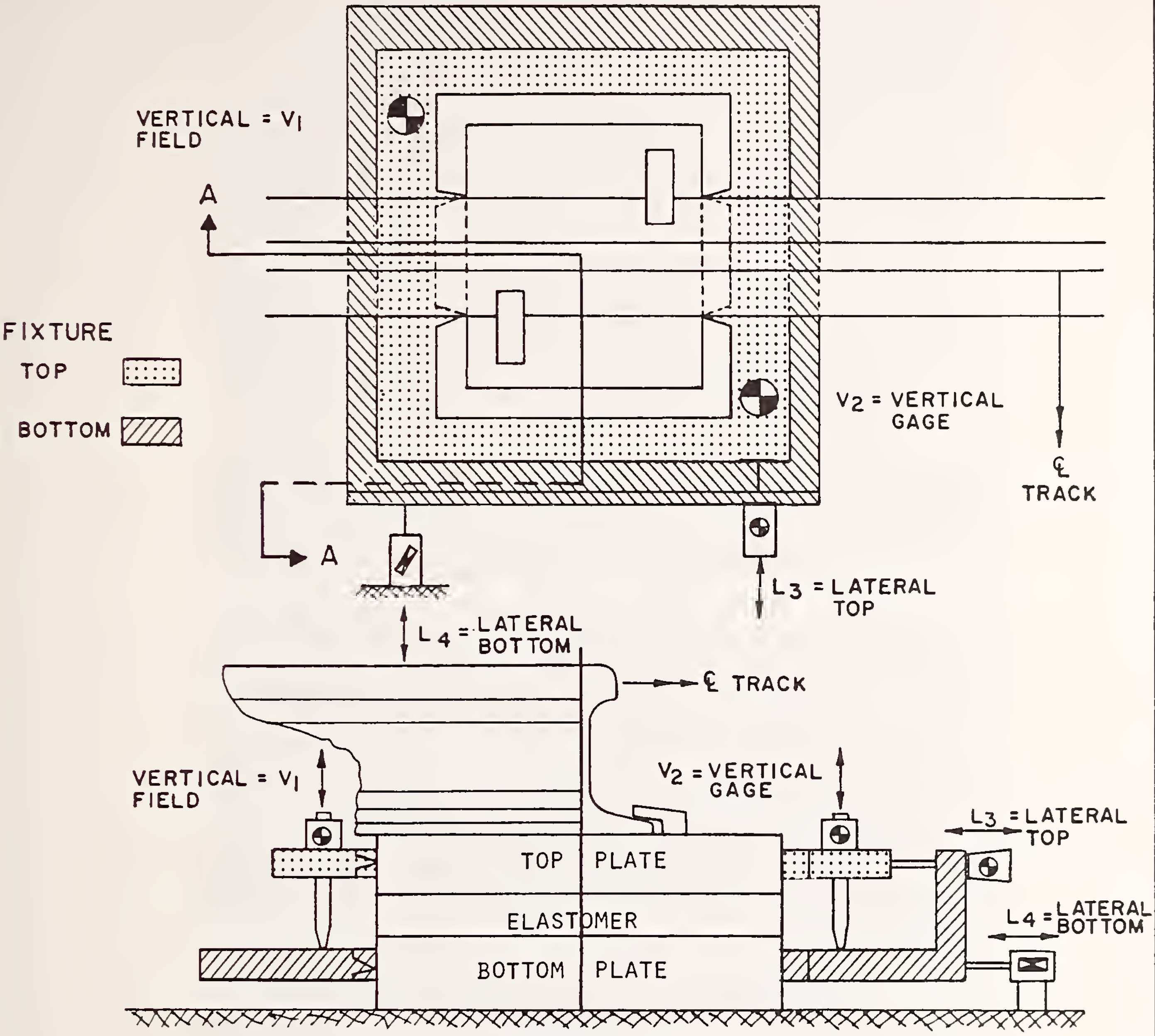
FIGURE 2A. FIELD EQUIPMENT AND INSTRUMENTATION



SECTION A-A

VERTICAL DEFLECTION $= \dfrac{V_1 + V_2}{2}$

ROLL $= V_1 - V_2$

LATERAL TOP PLATE DEFLECTION W/RESPECT TO BOTTOM PLATE = L_3

LATERAL BOTTOM PLATE DEFLECTION W/RESPECT TO INVERT = $L_4 \approx 0$

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FIGURE 2B. FIELD EQUIPMENT AND INSTRUMENTATION

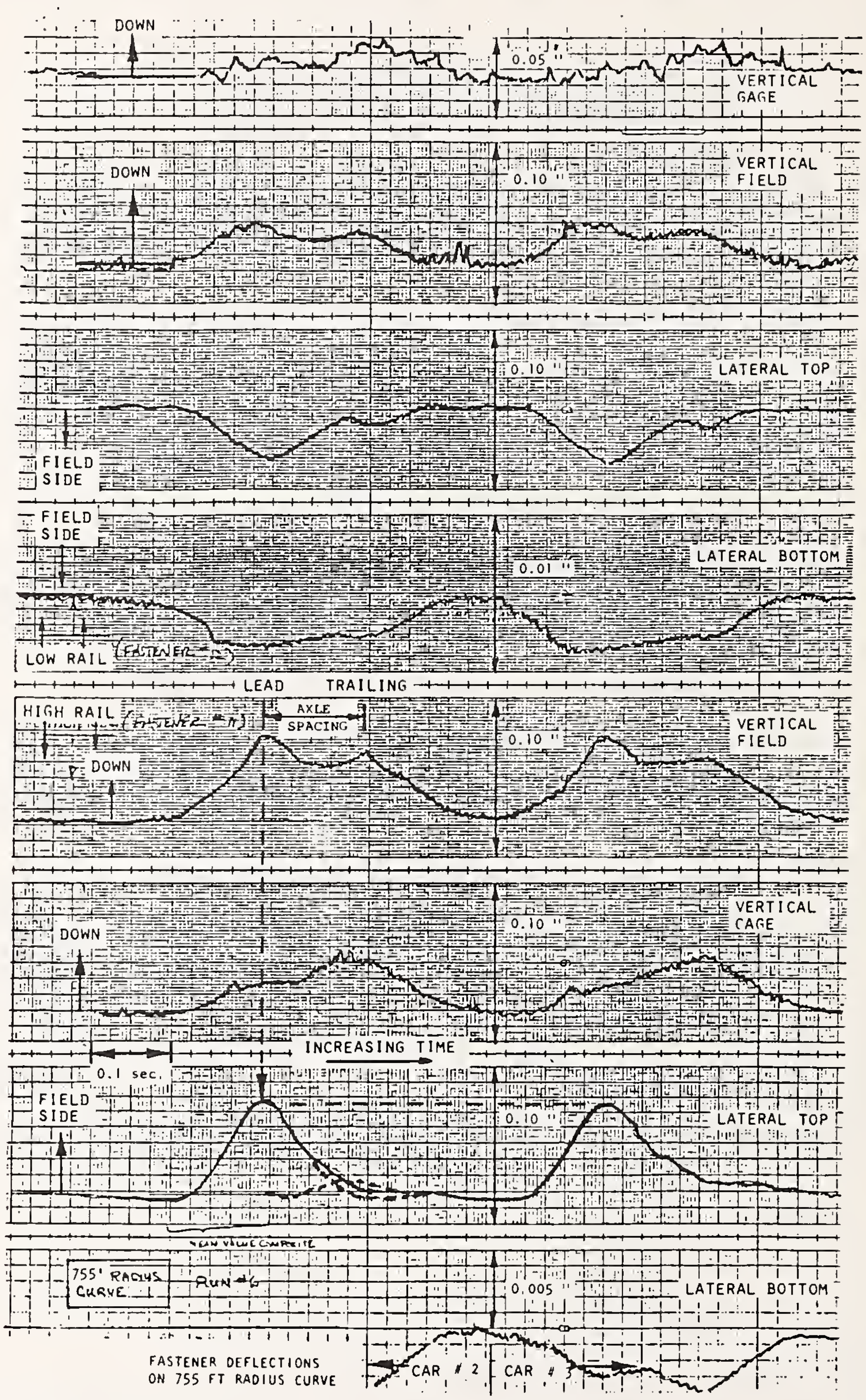

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FIGURE 3. FIELD DATA, 755' RADIUS CURVE

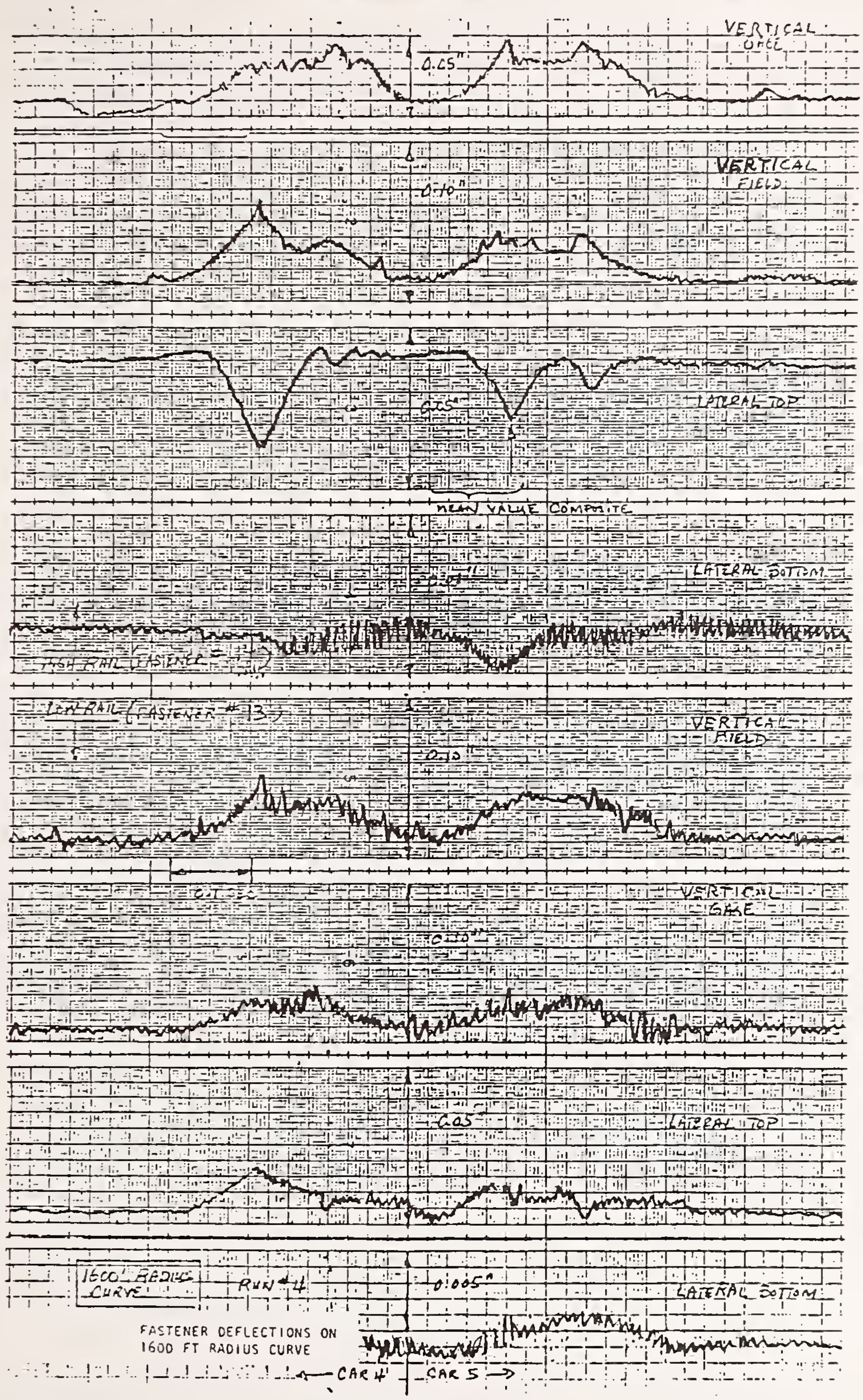

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FIGURE 4. FIELD DATA, 1600' RADIUS CURVE

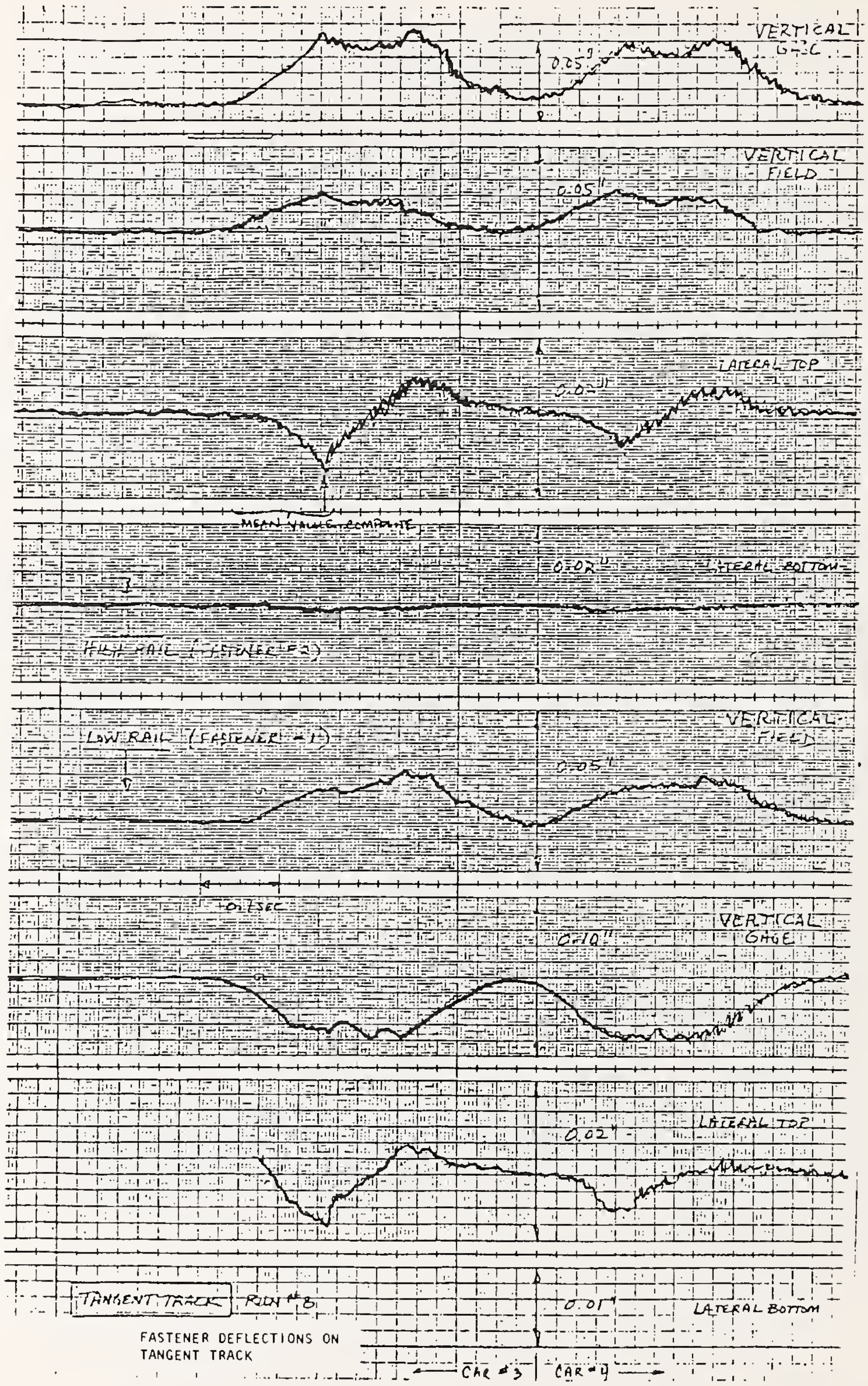

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FIGURE 5. FIELD DATA, TANGENT TRACK

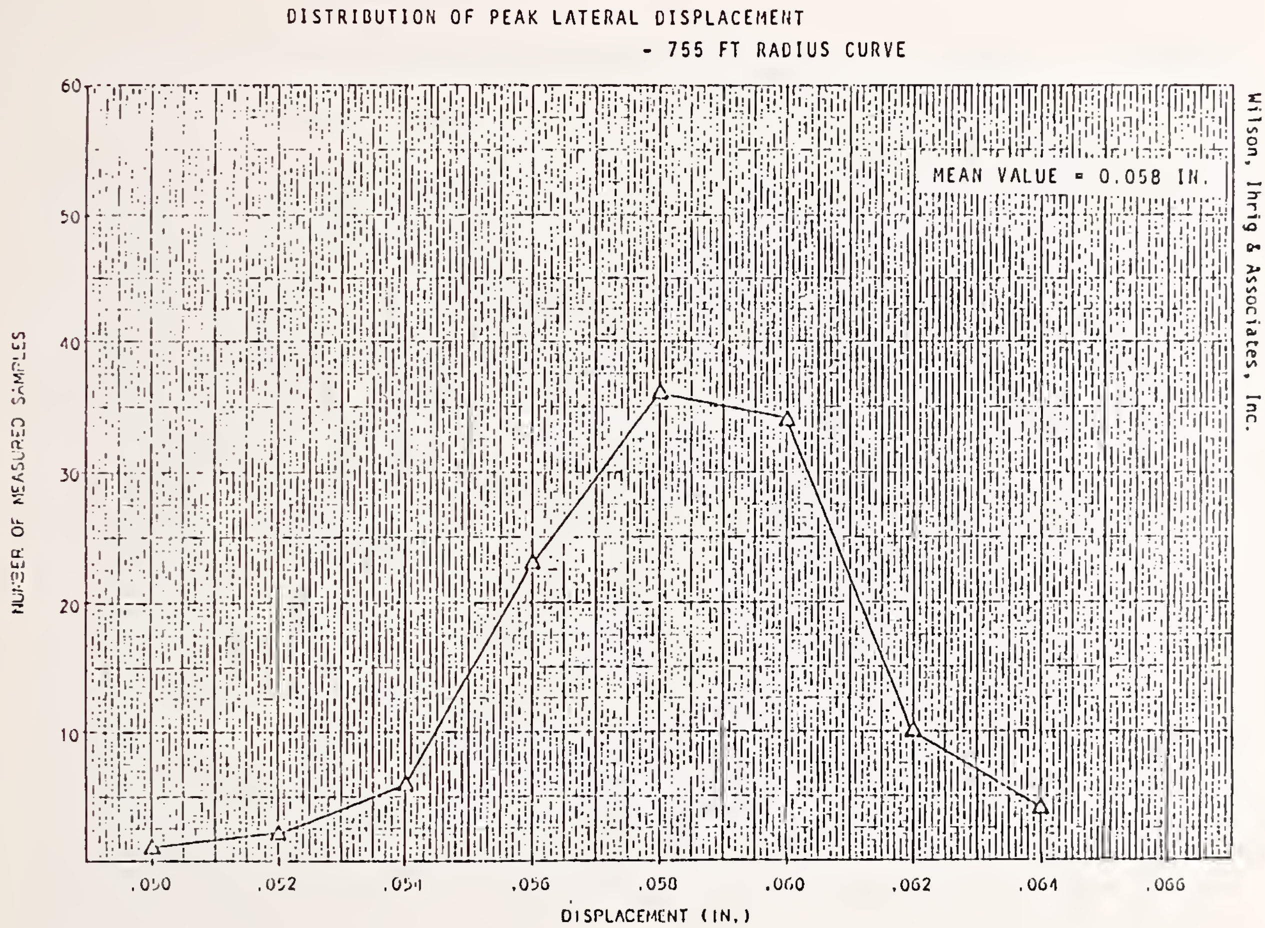

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FIGURE 6. DISTRIBUTION PLOTS, 755' RADIUS CURVE

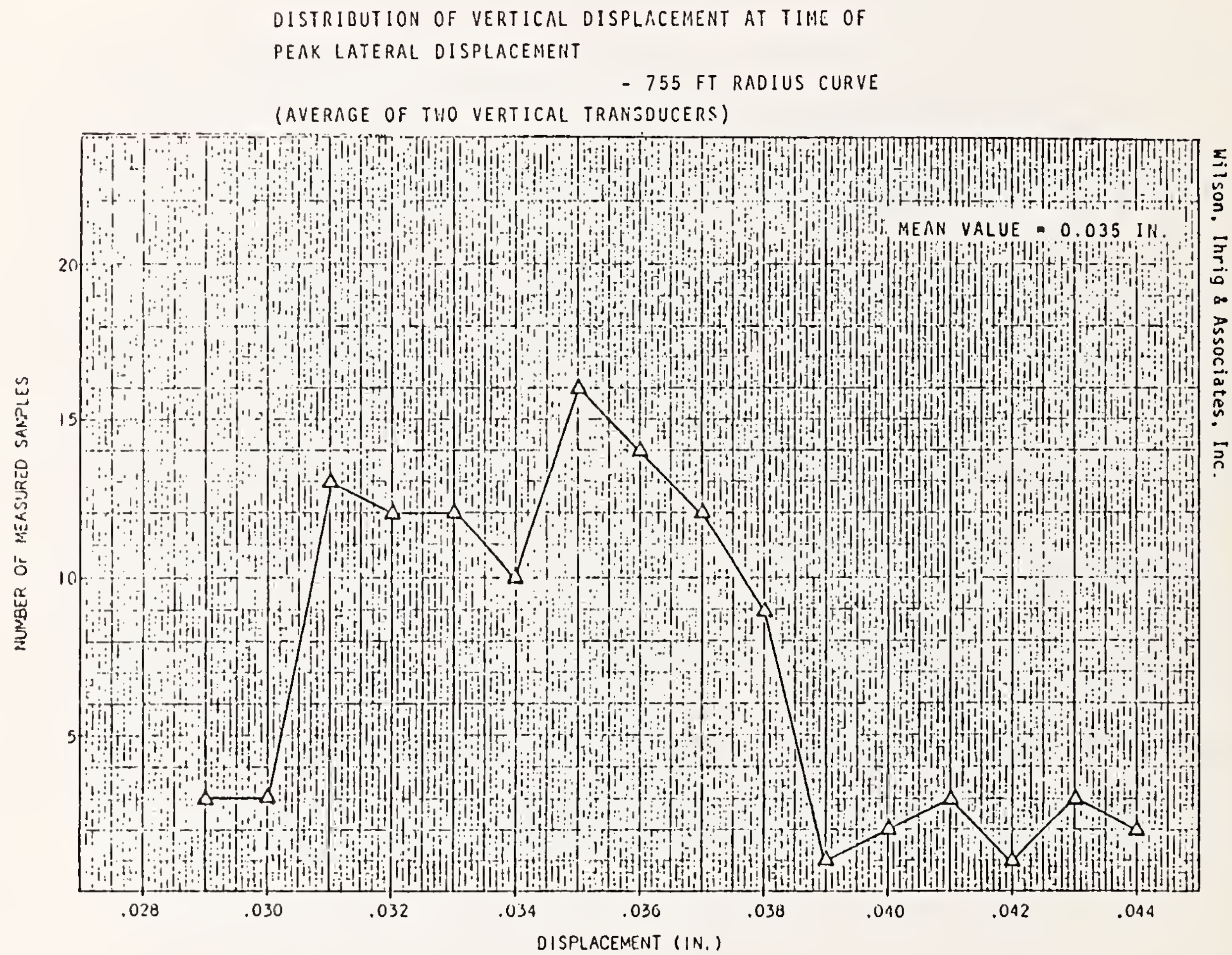

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FIGURE 7. DISTRIBUTION PLOTS, 755' RADIUS CURVE

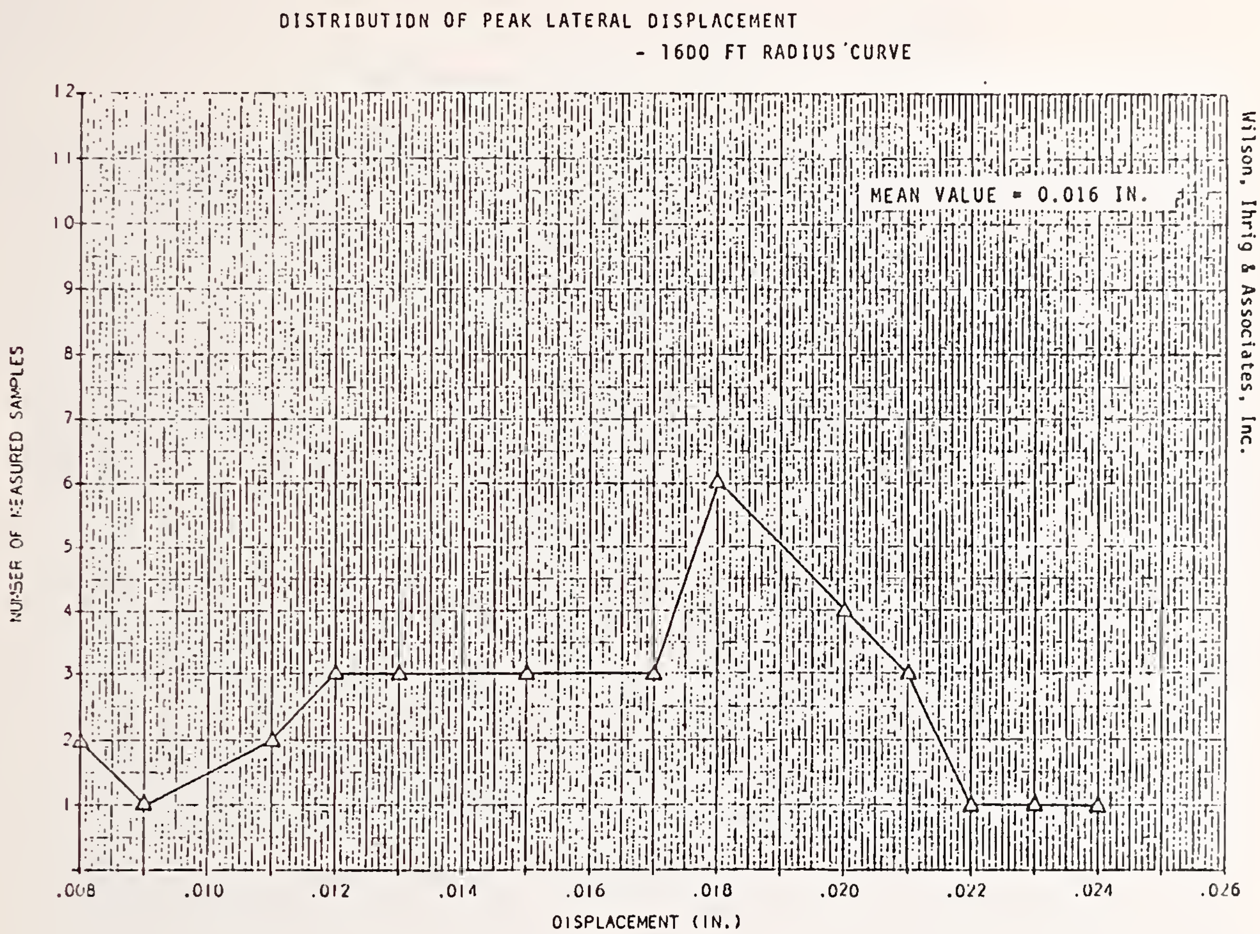

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FIGURE 8. DISTRIBUTION PLOTS, 1600' RADIUS CURVE

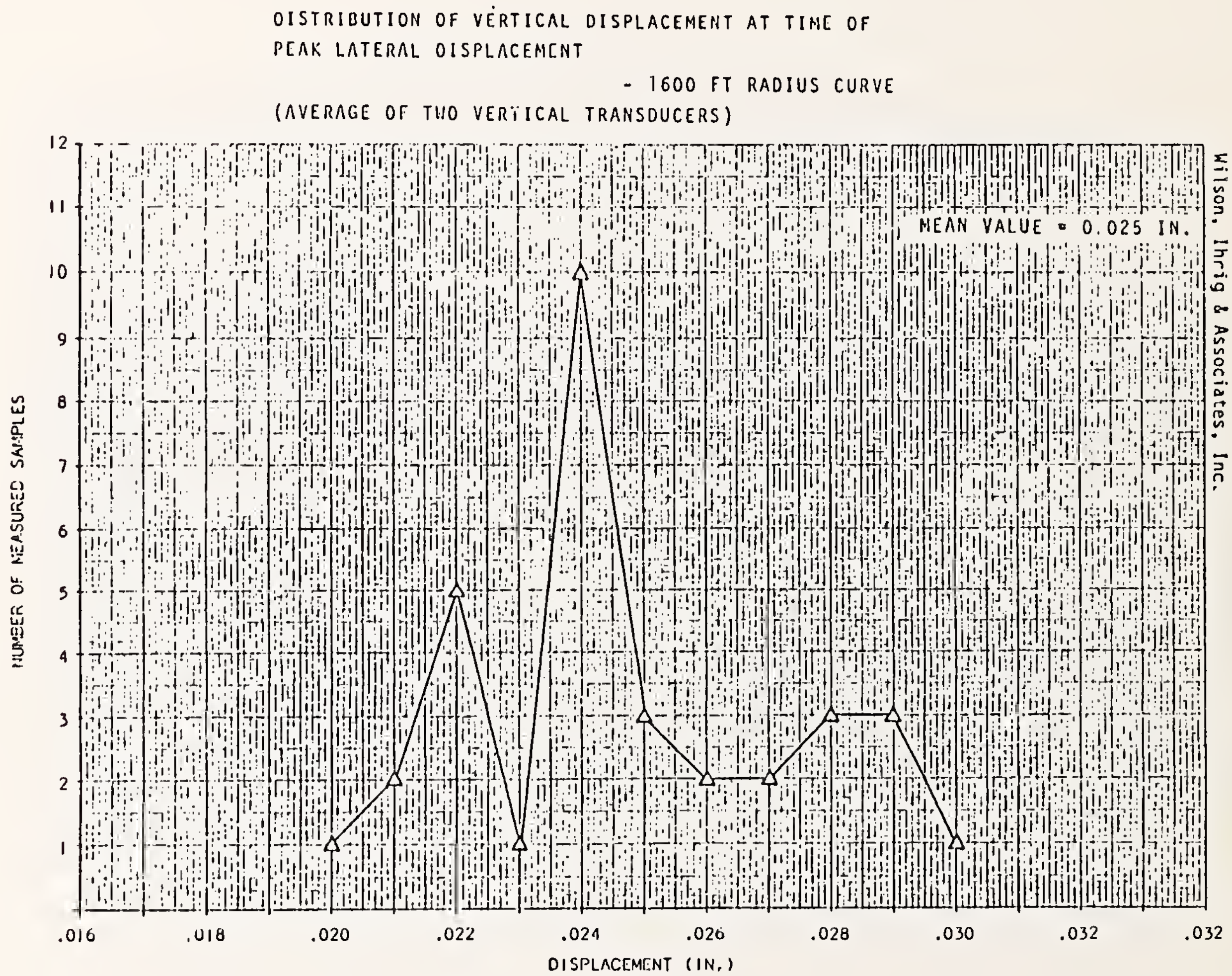

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FIGURE 9. DISTRIBUTION PLOTS, 1600' RADIUS CURVE

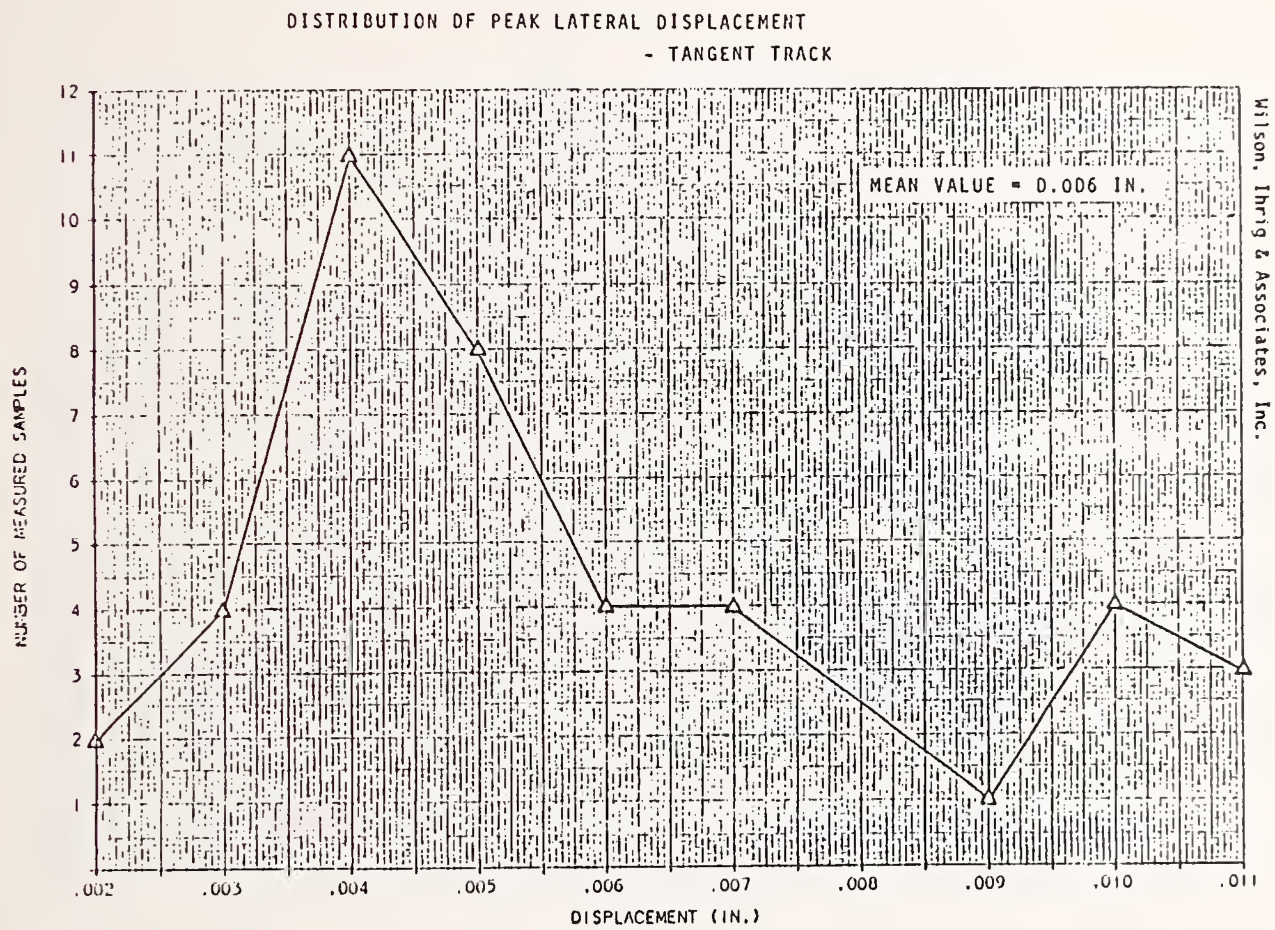

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FIGURE 10. DISTRIBUTION PLOTS, TANGENT TRACK

DISTRIBUTION OF VERTICAL DISPLACEMENT AT TIME OF
PEAK LATERAL DISPLACEMENT

- TANGENT TRACK

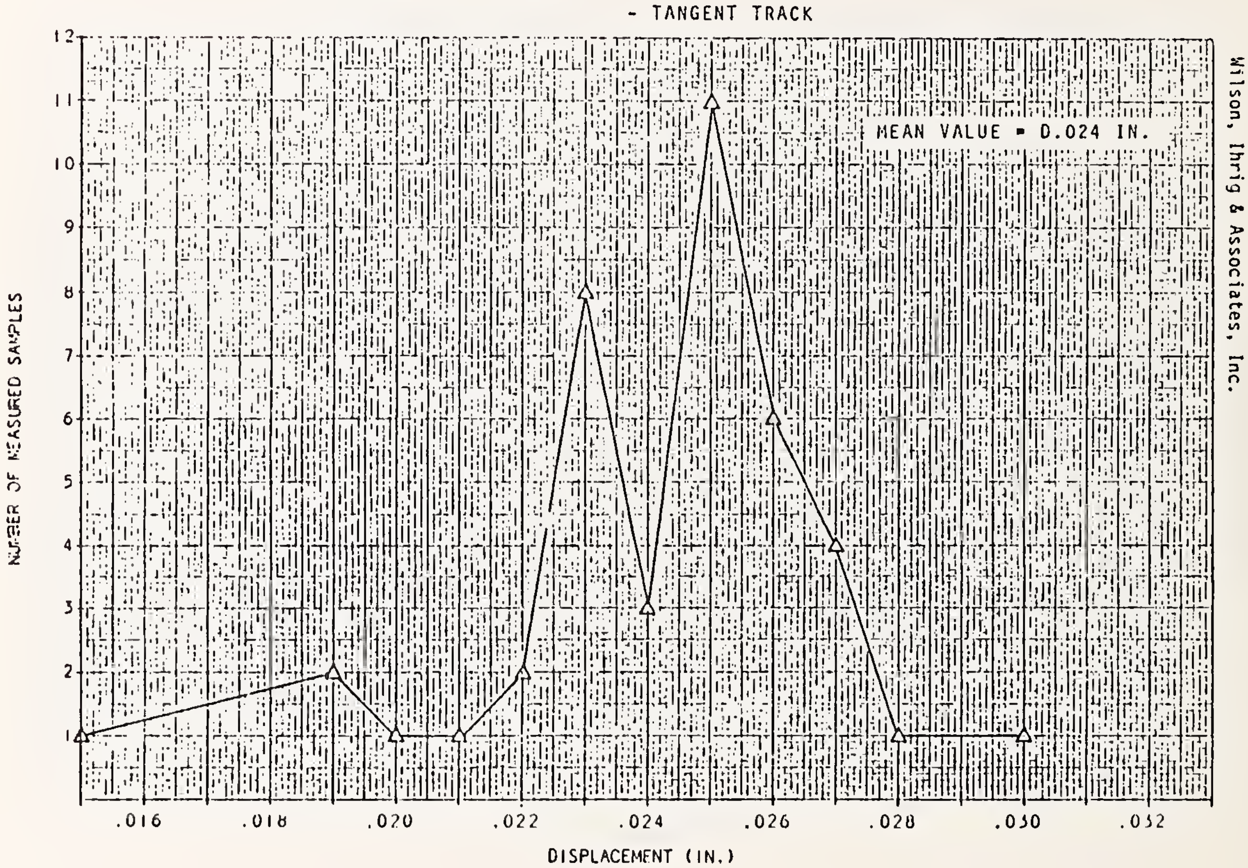

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FIGURE 11. DISTRIBUTION PLOTS, TANGENT TRACK

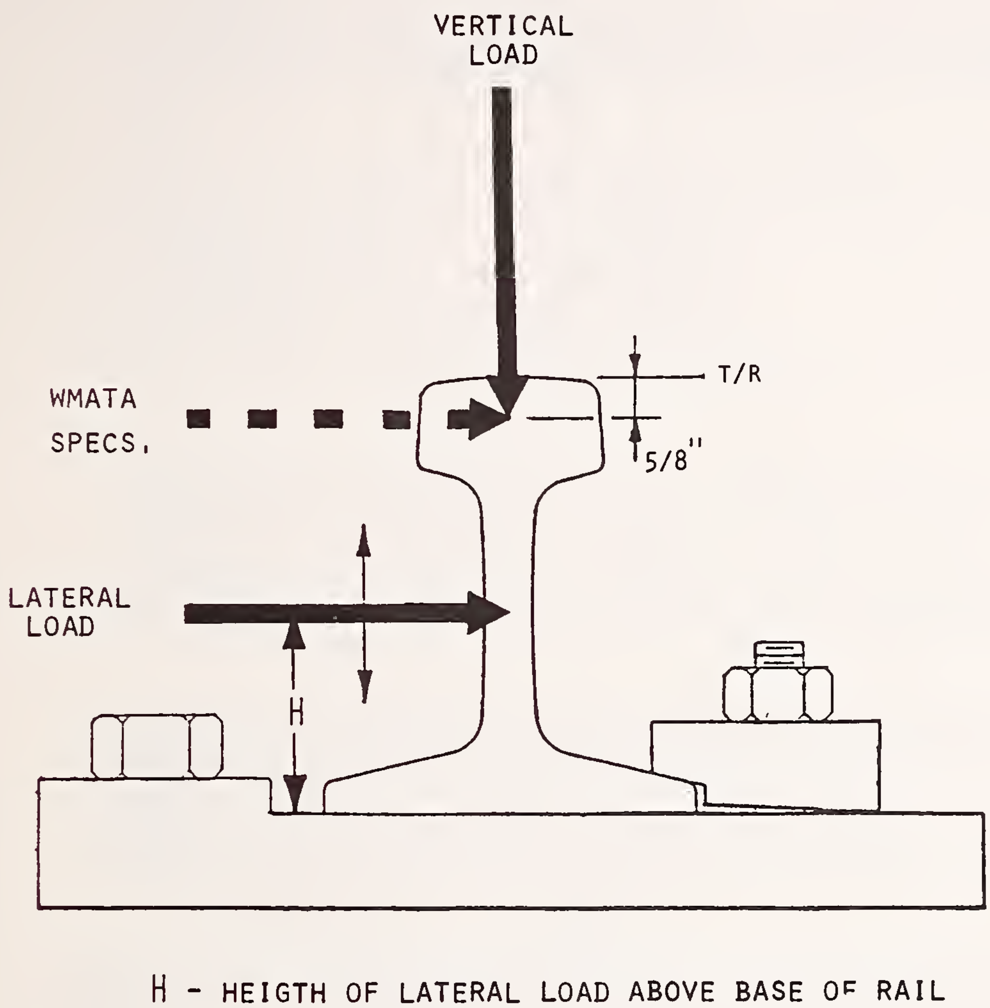

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FIGURE 12A. LABORATORY LOAD CONFIGURATION

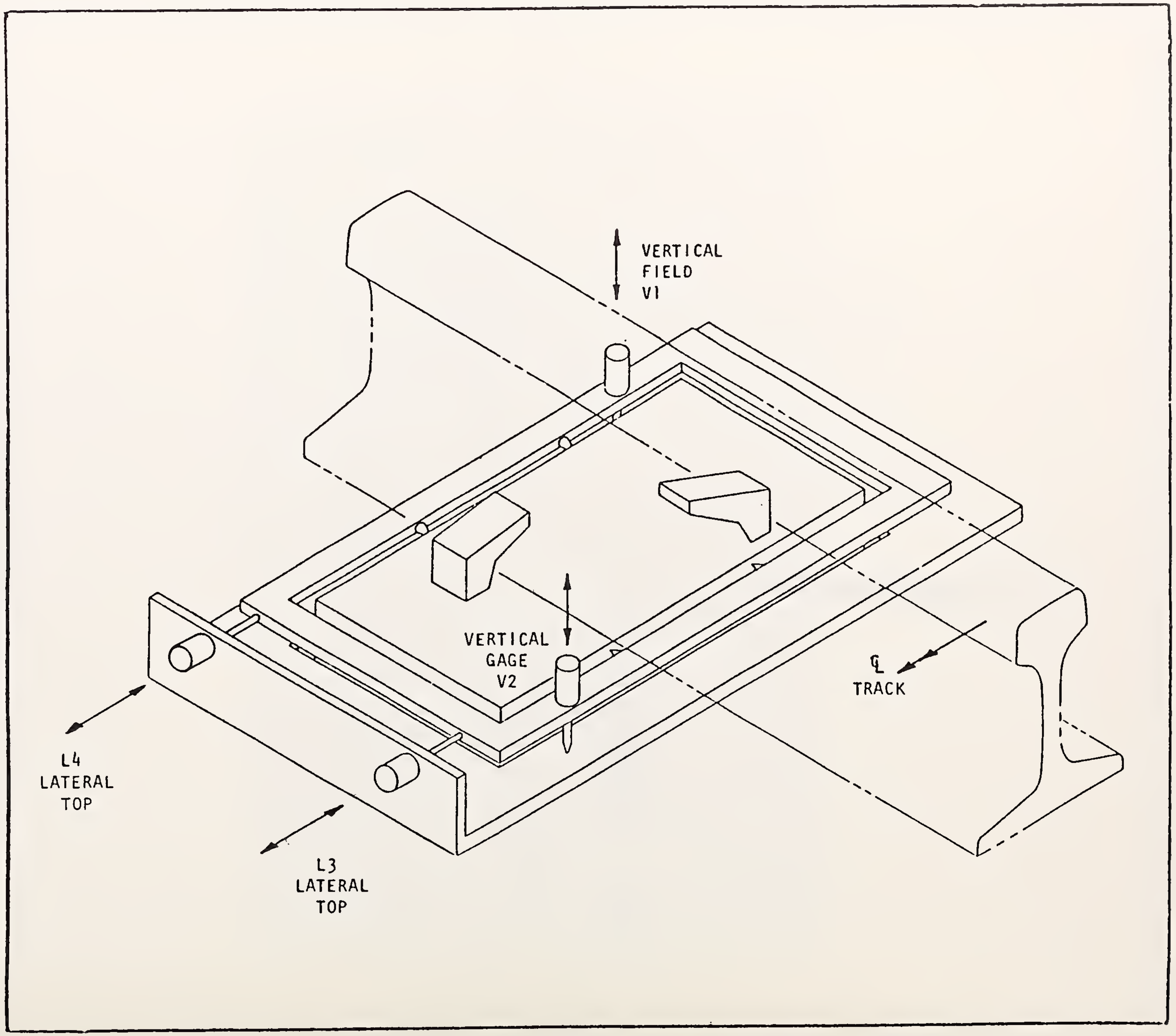

FIGURE 12B. LABORATORY INSTRUMENTATION

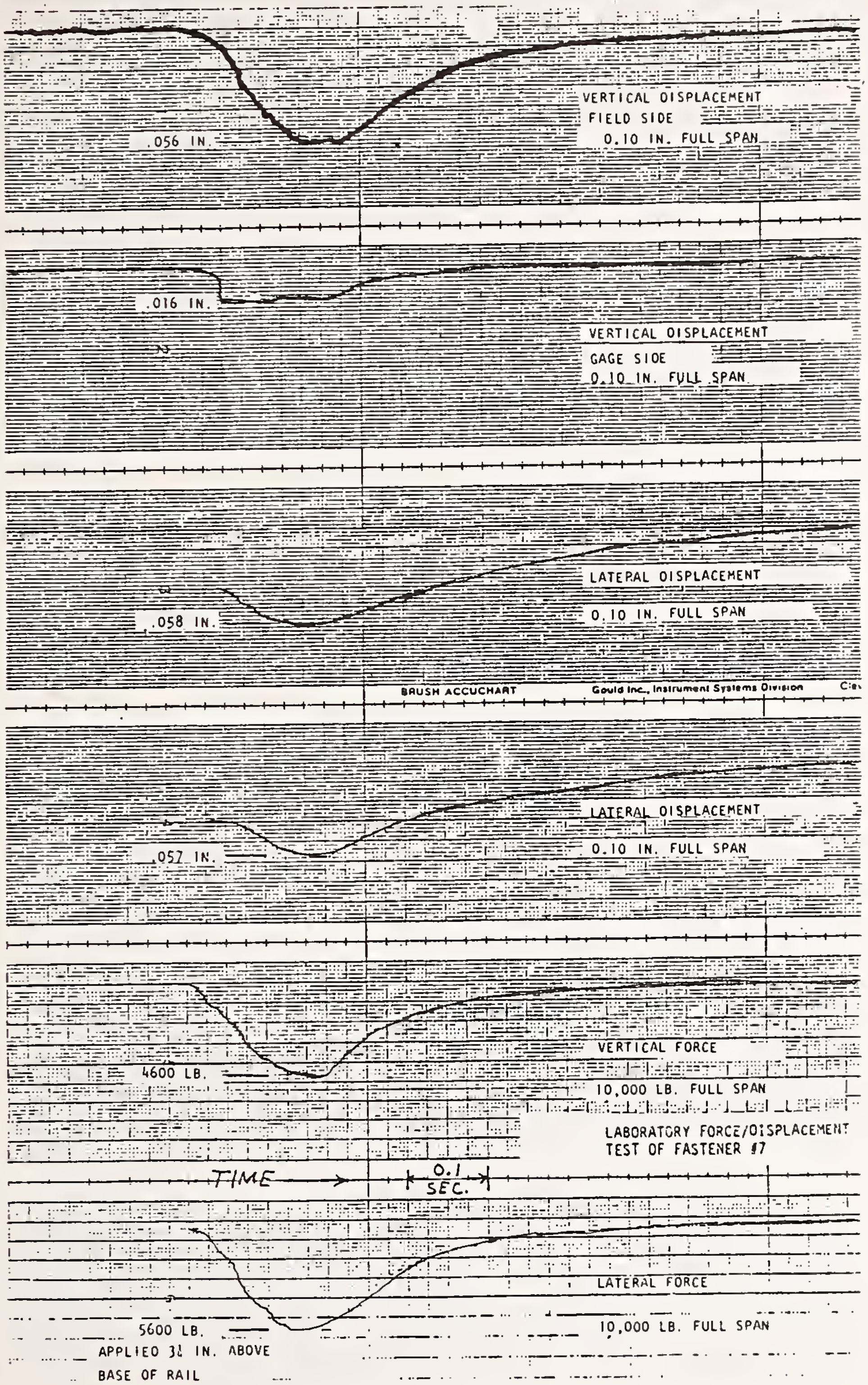

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FIGURE 13. LABORATORY DATA, FASTENER #7

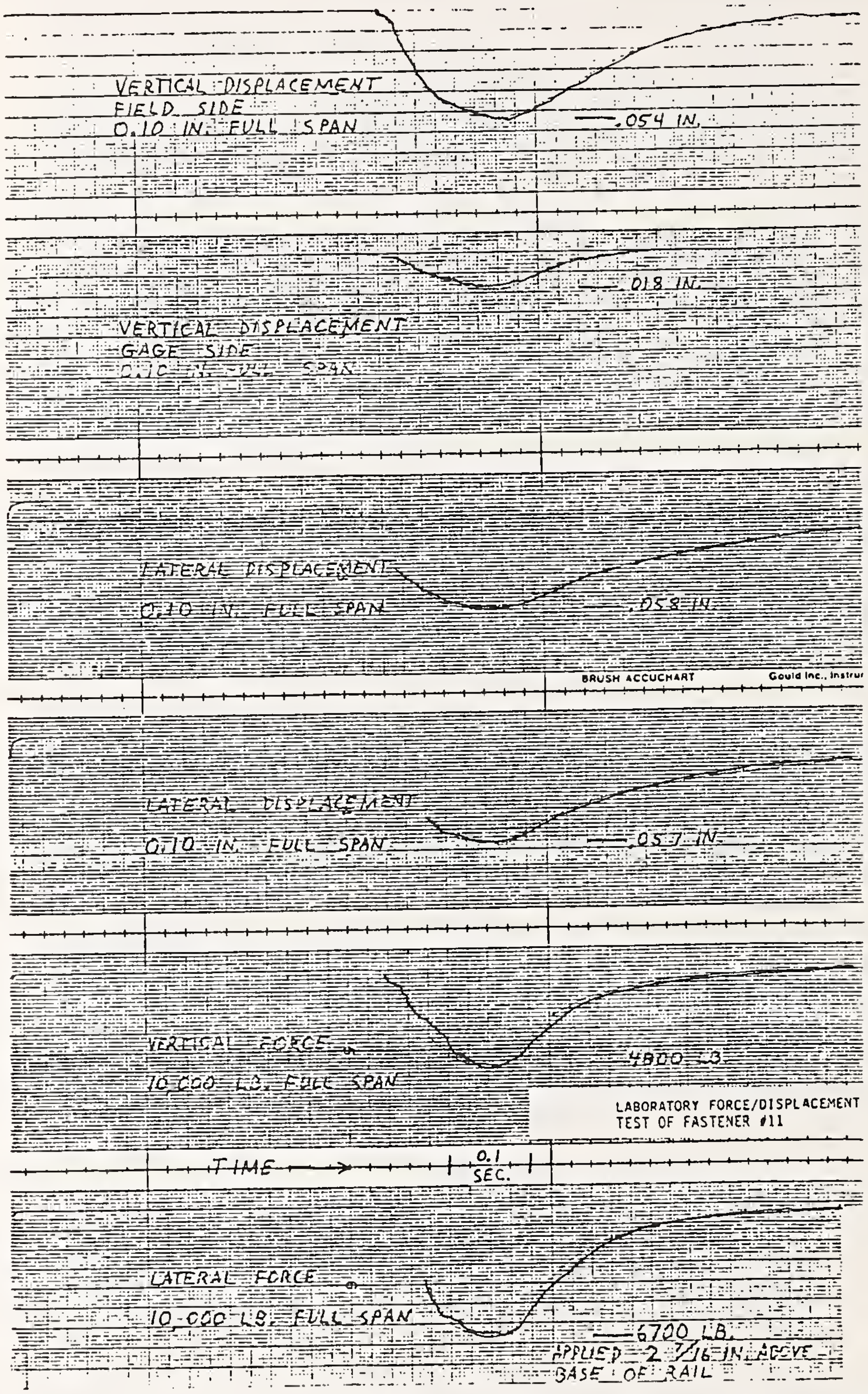

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FIGURE 14. LABORATORY DATA, FASTENER #11

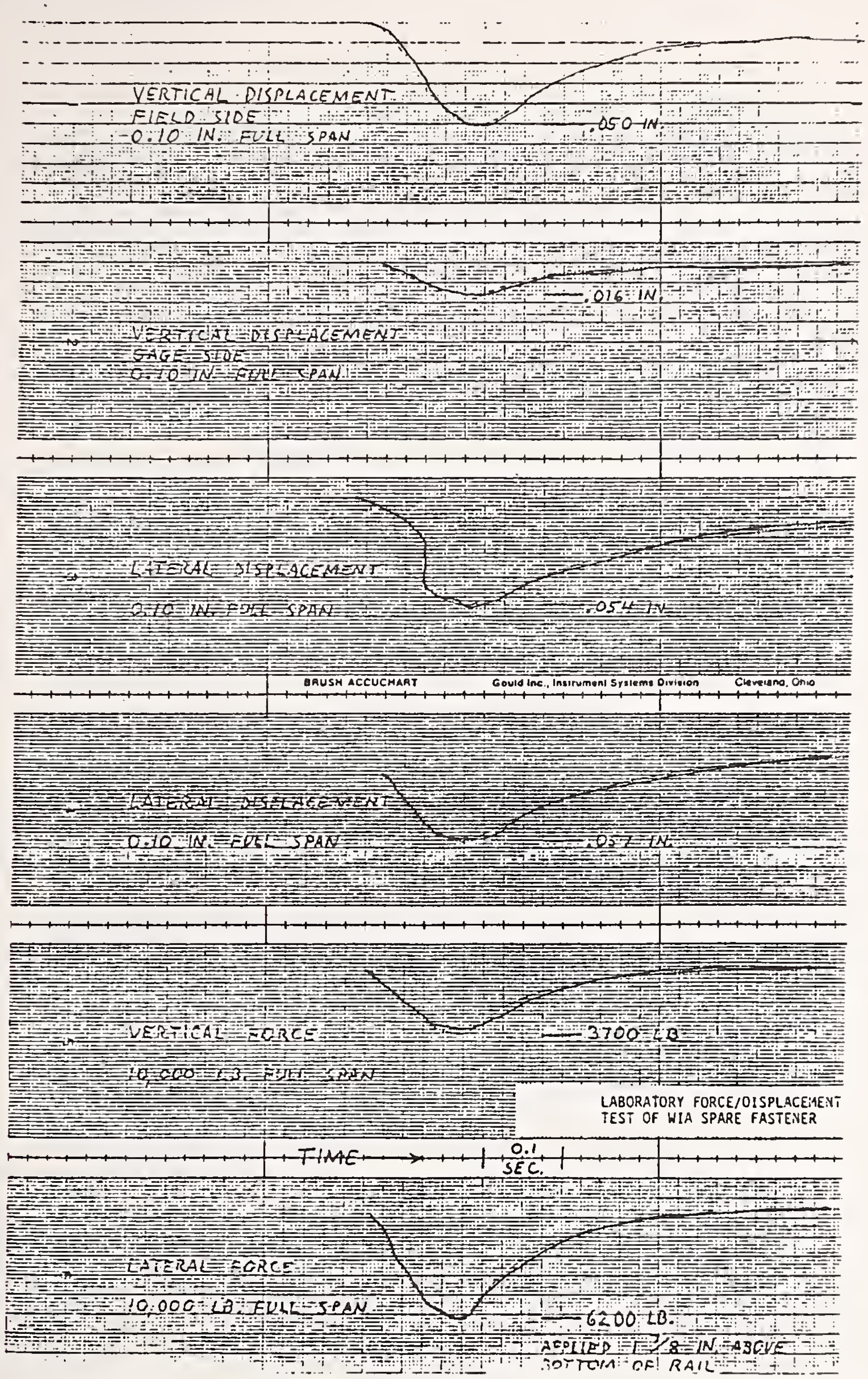

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FIGURE 15. LABORATORY DATA, WIA SPARE FASTENER

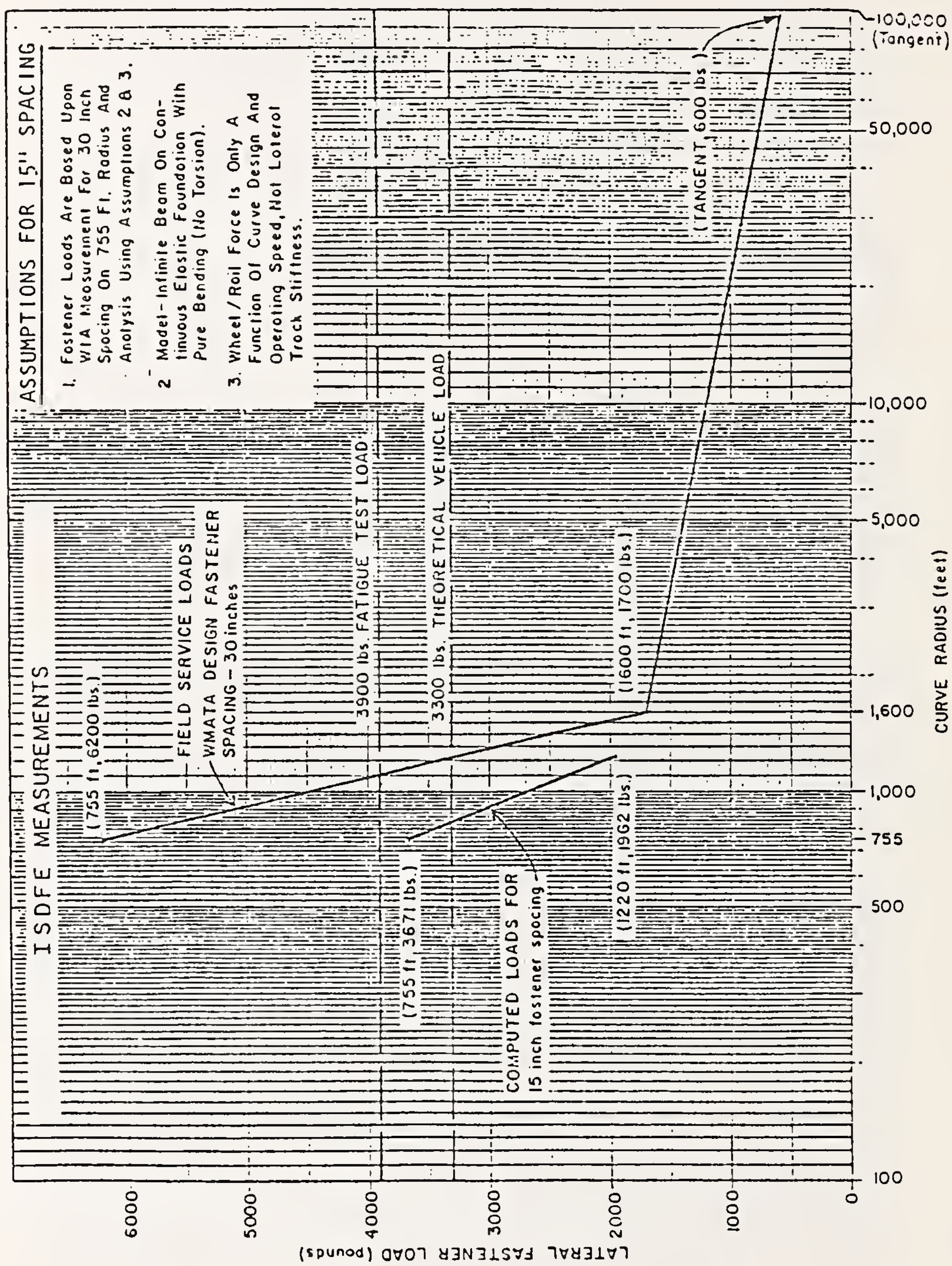

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FIGURE 16. ISDFE MEASUREMENTS

Measurement of Direct Fixation Fastener Load Environment on the Washington Metropolitan Area Transit Authority Metrorail System

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U.S. Department of Transportation
Transportation Systems Center

INTRODUCTION

Direct fixation fasteners (DFF) provide additional resilience for ballastless track in tunnels and on aerial structures. In many cases, DFFs also offer adjustability for easy maintenance. These fasteners, which in this case consist of an elastomer bonded between two steel plates, two rigid, rail fastening devices, and anchor bolts, which are a relatively new concept for transit track. A sufficient base of data from which design criteria can be selected has therefore not been established. Problems have been experienced by some transit properties using DFFs that are consistent with fastener overstressing and fatigue. It was clear that additional data was needed to aid designers in developing solutions to these fastener problems. Consequently, the Urban Mass Transportation Administration (UMTA) sponsored research to develop the data necessary to formulate guidelines for the acceptance of direct fixation fasteners.

This paper presents the results derived from this research to date, specifically data and conclusions from a field test on the Washington Metropolitan Area Transit Authority (WMATA). The field tests included measurement of wheel/rail loads (with instrumentation both on the rail and from an instrumented wheelset), fastener loads, and rail head lateral displacements. All measurements were made under revenue service or utilizing a special consist which included the instrumented wheelset. Presented below is a summary and discussion of the first phase of the reduction of the massive amounts of data collected on this project. This analysis included rail and fastener load environments, the influence of fastener stiffness on the load environment, and the effect of track gage on rail and fastener load environments. The results of the data analysis are placed in the context of current DFF design and acceptance specifications, and recommendations are made for consideration in DFF design and future specifications.

BACKGROUND

A fastener must, above all else, attach the rail to the tie or slab so that the rail provides sufficient support and guidance for the wheel loads that roll across it. It must do this without allowing excessive elastic or inelastic deformation, yet provide sufficient resilience to distribute wheel loads, and, when track geometry does need to be corrected, allow for easy maintenance. The DFF must not allow rail to run, i.e., move longitudinally under service or environmental loads.

Many of these requirements are conflicting. A fastener must offer resilient support, therefore be elastic under vertical and lateral loads; yet it must not allow excessive lateral deformation, allowing the rail to lay over or the wheel to drop. Relevant questions are: what is sufficient resilience and what is excessive deformation? Do current standards allow the fasteners that are being placed in service to fulfill their basic role of providing elasticity for load distribution and noise and vibration control?

The basis for specifying a DFF is that it must be capable of withstanding the maximum system loads without failing, and it must also be able to sustain a repetition of the working loads over its design life -- also without failing. The essential information necessary for developing good specifications to determine whether these criteria are met includes:

1) A suitable definition of fastener failure, and

2) A realistic estimate of service loads.

The definition of fastener failure actually has two related aspects. The first is the fracture, breakage, or physical separation of the fastener assemblage. The second is excessive deformation. If a fastener physically "breaks," it is also likely to lose its ability to support the rail. The rail may not, even then, deflect excessively because adjacent fasteners will assume some of the loads carried by the broken fastener; but, certainly, that fastener is no longer adequately performing its share of the work. If the fastener has no cracks, fractures, or other visible signs of failure, but allows excessive deformation, this too must be considered failure. Excessive deformation must be defined both in terms of the track system and the fastener as an individual component. The fastener cannot allow so much deformation to occur as to allow the wheel to drop off the rail, or the rail to roll over -- both highly unlikely occurrences. It must deform enough to allow adjacent fasteners to carry load but not so much as to allow them to carry all the load. Otherwise the only real limit to deformation is that which would be considered abnormal for the particular fastener being tested, i.e., excessive deformation would be whatever amount could lead to fatigue damage or be indicative of the presence of cracks or fractures. A fairly restrictive answer to how much a fastener can deform laterally is provided by current DFF specifications, see Figure 1. The WMATA specification shown allows a maximum of 0.125 and 0.3 inches of rail deflection laterally under 4 and 10 kips lateral load with a 13.5 kip vertical load. This specification limits the lateral stiffness of the fastener and therefore is a "de facto" stiffness constraint.

The second type of essential information for the development of a good fastener specification is a realistic estimate of the service environment that the fastener will experience. Table 1 shows some typical values for both static and repeated loads that are specified in existing test specifications. Again a good fastener must be able to withstand a proof load representative of the maximum system load and it must also be able to endure system loads for the anticipated life of the fastener. The repeated load should be an average system load to be consistent with economic design.

To estimate the values for these loads, it is necessary to start with the static wheel load of the transit car employed -- fully loaded with passengers. Then it is necessary to account for the influence of all other pertinent parameters. These include:

- vehicle speed
- vehicle suspension
- wheel type
- dynamic vehicle/track interaction
- track stiffness
- track geometry
- track type (i.e., jointed rail or CWR)
- track design parameters (e.g., superelevation, rail cant, etc.)

Very little data exists to help quantify the influence of these factors on the performance of direct fixation track. Being overly conservative in estimating system loads can lead to an inefficient and expensive design. Underestimating the loads can lead to early and excessive component failure. Not understanding the interrelationship of these parameters leads to one or the other of these possibilities.

The impetus to perform the tests described in this paper was provided by the failure of many fasteners on the WMATA system. It was clear that it was necessary to define the fastener service load environment, and examine the factors that influence these loads, to provide the data for the development of specifications to prevent the recurrence of this event. Fastener load environment was measured and the influence of track gage and fastener stiffness evaluated.

TEST DESCRIPTION

An examination of the fastener assessment criteria requires detailed data on the fastener load environment. Specifically, it was necessary to know not only the vertical and lateral wheel/rail forces, but what portion of these forces is carried by each individual fastener. A test program was developed and implemented on the Washington Metro between August and October of 1981. The test was to measure directly the fastener load environment; and also to investigate how changes in specific variables influenced that environment.

The fastener tests were performed in conjunction with truck tests employing an instrumented wheelset. Two test zones were chosen on curves 37 and 38, adjacent 755 foot radius curves. It was intended to select those areas on these curves that had the highest lateral loads. To do this, survey runs with the instrumented wheelset (Figure 2) were made and correlated with track geometry data and a visual inspection of the high rail. A section on each curve was chosen where the instrumented wheelset indicated the highest forces were generated. These were also the areas of most side-wear on the rails.

These two zones were then instrumented by Batelle Columbus Laboratories as shown in Figure 3. Baseplates were developed which accepted and measured the loads normally transferred from the fastener to the slab. These loads were measured in three locations on the high rail and one location on the low rail on curve 37 and on two positions on the high rail in curve 38. Rail shear circuits were installed to measure vertical and lateral rail loads and lateral rail head displacement was also measured.

The test zones were on continuous welded rail, direct fixation slab track in tunnels. There was a superelevation of 4 inches which was deficient by 4-1/2 inches for the forty miles per hour design speed. Balance speed was approximately twenty-eight mph. Average measured speed through the test zones was thirty-two mph through curve 37 and thirty-six mph through the test zone in curve 38. The empty weight of a WMATA car is 72,000 pounds and, with a crush load, approximately 100,000 pounds. Data was collected during the morning or afternoon rush hour under normal service. One day's data (with fastener A at normal WMATA gage - 56-3/4 inches) was taken under off-peak loads. The test zone in curve 38 was used for four test days with fasteners B and C and both test track gages. Curve 38 was also on a +4% grade with trains accelerating as they were leaving Union Station. Curve 37, on the other hand, was a -4% grade entering the station. Both curves had seen service for approximately 3 to 4 years.

The track structure was altered to include different fasteners (primarily examining the effect of different fastener lateral stiffness) and two different track gages. There were six days of testing in curve 37 where three different fastener types were placed in track at two different gages: 56-1/2" and WMATA standard (on curves only) 56-3/4". A fourth fastener of reduced lateral stiffness was tested out-of-service. A test matrix is shown in Table 2. Two of the fasteners tested, fasteners A and B, were of approximately the same lateral stiffness, see Figure 1. These fasteners are both employed, as is, on the Washington Metro. The third, fastener C, was a modification of fastener B that reduced the lateral stiffness of the fastener by approximately 20-25%. The fourth fastener, D, was a radical modification of fastener A which reduced the lateral stiffness by allowing the elastomer to carry all the lateral load. Fastener E is another brand of DFF also used on WMATA, with a lateral stiffness similar to that of fasteners A and B. This fastener was in place during runs of the test trains.

RESULTS

Load Environment

Measurements were recorded under 30 to 50 six to eight car trains each day. Figure 4 displays the average value of the peak vertical and lateral loads on the high rail for lead axles measured in the rail and the fastener at each instrumentation position. By "peak load" is meant the greatest value of force measured for each wheel as it rolls by the instrumentation position. Presumably this value occurs as the wheel is passing over the center of the instrument.

Recordings for fasteners B and C were made during peak traffic hours. The vertical loads were slightly greater in curve 38 than in curve 37. Vertical loads there ranged from approximately 13.2 kips to 16.1 kips whereas in curve 37 the magnitudes ranged from about 13.0 kips to 14.5 kips. Fastener A, which for this series of tests experienced off-peak traffic, recorded, on the average, approximately 1.5 kips less load per wheel vertically than in fasteners A and B. It is of importance to note that the vertical rail loads measured for fastener D taken under the test train were in the same range as the off-peak measurements of fastener A, and 1.5 to 2 kips less than fasteners B and C.

Vertical fastener loads were approximately 35 to 40 percent of the vertical rail load, the remainder of the load being distributed among adjacent fasteners. There was a slight shimming problem in curve 38 so the fastener at position 2 apparently carried a larger portion of the load than the fastener at position 3. The net impact of this problem is difficult to assess. As seen in Table 3, which displays the average of results for all instruments in each test zone, vertical loads, but not lateral loads, are slightly higher in curve 38 than in curve 37. This is more likely an effect of speeds being approximately 4 mph higher in 38 than the effect of the shimming which averages out over the two fasteners tested, i.e., the peak loads are higher in one fastener but correspondingly lower in the other.

The relatively low vertical stiffness of the DFF's, i.e., their ability to distribute the rail loads to reduce the peak vertical fastener load, is contrasted by their relative stiffness laterally. Lateral rail loads, which average from approximately 4.3 kips to 7.2 kips, were in the same range as the lateral fastener loads which averaged from 3.7 kips to 6.4 kips. In some cases (note especially the lateral fastener loads for the 56-1/2 inch gage in curve 38), fastener loads were recorded as higher than their corresponding rail loads.

This seemingly impossible occurrence was probably due to the fact that rail loads were measured between fasteners while fastener loads were measured directly at the fastener. Results from the instrumented wheelset indicate that lateral rail loads rise as much as 1 kip at fasteners. This is probably due to an increased stiffening directly at the fastener. Figure 5(a)-(c) shows the joint probability density and the individual probability densities for the lateral and vertical rail loads for fasteners A, B and C in curve 37. This figure also shows the standard deviation about the mean for each load. In each case, the lateral rail loads appear to possess a relatively normal distribution about the mean. The differences in the vertical distribution exhibit some interesting properties.

The vertical rail load probability density distribution for fastener A appears to have a relatively normal distribution with a slight skew to the right. The distributions for fasteners B and C appear very similar to this distribution on the low-load side, but are skewed very much to the right or the heavy wheel load side. These distributions are indicative of traffic patterns that have a common load base but with the occurrence of heavy wheel loads during the peak hours for fasteners B and C. Individual vertical rail loads during rush hours appear to reach, on rare occasions, nearly 20 kips during rush hour, while lateral loads can reach 10 kips. These maximum load events do not appear to necessarily occur simultaneously, and it may be possible to discount some of the farthest outliers as measurement errors.

The share of the rail load that is actually assumed by the fastener is shown in Figure 6. Figure 6(a) shows the probability density histogram of the lateral and vertical fastener loads for Fastener A at location 5H on curve 37. The loads appear to be symmetrically distributed with a very small standard deviation. Lateral and vertical fastener loads are about equal. Figure 6(b) shows the load histogram for Fastener B for the same location under peak-hour traffic. Notice that there is somewhat more scatter of both vertical and lateral loads, and that the mean lateral load has increased by more than 1 kip, while the mean vertical load has actually decreased by a small amount.

Figure 6(c) shows probability load density for fastener C. Although this data was taken under peak traffic load as was the data for fastener B, the fastener loads are virtually identical to those of fastener A, which were measured under lightly-loaded cars.

All the above figures show the loads under lead axles only. Figure 6(d) shows a probability density histogram for all axles, both lead and trailing. A slight decrease in vertical mean load can be seen, with a slight reduction in scatter. The effect of the trailing wheels on the lateral load distribution is quite evident as the small load pyramid can be seen centered about zero. The greatest negative load measured was -1.4 kips.

The above results must be considered in the context of the WMATA system as a whole. Not only the curves, but the test zones in the curves were selected in an attempt to approach the most severe load environment. In fact, this goal was achieved. Figure 7 shows the extremes of the probability density histogram from a survey of lateral loads of the entire WMATA red line that was made with the instrumented wheelset. Recalling from Figure 4 that the peak-hour loads measured in the test zones were up to 1.5 kips greater than the test train lateral loads, one could estimate that the maximum occurring lateral load along the red line would probably be less than 11.5 kips. Indeed, the mean loads measured in the 755 foot radius curve, even when adjusted for peak loads, have a probability of occurrence of less than 1%. Meanwhile, if the WMATA vehicles employed a soft suspension and had wheels with a 1:20 taper, lateral loads of 5 kips would probably occur as infrequently as 0.1% of the time.

Test Variables

The two primary variables affecting fastener load environment being investigated in this test were track gage and fastener stiffness. With respect to track gage, the results showed no clear trend. Although from Figure 4 and Table 3, it would appear that vertical and lateral loads were slightly higher in the test zone with the tighter gage, the differences are insufficient to determine whether this effect is real and due to the difference in gage, or just due to miscellaneous, undetermined factors.

The data documenting the effect of fastener stiffness does however show some interesting trends. Fasteners A and B are production fasteners that have been used at WMATA. Fasteners C and D are modifications of B and A respectively. Figure 8 gives an indication of the relative effect of the modifications. The load/deflection lines for fasteners A, B, and C are based on a linear regression of data points from a minimum of 412 wheel passages. Rail loads were measured in the cribs 18 inches from the fastener. For fastener D, only four points were available. The results shown should be considered only an indication of the difference in relative stiffnesses because rail loads were not measured in the same location as the rail displacements.

Figure 9 shows the lateral fastener peak load response for an adjacent peak lateral rail load in curve 37. Also shown is the peak lateral fastener load as a percentage of rail load for fasteners A, B, and C in curve 37. The difference in behavior, i.e., in the load distribution characteristics, between fasteners A and B and C can readily be seen. The difference in distribution characteristics seems to diminish as load increases. The trends show that fastener C distributes the load better than the two stiffer fasteners. Results from runs over fastener D show that in this particular circumstance, with speeds roughly near balance speed at 30-32 mph, and lightly loaded vehicles, the lateral rail head deflections are approximately the same as those of fastener C with heavily loaded cars (see Figure 10), and not much greater than fastener A with lightly loaded cars. It is apparent that the reduction in lateral stiffness by approximately 40% has resulted in a corresponding increase in deflection, but the amount of deformation does not appear to be sufficient to reject the fastener.

An examination of Figure 11 shows that for the same train velocity and similar vertical wheel/rail loads (recall Figure 4), there does appear to be a significant reduction in rail load with fastener D as compared to its unmodified incarnation, fastener A. Even greater is the difference in peak lateral loads that are transmitted through the fastener. Here we see reductions by two-thirds in the lateral fastener loads.

The reduction in lateral rail load with the softer fastener is further supported by the data in Figure 12. This data was collected under the test train curve 37 with fasteners D and E installed. Fastener E has lateral stiffness characteristics very similar to fasteners A and B and is also a DFF employed by WMATA. It can be seen that the rail vertical load response as a function of test consist speed (in Figure 11(b)), is virtually identical for both types of fasteners. The lateral rail load for the stiffer fastener is larger than the lateral rail load for fastener D, although this difference seems to lessen as speed and lateral load level increase.

IMPLICATIONS OF TEST RESULTS ON FASTENER SPECIFICATIONS

Load Level

As stated earlier, for the vertical and lateral loads that were being investigated in this test, there are two critical loading conditions: proof loads and repeated working level loads. The fastener acceptance specifications must ensure that a particular fastener, i.e., of a specific design and manufacturing run, can withstand both of these imposed load conditions. The work performed at WMATA examined the vertical and lateral system loads and, in particular, focused on the severe environment of a 755 foot radius curve. The results of these tests have produced data that allows some conclusions to be drawn as to how well current specifications reflect actual conditions.

Maximum Load

The maximum vertical and lateral fastener loads measured in the test zones were 11.0 kips and 7.5 kips respectively. These loads are very probably at the high end of loads that will be seen by fasteners on the red line. In fact, the 11 kip load was the result of a shimming problem that resulted in one fastener carrying most of the vertical load burden. The highest load otherwise was less than 8 kips, the 11.0 kips representing approximately a 40% increase in load due to poor fastener base plate installation. If one used 8 kips vertically and 8 kips laterally as anticipated high loads, and added a 50% safety factor, then the resultant of 12 kips in both directions could be used as an acceptance proof load. The WMATA acceptance specifications appear to be conservative, even for their vehicles with stiff suspensions and cylindrical wheel. Increasing the proof load specifications could only result in an uneconomical design.

Fatigue

In Table 3, the mean vertical and lateral loads for all the test conditions were presented. If one were to design a fatigue specification for the two test curves, one could choose a combination of loads that would place and retract a 6.5 kip vertical and 5.6 kip lateral load on each fastener to be tested. The lateral load could alternate a 5.6 kip load from one direction with a 2.0 kip load from the opposite side of the rail on alternate applications of the vertical load.

Such a loading condition would be quite different from the WMATA specification. The applied maximum lateral load measured was 60% greater than the test specification while the measured vertical load was more than 50% less than the specification. How application of the measured loads would affect the fastener's fatigue performance relative to application of the current specification is currently being investigated. However, the measurements do show that the current specifications do not accurately replicate the fastener load environment.

It is quite possible that the current acceptance standards apply a more severe set of loads for some fastener failure modes and less severe for others. It is safe to say that the measured loads would probably adequately assess a fastener's likely performance for a 755 radius curve, with relatively good track geometry, for WMATA's current vehicles. However, these conditions exist on only a small portion of WMATA lines. These conditions exist where rail loads average 14.2 kips vertically and 6 to 7 kips laterally, in other words probably less than 0.5% of the whole system. If one were to take the average condition literally, based on a survey of the entire line, then the average lateral load would probably be less than 2 kips. This value would not be an appropriate value for the whole system; however, the designer could easily predict where this value would be invalid, i.e., on curves. Would it not be appropriate to investigate whether it would be economical to use different fastener designs for load environments more severe than those in normal tangent (or nearly tangent) track?

Fastener Stiffness

The data has indicated that fasteners with lower lateral stiffnesses distribute applied loads better and therefore do not experience the same loads as stiffer fasteners. The data also indicates that fasteners of relatively lower lateral stiffness tend to reduce loads on other track components and therefore may be more desirable than stiffer fasteners. Current standards do not take the fastener stiffness into account in assigning loads to be used in acceptance testing; and, in fact, seem to discriminate against fasteners that may be more cost effective in the long run by establishing high, minimum stiffness requirements. In fact, it may be more desirable to establish a maximum allowable stiffness and allow any lesser value as long as the fastener can pass the proof and fatigue tests.

Influence of Vehicles Parameters

Another very important factor that must be considered when assigning acceptance test loads is the type of vehicle that is employed. It is not sufficient to estimate rail loads based on vehicle dead weight alone. Wheel taper and primary suspension stiffness are two other very important factors.

TABLE 1. MAGNITUDES OF LOADS IN STATIC AND REPEATED LOAD TESTING OF DFFS FROM VARIOUS PROPERTIES

PROPERTY	VERTICAL LOAD (KIPS)	LATERAL LOAD (KIPS)	REPEATED LOAD (KIPS)
WMATA (WASHINGTON, D.C.)	15	10, 13.5	13.5, +3.5, -2.7, 3M CYCLES
MTA (BALTIMORE)	18	12, 16.2	16.2, +4.7, -3.2, 3M CYCLES
MDCRTA (MIAMI)	16	16.2, 12	16.2, +4.7, -3.2, 3M CYCLES
MARTA (ATLANTA) 1976	15	13.5, 7.5	13.5, +3.9, -2.7
BART		3	19^0, $10^0 6'$, 15, 15, 3M CYCLES

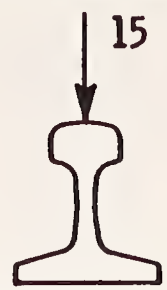
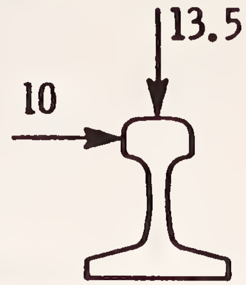
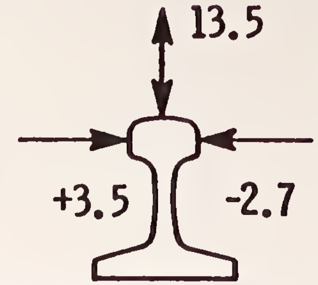
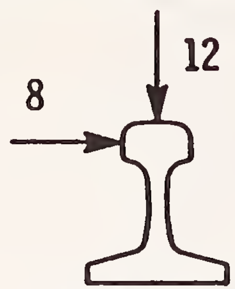
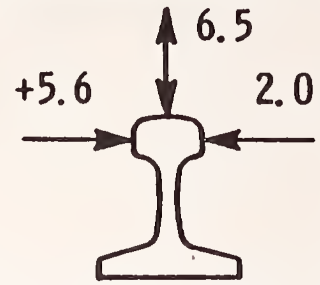
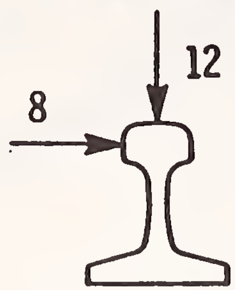
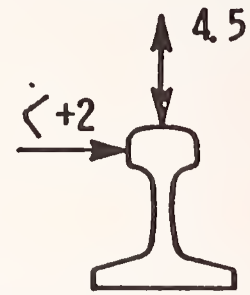
TABLE 2. TEST MATRIX FOR VARIABLES TESTED UNDER REVENUE SERVICE ON WMATA

	CURVE 37						CURVE 38			
	TEST DAY									
VARIABLE	1	2	3	4	5	6	7	8	9	10
FASTENER A	X					X				
B			X	X			X			X
C		X			X			X	X	
D										
GAGE 56-1/2				X	X	X			X	X
GAGE 56-3/4	X	X	X				X	X		

TABLE 3. A COMPARISON OF THE MEAN VERTICAL (V) AND LATERAL (L) LOADS MEASURED IN EACH TEST ZONE FOR EACH FASTENER AND EACH TRACK GAGE

TRACK GAGE	MEASUREMENT LOCATION	CURVE 37						CURVE 38			
		A		B		C		B		C	
		V	L	V	L	V	L	V	L	V	L
56-1/2	RAIL	-	-	-	-	-	-	15.1	5.1	14.6	5.4
	FASTENER	-	-	-	-	-	-	6.3	5.6	6.3	4.9
56-3/4	RAIL	12.5	4.9	13.9	5.9	13.6	5.8	14.2	5.2	14.5	5.3
	FASTENER	4.4	4.4	4.7	5.4	4.5	4.4	6.2	5.5	5.9	4.6

TABLE 4. COMPARISON OF WMATA FASTENER ACCEPTANCE SPECIFICATIONS AND MEASURED VALUES IN THE TEST ZONE AND ALONG RED LINE

	VERTICAL LOAD (KIPS)	LATERAL LOAD (KIPS)	REPEATED LOADS (KIPS)
WMATA TW-8	 15	 13.5 10	 13.5 +3.5 -2.7
MEASURED VALUES 755' CURVES	 12 8		 6.5 +5.6 2.0
RED LINE	 12 8		 4.5 +2

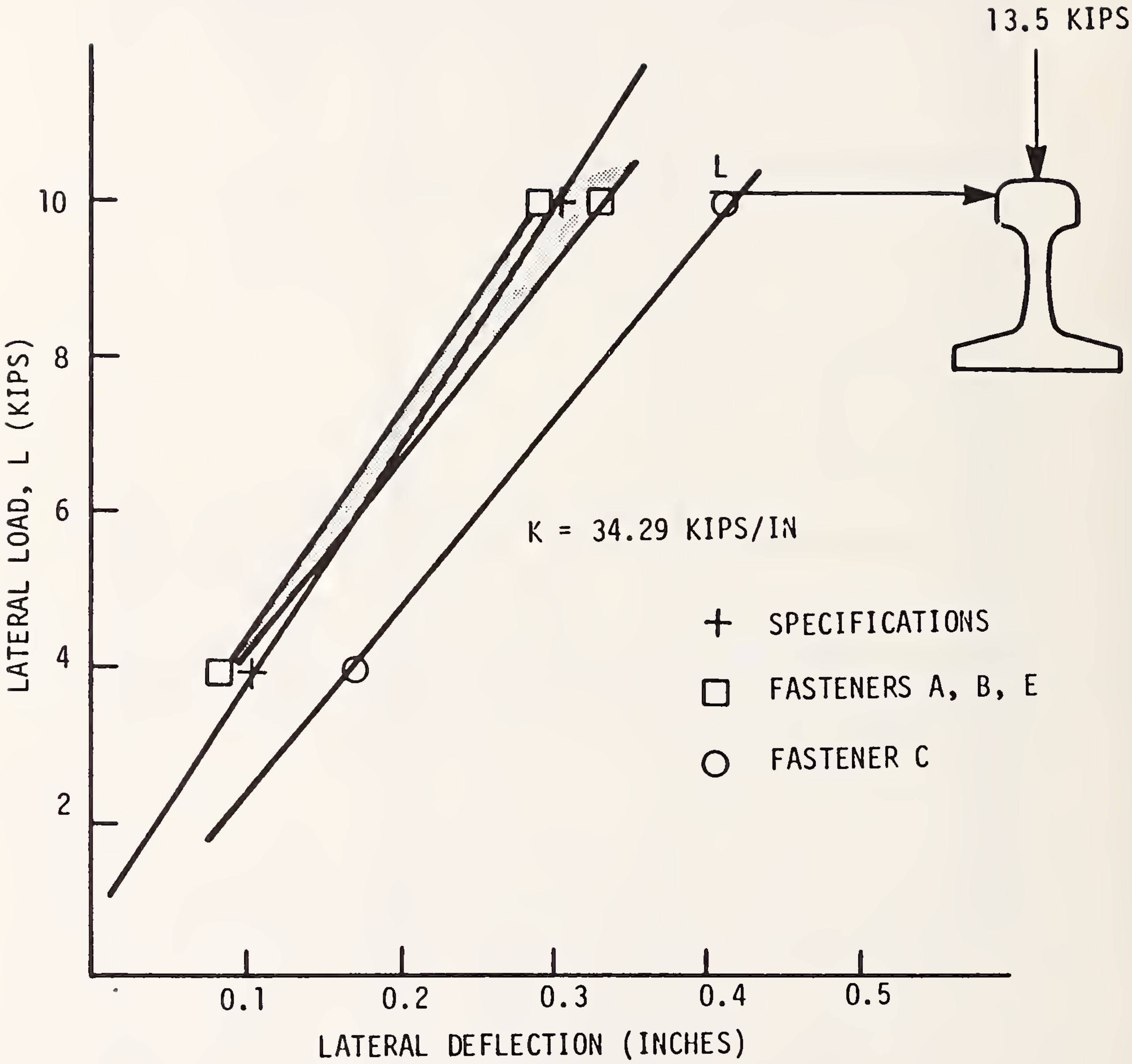


FIGURE 1. WMATA LATERAL LOAD/DEFLECTION REQUIREMENT (TW-8)

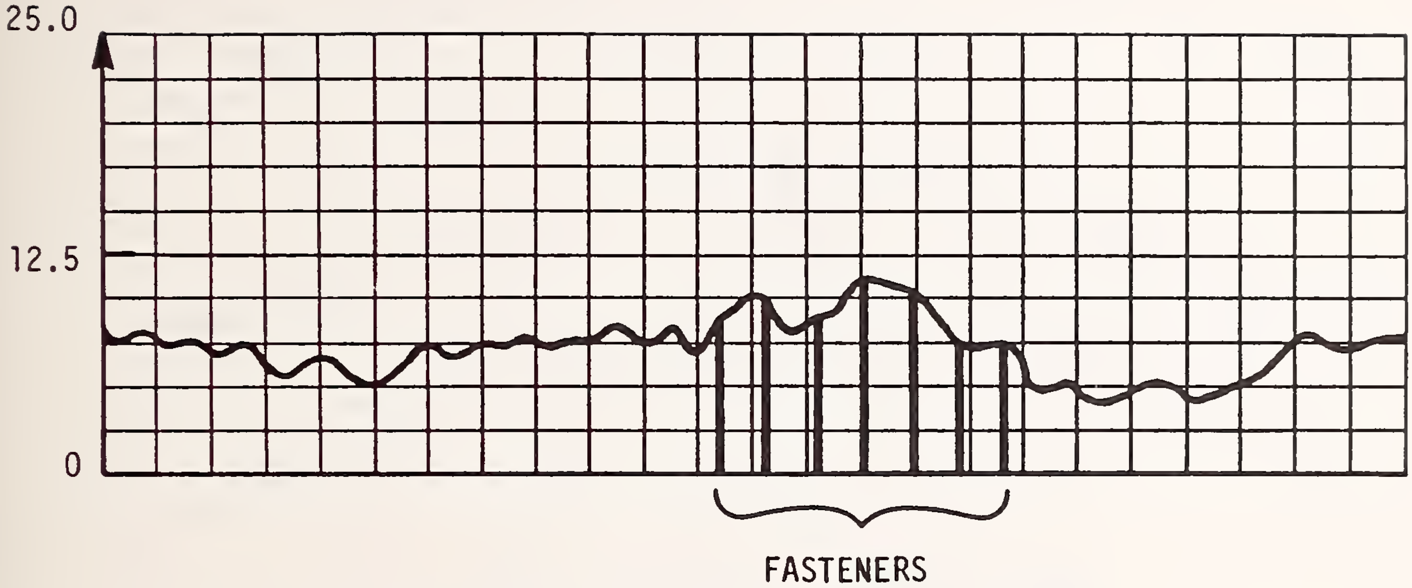


FIGURE 2. SURVEY RUN OF CURVE 37 WITH INSTRUMENTED WHEELSET

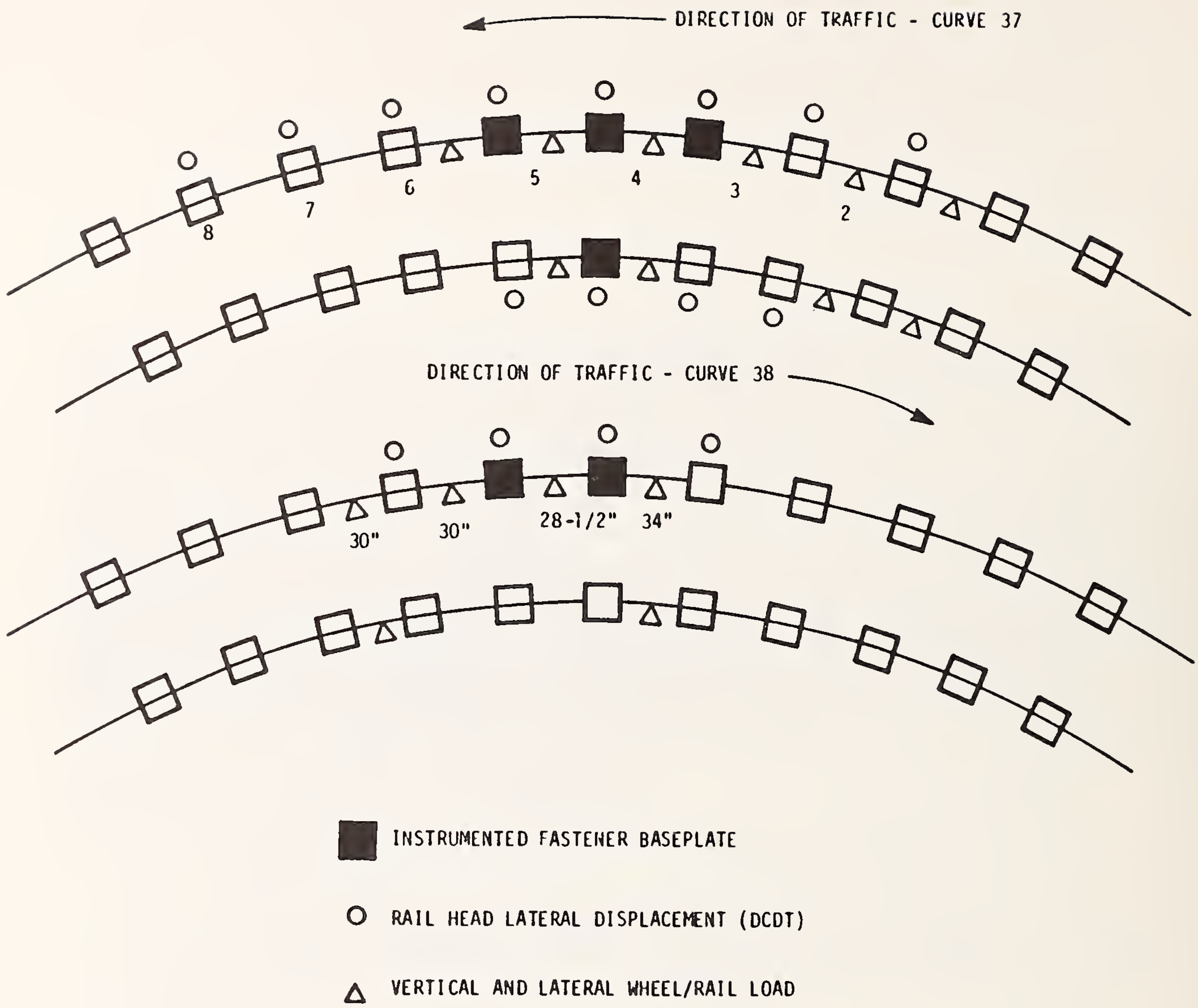


FIGURE 3. WAYSIDE INSTRUMENTATION CONFIGURATION AT TEST ZONES IN CURVES 37 AND 38, ON RED LINE, NEAR UNION STATION/VISITORS CENTER

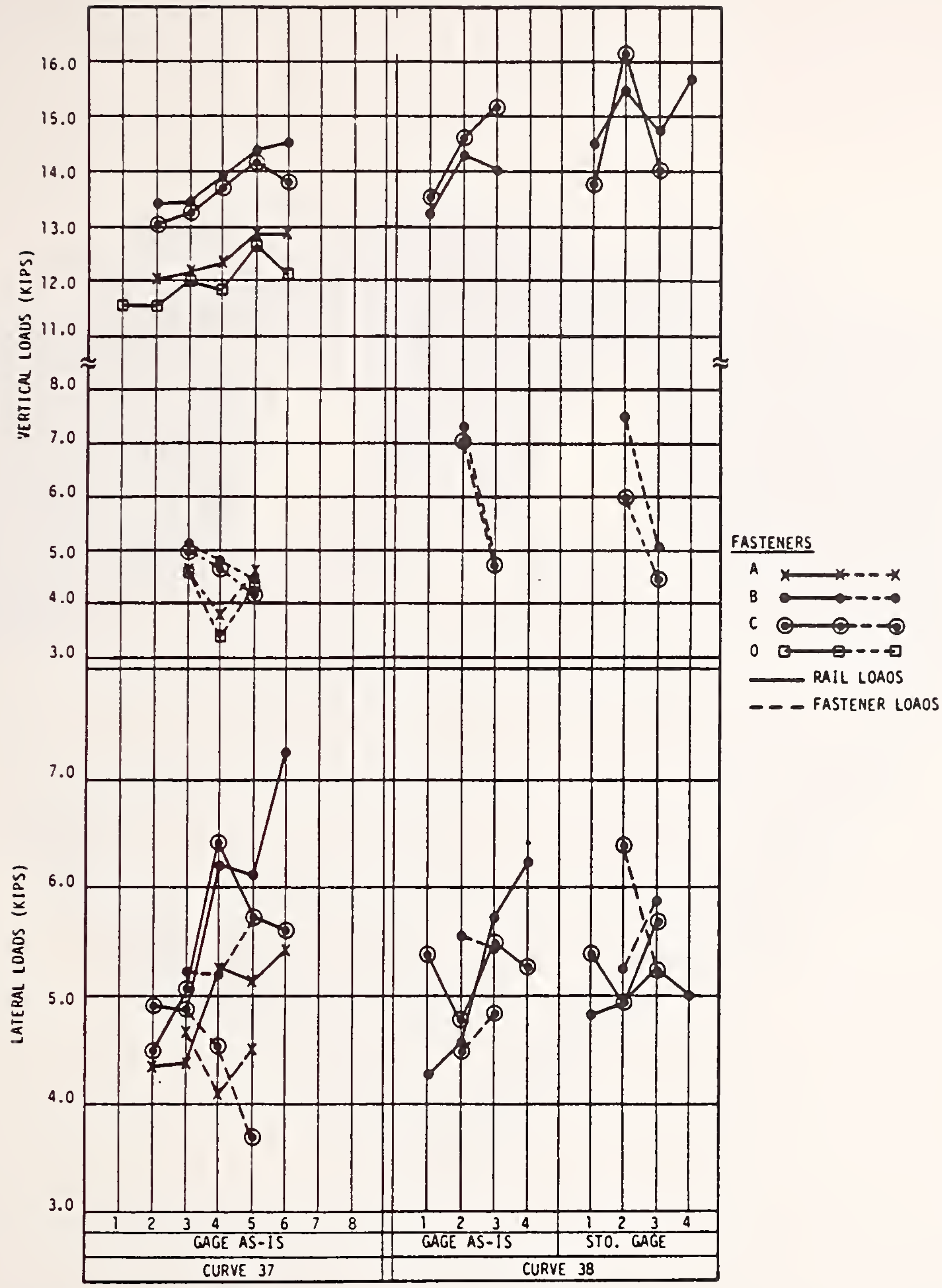


FIGURE 4. MEAN PEAK VERTICAL AND LATERAL LOADS IN THE RAIL AND TRANSMITTED THROUGH THE FASTENERS BY POSITION IN THE CURVE (DIRECTION OF TRAVEL INDICATED BY ASCENDING POSITION NUMBER)

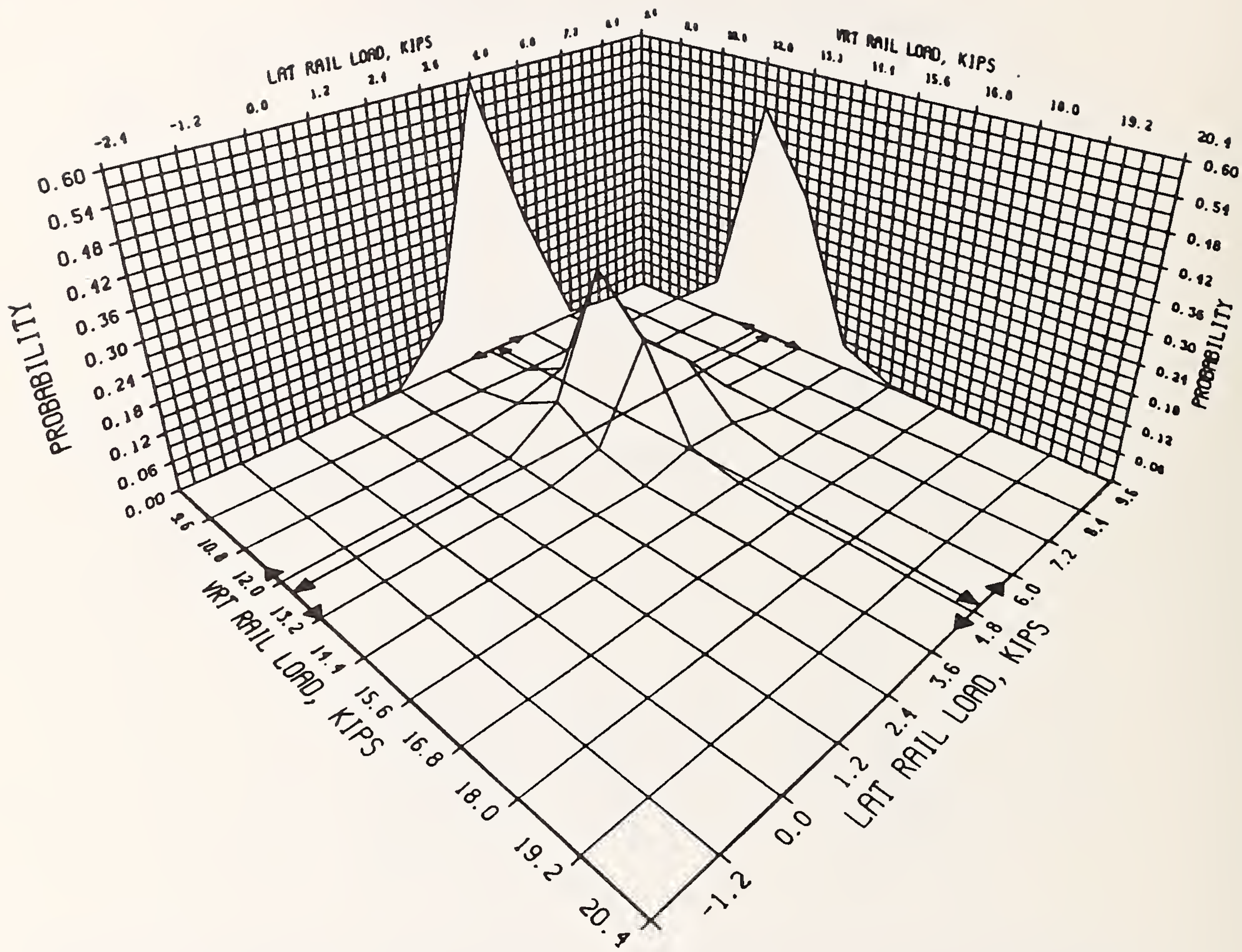


FIGURE 5A. JOINT PROBABILITY DISTRIBUTION OF MEASURED VERTICAL AND LATERAL RAIL LOADS ON CURVE 37, FASTENER A

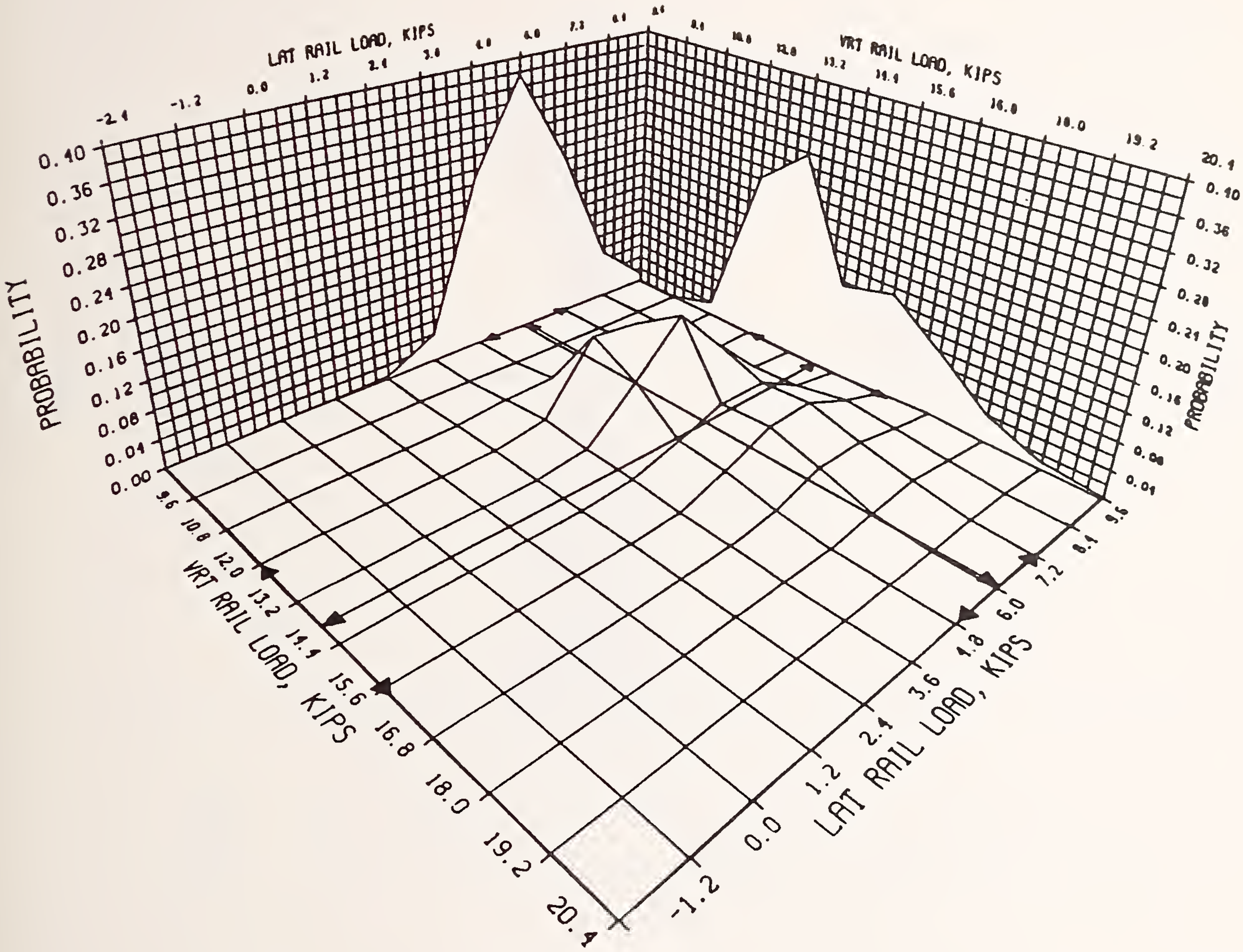


FIGURE 5B. JOINT PROBABILITY DISTRIBUTION OF MEASURED VERTICAL AND LATERAL RAIL LOADS ON CURVE 37, FASTENER B

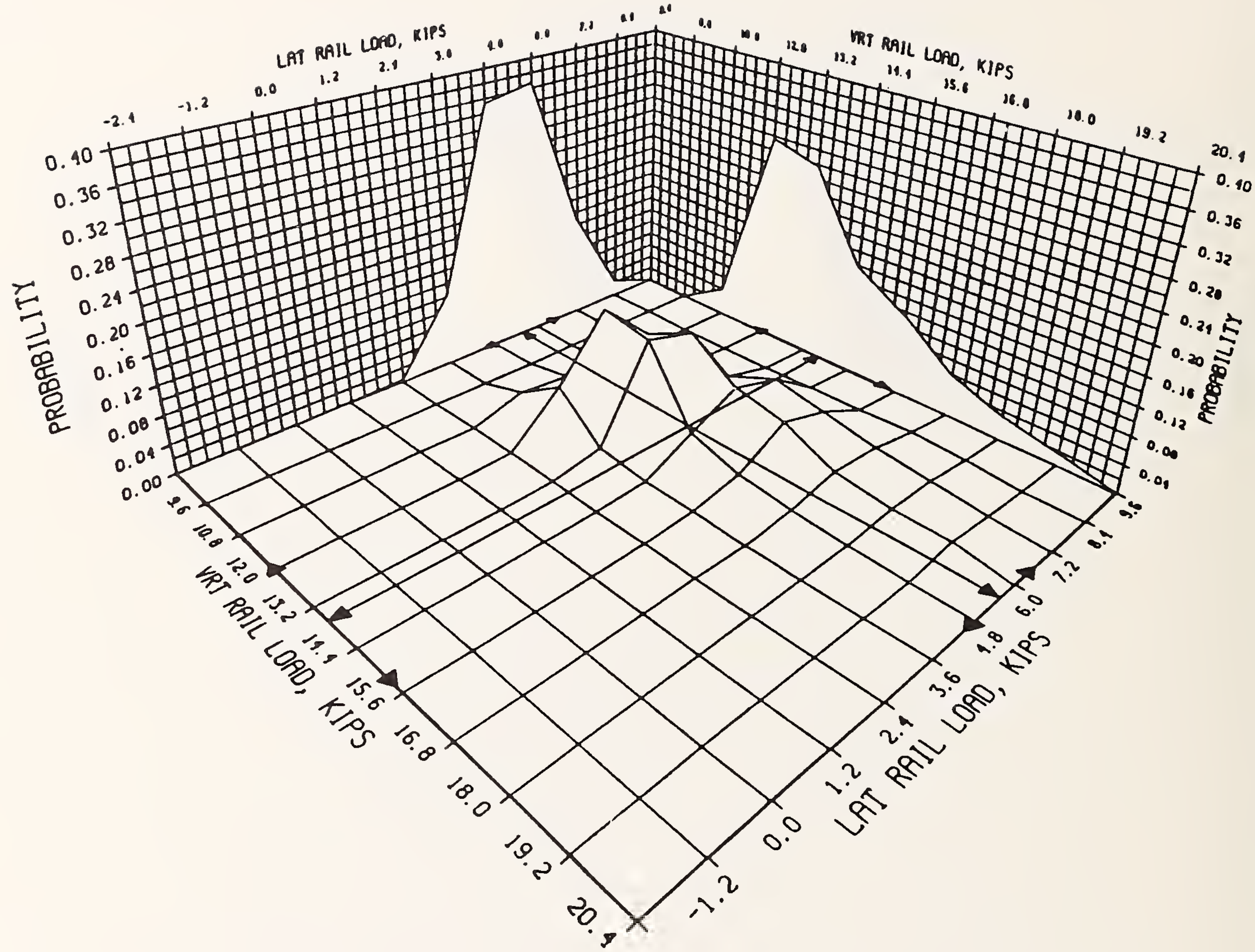


FIGURE 5C. JOINT PROBABILITY DISTRIBUTION OF MEASURED VERTICAL AND LATERAL RAIL LOADS ON CURVE 37, FASTENER C

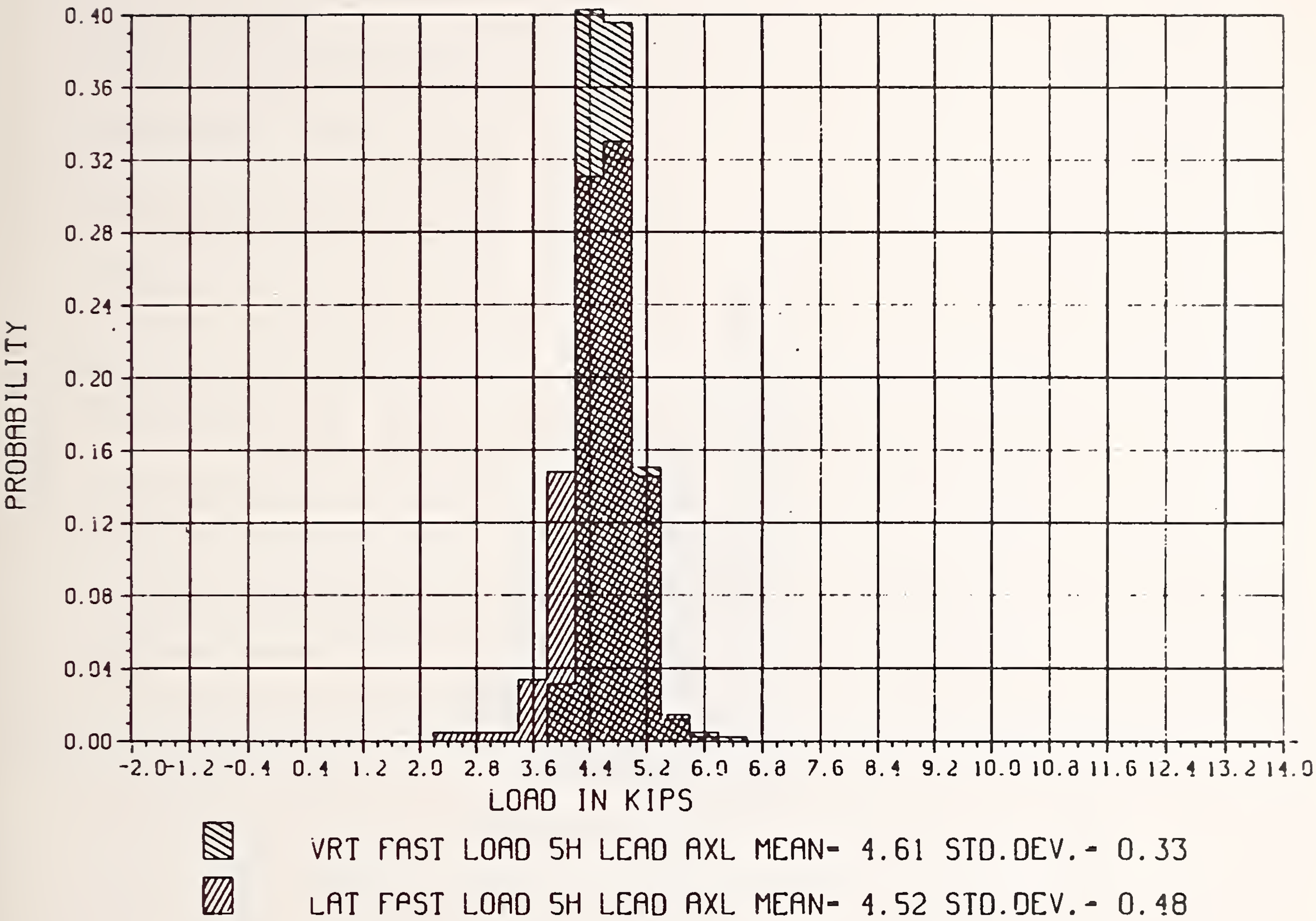


FIGURE 6A. PROBABILITY HISTOGRAM FOR LATERAL AND VERTICAL FASTENER LOADS FOR LEAD AXLE AT FASTENER 5 IN CURVE 37 FOR FASTENER A. TRACK GAGE IS 56-3/4" (A)

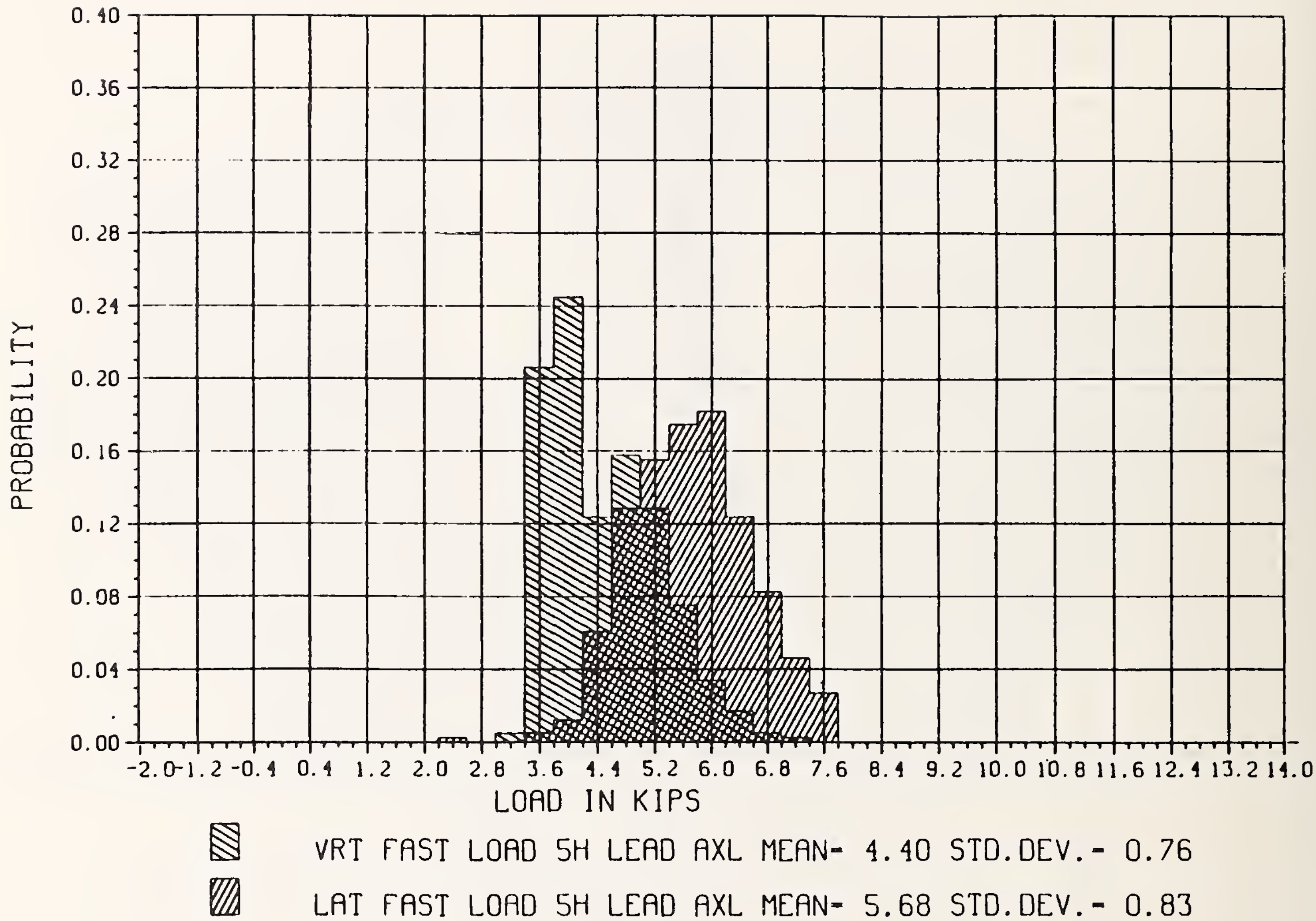


FIGURE 6B. PROBABILITY HISTOGRAM FOR LATERAL AND VERTICAL FASTENER LOADS FOR LEAD AXLE AT FASTENER 5 IN CURVE 37 FOR FASTENER B. TRACK GAGE IS 56-3/4" (B)

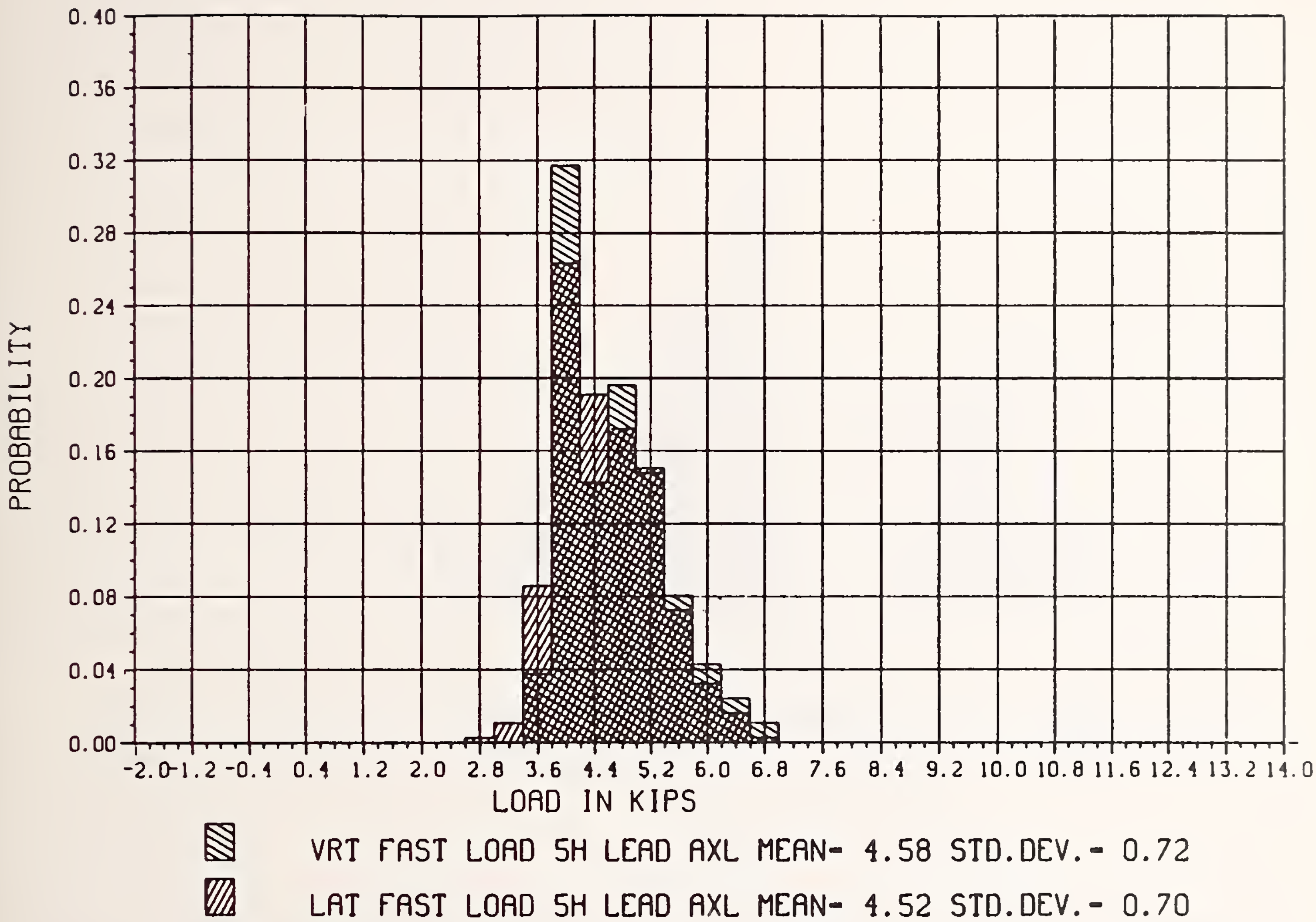


FIGURE 6C. PROBABILITY HISTOGRAM FOR LATERAL AND VERTICAL FASTENER LOADS FOR LEAD AXLE AT FASTENER 5 IN CURVE 37 FOR FASTENER C. TRACK GAGE IS 56-3/4" (C)

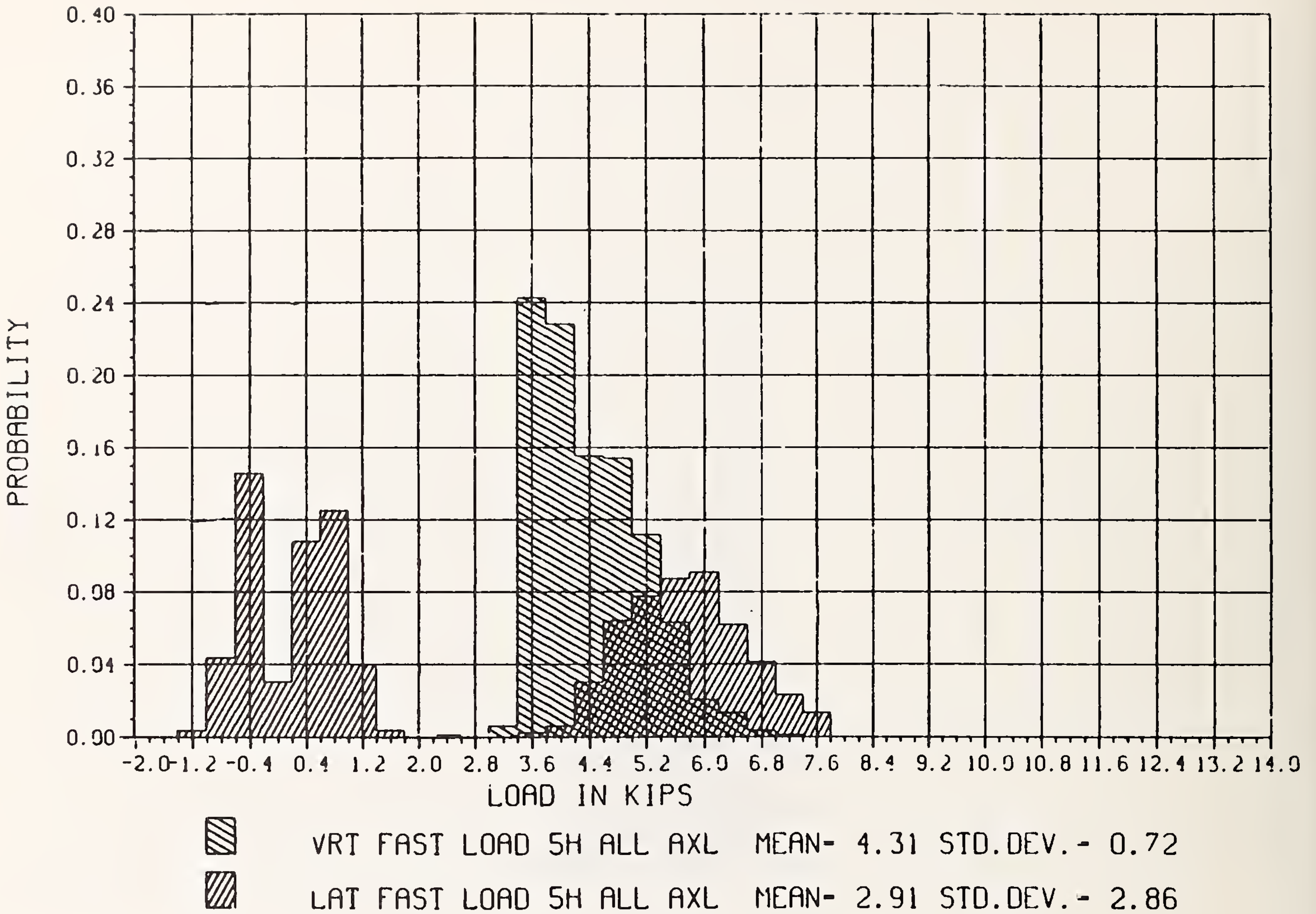


FIGURE 6D. PROBABILITY HISTOGRAM FOR LATERAL AND VERTICAL FASTENER LOADS FOR LEAD AXLE AT FASTENER 5 IN CURVE 37 FOR FASTENER D. TRACK GAGE IS 56-3/4" (D)

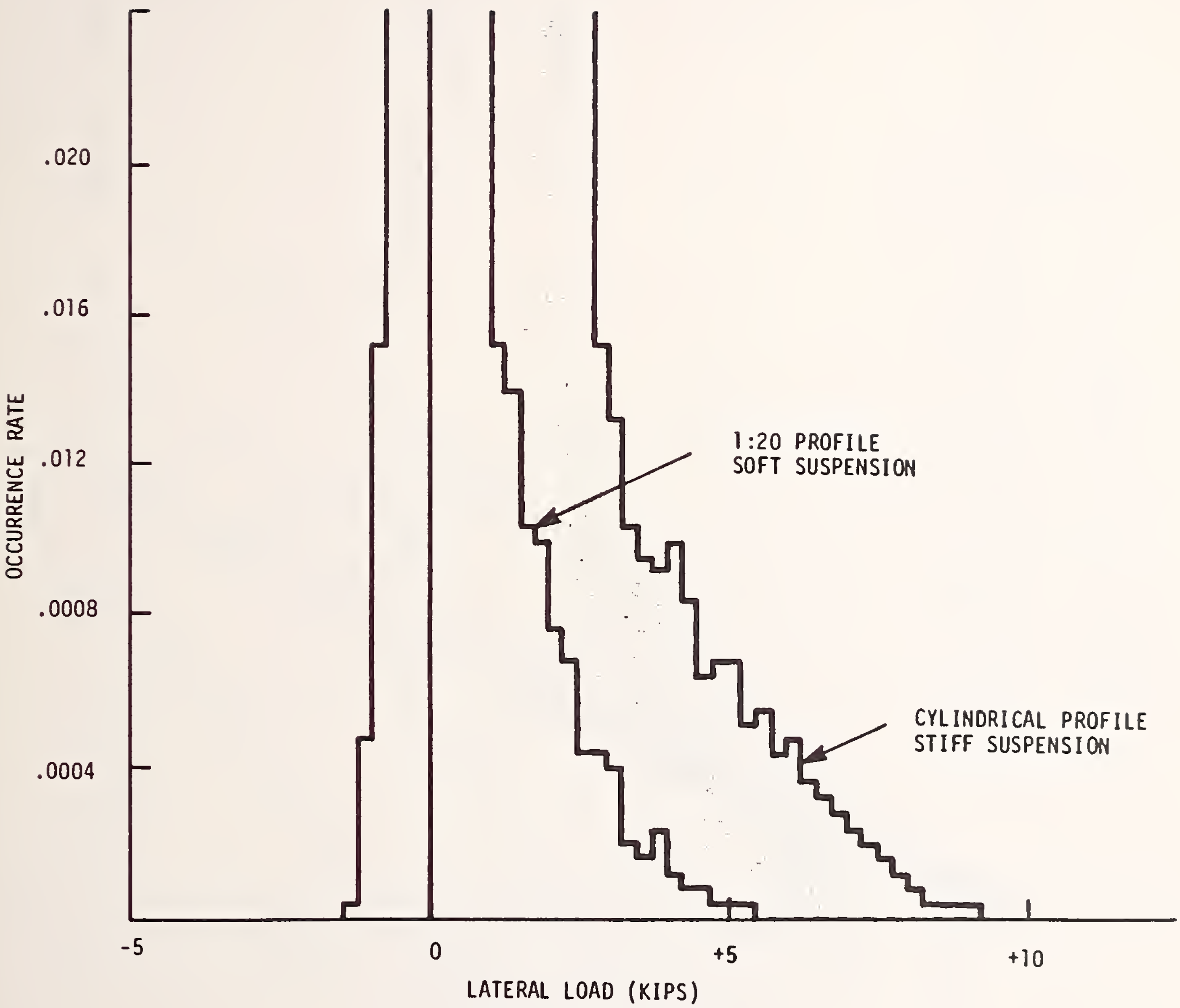


FIGURE 7. INSTRUMENTED WHEELSET FREQUENCY HISTOGRAM OF LATERAL RAIL LOADS ON WMATA RED LINE

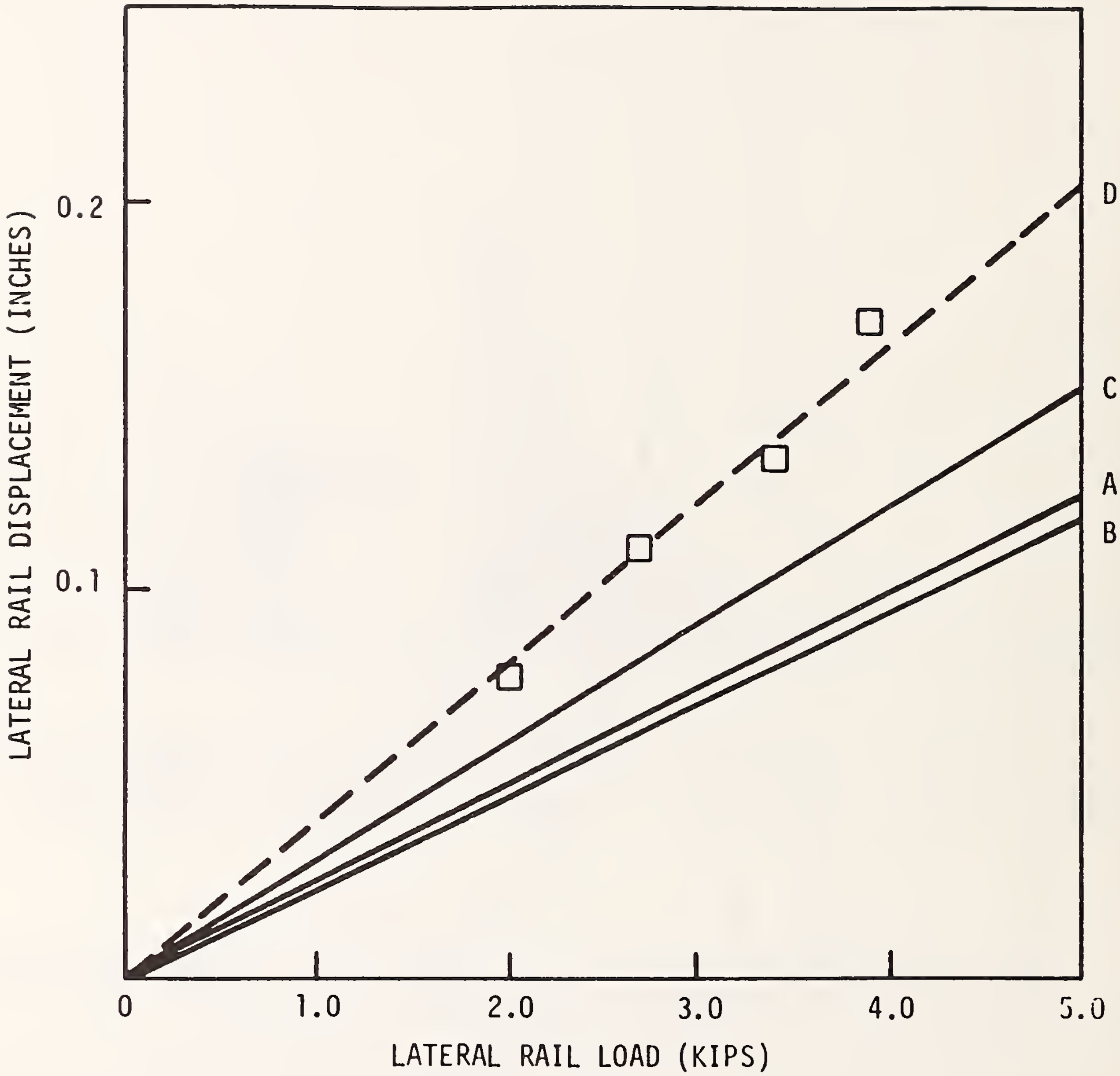


FIGURE 8. MEASURED RAIL RESPONSE OF FOUR DIFFERENT FASTENERS TO A MEASURED LATERAL LOAD APPLIED 18 INCHES FROM THE FASTENER

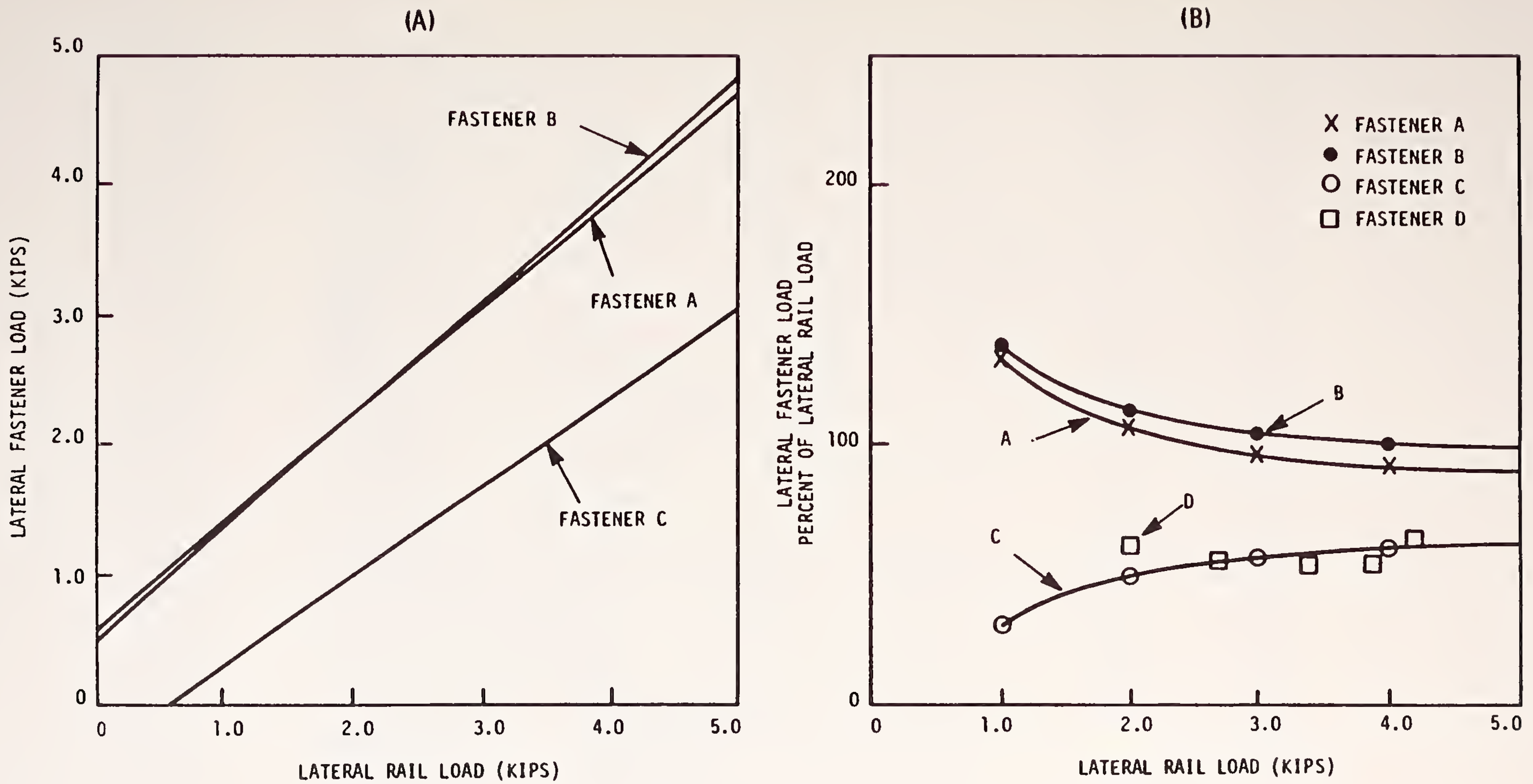


FIGURE 9. (A) FASTENER LOADS FOR FASTENERS A, B, AND C FOR ADJACENT RAIL LOAD
(B) SAME FASTENER LOAD AS A PERCENTAGE OF THE RAIL LOAD

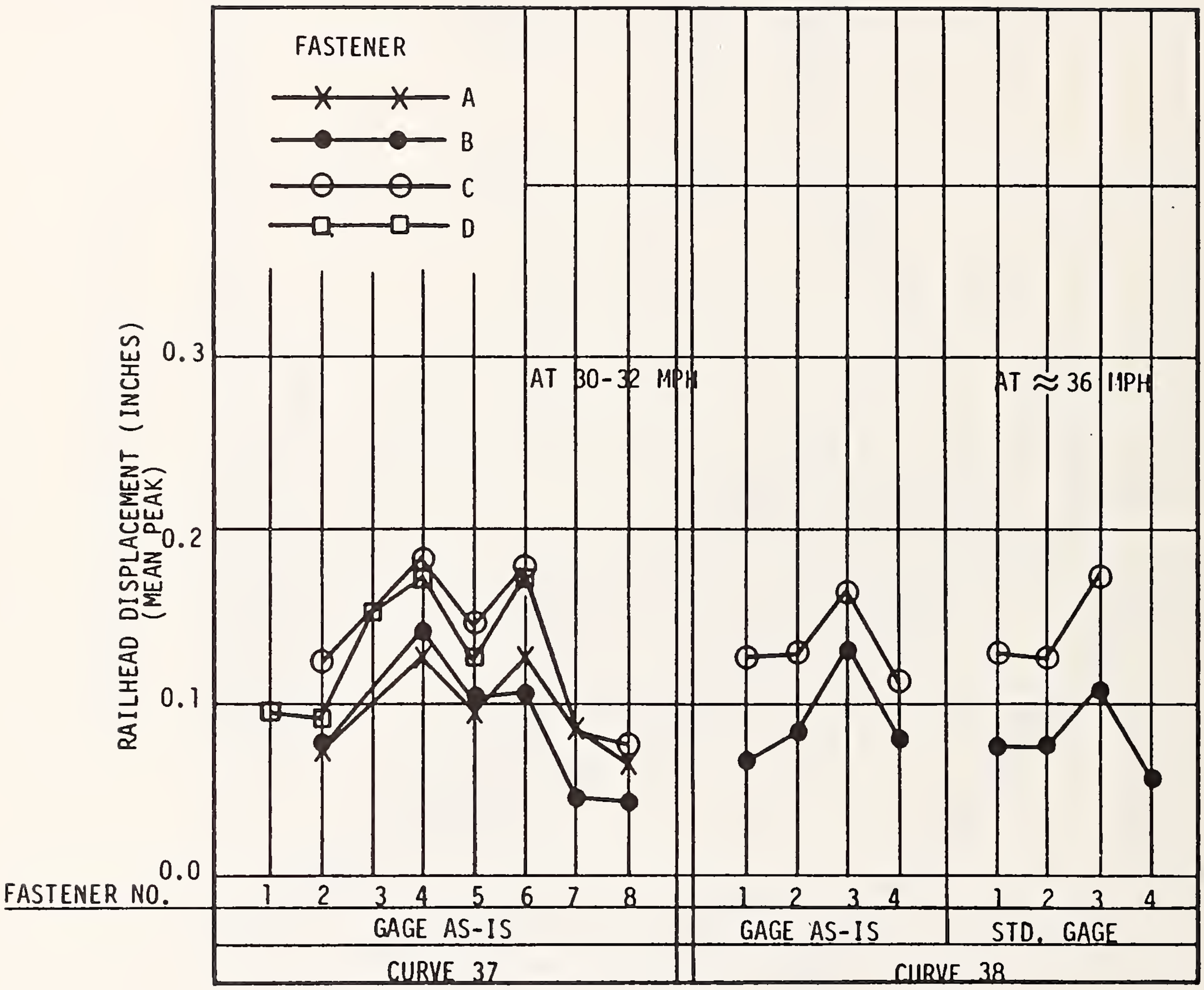


FIGURE 10. AVERAGE LATERAL RAIL HEAD DISPLACEMENT FOR FOUR FASTENERS

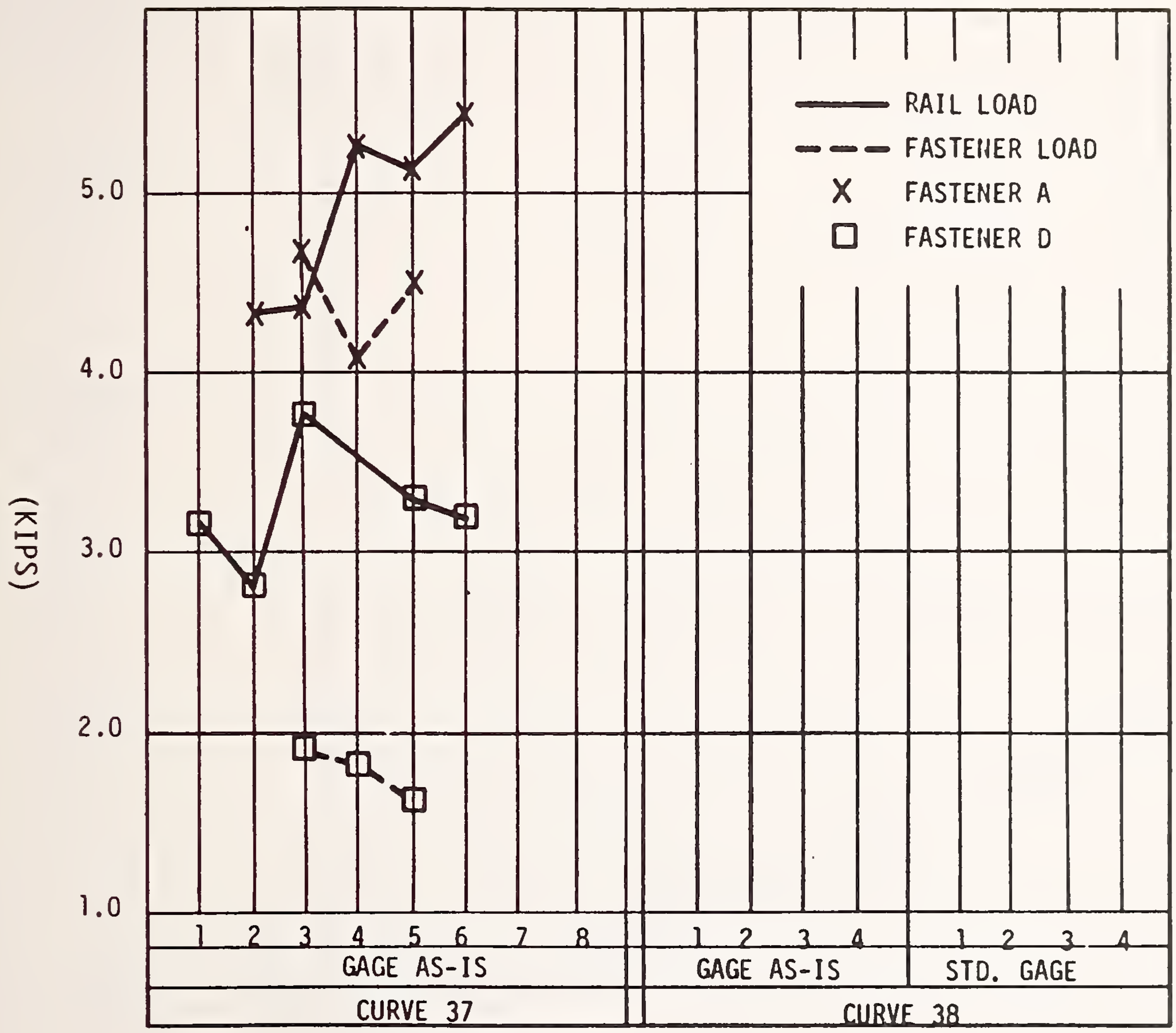


FIGURE 11. COMPARISON OF FASTENER A AND D LATERAL RAIL AND FASTENER LOADS

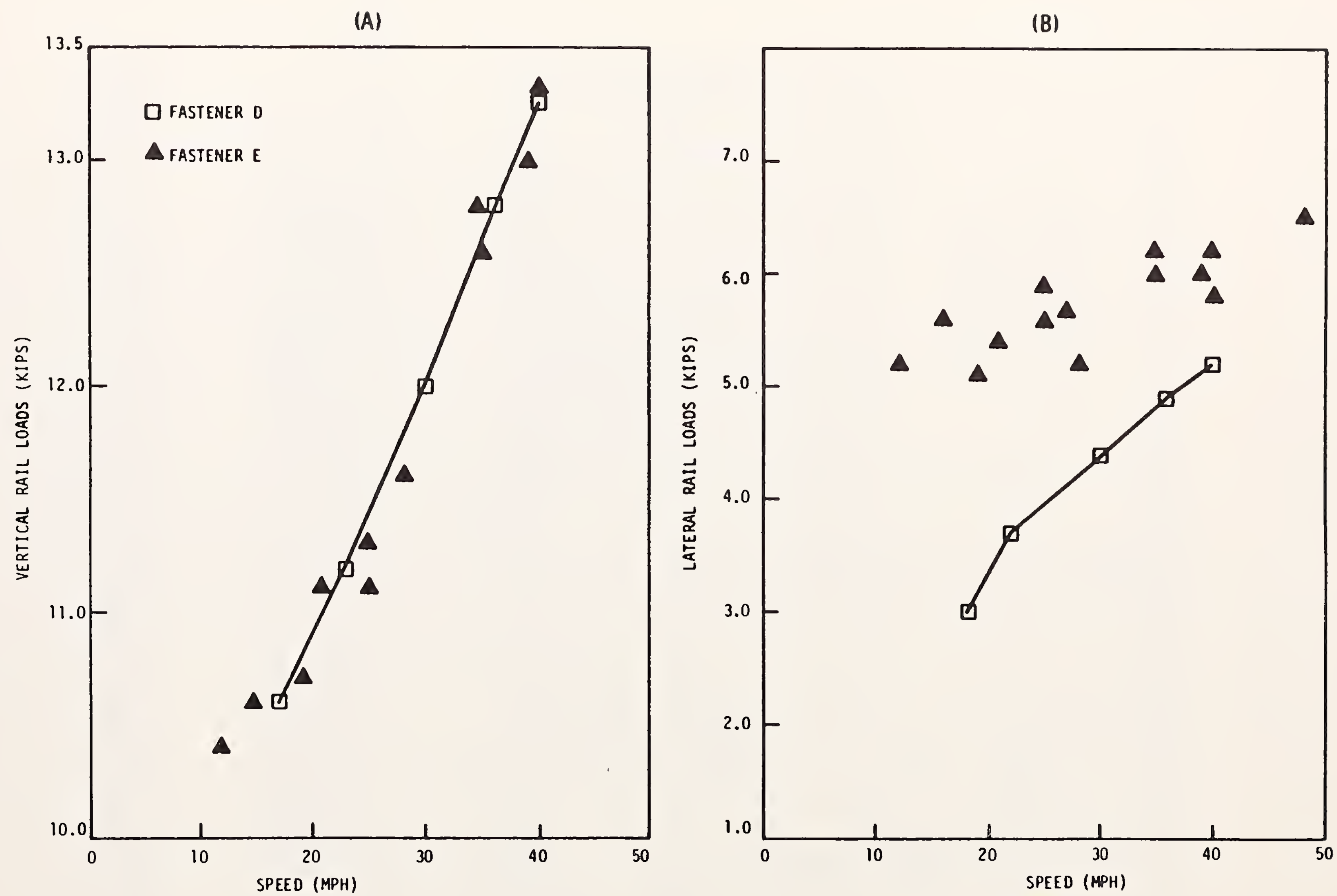


FIGURE 12. (A) VERTICAL AND (B) LATERAL RAIL LOADS AS A FUNCTION OF VEHICLE SPEED FOR TWO FASTENERS AND THE TEST TRAIN

Weinstock: I was wondering how much weight people would put on the observation that on normal ballasted track they did not see a wide range of fluctuation in dynamic forces for the 40 foot wavelength region while on track with direct fixation fasteners irregularities were observed? What is the probability that DFF's are causing these dynamic force fluctuations?

Phillips: Well, I think that is the meaning that one can interpret from that data. I would ask the group here whether their experience with the characteristics of tie and ballast versus direct fixation track, supports that conjecture.

Lohrmann: I would say that direct fixation shouldn't be used generically in that question. Maybe for these fasteners, under the applied test conditions, these were the results. Maybe if we changed the lateral softness of the fastener, it will act more like ballasted track. Does that make sense?

Weinstock: And what would it do when you soften the fastener?

Lohrmann: Well, I would like to look at that, I think that vertically the vibration people would be worried about softening the track too much.

Sluz: Track geometry measurements were made on all of the test curves, both in the wood tie sections and the direct fixation fastener sections. The wood tie sections had about the same amount of traffic over them as the direct fixation sections. However, they did not show the same amount of wear - those are relatively young sections for wood tie tracks - all the spikes were still in and they were maintained very well. There was a lot more wear apparent in the direct fixation track. That maybe due to the fact that it was stiffer laterally and that lateral head wear then had a tremendous influence on loads. You go back to what Mr. Phillips brought up in his presentation, whether it was due to the fastener, variations in the fastener stiffness or whether the problems in the fastener were due to vehicle parameters is difficult to assess.

Tillman: This is along the same line. Mr. Phillips, you said you got this phenomenon which was on the wavelength of 39'.

Phillips: 40' and 39'.

Tillman: 39 or 40 feet which is right at the length of welded rail. What would be the possibility of getting some of the 78' rail put in a section of track and seeing whether or not it's a metallurgical problem as opposed to some other problem.

Phillips: One of the things of course is it takes several years to build up the characteristics. It might be better to see if 78' is presently used in any transit system.

Bharadwaja: Is it not reasonable to conclude we have not yet developed a DFF track which would simulate the old track with ties and ballast.

Phillips: It would certainly be an implication there.

McEwen: As a follow on to that, I'd like to suggest that we procured a number of fasteners and we've assumed that those fasteners conformed to the specifications that were used to procure them. We don't necessarily have precise information with respect to the acceptance testing of those fasteners. I think it would be useful to obtain the actual characteristics of the fasteners in use.

Wilson: Mr. Sluz, when you changed fasteners in a test zone, how far on each side of the test section did you use, for say the soft fastener C or D?

Sluz: Sixty fasteners ahead of the test section or about 150 feet. And a short length behind the test zone. We tried to establish a sufficient transition length to take out any of the dynamic effects of switching from a stiffer to a softer zone. We would have made the section even longer but we were limited in how many fasteners we could change over in a night. It was something like 60 fasteners.

Wilson: The other thing is when you measured the forces on the fasteners or transferred from the fasteners to the invert did your instrumentation then convert that back to rail-head forces or were they really just the shear force and the verticle force on the fastener.

Sluz: The way that was measured was that the fastener itself was anchored to a cradle. The cradle was put on I-beam elements which were strain gaged in particular orientations.

Weinstock: I believe you had the moments on the base plate as well as the lateral and vertical forces on the base plate.

Sluz: The moment was done by a manipulation of the vertical and lateral forces. In essence it was the vertical and lateral forces on the fastener because those I-beam elements were on a base plate which was anchored to the slab.

Wilson: Then on your last slide you had shown the test conditions on the top and then the major conditions below with the vectors shown on the same place.

Sluz: That was to simulate the laboratory conditions. In other words, if you had one fastener, and one fastener only, and you were going to apply a lateral and a vertical load on that fastener to simulate field conditions then, the figure illustrates what those loads should be. In other words, this is load representation, not an actual force diagram. This is the lateral load to be put on the fastener. Naturally we'd have to match the overturning moments measured in the field to determine exactly where we should place the loads.

Wilson: For the 5.6 it should be down at the base of the rail and then you would have to add the moment in.

Sluz: The test program that we are now embarking on will essentially answer that question for us. We will duplicate from the same instruments used in the field, the location of the vertical and lateral load and the overturning moment. From that we will determine how to apply it to the rail head.

Dunn: Mr. Chen, I'd like to hear the reaction of someone like Tom O'Donnell or Jim Palmer to the idea of having different fasteners for tangent and curved track.

O'Donnell: I think that a long time ago at Washington, I suggested that, in the areas where we could use the Pandrol type fastener. We put in these fasteners at State and Amory. There was a similar shoulder to the Portec shoulders that you saw here yesterday. The reason we put these fasteners in, was to get some super elevation and decide whether that would help on rail/wheel wear. We did put this 1100 or 1200 feet of track in with the Pandrol fastener and it worked out pretty well for the fastener. I think the total price per unit was $15 so in areas where you could use that fastener and you didn't have any noise and vibration problems that I think would be a good thing to do. You're getting down to where it costs so much for these fasteners you just have to go for something.

Keffler: That's a case where the two fasteners were distinctly different visually. When you're writing a specification you may wind up with 2 fasteners that behave quite differently but that look identical. Do you see a problem with the maintenance forces 10 years from now not being able to differentiate one from the other or to know why one is painted yellow and one isn't?

O'Donnell: No, you could see the difference if you ended up with any of the 3 different fasteners.

Chen: We did have some other problem with that area after Mr. O'Donnell left. We had some corrugations on the low rail. We don't know why.

O'Donnell: Well the theory on that is you had a soft high rail and a very stiff...

Chen: ... and a stiff low rail you can tell when you run through that section, a lot of noise. Fortunately nobody lives above there or we could be facing problems.

O'Donnell: With the regular WMATA fastener, we got a lot of corrugations. In fact with some of the tests we did with TSC and grinding we reduced the noise to 13 decibels down at Foggy Bottom.

Chen: I think one possible cause of these corrugations could be due to some wheel flats. And our braking system is very sensitive. Of course other vehicles run in the area also such as locomotives or other non-revenue vehicles so we don't know what really causes the corrugation.

Hanna: I have a question related to the last question. Can we have Mr. Sluz's last slide? These loads shown, the 6.5, 5.6 and 2; could they occur at the same location? That is my first question. Secondly, if so, what is the ratio in terms of frequency between the 2 and 5.6?

Sluz: No, the maximum vertical and lateral loads did not necessarily occur at the same time.

Hanna: I'm talking about the reverse lateral - whether the reverse occured at the same location?

Sluz: When the trailing axles were included, there were quite a few loads in the opposite direction. We didn't do correlation of how often they occured after particular levels of load on the lead axle but there was a sufficient number of those types of occurrences to say that probably they occured randomly and had to do with the orientation of the truck going through the zone, not necessarily any linkage between the load in the lead axle and the load in the rear axle. There are many things that can happen, especially with the irregularities that existed in the test zone, to randomly influence the pattern of load application. If you looked, for instance, at curve 38 at the part where we suspect the highest lateral load occured, it appeared to be almost a gouge in the rail and there were many possible orientations of the wheel on its path over that spot.

Palmer: In response to Mr. Dunn's comment regarding different types of fasteners. I don't have a serious problem with it as long as one can distinguish physically between them. Presently we handle a large variety of fastening systems now and we don't have major problems as long as there is a difference. However, my problem in listening to the discussion is that in my mind, the restraining rail systems certainly have a lot more benefit then trying to solve the problem of curves with fasteners. When you have a low rail that's essentially not working very much, why not establish a system so that the low rail is starting to share a lot of the load.

Chen: We do have restraining rail on curves less than 755° on only 2 locations.

Weinstock: One problem on the restraining rail is that the force that is exerted on the restraining rail is comparable to the high rail forces without the restraining rail so you're just changing the location of the problem from the fastener standpoint. Holding on to the high rail, holding on to the restraining rail, so you still have the same load profile.

Palmer: You do have the same load profile, however the restraining rail system, you certainly can design that so it more effectively reacts against lateral loads. Also essentially what we do in our system is we design so that the loads are initially taken by the restraining rail, after a small amount of wear it starts sharing the load between the restraining rail and the high rail.

Phillips: And that brings up the subject that's been avoided so far and that is lubrication of the rail. WMATA as a practice has not lubricated until recently...

O'Donnell: ...No, when the original restraining rail was replaced we put in back of the wheel lubrication so that the restraining rail is lubricated. In fact Boston has historical data on restraining rail that was installed in 1950 that's still in use. I hear so much about noise and how it's going to wear out so fast.

Phillips: Not if you lubricate.

O'Donnell: It's had 30 years of life and it still has quite a bit of life left in it and think how many outer rails that restraining rail has saved in 30 or 32 years.

Phillips: And the advantage is that the restraining rail applies the lubrication to the back side of the wheel...

O'Donnell: ... The back side of the wheel plus the fact that you have an extra rail in there and you're a hell of a lot safer. In my 28 years in Boston I've seen many, many derailments avoided because of the restraining rail.

Keffler: And the other condition is the contact area on the restraining rail is higher than the contact area on the high rail and you're distributing that point load of the wheel over a larger area so the wear ratio is lower.

Phillips: We've, with Dr. Weinstock, done some curving mechanics studies with restraining rails and some tests were done at Pueblo with restraining rail. One of the things that comes up with these measurements is what happens on other properties and we are hoping that UMTA's funding is going to allow us to make some measurements on PATCO with an instrumented wheel set. Where also by the way they have a steerable truck now in revenue service and possibly at the MBTA where we would like to attempt to look at restraining rail with the instrumented wheelset. That presents a number of problems because of the location of the forces on the wheelset but ENSCO has indicated that they feel that they can calibrate it in such a way as to provide some answers in that area.

Palmer: If you are interested in comparing the loadings from concrete and wood tie construction, SEPTA is presently putting into service a new fleet as part of the subway system and will have a large range of construction types in that system. If you're interested in seeing what type of loadings and what type of a force profile is generated.

Question: I've heard a lot this morning about the implications of what should happen the next time curve 37 is rebuilt or any one of us builds a curve similar to curve 37 but I'm interested in how do I take the data we've discussed the past two days and take it home and apply it to other situations. For example, light rail transit track with extremely tight radius curves that are miniscule compared to the 755° radius. I'm talking about curves nearly one tenth that radius, around 82 feet. Can you safely extrapolate that data?

Weinstock: I'm willing to take a risk and make an estimate of wheel rail forces for design purposes as a design load. That would be that the wheel rail force on the high rail is not going to exceed 85% of the vehicle force. If it does, your system's got trouble anyway. The wheels start to climb, there are things wrong with the system if wheel rail forces are getting up that high under normal operations. On the low rail you can expect the force to be no more than 60% of the vertical force.

Sluz: This question is the essence of what we are trying to do in transferring the results of our tests to the general industry. If I were a system designer, and had conditions similar to WMATA, i.e. car weight and track construction, I would feel very comfortable using the numbers from our tests in designing and specifying track components. For application to a dissimilar system, perhaps with lighter cars and different track conditions, it would be the trends of our WMATA tests that would be of use to me. The most important information that might be useful is the importance of designing a system that distributes, rather than concentrates loads; and the importance of testing components under the proper environment.

Certainly a system with very short radius curves and very low vehicle speeds is not the same as the system we tested. Without hard data for your specific conditions, analysis and engineering judgement based on other conditions for which data exists are your primary tools.

Question: Can any of you gentleman tell what the car data is at WMATA, the wheel spacing, the truck spacing, the axle load?

Chen: 7.5 foot truck axle spacing, 52 feet between the truck centerlines.

Question: And what's the crush load?

Chen: Crush load - 120 thousand lbs per car.

The car itself weighs about 72,000 to 75,000 lbs. 72,000 lbs was original.

Phillips: The North American Car Roster still has it as 72 thousand pounds, I believe you because the forces that we looked at seem consistent with the heavier car.

Chen: We performed an experiment. We asked for volunteers to determine how many people can squeeze into a car.

We are also in the process of changing from a cylindrical wheel to a tapered wheel and the new car we have ordered from Italy has a tapered wheel. We don't know whether the new truck is as stiff as the one we have now.

Phillips: Excuse me, Mr. Chen, according to the drawings that new truck, the Breda truck, will be a Chevron truck, rather than a doughnut, and it will be much softer in the vertical direction but will still be stiff in the longitudinal direction. People are just beginning to realize the importance of longitudinal stiffness in improving the steering and reducing the wear on curves.

McEwen: We've been talking from the fastener up. There are problems from the fastener down. What are the loads transferred to an aerial structure? That's one of the things we really don't know about.

Sluz: We didn't measure longitudinal loads or the in place rail stresses. We did get vehicle and lateral loads that were transferred from the fastener to the structure in this test program. Certainly your point is a good one, there are many more things we need to know.

Lohrmann: One thing that the tests show is that you can't increase safety by just increasing your test load. WMATA has a requirement for no more than 0.3" deflection at 12 kips load. It is not an improvement to increase this load to 15 kips, it just makes for a stiffer fastener and I think from what Mr. Sluz showed, this is not the way we want to go.

Question: I may have gotten the wrong impression; but I take it that the returns you get from reducing your center-to-center spacing on fasteners is not that significant.

Lohrmann: I guess how significant it is depends on how many curves you have between 850' and 1200' radius. If you don't have many curves in that range then you've gained nothing, if you do, then maybe you've gained a lot. Not having a verified model, it is difficult to predict what the load distribution for each new fastener would be, so it makes it difficult to predict what you would gain.

Sluz: The instrumentation is being improved and is costing less to use. The best place to test new components is track under actual loads, so maybe it would not be too far-fetched (after a component passes minimum qualifying tests) to field test it and its effect on the whole system.

Weinstock: The best use for field data is to test analyses and the analytical framework. With the type A fastener, we were predicting that there might be certain situations where the fastener would see a load higher than the wheel/rail load. Now with these analytical models we can start to talk about directions for fastener design. But no matter now good my analyses are, you're not going to believe it, I'm not going to believe it until we go out in the field and test it. We are at a point where we can use models to help us decide what we want in terms of fastener stiffness for load distribution and then we can go out and test the concept.

DFF PROBLEMS AND POTENTIAL SOLUTIONS

Noise and Vibration of Rail Rapid Transit Systems: Effects of Vehicle Suspension and Track Stiffness

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Abstract

The New York City Transit System has been engaged in efforts to reduce noise and vibration caused by the operation of our rapid transit system. Our efforts are concentrated on replacing bolted rail with continuous welded rail utilizing resilient rail fasteners.

We have conducted studies and experiments to determine the effect of a fastener's stiffness and damping on its ability to lower noise and vibration. We have also learned that the subway car suspension stiffness significantly affects the level and frequency content of groundborne vibration.

In this paper, I will review the New York City Transit Authority's experience in these areas, as well as the experience of others. The evidence suggests a strong interaction exists between the vehicle dynamic characteristics and the track dynamic characteristics that affect the level and frequency of noise and vibration.

New York's Direct Fixation Fastener

The New York City Transit Authority has been using the Liberty, or Nelson Moses fastener since 1961. The fastener has been changed over the years to make it a better vibration isolator as well as easier to install and maintain. At the present time, it is 7/8 inch thick, 50 durometer, having core holes to improve the shape factor, and fitted into a metal box, or container plate, made of 3/8 inch thick steel. Two versions are used. The 14 inch fastener is for direct attachment to the concrete subway track invert, and the 8 inch version is for attachment on top of wood ties. Approximately 60 miles of track in subway has been welded and fitted with this resilient fastener. This work will continue at 20 miles per year until the 400 miles of track in subway have been changed.

Figure 1 is a sketch of the present configuration fitted to a wood tie. When installed in subway, a 5 decibel reduction of vibration, as shown in Figure 2, is obtained.

When used on elevated structures, a 3 to 5 decibel noise reduction, shown in Figure 3, is obtained. The dynamic properties of the fastener are not the same for each application. For use in subways to reduce low frequency vibration, the elastomer should be as soft as possible. For use on open tie deck steel elevated structures, the fastener must be thick, relatively stiff, and have high damping, as explained by Kurzweil [1].

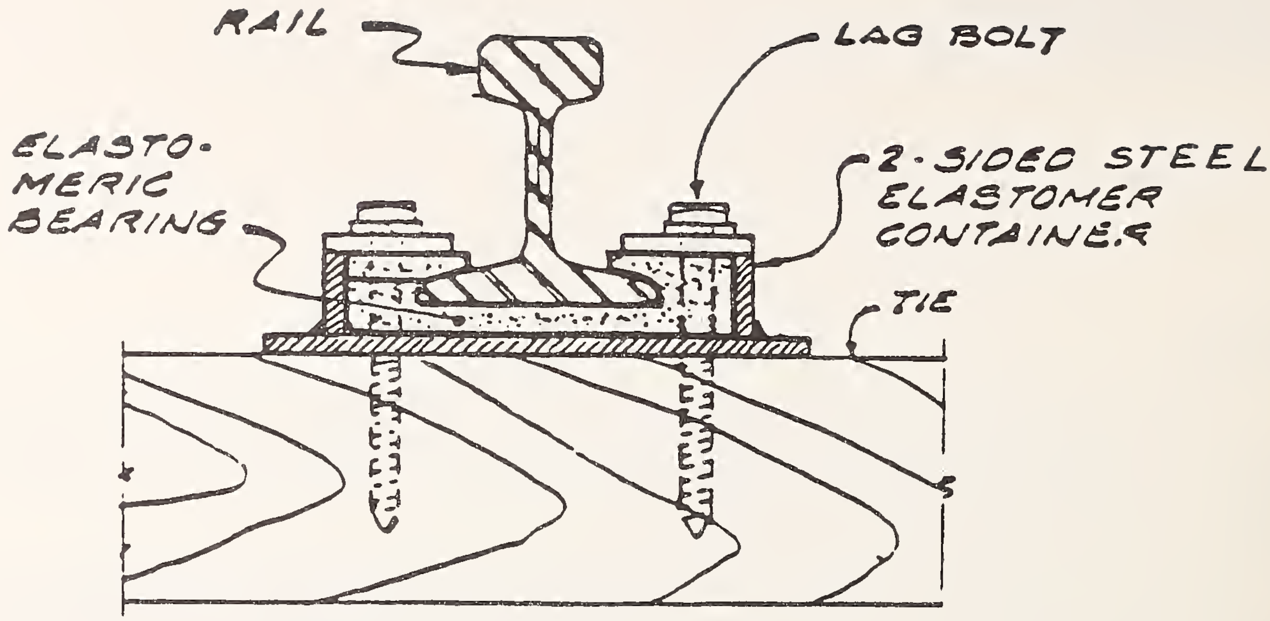


FIGURE 1. DFF FITTED TO A WOODEN TIE

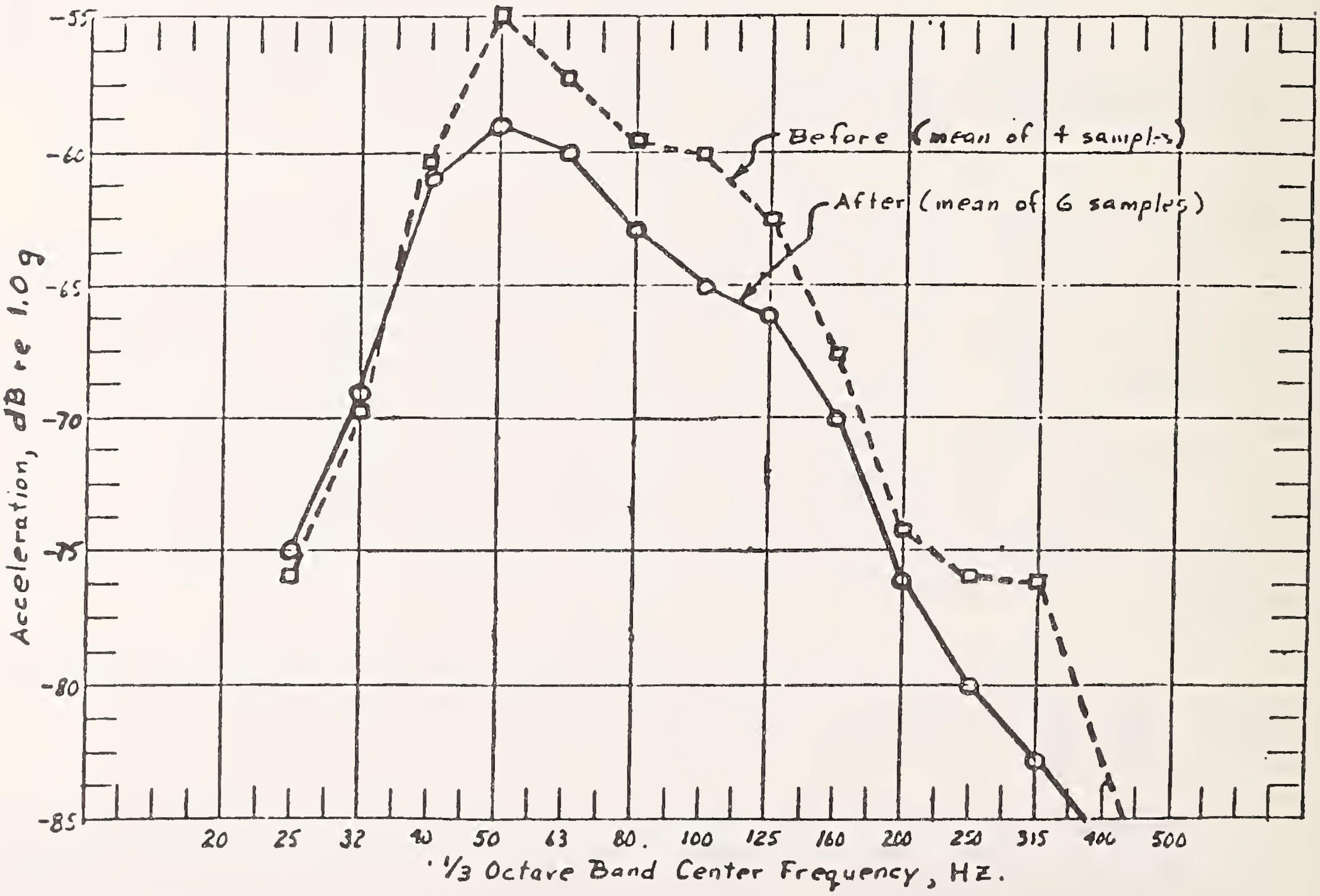


FIGURE 2. ACCELERATION LEVELS BEFORE AND AFTER THE INSTALLATION OF 1 INCH BUTYL RUBBER RAIL SEATS

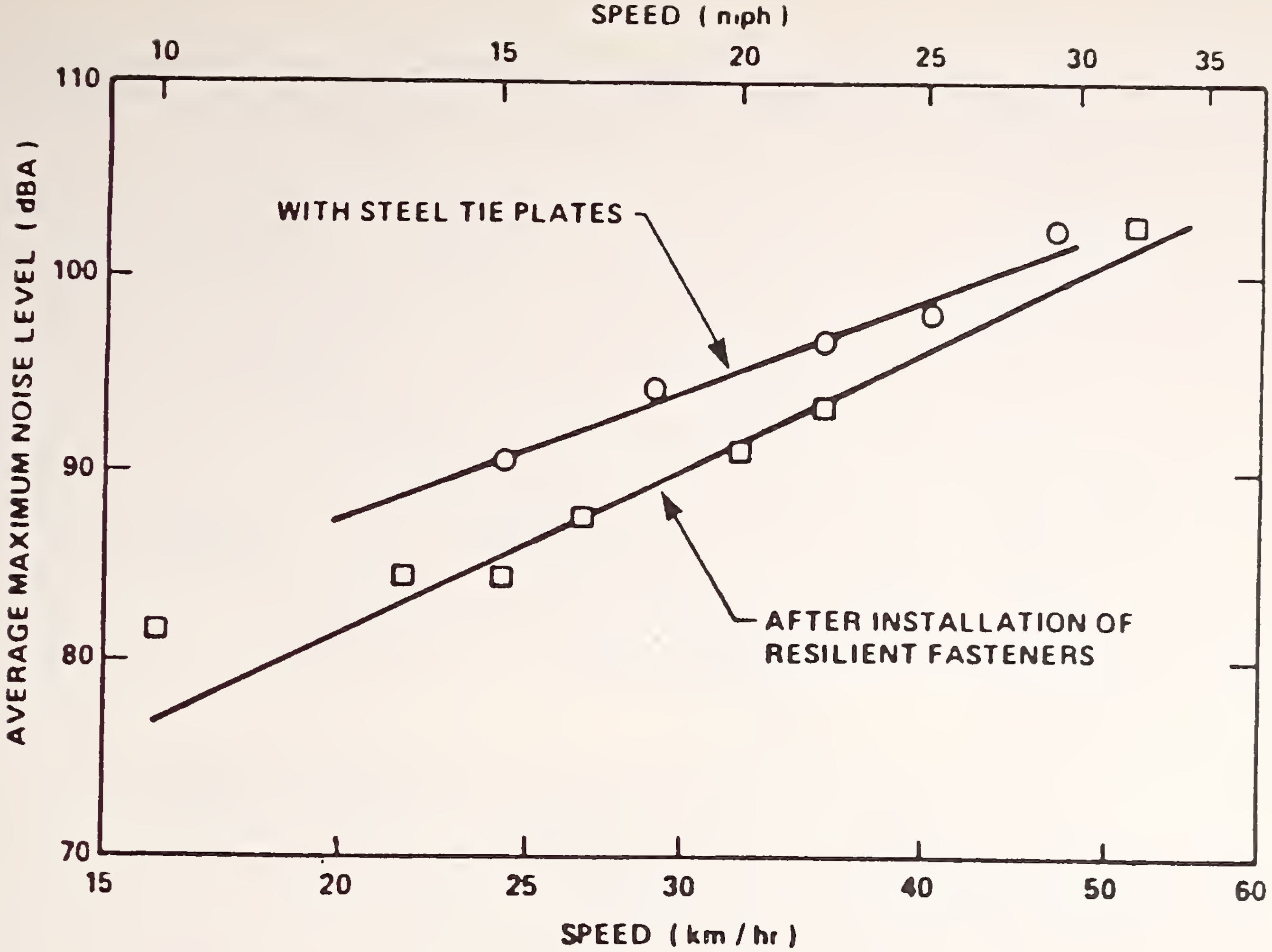


FIGURE 3. EFFECT OF RESILIENT FASTENERS ON WAYSIDE NOISE AT 25 FT FROM NYCTA ELEVATED STRUCTURE

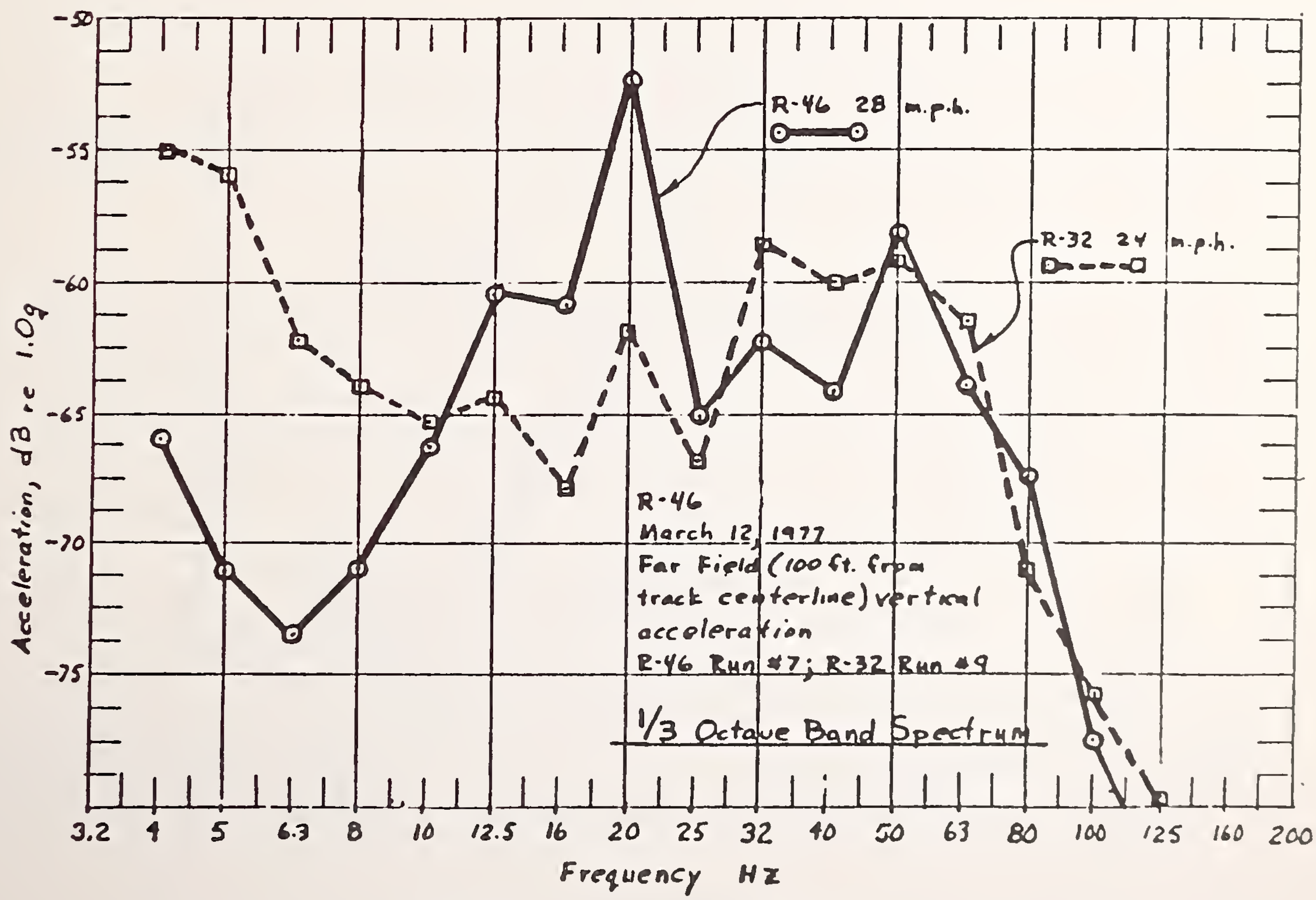
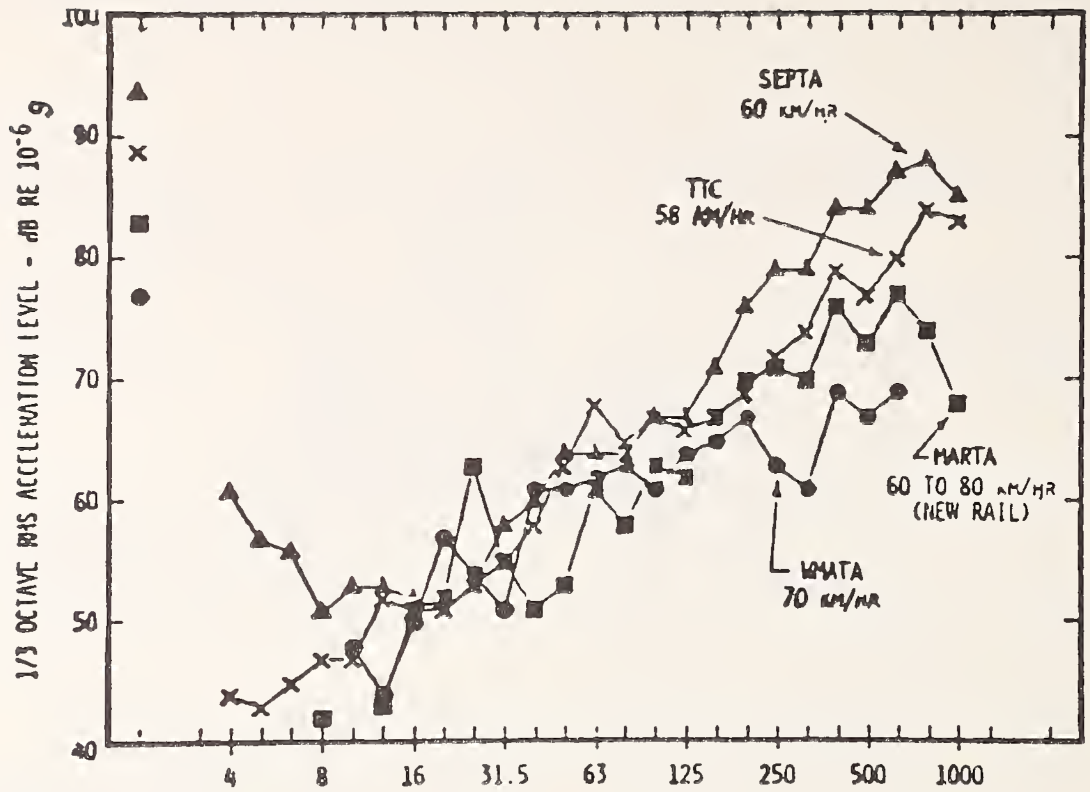


FIGURE 4. SEA BEACH TEST



Courtesy Wilson, Ihrig And Associates 1978

FIGURE 5. INVERT VERTICAL VIBRATION

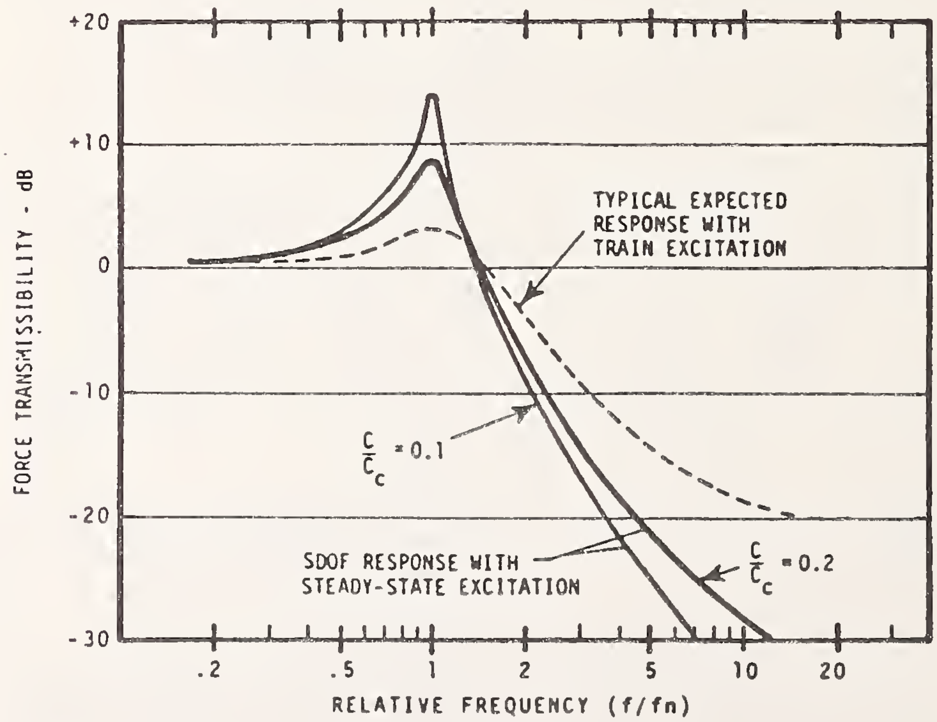


FIGURE 6. TRANSMISSIBILITY OF FLOATING-SLAB VIBRATION ISOLATION SYSTEMS

An "optimum" resilient rail fastener for use on New York's steel elevated structures will be developed and tested during 1984 under a $250,000 grant from UMTA.

New York City has over 60 miles of steel elevated structure generating noise that adversely affects over 250,000 people living, working, or going to school near the elevated structures. A study done by psychologist Dr. Arline Bronzaft [2] showed that the noise of the elevated trains lowered the reading levels of students by one year, compared to the reading level of the students on the quiet side of the school. A follow up study by Dr. Bronzaft [3] showed that the 3 to 5 dB noise reduction we obtained by installing the resilient rail fasteners raised the reading scores of the students to the level of the students on the quiet side of the school. There are 100 public schools, and numerous private schools, hospitals and other noise sensitive neighbors near our elevated structures, which provided the impetus for the Authority to embark on a major program to install resilient rail fasteners on our elevated structures. We have already installed 10 track miles of fasteners and have programmed 40 additional track miles for the next 5 years.

Subway Car Suspension Design

There are two basic types of subway car trucks in service in the United States. The first utilizes either steel coil springs or rubber/metal sandwiches (chevrons) as the primary suspension, characterized by low stiffness, resulting in a natural frequency of less than 10 Hz. The second utilizes a rubber donut around the journal bearing as the primary, characterized by high stiffness, resulting in a natural frequency of 20 Hz or greater.

The rubber donut primary truck, utilized in Washington, Atlanta, Miami, Baltimore, Chicago (some cars), the Long Island Railroad, and which were utilized in the 750 R-46 cars in New York City until the trucks were replaced with soft coil spring trucks, produces ground vibration that propogates long distances and couples well to light-weight wood frame residential buildings, causing perceptible, annoying vibration. Within six months after the R-46 went into service in New York City, we had received over 250 complaints about the vibration.

A number of tests were performed which showed that the R-46 truck produced a distinct component of vibration at 20 Hz, whereas our steel coil spring trucks did not. We also found that most of the complainant's homes had floor and wall resonances, as well as foundation/soil resonances at 20 Hz. Add to this the fact that the tie passage frequency at 25 mph is about 20 Hz, and the conclusion that 20 Hz is a frequency we should avoid in our trucks becomes quite clear. These studies are detailed in a paper [4] I gave at the June 1978 APTA meeting in Chicago.

Figure 4 clearly shows the 20 Hz component of the groundborne vibration generated by the R-46 car.

The question arose, was the 20 Hz vibration peculiar to New York City or did the subway cars in other cities that had stiff primary suspensions also show the 20 Hz vibration component?

Figure 5 compares the ground vibration spectrum of Washington, Atlanta, Philadelphia, and Toronto, and clearly shows the peak near 20 Hz for the Washington and Atlanta vibration, but not the Toronto or Philadelphia vibration.

When a subway car with a stiff primary suspension is operated over a floating slab designed to reduce vibration and groundborne noise, the audible portion of the spectrum above 20 Hz is attenuated, as expected, but the perceptible portion of the spectrum below 30 Hz is amplified because most floating slabs in the United States (NYCTA, WMATA and Baltimore) have a natural frequency of 16-20 Hz. If a force is applied to a spring-mass vibration isolation system at the system's natural frequency, the force is amplified. Figure 6, from the Handbook of Urban Rail Noise and Vibration Control[5], clearly shows this phenomenon.

Other studies that have been made relating to noise, vibration, and wheel-rail forces, support my conclusion that a rapid transit car truck should have a soft (less than 7 Hz) suspension system.

Summary, Conclusion and Recommendation

There is clear evidence that the dynamic properties of rapid transit car suspensions and the track support structures interact to affect the level of noise and vibration. If the dynamic characteristics of each are not carefully designed, unwanted and unexpectedly high levels of noise and vibration, and high loads imparted to the track fastener and structure, may result. Trying to retrofit an entire fleet of subway cars with a soft suspension is not, in my opinion, the way to "run a railroad".

I strongly recommend an interchange of information and greater interaction between the transit structure, track, and vehicle designers, to maximize the life of our equipment and eliminate the noise and vibration impact of our subways. There have already been complaints and lawsuits about the vibration caused by trains in Washington and Atlanta. Let us work to prevent this from happening in Los Angeles, Houston, and anywhere else a new system is being built, new subway cars are being purchased, or old transit systems are being rehabilitated.

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Direct Fixation Fastener Problems and Solutions

Amir N. Hanna
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Construction Technology Laboratories

I would like to begin by presenting a definition of direct fixation fasteners. A direct fixation fastener is a system consisting of steel plates, elastomeric pads, insulating components, and anchoring devices used to directly secure the rail to the underlying concrete slab or steel girder. In other words, in a direct fixation fastening system, no structural element is provided between the fastening system and the slab or girder. Thus, systems utilizing cross ties between the rail and slab, such as the "STEDEF" system, should not be classified as direct fixation fastening systems.

This session deals with direct fixation fastener problems and solutions. Therefore, I would like to review briefly the types of direct fixation fastener problems and outline the actions needed to eliminate them.

Direct fixation fastener problems result from one or more of four primary fastener deficiencies. These are:

1. inability of the fastener to control rail movements,

2. inability of the fastener to withstand traffic loads and environmental effects during its intended service life,

3. inability of the fastener to provide the required electrical insulation,

4. inability of the fastener to provide adequate noise and vibration attenuation.

These problems can be eliminated by the following measures:

1. use of a fastener design compatible with the intended purpose,

2. implementation of a good quality control program during production,

3. use of suitable construction and installation procedures,

4. implementation of an adequate maintenance program.

Generally, fasteners are designed to meet specification requirements. Therefore, specifications should account for anticipated construction, traffic, and environmental conditions. Thus, a fastener design that meets specification requirements will be capable of providing its intended functions. In this regard, I urge UMTA and TSC to embark on a program to develop improved specifications.

It is imperative that production fasteners be of an equal or better quality than those used in design qualification testing. This can be accomplished only if a proper quality control program is implemented and routine production tests are performed during production. Therefore, specifications should establish minimum requirements for an acceptable quality control program and assure its implementation by the producers.

Fastener problems often occur when certain installation procedures are used. These problems can be easily eliminated if installation methods compatible with fastener design are used. Therefore, specifications should outline the installation technique with consideration given to the fastener design. In this case, input may be required from fastener producers.

Tear and wear of fastener components should be expected to occur during the intended service life. Therefore, performance of regular maintenance will help slow fastener deterioration, maintain good track condition, and ensure safety. Therefore, the concept of "install and forget" should be disregarded and a reasonable maintenance program be developed and implemented. Thus, costly repairs are eliminated and safety is assured.

In summary, to reduce or eliminate direct fixation fastener problems, the following four actions are needed:

1. Develop improved specifications.

2. Assure good quality control during production.

3. Utilize suitable construction practices.

4. Implement a reasonable maintenance program.

To accomplish the goal of reduced direct fixation fastener problems, it is necessary that UMTA, TSC, and transit properties initiate a major effort to undertake these proposed actions.

DFF Problems and Potential Solutions

Thomas O'Donnell
Director of Maintenance
Metropolitan Dade County Transportation Administration

Good afternoon. It was interesting to hear Charlie Phillips' comparison of WMATA and BART. When we opened the WMATA Phase 1 system, I felt we had a pretty good system, but that the tighter curves needed more support. This seemed to be proven by the breaking of anchor bolts on the more severe curves. There were just four (4) curves on that line with a radius of about 755 feet. We opened up the other line and we never did get back to Phase 1 to do any work at all while we were busy with Phase 2 and its succeeding phases. If we had had guard rail on the four Phase 1 curves and, of course, they were also lubricated and the few water problems were taken care of, WMATA would have had an operation, in Phase 1, that would have been just as good as BART's.

Many of the things I was going to talk about have already been discussed, so I'll try to pick out a couple of issues that I think are interesting, specifically a couple of problems that came up in Washington. One was the Rhode Island aerial structure. I believe that was the first aerial that had continuous welded rail for almost a mile. Before I got there, before the rail was laid, I think the decision was made to go with an aerial fastener with low longitudinal restraint, mixed with high restraint direct fixation fasteners. The low restraint aerial fasteners were installed approximately 15 feet from the rigid end of the bridge toward the expansion end of the girder. That was the first piece of track I had ever seen with continuous welded rail that didn't have expansion joints. I was quite worried about it, so I checked it constantly. We never had any movement at all with that rail, I checked for eight years, no movement; but we had a lot of problems under the bridge. At every support, the elastomer under the sole plates crushed out. We found many of the sole plates were turned in the wrong direction, which may have contributed somewhat to the crushed elastomer. It is such a massive job to repair those elastomers; I believe they get one a week replaced in good weather. It will be an ongoing job for that method.

I have always wondered if the interaction between the continuous welded rail and the bridge was somehow passed down to the elastomer. We also observed that in the areas of the high restraint fasteners, most of the bolts (the stud bolts going through the grout pad) had so much force put on them that we had to renew all of the grout pads (or a great deal of them, anyway). We found the grout pads badly cracked, so it was an interesting problem as to what actually occurred. As far as I know there is no answer except to go back and renew the grout pads and keep renewing the elastomer bearing pads under the sole plate.

Another problem we had was with guard rail on two curves in Phase 2 (well, actually four curves). The original installation had the guard rail at the same plane as the running rail, but the restraining rail face was 2-5/8" from the gage side of the running rail, which meant the guard rail was not doing any work at all. The wheel was just not hitting the guard rail. That situation continued for about a year and sidewear developed on the high-side running rail. When that happened, of course, the train moved over and the guard rail became effective. It was the funniest thing, you'd really have to see it.

It was as though someone took a chisel and chiseled out part of the top of the running rail. I'm not sure of the time, but I estimate in about nine months, the flange of the wheel was actually riding on top of the restraining rail. I rode to Stadium Armory one day and I felt, in the quality of the ride, this problem occurring. That night we took all the restraining rail out. Fortunately we were able to get Boston's Tom Riley and Bill Bergoli to allow us to bend our rail up here. It has been replaced but we had to do a major retrofit design to do it.

The brace that was designed for the restraining rail was on five foot centers, attached to a Hixson fastener. We found the Hixson fasteners destroyed, so we put new ones in and fabricated some braces with six supports. We used six 7/8 inch tapered bolts to support the guard rail. These were placed in between the original supports to take some of that stress off the Hixson fasteners. We raised the rail 3/4 of an inch and we move it in 1-7/8 inch, so that the guard rail could start functioning properly. We put in a lubricator. One lubricator took care of the four curves and at last report it's doing very well. The rail currently has not worn much and I really don't know whether the wheel flange has made contact with the high rail yet or not. But again, I'm a fan of the guard rail coming from Boston and seeing how it has performed to provide a good safe operation here. I think it's a mistake to try to get along without restraining rail where you need it, and from what I have heard today there is a a need for this type of construction. There is also a need for some criteria to define a minimum radius where guard rail is required.

One other problem that we had in Washington was, as you've already heard, the terrible rail side wear that we experienced. We in maintenance felt that, in addition the the tight gage and the wheels and the trucks and the lack of lubrication, the unbalance (4-1/2 inch unbalance on some of these tight curves) was also a significant factor. So we welded some 100 lb AREA type B rail which gave us an inch more superelevation. In other words, it was an inch lower than the 115 pound rail that we took out. Then we got some templates and installed the Pandrol shoulders, and when they were ready, we put in the rail. We ended up with a superelevation of about 6-1/8 inches. I called Washington Monday and Bill Kiley reports that there is very little wear on the high rail in that area, so I think we did prove that superelevation, or the lack of it, is a real big factor in rail wear. I think I have used enough time, and discussed most of the problems that could be interesting.

DFF Problems and Potential Solutions

Herbert Weinstock, Senior Research Engineer
U.S. Department of Transportation
Transportation Systems Center

During the past few days we have heard a number of interesting discussions on fastener selection, design and testing. The meeting opened with a paper that described the wide variety of fasteners in current use. This paper was followed by a paper from one of the fastener manufacturers who asked a very important question: Why is a fastener used at all? That is, what are the functional requirements of a direct-fixation rail fastener. If I may, I would like to spend a few minutes discussing these questions.

The first requirement of the fastening system is to maintain the position of the rails that support and guide the transit cars. If the connection of the rail is too weak in the lateral direction, the gauge of the track will spread and the wheels will drop. The solution to the problem of supporting the rails in early track construction in tunnels was to extend standard tie and ballast track construction into the tunnels or to anchor wood ties to the foundation without using ballast. With the increased use of concrete slab construction, combined with shortages of wood and availability of resilient fasteners, the designers of track systems concluded that it was inefficient and somewhat awkward to use the tie and ballast construction and started to apply direct fixation techniques. One of the functions of the tie and ballast-type construction or a resilient fastener direct fixation system is the distribution of the concentrated wheel/rail load over a broader area to avoid high stresses in the foundation structure. Even the "tie saver" pad which has relatively little compliance discussed in Len Kurzweil's paper yesterday, does produce some redistribution of the load between the rail and tie to reduce the maximum stress level on the tie leading to an increase in tie life. The fastener system should produce a track that has a uniform track stiffness. If the track stiffness is not uniform, the normal wheel loads of a train (support of the static weight, curving forces) will produce deflections of the rails that will appear to the train as geometric track irregularities that will induce higher wheel loads and vibrations. A sudden change in stiffness of the track will have the same effect as a sharp geometry irregularity producing high impact loads.

As we have noted in the past few days, the resilient fastener is intended to provide a mechanism for not only spreading the concentrated wheel/rail loads over a broader area of foundation but is also desirable for attenuating the level of vibratory force inputs that are transmitted to the foundation. For typical rail and fastener systems, the stiffness variations available to the designer are not typically large enough to reduce the wheel/rail forces significantly (although as I noted before, sudden variations in stiffness can act to increase the forces). However, the introduction of compliance between the rail and the foundation permits the rail, to some degree, to react the force with its own inertia and to distribute the vibratory reaction over a broader length where it can be better dissipated. Some of the fasteners we have been discussing, for example the "Cologne Egg," attempt to increase the effective inertia of the rail. An additional requirement of the fastener is to provide a mechanism for dissipation of the energy associated with the vibratory motions.

The considerations of distributing the concentrated loads over as large an area as possible and attenuating vibratory forces would suggest making the fasteners as soft as possible. This raises the question of how soft can the fastener be without creating other kinds of problems. One issue that must be considered is the lateral restraint required to assure the gauge is maintained within measurable limits to assure safety. The track must have sufficient stiffness to handle the gauge spreading forces produced by trains in negotiating curves. At this point we can bound the forces we can expect in typical transit operations. The papers presented on experimental measurements of wheel/rail forces and fastener forces provide an indication of the order of the forces under typically poor conditions. As I noted in the earlier discussions, in this conference, a lateral wheel/rail force of 85 percent of the vertical wheel load indicates the existence of a dynamics problem that could result in wheel climb and derailment. Generally, lateral forces of 85 percent of the vertical load should not be tolerated and corrective actions should be taken on the system. Therefore, this number serves as a reasonable expected load to use in the design of the track system (before factors of safety are applied). In addition, analysis tools currently under development are near the point where accurate prediction can be made of wheel/rail forces under particular track conditions.

The lateral restraint of the rail fastener system should limit gauge widening to prevent wheel drop and simple geometric considerations can be used to determine how much rail defection can be tolerated. Certainly 1/4" of gauge widening will not produce a problem. In many applications you can probably have the gauge get as wide as 58" without reaching a limiting condition.

Another question that should be formally asked in our design criteria is: How many fasteners should the load be distributed over? The more fasteners that are active in reacting the load, the less chance we have of pulling an anchor bolt out of the concrete foundation and the smaller the foundation stresses.

From a pragmatic standpoint we would like the design to be somewhat forgiving of installation imperfections. An error in installation of 1/16 of an inch should not result in a change in the apparent stiffness of the fastener. In some of the fastener designs we have discussed in the past few days we have drastically non-linear load deflection characteristics where an installation error of the 1/16 of an inch can result in a very large apparent stiffness. This would cause the fastener to carry a disproportionately large share of the load resulting in premature failure. As I mentioned before, the large local stiffness also results in increasing the wheel/rail load, further accelerating the failure process. This effect can be inferred from some of the results in Andy Sluz's presentation.

I think at this point in time we have a good analytic framework. George Wilson has been working on developing parametric studies and tradeoffs for reducing noise and vibration and the influence of the properties of fasteners for 20 years. He has a good data bank that can start to be applied toward developing this tradeoff parametrically, so that we should be able to tell you that if you produce a stiffness of 3,000 pounds per inch per fastener you can expect this level of transmission vibration for this kind of track system. I have tools that will tell you that if you build these kinds of curves or these kinds of track irregularities, this is the force you can expect.

The thing missing is we haven't done a very good job of communicating this design information, or these specification requirements to the track construction engineers with their primary concern where it should be in terms of safety. If I'm responsible for safety in the system, the thing I'm going to specify hardest are things like fatigue life, and lateral restraint of the track. Considerations of the load and vibration attenuation are likely to be secondary considerations. I think we can do a better job of providing some information on what the tradeoffs are between them, and what the options are in terms of fastener parameter specifications and we should be doing some parametric studies using the analysis tools we have, putting the information into a format that the design engineer can use. If I want to buy a shock mount for a motor, shock mount suppliers will give me brochures that tell me exactly how to fit the mount, what the transmissibility is going to be, it'll talk about the applications, it'll tell me if it'll survive 270°, 550°, that I can go down to -60° with it; and it will give me a very thorough education of the tradeoffs and isolator design selection.

That level of information exists. We ought to be producing the same level of information in terms of selection of resilient fasteners and noting that requirements will differ from property to property. Just the weights of the cars will be different, the system will be different, it never rains in some places. The tools are there to put it together.

I'd personally prefer to see field testing to be a bit more selective, so that field tests should be selected for the specific purpose of verifying the analytic models that we're using to make these design extrapolations. Or, where there are preferred designs and we can demonstrate a preferred design, for demonstration testing of a preferred configuration. I think there's enough data at this point to be able to bound the types of environments. Doing a random field testing program of every property in the country will produce a nice bank of data, but I'm not sure that it would be that useful without the analytic framework to go with it. With the analytic framework and targeted test applications, I think we can do a great deal to provide some confidence.

When we're dealing with lab testing, if we're running off a competition between fasteners having different load deflection characteristics and different properties, the single fastener test is the wrong one to use. You have to build a rig that does, in fact, simulate the load application from the rail to the fastener system because if you have a soft fastener in competition with a stiff fastener, in a single fastener test, the stiff fastener is going to win. It might lose if it was a bank of fasteners applied through a rail where the load is being shared by five or six fasteners. And in all cases, the test should represent the simulation of the kind of railroading conditions that you expect to occur. Or, it should represent, in some sense, a bound on these conditions. If we want the fastener to be soft, we'd better make sure that our test procedure guarantees that it is soft.

Summarizing, I'd say that a good deal of information currently exists. What we really need to do is to put it together in a form that can be applied by the industry with a bit of emphasis on getting the analytic framework, getting the parametric design information into the field, complemented by some targeted field testing. The government does have numbers of tools that can be used for this purpose. I think the manufacturers have a very significant role and do have an important responsibility in educating people in terms of what the tradeoffs are and the basic design tradeoffs.

DFF Problems and Potential Solutions

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Herb has touched on many of the areas of the principal thing I want to address, which is the problem of designing or specifying and designing a rail fastener, which is supposed to do these two things: (1) fix the rail in a safe and durable manner; and (2) reduce the noise and vibration (hopefully, as much as we can get).

One of the areas that we have to be very careful of is the interpretation of the data that we get from these various test programs. Much of it, unfortunately, turns out to be specific to the system on which you're doing the test. I think one of the best examples I have of that was back in the days of developing the specification for the BART fastener. We relied on a series of tests that were done at the BART test track. Those tests showed that there wasn't much difference in the ground vibration, no matter what the stiffness of the fastener was. This was pretty conclusive. We had four or five different fasteners, maybe it was six, and a lot of tests, and they all came out about the same. So, as you may have noticed on one of the charts here today, that there was no vertical load specified on the BART fastener, the original BART fastener. That's because there was no vertical stiffness specified because we had concluded as long as you had a resilient fastener, that was all you needed and you were going to get a satisfactory result as far as ground-borne vibration was concerned.

It turned out that all of those tests were run with a vehicle that had resilient wheels that were so soft they swamped out any effect you could have ever created with a rail fastener. They were like a super resilient PCC wheel; they had far more static deflection than any of the rail fasteners, so that it was a totally invalid test for what was being represented, or what was supposed to have been tested. One has to be very careful in interpreting test results that they really are not specific to some crazy parameter that you didn't think of when you set up the test.

Another point that we have to watch out for is trying to standardize and using the "one size fits all" concept. We used to think you could do that with floating slabs, but, as we learned more and more, we find out that a floating slab that's designed and works beautifully in Toronto doesn't work well in Atlanta. In fact, it can make the problem worse. The same thing applies to rail fasteners. It's quite possible that a rail fastener could be designed to completely inappropriate stiffness for a specific system when you consider the whole system: the vehicle, the track support, the subway structure, the grounds that the subway structure is in, and the building that's the neighbor of the subway.

In the early analysis of the Washington Metro system, BBN derived a theoretical performance set of curves for soft rail fasteners and the way it turned out, if it had been possible at the time to build a fastener of the softness they recommended, the ground vibration in Washington would be worse than it is because the frequency range that turned out to be important in Washington was one in which a particularly soft fastener, if their theory is correct would have amplified the ground vibration, not reduced it.

This can happen in various ways. The design of the fastener or of a full resilient track support system has to take the whole dynamic system into account. Let me give you an example of some of the things that I think need to be considered. We've all heard Tony Paolillo talk about the parameter of the truck primary suspension stiffness, and that it has a strong effect on ground vibration. There's another factor which I've become aware of relatively recently because the new UTDC small vehicle, the linear induction motor vehicle, is a vehicle with a very light wheel and axle set. Tiny wheels, hollow axles, very light assembly with no motor and no gear box hanging on the axle, resulting in low ground vibration, even with a rough rail. The wheel and axle set appeared to have a tremendous influence on the ground vibration so I started thinking about this. BART has hollow axles and aluminum wheels; we don't hear about ground vibration complaints at BART. They may be there, but there are not enough that we hear about it.

We do hear things like, there's small wear, the wheel sets last a long time; the rail doesn't have much wear; and the ground forces are apparently less. CTA has aluminum wheels, they last a long time. The inertia of the wheel and axle set, I think, is having an effect. MARTA and Washington Metro have solid steel wheels and heavy wheel and axle sets and they're having wear problems and ground vibration problems. So, it's not just the stiff truck, I don't think. I think you have to get down a little finer than saying that the parameter we need to look at is the resonance frequency of the primary suspension in the truck. Also, we have to look at the wheel and axle set mass in deriving what's going to happen in terms of ground vibration.

What I'm getting around to is that in designing a rail fastener, it's not just an isolated component in a system. You need to look at the whole system and make a system design approach. It doesn't just hold the rail there and provide some vibration reduction. It has other effects and there are many other things such as the weight of the vehicle, for example, or the load that the vehicle may apply on the rail that should be taken into account.

Bob Gildenston mentioned that we ought to be having some noise and vibration criteria in the fastener specifications. Well, that's a very difficult problem. About all we can do there is to do it indirectly. You can't go to a laboratory and measure what noise and vibration reduction a fastener's going to have, but you can specify a stiffness, both vertically and in the horizontal directions: laterally and longitudinally, and that is what I want to address.

When we design a vibration isolation system for a machine, we always say that the horizontal stiffness is going to be somewhere between about .8 of the vertical stiffness and 1.2 of the vertical stiffness, so that we get the same vibration isolation for horizontal motions as for vertical. Well, nobody's ever done that, including me, for a rail fastener, but that's the sort of thing we should be considering and we've heard a lot of discussion about the lateral stiffness and its effects. A fastener softer laterally would allow spreading the load out. Apparently the stiffness we're specifying now is so great that we aren't even transferring the load between fasteners; all the lateral load is going into practically just the one fastener right by the application point. But we know in the vertical direction it's spreading out.

One of the things to consider when reviewing criteria for fasteners is that soft elastomers are very forgiving. Herb mentioned the problem of tolerance.

If you have a softer elastomer in the system, you don't have to worry so much about getting it within a millimeter of 1/16" of the right vertical alignment. The elastomer will creep to equalize loading so that small errors don't really matter. By using a softer fastener, which some advocate, we would eliminate a lot of the problem of the precision or tolerance which the fastener has to be located in order to avoid one fastener being heavily loaded and the adjacent one being lightly loaded.

It was also mentioned that the dynamic to static ratio has been added in recent specifications, and this is a very important factor, because with natural rubber, you can get a dynamic to static ratio as low as 1.2 where as neoprene has a higher ratio, 2.0 to 2.5. Well, that means you could get equivalent performance to a very soft neoprene fastener with a very stiff natural rubber fastener. So there you've got the rail being held by a very statically stiff fastener, but you're getting the noise and vibration by virtue of having a low dynamic to static ratio, which is very difficult to get with neoprene.

It was mentioned that vehicle engine mounts use natural rubber. General Motors buses with a diesel engine in a small compartment in back where there is such a horrible environment that many times they leave the doors open because the engine can't get enough cool ingain. Those are natural rubber mounts which are drenched with diesel fuel and fumes, I imagine, and a lot of heat and I'm sure General Motors doesn't use a mount that lasts only a few thousand miles. Natural rubber is a good engineering material. It has better mechanical properties than neoprene. Dupont has done a real selling job on neoprene and a real put-down on natural rubber over the years and it took a long time to learn about natural rubber, but it is a very good material and these oil tests that we have in the specifications are really giving a lot of trouble. We eliminated the oil tests from the floating slab specifications many years ago, because the floating slab rubber pads are under a concrete slab where oil can't get to them.

On a couple of occasions I've tried to find out what No. 1 oil and what No. 3 oil really represent. Are they brake fluid? Are they diesel oil? Are they gear box? Nobody seems to be able to tell me. The ASTM spec gives a very eloquent description of what they are in millipoises, and so forth, but what they are in terms of a transit system I don't know. I think we really need to either just eliminate the oil tests, since they've been there as far as I can tell because of historical precedent, or really find out if they're applicable to a rail fastener; because they're limiting the ability to specify an elastomer that would do a better job.

I'd just like to close by saying I think we really need to apply system design approach to rail fasteners for use as direct fixation devices in rail transit systems.

Palmer: It's not clear to me whether the tests are supposed to test the design of the fastener or your quality control instrument. My understanding is that the standards you deal with in quality control really can be handled through some kind of testing process, such as the dynamic-static test. Maybe I'm wrong, but could you comment on that?

Hanna: What I described yesterday were the qualifications of the design. However, I would say that the majority of specifications have quality control tests in addition to the design qualifications; though not to the same extent as the design test. At least they will give an indication as to whether the production fastener is more or less close to the ones tested for the design purposes.

Palmer: Are they tested in the same manner?

Hanna: Not to the same extent, no. Those tests that are repeated, are tested in the same manner.

Palmer: If you have established that the design does the job it's supposed to do, and then you run the quality control tests, could the quality control be more effectively handled through testing the quality of the workmanship rather than putting it through the same kind of test that's being applied for the design? It would seem that you have two different objectives and you should have two different approaches.

Hanna: Well, one thing you should realize, the possible changes during production of first dimensional tolerances, for example. It would have an effect on the performance. Secondly, tolerances in the quality of the material itself, and again, I believe that in elastomeric material you could get quite a range of variation within the material, and I think it is important to have the production tests to be correlated to the design tests. What I gather from what you said, you would like to eliminate the design tests and maintain only the production tests?

Palmer: No. What I'm saying is that the types of test you mention are, in my estimation, design type tests.

Hanna: Correct.

Palmer: Really, you're trying to see whether the design of the thing works under the loads you're going to apply. But when you get into the production of the actual fastening system, I don't understand why the quality control couldn't be done by some other method, such as a sampling of the elastomer to see whether it has the basic properties required by the design, or that the quality of the welding, or other materials employed are adequate.

Hanna: Well, I'd say it's been done in both ways, just to be on the safe side.

Wilson: The only way you can test or determine that an elastomer is being built according to the specification is to test the completed device for spring constant and that sort of thing. There is no sampling way you can do it. Cutting out a little piece of rubber and testing it just doesn't work. You have to test the complete and entire device for stiffness. And when you do that, you're testing the quality of the elastomer, the quality of the cure, and a number of things by that means. And it's not a very difficult test. It's done very quickly in an automatic machine.

McEwen: I think you'd have to qualify it also. Whatever is appropriate for that material. But for an A325 bolt you don't have to develop the whole assembly and run it through the whole gamut of tests to confirm it's a 325 bolt.

You've got to be attuned to the specific item you're talking about and the production element may be tested in some form similar to the original qualification test, or some other appropriate test.

Laurien: I think the thing you're talking about is already being accomplished, because in the specifications for purchasing of the fastener in our own case we have the qualification test. There is a production test of the completed fastener, but there is also a requirement of the manufacturer to have configuration control and quality control of his components and inspection during manufacture with the right of the customer to come in at any time and check those records. And it is there in both forms.

Hixson: Dr. Wilson, in your experience with elastomers, is there any particular elastomer that has a better ability to absorb noise?

Wilson: Different elastomers have different applications. For these rail applications, it seems because of the conflicting requirements between noise and vibration reduction and fixing the rail, what you want to do is get an elastomer that has the minimum dynamic to static stiffness ratio to give the best static control of the rail that you can have and at the same time give the noise and vibration reduction you'd like. So I think that's the parameter you want to look at. Of course, you need adequate strength and durability of the elastomer also, but from the noise and vibration standpoint and the rail stability standpoint minimizing the dynamic-to-static stiffness is the desirable property.

Weinstock: George, any benefit to historesis on the material?

Wilson: The problem with historesis in the material is that it increases the dynamic stiffness very rapidly, and so that's a conflicting requirement. You know butyl rubbers and things like that are highly damping, i.e., provide a high degree of damping, but that's at conflict with what you'd like to do. Now, that will work in the kind of situation that Dr. Kurtzweil was describing yesterday, for the special case of the steel aerial structure. I don't think it works for subway fasteners.

Lovejoy: You're stating that the BART design was invalid because you tested a car with resilient wheels. That suggests that a property that can use resilient wheels perhaps should have a different fastener, backend or design, than one that doesn't?

Wilson: They should certainly be coordinated. But, there is no blanket answer to that question. What I'm saying is that you have to coordinate the requirements so that you don't wind up with a two degree of freedom system that's got a big high resonant peak in it such as the Rockwell truck in New York (for the particular set of dynamic stiffness parameters). No, there aren't any resilient wheels around that are similar to the ones at the BART test track. Those were extremely soft. The only comparable thing is a PCC super-resilient wheel, and I don't think we're going to see anything like that in the foreseeable future; that was an extreme case. The general answer is that the two properties must be coordinated and properly handled, not as independent pieces that are to be put together sometime five years down the road, and something happens and we wonder what went wrong.

Bharadwaja: Can any one of you -- I'm giving you an open option rather than asking it as a question -- give me an answer to the uplift forces that the anchor bolts in our direct fixation fasteners have seen or will see, and what solutions can any of you think of for research or development to work on that? I think that has been one of the problems on our anchor bolts for direct fixation systems.

In the first session I also asked, but I would like someone to answer, how that bonding gives us a triple protection against uplift? That's what Mr. Gildenston said yesterday, so I would like that also to be answered by one of you.

Wilson: Well, the uplift on the bolts is a fatigue problem. The early TTC installations didn't have the spring washers, and they broke a lot of anchor bolts. TTC put in the spring washers so that the high alternating force was not applied to the anchor bolt, and they stopped breaking. They've had a successful installation for many years. The use of the very high strength bolts for the bonded fasteners is supposed to take care of that. It seems to work at BART; there weren't a large number of bolt failures. I think it's a matter of avoiding alternating stress in the anchor bolt, because the alternating stress is the one that fatigues the bolt and causes it to fail. If your design incorporates an appropriate means, whether it be unbonded or bonded fasteners, to make sure that bolt sees primarily a static load, then it's not going to break.

Bharadwaja: How will it see a static load when you have that spring rail in your neoprene? Mr. O'Donnell, in the Washington rivet failures was there an indication that they had repeat failures in spite of having a bonded fastener?

O'Donnell: The special work was unbonded and the only breaking problems we had were in the high radius curves. The only bolt breaking problems on the special work was when the nut was tightened down on that coil spring, and took the protection away. We didn't have any broken bolts on the special work until we tried to hold the special work by tightening the bolt, and of course, when they did break, we stopped it. But we felt that the breaking on the high radius curves was from lateral loads.

Wilson: And how did the lateral loads get to the bolt?

O'Donnell: I was told that the Landis fastener in Washington was built to transfer the stresses to those bolts.

Wilson: To the anchor bolts instead of to the bottom plates?

O'Donnell: Yes.

Reynolds: By the same token, that failure of the rivet while in the Hixson fastener in Washington, I think is due to the fact that there is nothing in there to relieve the uplift force, such as the double bore washer that your Toronto fastener has and that Dr. Wilson is referring to.

Gildenston: Of the instrumented testing in Washington, is there any way they could look at the uplift forces?

Lohrmann: It showed just very minimal deflection in the upward direction.

Wilson: I think it was like 1/10th or 1/20th of the positive load. It was very small.

Gildenston: How many pounds might be involved in this -- pulling out the bolt?

Wright: Well, I don't really remember the exact magnitude, but they would be on the order of the same ratio as the deflection, particularly on the part that Mr. Lohrmann's paper put it. Perhaps a tenth or an eighth of the downward force.

Weinstock: You're talking about five to eight kips as a downward force on each fastener, so you're probably talking about something less than a kip.

Wilson: It's very small.

Gildenston: I think there might be one point here in which you describe the loading; again, you have to have the spring or some spring element -- whether it be a rubber washer, donut or whatever -- on the top of the top plate to give a uniform loading to the anchor bolt. If it's a sharp jolt being transmitted directly from the top plate, through the anchorage assembly, then even though it may only be one kip, you may fail that very rapidly. It's that uniform loading through either a spring or an elastomer that smooths out the application of the load. The amount of deformation of the upward movement of the plate is basically very minimal, but it is there, gives away at the rail...

Wilson: If your anchor bolt is tightened down to where it's very close to the fatigue limit of the steel in the bolt, and the train comes along and puts another kip on there and takes it over the limit, it's going to break it.

Question: So, is it tensile fatigue failures, or combined bending and fatigue.

Lohrmann: The WMATA experience, the laboratory testing, that was done on Landis bolts or on the fasteners that had broken was that it was a bending fatigue. And it was by the laboratories.

Weinstock: Which meant it was done by the lateral loads.

Lohrmann: Unfortunately, we don't have any cross-sectional views of the fasteners used in Washington here propped up on the wall, but I would say that in almost all the fasteners there is an elastomer component between the top of the top plate and then whatever washer or whatever is on top of the anchor bolt or the welded starter, to get some -- it isn't a direct bang into the top of that washer, there is some giving there.

Weinstock: All of these fasteners have had high lateral load environments on them that were taken by the anchor bolts finally. And, that will start to work -- the concrete, and encourage what might look like pull-up.

Wilson: You see the design of the original BART Landis fastener does not do that. It doesn't transfer the lateral load to the anchor bolt. It's these later designs that have the nylon inserts that transfer it to the anchor bolts.

Weinstock: As long as you are not trying to stiffen it up.

Lohrmann: Somebody said the design forced a direct lateral contact.

Well, while it goes back to this lateral deflection test requirement, where the fastener had to meet the overturning moments of the lateral load test, it just about had to make very little clearance between the nylon insulator and the top steel plate to keep the lateral deflection down to a minimum, to pass this lateral load/deflection requirement.

Weinstock: That was brought about by not specifying a maximum stiffness. What you've effectively done is specified a minimum stiffness at a particular load point.

Wilson: What you've described, Mr. Lohrmann, is a design solution for doing it; it's not the only way to do it, and as it's turned out, it's an unfortunate selection of a design procedure for doing it. I think one of the best examples of how that was unfortunate, in terms of noise and vibration is that if you take a TTC fastener and don't make any changes in it but double the thickness in the rubber pads, which cuts the stiffness approximately in half, maybe a little less than that, you get a nice reduction in ground vibration, three or four decibels. This has been demonstrated a number of times in Toronto. On the Bart fastener, where the soft fastener in Bart is one-fourth the stiffness of the standard fastener, but which has these little nylon inserts which make it very stiff laterally, you don't get any ground vibration reduction at all with that softer vertical fastener. It depends on how you get the lateral stiffness, as to whether or not the fastener is an effective vibration isolator, and that's one of the things that we need to figure out a way to handle.

Gildenston: That has been restricted to the manufacturers by the design, the call out of criteria within the specifications.

Question: Let's pursue that same question. How would we estimate that uplift is, someone says, 1/10th, 1/8th, and so on.

Weinstock: Yes, we could estimate it from the force on the rail and from the stiffness characteristics of the fasteners and you will find that the uplift is a small number compared to the typical pre-load number for bolts. It is predictable.

Bharadwaja: If it is predictable, and it is a small number, is there any analytical or any other knowledge that any of you could give us. If you put that in some form of specification. In Miami, we had to go with a so-called vertical uplift resistance range just under the insulator and in the top plate but we did not exactly know what amount we needed.

Weinstock: The analytical tools for doing that exist.

Wilson: It's very easy. Calculate the deflection of the rail, as a resiliently supported beam with continuous resilient support, you can get this uplift pretty accurate.

Hanna: It's roughly ten percent.

Weinstock: If you like, we do have a computer program sitting on a local DEC 10 that will take this and break it up into the individual restraints so we could talk about the fastener, we could also include several piecewise linear steps that could include fancier curves if we knew what the curves ought to be. But the tools are fairly good. The beam on elastic foundation, if you know that fasteners are uniform, will work very well. The place that I'm more concerned about the analysis, is the place where we do not have the uniform installations and you have a fairly stiff pad, or you're talking about a dimension that is three-eighth's of an inch, and you have an installation process that has a tolerance of three-eighths of an inch. So, in that case, or when you're talking about a stiff system and where tolerance variations could be significant, then this kind of model becomes effective in that it now tells you the kind of track irregularity that you will see, as an input to a vehicle to influence what the dynamic forces on the system are going to be.

Wilson: We've developed a similar program for our computer because of questions people have raised about deflections of floating slabs, and what's the stress in a rail, if you put it on a floating slab. It can be done. It's very straightforward.

Quigley: Justifiably, in the past manufacturers have been, in effect, forced to design anchorage inserts that are compatible with direct fixation fastener systems, which is the right thing; having to do something specifically for the industry, rather than having to rely on concrete wall inserts, atomic installation, earthquake inserts, and things like this. However, we continue to spend your money on coming up with designs that will withstand 20 and 40 thousand pound pull-out forces, and really not addressing to this lateral load specification. Maybe things have gotten off a little in the wrong direction. Is this correct?

Weinstock: I have a concern that some of the preloads that have been asked for may have gotten a little bit too high. One thing you do want the preload for is to maintain the friction surface between the base plate and the concrete so that you're not going to have slipping, but I don't think you're talking about the levels of torque on the anchor bolts that are being applied now as being reasonable.

Gildenston: If you look at the test being performed for the anchorage as a separate item, then you'll say, well, I'll be able to run out and apply 20 thousand pounds unrestrained to an anchor insert and test it that way, or 40 thousand pounds restrained; well, if you take that and multiply it by let's say, 4, and equate two fasteners, then actually lay those fasteners over those anchor inserts, put a rail on top and pull upward 4 times 40 thousand pounds, you're going to destroy the fastener before you even get close to that type of upward lift. And I have echoed what he's saying, that we've gotten a little bit out of balance checking those anchor inserts in that particular mode, say the uplift mode. We're applying force levels that the fastener could not impart to anchor insert -- it's impossible, the fastener would fail first. Dr. Weinstock says we have to start getting the generalists to look at these footprints and the overall system, because sometimes we've gotten out of balance, and need the generalist that looks at the entire system constantly, to reevaluate and evaluate some of these tests and the criteria they follow.

Raab: This question to me seems like it's nibbling around the advantage of performance specifications as opposed to design specifications. I don't know whether we really exhausted that topic yesterday, and as I've said since we're nibbling around the edges, does anyone want to say anything more on the pros and cons of either or both of those kinds of specifications?

McEwen: I'd like to share a comment that Dr. Hanna and I talked about yesterday, and I think what it comes down to is we need to agree upon some basic standardized forms of tests that are able to be utilized for all types of applications so that we can all agree on the answers. Right now we have too many different types of tests on which we don't agree on the results of the answers! I think Bob's concerned about 40 thousand pounds uplift not being a realistic test.

Raab: Now, once again those tests might be designed in order to see whether or not you are meeting the design specifications or they could be to see whether or not you are meeting the expected performance intended for the unit being procured.

McEwen: I think that we have to look down far enough and to the ultimate intent. We're trying to meet performance. The individual element is a step in that direction, that's all.

Weinstock: Yes, but one of the things we have to do is define performance, we have to get a performance definition down. Once the performance definition is down, the rational test starts to fall out of it, in terms of the key parameters that influence performance. If we try to home in too fast on the uniform test, or the standard test, we're going to run the risk of the student spending all of his time learning how to pass the quizzes. And not worrying about whether it does its job, and I think that may be one of the places that the WMATA specification broke down.

Hanna: I would like to comment what Mr. McEwen and Dr. Weinstock agree on is what we're looking for is the performance test which will simulate track reality, and that is what, I think will probably satisfy almost everybody.

McEwen: I'm not saying it won't, even with this kind of specification that has been written. I think we're all hearing of examples of inserts pulling out of the invert, even so. What I'm saying is, properly done, the specifications can be met, and this gives you a good safety factor to account for some of the lousy workmanship that you get in the deal.

Sluz: I don't think that that's what it shows, because after all, the fasteners and anchorages do pass these tests, and there is quality control exercised in the way the track is constructed. I think what it shows is that the basic failure mechanism that is being tested for in the specification, is different from the actual mechanism of failure.

Weinstock: I might also speculate that some of the anchorage requirements have contributed to the pull-out, so that pre-loading the thing down, you may even be starting to fail things.

Hampton: A lot of this discussion seems to be talking about research. Then the comments about specifications, and I assume we're talking about procurement specifications. A lot of these variables are discovered after the fact. There is always a desire by the designer to do all this and then evaluate what he's got, just to purchase these things. Most of our design research has got to go before purchase so that you can come up with some parameters that a designer can pick from. I don't see that one property or another when they are installing fasteners like this onto concrete, have got many particular variables in their own systems. What you are discussing needs to be simplified a little more before it can be used generally.

Weinstock: Now, my contention is that we have not done a good enough job disseminating and formatting the design information to the industry, and again I blame me, I blame Dr. Wilson, I blame the manufacturers, and we should be starting to do a better job of getting that information into the format, and stating what it is we know, and what it is we have and what we feel the trade-offs are.

Wilson: Many of these things we didn't know about until these new capital facilities were put in at great cost, and then, we find out about it.

Dunn: I'd like to discuss the oil selection tests that's been in the specifications since the beginning of time. They obviously were not put in there because anyone thought there was going to be a rash of accidents that involve someplace getting flooded with boiling oil, or any more than the heat agent test at 70 hours at 100 degrees Celsius represents the real environment here. They were put in there to assure a certain quality of elastomer that will give long life and all of the other virtues desired of a good elastomer. If we delete that (and certainly with all of the discussion here that proposition is worthy of being investigated); but if we delete that, is it not possible that in order to assure an elastomer of the same quality, be it natural rubber or neoprene or whatever, we may have to put in twelve new tests, take out this one, and put in three, six, ten, twelve new ones?

Wilson: Well, I don't think that's true because for one thing, we may have these oil tests because a certain elastomer manufacturer convinced people that that was the appropriate thing to do, because neoprene will pass those tests and natural rubber won't.

Dunn: Natural rubber representatives from Gates, Goodyear, Firestone, and Goodrich all said they could meet that test.

Wilson: They can't.

Gildenston: I have to support what Ron says at that time, and he said they could.

Wilson: Well, maybe they thought they could, but...

Anon.: That's the difference.

Gildenston: I would like to point out that there has been a recent application of natural rubber used for the primary suspension of the EMD locomotive. Now I can't think of anything that would be closer to the transit environment. If natural rubber will hold up on an EMD locomotive, it will hold up in transit track.

Dunn: It may hold up, but that's not the point. If we simply delete this specification and that allows the use of natural rubber, it might also allow the use of very cheap synthetic elastomers that can't withstand the environment.

Reynolds: If you put the tensile requirement up by 50% to 3000 for instance, nothing but natural rubber will pass it.

Anon.: The other possibility is testing the whole assembly.

Anon.: ...or lowering the temperature to a more reasonable level.

Anon.: That would allow other synthetics that would still provide oil resistance and ozone resistance.

Anon.: The point is that natural rubber is by far cheaper than neoprene.

Anon.: There is some basis for the boiling in oil test because it simulates aging. However, they are not testing the fastener as a whole but elastomer specimens that are not totally exposed. It may not be appropriate to throw the entire test out, but to make it more realistic.

Gildenston: When we did a survey for New York on developing fasteners for their elevated structures, the issue of the oil used in lubricating restraining rails on curves and ethylene glycol for de-icing came up. Maybe tests of these substances would make more sense than boiling in oil. We should do a survey to determine what kind of materials fasteners are exposed to.

Wilson: One of the features of the floating slab elastomer specification was that the water absorption test was to be performed on the intact elastomer pad, not an ASTM test strip. That worked pretty well, but later on it was changed to an elastomeric test strip when we eliminated many of the synthetics from use.

Gildenston: What we should be doing is determining whether we have a quality natural rubber or a quality neoprene or whatever it is we are testing.

Dunn: Then you would need a specific test for each separate material or specify the material, tying the manufacturer's hands.

Question: What about the durometer-hardness test, is that obsolete?

Wilson: No, it's in there; it's a measure of the quality of the compound. The quality and stiffness of the material tested is dependent on the durometer value. If you get a very hard rubber, it has a lot of things dumped into it that aren't rubber. A very soft rubber has to be primarily the elastomer that you're after, with high tensile strength and more elongation before break. Also the softer durometer rubber gives us better noise reduction within a given envelope of space. Generally all the floating slab compounds are 45 or 50 durometer. Older ones, such as the BART fastener are 60 or 70, but that had no stiffness specification. It had to meet a fatigue test and a lateral deflection test and that was all.

Anon.: Are the dymanic-to-static stiffness ratio and durometer hardness specified at the same time? Can they be in conflict with each other?

Gildenston: The dynamic-to-static stiffness ratio is a measure of the properties of the material itself, the durometer is more a measure of the surface hardness of the material.

Ortwein: The durometer hardness is a function of the dynamic-to-static stiffness. Also, besides boiling in oil, the flame spray test eliminates the potential use of natural rubber. These two tests must be eliminated if the benefits of natural rubber are to be utilized in fasteners.

Wilson: We have experience in North America that says the fastener does not have to be flame proof. We had that terrible fire in Toronto and the experience that we all heard about yesterday at BART. In neither case were the fasteners damaged. In BART they estimated that the fastener temperatures didn't exceed 250°F.

Ortwein: We have a problem in this market because we don't like to use neoprene. It's not a problem in the manufacturer, but we feel our fastener is a better fastener with natural rubber.

Gildenston: Weren't there some tests performed that showed that there was less exposure to ozone in a subway then at ground?

Wilson: Around 1971 we did four tests in three different cities. We left rubber test strips in the subways for six months. After analysis in England it was determined that they had less exposure to ozone than could have been expected at street level.

DiMasi: I would like to throw out a couple of ideas concerning the testing of fasteners. First after performing the repeated loading test, it might be a good idea to non-destructively evaluate the fastener with, say, ultrasonics to determine if there has been any damage. Certainly this would be more thorough than just visual inspection.

The current WMATA specification contains what is called a "stability" requirement, which says that the stability of the fastener in any direction must be maintained. I believe this means that the fastener must have some fail-safe captivation device in case of bond failure. This must be worded more carefully.

Keffler: There is a section of the specification that we wrote in 1969 which says "... the stability of the fastener must not depend on the elastomeric bond alone ..." (or words to that effect). This was intended to provide some mechanical captivation of the top plate in case of elastomeric bond failure. However since that time we've observed very few bond failures.

Question: How do you view the Clouth (Cologne Egg) fastener, which has no mechanical captivation; i.e., if the bond became unglued, the top plate could pop out.

Keffler: That's true, but we've never really seen any elastomer failures.

Wilson: We've seen only metal failures.

Keffler: The worst we've seen is the top plate sometimes corroding and the elastomer coming apart, although firmly bonded to a layer of rust.

Anon.: That's a quality control problem.

Weinstock: Is anyone prepared to write a new performance specification?

Wilson: Well, we are doing it; we will have to do it in the future and this conference is a marvelous opportunity to exchange ideas. Maybe it will be the catalyst to lead to a new generation of fastener specifications.

Keffler: We have been waiting since the TSC tests were completed for the data to use in generating a new specification and now we are in the process of doing it.

Ortwein: The only test done on our fasteners in Germany is the repeated load test (both vertical and horizontal simultaneously) for 3M cycles, 2.5M cycles at normal (room temperature), 700K cycles at 70°C, and 300K cycles at -25°C.

Question: Can we have some comments on the desirability of horizontal and vertical adjustment of the fasteners?

Wilson: There are many successful applications of DFF's without any adjustment capability.

Weinstock: If you've had some wear or your gauge has widened, then there would be a need to adjust the fastener gauge.

Anon.: That's the logic, but in the real world does anyone ever touch that rail once it's in.

Sluz: There are some unforeseen occurrences, such as the floating slab problems they had in WMATA where they had to shim the rail 1/2 inch vertically. Also, since rail does not wear evenly, it may be useful to have the capability of adjusting a portion of it to eliminate the need for replacing or transposing only a segment.

In some cases the adjustability can cause the problems as documented in the TSC survey report which Mr. Witkiewicz talked about yesterday.

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