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EPOXY STRIPING FOR IMPROVED DURABILITY

February 1978

Final Report

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Prepared for

FEDERAL HIGHWAY ADMINISTRATION

Offices of Research & Development

Washington, D. C. 20590

FOREWORD

This report should be especially of interest to individuals associated with highway lane delineation. However, it may have a broader spectrum of interest among individuals dealing with epoxies, urethanes and paints.

It presents formulations for a series of two component, fast curing, solvent-free epoxy and urethane striping materials for highway lane delineation. In addition, it describes laboratory and field evaluations of the performance, including durability, of such materials as compared to that of alkyd or thermoplastic striping paints.

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Charles F. Scheffey

NOTICE

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16. Abstract

A new series of fast-curing, solvent-free epoxy and urethane compounds for traffic lane markings of improved durability were developed in the laboratory and limited field tested. Of this series, three epoxy formulations (E-3, E-10, and E-26) gave, compared to alkyd-based and thermoplastic striping materials, excellent visibility and durability on either aged or fresh portland cement concrete and bituminous surfaces in film thicknesses from 7 to 60 mils.

These three epoxies were two-component, solvent-free systems with no track times of less than three minutes on ambient roadway surfaces starting with safe and relatively low mixture temperatures of 70 to 85°C.

Durability was determined by outdoor exposure panels, by a new type of laboratory-simulated wear tester developed during the program, and by examination of stripes applied to highways in Massachusetts and Maine. Simulated laboratory tests were correlated with actual highway tests to demonstrate the effects of weather, temperature, tire, tire stud, and snowplow on stripe durability and bead loss.

17. Key Words
Epoxy, Highway, Stripes, Durability, Simulated Wear Tester, Beads

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Finally, Amicon would like to thank Hugh Dunston, Town Manager, for the use of several road surfaces at York Beach, Maine.

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I. INTRODUCTION AND SUMMARY

The Amicon Corporation has completed a two-year development and testing program involving the formulation, laboratory evaluation and limited field testing of a new series of fast-curing, solvent-free epoxy and urethane compounds for traffic lane markings of improved durability.

Although results with the urethanes were generally disappointing, several very promising new epoxy paints were developed during the program. The best of these epoxies gave excellent visibility and durability on either aged or fresh portland cement concrete and bituminous surfaces in film thicknesses from 7 to 60 mils. Three epoxy formulations (E-3, E-10, and E-26), which were hand applied during the first phase of the program, still retain lane-delineating character in their third winter season. These three epoxies were two-component, solvent-free systems, tested with and without glass beads. All gave the desired no-track times of less than three minutes on ambient roadway surfaces, starting with safe, and relatively low mixture temperatures of 70 to 85°C.

Durability was determined using outdoor exposure panels, by examination of stripes applied to highways in Massachusetts and Maine, and by a new type of laboratory test developed during this program. This laboratory test procedure can simulate wear from tires, studded tires or snowplows and can be operated at or below freezing temperatures and with salt, sand, or other environmental variables. Durability results using this simulated wear test machine correlated very well with results of highway striping tests, and allowed determination of the mechanisms for bead loss and paint failure for each of the types of paint tested.

Most environmental factors, such as rain, snow, ice, salt, and sand, were shown to have surprisingly little effect on the most durable epoxy compounds. Snowplows caused almost no damage to, or removal of, stripes below 30 mils in thickness in either highway or simulated wear tests. The well-known "chalking" effect observed with these, as with all, highly pigmented epoxy paints, appeared to be a benefit to visibility and durability. This slow formation of a removable, powdery, "chalky" surface layer during UV exposure seemed to serve as a self-cleaning mechanism to remove dust and tire marks and maintain reflectance of the epoxies.

The most significant erosion and loss mechanism for the epoxies, experienced during cold winter months or in low temperature laboratory tests, is a "cold impact" or chipping damage which originates at exposed aggregate surfaces where very high localized stresses can start microscopic cracks. Continued impact then leads to chipping away of small epoxy flakes. The small bare spots which first form on the peaks of the exposed aggregate then grow and merge as failure propagates into the surrounding porous cement. This mechanism suggests that these epoxy paints should have more than two-year durability in warm southern states and also that an increase in the low temperature impact strength, which could be incorporated in a second-generation series of epoxy paints, would be the single factor most likely to provide important increase in the durability in northern states.

Hence the fast-cure epoxy paints produced during this program not only out-performed the best commercially-available paint and striping systems which were applied as controls, but offer the prospect of application via modified airborne spray equipment at lower and safer temperatures, and without the need for environmentally objectionable volatile or flammable solvents. The inherent cost, durability, environmental and safety advantages of such epoxies strongly suggest their future highway delineation use.

The major task remaining to be done in order to provide a practical striping method involves equipment development. present-day application equipment has been designed for fast-drying, solvent-based paints or for slow-curing, two-component compositions, but cannot handle the very fast-curing, solvent-free epoxies developed under this program.

Although we were able to locate three equipment suppliers who are developing promising new airless epoxy striping equipment, no equipment is yet available which can apply these epoxy stripes to highways. All test stripes had to be applied by hand mixing techniques. This not only precluded striping any long stretches of highway but also limited the cure speed of the epoxy formulations tested. Several epoxies were developed which have no track times less than three minutes. These had to be eliminated from road testing because their reactivity prevented hand mixing.

Our principal recommendation, therefore, is that the Highway Administration encourage established equipment manufacturers to design and construct practical and reliable airborne airless spray equipment for applying these new epoxy traffic paints.

II. FORMULATIONS AND LABORATORY SCREENING TESTS

A. Program Objectives

The overall objectives used in selecting and formulating candidate materials were:

1. Durability - should withstand a minimum of three years of high density traffic under winder conditions involving heavy snowplowing and sanding.

2. Fast curing - non-tracking three minutes after application at road temperatures above 75°F (24°C). Supplemental heat can be utilized if method is reliable and not too costly.

3. Assume use of meter-mix-dispense equipment.

4. Coatings to be applied in 10-15 mil (0.254 - 0.381 mm) thickness in single pass.

5. Excellent adhesion to concrete and bituminous roadways, both old and new.

6. Good retention of reflective glass beads for good reflectance, initially and after aging.

7. Environmental resistance. No degradation due to sunlight, freeze-thaw, salt, or hydrolytic attack.

8. Solvent free. No environmentally undesirable vapors released during or after application.

9. Can be pigmented white with good color retention.

10. Cost not excessive. Comparable to existing paints on a highway-mile basis.

11. Nontoxic to handle and apply.

12. Availability. Ingredients must be available in large quantities in the U.S. for the foreseeable future.

B. Formulations and Controls

During the first few weeks of the program, a large number of epoxy and urethane formulations were considered for use as candidate formulations. Generally these candidates were selected based on Amicon's background technology or some prior evidence indicating some reasons why the proposed formulas might meet the objectives stated above.

Epoxy resin-curing agent combinations were considered based on prior evidence of toughness and environmental stability. Urethane systems (i.e., catalyzed isocyanate-polyol combinations) were considered based on prior evidence of fast-cure, toughness, abrasion resistance, and impact strength. For these reasons, and because of their exceptional hydrolytic stability, most of the urethanes were made from polyols derived from polybutadiene.

Many of these early, potentially-useful combinations had to be eliminated for cost, viscosity, toxicity, or some other disqualifying reason. This then reduced the candidate list to the 46 epoxy and 20 urethane formulations listed in Tables 1 and 2.

After completion of the laboratory screening test series described in the following section, the formulation list was then reduced to the 10 "finalists" (7 epoxies and 3 urethanes) listed in Table 3. These 10 finalists

TABLE 1. EPOXY COMPONENTS

NO.	TRADE NAME	DESCRIPTION	VENDOR
A	EPON 828	Diglycidal ether of bisphenol A (DGEBA) resin	Shell
B	Apogen 102	Methylolated DGEBA resin	Apogee
C	EPIREZ 5132	Reaction product of DGEBA and dimerized fatty acids	Celanese
D	ED11419	Low viscosity aliphatic diluent epoxy resin	Celanese
E	XD7160	Polyglycidyl ether of glycerin resin	Dow
F	ER50727	High reactivity, modified glycidyl epoxy resin	Celanese
1	Epicure 879	Accelerated aliphatic amine curing agent	Celanese
2	Epicure 874	Accelerated aliphatic amine curing agent	Celanese
3	Nonyl Phenol	Alkylated phenol	Rohm & Haas
4	AEP	Aminoethyl piperazine	Shell
5	TMD	Trimethyl hexamethylene diamine	Thorson
6	DCAA	Dichloroacetic acid	Fisher
7	AJICURE QX2	Amine curing agent	AJI-CHEM
8	Epicure 827	Aliphatic amine curing agent	Celanese
9	Ancamine AD	Aliphatic polyamine curing agent	Anchor
10	2052-8-1A	Modified aliphatic amine curing agent	Diamond
11	TVR-1	Experimental, high reactivity mercaptan curing agent	Diamond
12	DION-3-800LC	Trifunctional mercaptan curing agent	Diamond
13		Epoxy adduct of D + 8	
14	LMB 1601	Difunctional mercaptan curing agent	Ciba

TABLE 2. URETHANE COMPONENTS

NO.	TRADE NAME	DESCRIPTION	VENDOR
A	Poly BD	Polybutadiene polyol resin	Arco
B	MDI	Methylene bisphenyl isocyanate resin	Upjohn
C	Hylene W	Liquid aliphatic (H_{12}MDI) diisocyanate resin	Dupont
D	IPDI	Isophorone diisocyanate resin	Veba
E	DDI	DDI diisocyanate resin	General Mills
1		N,N-bis(2 hydroxypropyl) aniline	Upjohn
2		1,4-butanediol	
3	MDA	Methylene-dianiline	
4	IPDA	Isophorone-diamine	Veba-Chemie AG
5	DBTDL	Dibutyl tin dilaurate	M & T
6	DABCO	1,4-diazabicyclo (2,2,2) octane	Houdry
7		Reaction product of DGEBA + D	

TABLE 3. COMPOSITION OF EPOXY AND URETHANE FORMULATIONS SELECTED FOR LIMITED ROAD TESTING

EPOXIES	
E-3	Bisphenol A/Epichlorohydrin liquid epoxy resin (A). Curing agent is a modified aliphatic amine (4). Mix ratio (by weight): 5A/1B.
E-10	Same chemical composition as E-3 with accelerator added (3, 6). Mix ratio changed to 1A/1B.
E-25	Composition similar to E-3 except part of the Bisphenol A/ Epichlorohydrin resin is replaced with an epoxy ester resin (C) to introduce more flexibility in the system. Mix ratio: 3A/2B.
E-26	Polyepoxide (D) cured with aliphatic amine (8). Mix ratio: 4A/1B.
E-42	Bisphenol A/Epichlorohydrin liquid resin (A) cured with a modified mercaptan-type curing agent (11). The curing agent exhibits less yellowing than most fast-curing mercaptans. Mix ratio: 3A/2B.
E-45	Composition similar to E-26 but the resin is more flexible and less reactive (F) with low-cost accelerator added (3). Mix ratio: 2A/1B.
E-46	Composition similar to E-45 but the system is less reactive than E-45. Curing agent is aliphatic amine (8). Mix ratio: 5A/1B.
POLYURETHANES	
U-5	Polybutadiene-based polyol (A) with short-chain diol extender (C). Aliphatic isocyanate based on $H_{12}MDI$ (3) plus metal salt catalyst (6). Mix ratio: 5/1.
U-6	Similar to U-5 using MDI aromatic isocyanate (B). Mix ratio: 6/1.
U-8	Similar to U-5 using IPDI aliphatic isocyanate (D). Mix ratio: 9/2.

were then converted into useful paint systems by filling each with 50% by weight of the following filler mixture:

Rutile TiO_2	50%
Silica	30%
Clay	10%
Talc	10%

Hence, each of the 10 paints, which were then used for highway striping (as described in Section IV) and for the accelerated wear test experiments (as described in Section III), contained 50% organic (resin and hardener) plus 25% pigment solids (TiO_2) plus 25% extender solids (silica, clay, and talc).

1. Control Paints

After consultation with the Highway department contract monitors and with other authorities on the state of the highway striping cost, a series of widely used commercial paints were selected to serve as reference controls during the highway tests and simulated wear tests described in Sections III and IV. These six controls were:

a. Alkyd paints

1. Gleem-White Traffic Paint M7.01.10 (50 sec. dry). Baltimore Paint Company.

2. Gleem-White Traffic Paint M7.01.08 (20 sec. dry). Baltimore Paint Company.

3. Alkyd-White Traffic Paint. Mass Spec. P-218 (30 min. dry). Franklin Paint Company.

b. Chlorinated rubber paints

1. Chlorinated White Traffic Paint M7.01.10 (5 min. dry). Smith Paint Company.

2. Chlorinated White Traffic Paint M7.01.10. Franklin Paint Company.

c. Thermoplastic striping system

White thermoplastic traffic line M7.01.04 (2 min. dry time at 50°F (10°C). Traffic Control Devices.

C. Laboratory Test Procedures and Results

1. Test Procedures

a. No-track time

No-track time was determined according to ASTM D-111-67, "No-Pick Up Time of Traffic Paint." This procedure requires rolling a known weight across a paint stripe until the rubber tires no longer pick up paint. No track will determine the length of drying time after application for no pickup of traffic or pavement marking paint by the tire of an automobile. Since materials were required to have less than a three-minute no-track time, higher temperatures were evaluated for application.

b. Viscosity

Viscosity for paint components was determined using a Brookfield Viscometer (Model HAT) at room temperature. The Brookfield Viscometer used in this method is a modified rotating cylinder instrument. Viscosity is a critical factor in the utility of a paint. For fast-curing paints, high viscosities would hinder efficient mixing and uniform spraying. Viscosities are recorded in centipoises (cps). A centipoise equals .001 Pascal seconds (Pa-s).

c. <u>Abrasion resistance</u>

Abrasion resistance was determined using the standard Taber Abrasor (Taber Instrument 6) and ASTM Method D-1044, "Resistance of Transparent Plastics to Surface Abrasion." A modified traffic paint procedure utilizing Calibrase CS-17, hard rubber wheels, was used. Paints were cast 15 mils (0.38 mm) on cleaned steel panels.

In addition to the four panels of each material tested at Amicon, panels were also evaluated at the Federal Highway Administration office in Washington. Both labs agree on results. The wear index for a paint is the weight loss of material in milligrams per 1000 cycles.

d. <u>Flexibility</u>

Flexibility was determined by casting 15-mil (0.38 mm) films of paint over a cleaned, aluminum panel and bending the cured stripe over a 3/4" to 1/5" (19 to 5.1 mm) mandrel. The ability of a stripe to withstand a small mandrel or high degree of bend indicates the more flexible materials. Testing was rated as follows:

Rating	Flexibility	Mandrel Diameter	Failure (degrees)
1	Rigid	3/4" (19 mm)	Up to 15°C
2		3/4" (19 mm)	15 to 24°
3		3/4" (19 mm)	25 to 40°
4		3/4" (19 mm)	45 to 60°
5		3/4" (19 mm)	60 to 100°
6		1/2" (13 mm)	50 to 100°
7		3/8" (9.5 mm)	50 to 100°
8		1/5" (5.1 mm)	50 to 100°

Rating	Flexibility	Mandrel Diameter	Failure (degrees)
9		1/5" (5.1 mm)	Greater than 100°
10	Flexible	Does not crack under any bend	

Most epoxy systems ran from rigid to moderately flexible, while the urethanes were quite flexible. Flexures at room temperature and -28°C would indicate the relative degree of flexibility over most road test temperatures.

e. Hardness

Shore D hardness gauges were used to force a needle into the paint surface and indicate the relative resistance to penetration. Hardness recordings give one measure of resistance to abrasion.

f. Discoloration

Test panels of all candidate paints were cast on aluminum panels and set on the Amicon rooftop at 45° facing south for environmental exposure. Paints were inspected monthly for discoloration or fading. The epoxies were least effected by sun, wind, and rain; the control paints generally discolored more than the epoxies; the urethanes made from aromatic isocyanates generally showed most rapid and severe discoloration.

g. Chemical resistance

Test panels were soaked in beakers of gasoline, water, and aqueous salt solution (10%) according to ASTM D 2792-69. Acceptable materials showed little or no degradation after several months at room temperature. Most of the epoxies and urethanes evaluated met the requirements of these tests.

2. Results and Discussion

Epoxies

Five different resin components were combined with fifteen different hardeners to produce 46 formulations for lab testing. Table 4 lists these epoxy components and Table 5 lists the urethane formulations and their corresponding no-track, applicability, abrasion, and discoloration results.

No-track times on the 46 formulations ran between 30 seconds and three hours. The cutoff for all no-track acceptability was 15 minutes at room temperature. When such formulations were heated to between 175° and 200°F (79.4° and 93.3°C), they easily produced no-track times under three minutes on ambient surfaces. On the other hand, formulations that produced room temperature no tracks of less than one minute were far too fast for any available application equipment.

Many formulations were too viscous to mix and therefore not acceptable for machine pumping. Some components proved incompatible, producing gritty, cheezy, and poor films. These formulations were also dropped from further testing. Materials which passed the first rounds of testing were: E-1, 2, 3, 8, 9,10, 13, 14, 15, 23, 25, 26, 30, 42, and 45. Formulation properties were retabulated and listed in levels of striping desirability. The best seven candidates were singled out and summarized in Table 6. Each system offered reasonable mix ratios and

TABLE 4. PRELIMINARY LAB TESTS ON EPOXY FORMULATIONS

FORMULATION NO.	COMPONENTS [1/] A	COMPONENTS [1/] B	ROOM TEMPERATURE NO-TRACK TIME (minutes)	APPLICABILITY	ABRASION WEAR INDEX (gm)	UV DISCOLORATION (months)
1	A	1	65	Gritty	88	---
2	A	2	40	Discolors	87	---
3	A, 3	4	36	Good	55	2
4	A, 3	5	66	Discolors	--	5
5	A	3,5	58	Too slow	--	---
6	A	5	132	Too slow	--	---
7	A, 6	5	59	Too slow	--	---
8	A, 6	4	37	Gritty	97	---
9	A, 3, 6	4	26	Poor	60	---
10	A, 6	3,4	28	Good	69	2
11	A	7	---	--	--	---
12	A	3,7	---	--	--	---
13	A	7	16	Poor	63	5
14	A, 3	7	29	Poor	55	---
15	A	3,7	35	Poor	62	---
16	B	1	37	Viscous	--	---
17	B, 3	4	22	Viscous	--	0.5
18	B, 3	5	38	Viscous	--	5
19	B	3,5	40	Viscous	--	---
20	B, 6	5	53	Viscous	--	---
21	B	5	65	Viscous	--	---
22	B	7	7	Viscous	--	0.5
23	A, C	7	32	Too slow	55	0.5
24	A, C	7	50	Gritty	--	0.5
25	A, C, 6	1	---	Poor	76	---
26	D	8	12	Good	70	5
27	A	8	180	Too slow	--	---
28	D	7	35	Too slow	--	---
29	D	2	15	Poor	--	---

TABLE 4. PRELIMINARY LAB TESTS ON EPOXY FORMULATIONS (continued)

FORMULATION NO.	COMPONENTS[1/] A	B	ROOM TEMPERATURE NO-TRACK TIME (minutes)	APPLICABILITY	ABRASION WEAR INDEX (gm)	UV DISCOLORATION (months)
30	A	10	12	Poor	64	---
31	D	D,8	3	Poor	--	---
32	A	D,8	3	Poor	--	---
33	A	10	4	Poor	--	---
34	A, 3	4,10	21	Too slow	--	---
35	D	10	>0.5	Too fast	--	---
36	D	10	>0.5	Too fast	--	---
37	A	9	26	Discolors	--	---
38	D	9	31	Too slow	--	---
39	B, E	10	2	Viscous	--	---
40	D	12	30	Too slow	--	---
41	D, 3	8	11	Poor	--	---
42	A	11	4	Good	--	---
43	F	14	14	Cheezy	--	---
44	A	14	40	Too slow	--	---
45	F	3,8	--	Good	--	---
46	F	8	--	Good	--	---

1/ Codes identified in Table 1

TABLE 5. PRELIMINARY LAB TESTS ON URETHANE FORMULATIONS

FORMULATION NO.	COMPONENT 1/ A	COMPONENT 1/ B	ROOM TEMPERATURE NO-TRACK TIME (minutes)	APPLICABILITY	ABRASION WEAR INDEX (gm)	UV DISCOLORATION (months)
1	A,B	1,6	3	Gritty	130	0.25
2	A,C	1,6	30	Too slow	108	4
3	A,C	1,6	30	Too slow	---	--
4	A,C	1,2,6	60	Discolors	---	--
5	A,C	3,6	3	Good	129	<5
6	A,B	3,6	1	Good	128	1
7	A,B/A,C	3,6	8	Viscous	---	--
8	A,D	3	9	Good	39	<5
9	A,D	2	35	Too slow	---	--
10	A,D	3	3	Discolors	---	--
11	A,C	3,4,7	6	Viscous	---	--
12	A,C	2,4,7	20	Too slow	---	--
13	A,C	2,4,7	15	Components crystallize	---	--
14	A,C	2,5	>30 sec	Too fast	---	--
15	A,D	3,6	13	Gritty	---	--
16	A,D	7,8	>30 sec	Too fast	---	--
17	A,E	3,6	10	Gritty	166	--
18	A,E	3,6,7	3	Discolors	---	--
19	A,C	3,6,7	3	Discolors	129	--
20	A,E	9	40	Too slow	---	--

1/ Codes identified in Table 2

TABLE 6. SECONDARY LAB SCREENING TESTS

FORMULATION	MIX RATIO	ROOM TEMP. NO TRACK TIME (min)	TEMP FOR 3 MINUTE NO TRACK (°F)**	VISCOSITY @ 180°F (82°C) (cps) A	B	TABER ABRASION (gm)	FLEXIBILITY MANDREL* RT	-28°C	SHORE D HARDNESS RT	-28°C	POUNDS PER GALLON***	RAW MATERIAL COST ($/lb)
Epoxies												
E-3	4/1	38	225	2600	320	104	2	2	83	87	12.6	1.10
E-10	1/1	30	210	460	3720	94	5	2	81	84	12.1	1.10
E-25	1.2/1	29	240	920	3720	85	1	1	78	82	12.3	1.40
E-26	4/1	12	175	700	240	68	4	6	85	84	11.6	1.50
E-42	1.4/1	4	---	--	--	37	6	5	81	86	12.9	1.40
E-45	2/1	--	200	700	320	29	3	4	79	84	11.4	1.60
E-46	5/1	--	250	200	80	52	7	7	81	85	12.5	--
Urethanes												
U-5	5/1	5	---	--	--	20	7	8	45	54	12.3	--
U-6	6/1	2.7	70	--	--	270	7	8	--	--	11.8	--
U-8	5/1	48	---	--	--	50	7	8	44	49	12.6	--
Controls												
Gleem 50 Sec. Alkyd	---	6	---	--	--	140	-	-	44	69	12.0	--
Smith Chl. Rubber	---	9	---	--	--	206	-	-	--	--	12.0	--

* Mandrel Bend - rated 1 (not flexible) to 10 (flexible).

** °F = (1.8) °C + 32.

*** 1 lb/gal = 119.8 kg/m³

viscosities which proved to be important for limited hand application at a later date. Raw material costs ranged between $1.10 to $1.60 per pound ($2.43 to $3.53 per kilogram).

Urethanes

Twenty formulations were prepared from fifteen different urethane components and tested by the same criteria used on epoxies. Table 3 lists the components and Table 5 the preliminary lab test results. Although most of the urethanes reacted quickly enough for road stripe application, some were either too viscous, gritty, or discolored during mixing. The best systems tested in the preliminary lab tests were U-5, U-6, and U-8. These formulations are also listed in Table 6 with the better epoxies and paint controls. The U-5 and U-8 were non-yellowing, aliphatic isocyanate systems with good applicability and moderate abrasion. On the other hand, the aromatic isocyanate, U-6, did yellow slightly but offered attractive mix viscosity, fast cure, and ease of application. Unfortunately, many of the urethane systems required the addition (up to 30%) of solvent to enable hand application of test stripes.

III. ACCELERATED (SIMULATED) WEAR TEST RESULTS

A. Equipment Design

A new type of simulated wear tester was constructed to attempt to simulate actual highway wear mechanisms and to screen paints for highway application. Figure 1 and 2 illustrate this test device. Basically, a slab of highway pavement (concrete or asphalt) is painted in pie sections with test stripes, rotated beneath a horizontal support beam and worn with a series of miniature tires or snowplows.

Vehicle or snowplow weight was simulated by means of compressing a set of compression springs a known distance against the test road surface. Vehicle speed was controlled by means of a variable speed controller on a 3/4 horsepower (560 watt) motor. The total number of cycles was monitored by a revolution counter.

1. Simulated tire tests

   A pair of 3-inch (76 millimeters) diameter, solid rubber tires were mounted on opposite sides of the horizontal load bar to simulate actual tire wear. A styrene butadiene/carbon black filled rubber with a slightly harder surface (76 Shore A hardness) than the average passenger car tire of 65 Shore A hardness. Although simulated tires could only be aligned to move tangentially across the surface, casters and cambers were adjusted to minimize sliding, vibration, and shimmy. Vertical force was checked daily by readjusting the compression springs.

2. Simulated studded tire tests

   Rubber tires were drilled and pressed with carbide-tipped, tire studs as used on Massachusetts

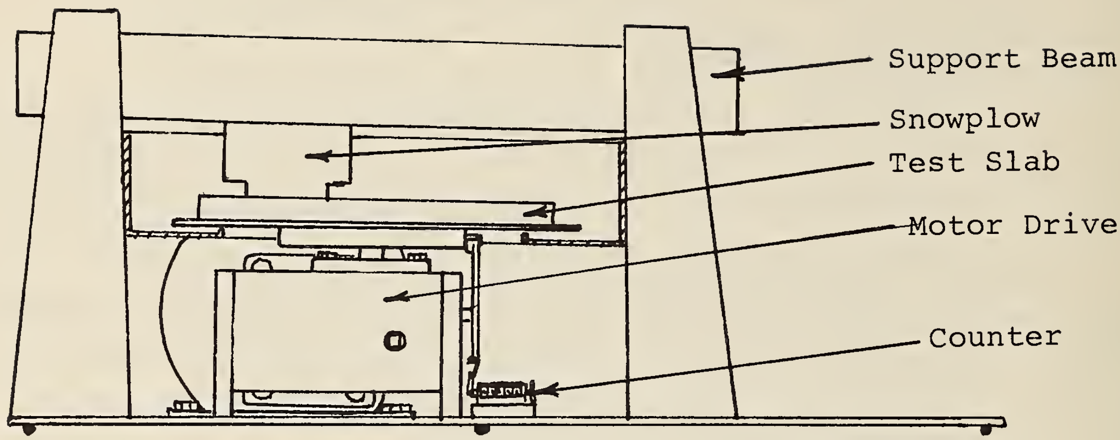


FIGURE 1: SIMULATED SNOWPLOW TEST APPARATUS
(tires replace plow during tire tests)

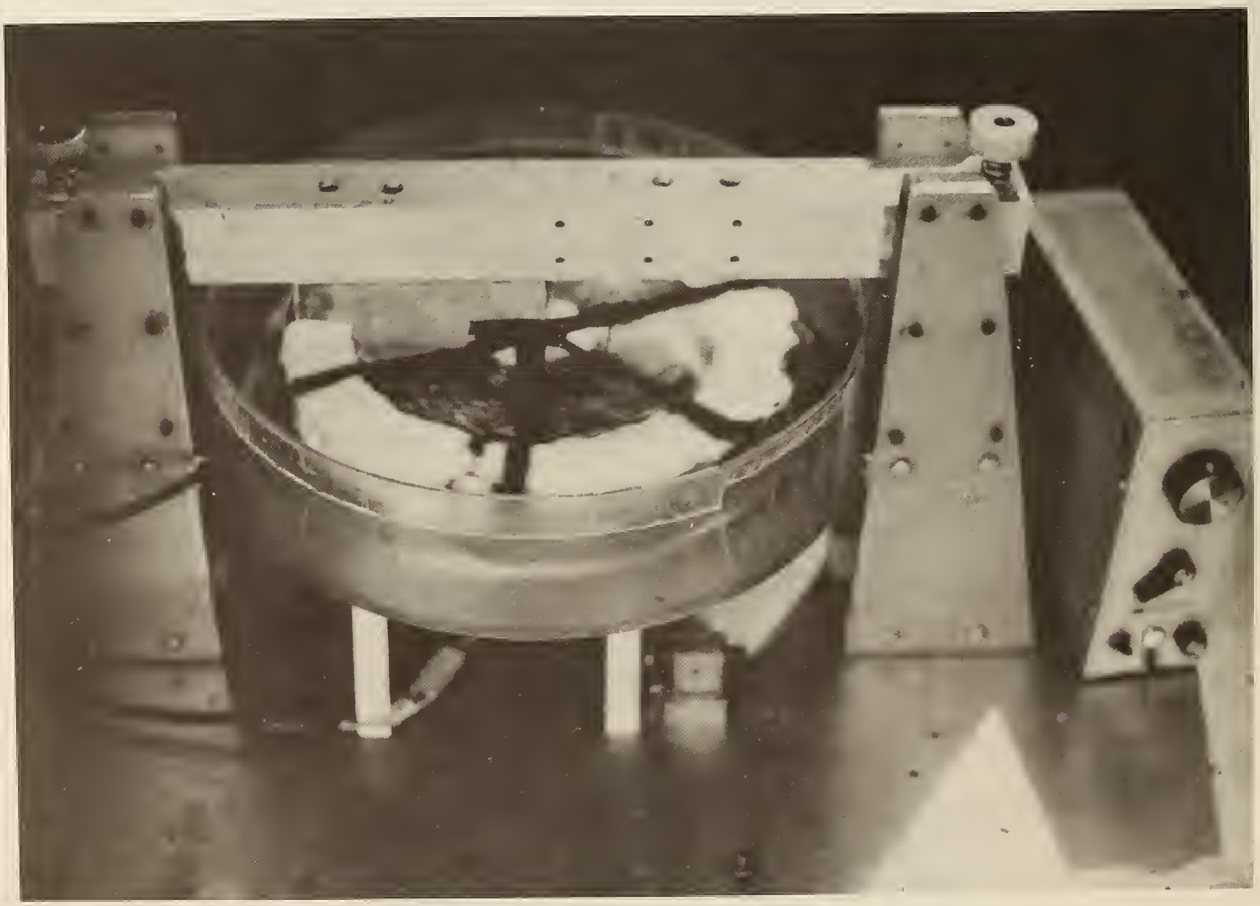


FIGURE 2: PHOTOGRAPH OF APPARATUS

highways. The number and pattern of studs replicated those found on a typical fourteen-inch (356 millimeters) snow tire.

3. Simulated snowplow tests

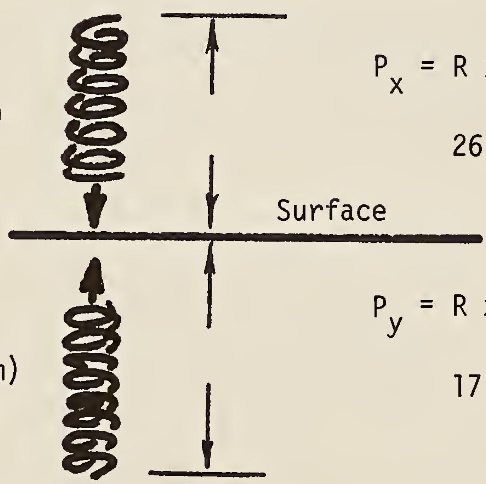
Snowplow simulation was achieved by cutting a 3-inch (76 millimeters) section from a typical Massachusetts, high-carbon steel snowplow and bolting it directly to the horizontal cross member. Since a typical plow weighs about 1500 pounds (680 kg), a similar loading (22.7 pounds/in^2)(15960 kg/m^2) on the simulated blade would correspond to about 8.5 pounds (3.86 kg). Compression springs maintain proper plow pressure while the actual plow pressure is controlled by adjusting nuts (Figure 3). Initially the plow blade is brought in contact with the test surface and then the adjusting nuts tightened to increase the tension on both upper and lower springs. The effective pressure can then be calculated by subtracting the compressed height from the free height and multiplying the spring load rate factor. Subtracting the two forces and multiplying by two (springs at both ends of the bar) yields the effective downward pressure on the surface (see Example 1). The simulated plow blade is located 4.5 inches (114 mm) from the center of the test plate and approaches the test stripe at a 20° angle (see Figures 3 and 4) while the blade's slightly curved face runs 55° to the road surface. This setup closely approximates the vertical plow force and horizontal force encountered during snowplowing at constant velocity.

EXAMPLE 1: SPRING SPECIFICATIONS

COMPRESSION SPRING NO.	FREE LENGTH	RATE	SOLID HEIGHT
LC-0725-2	1 inch (25.4 mm)	42 lbs/in (7.5 kg/cm)	0.397 inch (10 mm)
LC-0725-6	2 inch (50.8 mm)	20 lbs/in (3.6 kg/cm)	0.686 inch (17.4 mm)

PRESSURE SPECIFICATIONS

Spring No.
LC-0725-2
Compressed
3/8" (9.5 mm)



P_x = R x F = 42 (1.0 - 0.375) =

26.25 pounds (11.9 kg)

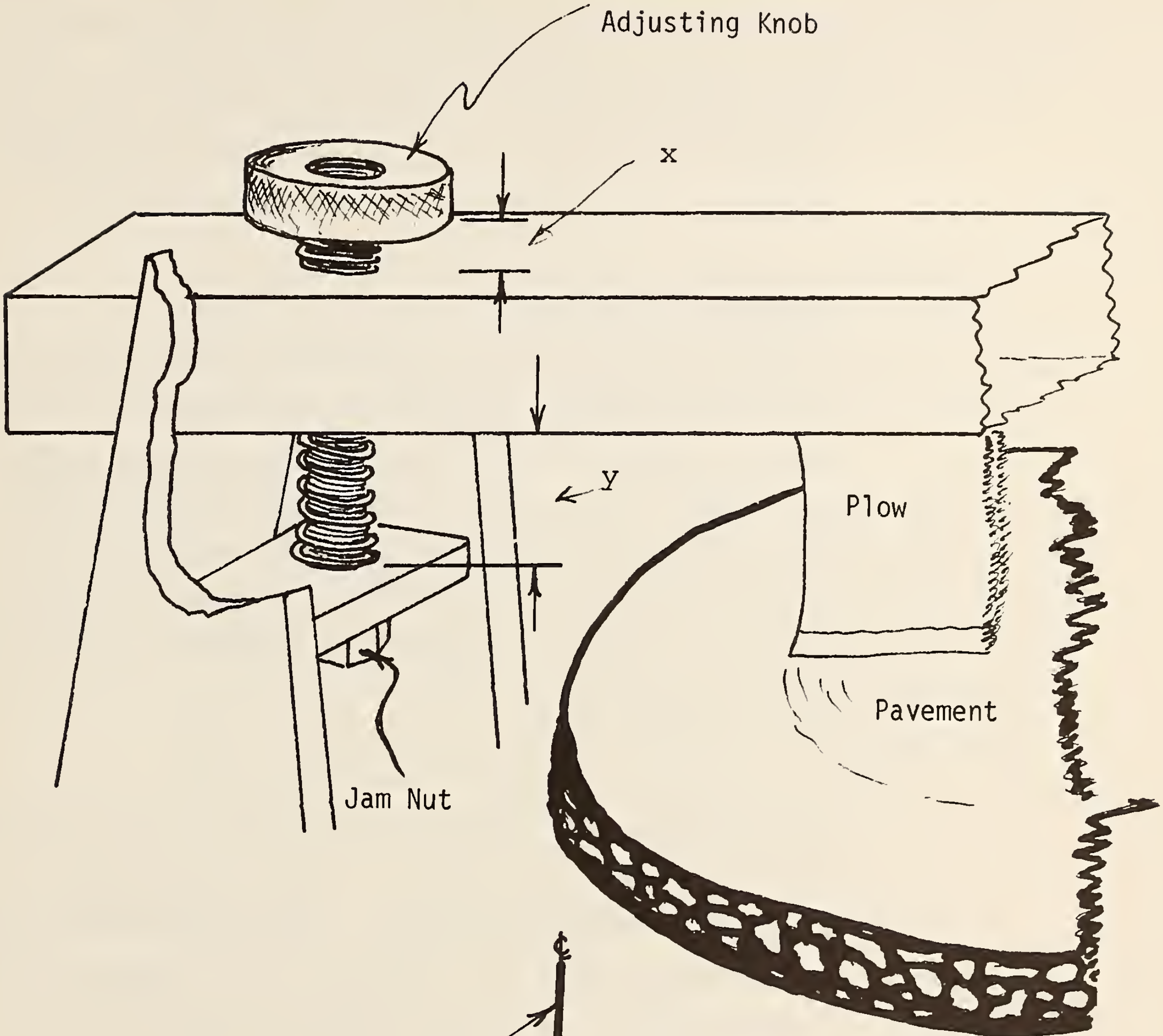
Spring No.
LC-0725-6
Compressed
7/8" (22.2 mm)

P_y = R x F = 20 (2.0 - 1.125) =

17.5 pounds (7.9 kg)

EFFECTIVE DOWNWARD PRESSURE = 2 (P_x - P_y) = 17.5 pounds (8.0 kg)

FIGURE 3: PLOW PRESSURE CONTROLLER



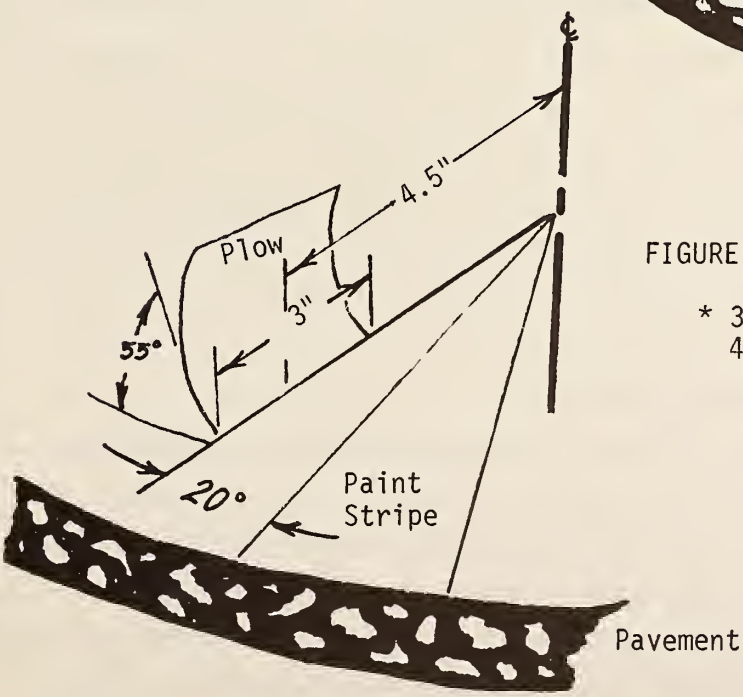


FIGURE 4: PLOW CONFIGURATION

* 3" = 76.2 mm
4.5" = 114.3 mm

4. Test surfaces

Several different test surfaces were prepared for evaluation in the simulated wear tester. An attempt was made to replicate both fresh and aged surfaces of both bituminous cement and portland cement concrete.

Bituminous Surfaces

A fresh bituminous surface was simulated by casting a 1-1/2" (38 mm) thick slab by 12 yards (11 metres) long of Type I-1 top regular bituminous cement mixture atop tar paper in the Amicon parking lot. After steam rolling to 3/4" (19 mm) using 285 lbs. per inch tread (51 kg/cm) and cooling, one square foot sections (.09 m^2) were removed by diamond saw and fashioned into circular disks.

Aged bituminous sections were cut from scarified road sections removed from road renovation in Arlington, Massachusetts. The road slabs were sectioned into 3/4" (19 mm) thick slabs to enable easier use in the simulated wear device. The surface itself was approximately ten years old and offered a rough surface of exposed red trap rock. All bituminous surfaces were epoxy/fiberglass backed for added reinforcement.

Concrete Surfaces

Fresh portland cement concrete slabs were prepared by Herman Protze Company, Newton Highlands, Massachusetts. Type I, air-entrained concrete was cast into 3/4" (19 mm) deep polyethylene dishes and cured. Specifications and analysis performed on these test specimens are listed in Appendix A.

Aged concrete surfaces were cast in a similar manner but the surface was washed well with water to produce an exposed aggregate. Specifications on these slabs are also listed in Appendix B.

5. Environmental controls

Various test temperatures could be achieved by placing the unit outside, in the lab, or even inside a freezer. Wear tests using plows or tires were run at several temperatures from 0° to 35°C.

The effects of sand, salt, rain, snow, and ice were also evaluated on the simulated wear tester. Sand and salt could be sprinkled on the surface during testing with either tires or plow, as could water to simulate rain. Snow and ice test conditions were determined by placement of the tester with test surfacing specimen outside during the winter in actual snow and sleet conditions.

B. Simulated Wear Test Procedures

Washed, dried test surfaces were sectioned off in six pie sections of equal size with tape (one tape thickness) ~0.007"). Paints were cast into the pie sections and the excess removed by drawing a blade across the tape (Figure 5). These painted sections were immediately sprinkled with Massachusetts Specification M7.01.07 beads at a rate of 6 pounds per gallon of coverage when tests were planned for beaded stripings. All paints were then cured three days at 40°C prior to testing.

Test panels were then clamped onto the turntable, the counter set at zero, speed set (400 counts/minute = 10 mph {16 km/h}), plow or wheels set on the surface, pressure set with compression spring jam nuts, and the

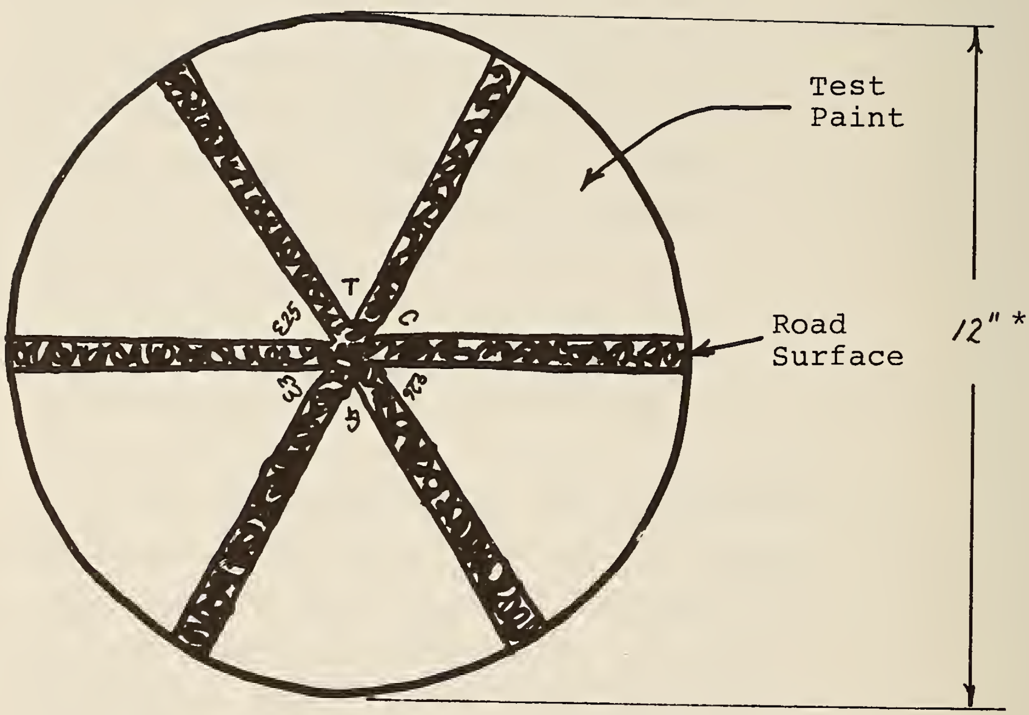


FIGURE 5: TEST SLAB CONFIGURATION

*12" = 305 mm

test started. Compression settings, speeds, and stripe inspections were performed daily. Records and photographs were maintained on all test slabs and compiled on the simulated tester data sheet (Table 7).

C. Simulated Wear Test Results

1. Scope of Testing

Eleven paints and four test surfaces were studied on the simulated wear tester:

PAINTS	SURFACES
Thermoplastic	Fresh concrete
Gleem 20 Sec. Alkyd	Exposed aggregate concrete
Franklin Alkyd	Fresh bituminous
Franklin Chlorinated	Aged bituminous
U-5	
U-8	
E-3	
E-25	
E-26	
E-42	
E-45	

A total of 180 tests were conducted using the simulated snowplow, tires, or studded tires. Temperatures ranged from $-18^{\circ}F$ ($-28^{\circ}C$) to $+70^{\circ}F$ ($21^{\circ}C$), surfaces were dry, water wet, iced over, wet with salt water or with a mixture of sand and water. Tests were run at 6 to 12 miles per hour with a simulated plow and vehicle weight of about 6,000 pounds (2727 kg). Speeds were maintained constant throughout the tests. Preliminary tests were run 1000 cycles and final tests were run to failure (the device failed at 25 million cycles). Tests run to failure were performed on beaded as well as

TABLE 7: SIMULATED TESTER DATA SHEET

Test Surface:______________________ Date:_______________

Paint Samples: A ______ D ________ Temp:_______________

B ______ E ________ % Rel. Humidity:_____

C ______ F ________

Machine Specs:

Speed Setting: ______________ Top Spring Compression: ______ in

Total Cycles:_______________ Bottom Spring Compression ____ in

Total Time:________________ Ave. Plow Weight/in:____________

Actual Ave. Counts/min:_______ Ave. Plow Speed (MPH):__________

Environment: ____

____

____

Results:

Paint	Leading Edge	Middle	Trailing Edge	Overall Evaluation
A				
B				
C				
D				
E				
F				

unbeaded stripes.

At each test condition, a pavement panel was rotated beneath a three-inch section of steel snowplow. Actual plow attitudes were approximated by angling the plow 55° and skewing the edge 20° to the radius of the test panel. Both plow weight and recoil were simulated with the use of compression springs. Temperature was controlled by placing the entire tester in the refrigerator/freezer while salt, sand, water, and ice were sprinkled onto the surface to simulate various weather conditions.

2. Simulated Snowplow Tests

Table 8 lists the short-term tests run with the simulated snowplow on bituminous and concrete surfaces. Results are listed in Table 9.

a. Environmental effects

Tests (1000 revolutions) were run on fresh bituminous surfaces (plates 1-4, 7, and 8-15) containing unbeaded test stripes of two paint controls (Gleem and Franklin Alkyd), two epoxies (E-25 and E-42), and two urethanes (U-5 and U-8). Sprinkling salt, sand, and water solutions onto the panels at temperatures above freezing only seemed to lubricate the plow. However, temperatures below freezing had different effects on each of the paints tested. The urethanes and E-42 (which ultimately peeled rapidly in road tests) were easily peeled at sub-freezing temperatures. Epoxy, except for E-42, and conventional paints failed to peel at any temperature. The presence of ice and snow on the stripes at sub-freezing temperatures offered protection for the stripe.

TABLE 8. SIMULATED SNOWPLOW WEAR TESTS

PLATE SURFACE NO.	SURFACE	TEST ENVIRONMENT	TEMP. (°F)**	% RH	NO. OF CYCLES	TEST SPEED (mph)***	EFFECTIVE PLOW WEIGHT (pounds)****
1	Fresh bituminous	Water spray	70	--	10,000	8	1600
2	Fresh bituminous	Water spray, salt, sand	50	--	10,000	8.2	1600
3	Fresh bituminous	Ice	25	--	10,000	7.0	1600
4	Fresh bituminous	Snow and sleet	20	--	7,800	12.5	3000
5	Fresh concrete	Dry	70	21	1,000	6.9	3000
6	Fresh concrete	Dry	-18*	15	1,000	6.8	3000
7	Fresh bituminous	Dry	70	21	1,000	6.9	3000
8	Fresh bituminous	Dry	-18	15	1,000	6.9	3000
9	Aged bituminous	Dry	70	21	1,000	6.9	3000
10	Aged bituminous	Dry	-18	15	1,000	6.9	3000
15	Fresh concrete	Dry	30	80	1,000	6.9	3000

* Surface pre-frozen three days at -18°F (-27.8°C); test duration 4 minutes.

** °F = (1.8)°C + 32.

*** 1 mph - 1.61 kilometers per hour

**** 2.2 pounds = 1 kilogram

TABLE 9. GROSS CATEGORIZATION OF SHORT-TERM SIMULATED WEAR TESTS

SNOWPLOW RESULTS

	TEMPERATURE				SURFACE @ 20°C			SURFACE @ -28°C			SPEED ON FRESH BITUMINOUS	
	20°C	10°C	-15°C	-28°C*	CONCRETE	BIT	AGED BIT	CONCRETE	BIT	AGED BIT	6 MPH**	12 MPH**
Best	E-25	U-8 E-25	E-42 U-8	E-26 Franklin	E-45 Gleem	E-26 E-45	E-45 Gleem	Gleem E-26 E-45	E-26	E-26 E-26	E-42 U-8	E-42 E-25
Good	U-8 U-5	U-5 E-42	E-25 U-5	E-25 E-45	E-25 E-26	U-8 Franklin E-25	E-25 E-26	E-25 Franklin	Franklin E-25 E-45	Franklin E-45 Gleem	E-25 U-5	U-8 Franklin
Poor	Franklin Gleem	→ →	→ →	U-8 →	U-8 Franklin	Gleem	U-8 Franklin	U-8	Gleem U-8	U-8	Franklin Gleem	U-5 Gleem

GROSS CATEGORIZATION OF SIMULATED WEAR TESTS

TIRE RESULTS

	SURFACE AND TEMPERATURE EFFECTS (1000 CARS @ 6 MPH) @ 20°C			SURFACE AND TEMPERATURE EFFECTS (1000 CARS @ 6 MPH) @ -28°C			810,000 CARS ON FRESH BITUMINOUS		
	CONCRETE	BITUMINOUS	AGED BITUMINOUS	CONCRETE	BITUMINOUS	AGED BITUMINOUS	20°C 4 MPH**	0°C 4 MPH**	0°C 12 MPH**
Best	E-45 E-25 E-26	E-45 E-25 E-26	E-45 E-25 E-26	E-45 E-25	E-45 E-25 E-26	E-45 E-25	E-45 E-25	E-25 E-45 E-26	E-25 E-26 E-45
Good	U-8	U-8	U-8	E-26 Franklin	U-8 Franklin	U-8 Franklin E-26	E-26 U-8	U-8	U-8
Poor	Franklin Gleem	Franklin Gleem	Franklin Gleem	U-8 Gleem	Gleem	Gleem	Franklin Gleem	Gleem Franklin	Franklin Gleem

*Dry, all others wet.

**1 mile per hour = 1.61 kilometers per hour

Test panels of paints on fresh concrete, fresh bituminous, and aged bituminous were plowed dry at $-18^{\circ}F$ and $70^{\circ}F$ ($-28^{\circ}C$ and $21^{\circ}C$) for 1000 cycles. Although peeling did not occur on any of the stripe surfaces, as test temperatures decreased, smudging created dirtier stripes. Also at lower temperatures abrasion became more evident across the leading stripe edge.

b. Plow characteristics

Due to the irregularities in the pavement surface, plow weight produced little wear on 15-mil (0.38 mm) thick stripes. As a matter of fact, except for minor abrasion on all paints and epoxies and some peeling of urethanes, the snowplow had little effect on the wear of 15-mil (0.38 mm) thick stripes. What little wear was observed was noted across the leading edge of the stripe, either as abrasion at the exposed pavement aggregate or peeling.

Plowing speed had the same effect as increased plow weight, i.e., the time to form the leading edge ramp is decreased. However, as before, once the ramp was carved within the first several hundred plowings, the stripe showed little change subsequently.

Extended snowplowings at $32^{\circ}F$ ($0^{\circ}C$) on a fresh bituminous surface produced very little epoxy stripe wear after the first 1000 cycles. While the control paints failed continuously until they were obscured completely after several hundred thousand cycles, the epoxies continued to show only minor wear across the leading 3/8" (9.5 mm) of stripe. Only after the road surface began to erode after five million cycles did the epoxies begin to show wear. After eight million cycles when the tests were stopped, the epoxies were the only paints offering any day or night visibility.

After careful evaluation of test results and actual road observations, a factor of 5,000 cycles of simulated wear was equated to 1 road plowing.

c. Surface characteristics

Harder (concrete) or frozen surfaces led to faster degradation of stripes than softer (bituminous) surfaces. Although stripe wear was minimal on a 15-mil (0.38 mm) thick stripe, road grime from plow abrasion on bituminous surfacing led to premature stripe visibility loss. Concrete produced less road grime but offered a harder, less resilient test surface. High spots, exposed aggregates, and leading edges resulted in the primary failure points further spreading to the matrix. As the number of cycles increased surface grime proved more abrasive towards the softer, conventional paints and quickly darkened them beyond recognition. Epoxy films were generally cleaner and more easily cleaned with water (rain).

Although 15-mil (0.38 mm) thick stripes offered little hindrance to plows, heavier castings of thermoplastic control stripes (70 mils) (1.78 mm thick) deteriorated from the inception of snowplow testing. Within the first several hundred plowings (cycles) the stripe was almost completely destroyed. Thin stripe thickness resistance to snowplows was reaffirmed at a later time in the program with graduated thicknesses in highway stripes.

3. Simulated Tire Tests

Paints and surfaces screened in the snowplow tests were also screened with simulated tire wear. Tires were affixed to the support beam and aligned to run tangentially along the specimen surface. A simulated car weight of 3000 pounds (1361 kg) was obtained by adjustment of compression springs above and below the support beam. Table 10 lists preliminary short-term simulated tire tests run on the epoxies, urethanes, and conventional paints listed in Section 3A. Results are tabulated in Table 9.

a. Environmental effects

Water, snow, ice, and salt produced no visible effect on the wear of any stripe. If anything, the lubricating effect noted above may have improved durability. Although sand and road grime had little effect on epoxies and urethanes, their presence caused rapid abrasion and loss in visibility of conventional paints. Conventional alkyd and chlorinated rubber paints offer a softer, chalking type surface which becomes easily eroded by dust and sand.

Dry, sub-freezing temperature conditions proved detrimental to all striping materials. Long-term tire wear across frozen stripes led to peeling and abrasion of the more resilient epoxies and urethanes. Failure started at any exposed aggregate surface and propagated across the matrix.

b. Tire wear factors and observations

Although the effects of several tire speeds were evaluated, simulated speeds above 15 miles (24 km) per hour were found to be unsafe for use on the

TABLE 10. SIMULATED TIRE WEAR TESTS

SURFACE NO.	SURFACE	TEST ENVIRONMENT	TEMP. (°F)*	% RH	NO. OF CYCLES	TEST SPEED (mph) ***
5	Fresh concrete	Dry	70	21	10,000	4.6
6	Fresh concrete	Dry	-18	15	1,000	6.8
7	Fresh bituminous	Dry	70	21	1,000	6.9
8	Fresh bituminous	Dry	-18	15	1,000	6.9
9	Aged bituminous	Dry	70	21	1,000	6.9
10	Aged bituminous	Dry	-18	15	1,000	6.9
11	Fresh bituminous	Dry	70	21	810,000**	4.2
11	Fresh bituminous	Dry	30	90	810,000	12
12	Fresh bituminous	Dry	30	90	810,000	6
13	Aged bituminous	Dry	30	90	810,000	6
14	Fresh concrete	Dry	30	90	810,000	6

* $^{o}F = (1.8)^{o}C + 32$

** Three-month equivalent to ≈ 9,000 ADT Rt. 128.

*** 1 mile per hour = 1.61 kilometers per hour wear tester. Limitations of the cross beam also restricted gross vehicle weight simulation beyond 3,000 pounds (1361 kg). No appreciable accelerated wear could be attributed to simulated high vehicle weights or high speeds. However, tire wear was accented as tire caster and camber were changed in relation to travel. Extended tests were not run on these configurations, but the greater the slip angle of the tire, the greater the tire and stripe wear.

Short-term tests (less than 10,000 cycles) produced only slight smudging of test stripes with no wear. After almost a million cycles, pronounced wear occurred at the leading edge of a stripe, especially at points over exposed aggregate. Conventional paints barely survived a half million cycles, while epoxies only showed marginal wear after five million cycles.

A few brief experiments were run with studded tires but severe vibration, stud loss, and quick grooving of paint stripes prevented further evaluation.

c. Surface factors and observations

Whereas conventional striping failed by grit and grime smudging across the tire-tracked area, epoxies abraded only slightly on the peaks of the exposed aggregate. This wear characteristic was more pronounced at sub-freezing temperatures at the leading edge of the epoxy stripe. Wear intensity is less severe on warm, flexible surfaces than on cold, hard surfaces.

Because of the continuous tire pressure across the test surface, bituminous test surfaces had to be fiberglass/epoxy reinforced for added strength.

D. Conclusions and Correlations

The following list of paints were evaluated on the simulated highway wear tester:

Epoxies	Urethanes	Control Paints
E-25	U-5	Franklin Chlorinated Rubber
E-26	U-8	Gleem Alkyd
E-42		Thermoplastic
E-45		

1. Short-term Tests

The relative short-term performance (less than 10,000 cycles) of the above listed materials with respect to temperature, surface, and vehicle speed are tablulated in Table 9. The following conclusions can be drawn about each type of material in the unbeaded form.

Epoxies

a. Epoxies showed the least wear of all stripes by simulated snowplow and tire tests.

b. Epoxies tend to crack at warmer temperatures on the more flexible pavement when subjected to simulated tire wear.

c. On all surfaces there was little difference in wear, E-45 was slightly cleaner than E-26 or E-25. E-42 tended to peel in the few test runs utilizing the simulated plow.

Urethanes

a. Urethanes tend to abrade and peel. They peel when snowplowed at low temperatures and abrade when subjected to tire wear at warm temperatures.

b. Poorer adhesion on portland cement concrete than on asphalt concrete surfaces was noted for urethanes.

c. Urethanes became dirtier from wear at lower test temperatures than epoxies but not as dirty as conventional traffic paints.

Alkyd Paints

a. Alkyd paints tended to smudge and crack, especially at warmer temperatures on asphalt concrete surfaces.

b. Alkyd paints tended to abrade and became dirty when tested at lower temperatures.

c. The rate of speed of the plow or tire tests had little effect on alkyd paint stripes; wear was essentially related to the number of cycles of either test procedure.

Thermoplastics

Thermoplastic samples were not obtained until after short-term testing was concluded.

2. Long-term Results

Extended wear tests (greater than 10,000 cycles) were run on the paints listed above. Whereas short-term evaluations did not utilize glass beads, test slabs in long-term evaluations contained both a beaded and unbeaded stripe. As previously indicated for beaded specimens, Massachusetts Specification M7.01.07 glass beads were sprinkled onto fresh cast paints at rates of six pounds of beads per gallon of paint.

Bead-wear Mechanism

Extended wear tests were performed on both beaded and unbeaded stripes. Stripes containing beads generally retained stripe integrity and night visibility longer than their unbeaded counterparts. (The mechanisms of bead failure due to simulated snowplow and tire tests were studied microscopically.

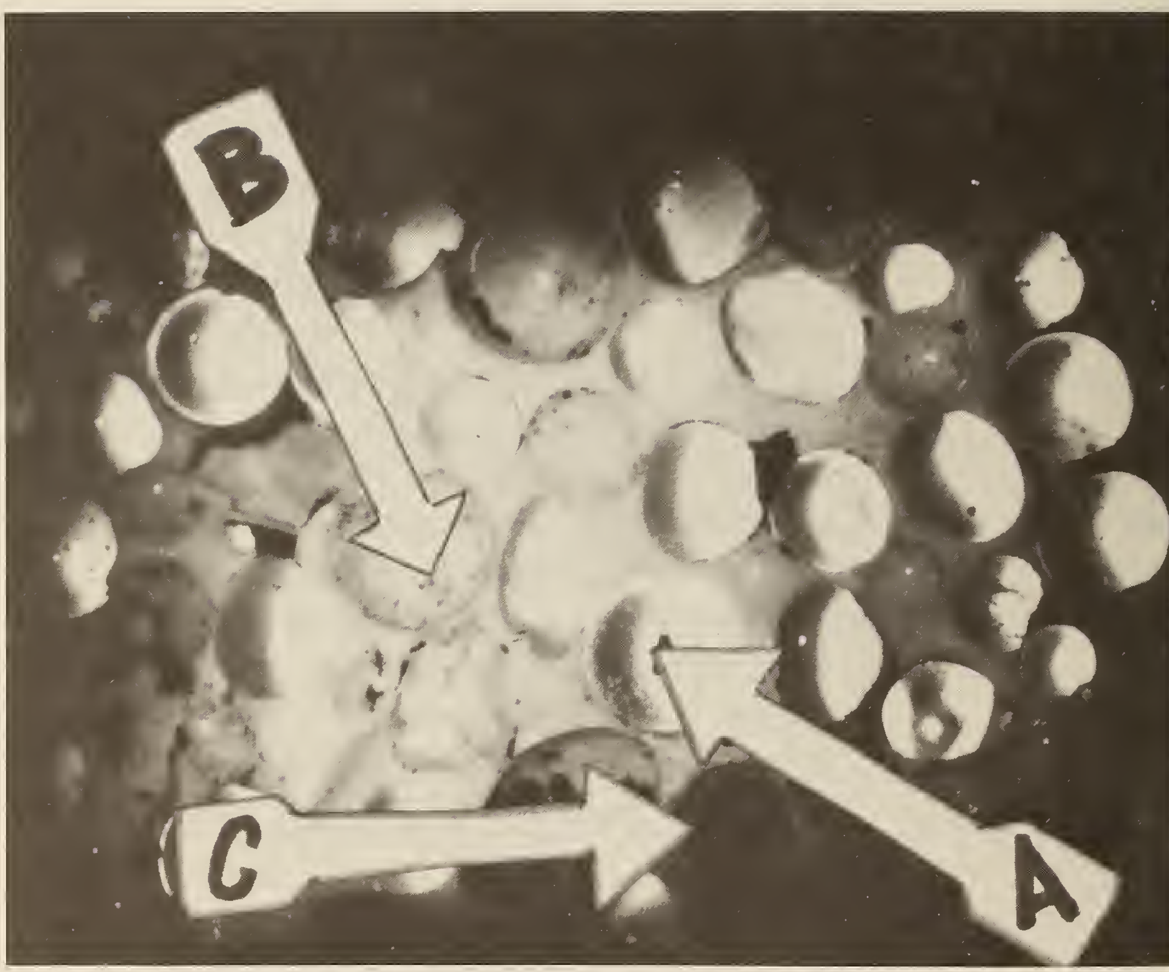
a. Bead-wear mechanism associated with tire testing

   When a rotating tire contacts a glass bead imbedded in a highway stripe, the entire momentum of the vehicle is impacted on the inelastic bead and transferred to the matrix itself or at the interface between the bead and paint. In simulated traffic tests on the study striping materials, all the materials, except the thermoplastic, showed tire-related bead failures resulting in stripe discoloration. Bead loss in highway stripes and subsequent filling of the bead holes with road grit or dust gives a stripe a dirty appearance. Figure 6 is a photograph depicting the above mentioned conditions resulting from simulated tire wear tests.

b. Snowplow

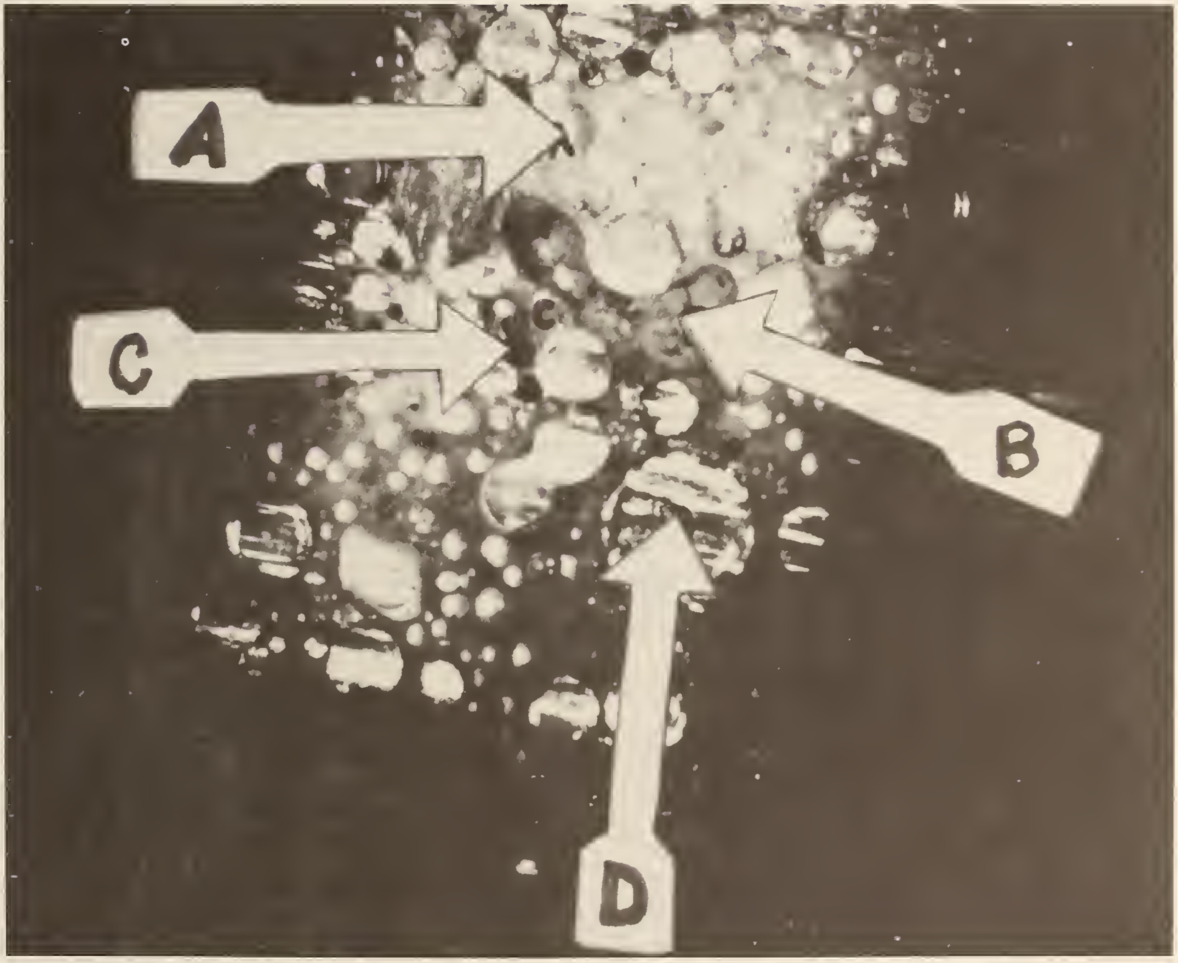
   In addition to the effects on beads noted for simulated tire wear, simulated snowplow wear produces another type of bead failure mechanism, a shearing of beads. Figure 7 is a photograph of a beaded area sheared by a snowplow. The smaller, untouched beads were still intact while the larger beads were either sheared or dislodged. Although sheared beads were found in all test paints, epoxy paints showed more than urethanes, conventional paints, and thermo-

FIGURE 6. SIMULATED BEAD WEAR (TIRES)



A - Intact bead; B - Empty bead hole; and C - Empty bead hole filled with grit (40X)

FIGURE 7. SIMULATED BEAD WEAR (SNOWPLOW)



A - Intact bead; B - Empty bead hole; C - Empty bead hole filled with grit; and D - Sheared bead (40X).

plastics. As seen in the photo, sheared beads still offer some night retroflective capabilities.

Extended simulated snowplow test results are listed in Table 11, while simulated tire results are listed in Table 12. In addition to day inspection of stripes, a light beam was incidentally projected across the surface in a dark room to determine relative night retroreflectance. Retroreflection angles replicated actual street conditions. Photographic slides were taken and slides compared to determine their relative night retroreflection.

Bead retention was evaluated microscopically by performing bead counts across several areas of test stripe. The results are listed in Table 13. The following conclusions can be drawn about each type of beaded material subjected to long-term tests.

Epoxies

a. On extended wear tests, the epoxies show the least wear of all stripes by both snowplow and tire tests.

b. Epoxies tend to retain beads longer than conventional paints and thermoplastics, thus increasing stripe life.

c. Bead loss is slightly faster in the more flexible E-25 and E-26 systems.

d. Bead loss is about the same for tire and snowplow wear.

TABLE 11. LONG-TERM SIMULATED SNOWPLOW WEAR TESTS
(Fresh bituminous at $0^{o}C$, 8 MPH and 1500 pound plow)***
Visual Observations

STRIPE	750,000 CYCLES			2,000,000 CYCLES			5,000,000 CYCLES			8,000,000 CYCLES		
	VISIBILITY		BEAD**	VISIBILITY		BEAD	VISIBILITY		BEAD	VISIBILITY		BEAD
	DAY	NIGHT	RETENTION	DAY	NIGHT	RETENTION	DAY	NIGHT	RETENTION	DAY	NIGHT	RETENTION
Gleem	F*	P	30/10/60	F	P	30/10/60	F	P	30/--/70	F	P	10/5/85
Chlorinated R.	F	P	10/--/90	P	P	5/--/95	N	N	5/--/95	N	N	None Visible
Thermoplastic	P	P	None Visible	N	N	None Visible	N	N	None Visible	N	N	None Visible
E-3	E	E	90/10/--	E	E	85/10/5	E	E	90/10/--	G	E	20/75/5
E-25	E	E	90/10/--	E	E	85/10/5	E	E	75/20/5	F	G	--/70/30
E-26	E	E	90/10/--	E	E	80/20/--	E	E	80/20/--	G	E	30/65/5

* Rating System:

Non-existant → Poor → Fair → Good → Excellent
N P F G E

** % beads intact/% beads sheared/% beads missing.

*** 8 MPH = 12.875 kilometers per hour
1500 pounds = 680.4 kilograms

TABLE 12. LONG-TERM SIMULATED TIRE WEAR TESTS
(Fresh concrete at $0^{\circ}C$, 8 MPH and 3,000 pound Vehicle)***
Visual Observations

STRIPE	750,000 CYCLES VISIBILITY DAY	NIGHT	BEAD RETENTION**	2,000,000 CYCLES VISIBILITY DAY	NIGHT	BEAD RETENTION	5,000,000 CYCLES VISIBILITY DAY	NIGHT	READ RETENTION
Gleem	E*	E	80/20	E	G	70/30	G	G	50/50
Chlorinated Rubber	E	E	80/20	G	G	70/30	G	F	50/50
Thermoplastic	E	P	None visible	E	P	Couple visible	E	F	Very few visible
E-3	E	E	100/0	E	E	95/5	E	E	95/5
E-25	E	E	100/0	E	E	95/5	E	E	90/10
E-26	E	E	95/5	E	E	90/10	E	E	80/20

* Rating System: Non-existant → Poor → Fair → Good → Excellent
N P F G E

**% beads intact/% beads gone.

*** 8 MPH = 12.875 kilometers per hour
3000 pounds = 1360.8 kilograms

TABLE 13. MICROSCOPIC ASSESSMENT OF BEAD RETENTION ON EXTENDED WEAR TESTS

STRIPE	INITIAL		AFTER 5 MILLION TIRE CYCLES		AFTER 8 MILLION SNOWPLOWING CYCLES		
	% AREA EXPOSED BEADS*	% BEADS LOST**	% AREA EXPOSED BEADS	% BEADS LOST	% AREA EXPOSED BEADS	% SHEARED***	% BEADS LOST
Thermoplastic	--	--	4%	40%	Indistinguishable		
Gleem Alkyd	27%	26%	16%	50%	8%	30%	62%
Chlorinated Rubber	23%	25%	15%	68%	5%	15%	72%
E-3 Epoxy	41%	0%	38%	6%	36%	70%	13%
E-25 Epoxy	30%	0%	29%	11%	19%	65%	25%
E-26 Epoxy	31%	4%	23%	20%	20%	60%	28%

* % area exposed beads is the number of beads times the area of an average 50-mesh bead per square inch**** of stripe at 20 magnifications.

** $\%\ \text{beads lost} = \frac{\text{No. beads lost} \times 100\%}{\text{No. beads lost} + \text{No. beads present}}$ per square inch at 20 magnifications.

*** $\%\ \text{sheared} = \frac{\text{No. beads sheared}}{\text{No. sheared} + \text{No. lost} + \text{No. intact}} \times 100\%$ per square inch at 20 magnifications.

**** A square inch = 645.2 square millimeters

e. Tires eventually dislodge beads from epoxy, whereas a majority of beads are sheared from the epoxy by the snowplow.

Urethanes

a. Because of their rapid peel rates, urethanes were not run in extended wear tests.

Conventional Paints

a. Paints were severely worn and smudged during the extended wear tests.

b. Paints lost beads faster than any of the materials tested.

c. The rate of bead loss was approximately the same for plow and tire wear.

d. The effective exposed bead area was 30 to 50 percent less than the epoxies, yielding less night visibility and shorter wear life.

Thermoplastics

a. By the nature of their thickness, 20 to 125 mils (0.5 - 3.1 mm), thermoplastic stripes are severely damaged by snowplows.

b. The snowplow dislodges matrix and beads in large chunks.

c. Tire wear is very slow on the thermoplastics and likewise the advent of night retroreflection. Beads are exposed as the thermoplastic wears away.

d. Bead loss by tire wear was 40 to 50 percent of the number exposed.

e. Exposed beads never comprised more than 5% of the total surface area. This resulted in poor night retroreflection.

f. The life of the stripe could not be determined since tire wear tests were curtailed after five million cycles.

IV. ROAD TEST RESULTS

A. Road Test Procedure

The epoxy and urethane paints evaluated in simulated wear tests, along with several control paints, were hand applied to stretches of highway to determine their performance and establish a correlation with simulated wear results. Two sets of stripe applications took place: one during October of 1975 and a second during October of 1976.

1. Selection of Test Sites

Four test sites were ultimately chosen by the Massachusetts State Highway Department, Federal Highway Administration, and Amicon for hand application of test stripes.

Route 1, Danvers, Massachusetts

Route 1 in Danvers, Massachusetts, is a 27-year old, two-lane, portland cement highway severely eroded by 17,000 cars per day and 60 snowplowings per season. Because of the age of the road, most of the test area consists of exposed base aggregate and a few exposed reinforcing rods. Stripes were cast in the passing lane of the south-bound side.

Route 128, Lynnfield, Massachusetts

Route 128 in Lynnfield is a three-lane, 14-year old bituminous highway worn and eroded by 25,000 cars per day and 60 snowplowings per season. Stripes were cast on the inside travel lane of the south-bound side.

York Beach, Maine

A fresh bituminous surface runs along the Maine coast at York Beach. Crosswalk stripes were applied on this relatively unworn surface and subjected to heavy winter plowings. Storms during the winter carry rocks, sand, and debris up onto the road and are then plowed back onto the beach. Winter automobile traffic was nil. The highway is about 10-15 feet (3 - 4.6 m) above sea level and the distance from normal high tide to the road varies from 20 to 125 feet (6.1 - 38.1 m).

The combination of the three sites provides an aged bituminous surface with high traffic density and moderate snowplowing; an aged concrete surface with high traffic density and moderate snowplowing; and a fresh bituminous surface with minimal traffic density but maximum environmental wear. At a fourth site parallel stripes were applied to a selected area of the Amicon parking lot. These were snowplowed about 50 times during the winter but received virtually no traffic overlay. Their purpose was to clarify the effect of snowplowing in the absence of traffic density.

2. First Application

Prior to the first application of test stripes to the two highway and the York Beach sites, a practice area was established on the bituminous surfaced Amicon parking lot. The application technique developed was to first outline the four-inch wide stripe areas in masking tape. To speed this procedure, a folding wooden pattern of three sections, four inches by five feet, was stretched out and outlined with tape. The materials were packaged in pre-measured kits containing enough material to cover the stripe area at 0.010 - 0.015 inch (0.25 - 0.38 mm) thickness. The material was mixed and then poured along the length of the stripe. A second man followed immediately with a trowel to spread the material uniformly, while a third man used a brush to insure wetting and coverage of the whole area. If glass beads were to be added, a fourth man followed immediately behind shaking beads onto the surface.

a. Test pattern

Three sets of transverse stripes were cast at each of the Route 1 and Route 128 localities. Figures 8 and 9 depict the stripe layout. Each set consisted of 15 feet by 4 inches (4.6 meters by 102 mm) stripes, each approximately 10 to 15 feet (3.0 to 4.6 meters) apart. Sets were placed 40 to 60 feet (12 to 18 meters) apart. The first set at each site consisted of unbeaded 15-mil (0.38 mm) stripes. The second set was beaded, while the third was unbeaded. All three sets were cast in an identical sequence of materials.

At the Route 1 site, stripes began just over the crest of a hill and proceeded down the hill to the bottom. No turnoffs occurred throughout the length of the striping area but did occur several hundred feet beyond the third set.

On Route 128, the three sets of stripes were cast on the inside travel lane. This stretch of road is relatively straight and flat with the nearest turnoff about one-half mile (1.6 kilometers) away.

At York Beach in Maine, test stripes of the study formulations were placed alongside crosswalks. The study formulations were placed in randomly selected

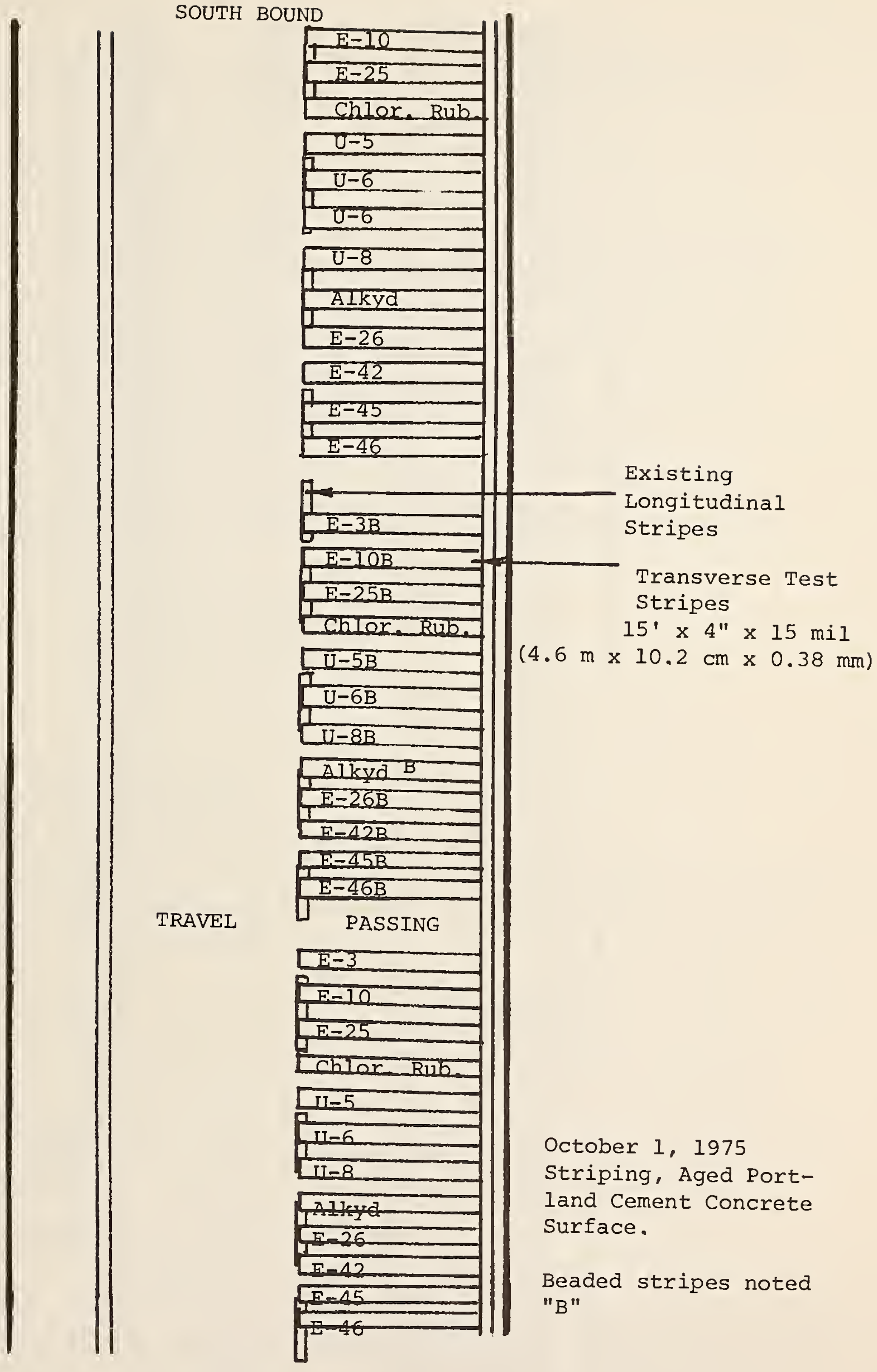


FIGURE 8. ROUTE 1 DANVERS, MASSACHUSETTS, STRIPING LAYOUT

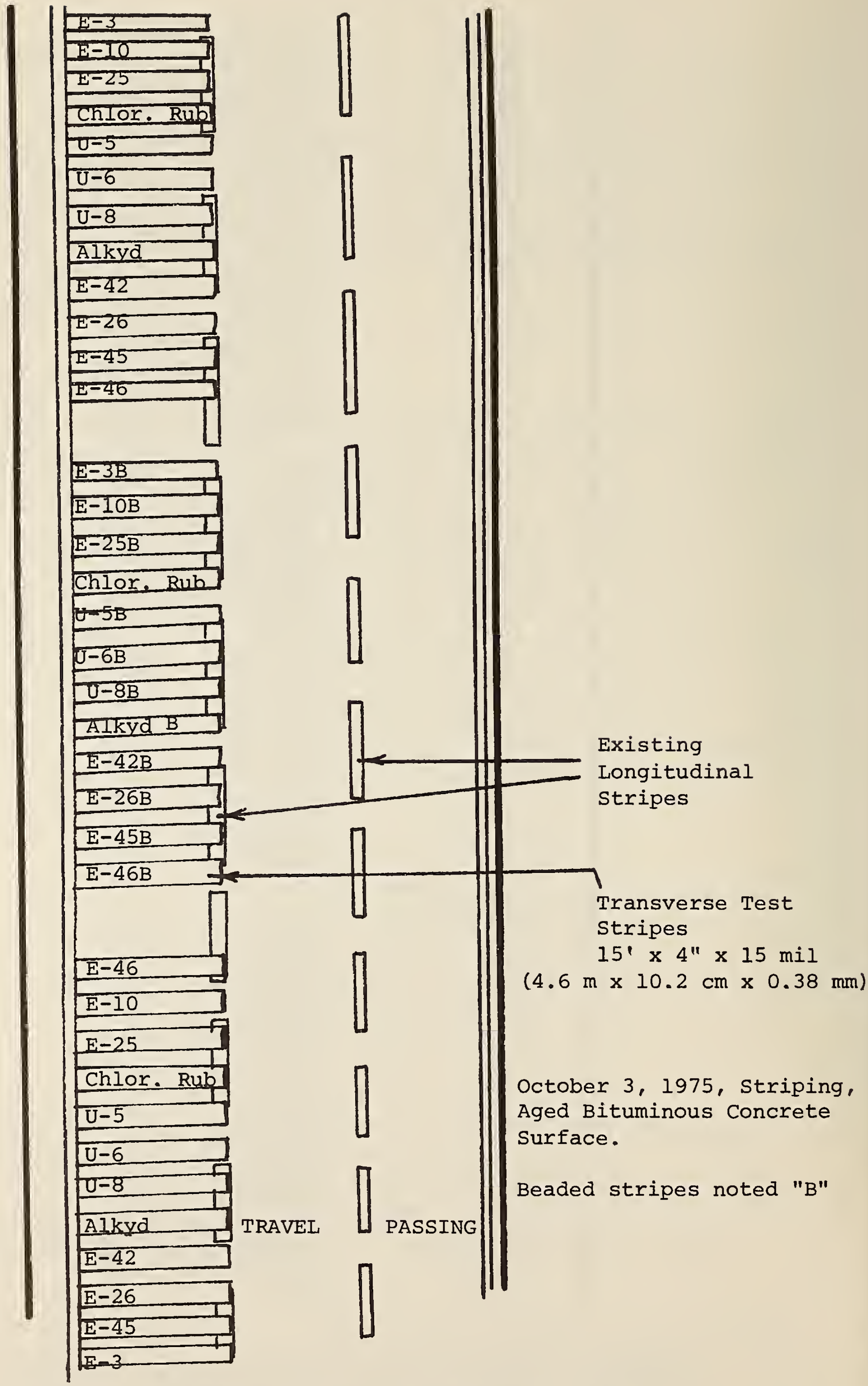


FIGURE 9. ROUTE 128 LYNNFIELD STRIPING LAYOUT

locations. In Figure 10 the beaded stripes are suffixed with a B.

b. Formulations

Formulations used in the first highway application of test striping were: epoxy formulations coded E-3, E-10, E-25, E-26, E-42, E-45, and E-46; polyurethane formulations coded U-5, U-6, U-8; alkyd paint and chlorinated rubber paint. Detailed information concerning their composition is listed in Section II.B. The fillers used in all the experimental materials is 40% (by weight) and is composed of:

Titanium dioxide	50%
Silica	30%
Clay	10%
Talc	10%

c. Application

Striping began on Route 1 in Danvers about 9:45 a.m. on October 1. Highway department crews blocked off traffic and set up cones. Stripes were placed in the passing lane and also extended about three feet into the travel lane. Air temperature was about 55°F (12.8°C) when we began and about 75°F (24°C) when we finished at about 2:30 p.m. The temperature of the road surface remained below 70°F (21°C) all day. Figure 11 illustrates the application technique used on Route 1.

On the following day it rained so striping on Route 128 was postponed until October 3. Again, the Mass. D.P.W. personnel controlled traffic. The stripes were placed in the right-hand travel lane and extended three feet into the breakdown lane. The

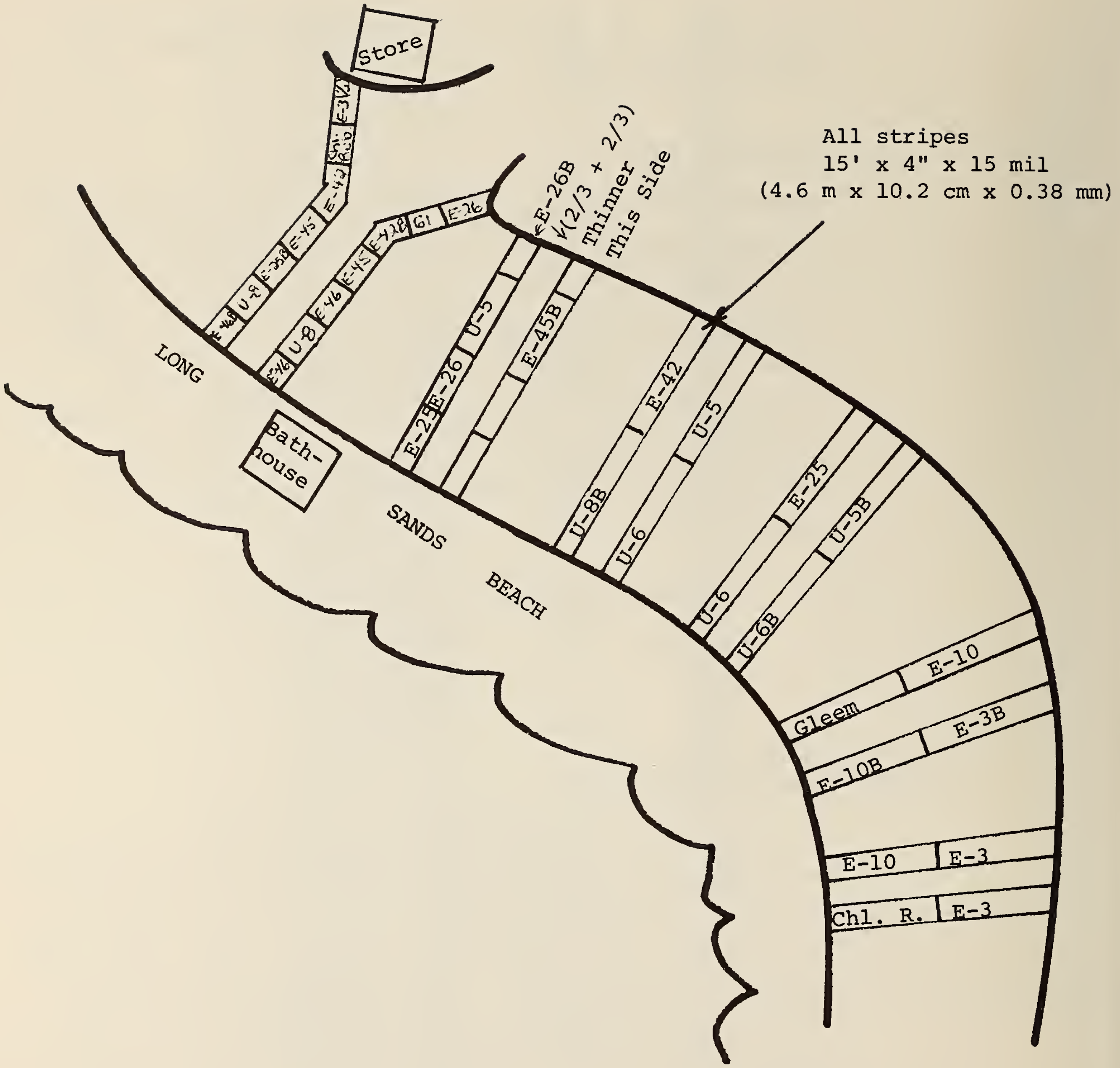


FIGURE 10. YORK BEACH STRIPING LAYOUT

October 6 & 7, 1976, Striping, Fresh Bituminous Concrete Surface.
Beaded stripes noted "B"

FIGURE 11. HAND APPLICATION OF LIMITED ROAD STRIPES (ROUTE 1)

order of application was slightly modified to enable slower curing materials a longer cure time. The temperature on October 3 was 45°F (7.2°C), a 10°F (5.6°C) cooler than the temperature during the Route 1 application.

The following week on October 6 and 7 the stripes were applied in York Beach, Maine. Fifteen foot stripes were placed beside crosswalks over a 200-yard section of road. Application temperatures for both days were about 55°F (12.8°C) and comparable to those experienced on Route 1.

The relative ease of hand application of the study materials was judged as follows:

(1) E-3. Good flow out. Easy to apply. Good bead adhesion. Tack free or set in approximately one-half hour at ambient conditions.

(2) E-10. Same handling as E-3; sets slightly faster.

(3) E-25. Did not flow as well as E-3; higher viscosity and sets slightly slower.

(4) Chlorinated Rubber (Smith Paint - Mass. Spec.). Skinned rapidly. Poor bead wetting on part of stripe.

(5) U-5. Flow out was fair. Some brush marks retained. Good bead wetting.

(6) U-6. Very difficult to spread.

(7) U-8. Better handling than U-5. Slower drying than U-5.

(8) Alkyd (Baltimore Paint - Gleem 50 Sec.). Applied well but poor bead wetting on part of stripe.

(9) E-26. Very good flow and easy application. Good bead wetting. Fast set.

(10) E-42. Higher viscosity than E-26; flow out not as good. Good bead wetting and fast set.

(11) E-45. Almost identical to E-26.

(12) E-46. Very low viscosity, but also very slow dry. Was still slightly tacky at finish.

d. Inspection and results

Initially, stripes were monitored once a week without traffic protection. For several days after the stripes on U.S. 1 and Route 128 were applied, all of the unbeaded stripes except the alkyd became dirty gray. This color rubbed off easily and was apparently road and tire dirt since after the next rain all became clean and stayed clean. All of the beaded stripes remained clean looking throughout. Two of the experimental materials, the unbeaded U-6 polyurethane, began to peel off the road while the E-42, the mercaptan-cured epoxy, showed chipping. Otherwise, all the other stripes seemed to be in good shape.

Over the next several weeks of November, the U-6 yellowed and continued to peel, while the E-42 chipped more. All the rest of the materials continued to look good.

By the time December came, the U-6 had failed completely across the lane in a manner apparently similar to poorly-bonded thermoplastic striping. Apparently, the high viscosity of the material inhibited adequate wetting of the highway surface. Of the remaining urethanes, U-8 and U-5, U-8 was the better looking.

Both control materials had a minimum amount of chip damage with slight signs of wear in the main tire track area. For the seven epoxy materials, six were very similar, i.e., some stripe loss by chipping from apparent high spots in the tire track areas, but no signs of other wear or color change. However, E-42 striping contained several fairly large areas of missing stripe.

Glass bead retention on all epoxy and urethane stripes was excellent, while most all beads were gone from the controls. There seemed to be little to no significant difference between results on bituminous and portland cement concrete.

The most dramatic change in the stripes occurred over the cold period during the later part of December and early January of 1976. The alkyd, having the greater wear, and chlorinated rubber stripes were almost completely faded across the entire stripe. The urethanes, U-5 and U-8, were essentially gone in the tire track and almost completely gone outside the track area. All of the epoxies failed in varying degrees in the tire track area but had little or no failure outside the track area. E-25, E-26, and E-3 were the best of the epoxies.

By the advent of spring, all stripes showed some degree of failure in the tire track areas. Most stripes performed better on the portland cement concrete (Route 1) than on bituminous. In summary, the epoxies showed substantially greater durability than either the urethanes or the paints. Epoxies wore very little or not at all in the normal striping zones. Wear in the tire track area appeared to start at the aggregates rather than the binder. Impact, as opposed to peeling, erosion, or adhesion failure was the dominant mode of epoxy wear. The paints, both alkyd and chlorinated rubber, failed from a "top-to-bottom" erosion mechanism. The urethanes ultimately yellowed and peeled. Six month observations made on April 6 and May 5 are summarized in Table 14 and photographed in Figures 12 through 26.

In late July, a final inspection was made of the test stripes on Route 1 in Danvers and Route 128 in Lynnfield. (The York Beach stripes had been painted over and were of little further value.) All stripes were evaluated for day and night visibility, wear characteristics, and bead retention. The results are contained in Table 15. In brief, no discernible changes were noted in the epoxies in the four months since the April inspection; however, the control paints continued to fade and the urethane peeling was more prominent than before. Figures 27 and 28 illustrate the marginal differences in the stripes after six months of winter wear and four months of summer wear.

TABLE 14. FINDINGS OF APRIL 6 AND MAY 5 INSPECTION OF HIGHWAY TEST STRIPES

OVERALL CONDITION	SITE AND STRIPE MATERIAL			STRIPE APPEARANCE		
	ROUTE 128	ROUTE 1	YORK BEACH	VISIBILITY	WEAR CHARACTERISTICS	BEAD RETENTION
Good	E-25 Chl. R. U-8	E-3 E-25 E-10 E-26	E-3 E-25 E-10 E-26	Good, stripe mostly intact, tire track area almost gone.	Local chipping, some leading edge loss.	Dirty in some areas, beads still visible, decent night reflection.
Fair	E-3 E-10 U-5 E-26 E-45 E-46	E-45 E-46 U-5 U-8 Chl. R.	E-45 E-46 U-8 E-42 U-5	Fair, tire track area pretty much obliterated.	Mostly chipping, epoxies aggregate initiated on concrete.	Few beads in tire track area; many still visible at stripe ends.
Poor	E-42 U-6 Alkyd	E-42 U-6 Alkyd	U-6 Chl. R. Alkyd	Poor to nonexistent, worn badly, urethane severe peel, epoxy severe chipping, very little stripe remaining.	Severe peel in urethanes, paints abraded (fading).	No beads, holes or abraded smooth.

FIGURE 12. ROUTE 1 STRIPES (APRIL 6, 1976)

Composite view of first six stripes in first group on Route 1; facing northward. Listed in order, front to back:

#6 (closest) U-6; #5 U-5; #4 chlorinated rubber;
#3 E-25; #2 E-10; #1 (furthest away) E-3.

Note superiority of #3, #2, and #1 over #6, #5, and #4.

FIGURE 13. ROUTE 1 STRIPES (APRIL 6, 1976)

Composite view of all stripes in first group on Route 1; facing northward. These stripes listed in order, front to back:

#12 (closest) E-46; #11 E-45; #10 E-42; #9 E-26; #8 Alkyd Gleem; #7 U-8; then pretty much indistinguishable.

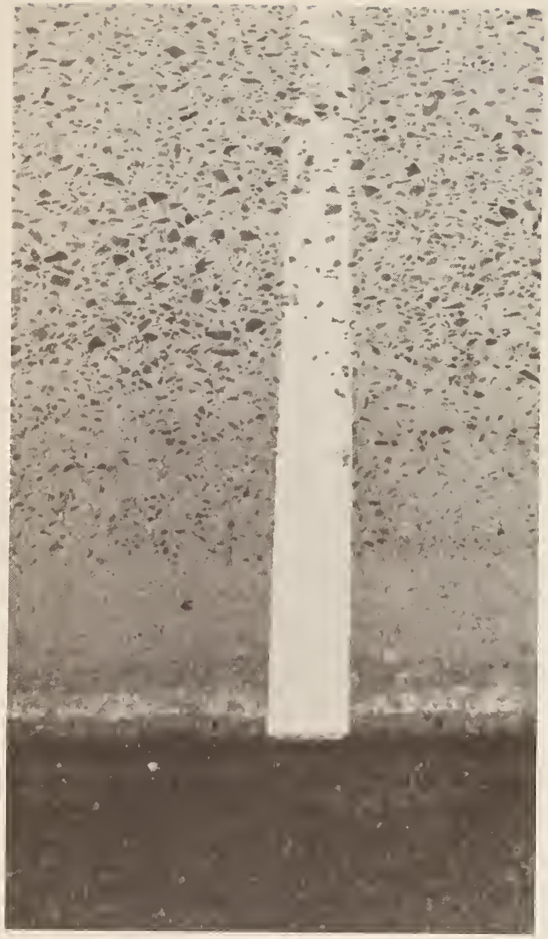


FIGURE 14. STRIPE #1 ON ROUTE 1

Curb shot E-3. Note chipping at aggregates.

FIGURE 15. STRIPE #4 ON ROUTE 1

Full shot. Chlorinated rubber. Note mostly worn away; discolored in center line region.

FIGURE 16. URETHANE STRIPE ON RT 1

Note loss of adhesion.

FIGURE 17: ROUTE 128 STRIPES (APRIL 6, 1976)

Composite view of first group of stripes on Route 128; looking southward. Listed front to back:

#1 (closest) E-3; #2 E-10; #3 E-25;
#4 chlorinated rubber; then the urethanes

FIGURE 18: ROUTE 128 STRIPE #4
CHLORINATED RUBBER

FIGURE 19: ROUTE 128 STRIPE #3
E-25

FIGURE 20: ROUTE 128 STRIPES (APRIL 6, 1976)

View of both Stripe #3 (E-25) and Stripe #4 (chlorinated rubber). Note also Stripes #5 and #6 (urethanes U-5 and U-6) at the top of the picture.

FIGURE 21: YORK BEACH STRIPE (E-3)

First crosswalk, north stripe. Foreground is chlorinated rubber control; background is E-3. Note abrupt discontinuity and severe degradation of control.(April 21, 1976).

FIGURE 22: YORK BEACH STRIPE (E-10B)

Second crosswalk, stripes at oceanside (camera faces north). Nearest is Gleem Alkyd Rubber control; furthest away is E-10B. (April 21, 1976)

FIGURE 23: YORK BEACH STRIPE (E-26 & U-6)

Third crosswalk, facing ocean. Foreground center is E-26; background left and right is urethane (both U-6). (April 21, 1976)

FIGURE 24: YORK BEACH STRIPE (U-8 & E-46)

Sixth crosswalk, southern stripe. Close-up shot of interface between U-8 (foreground) and E-46 (background). Large chip missing from U-8. (April 21, 1976)

FIGURE 25: YORK BEACH CROSSWALK (APRIL 21, 1976)

Fifth crosswalk, looking across from the oceanside across the road. Front-to-back listing:

Left	Right
(1) E-25 (closest)	(1) Gleem (closest)
(2) E-26	(2) Chlorinated rubber
(3) U-5	(3) E-45

FIGURE 26: ROUTE 1 STRIPE OVER-PAINTING

Photograph illustrating failure at locus of over-painting only (April 6, 1976)

TABLE 15: FINDINGS OF THE JULY 28 INSPECTION OF HIGHWAY TEST STRIPES

OVERALL	MATERIAL			APPEARANCE OF STRIPES		
CONDITION	ROUTE 128	ROUTE 1	YORK BEACH	VISIBILITY	WEAR CHARACTERISTICS	BEAD RETENTION
Good	E-25 E-26	E-3 E-25 E-26 E-10	Obscured	Dirty in tire track area, high gloss.	Going in tire track area, beaded better on concrete, wear at aggregate.	Dirt in tire track areas are filled bead holes, beads still found in median and stripe zones, few holes in these areas.
Fair	E-3 E-10 Chl. R. E-45 E-46 U-8	E-45 E-46	Obscured	Not continuous across lane, better at ends.	Tire track wear not much different from previous inspection, aggregate initiated chipping on concrete.	No beads in tire track areas for epoxies; no beads at all in chlorinated rubber or urethanes
Poor	E-42 Alkyd U-5 U-6	E-42 Chl. R. U-8 U-5	Obscured	Poor to non-existent, little stripe left in ends.	Gone in tire track area, going fast in other areas, worn more than on previous inspections.	No beads, holes in urethanes, abraded smooth in alkyd.

FIGURE 27: NON-BEADED STRIPES ON ROUTE 1 IN DANVERS (APRIL)

Stripes on Route 1 in Danvers (from back to front): E-3, E-10, E-25, and Chlorinated Rubber. Photographed on April 6 after six months of winter wear.

FIGURE 28: NON-BEADED STRIPES ON ROUTE 1 IN DANVERS (AUGUST)

Stripes (from back to front): E-3, E-10, E-25, and Chlorinated Rubber. Photographed on August 2, four months after Photo 1. The sky was overcast and pavement damp during this observation.

e. Conclusions

The significant findings relevant to our first hand-applied stripes are:

(1) Lane delineating areas were still ready for another season. The better epoxy systems were still satisfactory for day and night visibility in the lane-delineating region. While the urethanes and controls would require repainting before winter, the epoxies would not.

(2) No summer wear. No obvious deterioration in the epoxy stripes was experienced in the summer months. This is consistent with our hypothesis of cold-precipitated embrittlement failure. Of course, it is also consistent with snowplow-induced failure.

(3) Bead durability. A close examination of the epoxy stripes during daylight hours and observations made at night indicated the presence of beads in the stripes. None of the other striping materials were found to contain beads.

3. Second Application

A second set of hand-applied stripes were cast on October 19 and 22, 1976 on the two test surfaces previously employed (Route 1 and Route 128). Test patterns, formulations, and inspections differed from that of the previous set of stripes to enable correlation with laboratory simulated wear characteristics. All formulations were applied in the manner used previously.

a. Test patterns

In order to differentiate wear mechanisms, a series of test stripes were set that would offer graduated thicknesses for snowplow wear, transverse and longitudinal stripes to determine tire and environmental wear differences across the road. Figures 29 and 30 illustrate the patterns employed at both test sites. Each set of stripes was placed immediately in front of the previous application and in the same lane. Transverse stripes were 15 ft. by 4 inches by 15 mils (4.6 m x 10.2 cm x 0.4 mm); longitudinal stripes were 15 ft. by 4 inches by 15 mils (4.6 m x 10.2 cm x 0.4 mm); and graduated stripes were 1.5 ft. by 4 inches by 7, 30, 45, and 60 mils (46 cm x 10.2 cm x .2, .75, 1.1, and 1.54 mm). Care was taken not to cover any existing stripes.

The first series of alternating transverse and longitudinal stripes offered a comparison between both types of stripes and hopefully clarify discrepancies in both testing techniques. The second series of graduated stripes was designed to elucidate the effects of snowplowing on film thickness as well as clarify the gelling and spreading problems experienced in hand applying longer transverse stripes. The third series of longitudinal test stripes was applied to replicate the first series and eliminate any inherent road anomalies, i.e., bad surface, adverse traffic patterns, etc.

All stripes applied on both dates contained the six pounds of Mass. Spec. #M7.01.07 beads/gallon of paint. However, some of the thicker stripes required premixing of the beads with the paint, while

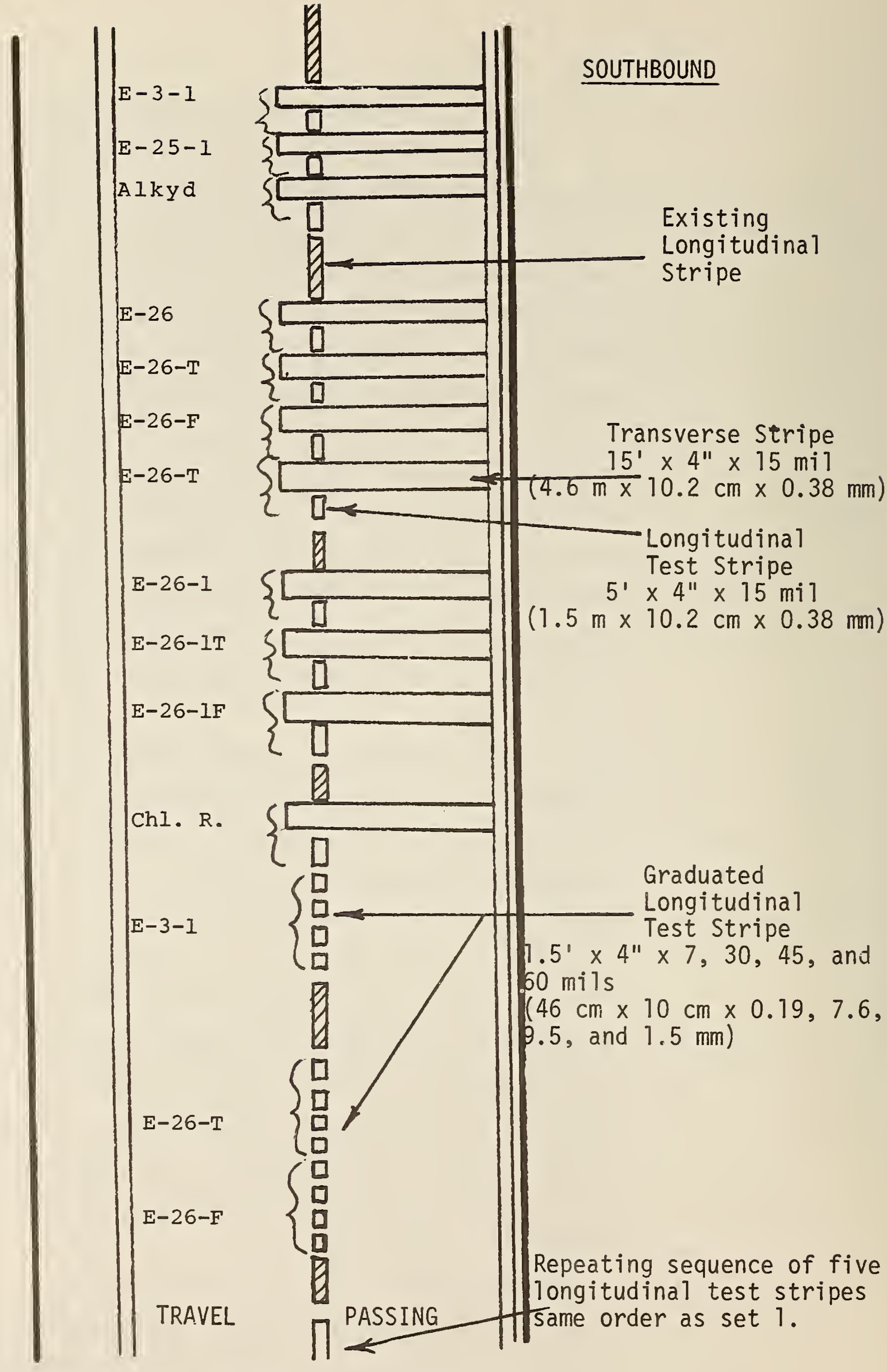


FIGURE 29: SECOND ROUTE 1 STRIPING LAYOUT

October 19, 1976, striping, aged portland cement concrete surface, all stripes beaded.

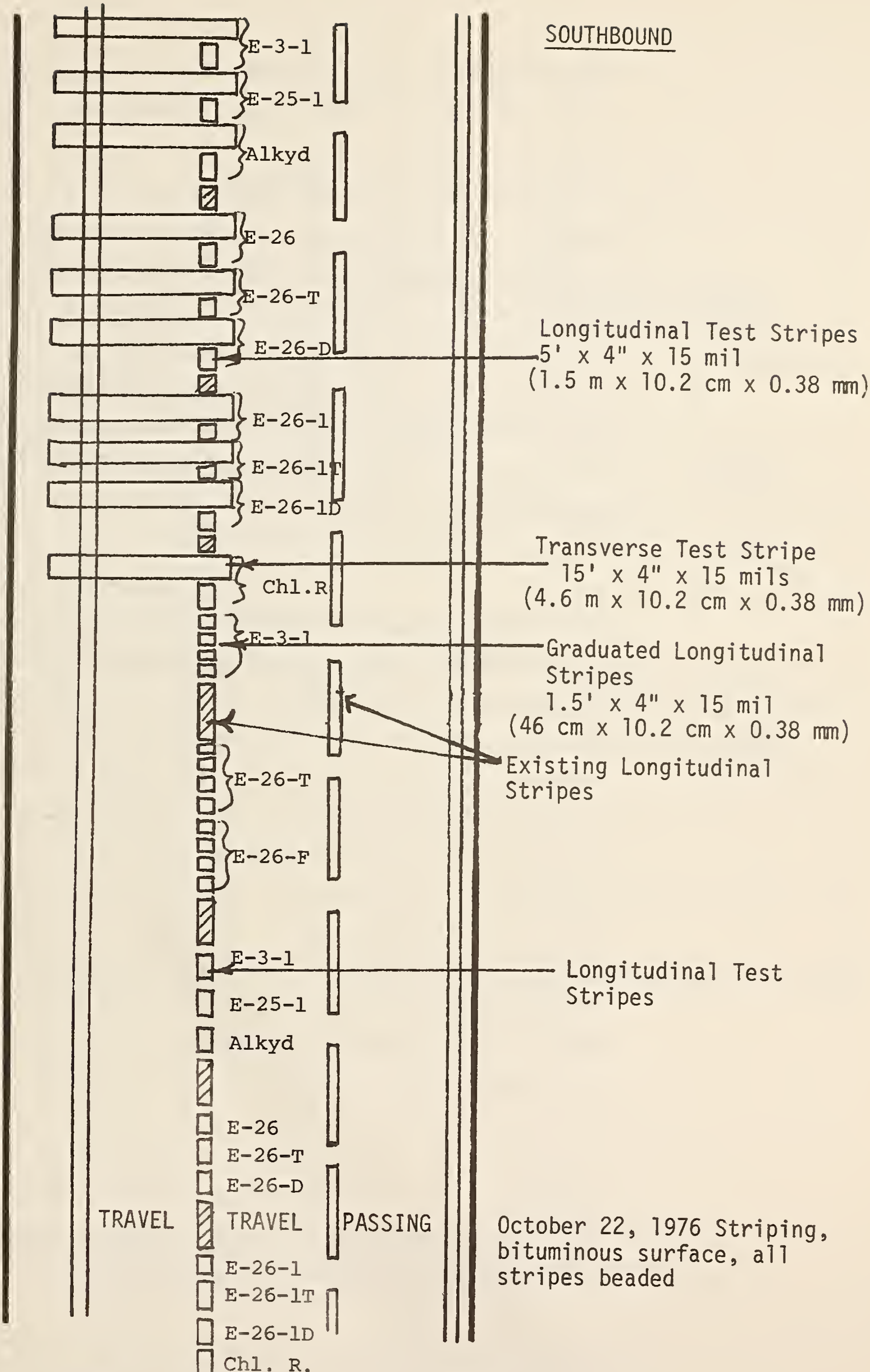


FIGURE 30: SECOND ROUTE 128 STRIPING LAYOUT

the thinner, conventional 15-mil (0.375 mm) stripes were gently sprinkled with beads after casting.

b. Formulational improvements

During the course of the first limited road applications, several observations suggested modifications in the existing E-3, E-25, and E-26 systems. The formulating strategy had been to increase the flexibility of the epoxy and the likelihood of realizing major performance improvements depends very much on the validity of our hypothesis that improved cold temperature flexibility was the key to longer epoxy stripe life.

Five formulations emerged from the preliminary screening as the most suitable candidates for inclusion in the second phase of limited road tests. One was rigid like E-26, had the same resin as E-26 on the "A" side and a much faster curing agent on the "B" side (five minutes no-track time at room temperature versus 12 minutes for E-26). This system was called E-26-1. The other four systems were rubber modified versions of E-26 and E-26-1. Two had only enough rubber to toughen them (designated E-26-T and E-26-1-T). The other two had enough rubber to keep them flexible at temperatures as low as $-31^{\circ}F$ ($-35^{\circ}C$). These were designated E-26-1-F and E-26-F. Figure 31 is a plot of hardness versus temperature for the six systems. In an homologous series, hardness is a good indication of modulus. The properties of these systems can be appreciated as follows:

A 15-mil drawdown of E-26 (or E-26-1) on a Q-panel will snap when the panel is bent about 15° on a

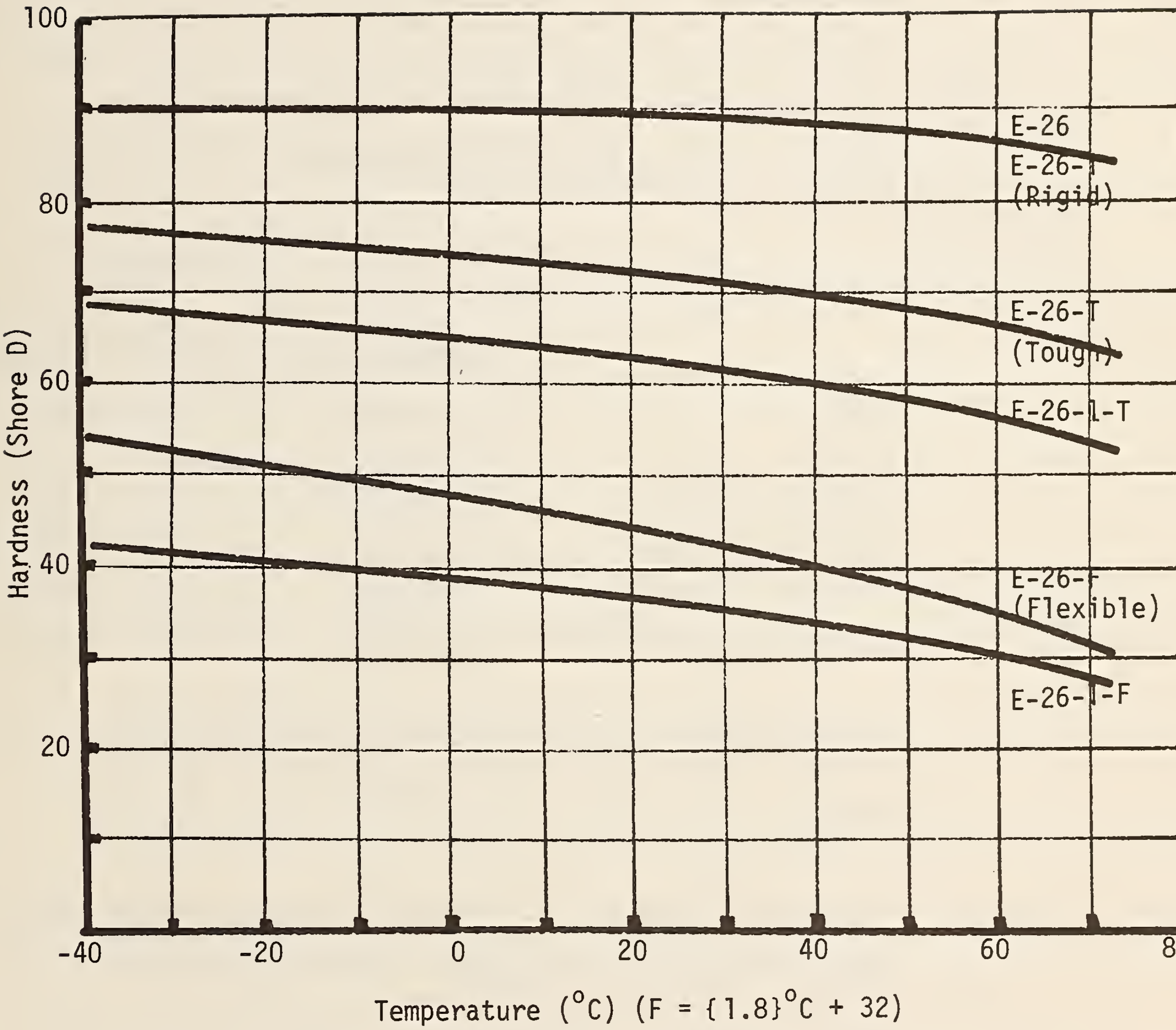


FIGURE 31: HARDNESS VERSUS TEMPERATURE CURVES FOR E-26 AND FOR NEW CANDIDATES FOR LIMITED ROAD TESTING (Hardness is employed as an index of modulus)

quarter-inch mandrel. Tough version (E-26-T or E-26-1-T) may be bent approximately 27° without snapping. The flexibilized version may be bent a full 360° and will not snap even when creased--even if the test is conducted on a panel at 32°F (0°C).

The no-track times of these systems are tabulated below:

	No Track @ Room Temperature	Mix Temperature for 3-Minute No-Track on Ambient Surface
E-26	12 minutes	175°F (79°C)
E-26-1	5 minutes	140°F (60°C)
E-26-T (tough)	5 minutes	150°F (66°C)
E-26-1-T (tough)	5 minutes	140°F (60°C)
E-26-F (flexible)	7 minutes	175°F (79°C)
E-26-1-F (flexible)	6 minutes	180°F (82°C)

Three-minute no-track times at 140°F to 150°F (60°C - 66°C) are very impressive for an epoxy system.

Figures 32 and 33 illustrate the degrees of toughness and flexibility which can be achieved by varying the amount of rubber in the system over the annual range of temperatures likely to be encountered on roads in northern temperate climates (only the 0%, the 25%, and 40% loadings will be road tested).

Ten striping paints (Table 16) were hand cast on both highway surfaces. Two controls, Franklyn Alkyd (Mass. Spec. #M7.01.01) and Franklin Chlorinated Rubber (Mass. Spec. #M7.01.10),

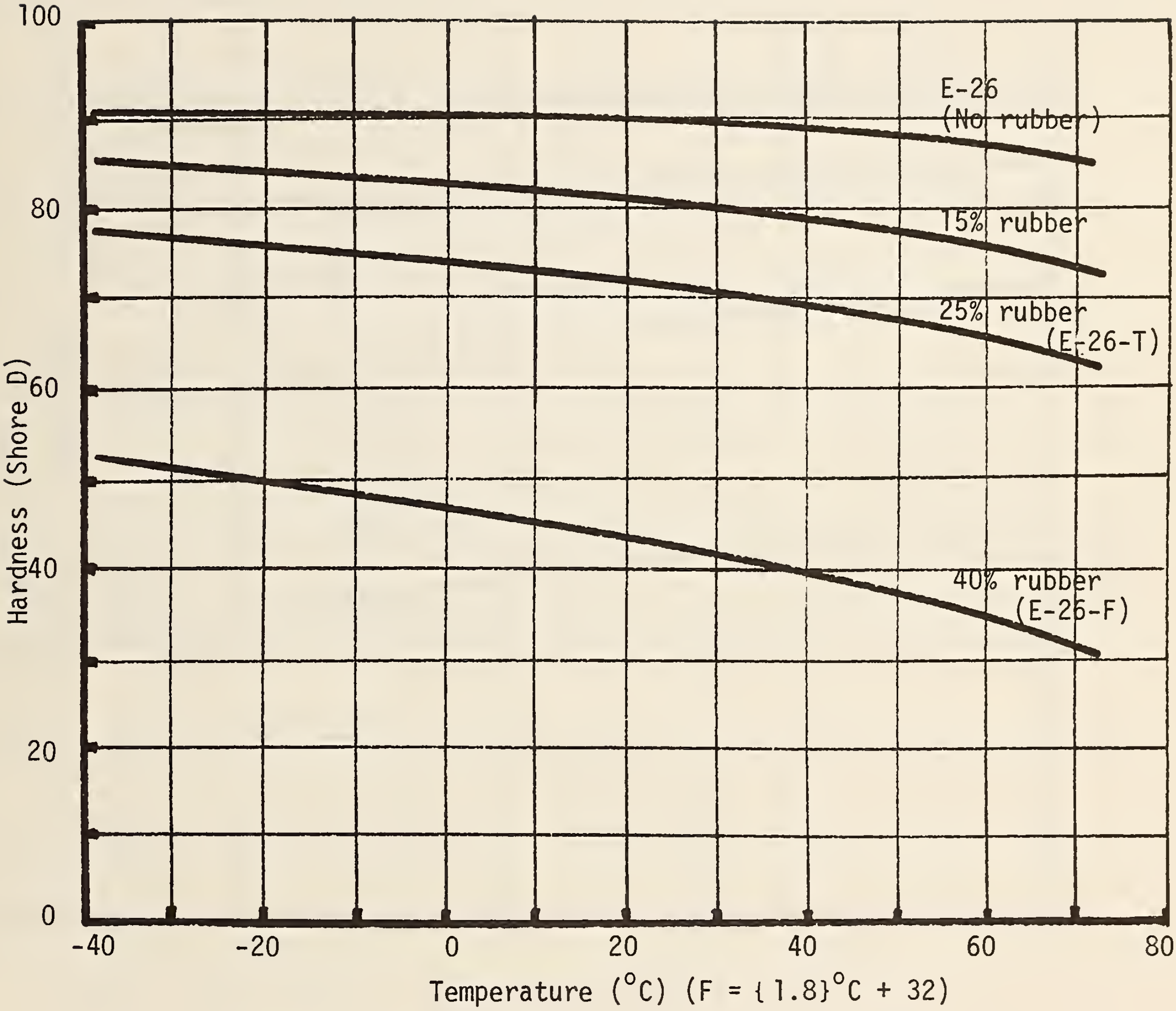


FIGURE 32: HARDNESS VERSUS TEMPERATURE CURVES USED TO ILLUSTRATE THE EFFECT OF RUBBER ADDITION TO THE E-26 SYSTEMS (E-26 was bead tested during the 75/76 winter.

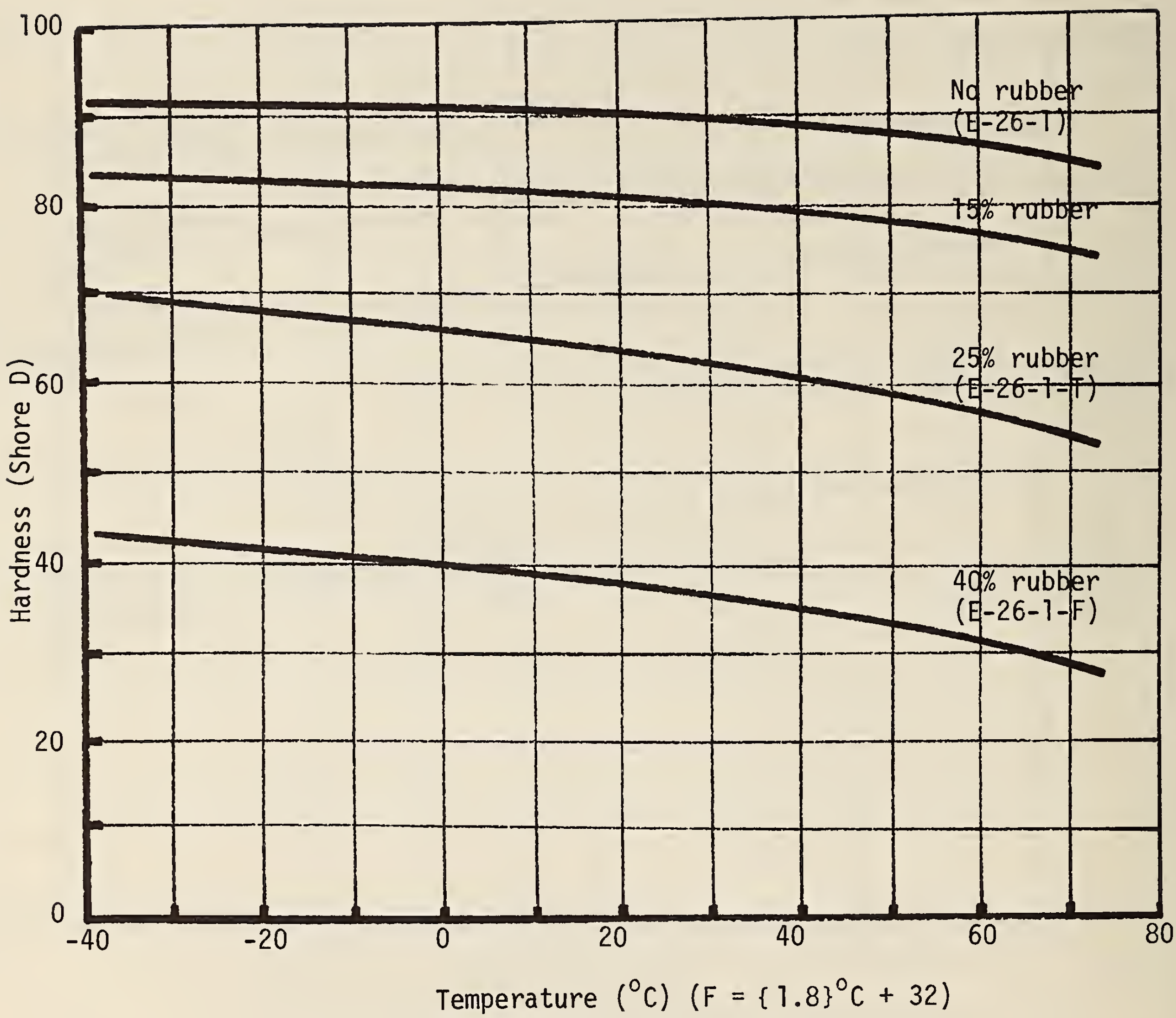


FIGURE 33: HARDNESS VERSUS TEMPERATURE CURVES USED TO ILLUSTRATE THE EFFECT OF RUBBER ADDITION TO THE E-26-1 SYSTEM (E-26-1 is a faster curing version of E-26)

TABLE 16: SECOND STRIPING FORMULATION

MATERIAL	MIX RATIO BY WEIGHT	% FLEXIBILIZER	COMPOSITION A COMPONENT	B COMPONENT
Paints				
Franklyn Alkyd	100	--	One component diluted 25% with toluene or xylene	
Franklyn Chl. Rubber	100	--	One component diluted 25% with toluene or xylene	
Epoxies				
E-3-1	5/1	--	Bisphenol A/ Epichlorohydrin Liquid epoxy resin	Modified aliphatic amine
E-25-1	6.5/1	--	Epoxy ester for more flexibility	Modified aliphatic amine
E-26	10/1	--	Modified polyepoxide	Aliphatic amine
E-26-D	2.6/1	10	Same as E-26 but with flexibilizer	Aliphatic amine
E-26-T	3/1	20	Same as E-26-D but more flexibilizer	Aliphatic amine
E-26-F	1/1.1	35	Same as E-26-T but more flexibilizer	Aliphatic amine
E-26-1	7.4/1	--	Same as E-26	Much faster aliphatic amine
E-26-1D	1.5/1	15	Same as E-26-1 but with flexibilizer	Much faster aliphatic amine
E-26-1T	1/1.9	25	Same as E-26-1D but more flexibilizer	Much faster aliphatic amine
E-26-1F	3/1	40	Same as E-26-1T but more flexibilizer	Much faster aliphatic amine

solvent-based paints were used. Both contain about 25% volatile solvent.

c. Application

On October 19, 1976, test stripes were applied to Route 1 in Danvers under the protection of the Massachusetts Department of Public Works. Air temperature at the onset of application was 45°F (7.2°C), relative humidity of 16%, road temperature of 50°F (10°C), and a light breeze of 5 to 10 miles per hour. Figure 29 illustrates the paints and pattern cast during the day. The first three control paints were applied with relative ease; however, increased mixing viscosity and rapid cure hindered uniform application of the toughened (T) and flexibilized (F) E-26 series. A repeat E-26-T stripe was mixed with a small quantity of solvent to ensure proper thickness control. The E-26-1 series proved to be less of an application problem. Beading the graduated stripes became a problem with the fast-curing materials and necessitated premixing some of the beads in the paint before casting. All thickness graduations contained the six pounds of beads/gallon of paint. By mid-afternoon, all the stripes were completed. Temperature had risen to 65°F (18.3°C), relative humidity dropped to 4%, road temperature rose to 65°F (18.3°C), and the wind had fallen off slightly. Cones were left for approximately one hour after the final stripe was applied.

Several days of rain and extremely high winds delayed the Route 128 application until Friday, October 22. During this delay the two flexibilized E-26 and E-26-1 versions on Route 1 began to peel severely. Both systems were scrapped from the Route 128 format and replaced with a system half as flexible as the T recipe. These recipes were called E-26-D and E-26-1-D.

A schematic of the Route 128 stripes in Lynnfield is represented in Figure 30. On Friday air temperatures were about the same as those experienced on Route 1 but winds and humidity were higher. No application problems were experienced and by mid-afternoon the stripes were finished. Air and road temperature fluctuations replicated those recorded on Route 1 during the same application period.

d. Inspections

Route 128 was inspected daily and Route 1 weekly. Closer inspection with the protection of the Mass. D.P.W. was conducted on December 10 and without protection on January 17. To document wear patterns each stripe was photographed immediately following application, again on December 6, and on January 18. In addition to visual and photographic monitoring, a daily record (Figure 34) was maintained for daily high and low temperatures, precipitation, and road surface maintenance schedules.

e. Observations

Three or four distinct changes occurred during the first four months of observation. Except for the peeling of the two flexibilized epoxies immediately following application, none of the stripes showed any change or wear until the end of November. Even after the early three-inch snowfall on November 10, which required a plowing and some salting, the 60-

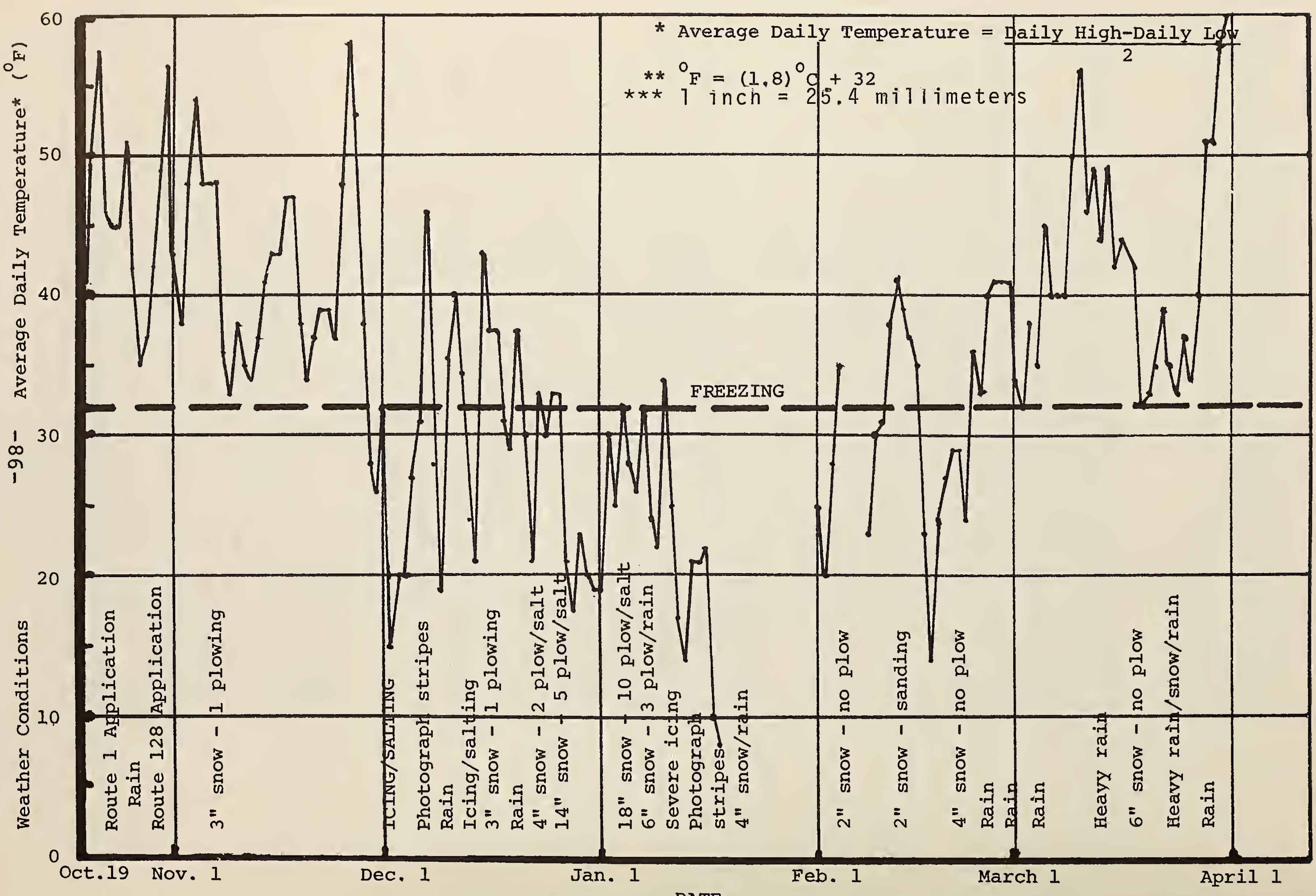


FIGURE 34: AVERAGE DAILY TEMPERATURE AND ENVIRONMENTAL CONDITIONS AT ROUTE 1 AND ROUTE 128 STRIPING TEST AREAS

mil graduated stripes showed no ill effects of plowing. November was unseasonably warm and dry for New England, with the last few days of the month experiencing a record high temperature of almost 70°F (21°C).

Winter's freezing temperatures came on rapidly. As the average daily temperature sank below freezing, the transverse stripes began to change radically. Chipping became extensive on the control paints, especially in the tire track areas. The epoxy formulations also began chipping or peeling in the tire track areas at places where the aggregate was prominent. For three or four days temperatures remained below freezing and stripes continued to deteriorate.

After the first week of continuous cold temperatures, the next couple of weeks were somewhat anti-climactic. The next major change in the stripes occurred several days after Christmas as the long-awaited snows came. Heavy snow smothered the striping areas for the following two weeks. Almost 50 inches of snow fell in 17 days, equaling the total snowfall for the entire previous year. Snow-plowing, salting, and sanding were extensive during this period. For the last ten days of this period, the stripes on Route 128 were completely concealed by hard packed snow and ice and were never in direct contact with traffic.

Very little snow fell in the interim between the blizzards of January and the final inspection of stripes in April. The epoxies changed very little, if any, since January. The paints were almost completely gone.

f. Results

(1) Transverse stripes

Photographs of the stripes taken at the initial application of the stripes and during the December, January, and April inspections were compared. A 20-point rating system was established (see Table 17) to evaluate performance of the various stripes. Figures 35 and 36 illustrate the performance (durability) evaluations,based on the 20-point system, given to candidate stripes, initially and at inspection times at each of two test sites. Generally, Route 128 stripes were better than their Route 1 counterparts. This may be attributed to greater pavement flexibility and the ice layer covering the stripes during plowing and tire traffic. All of the failure during the first cold week of December was either chip or peel initiated at the aggregate in the tire track areas. During the subsequent weeks of severe ice, snow, saltings, and plowings, chip and peel failure continued. Stripes got dirtier, lost beads, and degraded by abrasion.

On Route 1, the control paints, and the epoxies, E-3-1, E-25-1, and E-26, showed little wear in December but failed almost 50% during the snows. Meanwhile, the flexibilized E-26 series exhibited more peel during December than the E-26 but the peeling tapered off and it was better than the controls. As of January 18, the E-26-T epoxy formulation was marginally better than E-26, E-26-F, E-3, and E-25. The best stripe on Route 1 during the entire season

TABLE 17. RATING OF TRANSVERSE STRIPE WEAR

WEAR	RATING NO.	ROUTE 1			ROUTE 128		
		DECEMBER	JANUARY	APRIL	DECEMBER	JANUARY	APRIL
New	20						
	19	E-26-1T			E-3, E-26-1T, E-26-1, E-26-T, E-26-D		
	18	E-25			Alkyd, Chl. R., E-26		
	17	E-26					
	16	E-3	E-26-1T		E-25, E-26-1D	E-3	
Minor chip, minor wear	15	E-26-1		E-26-1T			E-3
	14	Alkyd					
	13	Chl. R.					
	12	E-26-T				E-26-1T	E-26-1T
	11	E-26-F				E-26-D, E-26	
Tire track wear, mod. chip	10	E-26-1F				E-25	
	9		E-26-1			E-26-1	E-25, E-26
	8		E-26-T	E-26-1		E-26-T	E-26-D
	7		E-25, E-26-F			E-26-1D	E-26-T
	6		E-26	E-26		Alkyd,Chl. R.	
Tire track gone, heavy chip	5		E-3	E-3			Alkyd
	4				E-26-1F		E-26-1
	3						Chl. R.
	2		E-26-1F	E-26-T with solv.			
	1		Alkyd,Chl. R	E-26-T, E-26-1F, E-26-F			
Gone	0			Alkyd,Chl.R.			

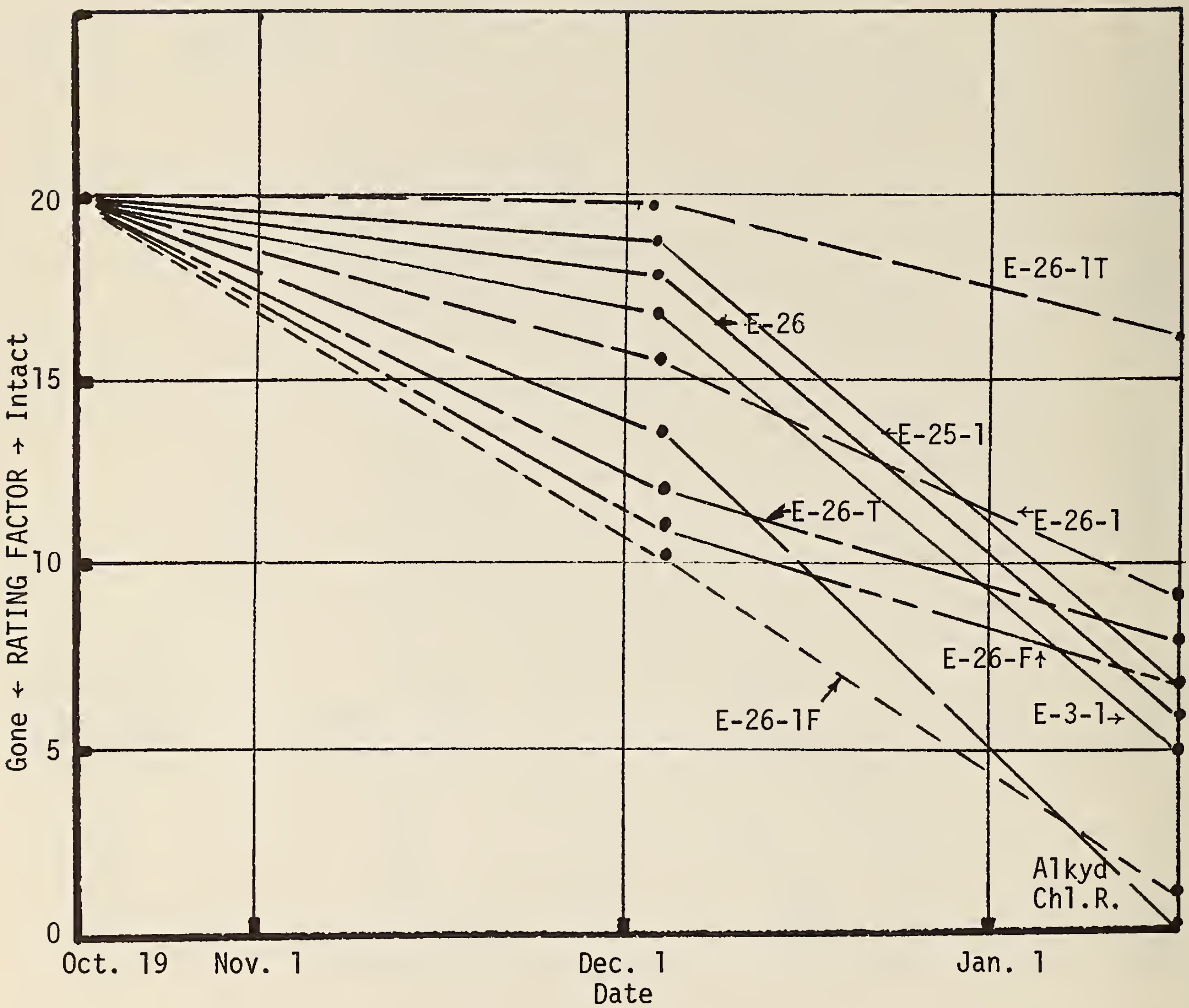


FIGURE 35: ROUTE 1 TRANSVERSE STRIPE WEAR

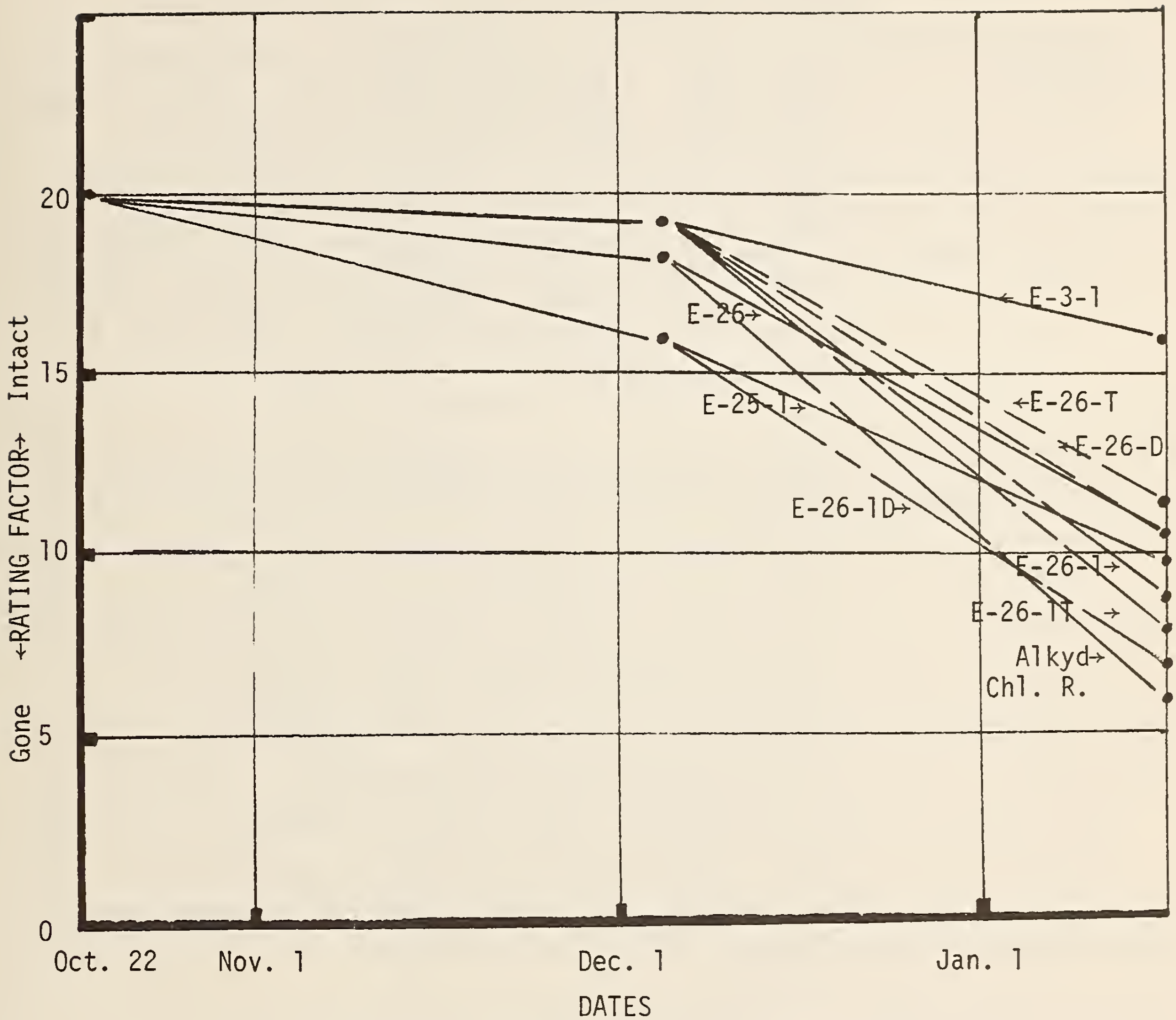


FIGURE 36: ROUTE 128 TRANSVERSE STRIPE WEAR

was the E-26-1-T formulation. It was 30% better than the E-26-1, 60% better than E-26-1-F, and 50% better than last year's best, E-3. All stripings of formulations in the E-26-1 series showed little change in wear rate during cold weather and snowplowing. These stripes are dirty but still offer some degree of night retroflection. The alkyd and chlorinated rubber paints failed most rapidly during the snowplowing period. They are almost nonexistent.

Epoxy formulation, E-3-1, on Route 128 was as good as the E-26-1-T on Route 1, while the other control paints on 128 and epoxies, E-25-1 and E-26, were markedly worse than E-3. The second best set of stripes on Route 128 were the E-26 series, with E-26-T being only marginally better than the other two. While The E-26-1-T was best on Route 1, the entire E-26-1 series were the worst epoxies on Route 128. The worst transverse stripes on the 128 surface were the alkyd and chlorinated rubber paints.

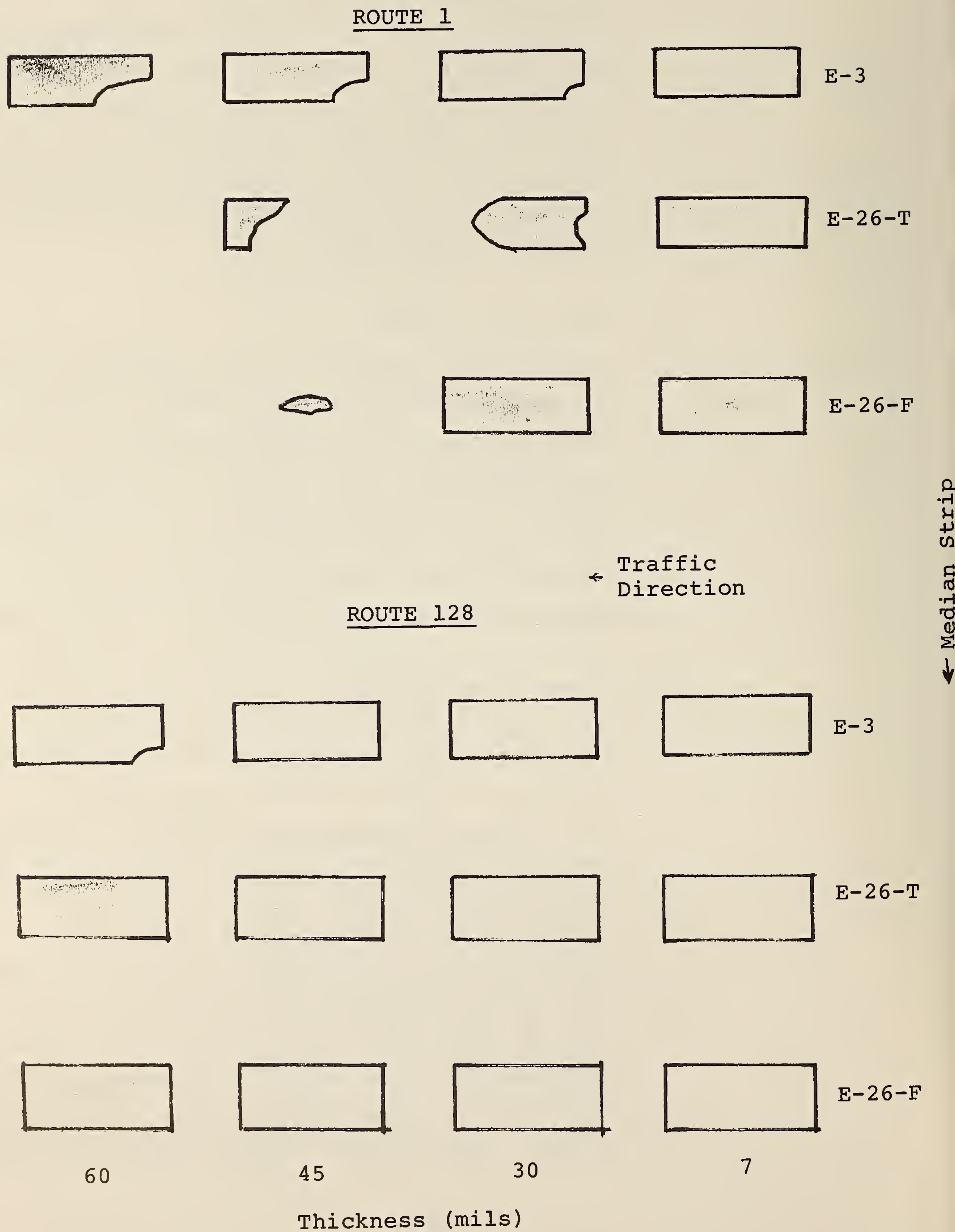
(2) Longitudinal stripes

Stripes of alkyd and chlorinated rubber paints were the only longitudinal stripes showing any wear at either test locality. On the other hand, the epoxy stripes were generally free of chips and peel but somewhat dirtier than the others. This grime buildup occurred more readily during the plowing than the cold period and it appears to correlate with bead loss. Closer inspection of the dirty stripes confirms that bead holes become filled with road grime giving the stripes a dirty appearance. E-3 was the cleanest stripe at both localities, while the more flexibilized E-26 and E-26-1 series were progressively dirtier. Unlike the two solvent-based conventional paints, all of the epoxy longitudinal stripes still offer some acceptable degree of night retroflection.

(3) Graduated stripes

Figure 37 is a sketch of the graduated stripes on both surfaces after the intense plowing operations. All of these stripes were white and completely intact prior to the heavy snows. All chipping occurred at the leading edge closest to the median strip. This is probably due to the angle of the plows (i.e., pushing snow towards the gutter) on the road surface. The stripes on Route 1 were more severely chipped than on Route 128. Once again, this can be attributed to the ice covering on the Route 128 stripes during the ten days of heavy plowing, while Route 1 during the same period was cleaned to the surface. As indicated for the 15-mil (0.375 mm) longitudinal stripes, none of the 7-mil (0.175 mm) graduated stripes showed any adverse effects of plowing. At 30 mils some sign of wear was noticed, at 45-mil (1.1 mm) more so, and at 60 mils (1.5 mm) even more. As depicted in the sketch, the Route 1 stripes were dirtier than those on Route 128 and the thicker stripes were dirtier than the thinner

FIGURE 37: GRADUATED STRIPES



ones. As previously mentioned, grime buildup on stripes seems to increase as beads are lost.

g. Conclusions

The data tend to support our original hypothesis of using more flexible systems for improved winter stripe wear. However, the optimal degree of flexibility was obtained with formulations not too different from the original ones. On Route 1, both slightly flexibilized E-26 systems were markedly better than the original or highly flexibilized versions. The same was true for Route 128, although the differences were less.

Low temperature flexibility appears to be an important criteria in designing the perfect traffic stripe. However, flexibility is in a trade off with adhesion to both road and bead surfaces. As evidenced by dirt pickup, the more flexible versions had higher bead losses and also peel easier than the more rigid systems.

B. <u>Simulated Road Wear Testing, Transverse Stripe Testing, and Real Wear</u>

1. Simulated wear mechanisms

a. Stripe durability

The epoxy paints,applied in 15 mil (0.38 mm) thicknesses, were virtually unharmed through the first five million cycles of simulated snowplow wear. All retained excellent day and night visibility. However, during the next three million cycles as the pavement abraded and the 15-mil (0.38 mm) film became more vulnerable, stripes wore faster. E-25 lost considerable day visibility due to smudging, while E-3 and E-26 remained relatively clean. Abrasion of the epoxy stripes was along the leading edges, while conventional paints were eroded and smudged throughout. Plow and "road grit" riding under the blade quickly abraded the chlorinated rubber and with less severity, the alkyd (Gleem). Both offered some marginal night visibility while they lasted. The thermoplastic stripe, on the other hand, was severely and promptly degraded by the snowplow; it lost its delineating integrity within the first several thousand cycles. Even at the start, the thermoplastic did not have the night retroflection exhibited by the other materials.

b. Bead retention

Beads add a great deal of life and visibility to a delineating stripe. The ultimate effect of snow-plows on beads in various striping materials has been demonstrated on the simulated wear tester. All of the epoxy stripes had excellent day and night visibility with their whole and sheared beads intact after three million cycles. Significantly, the sheared beads still retroflect well. However, as the pavement material abraded (after five million cycles) the E-25 began to lose beads while E-3 and E-26 remained essentially unchanged (E-26 had a slight edge in bead retention). The reference paints, on the other hand, lost their beads and corresponding night visibility quickly. The vacuoles created by bead loss in paints fill with dirt and grit. This seems to promote abrasion and smudging. Snowplowing never exposed the beads in the thermoplastic but tore them loose with chunks of striping. Night visibility of thermoplastics declined throughout the test as smudging obscured the stripe.

c. Simulated tire wear tests

(1) Stripe durability

After one million cycles (1 cycle = 1 car, recalling that for each cycle two wheel contacts are made) the epoxy paints (E-3, E-25, and E-26) offer excellent day and night visibility with no apparent tire damage. Stripe durability in this case appears to be a matter of superior bead retention.

Conventional paints (alkyd and chlorinated rubber), on the other hand, quickly lost chips of paints from bubbles formed during casting. Abrasion has been noted across the entire stripe; and although both are clearly legible, they show more wear than any other test material. After one million cycles the stripes of unbeaded paints were almost completely gone. Thermoplastic striping showed only minor wear across the leading edge of the stripe with no visible deterioration elsewhere.

(2) Bead retention

As noted in the snowplowing tests, beads add a great deal of life and visibility to a stripe. After several million cycles beads have been unharmed and are completely intact in the epoxies (E-3, E-25, and E-26). However, pock marks indicate some bead loss in the conventional paints. The chlorinated rubber quickly lost a small portion of beads in the tire track area, especially along the leading edge, while the alkyd lost two to three times as many beads in similar areas. Although beads have been lost, retroflection and visibility of stripes are still good after one million cycles. Thermoplastic stripes that lack retroflection in snowplowing tests exhibit such during tire tests. The tires abrade the thermoplastic, thus exposing the retroflective beads.

2. Transverse stripes

Route 1 in Danvers is an old portland cement concrete highway experiencing severe traffic use. The selected test area is located on a downward stretch of road devoid of turnoffs. Worn tire track areas and exposed reinforcing rods reflect a 25-year abuse of the surface by 100 to 150 million motor vehicles and several thousand snowplowings (Figures 11 through 16). Transverse test stripes were cast across the passing lane of Route 1. Photos of stripe wear and exposed aggregate strongly suggest the presence of uneven wear patterns. If an exaggerated road profile is sketched for the test area (Figure 38) uniform wear zones can be established. Each tire track furrow is typically 4.5 feet (1.4 m) across and located about half a foot (13 mm) from the center of the lane. Transverse stripes running across the Route 1 passing lane failed in these areas first. The second most severe area of stripe failure was in the lane center, followed by

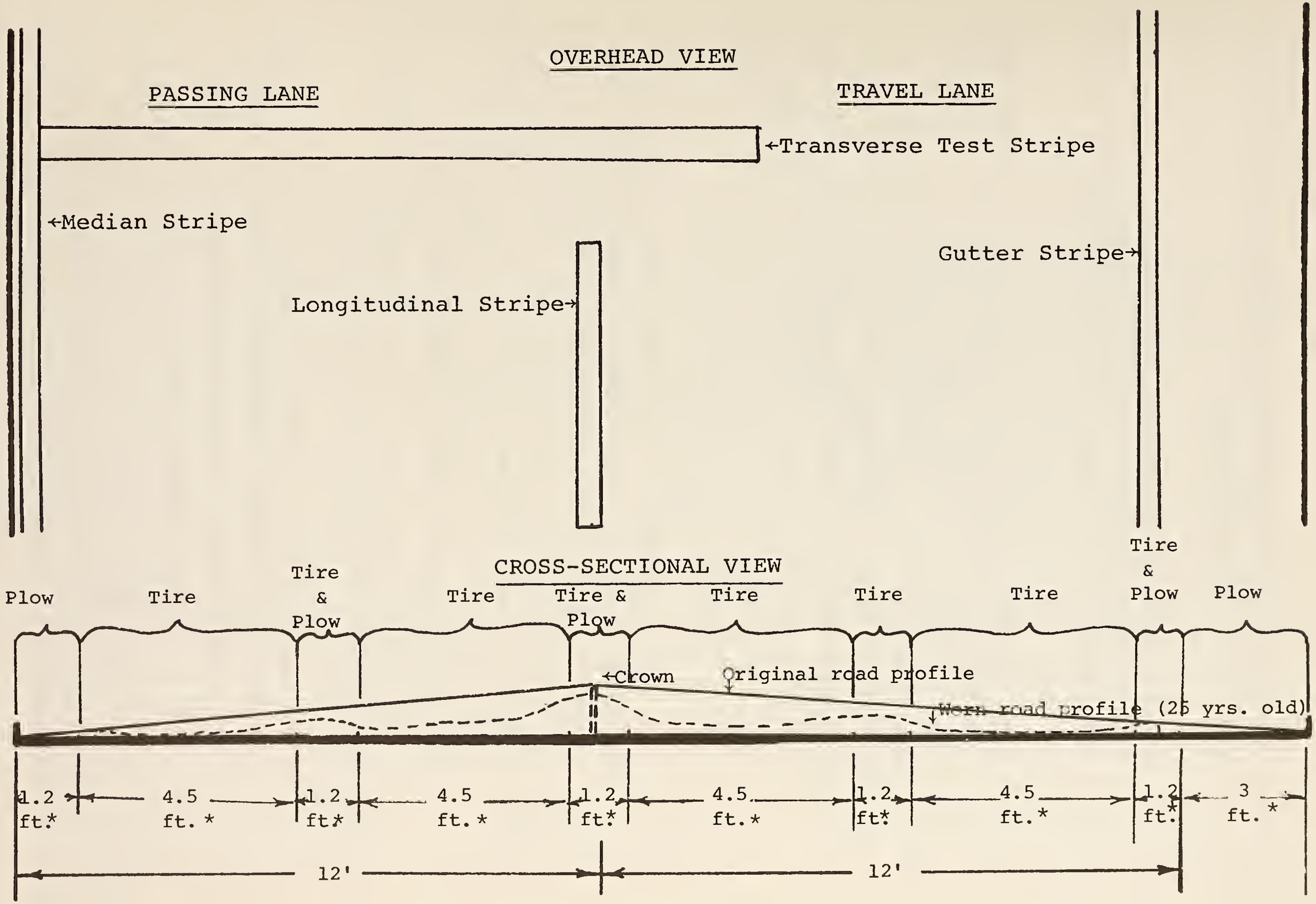


FIGURE 38: ROAD AND STRIPE WEAR ON ROUTE 1

* 1 foot = 0.3048 meter where indicated

striping in the longitudinal area, and finally by stripes in the median area.

Epoxy stripe failure in the tire track area was predominantly initiated at aggregate sites, followed by stripe abrasion on the cement.

Although the epoxies show significantly better bead retention than either urethanes or paints, the bead loss in the tire track area is very high. Grime was found in the vacant bead holes, giving the stripes a dirty appearance. Very fine beads can still be found in these fragmented stripe sections, yielding minimal night visibility. All of these wear mechanisms have been obtained on the simulated wear tester for all the test materials.

Likewise, the wear of the inner median segment of transverse stripes more closely resembles the wear patterns seen on the simulated snowplow tester. Stripes chip along the leading and trailing edges. Although more beads were found intact in the median area than in the other areas, a few beads were found sheared, and the remainder were missing. Longitudinal and center lane wear appears to be a combination of both simulated mechanisms.

What actually happens across the transverse stripe can be demonstrated statistically from the uniform road wear patterns reflecting the 25-year history of the Route 1 surface. The location of wear furrows suggest a tendency for motorists to drive centrally within their lane. If this central tendency is significant and we assume a normal distribution of traffic across the lane, then a normal curve can be drawn for traffic flow (Figure 39). For every point within this distribution, we can establish a set of corresponding tire tracks. If we consider the average passenger car (60" {1.5m} wheel track) as a normal vehicle, we arrive at the distribution seen in Figure 40. The breadth of both distributions is assumed to be the dimensional limits of the lane and set at three standard deviations. Superimposing the actual exaggerated road profile onto both graphs, we see that percentage of traffic volume can be derived from the area under the normal curve. As defined by a normal distribution, the area under the curve is determined by:

1

$$A = \int_{o}^{t} \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt$$

$$t = \frac{\overline{X}-\mu}{S_{\overline{X}}}$$

with t in units of standard deviation.

Since the tire track section of transverse stripe lies between 0 ($\overline{X}$) and 2.44 σ, the tire track area represents 98.58% of the total tire traffic. Likewise, the median section represents half of the remainder; i.e., 0.71% of the actual tire traffic. For an average daily traffic of 8000 cars per lane, 0.71% amounts to about 57 cars a day actually touching this area. If we neglect lane changing, the lane center represents the area outside the range as $t_o \rightarrow +1.5\ \sigma$ or (100 - 93.185%) = 6.82%.

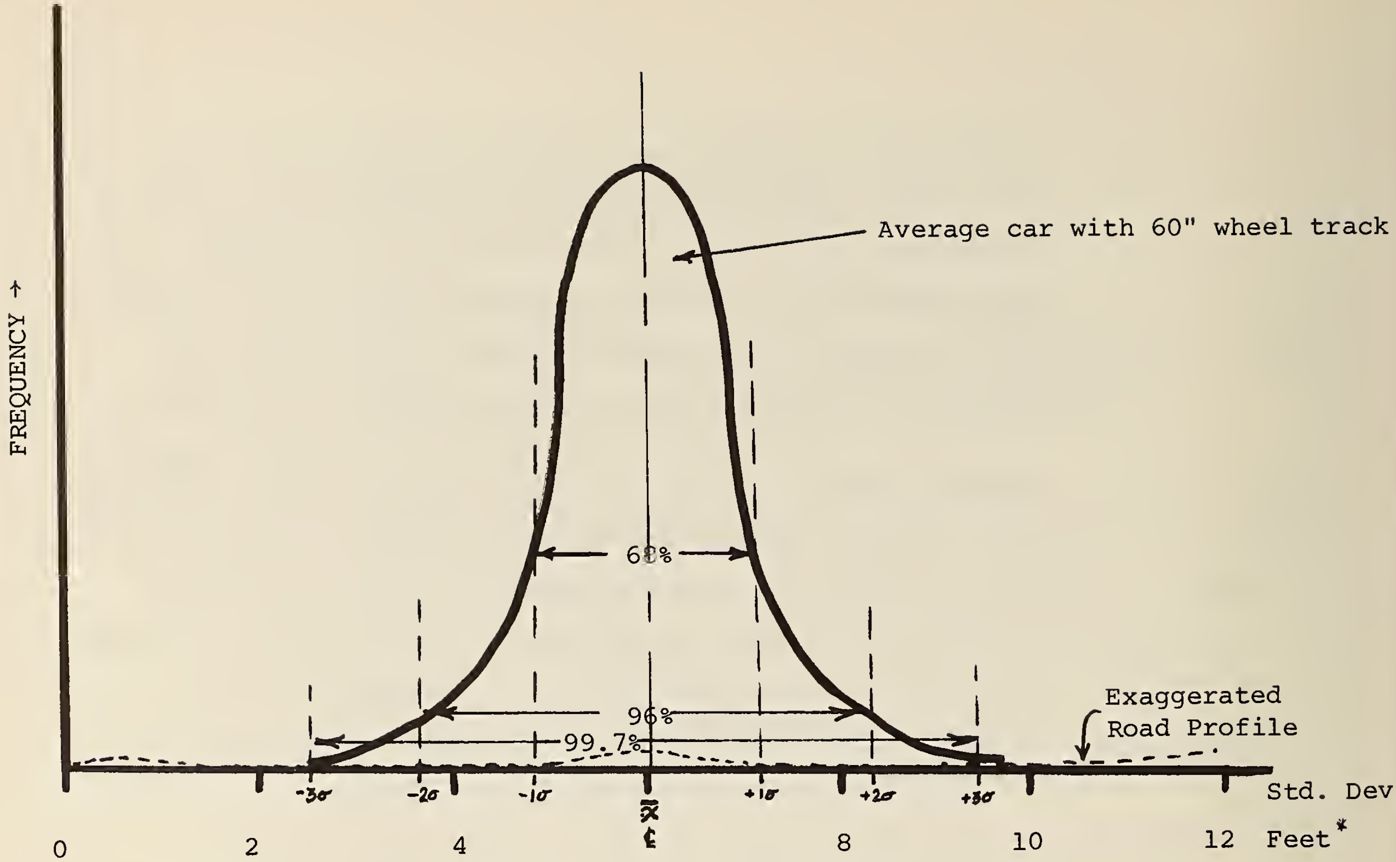
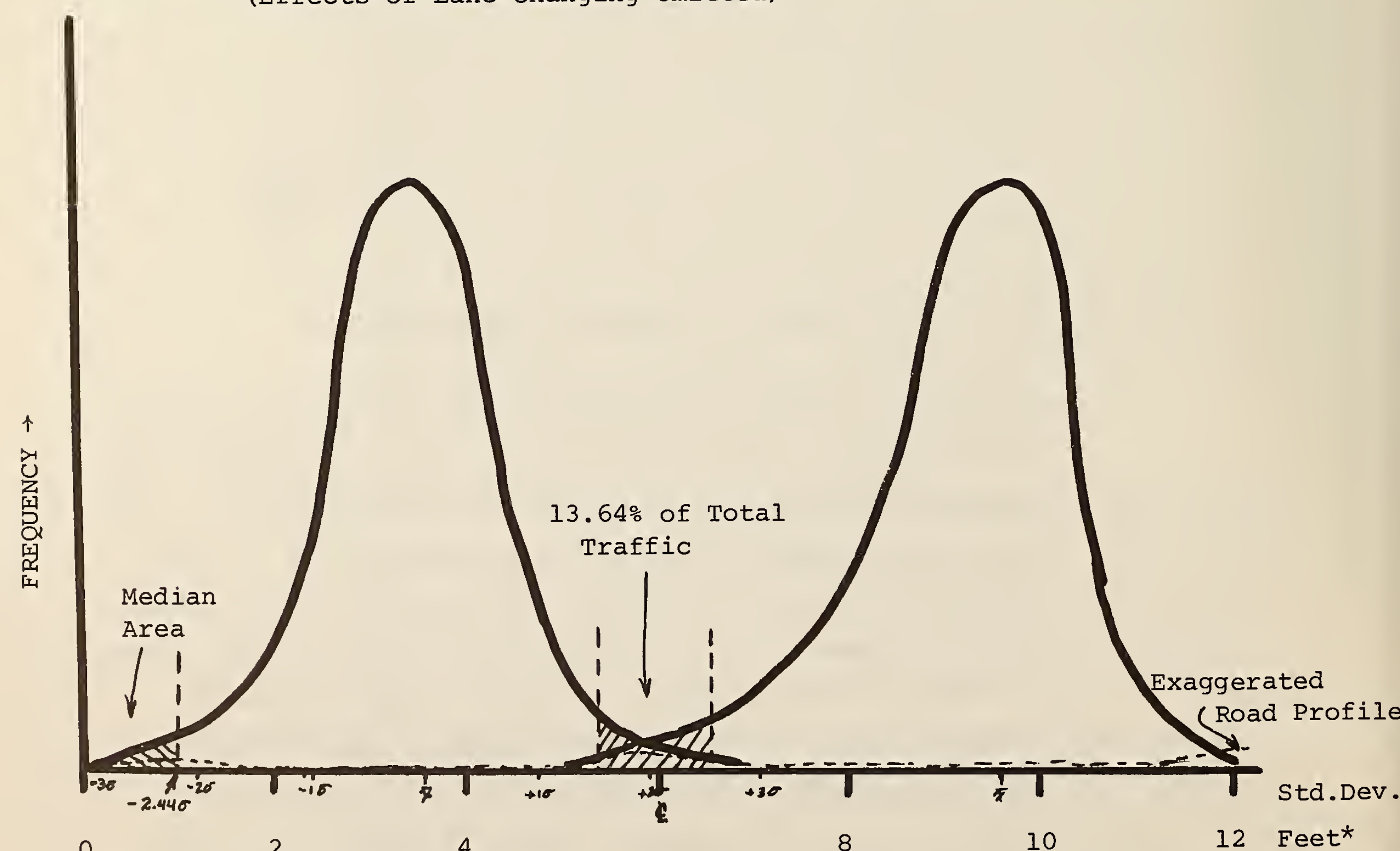


FIGURE 39: NORMAL DISTRIBUTION OF TRAFFIC WITHIN THE ROUTE 1 PASSING LANE
(Effects of Lane Changing Omitted)



* 1 foot = 0.3048 meter

FIGURE 40: WHEEL TRACK DISTRIBUTION FOR AVERAGE PASSENGER CAR
(Lane Changing Omitted)

Since both tires can occupy this area, the actual tire traffic in center lane becomes 13.64% of the 8000 ADT or almost 1100 tires a day.

Although some plow grit may abrade the stripes in the tire track area, the median center lane and longitudinal stripe areas are probably the only areas actually touched by the plow blade. If wear mechanisms and bead loss in each zone are compared with simulated tests, we find the tire track area to be almost pure tire wear; the median area almost pure snowplowing wear; and the center lane and longitudinal stripe areas a combination of both.

3. Traffic distribution, lane changing, and longitudinal stripes

a. Traffic distribution

Underwood's[2] study on traffic distribution for a three-lane highway (Figure 41) suggests that at higher traffic volumes the freedom of lane choice is minimized and the distribution of traffic across the roadway is uniform. While the use of the inside travel lane varies little with traffic density, the passing lane's use can increase almost two-fold.

If we apply Underwood's data to the two-lane Route 1 in Danvers and redistribute the inside travel lane traffic, we end up with Figure 42. Except for periods of low density traffic, traffic is evenly distributed across the two-lane road. For our purposes, we will assume an even distribution of 8000 ADT per lane for Route 1.

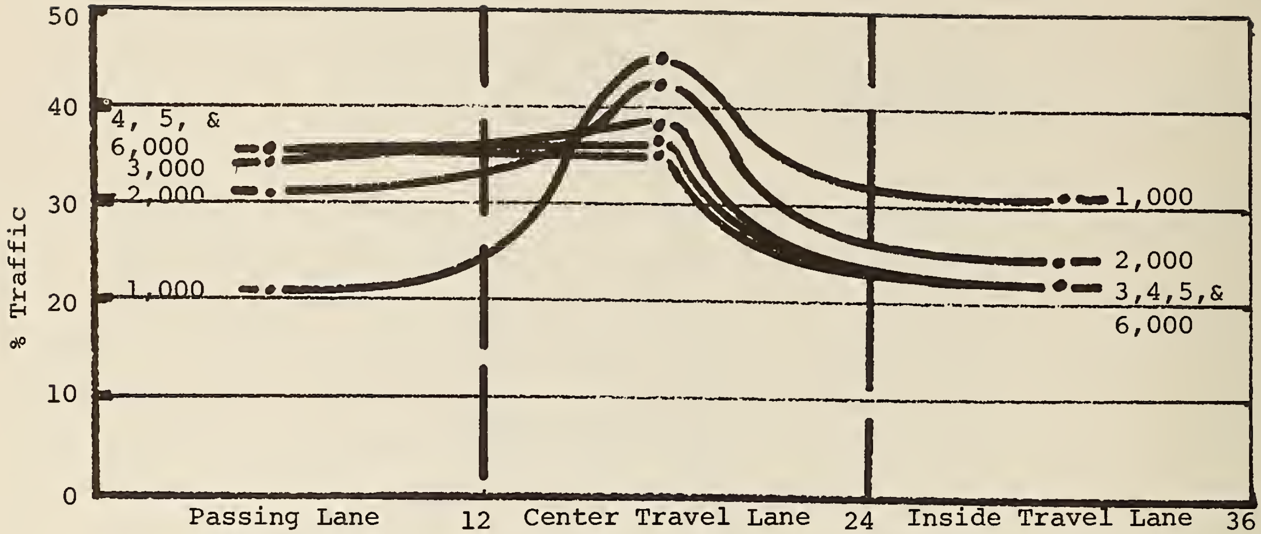


FIGURE 41: TRAFFIC VOLUME AND LANE USE (3 LANES)

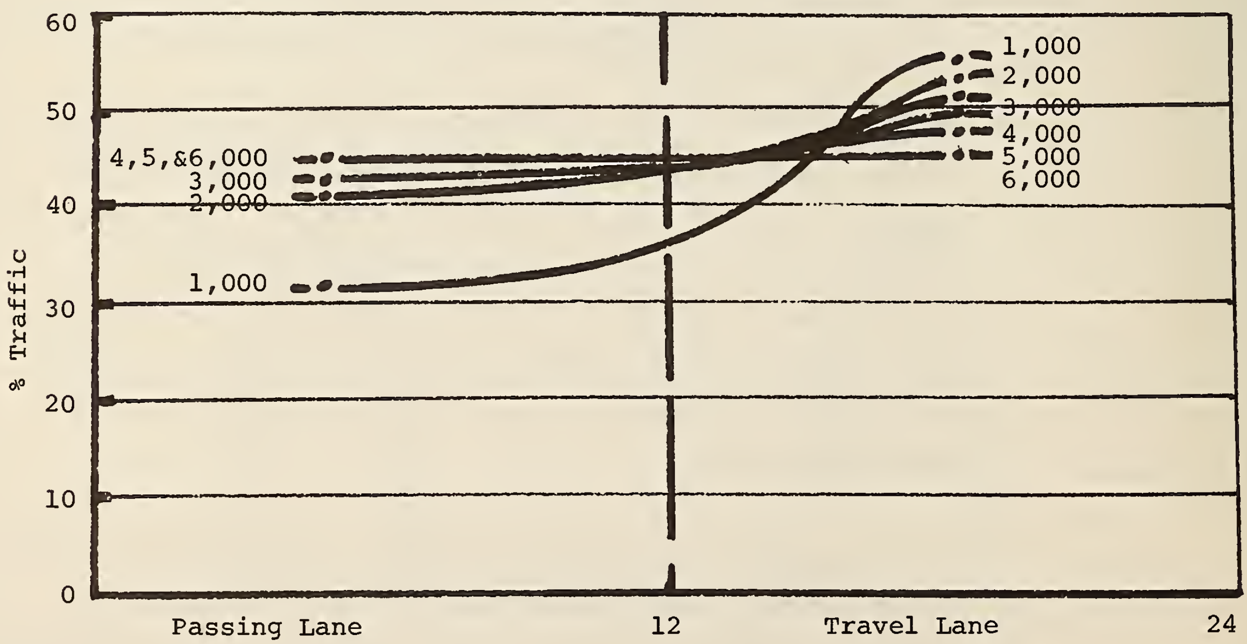


FIGURE 42: TRAFFIC VOLUME AND LANE USE (2 LANES)

Cirillo, Dietz, and Beatty[3] discuss average hourly traffic fluctuations (Figures 43 and 44) for urban and rural roads. The highest urban traffic volume per hour occurs during the evening rush hour; second highest volume per hour during the morning rush hour; and the third highest volume per hour during the mid-day period. Figure 45 represents a traffic density distribution for a road like Route 1 at various times of day. Over 50% of the ADT occurs between the 7 to 9 a.m. and 4 to 6 p.m. rush hours.

b. Lane changing

We have considered traffic distribution within the travel lane and across the highway but in order to understand the wear characteristics of longitudinal stripes, both have to be combined. Figure 46 depicts a rush hour and quiet hour traffic profile for a road like Route 1. Lane changing across the longitudinal stripe extends the distribution of each lane into the other. The hashed area above the longitudinal stripe in Figure 46 represents the percentage of motorists traveling across the lane. If the longitudinal stripe lies outside the range of 4 σ for both lanes, then according to the Camp-Meidell Unimodal Adjustment[4], 97.23% will lie under the curve and 2.77% of the traffic from each lane will change lanes in a normal road stretch. Since the passing lane has the opportunity to pass to the right and the travel lane to the left, the total effect of lane changing represents 5.54% of the traffic volume for a two-lane road. This, however, does not represent the complete traffic picture for a longitudi stripe. A small percentage of drivers (0.71%) from each lane will

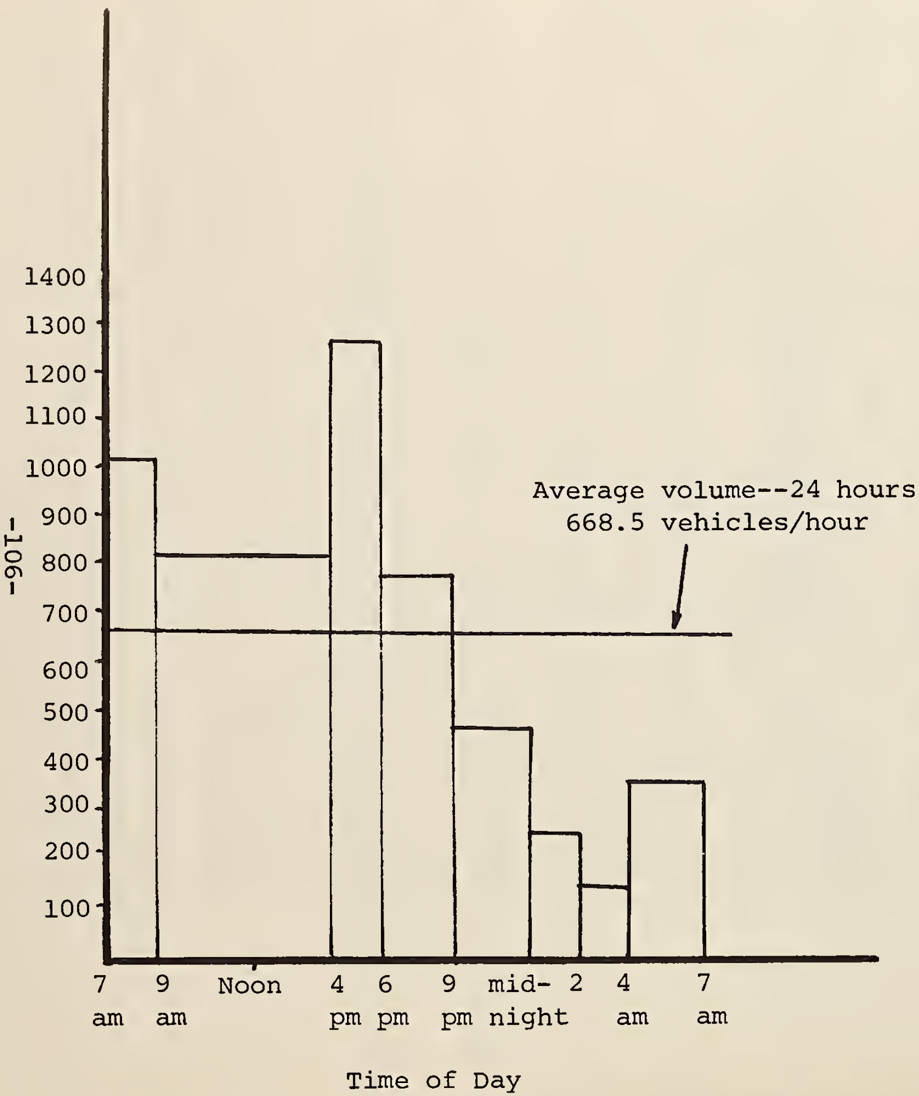


FIGURE 43: AVERAGE HOURLY TRAFFIC VOLUME ONE WAY--URBAN AREAS[4]

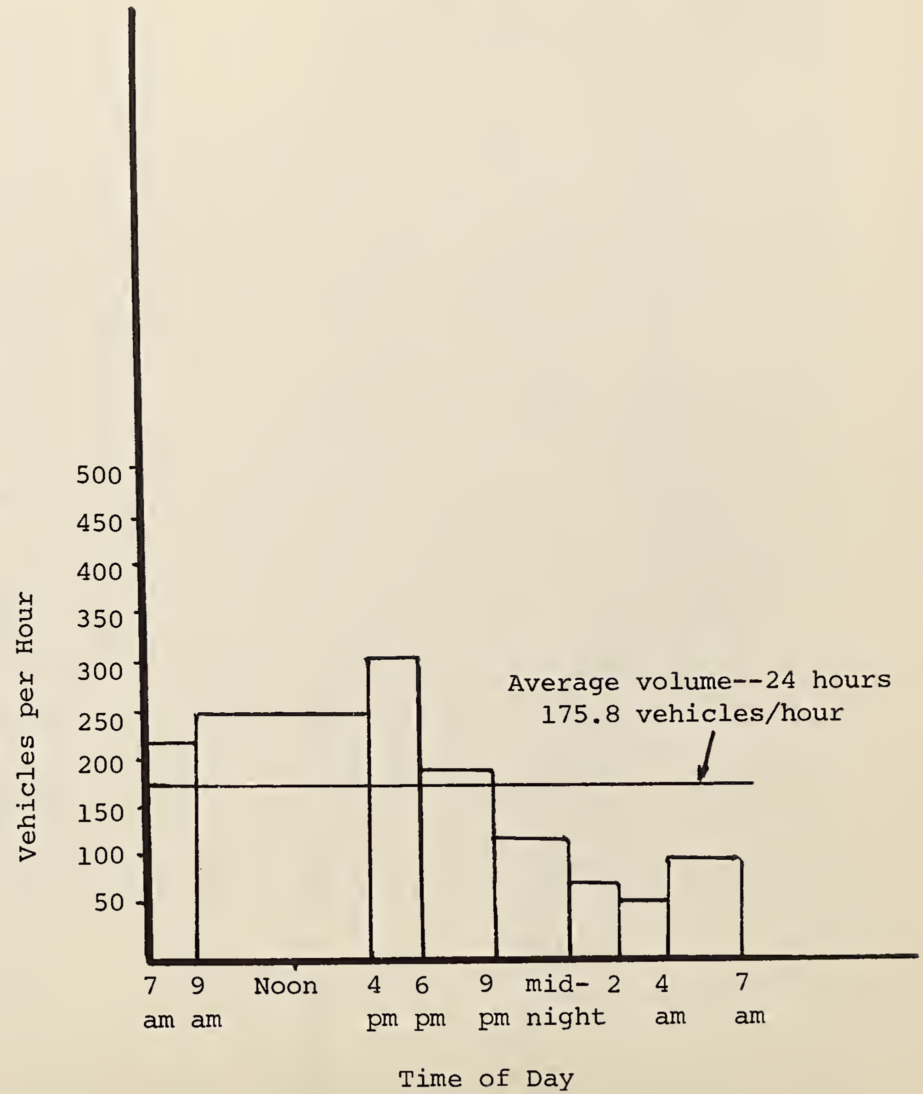


FIGURE 44: AVERAGE HOURLY TRAFFIC VOLUME ONE WAY--RURAL AREAS[4]

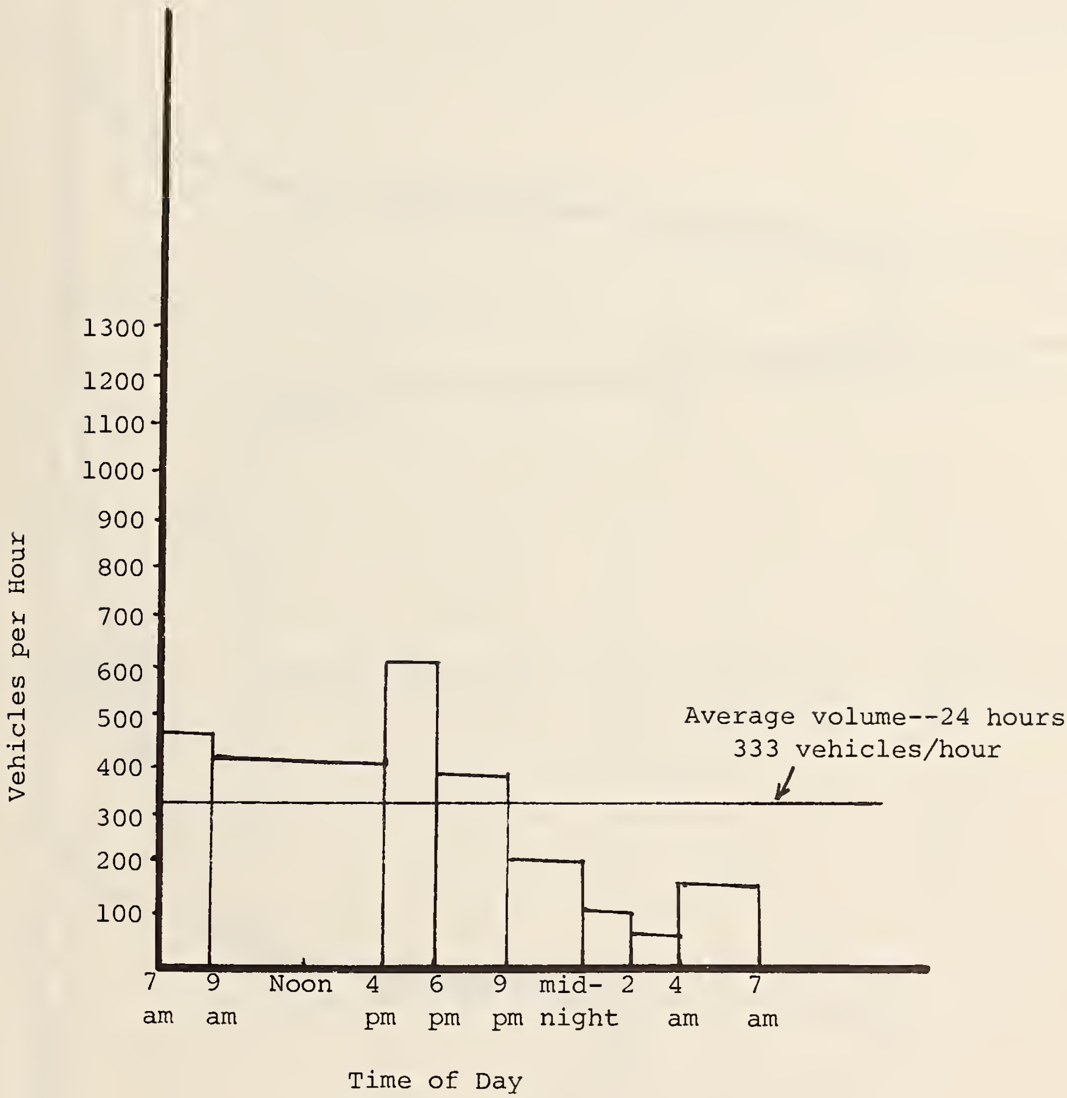
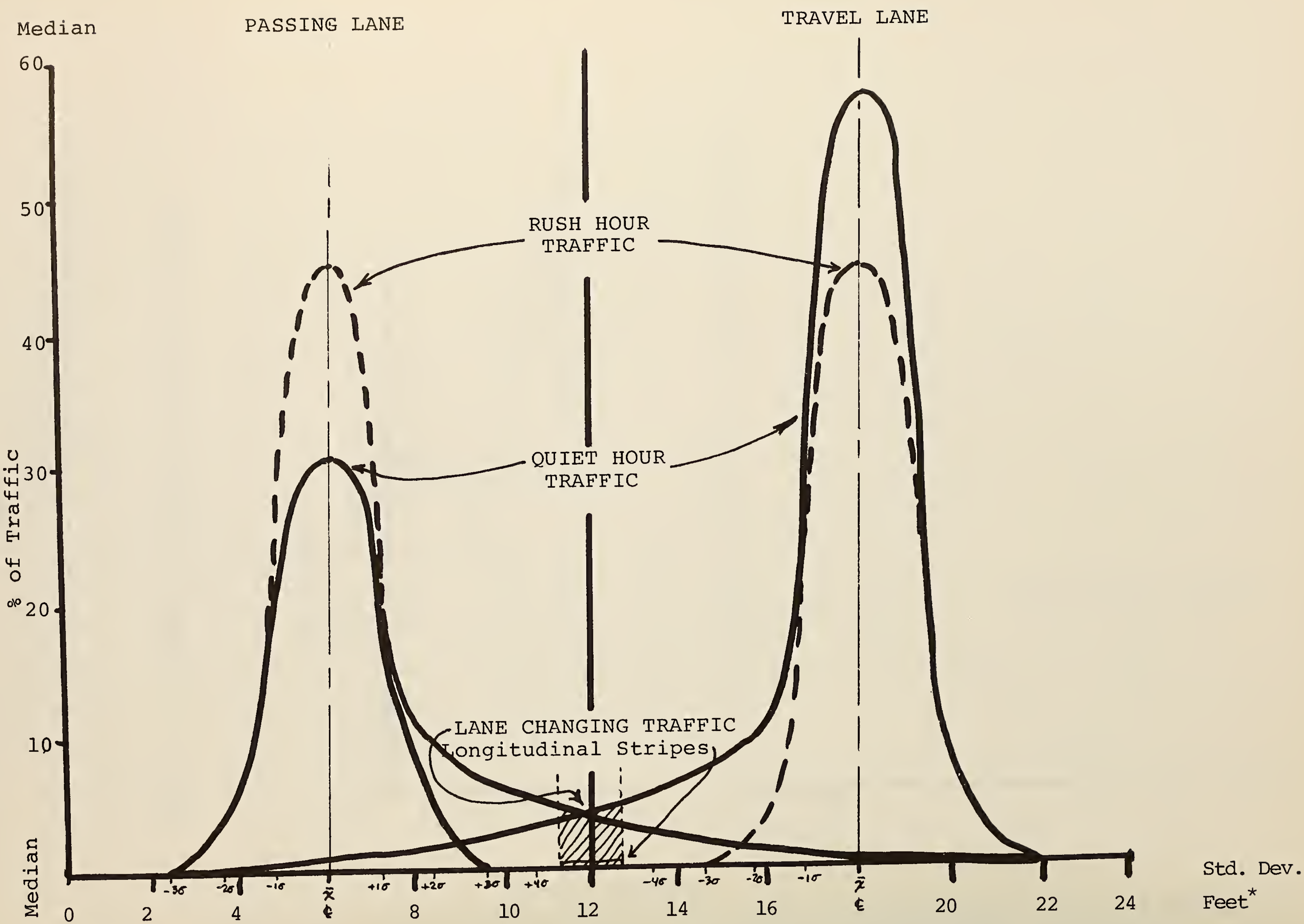


FIGURE 45: AVERAGE HOURLY TRAFFIC VOLUME ONE WAY--ROUTE 1



* 1 foot = 0.3048 meter

FIGURE 46: TRAFFIC PROFILE FOR 2 LANES WITH LANE CHANGING

drive on the stripe, so a more realistic percentage would be a summation of 6.96% of the ADT. This amounts to about 560 vehicles a day. Put another way, if tire traffic alone counted for roadway wear, the longitudinal stripes would last about 14 times longer than lateral stripes.

c. Longitudinal stripes

Assuming the normal traffic distribution as illustrated in Figure 46, actual wear patterns for a simulated two-lane stretch of road would yield tire and plow wear densities as tabulated in Table 18. Whether the stretch of Route 1 within the striping area contains a normal distribution of traffic is unclear. Turnoffs, cloverleafs, deceleration and acceleration zones, off ramps, special lighting and road signs would have a marked effect on the wear zones causing abnormal stripe wear and deviation from normal traffic distribution. For a comparison with the test stripes cast by Amicon, these wear mechanisms are best observed in the durable, weather-resistant epoxy stripes. Urethane performance should be excluded because of their tendency to peel and conventional paints omitted because of their adverse environmental degradation.

TABLE 18: WEAR ZONES

	% CONTACT			
	MEDIAL	TIRE TRACK	CENTER LANE	LONGITUDINAL
Snowplowing	100	Negligible	100	100
Tires	0.7	98.58	13.64	6.96

V. MACHINE APPLICATION OF FAST-CURING EPOXIES

The test formulations had to be applied to road surfaces by hand mixing because it became evident, very early in the program, that the standard application equipment, which is designed primarily for solvent-based paints, could not be used with these fast-curing, 100% solids formulations. Hence, an unexpected, but ultimately the most critical, aspect of the program turned out to be the search for "second generation equipment" which could be used to apply the new generation of paints.

A. Types of Equipment

Basically, present-day paints are either applied by extrusion or spray using one or two-component reservoirs, with or without heat. In order to find equipment that would be adaptable to our fast-curing epoxies, a list was prepared, with the help of the F.H.W.A. and Mass. D.P.W., of all well-known striping contractors. Each vendor was categorized as having either single or double-component equipment. Table 19 lists the single component (paints and thermoplastics) and two-component equipment contractors.

1. Single-component equipment

Epoxies have been used extensively in highway marking equipment only when used in the single-component configuration. Although epoxies are usually extruded as marker adhesives, some vendors do spray slow-curing epoxies. A single-component system requires batch mixing of the two components, heating, and spraying. No-track times are usually longer than three minutes. Laboratory tests on fast-curing epoxies typically with less than three minute no-tracks produce gel times (time to hardening) of less than a couple of seconds when

TABLE 19: SPRAYING CONTRACTORS

COMPANY	CONTACT	CAPABILITIES	AVAILABILITY	COMMENTS
Two-Component Contractors				
Keith Clark Route 1 Lake City, Michigan 49651	Keith Clark (616-839-4430)	Airborne mix, polyesters, paints	Will be striping Minnesota in July; available	Builds equipment; will develop to spray our material
Concept Development Inc. 1790 Stoney Hill Drive Hudson, Ohio 44236	Gerry Boetller Burt Morgan (216-656-2442)	Epoxies, paints, airborne/meter mix variant	Available	Equipment experimental
Safe-Line Inc. 7620 Bond Street Glen Willow, Ohio 44139	Harry Velotta (216-439-6992)	Airborne mix, polyesters, paints	Available	Equipment built by Clark; not too willing to experiment
James McCormick 736 Dixon Highway Mansfield, Ohio 44907	Mr. Blubaugh (419-756-6312)	Extruded two-component markers	Currently in Alabama; not interested in our job	Recommended: Flonson Equipment, Lombardy Striping and Chemetro Chemical
Graco Inc. Industrial Division P. O. Box 1441 Minneapolis, Minnesota 55440	(612-332-2262)	Hydra-Cat meter/mix epoxies	Under contract with Fuller	

TABLE 19: STRIPING CONTRACTORS (continued)

COMPANY	CONTACT	CAPABILITIES	AVAILABILITY	COMMENTS
Paint or Thermoplastic Contractors				
Traffic Control Devices 873 Walnut Street Newton, Massachusetts	Robert Borelli (617-969-6090)	Epoxy ?, paints, thermoplastic	Available	Will develop epoxy equipment (air spray mix), access to extruded epoxy equipment (Prismo)
Permaline of New England Brockton Massachusetts	Ray Borgarty (617-587-0617)	Paints, thermo-plastic	Available	
Lombardy Striping 2901 Clinton Avenue South Plainfield, New Jersey	Mr. Lombardy (201-755-4900)	Paints, thermo-plastics	Not interested	
Chemetro Chemical Inc. 2776 County Road 69 Gibsonberg, Ohio 43431	Tim Hickman (419-665-2367)	Paints, thermo-plastic	Booked through summer; not interested; lease and labor (35¢/ft.)	Recommended: Safe-line, Clark
N.E. Traffic Safety Lines Co. 219 N Methuen, Massachusetts	(617-682-4210)	Paints		
Turner Industrial Prod. Co. P. O. Box 4088 Springdale Station Stamford, Connecticut 06907	William Turner (203-322-2824)	No experience	No equipment available; has to be assembled	

TABLE 19: STRIPING CONTRACTORS (continued)

COMPANY	CONTACT	CAPABILITIES	AVAILABILITY	COMMENTS
Paint or Thermoplastic Contractors (continued)				
Baltimore Paint & Chem. Corp. 2325 Hollins Ferry Road Baltimore, Maryland 21230	Edward Countryman (301-837-3030)	Paint	Available	Have to purchase equipment
Mass. D.P.W. Nashua Street Boston, Massachusetts	Bob Connelly (617-727-4717)	Paint	In Massachusetts only	

batch mixed at typical spray temperatures in paper cup volumes. If these systems were batch mixed in a 55-gallon tank as is often used, reaction and exothermic factors could prove hazardous.

2. Meter/mix systems

Systems based on meter/mix dispense are not new to the epoxy application field. The system utilizes two independent feed reservoirs which air pump and meter a hot filler/resin component and a curing agent. Although blending is rapid and spraying or extrusion uniform, most materials currently used in this equipment do not provide the extremely fast cure times needed for a three-minute no-track material.

Materials having less than three minute no-tracks would not only require extremely short mix times, but would require special solvent flush capabilities to prevent gelling within the mix chamber during skip stripe application and clean out. Beads are usually sprayed into the paint after application.

3. Airborne mix

Airborne mix systems are relatively new and also very scarce on the striping scene. Most of such equipment is being used for polyesters with no-tracks much longer than three minutes rather than epoxies. The airborne system also uses two reservoirs, one for resin and pigment, the other for hardener or curing agent. The two heated components are pumped through a metered orifice and sprayed through independent spray nozzles.

Mixing is accomplished by intersection of the spray fans of both nozzles prior to contacting the pavement. Beads can be shot onto the road surface before and after the spray fan. With polyesters, stripes sprayed from airborne mix systems have proven to be uniform and their placement easily controlled.

B. Benefits of Airborne Mixing

Airborne mixing offers attractive benefits with respect to the application of very fast-curing epoxies. Whereas meter/mix requires a mixing chamber to combine components, airborne mix combines components within the spray fan. This becomes a crucial difference when fast-curing epoxies are preheated before entering the meter/mix chamber. Since epoxy reactivity increases rapidly with temperature, premature gelling within the meter/mix chamber would cause a serious problem, especially during skip stripes or shutdown. An air or solvent flush of the chamber would be necessary to prevent complete gellation. Airborne mixing would not only eliminate the need for a flush but enable usage of almost any preheat temperature for the components.

C. Evaluation of Striping Vendors

Although airborne mix was expected to be the most advantageous approach to spray application of fast-curing epoxies, none of the two-component airborne mix vendors had ever used their equipment with fast-curing epoxies. Consequently, each of the six two-component contractors (Table 19) was contacted. Two of the six contractors were found to be under proprietary contractual agreements (Borelli/Prismo and Fuller/Graco) and one declined to get involved (McCormick). All three utilize meter/mix equipment with relatively fast-curing epoxies in a spray or extrusion configuration. The remaining three contractors (Clark, Safe-Line, and Concepts Development Institute) showed interest and, during the spring of 1976, each was visited. Each was pre-shipped five gallons of E-3 epoxy; unfortunately, none was able to demonstrate the applicability of the material during our visit. Component and cure properties of the E-3 samples are illustrated in Figures 47 and 48.

1. Meter/mix equipment

   Concepts Development Institute, Incorporated is a non-profit organization derived from retired businessmen wishing to help people in the early stages of product development. Burton Morgan, the managerial consultant, represents Jerry Boettler, the inventor of a meter/mix striper. Boettler has developed several pieces of meter/mix equipment and has applied limited stripes on the Ohio Turnpike. The specific unit evaluated for our materials was 12 foot long by 6 foot wide (3.6 m x 1.8 m) riding golf cart type spray unit. The self-contained unit contains the appropriate compressors, pumps, and generators to handle the two-component epoxies. A thirty-gallon (114 l) resin tank and ten-gallon (38 l) catalyst tank would prove ample for the longitudinal stripe requirements in Minnesota and Massachusetts.

   The heart of the entire unit is the spray gun. Although Boettler had several aluminum castings of spray guns available, none were blueprinted or duplicated. Thirty gallons of E-3 formulation were sent to Boettler for evaluation; however, after several unsuccessful attempts to demonstrate the equipment, other sources were sought. Although the

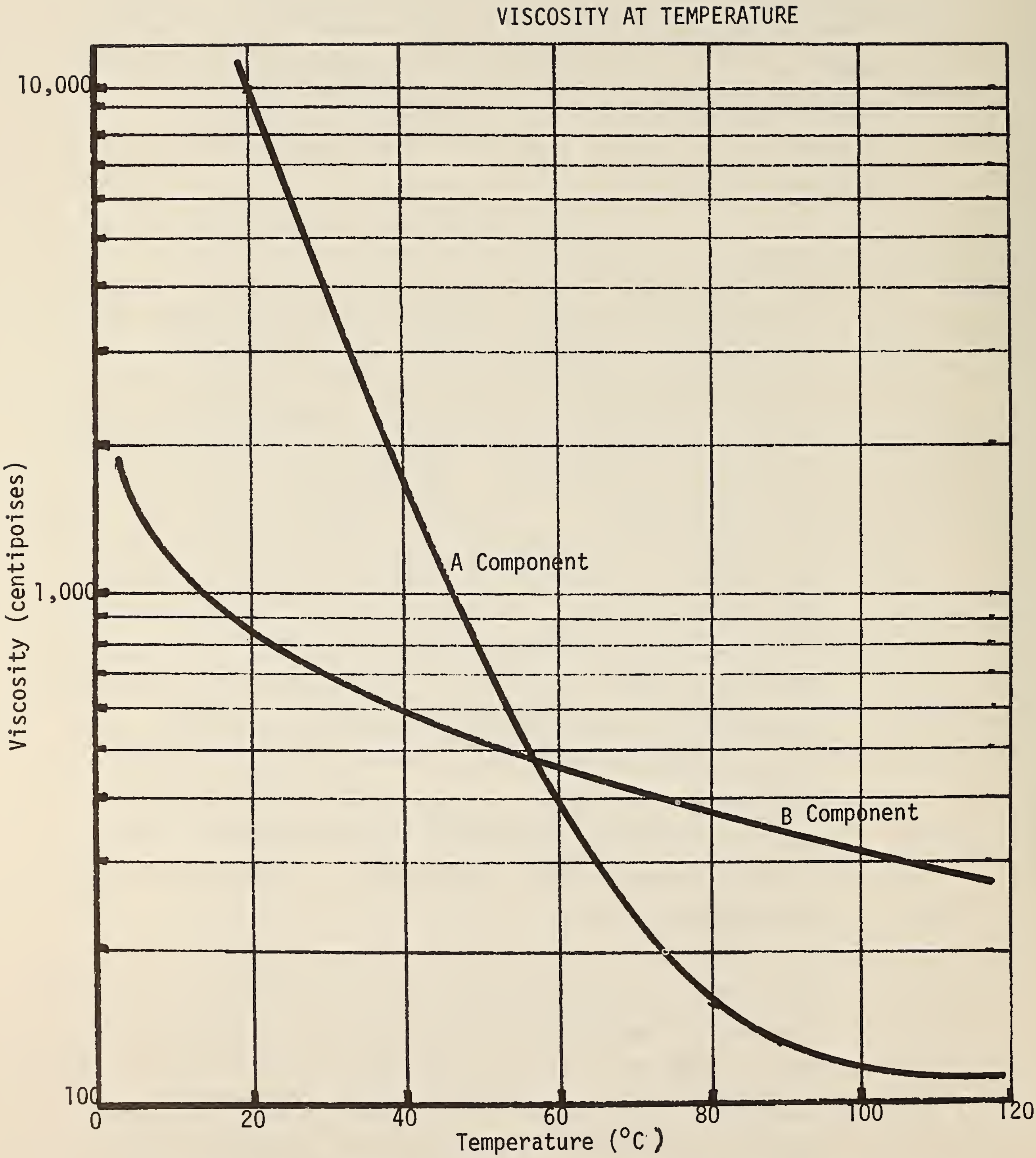


FIGURE 47: COMPONENT VISCOSITY OF AMICON E-3 EPOXY HIGHWAY PAINT

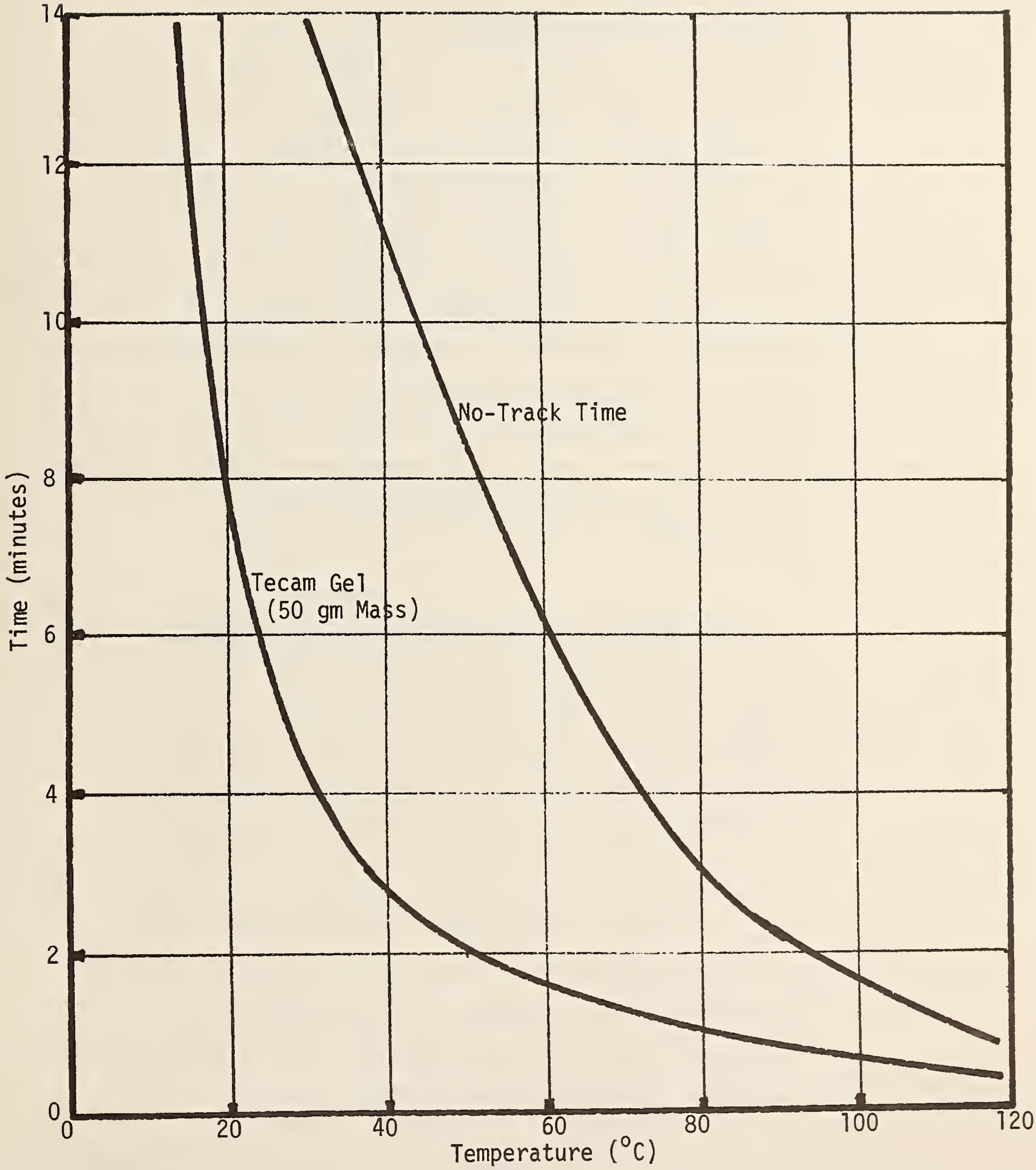


FIGURE 48: CURE PROPERTIES OF AMICON E-3 EPOXY HIGHWAY PAINTS

equipment would probably work in our application, the entire apparatus was too experimental to reliably cast longitudinal stripes.

2. Airborne mix equipment

a. Keith Clark Company is an established striping business operating out of northern Michigan with two-component airborne mix equipment. Clark had been striping roads in Minnesota, Michigan, and Ohio, since 1958 with single-component equipment and using two-component equipment since 1969. Not only does he stripe, but he was the only known two-component equipment builder in the Midwest. He supplies the other airborne mix vendor, Safe-Line, with his equipment. Keith had developed his own two-component spray equipment along with Maurice Booth of Precision Pumping Equipment (Owosso, Michigan).

Clark Company was visited during the early summer of 1976 to explore the feasibility of airborne/mix spraying for use with our materials. Although equipment was unavailable at the time, Clark was optimistic of its successful application. Following several weeks of evaluation, Keith successfully airborne/mix sprayed a length of E-3 epoxy paint. Adequacy of mixing was a primary concern; however, the samples prepared by Clark showed none of the characteristics (lower than specification hardness, cheesiness, color gradients) seen in stripes cast from poorly-mixed controls prepared at Amicon.

As his striping commitments intensified, Clark had to pull his equipment out of research and press them into operation. Booth and Clark submitted cost proposals of what would be entailed to further demonstrate the airborne/mix technique and eventually stripe our candidate materials in Minnesota and Massachusetts but insisted they could not pursue the work until the winter months when the equipment would be idle.

b. Safe-Line Incorporated is another established striper in Glen Willow, Ohio, capable of spraying two-component polyester stripes by airborne mix. Although Harry Velotta purchased his equipment from Clark Company, he did have the capabilities to spray two-component epoxies. Like Clark, Velotta was somewhat reluctant to test our material during his peak summer striping season but submitted a cost proposal and letter of intent showing his interest for the winter months.

D. Recommendations for Machine Application

As a result of our involvement with stripers, airborne/mix spraying was demonstrated as a viable technique for applying rapid curing two-component epoxy paints. However, before these materials can be demonstrated on the highway, a few material and equipment changes should be made.

1. Material modifications

a. The paints should be reapportioned to permit easier adaptability to existing equipment mix ratios.

b. Completely remove the filler from the low viscosity B components.

c. Clogging would be minimized if the filler is mixed in the resin component nozzle.

d. Minimizing the volatility of the components would maximize the efficiency of mixing.

2. Equipment modifications

a. Material recirculation would ensure adequacy of filler mixing and temperature uniformity.

b. Heat circulation from the truck radiator would minimize paint heating costs.

E. <u>Desirability of Full-Scale Field Tests</u>

Several epoxies developed during the course of this program more than amply met the long-term durability requirements of a longitudinal highway stripe. Reapportionment of the best of these systems to meet the requirements of airless, airborne mixing equipment would offer an attractive, clean method of applying extensive highway stripes. Unfortunately the rigorous striping commitments of the contractors and time restrictions under the current program have halted attempts for full-scale field testing of fast-curing epoxies. Completing full-scale testing of these fast-curing materials is highly desirable, especially if better and safer highway stripes are to become a reality.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. Materials

None of the urethanes evaluated over the course of this program were able to meet the proposed requirements of reactivity, durability, high adhesion, solvent free, reasonable cost, nontoxic, and made from readily-available components; but several epoxy formulations, notably E-3 and E-26-1-T, were able to meet or exceed these requirements. These two epoxies:

1. produced no-track times of less than three minutes when preheated to temperatures of 225°F (107°C).

2. out-performed conventional alkyd and chlorinated rubber paints in lab abrasion tests.

3. out-performed alkyd and chlorinated rubber paints by a factor of two to four times in simulated snow-plow and tire tests.

4. out-performed thicker thermoplastics by a factor of almost ten in simulated snowplow tests.

5. survived two winters in limited road testing while conventional materials barely survived the first.

6. retained beads for night retroflection for over a year in limited road tests.

7. were relatively unaffected by environmental conditions, such as wind, dust, moisture, and sunlight, whereas conventional paints were rapidly eroded.

8. in the longitudinal striping zone showed no wear in the summer months and marginal wear during the winter months.

B. <u>Wear Mechanism</u>

Comparing the three modes (lab screening, simulated wear tests, and limited highway tests) of physical testing of highway stripes, the following can be concluded:

1. Taber abrader results can be useful for eliminating bad behaviors but cannot separate super from ordinary materials.

2. Simulated snowplow tests and highway tests confirm:

a. snowplows have little to no effect on stripes less than 30-mils (0.75 mm) thick;

b. snowplows wear the leading and trailing edge of a stripe;

c. snowplows tend to shear beads in the tougher epoxies and dislodge them in the chalky alkyd or chlorinated rubber paints.

3. Simulated tire tests and highway tests confirm:

a. tire wear plays a major role in bead loss in paints;

b. stripe failure by tires is at least ten times slower than by snowplow;

c. epoxies wear better than conventional paints.

4. Limited highway tests confirm:

a. plow or tire failure of a stripe is dependent on its position on the highway;

b. beaded stripes out last unbeaded stripes;

c. although sections of transverse stripe aggree with types of simulated wear, only stripes within the longitudinal area will define a stripe's life.

C. Machine Application Methods

1. Formulations E-3 and E-26-1-T were spray applied successfully utilizing a slightly modified version of available airborne/mix equipment.

2. More time and effort should be placed in the modification of airborne/mix equipment to enable longitudinal stripe application.

3. These two epoxies, with their low preheat temperatures, could be plumbed to the radiator of the spray truck to minimize heating costs and space requirements.

4. The use of airborne mixing eliminates the need for flammable or toxic solvent flushes to clean the spray nozzles.

5. Modification of the equipment to permit continuous recirculation would ensure filler dispersion prior to spraying.

Overall, the recommendation is that considerable work by qualified equipment manufacturers needs to be done in order to develop efficient and economical airborne spray equipment which can be used by normal highway striping crews to apply these new fast-curing, 100% solids epoxy paints.

D. Recommendations for Further Improvement

The highway results and the simulated wear tests both point out that the single property improvements which would yield the most significant increase in life of these epoxies on the road surface would be an increase in low temperature impact strength. Exploratory work performed after the end of the program indicates that this could be accomplished by pre-reacting or "adducting" part of the Bis-A liquid epoxy component with 5 to 10% by weight of COOH-terminated liquid nitrile rubber (sent as B.F. Goodrich's CTBN). Except for a slight increase in the viscosity of the resin-hardener mixture, this elastomer addition has no adverse effect on cure rate, weathering, or any other property tested above. The conclusion therefore is that this modification is feasible and should be investigated as a means of further improving the performance of epoxy systems E-3 and E-26-1-T.

VII. REFERENCES

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HERMAN G. PROTZE
— INC. —
MATERIALS TECHNOLOGIST 36 JACONNET STREET, NEWTON HIGHLANDS, MASS. 02161 (617) 332-8460

June 19, 1975

AMICON CORP.
LEXINGTON, MASSACHUSETTS

ANALYSIS OF CONCRETE AGGREGATES
PAVEMENT ABRASION SAMPLES

Reference Number 75S-178AB

Date Received 6-5-75

Specimens: Two 100 lb. samples of concrete sand and crushed stone taken by us from the Everett, Mass. plant of Allied Concrete Corp. for use in laboratory trial mixture.

Method of Analysis: ASTM C33

Results

Sample	Glenview Sand		Lynn ¾" Stone	
Gradation	#4	0%	1½"	
	8	16	1	0%
	16	38	3/4	3
	30	60	1/2	37
	50	83	3/8	65
	100	96	#4	96
	F.M.	2.93	F.M.	6.64

	Glenview Sand	Lynn ¾" Stone
Weight, lbs/cu. ft.		
Dry Loose	101	90
Dry Rodded	110	103
Specific Gravity	2.53	2.86
Absorption, %	0.5	0.4
Silt, percent	1.9	0.8
Organic, Plate	0+	0
Lithology	granite silica mica	trap rock

Remarks: These materials are clean and well graded. They satisfy the requirements of ASTM C33 for concrete aggregates and were used in concrete for casting of pie-plate abrasion samples.

Respectfully submitted,

Robert E. Gates/lp

Robert E. Gates

3-Amicon

HERMAN G. PROTZE
— INC —
MATERIALS TECHNOLOGIST 36 JACONNET STREET, NEWTON HIGHLANDS, MASS. 02161 (617) 332-8460

June 25, 1975

AMICON CORPORATION
LEXINGTON, MASSACHUSETTS

TEST OF CONCRETE SPECIMENS
PAVEMENT ABRASION SAMPLES

Reference Number	75L-1574A
Date Made	6-17-75 by us
Source	Laboratory trial mixture Second series of 10 specimens
Class Concrete	6.6 sacks/cu.yd.
Water Cement Ratio	5.6 gals/sack
Cubic Yards	1.02
Cement	620 lbs. Dragon type I
Fine Aggregate	1340 " Glenview sand (Ref. No. 75S-178A)
Coarse Aggregate	1770 " Lynn ¾" stone blend (75S-178B)
Water	38.6 gals. total (including absorption)
Admixture	5 oz. Darex
Air Temperature	71°F 59% R.H.
Concrete Temperature	70°F
Slump	3¾"
Entrained Air	5.1% by Acme Air Meter
Workability	Satisfactory
Appearance	Satisfactory
Storage	Laboratory fog room
Date of Test	6-24-75
Age at Test	7 days
Specimen Number	2A
Dimensions	4x8"
Density, lbs/cu.ft.	149½
Compressive Strength	3890#
Remarks	Strength good but less than first series

Respectfully submitted,

Robert E. Gates

Robert E. Gates

3-Amicon

HERMAN G. PROTZE
— INC. —
MATERIALS TECHNOLOGIST 36 JACONNET STREET, NEWTON HIGHLANDS, MASS. 02161 (617) 332-8460

July 22, 1976

AMICON CORPORATION
LEXINGTON, MASSACHUSETTS

ANALYSIS OF CONCRETE AGGREGATES
PAVEMENT ABRASION SAMPLES

Reference Number	76S-203AB
Date Received	6-2-76
Specimens	Two 100 lb. samples of concrete sand and crushed stone taken by us from the Everett, Mass., plant of Allied Concrete Corp. for use in a special laboratory mixture.
Method of Analysis	ASTM C33

Results

Sample	Glenview Sand		Lynn ¾" Stone	
Gradation	#4	0%	1½"	
	8	13	1	0%
	16	30	3/4	5
	30	52	1/2	38
	50	80	3/8	70
	100	96	#4	94
	F.M.	2.71	F.M.	6.69
Weight, lbs/cu.ft.				
Dry Loose		100		90
Dry Rodded		108		103
Specific Gravity		2.56		2.86
Absorption, %		0.5		0.4
Silt, percent		1.7		0.6
Organic, Plate		0		0
Lithology		Granite Silica Mica		Trap Rock

Remarks — These materials are clean and well graded. They satisfy the requirements of ASTM C33 for concrete aggregates and were used in concrete for casting pie plate abrasion samples for you.

Respectfully submitted,

Robert E. Gates

Robert E. Gates

3-Amicon

HERMAN G. PROTZE
— INC. —
MATERIALS TECHNOLOGIST 36 JACONNET STREET, NEWTON HIGHLANDS, MASS. 02161 (617) 332-8460

July 22, 1976

AMICON CORPORATION
LEXINGTON, MASSACHUSETTS

TEST OF CONCRETE SPECIMENS
PAVEMENT ABRASION SAMPLES

Reference Number	76L-1134ABCD			
Date Made	6-23-76 by us			
Source	Laboratory mixture			
Class Concrete	6.6 sacks/cu.yd.			
Water Cement Ratio	5.6 gals/sack			
Cubic Yards	1.02			
Cement	620 lbs. Hercules type I			
Fine Aggregate	1340 " Glenview sand (Ref. No. 76S-203A)			
Coarse Aggregate	1770 " Lynn ¾" stone blend (76S-203B)			
Water	38.6 gals. total (including absorption)			
Admixture	5 oz. Darex			
Air Temperature	70°F, 65%R.H.			
Concrete Temperature	71°F			
Slump	4¼"			
Entrained Air	5.5% by Acme Air Meter			
Workability	Satisfactory			
Appearance	Satisfactory			
Storage	Laboratory fog room			
Date of Test	6-30-76		7-21-76	
Age at Test	7 days		28 days	
Specimen Number	1A	1B	1C	1D
Dimensions	4x8"	4x8"	4x8"	4x8"
Density, lbs/cu.ft.	147	146½	146½	146½
Compressive Strength	3360ψ	3350ψ	4370ψ	4390ψ
Remarks	Strength passable This concrete was used in casting the pie plate abrasion samples for you.			

Respectfully submitted,

Robert E. Gates

Robert E. Gates

3-Amicon

☆U.S. GOVERNMENT PRINTING OFFICE: 1979 O— 623-490/775

FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

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* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD–2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

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