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TERRAIN EFFECTS ON BUS DURABILITY

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Sandra L. Arlinghaus
John D. Nystuen

Center for Transit Research and Management Development
University of Michigan Transportation Research Institute
2901 Baxter Road
Ann Arbor, MI 48109

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FINAL REPORT

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16. Abstract

The purpose of this report is to provide terrain peer groups which may be used in combination with sets of Section 15 indicators as guidelines to understanding the impact of terrain on participating transit authorities. The method of deriving these terrain peer groups involves applying a Terrain Template, based on allometric growth and on topographic evidence, to partition 183 transit authorities into "steep," "intermediate," and "flat" terrain peer groups. The Template is checked, at a local scale in Ann Arbor, and is then used to establish nationwide terrain peer groups.

The hypothesis that bus durability is adversely affected in steep environments is tested, using Section 15 indicators, to illustrate the method of employing these terrain peer groups. Section 15 indicators, used to quantify transit concepts of mileage per gallon, maintenance efficiency, and maintenance value, provide support for this hypothesis.

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PREFACE

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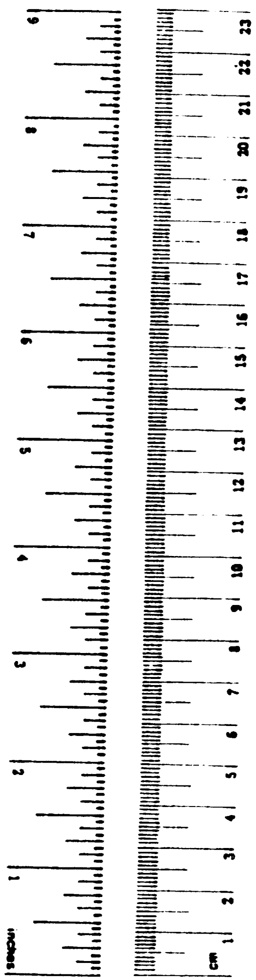
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

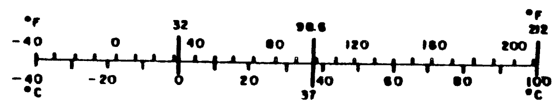
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2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

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



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



METRIC CONVERSION FACTORS

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TERRAIN EFFECTS ON BUS DURABILITY

INTRODUCTION

Steep grades in bus routes create strain on the motor and powertrain of a bus, while frequent alternation between uphill and downhill demands on the bus creates further stress on its internal systems. Terrain peer groups for buses formed from a set of transit authorities participating in the Section 15 reporting system, provide assistance in removing terrain considerations as a factor confounding other underlying questions, such as effectiveness of maintenance procedure and personnel. The application of a simple Terrain Template will permit either transit managers or UMTA to place an arbitrary transit authority into a "flat," "intermediate," or "steep" terrain peer group.

Of course, any abstract measure of terrain at the city-scale may fail to correspond with the topographic stresses along individual bus routes; traffic engineers may adjust routes to run along favorable terrain. To understand the nature of the Template, we tested it along a complete set of bus routes that have served Ann Arbor, Michigan. The results of this more comprehensive terrain analysis provided empirical evidence for fixing boundaries to partition a nationwide set of 183 transit authorities into "flat," "intermediate," and "steep" terrain peer groups. It also produced information on the shape of vertical profiles of bus routes which suggested a simple test, based on the precipitation regime, water load, and consequent drainage pattern, for forecasting the expected shape of the vertical profile of bus routes within specified sections of a transit authority.

Finally, Section 15 indicators leading to measures of mileage per gallon, maintenance efficiency, and maintenance value were partitioned according to terrain peer group. The results of this analysis showed high "mileage per gallon" values for well-maintained transit authorities in steep environments. The results also suggested numerical maintenance subclasses, within terrain peer groups, in which arbitrary transit authorities might compare their mileage per gallon to others in similar situations.

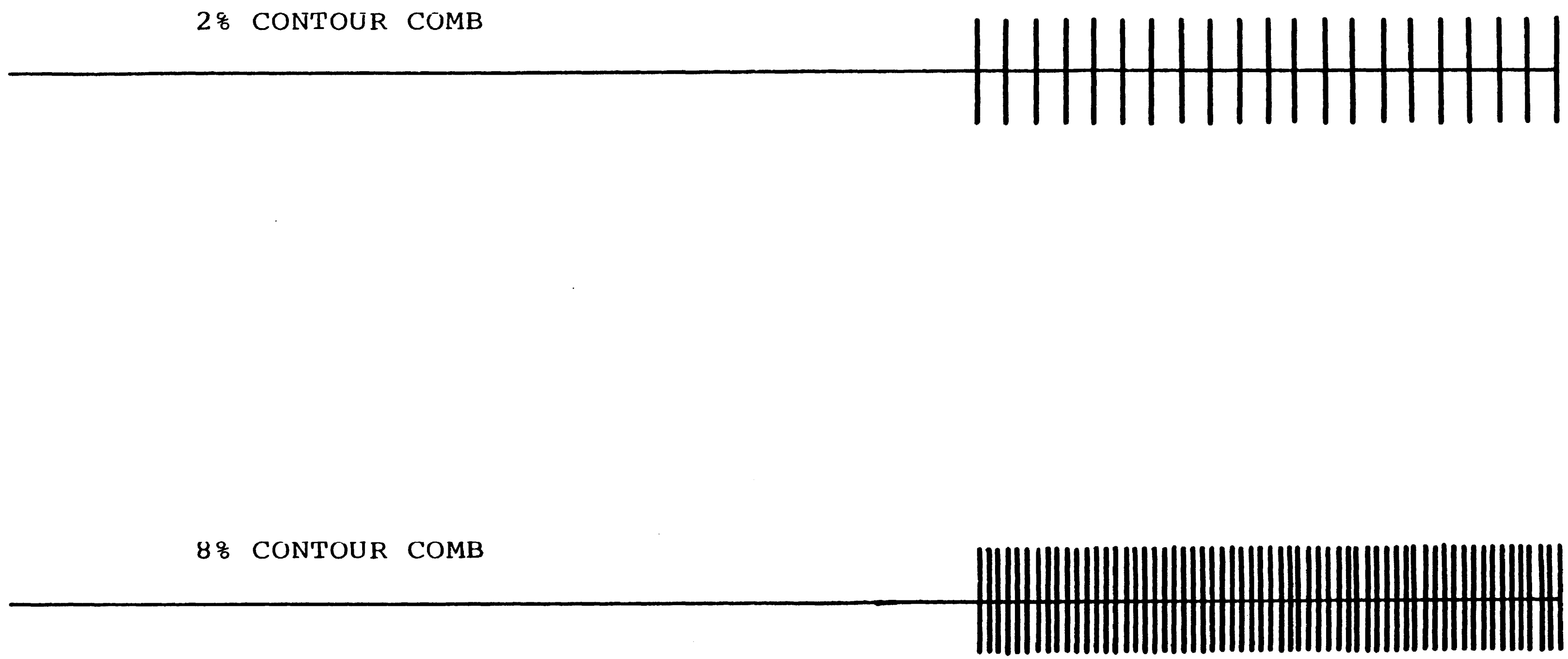
TERRAIN PEER GROUPS

The mechanics of constructing terrain peer groups involve constructing a template to be used to standardize differences in elevation on USGS topographic maps and applied, in this case, to the map series of scale 1:250,000. The construction consists of two parts: first, the approximation of the boundary of each transit authority, and second, the determination within this boundary of the terrain as predominantly flat, steep, or intermediate. To achieve the former goal, allometry was used to represent the city as a circle with radius proportional to population. To do this, census data pertaining to the city itself, rather than to a larger metropolitan region or urbanized area, was employed; bus routes run, predominantly, across terrain interior to the city. Population density, which contributes significantly to wear and tear on buses, has virtually no effect on terrain. As a pure terrain measure is sought, allometry is well-suited to the task. There is no additional input from phenomena unrelated to terrain, such as density, to confound the terrain data. Further, an advantage to using a simple shape, such as a circle, is to facilitate comparisons between cities. Service areas based on actual routing patterns would not preserve this characteristic of uniform shape, and thus, measures used to make shape-based comparisons might be suspect. To achieve the latter goal, sets of evenly spaced lines will be used to sample the unevenly spaced contour lines within the allometric circle and to classify the underlying terrain as steep, intermediate, or flat. The detail of these procedures is described below.

To construct a set of circles representing cities of various sizes, the law of allometric growth will be used to determine circle radius corresponding to city population as given in the 1980 census. Biologists use allometry to predict the size of an entire individual, within a given species, from the size of one of its parts; pediatricians apply this idea to predict adult heights of children (1). Stig Nordbeck and Waldo Tobler have used allometry to represent city size as a circle proportional to size of built-up area and to population inhabiting the built-up area (2). Nordbeck has found, from empirical studies, that the area of a United States city can be estimated by $A = 0.00151 \times P^{0.8757}$ where A is area in square miles and P is total city population (1, 2). Using $A = \pi R^2$, with R the radius of a circle of area A, associates a radius R with each city, given its population, as $R = 0.0219237 \times P^{0.43785}$ (2). Calculations were then made to determine population sizes that corresponded to radii of length 0.5, 1.0, 1.5, 2.0, 2.5,...,23.0 miles.

Population intervals were then centered on integral mile-values for R, and these radii were converted to the scale of a 1:250,000 map. Table 1 shows these values. These radii include all cities in the study. A set of circles of radii 0.25", 0.51", 0.76", 1.01",...,5.58" were drawn on transparent plastic; when superimposed on a topographic map, of scale 1:250,000, and centered on a central point distinguished on the map, the circumference served as the city boundary.

To analyze the terrain within a circle required sampling the spacing between the line pattern of contour lines. Hammond commented that terrain steeper than about an 8% grade causes problems for virtually any sort of vehicle, while Ullman noted that most railroad tracks run across terrain of less than 1.5% grade (3, 4). Thus, a city with a significant percentage of 8% grade would be characterized as steep, one with terrain of grade largely less than 2% as flat, and all others as intermediate. Generally, contour lines are wiggly; locally, however, all are topologically equivalent to short straight-line segments. Thus, we use a sequence of parallel short straight-line segments spaced to represent a 2% and an 8% grade on a 1:250,000 topographic map with a 50-foot contour interval (adjustments may be made easily for 100-foot and 200-foot contour intervals) to evaluate spacing between contours (3). On such a map, at 2% slope, contour lines would be 0.12" apart on the map; at 8% slope, contour lines would be 0.03" apart on the map (Figure 1). Draw a horizontal line perpendicular to the vertical parallel line segments through the set of vertical parallel lines and transfer the entire comb-like configuration to a transparency. When this contour-comb



CONTOUR COMBS TO BE APPLIED TO A 1:250,000 MAP WITH A 50-FOOT CONTOUR INTERVAL.

FIGURE 1: CONTOUR COMBS

transparency is superimposed on both the allometric circle and the topographic map, so that the horizontal line passes through the circle's center, the horizontal line samples contour line spacing in much the way that a hologram samples price markers on products in a supermarket. Rotating this line about the center produces a sort of radar scan of the city using this contour-comb. The use of the allometric circle and the contour-comb, as a template of transparencies applied to USGS maps, permitted rapid determination (in under one minute each) of the general terrain of most cities as steep, intermediate, or flat. Table 2 shows the results of applying the template to a set of 183 transit authorities; it provides data sufficient for replication of results, and it partitions the set of transit authorities into steep, intermediate, and flat terrain types.

Some cities, of course, did not fall clearly into one terrain type or another. We included these in the steeper of the two categories if more than just a single hill or ridge (or a small group of them) was of the steeper type; we included them in the flatter of the two categories if the relatively steep parts appeared, from the road pattern or from shading on the map, not to lie in regions likely to be served by buses. To make these decisions, we found it useful to make general maps by tracing both the drainage pattern and rail pattern onto the allometric circle. Figure 2 includes maps of this sort for selected transit authorities that did not fall clearly into a particular terrain type. It also includes maps of terrain in transit authorities typical of each terrain type. The river and rail networks

TABLE 1: ALLOMETRIC RADII BY POPULATION

Radius in miles	Radius in inches on 1:250,000 map	Population interval represented by circle (5) (1980 census data)
1	0.25	0-15,575
2	0.51	15,576-50,017
3	0.76	50,018-107,859
4	1.01	107,860-191,484
5	1.27	191,485-302,813
6	1.52	302,814-443,478
7	1.77	443,479-614,911
8	2.03	614,912-818,389
9	2.28	818,390-1,055,073
10	2.53	1,055,074-1,326,032
11	2.79	1,326,033-1,632,253
12	3.04	1,632,254-1,974,661
13	3.30	1,974,662-2,354,122
14	3.55	2,354,123-2,771,457
15	3.80	2,771,458-3,227,441
16	4.06	3,227,442-3,722,813
17	4.31	3,722,814-4,258,281
18	4.56	4,258,282-4,834,518
19	4.82	4,834,519-5,452,174
20	5.07	5,452,175-6,111,873
21	5.32	6,111,874-6,814,216
22	5.58	6,814,217-7,559,783

partitioned these circles into a number of regions, within each of which we determined, using the contour combs, whether they were flat, intermediate, or steep, and shaded them accordingly. The content of Figure 2 is organized, generally, according to increasing steepness of terrain; in flat cities it appeared that rails were often straight and that no topographic advantage was gained by running rails in river valleys. Thus, rail lines in flat cities, as well as those in substantially flat coastal areas of non-flat cities (e.g., Oakland), were omitted in Figure 2. In non-flat cities, both river and rail patterns were shown; in fact, curviness in railnet generally suggested non-flat cities.

Within the flat group of cities shown in Figure 2, Detroit, Indianapolis, Sacramento, and Stockton are all clearly flat; however, the drainage pattern in Indianapolis suggests a more undulating surface, and a corresponding increase in wear on bus brakes and powertrain, than does that of Detroit. Sacramento and Stockton both appear to have surfaces that show more topographic variation resulting from the need to cross river valleys than does Detroit, but less than does Indianapolis. River width also helps to determine extent of undulation; narrow streams may be bridged at grade level while wider streams, not easily bridged in that fashion, force change in elevation. Judging from local Ann Arbor field evidence, streams that appear on maps at a scale of 1:250,000 are wide enough to be of the latter sort.

Louisville and San Jose are both predominantly flat. An eastern section of Louisville near a stream feeding into the Ohio River is somewhat hilly; the general pattern of contour lines

TABLE 2: ALLOMETRIC RADII, POPULATION, AND TERRAIN TYPE OF 183 TRANSIT AUTHORITIES.

LOCATION	ALLOMETRIC RADIUS (IN INCHES) AT A SCALE OF 1:250,000	POPULATION (1980 CENSUS)	TERRAIN
New York City	5.58	7,071,639	flat
Chicago	3.80	3,005,072	flat
Los Angeles	3.80	2,968,579	steep
Philadelphia	3.04	1,688,210	intermediate
Washington D.C.	2.03	638,432	steep
Boston	1.77	562,994	steep
Detroit	2.53	1,203,368	flat
Cleveland	1.77	573,822	intermediate
Seattle	1.77	493,846	steep
San Francisco	2.03	678,974	steep
Baltimore	2.03	786,741	intermediate
Louisville	1.27	298,694	flat
Atlanta	1.52	425,022	intermediate
Minneapolis/St. Paul	2.03	641,181	intermediate
Pittsburgh	1.52	423,959	steep
St. Louis	1.77	452,801	intermediate
Oakland	1.52	339,288	steep
Houston	2.79	1,594,086	flat
Milwaukee	2.03	636,297	intermediate
Miami	1.52	346,931	flat
Denver	1.77	492,686	intermediate
Garden Grove	1.01	123,351	flat
Portland, OR	1.52	368,139	intermediate
San Antonio	2.03	785,940	intermediate
San Jose	2.03	629,400	intermediate
New Orleans	1.77	577,927	flat
Dallas	2.28	904,570	intermediate
Cincinnati	1.52	385,409	steep
Norfolk, VA	1.27	266,979	flat
San Diego	2.28	875,504	steep
Kansas City	1.77	448,028	steep
Salt Lake	1.01	163,034	intermediate
San Mateo	0.76	77,640	steep
Memphis	2.03	646,174	intermediate
Phoenix	2.03	764,911	flat
Buffalo	1.52	357,870	flat
Columbus	1.77	565,032	flat
Hartford	1.01	136,392	intermediate
Rochester	1.27	241,741	flat

LOCATION	ALLOMETRIC RADIUS	POPULATION	TERRAIN
Sacramento	1.27	275,741	flat
Omaha	1.52	313,939	steep
Providence	1.01	156,804	flat
Albany	0.76	101,727	intermediate
Springfield, MA	1.01	152,319	intermediate
Indianapolis	2.03	700,807	flat
Flushing			flat
Jamaica			flat
Dayton	1.27	193,536	intermediate
Madison	1.01	170,616	intermediate
Long Beach	1.52	361,355	flat
Toledo	1.52	354,635	flat
Birmingham	1.27	284,413	intermediate
Richmond	1.27	219,214	flat
Jacksonville	1.77	540,898	flat
Tacoma	1.01	158,501	flat
Syracuse	1.01	170,105	intermediate
Jackson Heights			flat
Nashville	1.77	455,651	intermediate
Tucson	1.52	330,537	flat
Fort Lauderdale	1.01	153,256	flat
Des Plaines	0.76	53,568	flat
Hampton, VA	1.01	122,617	flat
New Haven	1.01	126,089	intermediate
Des Moines	1.01	191,003	intermediate
Akron	1.27	237,177	intermediate
Oklahoma City	1.52	404.014	flat
Oceanside, CA	0.76	76,698	intermediate
Newport, KY	0.51	21,587	steep
Gary	1.01	151,968	flat
Charlotte	1.52	315,474	intermediate
Bridgeport, CT	1.01	142,546	flat
Fort Worth	1.52	385,141	intermediate
Riverside, CA	1.01	170,591	intermediate
Fresno	1.27	217,346	flat
Duluth	o.76	92,811	steep
Wilmington	0.76	70,195	intermediate
Spokane	1.01	171,300	flat
Tulsa	1.52	360,919	flat
San Bernardino, CA	1.01	118,794	flat
El Paso	1.52	425,259	intermediate
Canton	0.76	93,077	intermediate
New Bedford	0.76	95,478	flat
West Palm Beach	0.76	62,530	flat
Albuquerque	1.52	332,336	flat
Yonkers	1.27	195,351	steep
Winston-Salem	1.01	131,885	intermediate
Eugene	0.76	105,664	intermediate
Brooklyn	3.30	2,230,936	flat
Knoxville	1.01	175,045	intermediate

LOCATION	ALLOMETRIC RADIUS	POPULATION	TERRAIN PEER-GROUP
Ann Arbor	1.01	107,969	intermediate
Tampa	1.26	271,598	flat
Harrisburg	0.76	53,246	intermediate
Austin	1.52	345,890	intermediate
Santa Cruz	0.51	41,483	flat
Worcester	1.01	161,799	steep
Charleston, WV	0.76	63,968	steep
Chattanooga	1.01	169,728	intermediate
Youngstown	1.01	115,436	intermediate
Bay City	0.51	41,593	flat
Wichita	1.27	279,835	flat
Erie	1.01	119,121	intermediate
Santa Barbara	0.76	74,542	steep
St. Petersburg	1.27	236,893	flat
Flint, MI	1.01	159,611	intermediate
Lincoln, NB	1.01	171,932	intermediate
Kalamazoo	0.76	79,722	intermediate
Ft. Wayne	1.01	172,391	flat
Brockton, MA	0.76	95,172	intermediate
Allentown	0.76	103,758	flat
Kingston, PA	0.51	15,681	flat
Urbana/Champaign	0.76	94,245	flat
Portland, ME	0.76	61,572	flat
Clearwater	0.76	85,450	flat
Colorado Springs	1.27	215,105	intermediate
Corpus Christi	1.27	231,134	flat
Savannah	1.01	141,654	flat
Salem	0.76	89,233	intermediate
South Bend	1.01	109,727	flat
Shreveport	1.27	205,815	flat
Raleigh	1.01	149,771	intermediate
Baton Rouge	1.27	220,344	flat
Little Rock	1.01	158,915	intermediate
Stockton, CA	1.01	149,779	flat
Lexington	1.27	204,165	flat
Columbus, GA	1.01	169,441	intermediate
Rockford	1.01	139,712	intermediate
Jackson, MS	1.27	202,895	intermediate
Cedar Rapids	1.01	110,243	intermediate
Montebello	0.76	52,929	flat
Orlando	1.01	128,394	flat
Amarillo	1.01	149,230	flat
Peoria	1.01	124,160	intermediate
Torrance	1.01	131,497	flat
Utica	0.76	75,632	intermediate
Gainesville	0.76	81,371	flat
Gardena	0.51	45,165	flat
Lubbock	1.01	173,979	flat

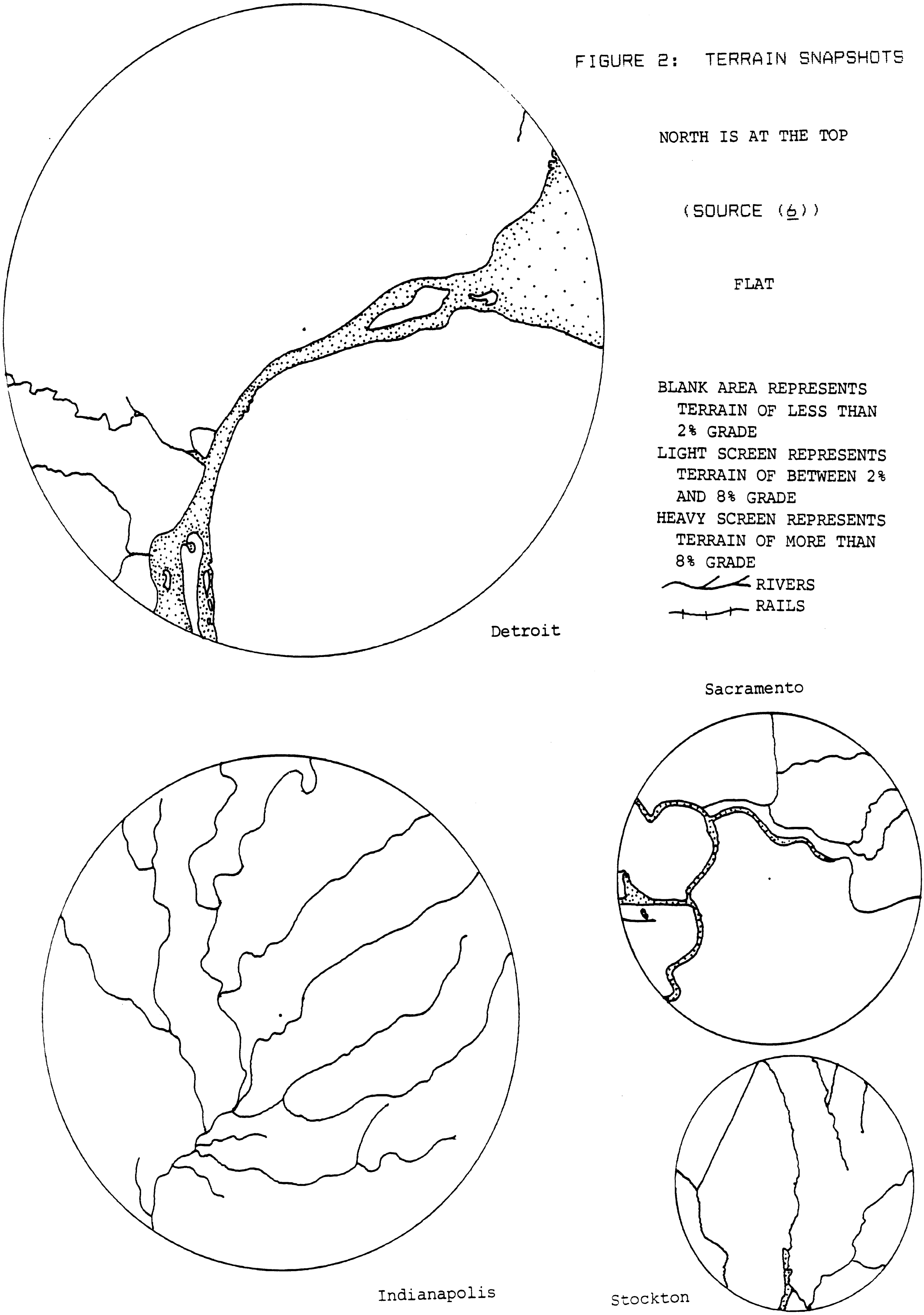
LOCATION	ALLOMETRIC RADIUS	POPULATION	TERRAIN PEER-GROUP
Saginaw	0.76	77,508	flat
Jackson, MI	0.51	39,739	intermediate
Ventura	0.76	73,774	steep
Springfield, IL	0.76	100.054	flat
Bakersfield	0.76	105,611	flat
Waukegan	0.76	67,653	flat
Johnstown, PA	0.51	35,496	steep
Appleton	0.76	58,913	intermediate
Mobile	1.27	200,452	intermediate
Lancaster	0.76	54,725	flat
Scranton	0.76	88,117	intermediate
Binghamton	0.76	55,860	intermediate
Lowell, MA	0.76	92,418	intermediate
Kent, OH	0.51	26,164	intermediate
Tallahassee	0.76	81,548	intermediate
Augusta	0.51	47,532	intermediate
Roanoke	0.76	100,427	intermediate
Asheville, NC	0.76	53,281	intermediate
Huntington, WV	0.76	63,684	intermediate
Sioux City	0.76	82,003	intermediate
Manchester, NH	0.76	90,936	intermediate
Daytona	0.76	54,176	flat
Oshkosh	0.51	49,678	flat
Boise	0.76	102,249	intermediate
Haverhill, MA	0.51	46,865	intermediate
Montgomery	1.01	178.157	intermediate
Altoona	0.76	57,078	intermediate
Harahan, LA	0.25	11,384	flat
Norwalk, Ca	0.76	84,901	flat
Rock Island, IL	0.51	46,821	flat
Gretna, LA	0.51	20,615	flat
Waterloo	0.76	75,985	intermediate
Topeka	1.01	118,690	intermediate
Kenosha	0.76	77,685	flat
Pensacola	0.76	57,619	flat
Monterey	0.51	27,558	flat
Davenport	0.76	103,264	intermediate
Dubuque	0.76	62,321	steep
Lynchburg	0.76	66,743	intermediate
Decatur	0.76	93,939	flat
Fayetteville	0.76	59,507	intermediate
Stamford	0.76	102,466	intermediate
Bradenton, FL	0.51	30,228	flat
La Crosse	0.51	48,347	flat
Laredo	0.76	91,449	intermediate
St. Cloud	0.51	42,566	flat

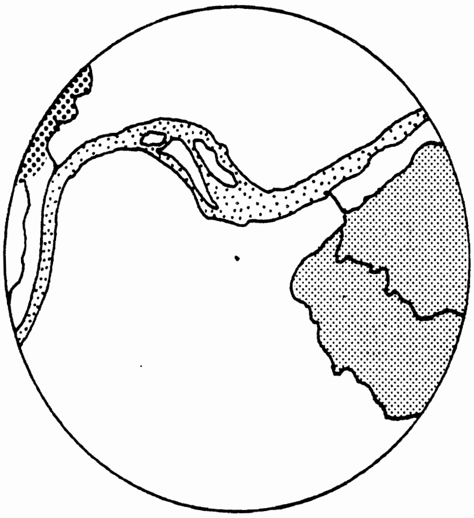
FIGURE 2: TERRAIN SNAPSHOTS

NORTH IS AT THE TOP

(SOURCE (6))

FLAT

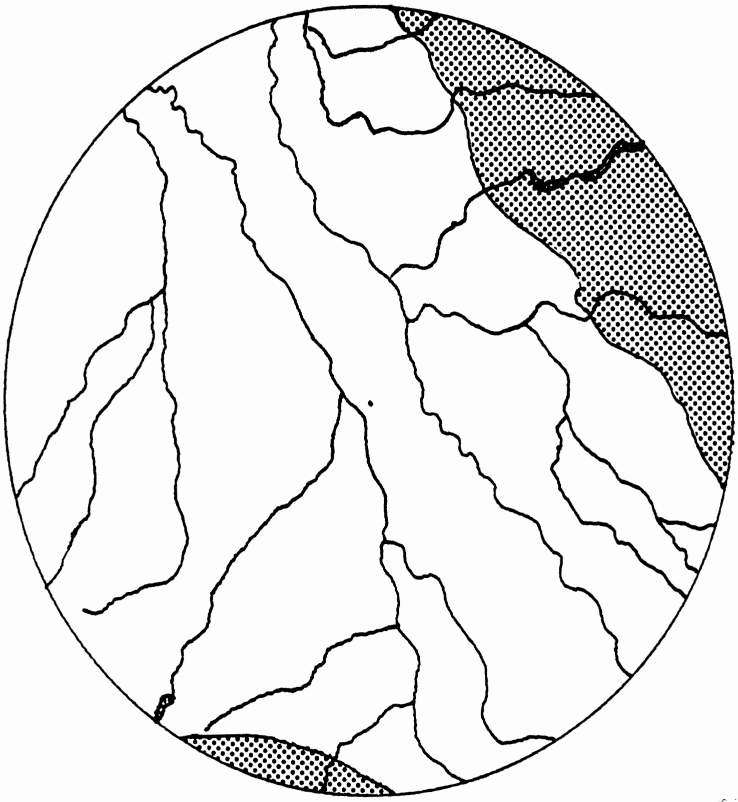




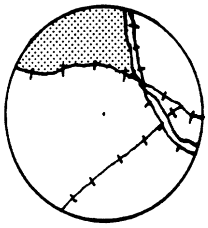
NORTH IS AT THE TOP

FLAT

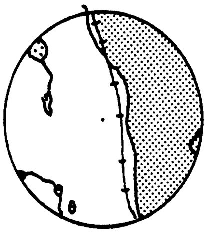
Louisville



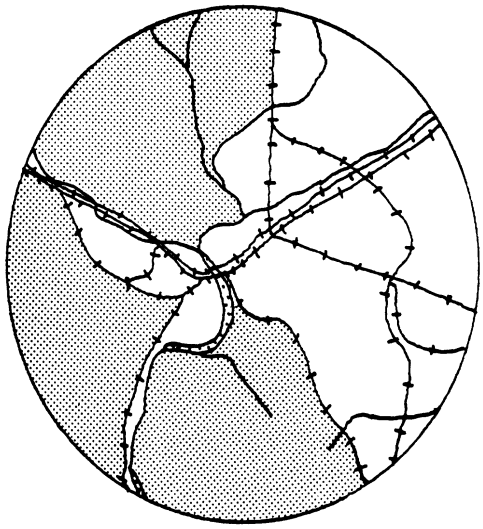
San Jose



Jackson MI

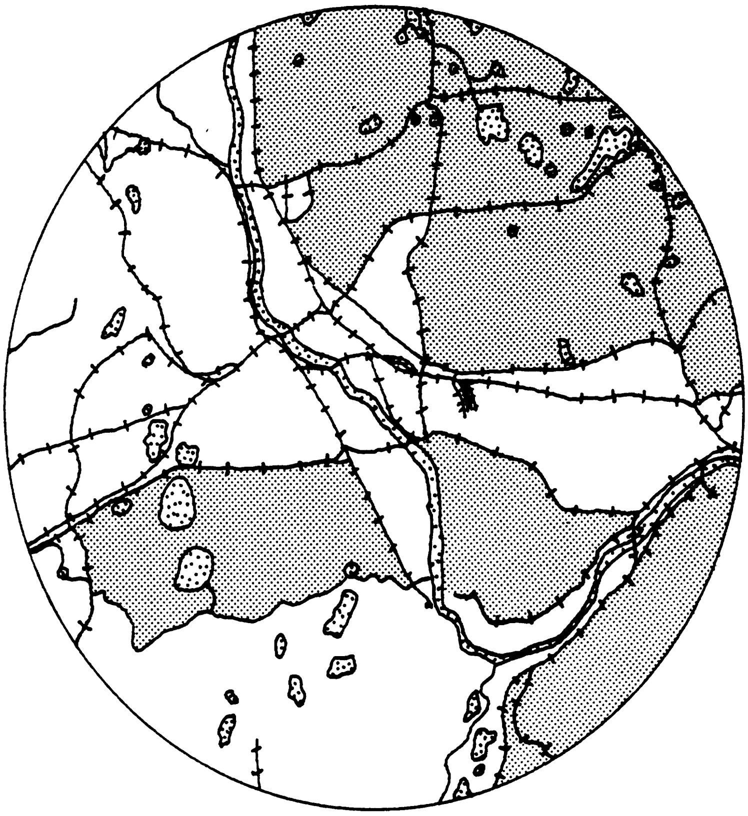


Brockton MA

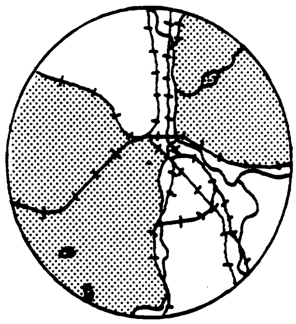


Dayton

NORTH IS AT THE TOP

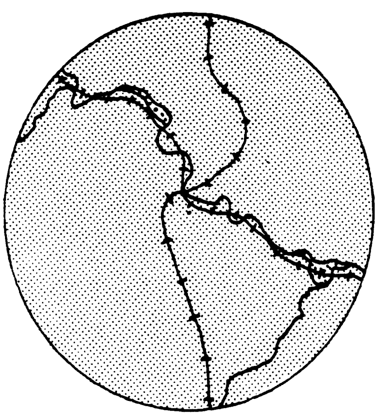


Minneapolis-Saint Paul

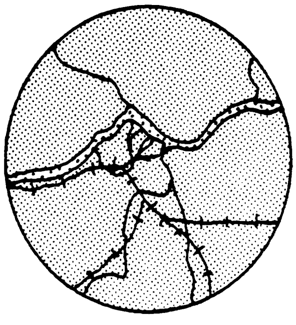


Kalamazoo

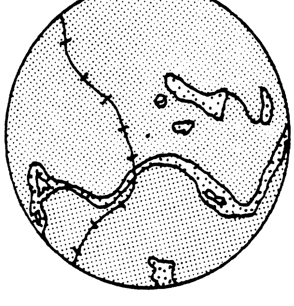
INTERMEDIATE



Ann Arbor



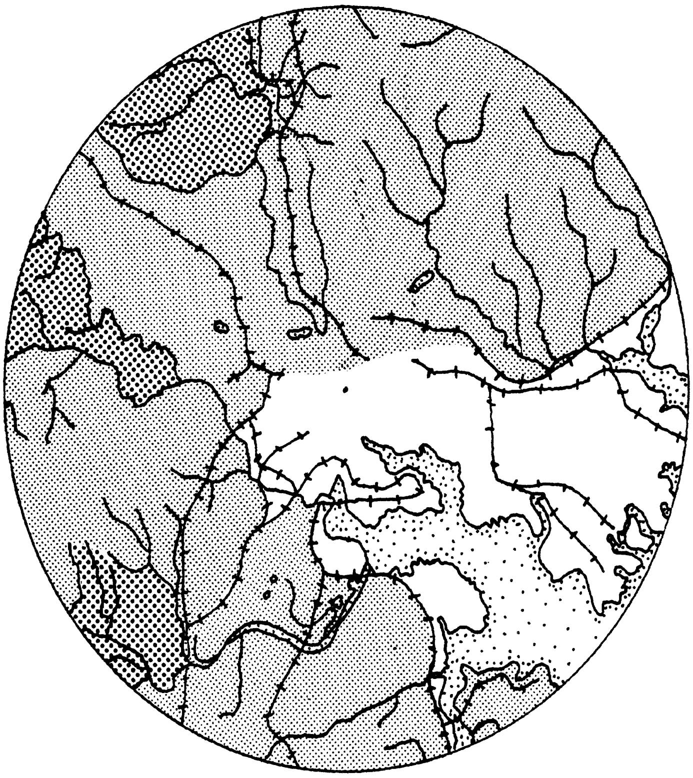
Lowell MA



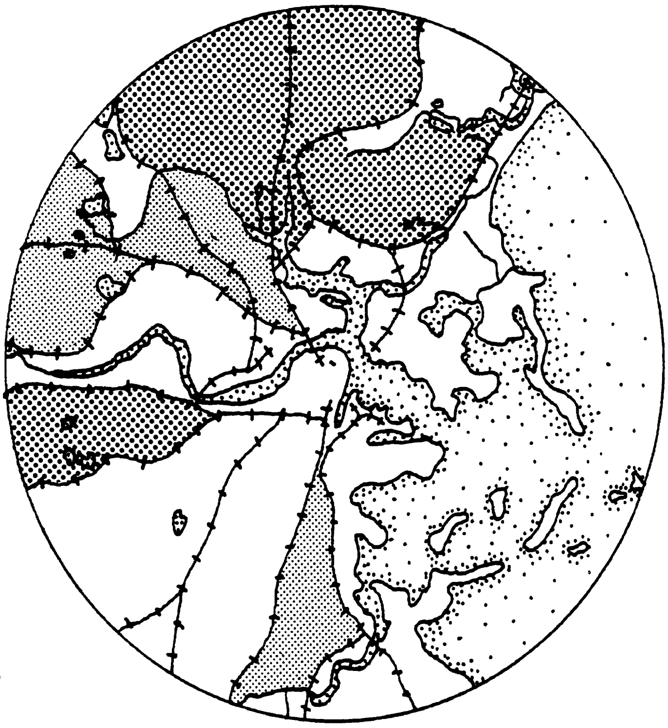
Haverhill MA

NORTH IS AT THE TOP

INTERMEDIATE



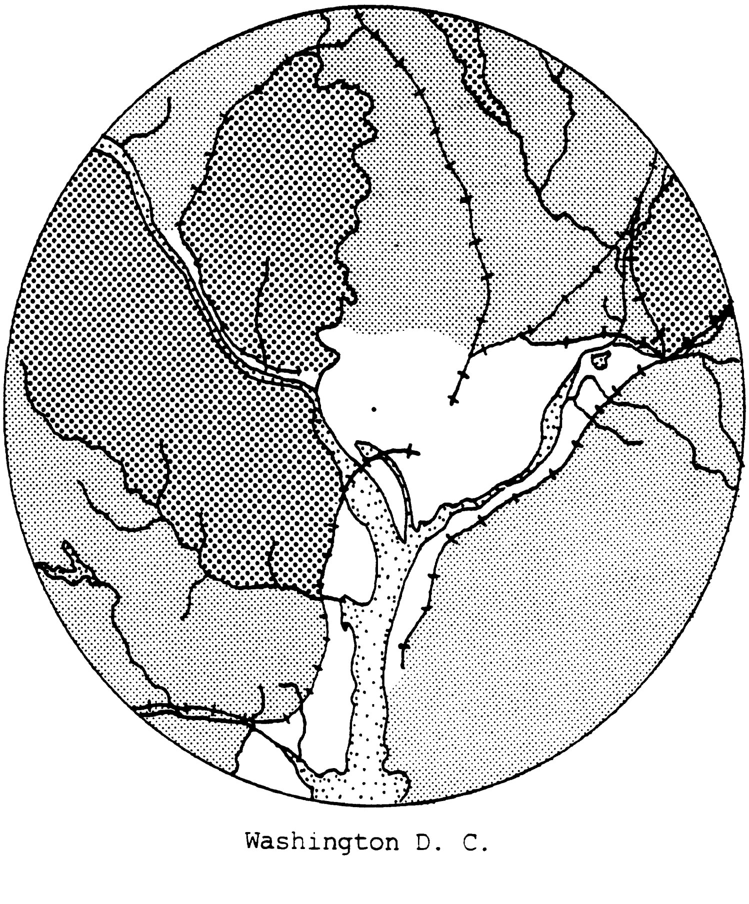
Baltimore



NORTH IS AT THE TOP

STEEP

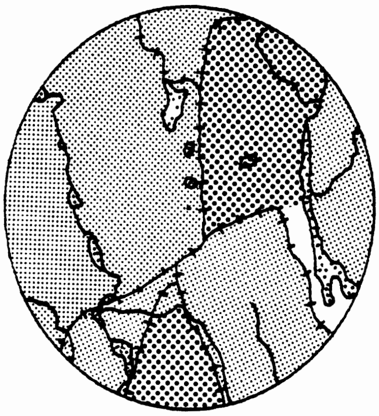
Boston



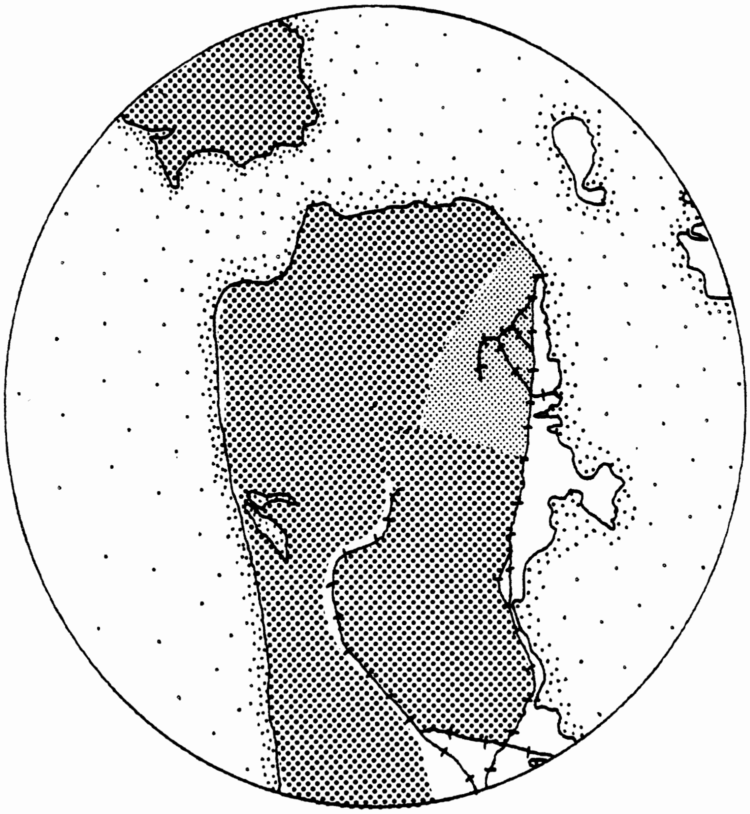
Washington D. C.

STEEP

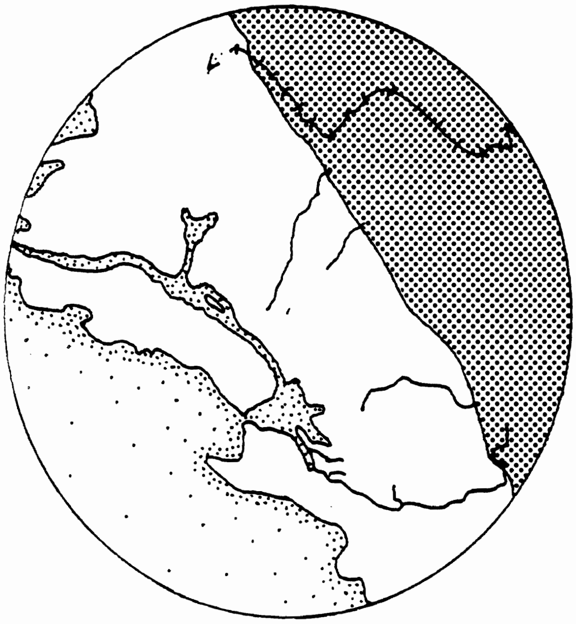
NORTH IS AT THE TOP



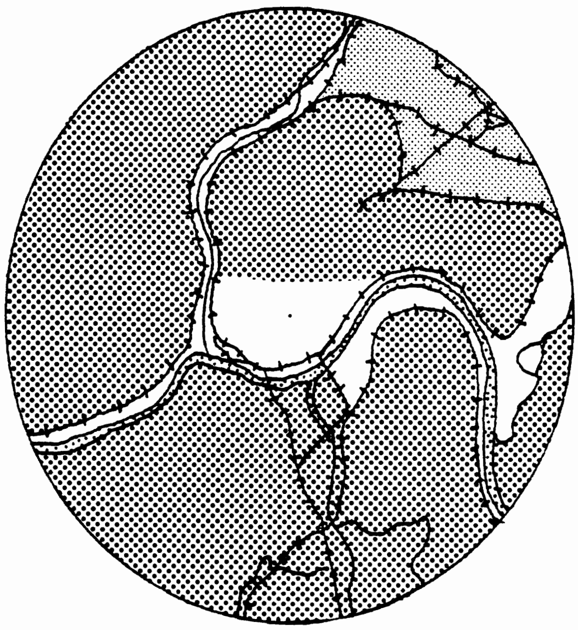
Worcester MA



San Francisco



Oakland CA



Cincinnati-Newport

suggests a clearly flat region elsewhere. San Jose, however, might have been classed as intermediate, or even as steep, if the road pattern had suggested that people live in the hills to the northeast of center. No evidence suggested this and thus we classed San Jose as flat since it appears that most bus routes would cross flat terrain.

In the intermediate class, the flattest city is Jackson, Michigan, and the steepest is Baltimore. Jackson and Brockton were the least steep; however, both maps displayed curvy railnets, at least one line in each of which ran along the river next to terrain classed as intermediate, suggesting topographic advantage from such placement. Dayton, Minneapolis-Saint Paul, and Kalamazoo showed a mixture of flat and intermediate regions but appeared, on the whole, to be predominantly intermediate. Ann Arbor, Lowell, and Haverhill are all intermediate as determined both from contour combs and from the shape of rail lines. Baltimore has a few steep areas; as these occur mainly in parklands, the city was placed in the intermediate class.

In the steep class, Boston and Washington contained a fairly even mixture of flat, intermediate, and steep regions. In both cases, a substantial amount of the steep terrain appeared to be in residential areas, requiring buses to shift through the entire spectrum of terrain types; thus, these were classified as steep. The remaining four cities, Worcester, San Francisco, Oakland, and Cincinnati appeared clearly steep, although each in a different way.

ANN ARBOR EXPERIMENT

Terrain analysis

Ann Arbor is a university town of population 107,969; it has 18 distinct bus routes serving this population as well as the population of 24,031 in Ypsilanti, Michigan, a smaller neighbor about three miles away (5, 7). Buses are housed in Ann Arbor in an Ann Arbor Transit Authority facility south of the CBD. A central stop in downtown Ann Arbor, at Fourth and Wiliam, serves as the terminus for all routes, and one at Michigan and Adams serves a similar function for routes going into the Ypsilanti CBD. Both CBDs are located about 1/2 mile from the Huron River. Except to the southeast, Ann Arbor's CBD is higher than is the territory immediately surrounding it; farther away from the CBD, glacial features such as moraines and hogbacks dominate the landscape and provide a generally rolling surface over which buses travel. Thus, the value of about 2% slope assigned by the Terrain Template might not faithfully represent the average slope along individual bus routes, although it should describe the percent slope across all the bus routes.

To investigate this, we mapped each of 18 actual bus routes and calculated the average percent slope of each of them. The mechanics of doing this involved finding the total relief and the total distance along each route; to obtain resolution of the topography finer than that in Figure 2, we used maps of scale 1:24,000 rather than maps of scale 1:250,000. The distance measurement is straightforward; to measure total relief along a

TABLE 3: ANN ARBOR, TOPOGRAPHIC BUS ROUTE ANALYSIS

Route number (8)	Number of contours crossed	Route length (in feet)	Per cent slope
1; in	41	14,000	420/14000=3.0
out	73	21,800	740/21800=3.4
2; in	84	42,000	850/42000=2.0
out	82	40,600	830/40600=2.0
3; in	119	56,400	1150/56400=2.0
out	same		
4; in	82	44,000	780/44000=1.8
out	same		
5; in	77	56,600	720/56600=1.3
out	same		
6; in	92	61,000	930/61000=1.5
out	same		
7; in	159	64,800	1600/64800=2.5
out	same		
8; in	32	14,600	330/14600=2.3
out	28	11,400	290/11400=2.5
9; in	28	13,800	290/13800=2.1
out	same		
10; in	42	19,600	215/19600=1.1
out	64	31,600	325/31600=1.0
11; in	34	13,200	175/13200=1.3
out	57	13,000	290/13000=2.2
12; in	109	56,200	1100/56200=2.0
out	same		
13; in	56	20,000	570/20000=2.9
out	52	18,600	530/18600=2.9
14; in	59	20,000	600/20000=3.0
out	50	17,400	510/17400=2.9
15; in	55	25,400	560/25400=2.2
out	52	24,800	530/24800=2.1
16; in	24	17,200	250/17200=1.5
out	same		
17; in	35	16,000	360/16000=2.3
out	same		
18; in	29	19,000	245/19000=1.3
out	same		

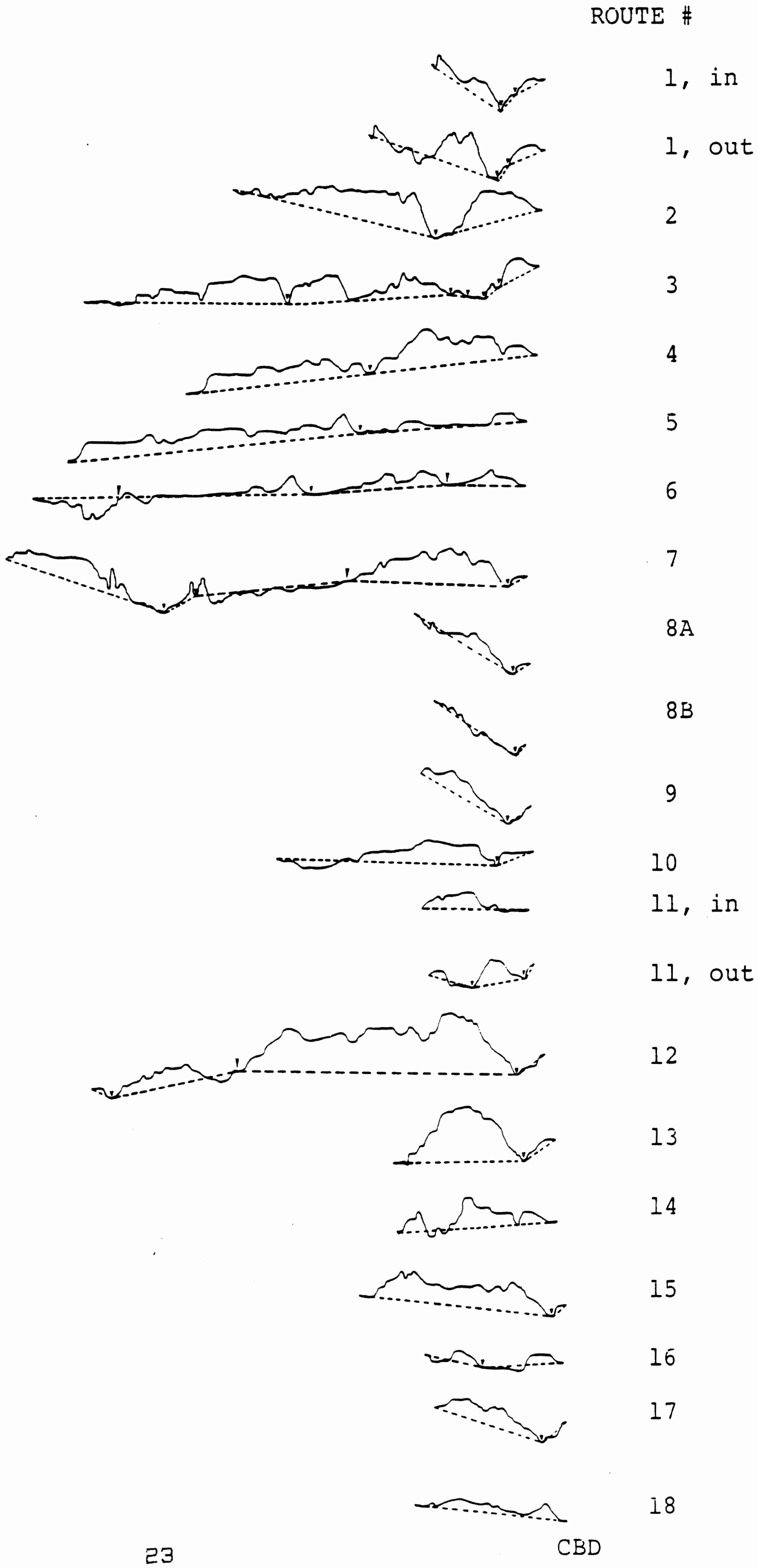
route, the number of contour lines the route crossed were counted, and this was converted to feet by multiplying this number by the value in feet of the contour interval (5 or 10 in this case) and adding 5 or 10 (as appropriate) to accommodate the ends of the bus route. Then (route relief / route length) gave an average percent slope along the route.

Table 3 shows percent slope derived from topographic route analysis for each of the 18 Ann Arbor bus routes. Some routes have different inbound and outbound paths; these are also noted in Table 3. These results were used to chart vertical profiles of each of these 18 bus routes (at a scale of 1:24,000). The profiles appear in Figure 3; both inbound and outbound profiles along a single route were included in this figure only if they appeared dissimilar. The vertical scale of the 1:24,000 profiles is 1 inch to 50 feet, and the horizontal scale is 1 inch to 2000 feet. Thus, the corresponding vertical exaggeration of the 1:24,000 profiles is 40 times that which appears in the landscape. Table 3 shows the percent slope along each route; the average of these values was calculated as 2.039, and the average percent slope across all routes in Table 3 was 1.953%.

Bus route structure

The vertical profiles of Figure 3 all appear to be quite bumpy; however, the general trend of some is a relatively smooth climb or drop toward the terminus in the CBD. That of others is oscillation with eventual settling at the terminus. Some of the topographic variation in these profiles results from features in the landscape, such as rivers, that force a drop along the bus route. The remainder of the topographic variation arises from

FIGURE 3: ANN ARBOR BUS ROUTE VERTICAL PROFILES



demand for bus service and the response of transit engineers in bus-stop placement. The arrowheads in Figure 3 represent all topographic features, such as rivers, creeks, or rails running in river valleys, that appear on the 1:250,000 map. Field testing showed that all features which appeared at this scale forced fluctuation in the surface route, while other topographic features that appeared only at the 1:24,000 scale produced fluctuations which were easily bridged, were not significant, and were therefore not included.

A topographic force, resulting from physical features and from economic demands, acts on each bus route. It is composed of fixed and variable components. In all terrain peer groups, streams which appear on a 1:250,000 map produce critical values in the vertical profiles of bus routes crossing those streams. In intermediate and steep classes, rails which appear on a 1:250,000 map produce additional critical values in the vertical profiles of bus routes crossing those rails. (Rails running alongside rivers contribute little; those which run in valleys with no river contribute much.) When each critical value is distinguished on a profile (by arrowheads in Figure 3), the profile is partitioned into a set of mutually exclusive intervals (labeled I_1, I_2, I_3,..., from left to right, or from outskirts to CBD, in Figure 3).

<u>Definition 1</u>

The fixed topographic force along a bus route, partitioned into n intervals by (n-1) critical values, is an ordered n-tuple in which the components of the n-tuple represent, in order, the percent slope of line segments joining the end of the route to the first critical value, the percent slope of the line segment joining the first critical value to the second critical value,..., the percent slope of the line segment joining the (n - 1)st critical value to the CBD terminus.

In Figure 3, the line segments referred to in Definition 1 are shown as dashed lines in each profile. Table 3 shows the fixed topographic force for all Ann Arbor bus route intervals; intervals are coded by left-right position within a route and by route number. For example, Route 7 has a fixed topographic force of (0.8, 0.4, 0.1, 0.2, 1.2) across its five intervals. The second interval from the left along Route 7 is denoted $I_2(R_7)$; designations of "in" and "out" refer to inbound and outbound routes. In Table 4, only those intervals included in Ann Arbor, as represented in the allometric circle of Figure 2, are included. Thus, Table 4 will be compatible for use with Figure 2. The rank-ordering (Table 4) shows the fixed topographic force generally to be less than the "intermediate" value of about 1.5 to 2.0% slope. The sequential ordering by route shows, when used in conjunction with Figure 3, that relative measurements of steepness, both within and between routes, is consistent with the positions of the dashed lines underlying the vertical profiles.

Definition 2

The variable topographic force along a bus route, partitioned into n intervals by (n-1) critical values, is an ordered n-tuple with order given as in Definition 1. For a given interval, the variable force is calculated as the sum of the absolute values of variation of the profile from the fixed

TABLE 4: FIXED TOPOGRAPHIC FORCE

Rank-ordering across all intervals		Sequential ordering by individual route number.	
Force value	Interval number	Force value	Interval number
2.9	$I_2(R_1$, out)	1.6	$I_1(R_1$, in)
2.5	$I_2(R_1$, in)	2.5	$I_2(R_1$, in)
1.9	$I_2(R_{8B})$	1.2	$I_3(R_1$, in)
1.8	$I_2(R_9)$	0.8	$I_1(R_1$, out)
1.7	$I_5(R_3)$	2.9	$I_2(R_1$, out)
1.7	$I_2(R_{17})$	1.3	$I_3(R_1$, out)
1.6	$I_1(R_1$, in)	0.5	$I_1(R_2)$
1.6	$I_1(R_{8B})$	0.6	$I_2(R_2)$
1.5	$I_4(R_{12})$	0.2	$I_2(R_3)$
1.5	$I_2(R_{15})$	0.4	$I_3(R_3)$
1.4	$I_2(R_{8A})$	0.0	$I_4(R_3)$
1.4	$I_1(R_9)$	1.7	$I_5(R_3)$
1.3	$I_3(R_1$, out)	1.2	$I_6(R_3)$
1.3	$I_1(R_{8A})$	0.3	$I_2(R_4)$
1.3	$I_1(R_{12})$	0.2	$I_2(R_5)$
1.3	$I_2(R_{13})$	0.0	$I_2(R_6)$
1.2	$I_3(R_1$, in)	0.2	$I_3(R_6)$
1.2	$I_6(R_3)$	0.0	$I_4(R_6)$
1.2	$I_5(R_7)$	0.8	$I_1(R_7)$
1.1	$I_1(R_{17})$	0.4	$I_2(R_7)$
0.8	$I_1(R_1$, out)	0.1	$I_3(R_7)$
0.8	$I_1(R_7)$	0.2	$I_4(R_7)$
0.6	$I_2(R_2)$	1.2	$I_5(R_7)$
0.6	$I_1(R_{16})$	1.3	$I_1(R_{8A})$
0.5	$I_1(R_2)$	1.4	$I_2(R_{8A})$
0.5	$I_1(R_{15})$	1.6	$I_1(R_{8B})$
0.4	$I_3(R_3)$	1.9	$I_2(R_{8B})$
0.4	$I_2(R_7)$	1.4	$I_1(R_9)$
0.4	$I_3(R_{12})$	1.8	$I_2(R_9)$
0.3	$I_2(R_4)$	1.3	$I_1(R_{12})$

Force value	Interval number	Force value	Interval number
0.2	$I_2(R_3)$	0.4	$I_2(R_{12})$
0.2	$I_2(R_5)$	0.2	$I_3(R_{12})$
0.2	$I_3(R_6)$	1.5	$I_4(R_{12})$
0.2	$I_4(R_7)$	0.2	$I_1(R_{13})$
0.2	$I_3(R_{12})$	1.3	$I_2(R_{13})$
0.2	$I_1(R_{13})$	0.0	$I_1(R_{14})$
0.1	$I_3(R_7)$	0.5	$I_1(R_{15})$
0.05	$I_2(R_{16})$	1.5	$I_2(R_{15})$
0.0	$I_4(R_3)$	0.6	$I_1(R_{16})$
0.0	$I_2(R_6)$	0.05	$I_2(R_{16})$
0.0	$I_3(R_6)$	1.1	$I_1(R_{17})$
0.0	$I_1(R_{14})$	1.7	$I_2(R_{17})$

force (measured at all points on the profile where the bus route crosses contour lines) divided by the length of the fixed force line.

Thus, for example, in Figure 4, the fixed force line links critical values, as in Figure 3, and has slope (30-10)/(2 x 2000) = 0.005. Multiplying by 100 produces a value of 0.5% average slope across I_2. The variable force across I_2 is the sum of the lengths drawn from the profile to the fixed force line, divided by the length of the fixed force line. Or, in this case, (5+10+15+20+30+35+40+45+40+30+25+20+15+10+5+5)/(2 x 2000)=0.0875. Multiplying by 100 produces a value of 8.75% variable force across I_2. Table 5 shows the variable topographic force for all Ann Arbor bus route intervals, coded as in Table 4.

Since contour crossings were the points used from which to measure deviations, rather than an evenly spaced net of points, steepness is reflected directly in this variable force measure, since steeper segments were sampled more frequently than smoother segments. Other techniques that might appear reasonable for measuring variable force include

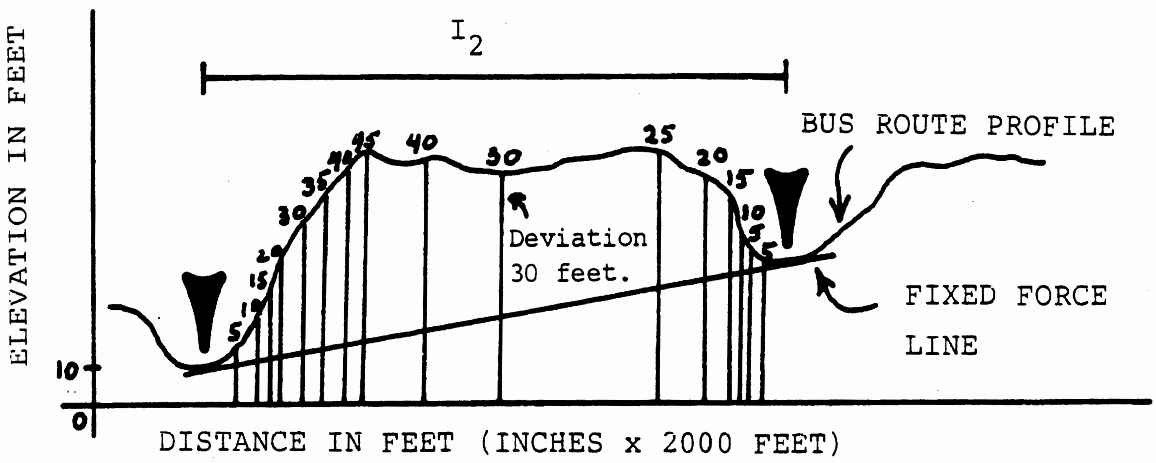
1) use of a regression line fit to the scatter of contour crossings of the profile to estimate general profile;

2) integration to find the area between the profile and the fixed force line. However,

1) regression is inappropriate, because elevation (measured along the y-axis) is not necessarily a function of distance (measured along the x-axis);

2) definite integrals cannot be used, because we do not

FIGURE 4: VARIABLE TOPOGRAPHIC FORCE CALCULATION



have an equation for the profile; approximation techniques, such as the trapezoidal rule or Simpson's rule, do not apply to the partition using contour line crossings--they require evenly spaced intervals, and this would result in the loss of the heavier numerical contribution of the steeper segments.

If the values in the rank-ordering of Table 5 are partitioned (roughly) into thirds, at the 8% level and at the 2% level, one-third contains bus route intervals that have a steep variable topographic force; another contains those of intermediate variable topographic force (between 2% (inclusive) and 8% (exclusive)); and the remaining one-third contains those of flat variable topographic force. Figure 5 shows the intervals from Table 5 mapped for the Ann Arbor allometric circle according to variable topographic force; route shape is represented abstractly as radial or circular. Here, routes 1, 4, 5, 8, 9, 13, 14, 15, 16, and 17 are radials, while 2, 3, 6, 7, and 12 are more circuitous. When the data in Table 4 are partitioned into thirds, corresponding exactly to the number of entries per third in the rank ordering column of Table 5, and then mapped as in Figure 5, the resulting map in Figure 6 shows the fixed topographic force across the intervals between critical values in Ann Arbor bus routes.

Comparison of Figures 5 and 6 yields several insights. First, radial routes that approach the CBD from the west have low variable force once they cross the tracks, even though the fixed force is steep just west of the CBD. This suggests that efficiency of bus routing across this terrain is good. Second,

TABLE 5: VARIABLE TOPOGRAPHIC FORCE

Rank-ordering across all intervals		Sequential ordering by individual route number	
Force value	Interval number	Force value	Interval number
25.3	$I_1(R_{13})$	6.8	$I_1(R_1$, in)
21.8	$I_3(R_{12})$	2.0	$I_2(R_1$, in)
15.1	$I_4(R_7)$	2.4	$I_3(R_1$, in)
14.0	$I_1(R_1$, out)	14.0	$I_1(R_1$, out)
12.8	$I_1(R_2)$	2.5	$I_2(R_1$, out)
11.5	$I_2(R_4)$	4.0	$I_3(R_1$, out)
11.3	$I_1(R_{15})$	12.8	$I_1(R_2)$
10.3	$I_2(R_3)$	7.5	$I_2(R_2)$
9.6	$I_1(R_{17})$	10.3	$I_2(R_3)$
9.4	$I_1(R_7)$	1.5	$I_3(R_3)$
8.2	$I_6(R_3)$	0.6	$I_4(R_3)$
8.0	$I_2(R_7)$	4.7	$I_5(R_3)$
7.7	$I_1(R_{14})$	8.2	$I_6(R_3)$
7.5	$I_2(R_2)$	11.5	$I_2(R_4)$
6.8	$I_1(R_1$, in)	0.9	$I_2(R_5)$
5.3	$I_1(R_9)$	2.0	$I_2(R_6)$
4.9	$I_2(R_{12})$	4.0	$I_3(R_6)$
4.7	$I_5(R_3)$	2.5	$I_4(R_6)$
4.0	$I_3(R_1$, out)	9.4	$I_1(R_7)$
4.0	$I_3(R_6)$	8.0	$I_2(R_7)$
3.8	$I_1(R_{8A})$	3.3	$I_3(R_7)$
3.3	$I_3(R_7)$	15.1	$I_4(R_7)$
2.5	$I_2(R_1$, out)	0.8	$I_5(R_7)$
2.5	$I_4(R_6)$	3.8	$I_1(R_{8A})$
2.4	$I_3(R_1$, in)	0.9	$I_2(R_{8A})$
2.4	$I_1(R_{16})$	1.7	$I_1(R_{8B})$
2.0	$I_2(R_1$, in)	0.6	$I_2(R_{8B})$
2.0	$I_2(R_6)$	5.3	$I_1(R_9)$

Rank-ordering across all intervals		Sequential ordering by individual route number	
Force value	Interval number	Force value	Interval number
1.7	$I_1(R_{8B})$	0.4	$I_2(R_9)$
1.5	$I_3(R_3)$	0.8	$I_1(R_{12})$
1.4	$I_2(R_{13})$	4.9	$I_2(R_{12})$
1.2	$I_2(R_{16})$	21.8	$I_3(R_{12})$
1.0	$I_2(R_{15})$	0.6	$I_4(R_{12})$
0.9	$I_2(R_5)$	25.3	$I_1(R_{13})$
0.9	$I_2(R_{8A})$	1.4	$I_2(R_{13})$
0.9	$I_2(R_{17})$	7.7	$I_1(R_{14})$
0.8	$I_5(R_7)$	11.3	$I_1(R_{15})$
0.8	$I_1(R_{12})$	1.0	$I_2(R_{15})$
0.6	$I_4(R_3)$	2.4	$I_1(R_{16})$
0.6	$I_2(R_{8B})$	1.2	$I_2(R_{16})$
0.6	$I_4(R_{12})$	9.6	$I_1(R_{17})$
0.4	$I_2(R_9)$	0.9	$I_2(R_{17})$

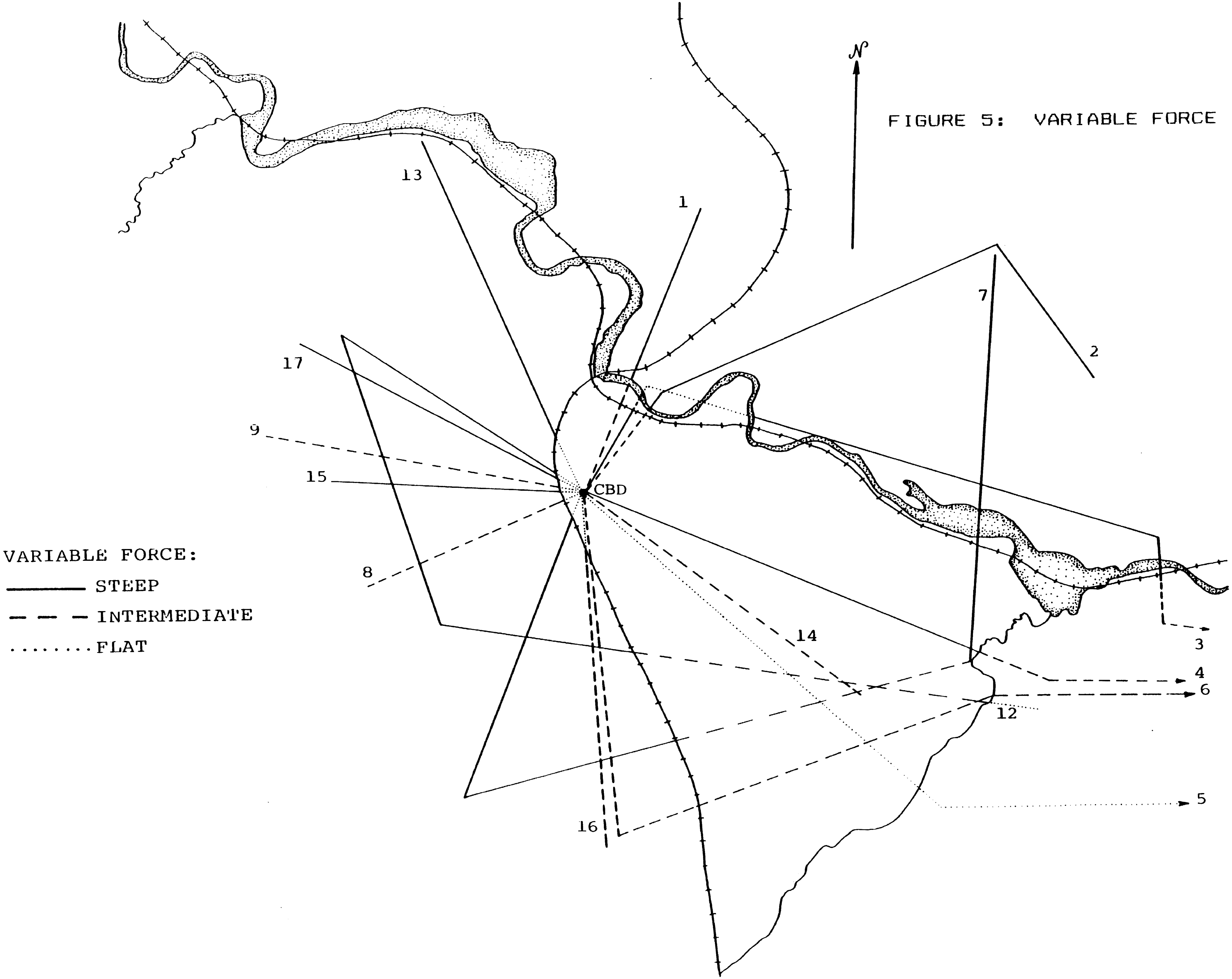


FIGURE 5: VARIABLE FORCE DIAGRAM

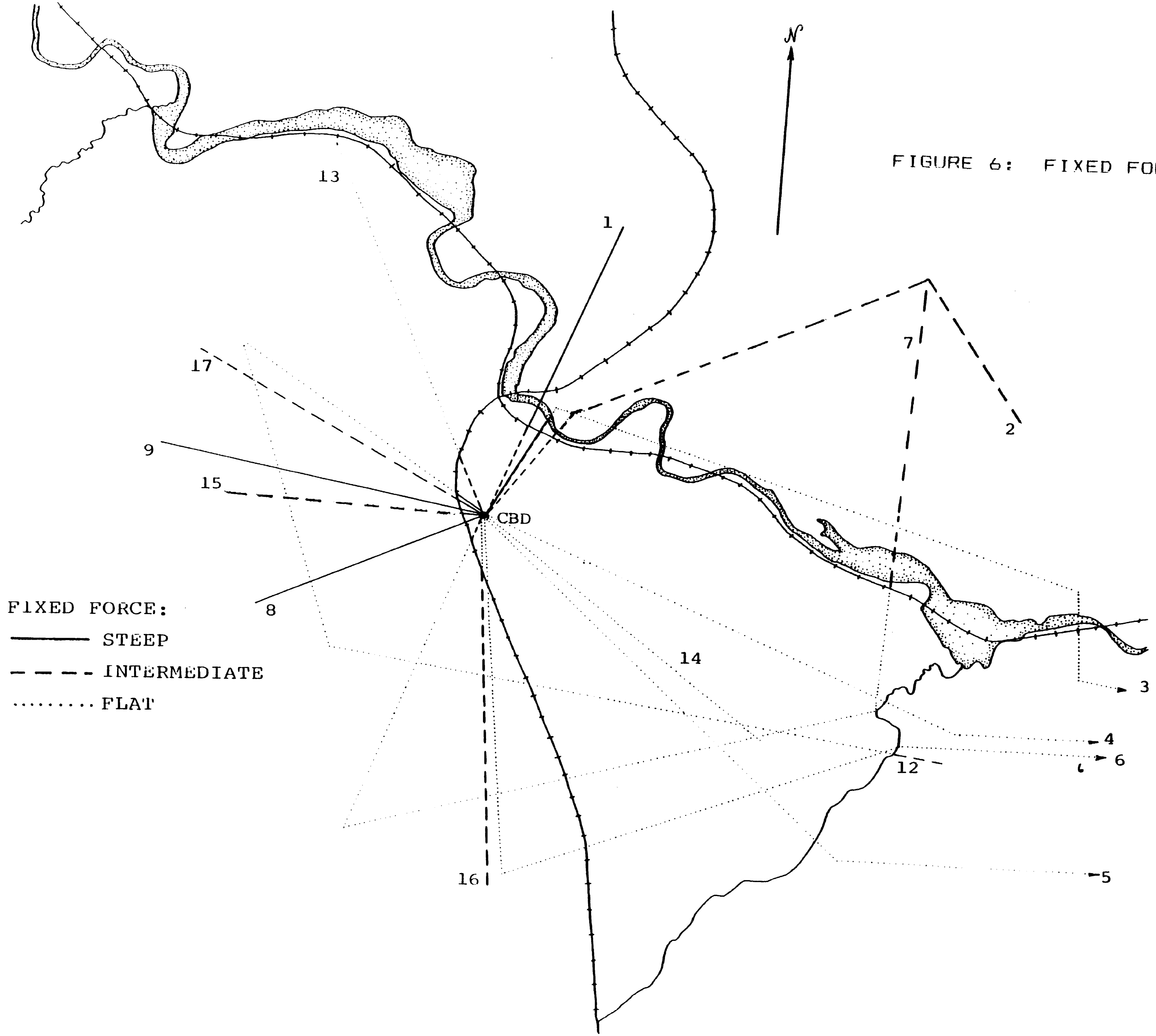


FIGURE 6: FIXED FORCE DIAGRAM

routes with steep variable force and flat fixed force experience more terrain stress than required by the critical values; review of demand for service and bus stop position is suggested (Route 7 is an example). Third, routes with steep fixed force may also experience steep variable force, as does Route 1, suggesting the possibility of using the notion of self-similarity to investigate roughness along such routes at a variety of scales, including at one local enough to pick up pot-holes (9, 10).

In addition to the fixed and variable force tables and maps, the broad pattern of critical value placement in profiles is useful in interpreting the variable force pattern. For example, Routes 4, 5, (6), and 16 show no change in sign of slope of the fixed force line around critical values, although they are not all classed as having the same fixed force throughout all intervals. Routes 11(in) and 14 have no critical values; all the rest have at least one critical value around which the slope of the fixed force line changes sign. These observations, coupled with the conceptual framework below, enable us to interpret the variable force pattern.

Simple harmonic motion describes natural fluctuations in an unencumbered environment; second order linear differential equations may be used to describe damping of this motion (interpreted for example as the motion of a stretched spring) as overdamped (Figure 7a), critically damped (Figure 7b), or underdamped (figure 7c). If these shapes are applied to the bus route profiles of Figure 3, Routes 1 in, 1 out, 2, 3,7,8A, 8B, 9, 10, 11 out, 12, 13, 15, 17, and 18 have at least some portion critically damped, while Routes 4, 5, and 11 (in) appear

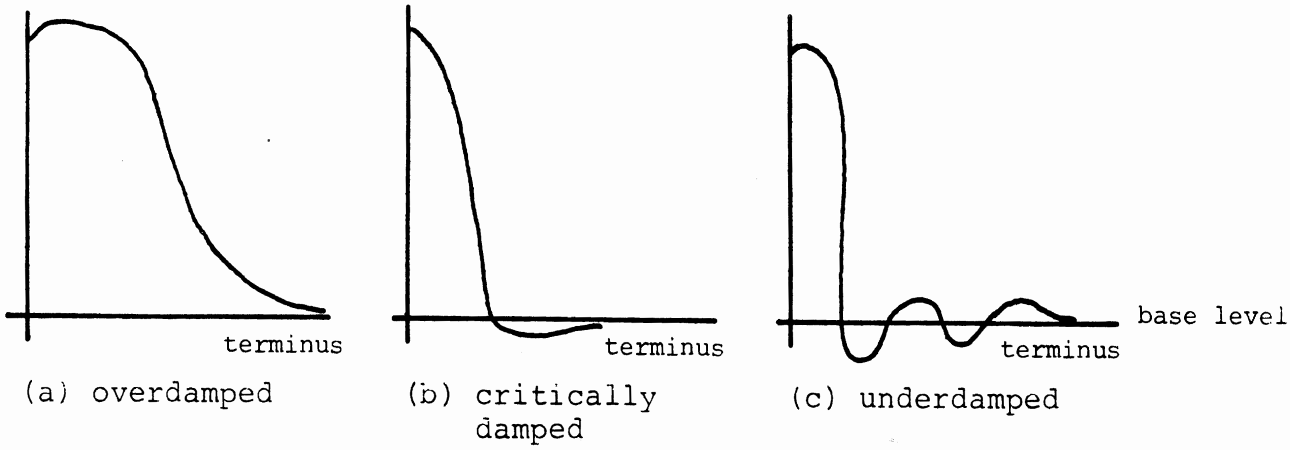


FIGURE 7: DAMPING TYPES

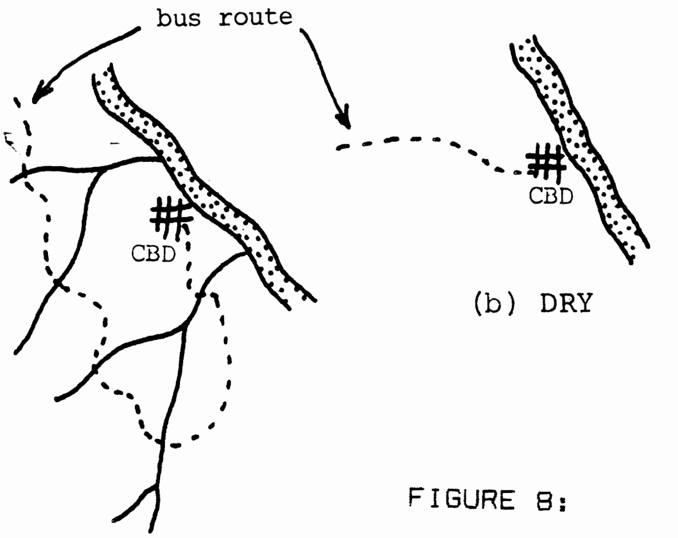
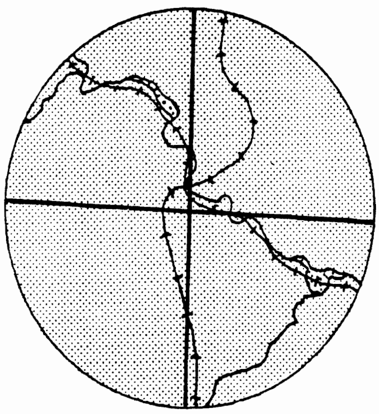


FIGURE 8:

BUS ROUTES AFFECTED BY PRECIPITATION



Ann Arbor

FIGURE 9.

overdamped, and Routes 6, 14, and 16 appear underdamped. All this taken together suggests that the following Theorem holds.

Theorem

In a vertical profile of a bus route, with distinguished critical values, the variable topographic force is critically damped around a critical value if and only if the slope of the fixed force line changes sign around that critical value.

Thus, within any set of bus profiles, the theorem enables rapid sorting of profiles, on the basis of the variable topographic force, into two sets: critically damped and non-critically damped. In terms of stress on buses, routes that show critical damping would probably exert the heaviest toll on brakes and powertrain, because the slope would generally be steep enough to negate any advantage in using downhill momentum to begin the uphill climb across the critical value. On overdamped or underdamped routes, or on overdamped or underdamped portions of routes across critical values that do not lead to critical damping, the momentum advantage might provide some savings in brake wear (downhill) and in energy consumption (uphill).

A significant implication of this damping classification is that bus profile shape may be forecast, given only the drainage network of a transit authority. Radial routes that begin on high ground and drop to the CBD terminus without crossing rivers (or rails) are non-critically damped (such as Route 14 in Figure 3). Radial routes that cross a single stream or rail line and then rise to the CBD are critically damped as are circular routes that cross tributary streams feeding into a river. Thus, given only a drainage net, one would forecast that cities in wet, humid climates located near rivers would have a larger percentage of critically damped bus routes than would their counterparts in drier climates (Figures 8a and b). The next section sorts the transit authorities of Figure 2 according to damping type and then characterizes bus route profiles in quadrants of the allometric circle representing these transit authority boundaries.

FORECASTS OF BUS ROUTE STRUCTURE IN SELECTED TRANSIT AUTHORITIES

This section turns around the material developed to analyze Ann Arbor bus route structure to forecast general bus route structure in the set of transit authorities represented in Figure 2. One consequence of this is an ordering, based on relative steepness, within the flat, intermediate, and steep groupings of Figure 2.

Using the 1:250,000 series of topographic maps and applying cross-hairs representing cardinal compass points on the allometric circle representing a city enables us to approximate the structure of a typical vertical profile of a radial route in a quadrant (Table 6 shows the use of this procedure for the transit authorities in Figure 2). Rivers that are crossed, and rails in intermediate or steep regions, give rise to critical values in the profile. When these critical values arise in conjunction with a steep fixed force (based on quadrant relief), the variable force is generally critically damped. The Theorem can be used to determine when exactly critical values lead to a critically damped variable force.

TABLE 6.

RADIAL ROUTES: TOPOGRAPHIC FORCES BY QUADRANT PER TRANSIT AUTHORITY IN FIGURE 3

TRANSIT AUTHORITY	QUADRANT NE	SE	SW	NW	PERCENT
Ann Arbor					
Fixed force	+	-	0	+	50
Variable force					
CBD damping	C	NC	C	C	
middle damping	NC	NC	NC	NC	
end damping	NC	C	NC	NC	33
Detroit					
Fixed force	-	-	-	-	0
Variable force					
CBD damping	NC	NC	NC	NC	
middle damping	NC	NC	NC	NC	
end damping	NC	NC	C	NC	8
Cincinnati/Newport					
Fixed force	+	0	0	+	50
Variable force					
CBD damping	NC	C	C	C	
middle damping	C	NC	NC	NC	
end damping	C	C	NC	NC	50
Dayton					
Fixed force	0	0	0	-	0
Variable force					
CBD damping	C	NC	C	C	
middle damping	C	NC	C	NC	
end damping	NC	C	NC	NC	50
Oakland					
Fixed force	+	+	-	-	50
Variable force					
CBD damping	NC	NC	NC	NC	
middle damping	C	C	C	NC	
end damping	C	C	NC	NC	42
San Francisco					
Fixed force	+	+	+	+	100
Variable force					
CBD damping	NC	NC	NC	NC	
middle damping	NC	C	C	NC	
end damping	C	C	C	NC	42

TRANSIT AUTHORITY	QUADRANT NE	SE	SW	NW	PERCENT
Louisville					
Fixed force	0	0	-	0	0
Variable force					
CBD damping	C	NC	NC	C	
middle damping	C	C	NC	NC	
end damping	NC	NC	NC	NC	33
Indianapolis					
Fixed force	0	+	+	+	75
Variable force					
CBD damping	NC	C	C	C	
middle damping	NC	C	C	C	
end damping	NC	C	NC	C	58
Sacramento					
Fixed force	0	-	0	+	25
Variable force					
CBD damping	NC	NC	NC	C	
middle damping	C	NC	C	C	
end damping	C	NC	C	NC	58
San Jose					
Fixed force	+	+	+	0	75
Variable force					
CBD damping	C	C	C	C	
middle damping	C	C	C	C	
end damping	C	C	C	C	100
Stockton					
Fixed force	-	-	0	+	25
Variable force					
CBD damping	NC	NC	NC	NC	
middle damping	C	C	C	C	
end damping	C	NC	NC	NC	42
Minn/St. Paul					
Fixed force	+	+	0	0	50
Variable force					
CBD damping	C	C	C	C	
middle damping	C	C	C	C	
end damping	C	C	NC	NC	83
Washington					
Fixed force	-	0	0	+	25
Variable force					
CBD damping	C	C	C	C	
middle damping	C	C	C	C	
end damping	NC	NC	C	NC	75

TRANSIT AUTHORITY	NE	SE	QUADRANT SW	NW	PERCENT
Kalamazoo					
Fixed force	+	-	+	0	50
Variable force					
CBD damping	C	C	NC	C	
middle damping	NC	C	NC	NC	
end damping	NC	NC	NC	NC	33
Jackson					
Fixed force	-	0	-	0	0
Variable force					
CBD damping	NC	NC	NC	NC	
middle damping	C	C	NC	C	
end damping	NC	NC	NC	NC	25
Baltimore					
Fixed force	0	-	+	+	50
Variable force					
CBD damping	C	NC	C	C	
middle damping	C	C	C	NC	
end damping	C	C	C	C	83
Boston					
Fixed force	0	-	-	0	0
Variable force					
CBD damping	C	C	C	C	
middle damping	C	NC	NC	C	
end damping	C	C	C	NC	75
Worcester					
Fixed force	+	-	0	0	25
Variable force					
CBD damping	C	NC	C	C	
middle damping	C	NC	C	NC	
end damping	C	NC	C	NC	58
Haverhill					
Fixed force	0	-	+	0	25
Variable force					
CBD damping	NC	C	C	NC	
middle damping	C	NC	C	C	
end damping	NC	NC	C	NC	50
Lowell					
Fixed force	-	0	-	+	25
Variable force					
CBD damping	C	C	C	C	
middle damping	NC	C	NC	C	
end damping	C	NC	NC	NC	58

TRANSIT AUTHORITY	QUADRANT NE	SE	SW	NW	PERCENT
Brockton					
Fixed force	0	0	-	-	0
Variable force					
CBD damping	C	C	NC	NC	
middle damping	NC	C	NC	NC	
end damping	NC	NC	C	NC	33

TABLE 7

CIRCULAR ROUTES: VARIABLE FORCE PER TRANSIT AUTHORITY

TRANSIT AUTHORITY	FREQUENCY OF CRITICAL DAMPING ON CIRCULAR ROUTES: FREQUENT	MODERATE	INFREQUENT
Ann Arbor		x	
Detroit			x
Cincinnati/Newport		x	
Dayton	x		
Oakland			x
San Francisco		x	
Louisville			x
Indianapolis	x		
Sacramento		x	
San Jose	x		
Stockton		x	
Minn/St. Paul	x		
Washington	x		
Kalamazoo	x		
Jackson		x	
Baltimore	x		
Boston	x		
Worcester		x	
Haverhill		x	
Lowell		x	
Brockton			x

TABLE 8: TRANSIT AUTHORITIES ORDERED WITHIN PEER GROUPS

FLAT: Detroit, Louisville, Stockton, Sacramento, Indianapolis, San Jose.
INTERMEDIATE: Jackson, Brockton, Dayton, Haverhill, Ann Arbor, Lowell, Kalamazoo Minn./St. Paul, Baltimore.
STEEP: Boston, Oakland, Worcester, Washington, Cincinnati, San Francisco.

When cross-hairs centered on the CBD are applied to Ann Arbor, as in Figure 9, four quadrants corresponding to quadrants on a compass are formed. A typical radial bus route from the southeastern edge of the circle to the center has potential for critical damping when it crosses the stream near the edge of the circle; there is no rail or river barrier elsewhere, either near the CBD or in the middle of the route, to force critical damping. Similarly, routes from the north to the CBD, as well as from the southwest to the CBD, are forced to cross the river (rails) near the CBD. Thus, as is noted in Table 6, critical damping along typical routes from the north and the southwest occurs only near the CBD. Table 6 shows variable force entries of this sort for all transit authorities in Figure 2; values are coded with a "C" if critical damping is possible in a route segment, and with "NC" if it is not (<u>11</u>). Table 6 also shows fixed force values for each quadrant relative to the fixed force value for the entire city. In the case of Ann Arbor, the fixed force along a typical radial route from the northeast was higher than the median of 0.8, that of a route from the southeast lower than 0.8, that of a route from the southwest about 0.8, and that of a route from the northwest higher than 0.8. This is coded in Table 6 by "+," "-," or "0" as appropriate.

According to this procedure, Ann Arbor is steepest in the northeast and northwest quadrants, flattest in the southwest quadrant, and has bus routes which exhibit critical damping of the variable force to all but the southeast of the CBD. In addition, the only critical damping of the variable force occurs near the edge of the allometric circle to the southeast. This corresponds well with the results of the test case of the previous section mapped in Figure 5.

Table 7 shows variable forces for circular routes; cataloging fixed forces for routes of this sort seems inappropriate, because often they cut across various radial routes. Thus Table 7 shows only the possible extent of frequency of critical damping along a circular route; this is a function of the intricacy of underlying drainage and railnets.

Table 8 rank orders the transit authorities of Tables 6 and 7 within terrain peer groups shown in Figure 2. Percentages of +'s and of potentially critically damped routes are calculated for each transit authority. To establish the order in Table 8, these two percentages are added and rank-ordered within terrain peer groups; numerical ties are broken using Table 7. Future work might involve executing this finer sorting within terrain peer groups for a larger sample of transit authorities. The point here, however, is to test the relation of a broader nationwide terrain classification to Section 15 indicators.

NATIONWIDE TERRAIN PEER GROUPS

The Ann Arbor experiment shows that the Terrain Template gives a reasonably accurate characterization of the general terrain, across which a transit authority runs its buses. Further, it suggests that the distinctions made in Table 2 between "flat" and "intermediate," and between "intermediate" and "steep," are also fair. Thus, Table 2 may be resorted to display clearly members of a "flat," of an "intermediate," and of a

TABLE 9: NATIONWIDE TERRAIN PEER GROUPS

FLAT

New York City, Chicago, Detroit, Louisville, Houston, Miami, Garden Grove CA, New Orleans, Norfolk VA, Phoenix, Buffalo, Columbus OH, Rochester NY, Sacramento, Providence, Indianapolis, Flushing, Jamaica, Long Beach, Toledo, Richmond, Jacksonville, Tacoma, Jackson Heights NY, Tucson, Ft. Lauderdale, Des Plaines, Hampton VA, Oklahoma City, Gary, Bridgeport CT, Fresno, Spokane, Tulsa, San Bernardino CA, New Bedford MA, W. Palm Beach, Albuquerque, Brooklyn, Tampa, Santa Cruz, Bay City MI, Wichita, St. Petersburg, Fort Wayne, Allentown, Kingston PA, Urbana/Champaign, Portland ME, Clearwater FL, Corpus Christi, Savannah, South Bend, Shreveport, Baton Rouge, Stockton CA, Lexington KY, Montebello CA, Orlando, Amarillo, Torrance, Gainesville, Gardena CA, Lubbock, Saginaw MI, Springfield IL, Bakersfield, Waukegan IL, Lancaster, Daytona, Oshkosh, Harahan LA, Norwalk CA, Rock Island IL, Gretna LA, Kenosha, Pensacola, Decatur IL, Bradenton FL, La Crosse WI, St. Cloud MN.

INTERMEDIATE

Philadelphia, Cleveland, Baltimore, Atlanta, Minneapolis/St. Paul, St. Louis, Milwaukee, Denver, Portland OR, San Antonio, San Jose, Dallas, Salt Lake City, Memphis, Hartford, Albany, Springfield MA, Dayton, Madison, Birmingham, Syracuse, Nashville, New Haven, Des Moines, Akron, Oceanside CA, Charlotte NC, Fort Worth, Riverside CA, Wilmington, El Paso, Canton, Winston-Salem, Eugene, Knoxville, Ann Arbor, Harrisburg, Austin, Chattanooga, Youngstown, Erie, Flint MI, Lincoln, Kalamazoo, Brocton MA, Colorado Springs, Salem, Raleigh, Little Rock, Columbus GA, Rockford IL, Jackson MS, Cedar Rapids, Peoria, Utica, Jackson MI, Appleton, Mobile, Scranton, Binghamton, Lowell MA, Kent OH, Tallahassee, Augusta, Roanoke, Asheville NC, Huntington, Sioux City, Manchester NH, Boise, Haverhill MA, Montgomery, Altoona, Waterloo, Topeka, Davenport, Lynchburg, Fayetteville NC, Stamford CT, Laredo.

STEEP

Los Angeles, Washington D.C., Boston, Seattle, San Francisco, Pittsburgh, Oakland, Cincinnati/Newport, San Diego, Kansas City, Omaha, Duluth, Yonkers, Worcester, San Mateo, Charleston WV, Santa Barbara, Ventura Johnstown, Dubuque.

"steep" terrain peer group at the nationwide scale. Table 9 shows these terrain peer groups.

MAINTENANCE DATA IN TERRAIN PEER GROUPS

Common driving experience suggests that fuel consumption increases in hilly terrain; thus, we examine the Section 15 indicator, annual vehicle miles per gallon of fuel, in each terrain peer group to formulate mileage guidelines for each terrain peer group. Of course, factors other than terrain type contribute to the lowering of miles-per-gallon figures. Among these are: frequency between stops, passenger load carried, quality of road surface, bus age, bus size, and quality of maintenance.

Table 10 shows 1983 Section 15 data for 183 transit authorities. They are partitioned according to terrain peer groups and, within each terrain peer group, into "large-," "mid-," and "small-" sized groupings of transit authorities. The Section 15 indicator, annual vehicle miles per gallon of fuel, was diasaggregated into the Section 15 indicators "total vehicle miles" and "energy consumption--gallons of diesel fuel" in order to calculate the averages shown in each of the groupings of Table 10. In selected instances, the quotient (total vehicle miles/gallons of diesel fuel consumed) did not tally, as it should, with the indicator "annual vehicle miles per gallon." In such cases, the value of the latter indicator was used in formulating averages. Very little variation occurred between pairs of groupings in Table 10; this suggested the need to

TABLE 10: MILES PER GALLON BY TERRAIN AND SIZE PEER GROUP

Terrain peer-group Size in # of buses.	1983 "Annual vehicle miles per gallon of fuel."
STEEP	3.6
500+ 100-499 25- 99	3.5 3.7 4.2
INTERMEDIATE	3.7
500+ 100-499 25- 99	3.6 3.7 4.1
FLAT	3.6
500+ 100-499 25- 99	3.6 3.7 4.1

introduce indicators, in addition to miles-per-gallon, that would draw out the sensitivity of the miles-per-gallon indicator to terrain type.

Mechanical evidence suggests that transit authorities performing excellent maintenance might show higher mile-per-gallon figures than would their counterparts performing poor maintenance, especially in hilly terrain. To characterize maintenance quality we invoked the transit concepts of (1) maintenance value, measured as total vehicle miles per dollar of maintenance expense; and (2) maintenance efficiency, measured as total vehicle miles per maintenance employee. Data for the first indicator appear directly in the 1983 National Urban Mass Transportation Statistics (12); data for the second indicator were calculated as total vehicle miles divided by the number of maintenance employees per vehicle in maximum scheduled service (where such an employee is assumed to work 2,000 hours per year). For both indicators higher values reflect higher quality in maintenance. The medians and interquartile ranges were calculated for each of "maintenance value," and "maintenance efficiency." These were used to partition the set of 183 transit authorities into sixteen mutually exclusive "maintenance" subclasses, as shown in Figure 10. Once the set of transit authorities was also partitioned into quartiles according to the miles-per-gallon indicator, bars were placed in each maintenance subclass of Figure 10 to (1) show, by their length, the percentage of the set of 183 transit authorities within each; and (2) show, by partitioning internal to the bar, the percentage of

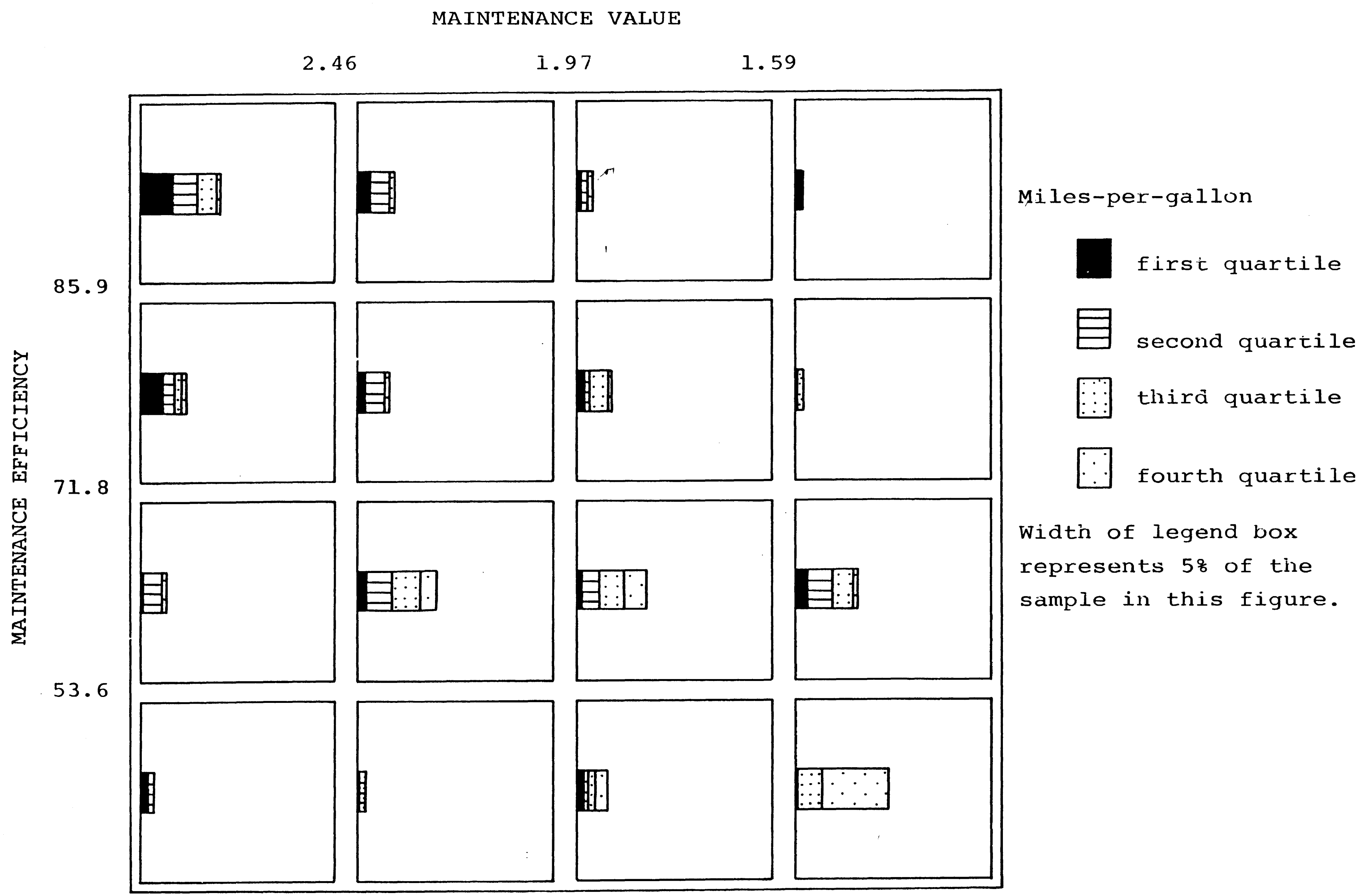


FIGURE 10: MILES-PER-GALLON INDICATOR WITHIN MAINTENANCE SUBCLASSES--MEASURED ACROSS THE ENTIRE SAMPLE OF 183 TRANSIT AUTHORITIES.

entries from the first, second, third, and fourth quartiles of the miles-per-gallon indicator in each.

The result is that Figure 10 compresses four "dimensions" of data (maintenance value, maintenance efficiency, percentage of transit authorities per subclass, percentage per quartile of the miles-per-gallon indicator) into two geometric dimensions. For example, the length of the bar in the upper left-hand corner of Figure 10 is between two and three times as long as the 5% box in the legend. This length demonstrates, graphically, that about 12% of the 183 transit authorities fall into this "best" subclass. The partitioning internal to this bar shows via shading that, of the transit authorities in this subclass, about 46% fall into the top quartile of the miles-per-gallon indicator, about 32% fall into the second quartile of the miles-per-gallon indicator, about 18% fall into the third quartile of the miles-per-gallon indicator, while only 4% lie in the fourth quartile of that indicator. Good maintenance and good gas mileage correspond across the entire sample. The subclass in the lower right-hand corner has the poorest maintenance performance. The shading internal to the bar shows that almost all transit authorities achieve mileage worse than the median and that a substantial majority score in the fourth quartile. Bad mileage corresponds to bad maintenance, as well.

When the data represented by Figure 10 is stratified, using a fifth data "dimension," according to terrain peer group, Figures 11, 12, and 13 emerge. These Figures represent, respectively, two-dimensional portraits of data for the steep,

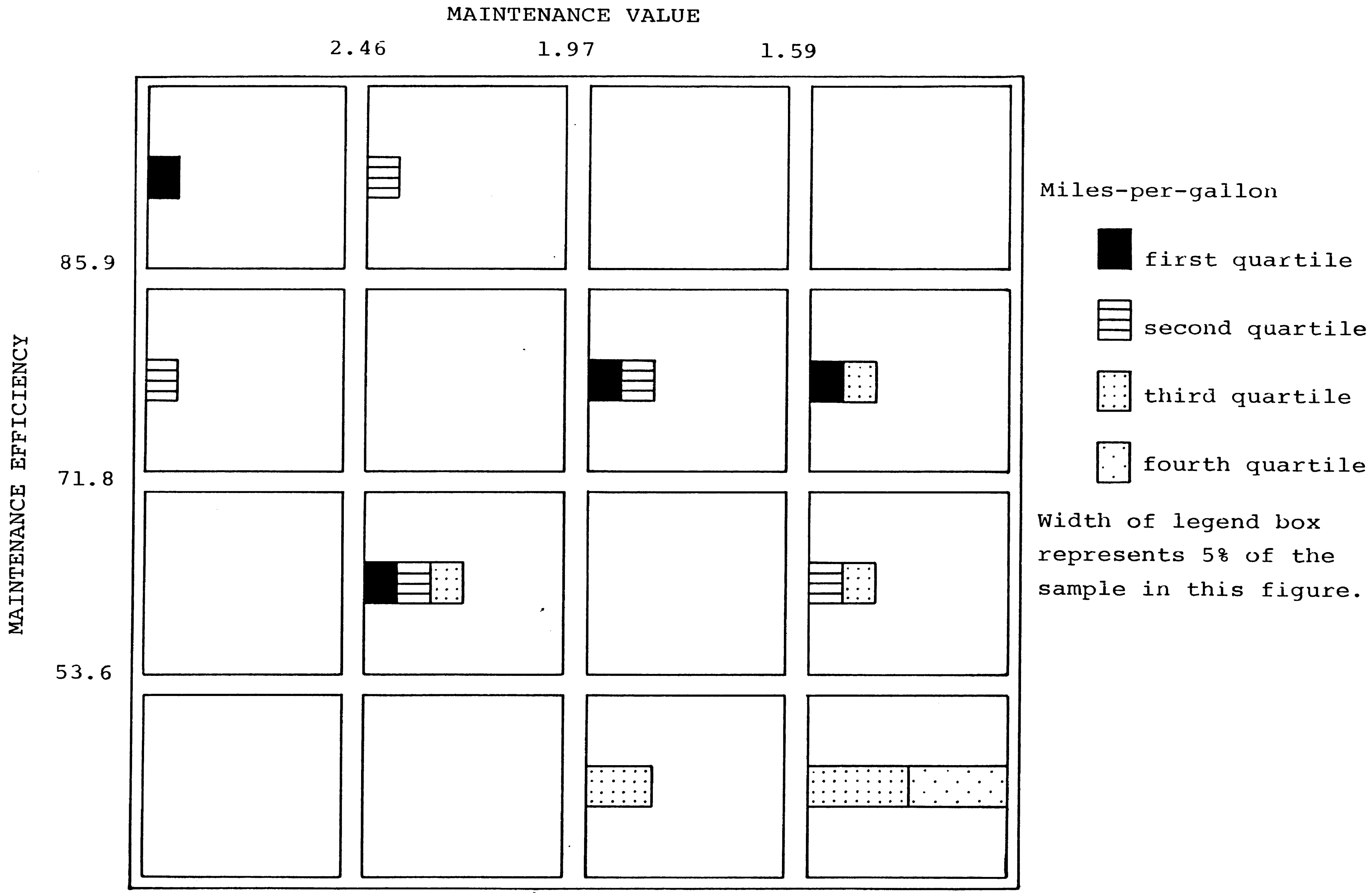


FIGURE 11: MILES-PER-GALLON INDICATOR WITHIN MAINTENANCE SUBCLASSES--MEASURED ACROSS THE STEEP TERRAIN PEER GROUP.

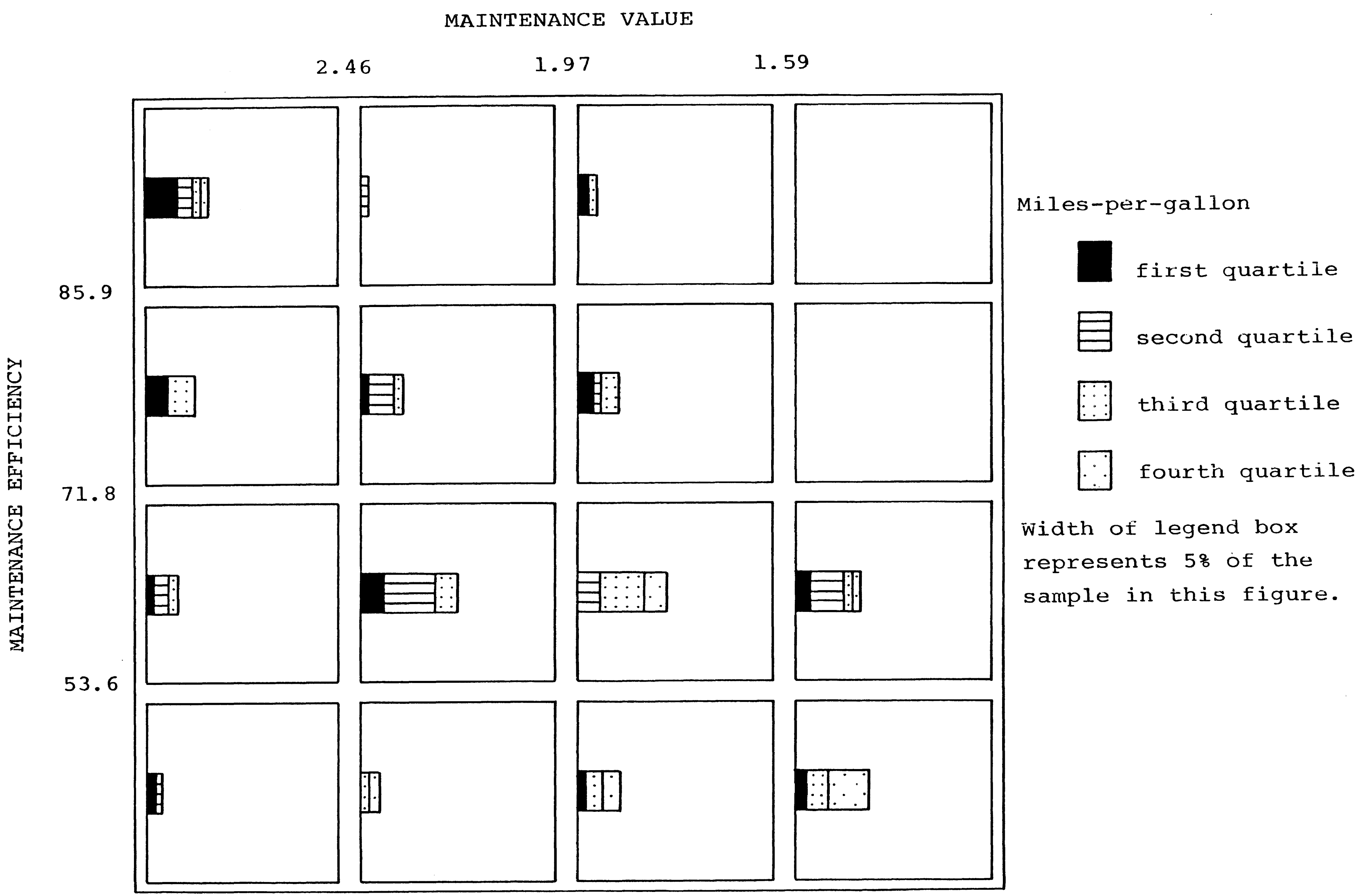


FIGURE 12: MILES-PER-GALLON INDICATOR WITHIN MAINTENANCE SUBCLASSES--MEASURED ACROSS THE INTERMEDIATE TERRAIN PEER GROUP.

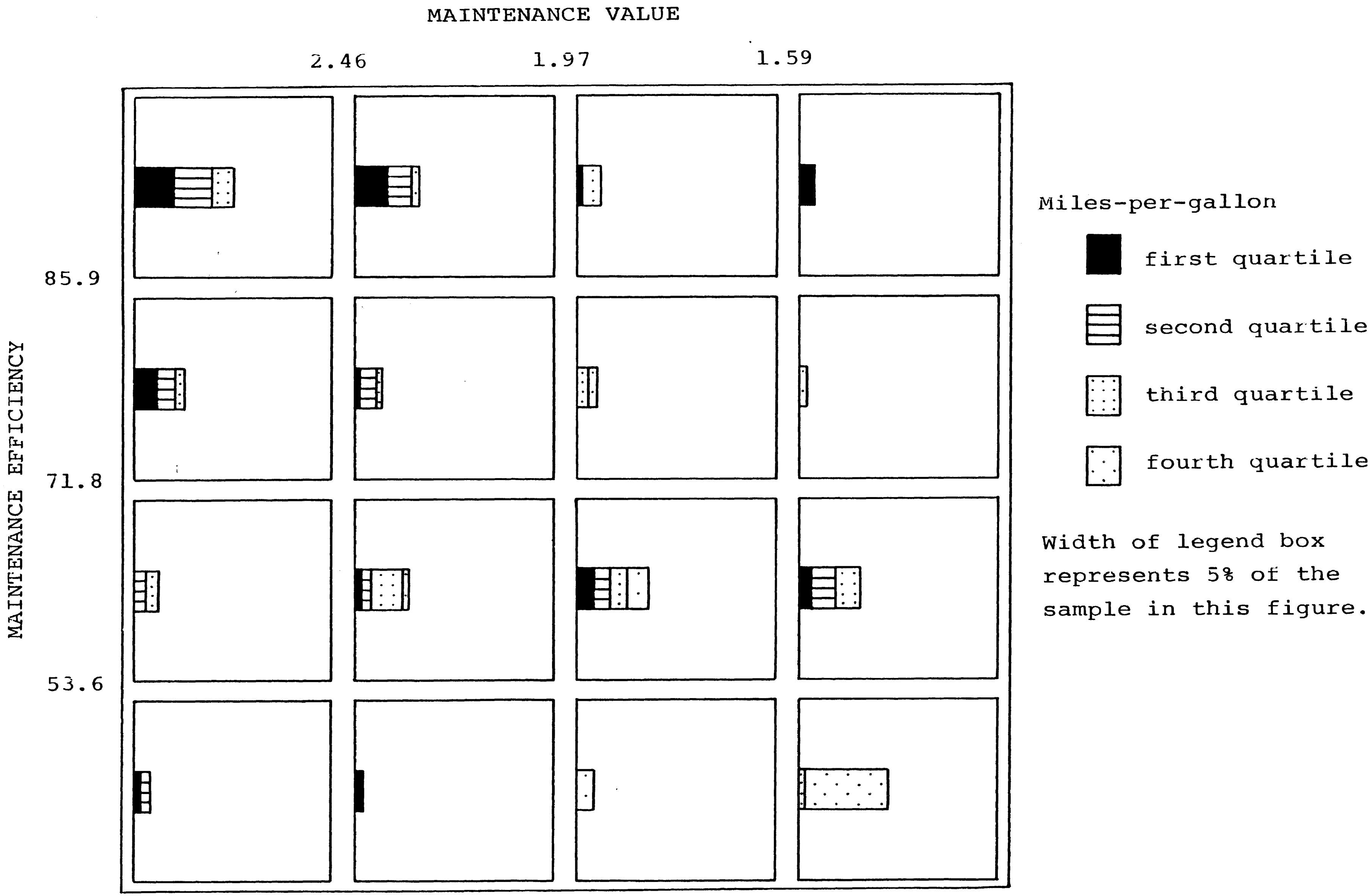


FIGURE 13: MILES-PER-GALLON INDICATOR WITHIN MAINTENANCE SUBCLASSES--MEASURED ACROSS THE FLAT TERRAIN PEER GROUP.

intermediate, and flat terrain peer groups. Generally, Figure 11 shows that a larger percentage of transit authorities have lower miles-per-gallon values than did the whole sample in Figure 10; this seems natural, because running buses up and down hills puts a low ceiling on miles-per-gallon values. Specifically, it shows that the ties between maintenance and miles-per-gallon are stronger in steeper environments than they are in the whole sample; in flatter surroundings other factors, such as frequency between stops, overshadow effects from terrain on miles-per-gallon.

Figure 12 shows the same partitioning for the intermediate-terrain peer group; its content is similar in structure to that of the entire sample. Figure 13 shows the same classification scheme for the flat-terrain peer group. The distinctions between maintenance subclasses fade increasingly within a Figure as one moves from Figure 11 to Figure 13. This suggests that, in the steep-terrain peer group, transit authorities with a low miles-per-gallon value are more likely to fall into the worst-maintenance subclass than are corresponding positions in the intermediate-terrain peer group; and, that those in the intermediate-terrain peer group with a low-miles-per-gallon value are more likely to fall into the worst-maintenance subclass than are corresponding positions in the flat-terrain peer group. Again, this effect appears to be a reflection of low-miles-per-gallon figures being induced by factors other than terrain in flatter environments.

An arbitrary transit authority might employ Figures 11, 12, or 13 to evaluate its mileage-per-gallon or to determine what increases in mileage-per-gallon might reasonably result from increased expenditure on maintenance. For example, a transit authority that belongs in the steep terrain peer group, that has a maintenance value figure of 1.80, a maintenance efficiency figure of 53.0, and that is getting 3.50 miles to the gallon, fits into one maintenance subclass. It might hope to increase its fuel consumption to over 3.80 miles to the gallon by boosting its maintenance efficiency to 72.0. Thus, transit authorities might use these tables as constructive guidelines to focus the direction of their maintenance effort; UMTA might use them to evaluate the quality of the maintenance effort, in conjunction with other factors mentioned previously, of a particular transit authority compared to its peers. In either application, however, it should be noted that (1) the guidelines suggested by these tables are very general, and (2) the figures in these tables are based on data which vary from year to year.

CONCLUSION

The major contribution of this report is to classify transit authorities according to terrain type into "steep," "intermediate," or "flat" peer groups. The typology was formed on the basis of empirical topographic evidence accumulated at the 1:250,000 scale using a Terrain Template. Closer examination of one transit authority, at the 1:24,000 scale, showed the more general procedure to be reasonable. Thus, nationwide terrain peer groups were established using the Terrain Template; these are enumerated in Table 9.

When the transit concepts of miles-per-gallon, maintenance efficiency, and maintenance value, quantified by Section 15 indicators, were introduced into these terrain peer groups, we found strong ties between quality of maintenance and miles-per-gallon in steeper environments. As this is a first effort in analyzing the relation between maintenance and terrain, a significant function of these data is to suggest a framework in which to test other transit concepts. As an example, these broad terrain categories might be employed in a regression analysis context involving several factors, in addition to terrain, related to vehicle performance (e.g., frequency between stops, passenger load). For in the end, the utility of these peer groups will rest in their capability to house interacting indicators in such a way that distinctions may be made among transit concepts that are significant to the development of transit policy.

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