Technical Report Documentation Page

1. REPORT No.
CA/TL-85/17

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE
Profile Index Requirements for Asphalt Concrete Pavements

5. REPORT DATE
December 1985

6. PERFORMING ORGANIZATION

7. AUTHOR(S)
Max L. Alexander, P.E.

8. PERFORMING ORGANIZATION REPORT No.
54324-643376

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Transportation Laboratory
California Department of Transportation
Sacramento, California 95819

10. WORK UNIT No.
F84TL66

11. CONTRACT OR GRANT No.

13. TYPE OF REPORT & PERIOD COVERED
Final

12. SPONSORING AGENCY NAME AND ADDRESS
California Department of Transportation
Sacramento, California 95807

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This study was conducted as a state-financed research project under the research project titled "Influence of Paving Procedures on the Profile Index of Asphalt Concrete Pavement."

16. ABSTRACT
The California profilograph was used to evaluate pavement smoothness before and after placing subsequent layers of asphalt concrete (AC) pavement. An improvement in the profile index (PI) can normally be expected with each layer of AC; however, the relative amount of improvement is influenced by the PI of the surface being covered. The data also indicates that pavement reinforcing fabrics can have a detrimental effect on the PI of the first layer of AC placed over the fabric.

17. KEYWORDS
Profile index, asphalt concrete pavement, pavement smoothness

18. No. OF PAGES:
190

19. DRI WEBSITE LINK
http://www.dot.ca.gov/hq/research/researchreports/1981-1988/85-17.pdf

20. FILE NAME
85-17.pdf

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF FACILITIES CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

PROFILE INDEX REQUIREMENTS FOR ASPHALT CONCRETE PAVEMENTS

Study Made by .... Pavement Branch

Under the Supervision of .... Robert N. Doty

Principal Investigator .... Roger D. Smith

Co-Investigator and Author .... Max L. Alexander

RAYMOND A. FORSYTH, P.E.
Chief, Office of Transportation Laboratory

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
CA/TL-85/17		

4. TITLE AND SUBTITLE
PROFILE INDEX REQUIREMENTS FOR ASPHALT CONCRETE PAVEMENTS

5. REPORT DATE
December 1985

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Max L. Alexander, P.E.

8. PERFORMING ORGANIZATION REPORT NO.
54324-643376

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Transportation Laboratory
California Department of Transportation
Sacramento, California 95819

10. WORK UNIT NO
F84TL66

11. CONTRACT OR GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
California Department of Transportation
Sacramento, California 95807

13. TYPE OF REPORT & PERIOD COVERED
Final

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This study was conducted as a state-financed research project under the research project titled "Influence of Paving Procedures on the Profile Index of Asphalt Concrete Pavement."

16. ABSTRACT
The California profilograph was used to evaluate pavement smoothness before and after placing subsequent layers of asphalt concrete (AC) pavement. An improvement in the profile index (PI) can normally be expected with each layer of AC; however, the relative amount of improvement is influenced by the PI of the surface being covered. The data also indicates that pavement reinforcing fabrics can have a detrimental effect on the PI of the first layer of AC placed over the fabric.

17. KEY WORDS
Profile index, asphalt concrete pavement, pavement smoothness.

18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		

DS-TL-1242 (Rev.6/76)

NOTICE

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quality	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2) square feet (ft^2) acres	6.432×10^{-4} .09290 .4047	square metres (m^2) square metres (m^2) hectares (ha)
Volume	gallons (gal) cubic feet (ft^3) cubic years (yd^3)	3.785 .02832 .7646	litre (l) cubic metres (m^3) cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s	28.317	litres per second 1/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G) (ft/s^2)	9.807	metres per second squared (m/s^2)
Density	(lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) (1000 lbs) kips	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British termal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (in-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch ($ksi\sqrt{in}$)	1.0988	mega pascals$\sqrt{metre}$ ($MPa\sqrt{m}$)
	pounds per square inch square root inch ($psi\sqrt{in}$)	1.0988	kilo pascals$\sqrt{metre}$ ($KPa\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{+F - 32}{1.8} = +C$	degrees celsius (°C)

ACKNOWLEDGEMENTS

The profile index data presented in this report were gathered and submitted by construction and materials personnel in several Caltrans districts. The names of all participants are not known, but the author wishes to express his appreciation to each person who assisted in gathering and analyzing the data and especially resident engineers R. F. Scamara, J. A. Ringgold, C. F. Russell, R. Riesgo, J. J. Maxwell, K. L. Bousfield, C. Puder, L. Brooks, L. Wadsworth and G. A. Ellis for their cooperation in making this study possible.

Appreciation is also extended to Stephan Wiley who prepared the computor graphs and Lydia Burgin who provided typing and editorial assistance.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

INTRODUCTION

The objective of this study was to gather data which would indicate the changes in profile index (PI) that can be anticipated as subsequent layers of AC pavement are placed. The effects of multiple layers, layer thicknesses, and the type of paving equipment and grade controls were to be evaluated.

California Department of Transportation (Caltrans) districts were asked to participate in this study by obtaining PI measurements(1) on selected test sections of several paving projects. The PIs were to be determined on the existing pavement surface of overlay projects and on each layer of AC for both overlay and new construction projects.

FINDINGS AND CONCLUSIONS

1. When AC pavement is placed in compliance with the California Standard Specifications, the PI will normally decrease with the addition of each subsequent layer of AC. The data indicate, however, that a 50% reduction in PI is not routinely achieved with the placement of each new layer.

2. When a layer of AC was placed directly over an AC or PCC pavement, the PI was reduced by 50% or more on only 65% of the tested 0.1-mile segments (the PI was reduced by less than 30% on approximately 15% of the tested segments).

3. When a paving fabric interlayer was included in the new pavement, the first layer of AC placed over the fabric often did not achieve any improvement in PI. (In fact, the PI of the new layer was actually higher than the PI of the underlying surface on nearly one-half of the 0.1-mile segments tested. Fewer than 20% realized the expected reduction in PI of 50% or more.)

4. The proportional decrease in PI that can be expected is largely dependent upon the PI of the surface being covered. When the PI of the existing surface is high, the relative improvement in PI will normally be greater than when the PI of the existing surface is low.

5. The thickness of the AC layer being placed (if between 0.08 ft and 0.15 ft) does not have a significant effect on the relative change in PI achieved by that layer.

6. Surface grinding of localized areas was necessary, on a significant number of AC overlay projects, to reduce the PI to 5 inches per mile or less.

7. A PI specification limit of 5 inches per mile is frequently not attained on overlay projects and appears to be overly conservative with respect to ride smoothness.

8. A maximum PI of 12 inches per mile is reasonably attainable on most overlay projects.

RECOMMENDATIONS

1. The "rule of thumb" that the PI will be decreased by 50% with each subsequent layer of new AC should not be relied upon for predicting the PI of AC overlays nor for determining the number of layers necessary to achieve a desirable PI. The anticipated reduction should not exceed 30% per layer.

2. The propriety of requiring a maximum PI of 5 inches per mile, when resurfacing an existing road with poor ride quality, should be reviewed.

3. An effort should be made to correlate PI with ride score.

4. When PI limits are specified for AC overlays, the smoothness (ridescore or PI) of the existing roadway, and the number of AC layers to be placed, should be taken into account.

5. Grinding of the surface course should be limited to correcting individual deviations in excess of 0.3 inch. Grinding for PI improvement should be done before placing the final course.

6. The maximum PI value specified for AC overlay projects should be increased to 12 inches per mile.

7. Additional research should be done to determine the causes of surface roughness in the first layer of AC placed over paving fabrics.

BACKGROUND

Caltrans' specifications for asphalt concrete pavements have been developed with two basic qualities in mind: durability and rideability. Durability is primarily a function of suitable materials and adequate compaction. Ridability is largely affected by paving equipment and procedures. In most cases, efforts to achieve one quality will enhance the chances of achieving the other. There has been some concern, however, that this may not be true in the case of recent changes in minimum layer thickness which were adopted to improve compaction.

Inherent properties of asphalt concrete make it necessary to place and compact AC pavements in a series of relatively thin layers. In the past, it has been common practice in California to allow individual layers to be as thin as 0.08 ft. Recent revisions in Caltrans' specifications require that most individual layers of AC be at least 0.15 ft thick(2). The purpose of this increase in (minimum) layer thickness was to extend the time that the AC remains hot enough for adequate compaction to be achieved.

Although there is no question that extending the heat retention period will benefit compaction efforts, a question has been raised regarding the effect that fewer, but thicker, layers will have on the smoothness of the finished pavement. Some contractors have expressed concern that where the new policy results in a decrease in the number of AC layers, it will hinder their ability to comply with PI requirements.

Specifying a PI limit on AC pavements is an arbitrary decision by the districts. However, when a PI requirement is specified, the normal limit is 5 inches per mile (ipm) or less for each 0.1-mile segment. Finished surfaces that do not meet this limit must be corrected(3).

Several concerns have been raised regarding the application of the PI requirements. These include:

a) The propriety of the 5 ipm limit on AC pavements, especially when applied to a rehabilitation project.

b) The propriety of expecting to correct major profile deficienies by simply adding one or more layers of AC.

c) The cost/benefit factor for grinding new AC pavements to reduce the PI.

d) The unsightly patchwork appearance, and possible reduction in service life, of a pavement that has been subjected to extensive remedial grinding.

The greatest of these concerns is whether a maximum PI of 5 ipm is really necessary to assure good rideability. In a previous California study(4) dealing primarily with PCC pavements, F. N. Hveem concluded that profile measurements do not furnish a direct index to ride quality. Appendix A of Hveem's report includes data which show that PCC pavements with PI values up to 10 were subjectively classified as "smooth". It should also be noted that a PI of 7 ipm is acceptable for new PCC pavements(5) and that PCC "replacement" pavements are exempt from PI requirements(6).

The current PI requirement of 5 ipm or less was arbitrarily set based on PI values which were being achieved on major new construction projects. Since the base materials for these projects were placed under strict grade controls, only minor deficiencies in the profiles remained to be overcome with the pavement. Under these conditions, the specified PI requirement is probably reasonable.

Today, however, a major portion of the new AC pavement is being placed to rehabilitate existing roadways. Following initial construction, many of these roads have become distorted by underlying expansive soil, fill settlement, pavement faulting, etc., thus creating major profile deficiencies. Under these conditions, it may not be possible to achieve the degree of smoothness that can be expected on a newly constructed roadway.

One objective of any paving project, whether new construction or a rehabilitation overlay, is to provide good ride qualities. The ability to accomplish this objective is dependent on the paving equipment used, the crew assigned to operate it, and the operating procedures being followed.

Paving machines are equipped with floating screeds which are designed to smooth out longitudinal undulations by adjusting the thickness of the new layer in the raised and depressed areas. Major bumps and depressions, however, cannot be completely eliminated with a single layer of new pavement. At best the magnitude of such undulations will be diminished with the addition of each subsequent layer.

Thus, it is logical to assume that the smoothness of the finished road surface will be improved in proportion to the number of layers placed. Some engineers and contractors have adopted the rule of thumb that the PI will be diminished by 50% with each subseqeunt layer of AC. A review of TransLab records, however, has disclosed very little recorded data to support this premise. Statements by the paving industry also tend to discredit the assumption of a 50% reduction. One manufacturer of paving equipment has shown mathematically(7) that the self-leveling, floating screed will reduce pavement undulation by approximately 30% with each subsequent layer.

Another factor which limits the amount of profile improvement that can be expected is the need to compact the new AC. Even though the paving machine may succeed in leaving a smooth surface, if the thickness of the layer is not uniform, because of undulations in the underlying pavement, a portion of the unevenness will be transferred to the new surface as the AC is compacted to a uniform density.

In most cases, pavements which do not conform to the PI requirements are corrected by grinding the surface. This in turn causes variations in appearance, texture, skid resistance, traffic-generated noise, and possible accelerated degradation of the new pavement. Many individuals believe, however, that a PI limit of 5 ipm is too restrictive and that the ground surface may be actually more distracting to the traveling public than the higher PI of the uncorrected surface.

The primary objective of this study was to determine the PI value that can be realistically expected on the finished surface as well as on intermediate layers of an AC pavement. It was also anticipated that the effects of construction variables, such as the number of AC layers, the thickness of individual layers, and construction equipment and procedures, could be evaluated.

DISCUSSION

General

A total of sixt-two profiles were measured following the procedures in California Test 526. Fourteen profiles were on existing pavement surfaces which were to be overlayed with new pavement. The remaining forty-eight represent subsequent layers of new pavement placed on nineteen test section from eight paving projects. The test sections ranged in length from 0.5 to 1.7 miles and the number of subsequent layers placed on individual test sections varied from one to three.

Although the data provide some general information regarding the reduction in profile index that can be anticipated with the addition of subsequent layers, the number of projects tested was insufficient to evaluate all possible variations in equipment and procedures which are allowed under the current Caltrans specifications.

Data from the eight paving projects are tabulated respectively in Tables A-1 through A-8 of Appendix A. The recorded data represents the PI values determined for each 0.10 mile segment of each layer of AC in each test section. Also, included in these tables are the length of each test section, the type of material being covered, the thickness of each AC layer, the average PI for each layer of each test section, and the change in PI expressed as a percentage of the PI of the covered surface. A summary of these data is presented in Table 1. In this summary, only the average values are listed for each test section.

Paving Over Fabric Interlayers

It became apparent early in the analysis that the first layer of AC to be placed over paving fabric was not providing the same improvement in surface smoothness as layers placed directly on the underlying pavement. In many instances, there were, in fact, substantial increases in the PI when paving over fabric.

The histograms plotted in Figure 1a show the frequency of occurrence for each degree of change in PI. The curves plotted in Figure 1b show the cumulative distribution of these same data. Data representing the first layer of AC placed over fabric are plotted separately so that the effect of this interlayer can be evaluated.

Test segments which had a PI of less than 5.0 ipm before being overlayed were arbitrarily eliminated from this phase of the analysis because of the disproportionate effect of minor changes in PI when these changes are expressed as a percentage of an original small value.

The lower curve in Figure 1b shows that less than 20% of the test segments had the expected 50% reduction in PI when a layer of AC was placed on paving fabric. In fact, more than 50% of the segments tested actually had an increase in PI on this first layer of AC over fabric.

Construction personnel have suggested several ways in which the fabric has hindered the operation of the paving machine and thereby affected the smoothness of the pavement surface. At times a tendency for the paving machines drive wheels to slip on, or sometimes pull, the fabric, causes the paving machine to surge and create an uneven surface. This has been observed to become more of a problem as the day progresses and the asphalt binder for the fabric remains fluid longer because of higher ambient temperatures and radiant heat from the sun. Haul trucks and other construction equipment also have been observed to cause ripples when driven on or across the fabric. This type of rippling, as well as excessive wrinkling and overlapping of the fabric as it is placed, can affect the uniformity of the mat thickness.

When AC is deposited in windrows, it is important that the pickup device, which transfers the material to the paving machine, is adjusted to pick up all of the material in the windrow. Failure to do so can lead to segregated materials and differential compaction. This cannot be done when paving over fabric since it becomes necessary to raise the pickup device an inch or so above the surface to avoid snagging and damaging the fabric.

Based on data gathered during this study, it is apparent that further effort is needed to identify the factors which affect the ride quality of the finished pavement when paving fabrics are used. These factors should then be corrected or taken into consideration when establishing specifications for construction procedures and PI for AC paving that includes fabrics.

It should be made clear, however, that it is not the intent of this report to discourage the use of paving fabrics. Benefits gained from fabric interlayers may outweigh the detrimental effect on the PI.

Paving Without Fabric Interlayers

The upper curve in Figure 1b shows that the addition of a single layer of AC does not consistently provide a 50% reduction in the PI of the pavement;

even when paving fabric was not included. When AC was placed directly over an AC or PCC pavement, the PI values of 65% of the test segments were reduced by 50% or more. The PI values of approximately 15% of the segments were reduced by less than 30%.

The data from the individual projects are plotted in Figures 2 through 9. In these figures, the numerical change in PI that was effected by adding a new layer of AC is plotted against the PI of the previous surface for each 0.10-mile segment of the test sections. All data from the same project are plotted in the same figure regardless of the final position of the layer in the structural section.

To aid in the further analysis of these data, the linear regression was calculated for the data from each project. The best-fit straight line through the data has been plotted, and the correlation coefficient stated, on each figure. Lines representing 50% and 100% reductions in PI have also been added. Since it has been shown already that the use of paving fabrics can have a detrimental effect on the PI of the next successive layer of AC, data from these layers are identified on the figures, but their values are excluded from the remaining discussion and analysis.

The correlation coefficients indicate a good correlation between the change in PI and the PI of the surface being covered. The slope of the regression lines indicates that the probability of reducing the PI values by at least 50% is greater when the PI of the surface being covered is relatively high. The data from Project 1 (Figure 2), for example, show that with the addition of one new layer of AC, the PI was consistantly reduced by at least 50% for all segments that had a beginning PI of 10 or more. When the PI of the existing surface was less than 10, the reduction was often less than 50%, and in many instances there was actually an increase in PI.

In most cases, the linear regression line crosses the 50% reduction line. When the PI of the existing pavement is greater than the PI at which these lines intersect, the PI will probably be reduced by at least 50% with the addition of one layer of AC. When the PI of the existing pavement is less than the value where these lines intersect, the possibility of the PI being reduced by 50% is progressively less.

Where the PI of the existing surface was low to begin with, there was frequently no improvement, or even an increase, in PI when the new layer was added. It is believed that this is caused by properties inherent in the paving and compaction process. There is also a noticeable difference in the scatter of the individual values about the regression line and in the points at which the regression lines cross the zero improvement lines for the different projects. This probably reflects, to some extent, differences in the paving equipment and the skill of the paving crews.

A large quantity of data was also made available from a ninth project but could not be evaluated with data from the other projects since profiles were recorded only on the existing pavement and on the finished surface after two layers of new AC were added. This project, which consisted of overlaying approximately 10 lane miles of existing pavement, was tested for PI in both wheel tracks throughout its entire length, both before and after construction. The specifications for this project included a requirement that the finished surface have a maximum PI of 5 inches per mile. Profile data representing 9.2 wheel path miles were arbitrarily selected from the submitted data. These were divided into 6 test sections which are recorded in Table A-9 of the Appendix and in Figure 10. The average PI values for each test section were within the specified limits but some of the individual segments did not meet the specified requirements and corrective action was required. The reduction in average PI for the six test section varied from 47% to 92% after adding the two layers of AC pavement.

Effect of Layer Thickness

An effort was made to evaluate the effect that the thickness of the added layer has on the PI of the finished surface. During this study, thicknesses of 0.08, 0.10, 0.13, 0.14, 0.15 and 0.20 ft were encountered. The majority were either 0.10 or 0.15 ft thick. Only one test section had a thickness of 0.20 ft and this was not included in this portion of the evaluation because it was placed directly over a fabric.

To simplify the analysis, the data were grouped into two categories; layers which were 0.10 ft or less in thickness and layers which was more than 0.10 ft thick. The presentation of the data, in Figures 11 and 12 were further simplified by plotting only the average PI values for each test section. Even though there appears to be more scatter in the results from the thinner pavements, the linear regression analyses of the two groups of data are similar. Based on the limited data from this study, it is concluded that layers up to 0.15 ft thick can be placed as smoothly as layers 0.10 ft or less.

It should be noted that the only 0.20 ft thick layer included in this study had a very low PI value, even though it was placed directly over fabric. The low PI, however, does not mean that the pavement was completely free of problems with surface smoothness. This pavement, and several other pavements which had been constructed with a 0.20 ft surface course over fabric, required considerable grinding, or extra effort during placement, to eliminate surface bumps. One contributing factor may have been the extended time that heat is retained in the thicker layer. Construction personnel reported that when the breakdown roller was operated on this hot, thick layer a wave frequently developed ahead of the roller drum. This remained as a bump where the roller reversed direction.

Specification Considerations

The data collected during this study confirm that surface grinding is frequently necessary to achieve a PI of 5 ipm or less on rehabilitation overlay projects. There is no evidence, however, that a limit of 5 ipm is necessary to provide a smooth riding pavement.

Caltrans also routinely uses the "ride score"(8) method to evaluate the ride qualities of existing pavements. This value becomes a primary factor in determining when rehabilitation is needed. Although both PI and ride score provide a measure of pavement smoothness, very little has been done to establish a correlation between the two. It is believed that several benefits could be gained if such a correlation were established.

First, there would be a tangible basis for setting a PI limit. Support for a PI specification would be increased by verifying a tangible need or benefit. Secondly, since ride scores are determined periodically on existing pavements, the capability of converting them to PI values would provide the designer and specificaiton writer with valuable information to develop an overlay plan which could produce the desired smoothness.

Consideration should also be given to requiring correction of major profile deficiencies prior to placing the finish course of the AC pavement. For example, it may be desirable to grind excessive bumps, or fill depressed areas, prior to adding the overlay. Although identifying the exact location of these problem areas may require the use of a profileograph during the contract, the ride score information available in advance may be sufficient to alert the designer to the need for extra work.

There may also be advantages to specifying a PI limit on the next-to-last lift of a multiple layer overlay. Grinding excessive bumps at this point may significantly improve the probability of meeting smoothness requirements on the finished surface without resorting to unsightly grinding, or other corrective measures, on the finished surface itself.

Even though a smooth riding pavement is an ultimate goal of any paving project, the same PI requirement may not be necessary for both new and rehabilitated pavements. It is possible that after being in service for a period of time, a resurfaced roadway with a significantly higher PI will ride just as smoothly as a newly constructed road which had a much lower initial PI. This assumption is based on the fact that a newly constructed road is more susceptible to distortions caused by faulting, settlement, swelling soils, etc, which have already occurred and been corrected by the rehabilitation overlay of an existing road.

REFERENCES

1. California Test 526 "Operation of California Profilograph and Evaluation of Profiles," State of California, Department of Transportation, Transportation Laboratory, Manual of Tests.

2. Standard Special Provision 39.01, paragraph 4a, State of California, Department of Transportation, July 4, 1984.

3. Standard Special Provision 39.09, paragraph 2 and 3, State of California, Department of Transportation, September 25, 1984.

4. Hveem, F. N., "Devices for Recording and Evaluating Pavement Roughness," HRB Bulletin 264 (1960).

5. Standard Specifications, Section 40-1.10, "Portland Cement Concrete, Final Finish," State of California, Department of Transportation, July 1984.

6. Standard Special Provision 40.50, paragraph 22, 7-2-84, State of California, Department of Tranpsortation, July 2, 1984.

7. "Principles of the Asphalt Finisher," Barber-Greene Company, Manual Page 6900, Release 105, 1977.

8. Bartell C. and Kampe, K., "Development of the California Pavement Management System, Volume 1 - System Description," California Department of Transportaiton, Division of Maintenance, Final Report, 1978.

Table 1

Summary of Profile Index Data
(Average Values for Individual Test Sections)

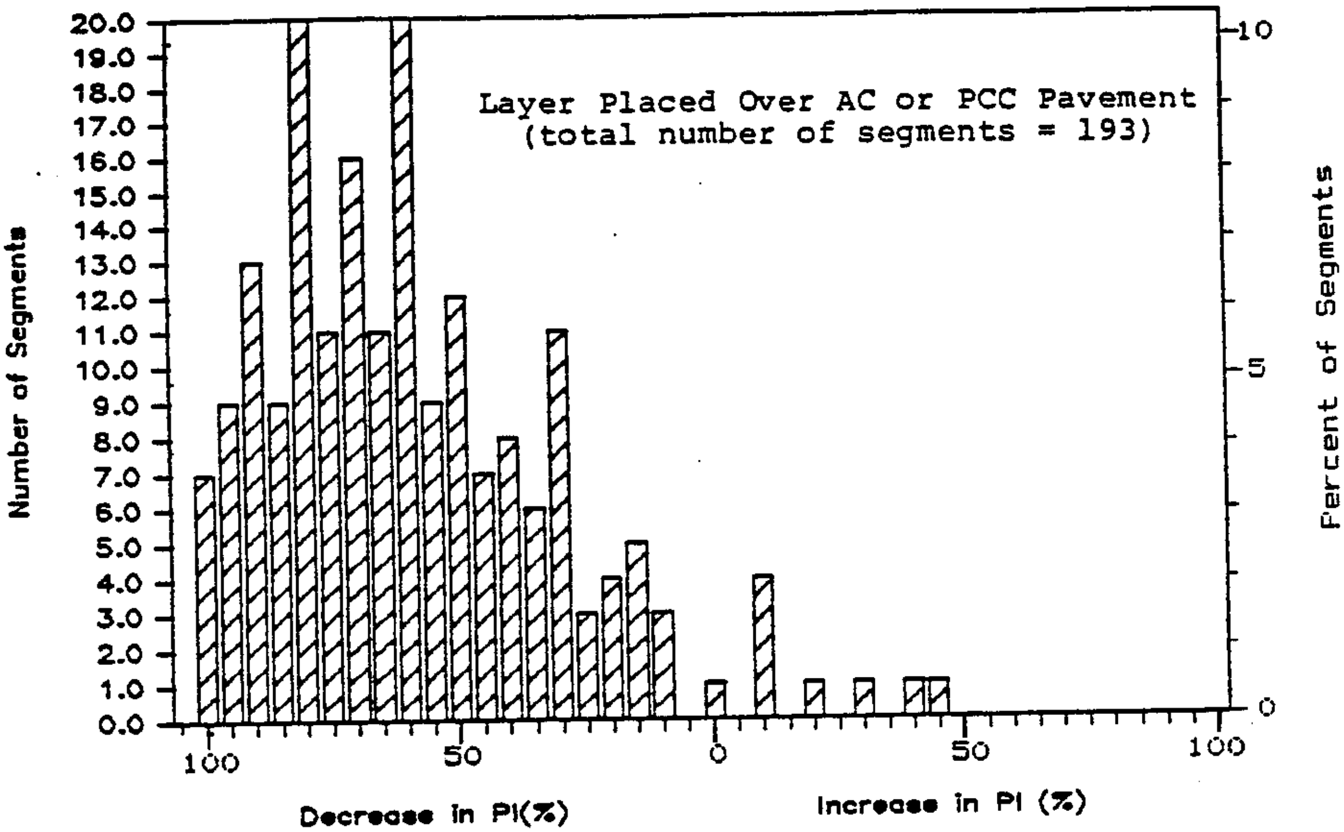
Project	Test Sec.	Overlay Thickness Layer 1	Overlay Thickness Layer 2	Overlay Thickness Layer 3	Average ** Profile Index Existing (x)	Average ** Profile Index Layer 1	Average ** Profile Index Layer 2	Average ** Profile Index Layer 3	Change in PI(%) Layer x/1	Change in PI(%) Layer 1/2	Change in PI(%) Layer 2/3
1	1	0.13'	0.13'	0.13'	13.0	4.2	1.6	1.8	-68	-62	+13
	2	"	"	"	25.1	4.3	2.9	1.9	-83	-33	-34
	3	"	"	"	23.2	5.7	1.9	2.3	-75	-67	+21
	4	"	"	"	18.0	4.5	2.8	2.3	-76	-38	-18
2	1	0.10'	0.10'*	0.10'	29.8	11.1	16.7*	13.9	-63	+50*	-17
	2	"	"	"	32.6	9.2	10.1*	7.2	-72	+10*	-29
	3	"	"	"	31.6	20.6	19.6*	13.2	-35	-5*	-33
	4	"	"	"	33.9	13.2	12.6*	7.1	-61	-5*	-44
3	1	0.10'	0.10'*	0.10'	23.5	6.9	13.7*	4.1	-71	+99*	-70
	2	"	"	"	22.4	9.7	8.9*	5.8	-57	-8*	-35
4	1	0.08'	0.14'*	0.15'	46.5	26.0	16.5*	8.4	-44	-37*	-49
5	1	0.15'	0.15'	-	-	17.1	8.4	-	-	-47	-
	2	"	"	-	-	17.8	16.3	-	-	-8	-
6	1	0.15'	0.15'	0.15'	-	1.6	3.6	-	-	+125	-
	2	"	"	"	-	11.1	3.2	-	-	-71	-
	3	"	"	"	-	-	6.1	1.6	-	-	-74
7	1	0.10'	0.20'*	-	7.4	4.0	3.3*	-	-46	-18*	-
8	1	0.10'	0.10*	0.15'	39.2	18.6	41.7*	-	-53	+124*	-
	2	"	"	"	28.7	4.7	10.8*	-	-84	+130*	-

*Layer placed over reinforcing fabric.

**Average of 0.10 mile segments in each test section.

DISTRIBUTION OF CHANGES IN PI

(After One Subsequent Layer of AC)



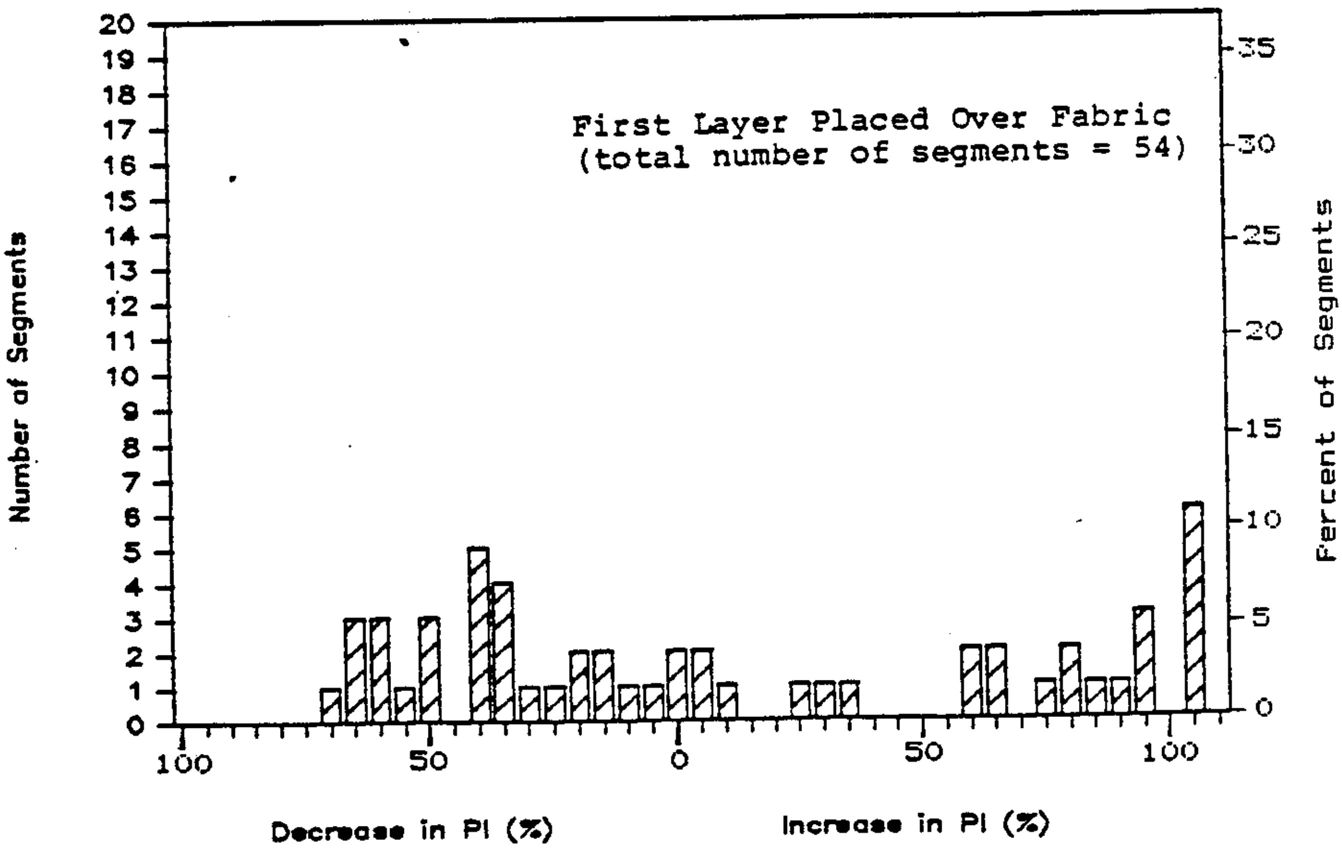


Figure 1b

CUMULATIVE DISTRIBUTION OF CHANGES IN PI
(After One Layer of AC)

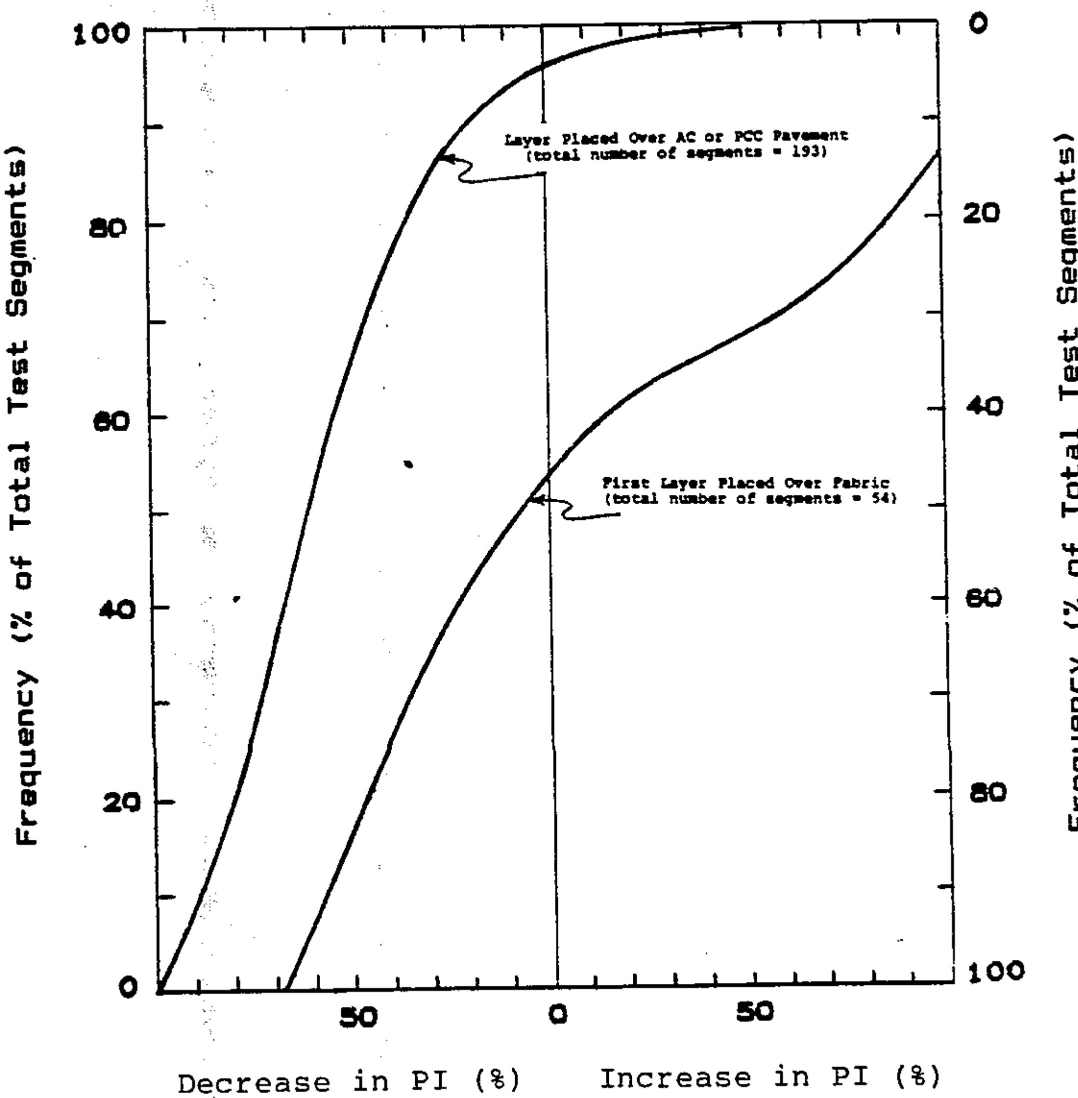
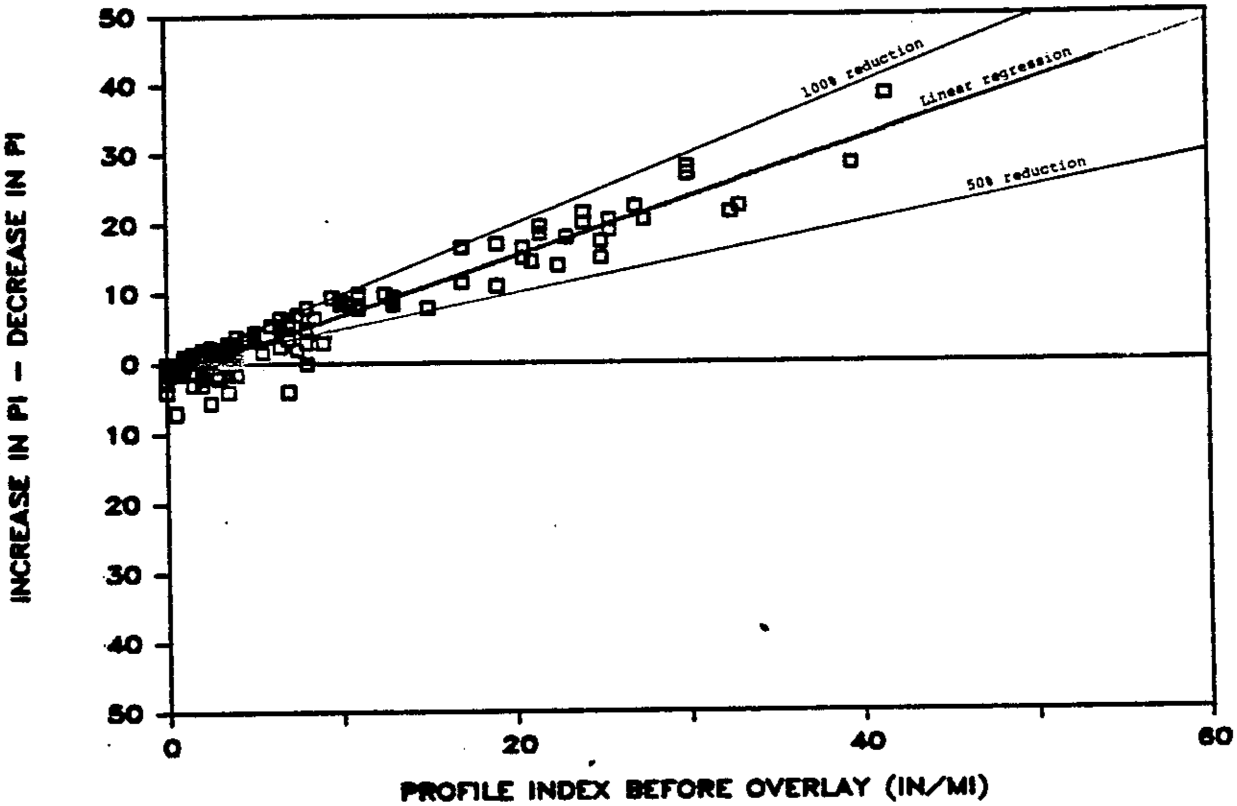


Figure 2

CHANGE IN PROFILE INDEX

After One Subsequent Layer (Project-1)

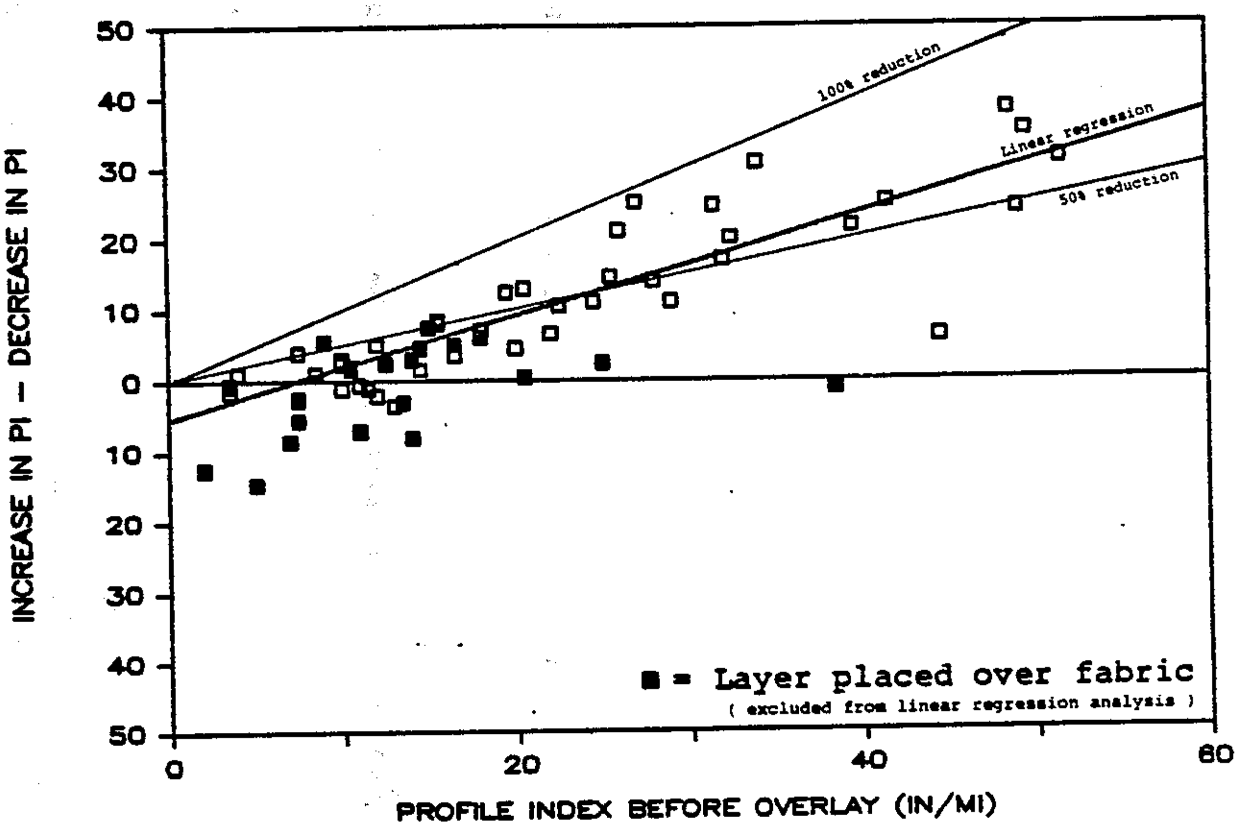


Number of data points	126
Avg. PI before.	8.5
Avg. PI after	2.9
Correlation Coefficient . . .	0.96
Slope	0.84
Y intercept	-1.56

Figure 3

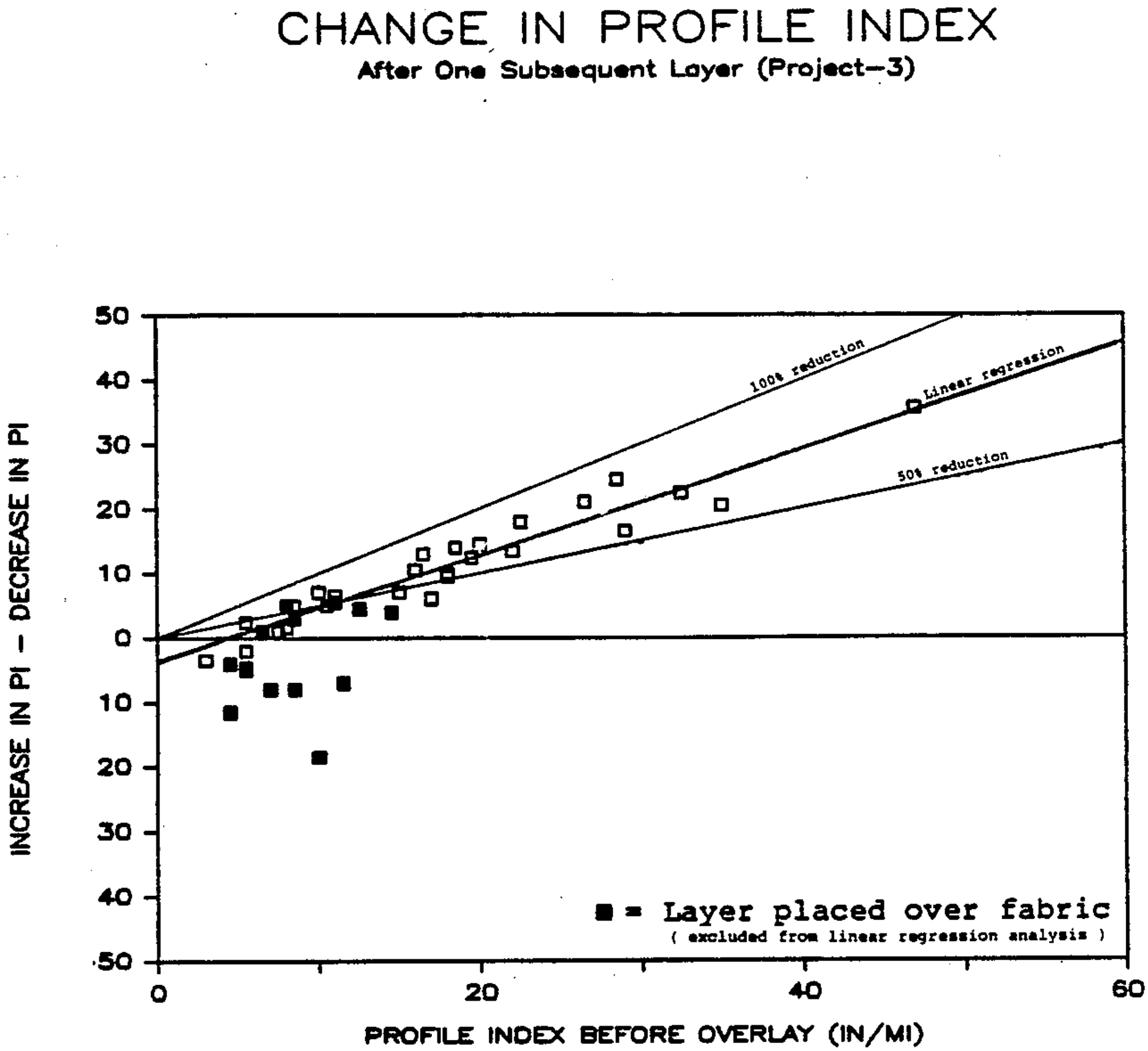
CHANGE IN PROFILE INDEX

After One Subsequent Layer (Project-2)



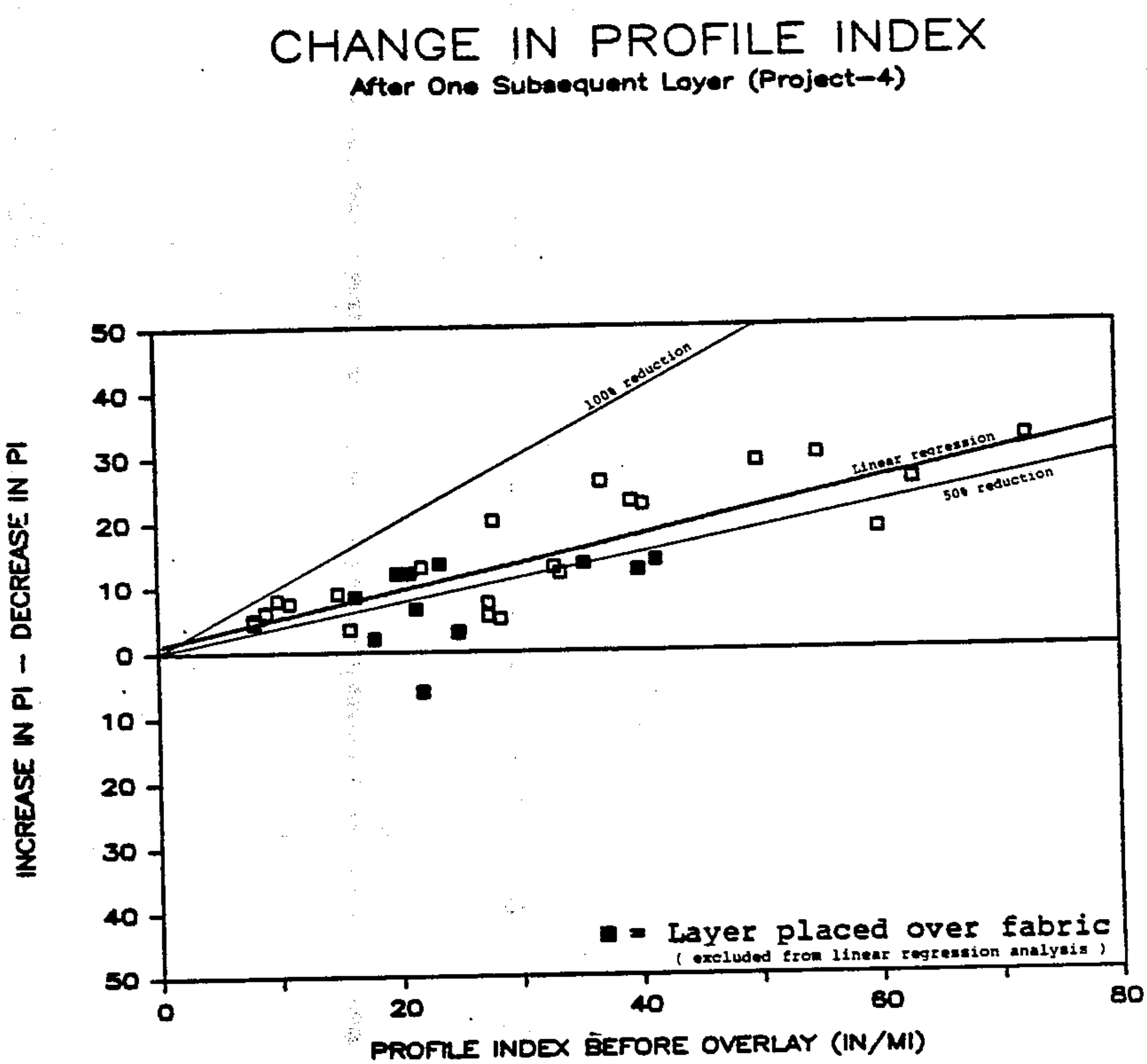
Number of data points	40
Avg. PI before.	23.1
Avg. PI after	11.4
Correlation Coefficient	0.87
Slope	0.72
Y intercept	-5.26

Figure 4



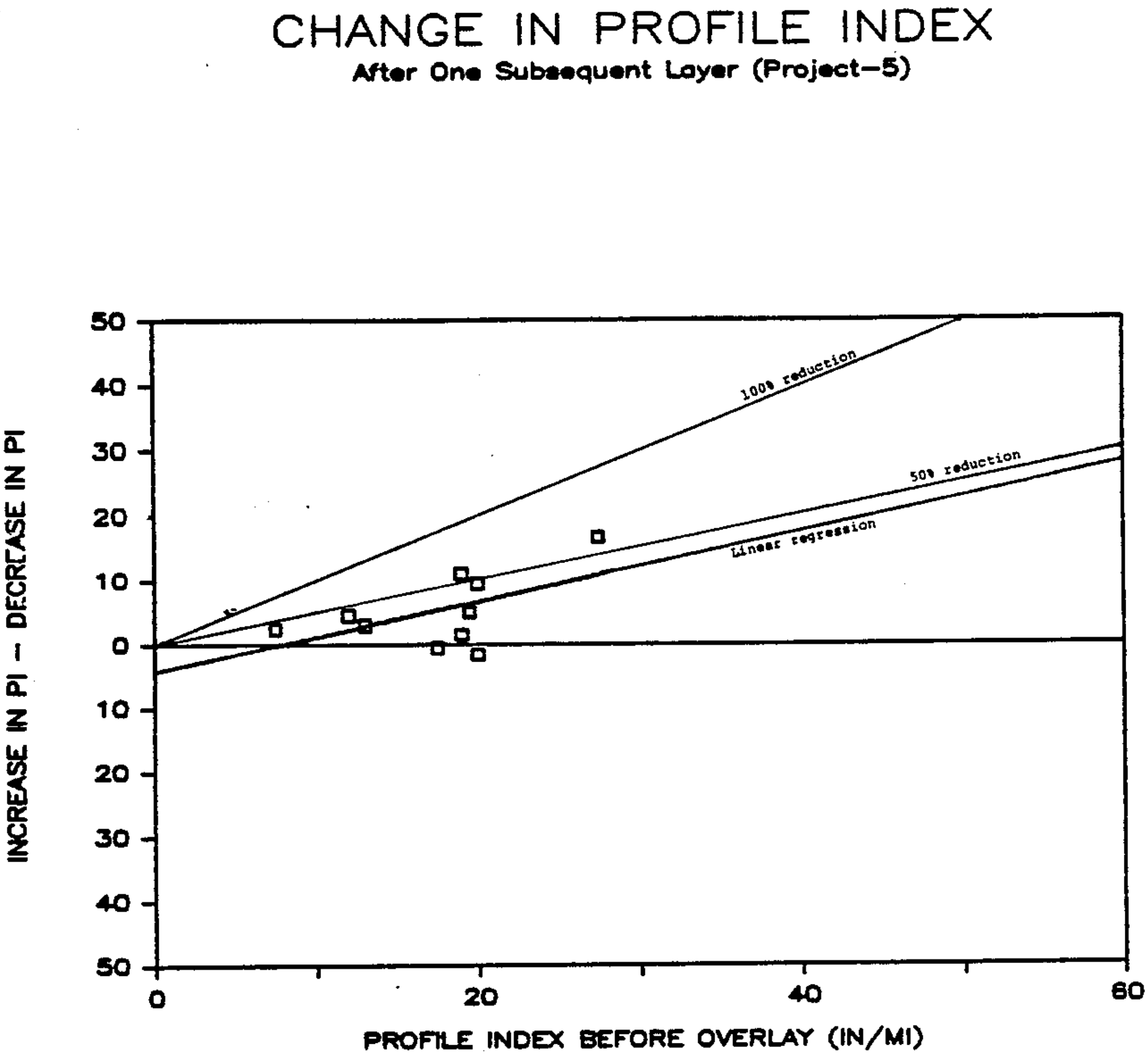
Number of data points	28
Avg. PI before.	17.4
Avg. PI after	6.7
Correlation Coefficient . . .	0.96
Slope	0.82
Y intercept	-3.58

Figure 5



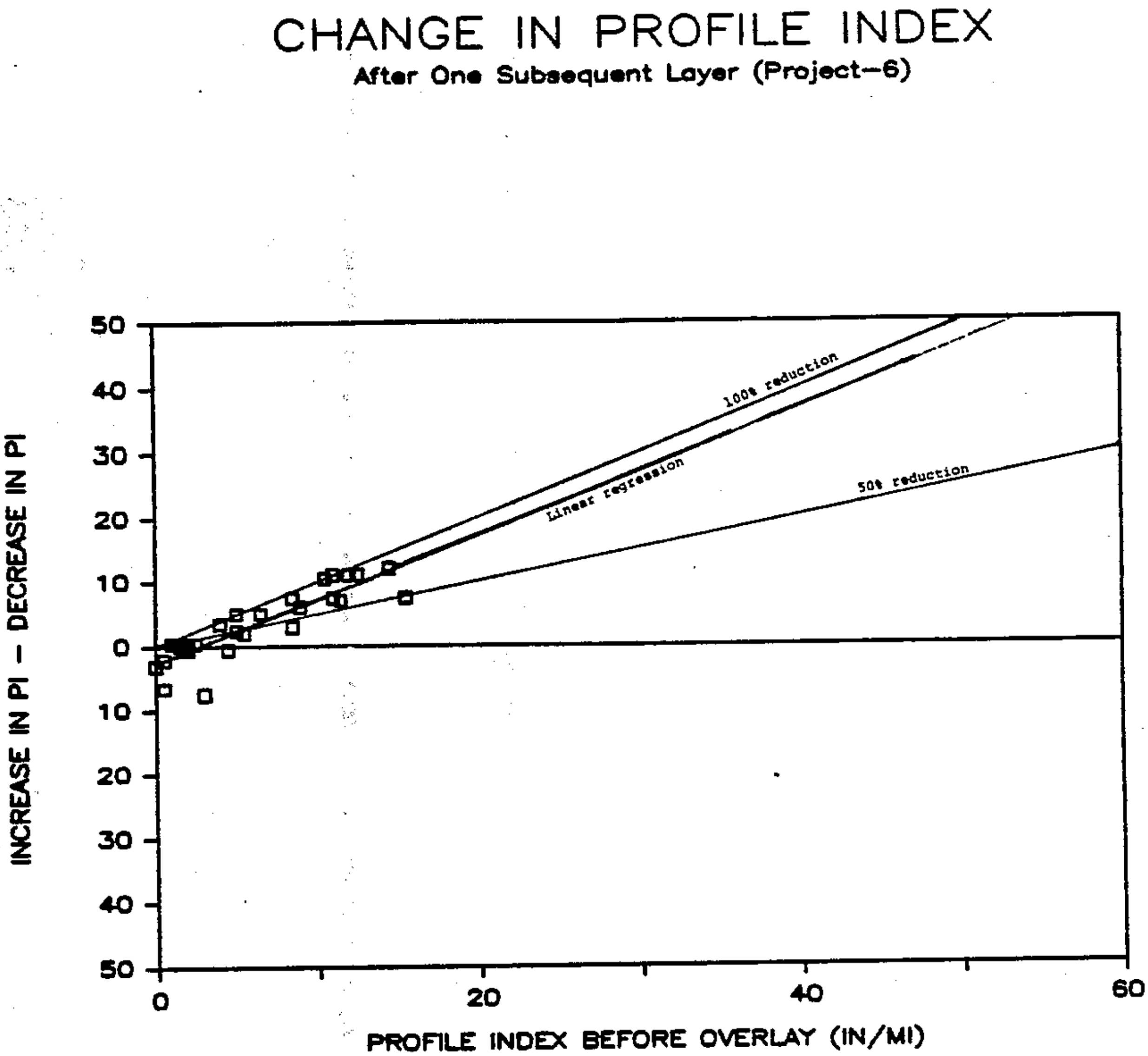
Number of data points 22
Avg. PI before. 31.5
Avg. PI after 17.2
Correlation Coefficient . . . 0.87
Slope 0.42
Y intercept 0.97

Figure 6



Number of data points	10
Avg. PI before.	17.5
Avg. PI after	5.5
Correlation Coefficient . . .	0.54
Slope	0.55
Y intercept	-4.36

Figure 7

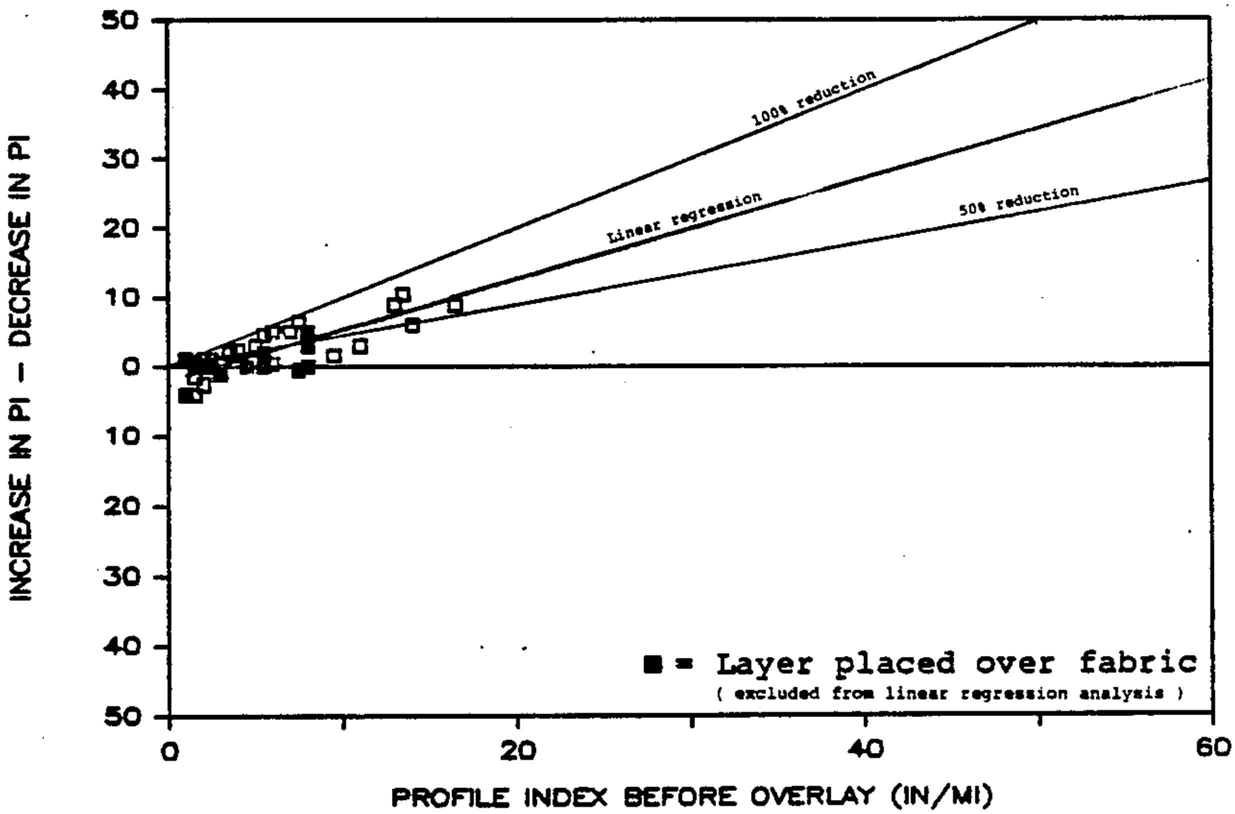


Number of data points	27
Avg. PI before.	6.3
Avg. PI after	2.8
Correlation Coefficient . . .	0.88
Slope	0.98
Y intercept	-2.63

Figure 8

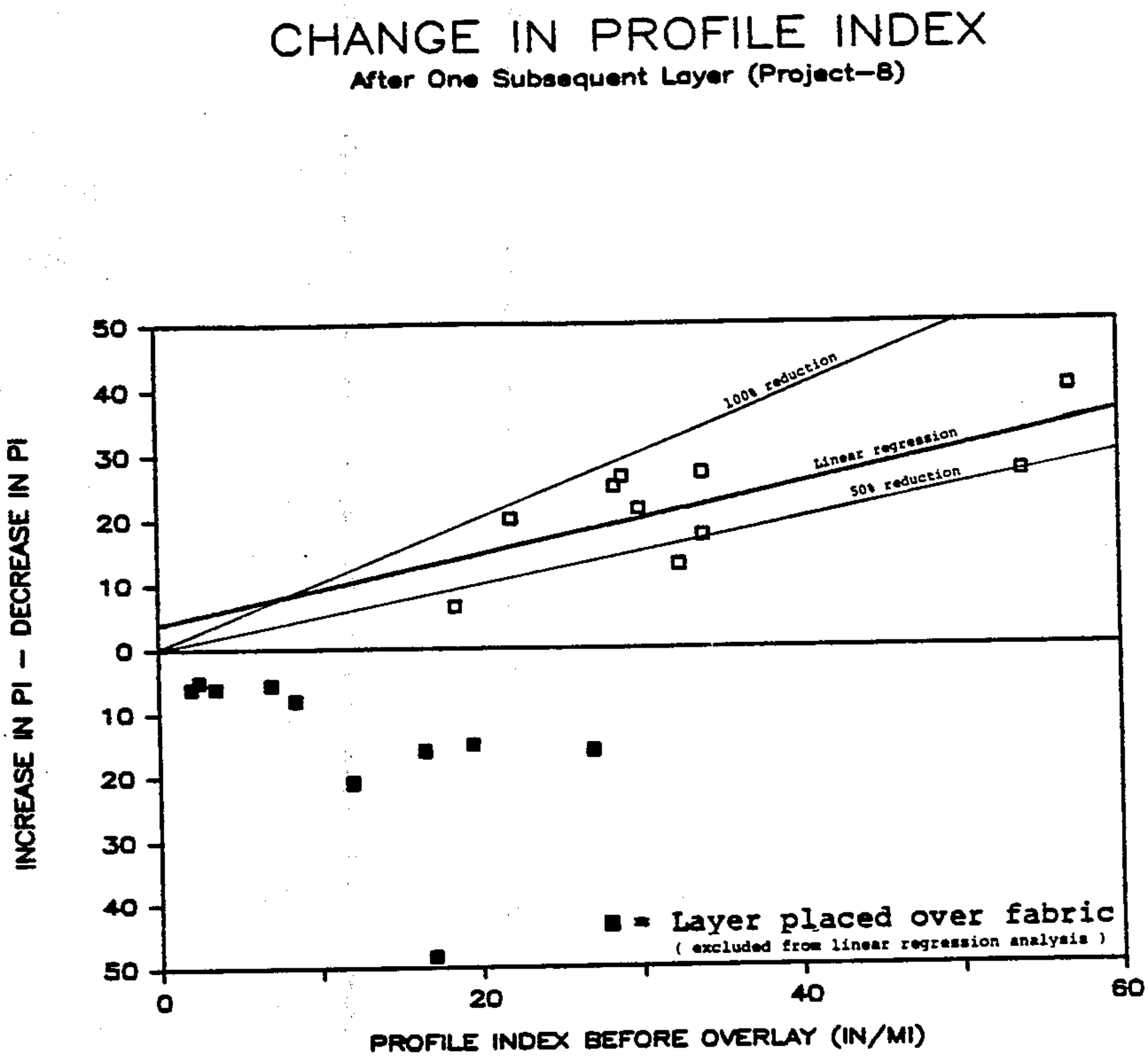
CHANGE IN PROFILE INDEX

After One Subsequent Layer (Project-7)



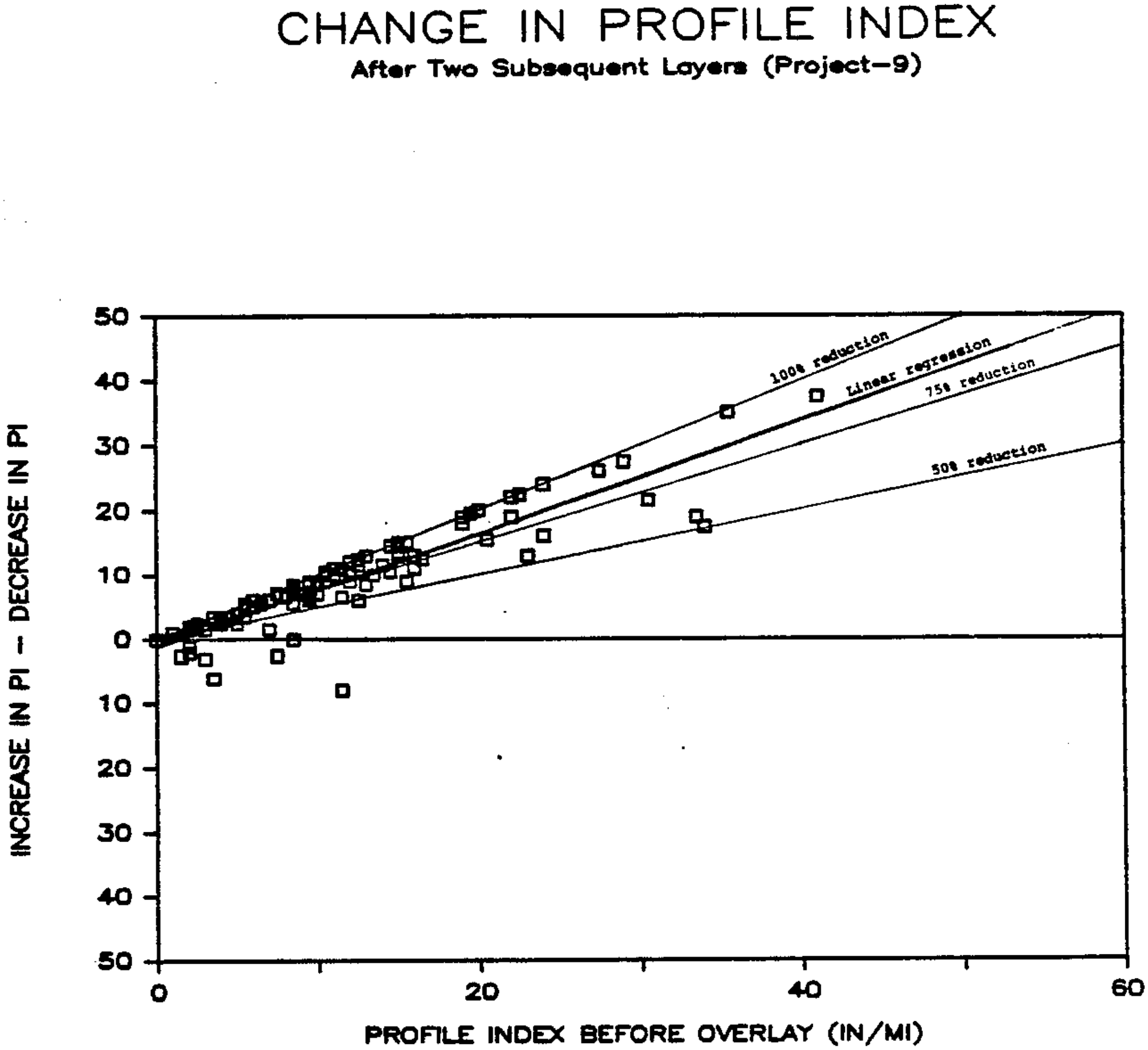
Number of data points 17
Avg. PI before. 7.4
Avg. PI after 4.0
Correlation Coefficient 0.84
Slope 0.73
Y intercept . . . . -1.98

Figure 9



Number of data points	10
Avg. PI before.	34.0
Avg. PI after	11.6
Correlation Coefficient . . .	0.74
Slope	0.54
Y intercept	3.82

Figure 10

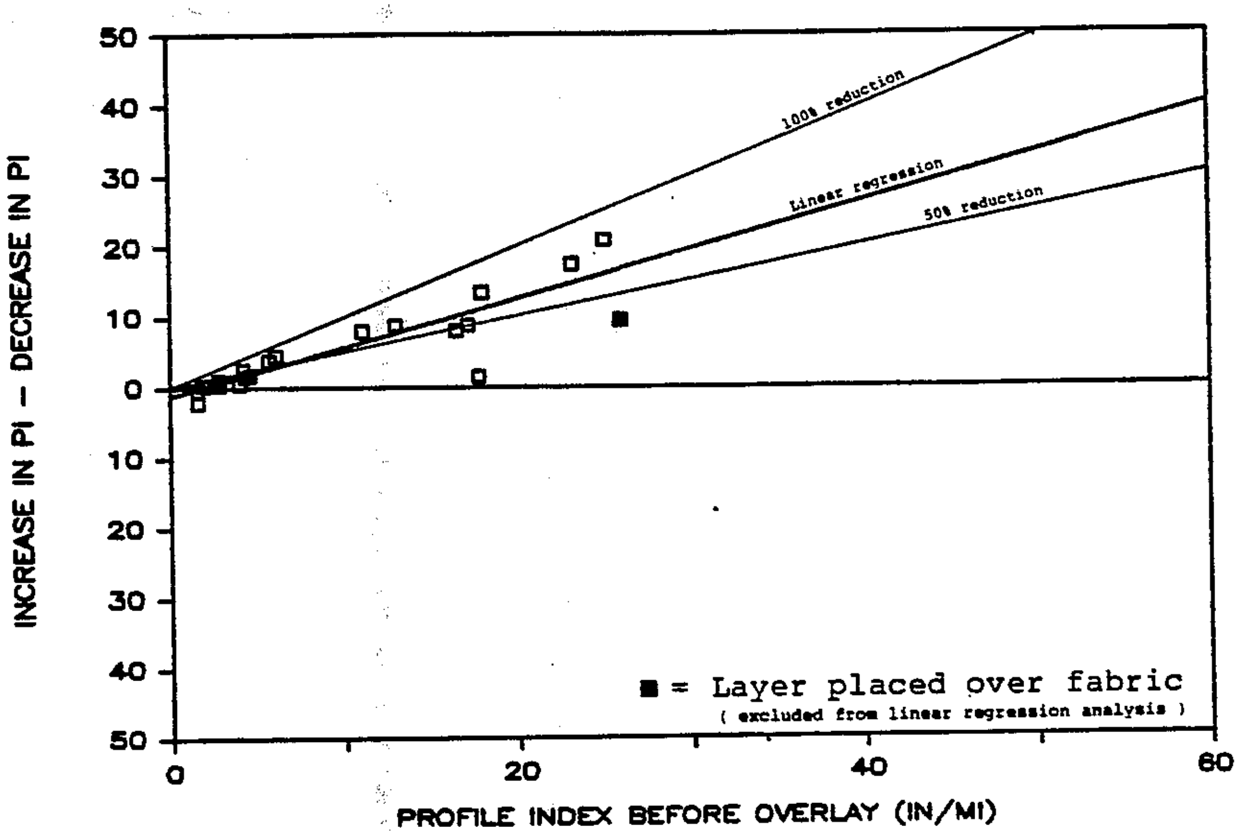


Number of data points	94
Avg. PI before.	12.0
Avg. PI after	2.4
Correlation Coefficient . . .	0.90
Slope	0.87
Y intercept	-1.02

Figure 11

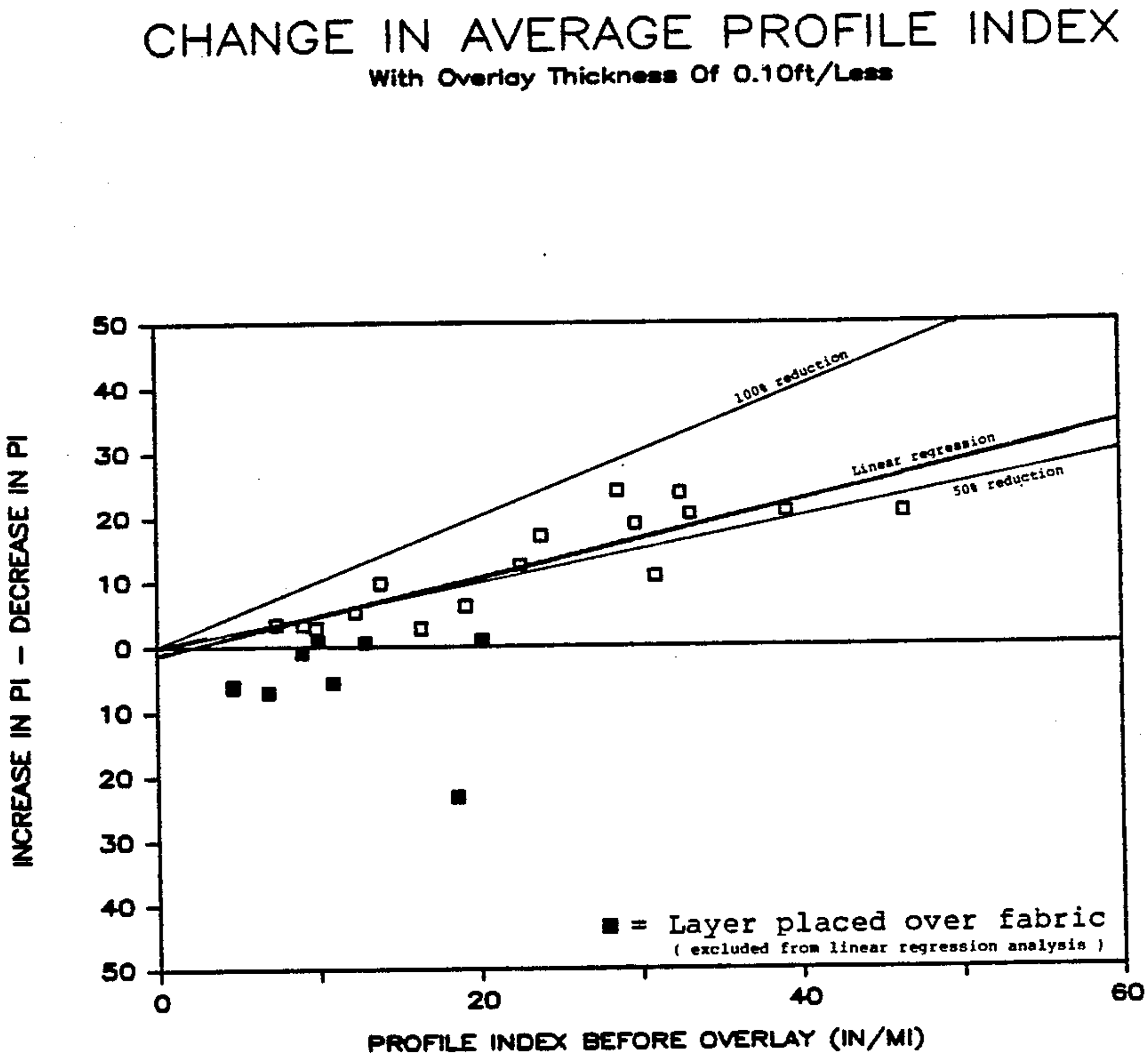
CHANGE IN AVERAGE PROFLIE INDEX

With Overlay Thickness > 0.10Ft.



Number of data points	18
Avg. PI before.	9.9
Avg. PI after	4.3
Correlation Coefficient . . .	0.90
Slope	0.69
Y intercept	-1.20

Figure 12



Number of data points	16
Avg. PI before.	23.6
Avg. PI after	11.0
Correlation Coefficient . . .	0.85
Slope	0.59
Y intercept	-1.20

APPENDIX A

Tabulation of Profile Index Data

TABLE A-1a

PROFILE INDEX DATA, PROJECT 1
Test Section #1 (1.5 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.13' AC) PI	After 1st Lift % Change	After 2nd Lift (0.13' AC) PI	After 2nd Lift % Change	After 3rd Lift (0.13' AC) PI	After 3rd Lift % Change
1	10.0	1.0	-90	1.5	*	0.0	*
2	7.0	11.0	+43	3.0	-73	1.5	*
3	13.0	4.0	-69	1.5	*	0.0	*
4	15.0	7.0	-53	1.5	-79	0.0	*
5	25.0	10.0	-60	1.5	-85	2.5	*
6	25.0	7.5	-70	0.5	-93	1.5	*
7	13.0	3.5	-73	2.5	*	8.0	*
8	3.5	5.0	*	0.5	-90	1.0	*
9	17.0	5.5	-68	4.0	-27	5.5	*
10	8.0	3.0	-62	5.0	*	1.5	-70
11	2.5	0.0	*	0.0	*	0.0	*
12	21.5	2.0	-91	0.0	*	1.0	*
13	11.0	1.0	-91	1.0	*	1.0	*
14	7.0	1.0	-86	0.0	*	1.5	*
15	17.0	0.5	-96	0.5	*	2.0	*
Avg	13.0	4.2	-68	1.6	-62	1.8	+13
σ	7.1	3.5		1.5		2.2	
(1)	13	5		0		2	
(2)	2	10		15		13	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-1b

PROFILE INDEX DATA, PROJECT 1
Test Section #2 (0.8 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.13' AC) PI	After 1st Lift % Change	After 2nd Lift (0.13' AC) PI	After 2nd Lift % Change	After 3rd Lift (0.13' AC) PI	After 3rd Lift % Change
1	27.0	4.5	-83	1.0	*	1.5	*
2	30.0	3.0	-90	4.5	*	1.0	*
3	20.5	5.5	-73	4.0	-27	2.5	*
4	30.0	2.0	-93	2.5	*	2.0	*
5	24.0	2.5	-90	1.5	*	2.5	*
6	32.5	11.0	-66	3.0	-73	1.0	*
7	24.0	4.0	-83	3.0	*	2.0	*
8	12.5	2.5	-80	2.5	*	2.0	*
Avg	25.1	4.3	-83	2.8	-33	1.8	-34
σ	6.4	2.9		1.2		0.6	
(1)	8	2		0		0	
(2)	0	6		8		8	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-1c

PROFILE INDEX DATA, PROJECT 1
Test Section #3 (0.9 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.13' AC) PI	After 1st Lift (0.13' AC) % Change	After 2nd Lift (0.13' AC) PI	After 2nd Lift (0.13' AC) % Change	After 3rd Lift (0.13' AC) PI	After 3rd Lift (0.13' AC) % Change
1	19.0	2.0	-89	3.5	*	0.5	*
2	41.5	3.0	-93	2.0	*	4.0	*
3	27.5	7.0	-75	3.5	-50	7.5	*
4	13.0	4.5	-65	1.0	*	1.5	*
5	9.0	6.0	-33	0.5	-92	1.0	*
6	39.5	11.0	-72	1.5	-86	4.5	*
7	21.0	6.5	-69	4.0	-38	1.0	*
8	25.5	6.5	-58	0.0	-100	0.0	*
9	23.0	5.0	-78	1.0	-80	0.5	*
Avg	23.2	5.7	-75	1.9	-67	2.3	+12
σ	11.2	2.6		1.5		2.5	
(1)	9	5		0		1	
(2)	0	4		9		8	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-1d

PROFILE INDEX DATA, PROJECT 1
Test Section #4 (0.9 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.13' AC) PI	After 1st Lift (0.13' AC) % Change	After 2nd Lift (0.13' AC) PI	After 2nd Lift (0.13' AC) % Change	After 3rd Lift (0.13' AC) PI	After 3rd Lift (0.13' AC) % Change
1	21.5	3.0	-86	1.0	*	1.0	*
2	33.0	10.5	-68	2.0	-81	5.0	*
3	22.5	8.5	-62	2.0	-76	1.0	*
4	21.0	6.5	-69	1.5	-77	0.5	*
5	20.5	4.0	-80	0.0	*	2.5	*
6	25.5	5.0	-80	1.0	-80	1.0	*
7	9.5	0.0	-100	1.0	*	0.0	*
8	8.0	0.0	-100	4.0	*	1.5	*
9	19.0	8.0	-58	8.0	0	5.0	-37
10	3.5	0.5	*	7.5	*	5.5	-27
Avg	18.0	4.6	-76	2.8	-38	2.3	-18
σ	8.9	3.8		2.8		2.1	
(1)	9	4		2		1	
(2)	1	6		8		9	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-2a

PROFILE INDEX DATA, PROJECT 2
Test Section #1 (0.5 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.10' AC) PI	After 1st Lift % Change	After 2nd Lift (0.10'AC on fabric) PI	After 2nd Lift % Change	After 3rd Lift (0.10' AC) PI	After 3rd Lift % Change
1	25.5	11.0	-57	18.0	+64	11.0	-39
2	27.0	2.0	-93	14.5	*	13.0	-10
3	51.5	20.5	-60	20.0	-2	15.5	-22
4	24.5	13.5	-45	16.5	+22	12.0	-27
5	20.5	7.5	-63	13.0	+73	16.5	+27
Avg	29.8	10.9	-63	16.4	+50	13.6	-17
σ	12.4	6.9		2.8		2.3	
(1)	5	4		5		5	
(2)	0	1		0		0	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-2b

PROFILE INDEX DATA, PROJECT 2
Test Section #2 (0.5 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.10' AC) PI	After 1st Lift (0.10' AC) % Change	After 2nd Lift (0.10'AC on fabric) PI	After 2nd Lift (0.10'AC on fabric) % Change	After 3rd Lift (0.10' AC) PI	After 3rd Lift (0.10' AC) % Change
1	15.5	7.5	-52	10.0	+33	7.0	-30
2	34.0	3.5	-90	4.0	*	3.0	*
3	49.5	14.5	-71	10.0	-31	11.0	+10
4	31.5	7.0	-78	15.5	+121	7.0	-55
5	32.5	12.5	-62	10.0	-20	7.5	-25
Avg	32.6	9.0	-72	9.9	+10	7.1	-29
σ	12.1	4.4		4.1		2.8	
(1)	5	4		4		4	
(2)	0	1		1		1	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-2c

PROFILE INDEX DATA, PROJECT 2
Test Section #3 (0.5 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.10' AC) PI	After 1st Lift (0.10' AC) % Change	After 2nd Lift (0.10'AC on fabric) PI	After 2nd Lift (0.10'AC on fabric) % Change	After 3rd Lift (0.10' AC) PI	After 3rd Lift (0.10' AC) % Change
1	28.0	14.0	-50	22.0	+57	15.5	-30
2	44.5	38.5	-13	39.5	+3	18.0	-54
3	29.0	18.0	-38	12.0	-50	7.0	-42
4	41.5	16.5	-60	11.5	-30	12.5	+9
5	12.0	14.0	+17	11.0	-21	11.5	+9
Avg	31.0	20.2	-35	19.2	-5	12.9	-33
σ	12.9	10.4		12.2		4.2	
(1)	5	5		5		5	
(2)	0	0		0		0	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-2d

PROFILE INDEX DATA, PROJECT 2
Test Section #4 (0.5 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.10' AC) PI	After 1st Lift (0.10' AC) % Change	After 2nd Lift (0.10'AC on fabric) PI	After 2nd Lift (0.10'AC on fabric) % Change	After 3rd Lift (0.10' AC) PI	After 3rd Lift (0.10' AC) % Change
1	26.0	5.0	-81	19.5	+290	7.0	-64
2	49.0	25.0	-49	22.5	-10	12.0	-47
3	32.0	15.0	-53	7.5	-50	3.5	-53
4	48.5	10.5	-78	8.5	-19	7.5	-12
5	10.5	9.0	-14	3.5	-61	5.0	*
Avg	33.2	12.9	-61	12.3	-5	7.0	-44
σ	16.2	7.7		8.2		3.2	
(1)	5	4		4		3	
(2)	0	1		1		2	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-3a

PROFILE INDEX DATA, PROJECT 3
Test Section #1 (0.7 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.10' AC) PI	After 1st Lift (0.10' AC) % Change	After 2nd Lift (0.10'AC on fabric) PI	After 2nd Lift (0.10'AC on fabric) % Change	After 3rd Lift (0.10' AC) PI	After 3rd Lift (0.10' AC) % Change
1	22.5	4.5	-80	8.5	*	3.5	-59
2	20.0	5.5	-73	10.5	+91	5.5	-48
3	26.5	5.5	-79	10.0	+82	3.0	-70
4	32.5	10.0	-69	28.5	+185	4.0	-86
5	11.0	4.5	-59	16.0	*	5.5	-66
6	47.0	11.5	-76	18.5	+61	4.5	-76
7	7.5	6.5	-13	5.5	-15	3.0	-45
Avg	23.9	6.9	-71	13.9	+99	4.1	-70
σ	13.3	2.8		7.8		1.1	
(1)	7	5		7		2	
(2)	0	2		0		5	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-3b

PROFILE INDEX DATA, PROJECT 3
Test Section #2 (0.7 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.10' AC) PI	After 1st Lift (0.10' AC) % Change	After 2nd Lift (0.10'AC on fabric) PI	After 2nd Lift (0.10'AC on fabric) % Change	After 3rd Lift (0.10' AC) PI	After 3rd Lift (0.10' AC) % Change
1	22.0	8.5	-61	5.5	-35	3.0	-45
2	18.0	8.0	-56	3.0	-63	6.5	*
3	29.0	12.5	-57	8.0	-36	6.5	-19
4	18.0	8.5	-53	16.5	+94	3.5	-79
5	19.5	7.0	-64	15.0	+114	8.0	-47
6	35.0	14.5	-59	10.5	-28	5.5	-48
7	17.0	11.0	-35	5.5	-50	7.5	+36
Avg	22.6	10.0	-57	9.1	-8	5.8	-35
σ	6.8	2.7		5.1		1.9	
(1)	7	7		6		5	
(2)	0	0		1		2	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-4a

PROFILE INDEX DATA, PROJECT 4
Test Section #1 (1.1 miles)

Segment	Exist. Pavt (AC) PI	After 1st Lift (0.8" AC) PI	After 1st Lift (0.8" AC) % Change	After 2nd Lift (0.14'AC on fabric) PI	After 2nd Lift (0.14'AC on fabric) % Change	After 3rd Lift (0.15' AC) PI	After 3rd Lift (0.15' AC) % Change
1	35.5	22.0	-38	28.0	+27	8.0	-71
2	28.5	23.5	-18	10.0	-57	2.0	-80
3	40.5	18.0	-56	16.0	-11	12.5	-22
4	39.5	16.5	-58	8.0	-52	3.5	-56
5	72.5	40.0	-45	27.5	-31	20.0	-27
6	33.5	21.5	-36	15.0	-30	6.0	-60
7	60.0	41.5	-31	27.5	-34	22.0	-20
8	63.0	37.0	-41	11.0	-70	3.5	-68
9	55.0	25.0	-55	22.0	-12	9.0	-59
10	50.0	21.0	-58	9.0	-57	3.0	-67
11	33.0	20.0	-39	8.0	-60	3.0	-63
Avg	46.5	26.0	-44	16.5	-37	8.4	-49
σ	14.5	9.0		8.2		7.0	
(1)	11	11		11		6	
(2)	0	0		0		5	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-5a

PROFILE INDEX DATA, PROJECT 5
Test Section #1 (0.5 miles)

Segment	Exist. Pavt (AC) PI	After 1st Lift (0.15' AC) PI	After 1st Lift (0.15' AC) % Change	After 2nd Lift (0.15' AC) PI	After 2nd Lift (0.15' AC) % Change	After 3rd Lift ( ) PI	After 3rd Lift ( ) % Change
1		19.0		8.0	-58		
2		7.5		5.0	-33		
3		12.0		7.5	-38		
4		27.5		11.0	-60		
5		20.0		10.5	-48		
Avg		17.2		8.4	-47		
σ		7.7		2.4			
(1)		5		4			
(2)		0		1			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-5b

PROFILE INDEX DATA, PROJECT 5
Test Section #2 (0.5 miles)

Segment	Exist. Pavt (AC) PI	After 1st Lift (0.15' AC) PI	After 1st Lift % Change	After 2nd Lift (0.15' AC) PI	After 2nd Lift % Change	After 3rd Lift ( ) PI	After 3rd Lift % Change
1		20.0		21.5	+8		
2		19.5		14.5	-26		
3		17.5		18.0	+3		
4		13.0		10.0	-23		
5		19.0		17.5	-8		
Avg		17.8		16.3	-8		
σ		2.8		4.3			
(1)		5		5			
(2)		0		0			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-6a

PROFILE INDEX DATA, PROJECT 6
Test Section #1 (0.9 miles)

Segment	Exist. Pavt (None) PI	After 1st Lift (0.15' AC) PI	After 1st Lift (0.15' AC) % Change	After 2nd Lift (0.15' AC) PI	After 2nd Lift (0.15' AC) % Change	After 3rd Lift (0.15' AC) PI	After 3rd Lift (0.15' AC) % Change
1		2.0		1.5	*		
2		1.0		0.5	*		
3		0.5		2.5	*		
4		0.5		7.0	*		
5		0.0		3.0	*		
6		1.5		1.0	*		
7		3.0		10.5	*		
8		4.5		5.0	*		
9		1.5		1.5	*		
Avg		1.6		3.6	+125		
σ		1.4		3.3			
(1)		9		2			
(2)		0		7			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-6b

PROFILE INDEX DATA, PROJECT 6
Test Section #2 (0.9 miles)

Segment	Exist. Pavt (None) PI	After 1st Lift (0.15' AC) PI	After 1st Lift (0.15' AC) % Change	After 2nd Lift (0.15' AC) PI	After 2nd Lift (0.15' AC) % Change	After 3rd Lift (0.15' AC) PI	After 3rd Lift (0.15' AC) % Change
1		11.0		3.5	-68		
2		11.0		0.0	-100		
3		11.5		4.5	-64		
4		8.5		5.5	-35		
5		5.5		3.5	-36		
6		14.5		2.5	-83		
7		15.5		8.0	-48		
8		10.5		0.0	-100		
9		12.0		1.0	-92		
Avg		11.1		3.2	-71		
σ		3.0		2.6			
(1)		9		2			
(2)		0		7			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-6c

PROFILE INDEX DATA, PROJECT 6
Test Section #3 (0.9 miles)

Segment	Exist. Pavt (None) PI	After 1st Lift (0.15' AC) PI	After 1st Lift (0.15' AC) % Change	After 2nd Lift (0.15' AC) PI	After 2nd Lift (0.15' AC) % Change	After 3rd Lift (0.15' AC) PI	After 3rd Lift (0.15' AC) % Change
1				6.5		1.5	-77
2				8.5		1.0	-88
3				12.5		1.5	-88
4				4.0		0.5	*
5				5.0		0.0	-100
6				9.0		3.0	-67
7				5.0		2.5	-50
8				2.0		2.5	*
9				2.5		2.0	*
Avg				6.1		1.6	-74
σ				3.4		1.0	
(1)				4		0	
(2)				5		9	

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-7a

PROFILE INDEX DATA, PROJECT 7
Test Section #1 (1.7 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.10' AC) PI	After 1st Lift % Change	After 2nd Lift (0.20'AC or fabric) PI	After 2nd Lift % Change	After 3rd Lift ( ) PI	After 3rd Lift % Change
1	9.5	8.0	-16	8.0	0		
2	11.0	8.0	-27	3.0	-63		
3	5.0	2.0	-60	1.0	*		
4	2.5	2.5	*	1.5	*		
5	7.5	1.0	-87	0.0	*		
6	1.5	5.5	*	3.5	-36		
7	1.5	3.0	*	2.5	*		
8	2.0	4.5	*	4.5	*		
9	3.5	1.5	*	1.0	*		
10	5.5	1.0	-82	5.0	*		
11	7.0	2.0	-71	2.0	*		
12	6.0	1.0	-83	0.0	*		
13	13.0	4.0	-69	1.5	*		
14	13.5	3.0	-78	4.0	*		
15	6.0	5.5	-8	5.5	0		
16	14.0	8.0	-43	5.0	-38		
17	16.5	7.5	-55	8.0	+7		
Avg	7.4	4.0	-46	3.3	-18		
σ	4.8	2.6		2.5			
(1)	11	6		3			
(2)	6	11		14			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-8a

PROFILE INDEX DATA, PROJECT 8
Test Section #1 (0.5 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.10' AC) PI	After 1st Lift (0.10' AC) % Change	After 2nd Lift (0.10'AC on fabric) PI	After 2nd Lift (0.10'AC on fabric) % Change	After 3rd Lift (0.10' AC) PI	After 3rd Lift (0.10' AC) % Change
1	32.5	19.5	-40	34.5	+77		
2	18.5	12.0	-35	33.0	+175		
3	57.0	17.0	-70	65.5	+285		
4	54.0	27.0	-50	43.0	+59		
5	34.0	16.5	-49	32.5	+86		
Avg	39.2	18.6	-53	41.7	+124		
σ	16.1	5.4		14.0			
(1)	5	5		5			
(2)	0	0		0			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-8b

PROFILE INDEX DATA, PROJECT 8
Test Section #2 (0.5 miles)

Segment	Exist. Pavt (PCC) PI	After 1st Lift (0.10' AC) PI	After 1st Lift (0.10' AC) % Change	After 2nd Lift (0.10'AC on fabric) PI	After 2nd Lift (0.10'AC on fabric) % Change	After 3rd Lift (0.10' AC) PI	After 3rd Lift (0.10' AC) % Change
1	28.5	3.5	-88	9.5	*		
2	22.0	2.0	-91	8.0	*		
3	30.0	8.5	-72	16.5	+94		
4	34.0	7.0	-79	12.5	+79		
5	29.0	2.5	-91	7.5	*		
Avg	28.7	4.7	-84	10.8	+130		
σ	4.3	2.9		3.7			
(1)	5	2		5			
(2)	0	3		0			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-9a

PROFILE INDEX DATA, PROJECT 9
Test Section #1 (1.3 miles)

Segment	Exist. Pavt (AC)	After 1st Lift (0.15' AC)		After 2nd Lift (0.10' AC)		After 3rd Lift ( )	
	PI	PI	% Change	PI	% Change	PI	% Change
1	14.5			4.0	-72		
2	1.5			4.0	*		
3	5.5			2.0	-64		
4	10.5			0.0	-100		
5	13.5			3.5	-74		
6	2.0			0.5	*		
7	10.5			0.0	-100		
8	5.5			2.0	-64		
9	7.0			1.0	-86		
10	9.5			3.5	-63		
11	16.5			4.0	-76		
12	10.0			1.5	-85		
13	41.0			3.5	-91		
Avg	11.3			2.3	-80		
σ	10.0			1.6			
(1)	11			0			
(2)	2			13			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-9b

PROFILE INDEX DATA, PROJECT 9
Test Section #2 (1.3 miles)

Segment	Exist. Pavt (AC) PI	After 1st Lift (0.15' AC) PI	After 1st Lift (0.15' AC) % Change	After 2nd Lift (0.10' AC) PI	After 2nd Lift (0.10' AC) % Change	After 3rd Lift ( ) PI	After 3rd Lift ( ) % Change
1	9.5			3.0	-68		
2	2.0			4.0	*		
3	3.0			6.0	*		
4	6.0			1.0	-83		
5	7.0			5.5	-21		
6	2.0			0.5	*		
7	8.5			1.0	-88		
8	7.5			10.0	+33		
9	5.0			1.0	-80		
10	8.5			8.5	0		
11	11.5			5.0	-57		
12	4.5			1.0	*		
13	30.5			9.0	-70		
Avg	8.1			4.3	-47		
σ	7.3			3.4			
(1)	8			5			
(2)	5			8			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-9c

PROFILE INDEX DATA, PROJECT 9
Test Section #3 (1.3 miles)

Segment	Exist. Pavt (AC) PI	After 1st Lift (0.15' AC) PI	After 1st Lift % Change	After 2nd Lift (0.10' AC) PI	After 2nd Lift % Change	After 3rd Lift ( ) PI	After 3rd Lift % Change
1	16.0			3.0	-81		
2	2.0			3.0	*		
3	2.0			0.0	*		
4	3.5			0.0	*		
5	2.0			0.0	*		
6	6.0			0.0	-100		
7	4.0			0.5	*		
8	2.5			0.0	*		
9	5.0			2.5	-50		
10	15.0			0.5	-97		
11	10.0			3.0	-70		
12	16.0			5.0	-69		
13	22.0			0.0	-100		
Avg	8.2			1.3	-84		
σ	6.9			1.7			
(1)	6			0			
(2)	7			13			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-9d

PROFILE INDEX DATA, PROJECT 9
Test Section #4 (1.3 miles)

Segment	Exist. Pavt (AC) PI	After 1st Lift (0.15' AC) PI	After 1st Lift % Change	After 2nd Lift (0.10' AC) PI	After 2nd Lift % Change	After 3rd Lift ( ) PI	After 3rd Lift % Change
1	24.0			8.0	-67		
2	3.5			9.5	*		
3	9.5			1.0	-89		
4	1.0			0.0	*		
5	5.5			0.0	-100		
6	7.5			0.5	-93		
7	2.0			0.0	*		
8	4.0			1.5	*		
9	0.0			0.0	*		
10	14.0			2.5	-82		
11	9.5			2.5	-74		
12	11.5			19.5	+70		
13	15.5			0.5	-97		
Avg	8.3			3.5	-58		
σ	6.8			5.7			
(1)	8			3			
(2)	5			10			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-9e

PROFILE INDEX DATA, PROJECT 9
Test Section #5 (2.1 miles)

Segment	Exist. Pavt (AC) PI	After 1st Lift (0.15' AC) PI	After 1st Lift (0.15' AC) % Change	After 2nd Lift (0.10' AC) PI	After 2nd Lift (0.10' AC) % Change	After 3rd Lift ( ) PI	After 3rd Lift ( ) % Change
1	33.5			14.5	-57		
2	22.5			0.0	-100		
3	14.5			0.0	-100		
4	12.5			0.0	-100		
5	20.5			5.0	-76		
6	13.0			0.0	-100		
7	12.0			0.0	-100		
8	15.0			1.5	-90		
9	9.0			2.0	-78		
10	6.5			1.0	-85		
11	5.5			0.5	-91		
12	9.5			0.5	-95		
13	20.0			0.0	-100		
14	19.5			0.0	-100		
15	29.0			1.5	-95		
16	24.0			0.0	-100		
17	15.0			0.0	-100		
18	19.0			1.0	-95		
19	11.5			0.5	-96		
20	27.5			1.5	-95		
21	35.5			0.5	-99		
Avg	17.8			1.4	-92		
σ	8.5			3.2			
(1)	21			1			
(2)	0			20			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

TABLE A-9f

PROFILE INDEX DATA, PROJECT 9
Test Section #6 (2.1 miles)

Segment	Exist. Pavt (AC) PI	After 1st Lift (0.15' AC) PI	After 1st Lift (0.15' AC) % Change	After 2nd Lift (0.10' AC) PI	After 2nd Lift (0.10' AC) % Change	After 3rd Lift ( ) PI	After 3rd Lift ( ) % Change
1	34.0			16.5	-51		
2	15.0			0.0	-100		
3	19.0			0.0	-100		
4	11.0			0.0	-100		
5	23.0			10.0	-57		
6	10.5			0.5	-95		
7	11.0			1.0	-91		
8	15.0			2.0	-87		
9	12.0			1.5	-88		
10	8.5			0.5	-94		
11	3.0			1.5	*		
12	10.5			1.5	-86		
13	12.5			1.0	-92		
14	13.0			4.5	-65		
15	15.5			6.5	-58		
16	12.0			3.0	-75		
17	8.5			0.0	-100		
18	8.0			1.5	-81		
19	8.5			3.0	-65		
20	12.5			6.5	-48		
21	22.0			3.0	-86		
Avg	13.6			3.0	-78		
σ	6.6			6.2			
(1)	20			4			
(2)	1			17			

*The % change of individual segments is not meaningful when the PI of the underlaying layer is less than 5.

(1) Number of segments with PI greater than 5.

(2) Number of segments with PI of 5 or less.

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

ESTIMATING HIGHWAY RUNOFF QUALITY

FINAL REPORT # FHWA/CA/TL-82/11

CALTRANS STUDY # E78TL10

Study Supervised by .... Earl C. Shirley, P.E.

Principal Investigator .... Richard B. Howell, P.E.

Co-Principal Investigator ..... Gary R. Winters, Biologist

Project Engineer .... James A. Racin, Assistant Engineer

Report Prepared by .... James A. Racin, Assistant Engineer and Richard B. Howell, P.E.

G. L. RUSSELL, P.E.
Chief, Office of Transportation Laboratory

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
FHWA/CA/TL-82/11		

4. TITLE AND SUBTITLE
ESTIMATING HIGHWAY RUNOFF QUALITY

5. REPORT DATE
September 1982

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
James A. Racin, Richard B. Howell, Gary R. Winters, and Earl C. Shirley

8. PERFORMING ORGANIZATION REPORT NO.
19703-604170

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Transportation Laboratory
California Department of Transportation
Sacramento, California 95819

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.
E78TL10

12. SPONSORING AGENCY NAME AND ADDRESS
California Department of Transportation
Sacramento, California 95807

13. TYPE OF REPORT & PERIOD COVERED
Final

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This research was accomplished under the Federal Highway Administration research project "Modeling Transportation Pavement Runoff".

16. ABSTRACT The development of regression equations for estimating the quality of runoff from highways is documented. Data were collected during the 1980-81 wet season at the two completely paved urban highway segments in California: I-405 in Los Angeles and I-680 in Walnut Creek. Data for evaluation of regression equations were collected during the 1979-80 wet season at U.S. 50 in Sacramento.

Rainfall and runoff were monitored continuously. Bubbler flow meters were used with automatic sequential samplers so that storm water samples could be collected to characterize entire storm events. Constituents analyzed were boron, total lead, total zinc, nitrate (nitrogen), ammonia (nitrogen), total Kjeldahl nitrogen, total phosphorus, dissolved orthophosphate, oil and grease, nonfilterable residue, filterable residue, total cadmium, and chemical oxygen demand.

Seventeen regression equations are reported. Vehicles during the storm was evaluated and accepted as a satisfactory independent variable for estimating the loads of total lead, total zinc, filterable residue, chemical oxygen demand, and total Kjeldahl nitrogen. Total residue was evaluated and accepted as a satisfactory independent variable for estimating total zinc, nonfilterable residue, and chemical oxygen demand. Estimates made using these equations should be limited to highways with average daily traffic of at least 30,000 vehicles. Antecendent dry days was found not to be a satisfactory independent variable.

17. KEY WORDS Highway, runoff, water quality, regression equations, monitoring, vehicles, lead, residue, zinc, chemical oxygen demand.

18. DISTRIBUTION STATEMENT
No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		

DS-TL-1242 (Rev.6/76)

NOTICE

The contents of this report reflect the views of the Office of Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Neither the State of California nor the United States Government endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quantity	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mmm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2)	6.432×10^{-4}	square metres (m^2)
	square feet (ft^2) acres	.09290 .4047	square metres (m^2) hectares (ha)
Volume	gallons (gal)	3.785	litres (l)
	cubic feet (ft^3)	.02832	cubic metres (m^3)
	cubic yards (yd^3)	.7646	cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s)	28.317	litres per second (l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G)	9.807	metres per second squared (m/s^2)
Weight Density	pounds per cubic (lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) kips (1000 lbs)	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British thermal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (ft-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch (ksi $\sqrt{in}$)	1.0988	mega pascals $\sqrt{metre}$ (MPa $\sqrt{m}$)
	pounds per square inch square root inch (psi $\sqrt{in}$)	1.0988	kilo pascals $\sqrt{metre}$ (KPa $\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{tF - 32}{1.8} = tC$	degrees celsius (°C)

ACKNOWLEDGEMENTS

There were many individuals involved in the various phases of the research. The authors wish to express their appreciation to the many individuals at TransLab who assisted; the maintenance, design, traffic, environmental and materials personnel in Districts 03, 04, and 07; individuals in the Headquarters Office of Computer Systems; the testing personnel at the Bryte Laboratory of the Department of Water Resources; the weather service personnel of the National Weather Service; and the consultation of Dr. Kenneth Kerri of California State University, Sacramento; and Nic Kobriger of Rexnord, Environmental Research Center, Milwaukee, Wisconsin.

Special acknowledgement is given to the maintenance personnel for performing site modifications, emergency repairs, and setting up lane closures during the course of the project. Particular acknowledgement is given to Sean Conner and Wayne Grams under the supervision of Irv Smitten at the Waltnut Creek Maintenance Station, and Wally Yeager under the supervision of Wayne Grable at the East Sacramento Maintenance Station.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

An assessment of potential impacts on receiving waters from nonpoint sources of pollution is required by both Federal and State laws. The Federal Highway Administration (FHWA) has sponsored research studies to quantify and forecast loads and concentrations of constituents found in highway runoff. Runoff modeling studies have been conducted by private, state, and university researchers at various locations in the United States to cover the wide range of climatic and topographic conditions. Since runoff sites which are located east of the Rocky Mountains reflect climates where precipitation occurs throughout the year, sites were established in California to characterize arid and semiarid regions, where precipitation occurs mostly from October through April.

Several models have been developed by universitites and government agencies. The "STORM" model (Storage Treatment Overflow Runoff Model) by the U.S. Army Corps of Engineers and the SWMM model (Storm Water Management Model) by E.P.A. were developed for urban basins, in which constituent loading rates must be specified for various land use categories. Highways are a specialized land use and are potential sources of nonpoint pollution. The paved surfaces can accumulate constituents, and during a rainfall event, the constituents can enter receiving waters via runoff. Most highway runoff modellers have used the concepts developed for urban models. In summary, dry days before the storm is used as a measure of constituent accumulation, and the washoff is characterized by an exponential decay equation. The Rexnord study sponsored by FHWA, developed a predictive procedure similar to the SWMM model specifically for highways. In contrast, researchers at the University of Washington, sponsored by the Washington Department of Transportation, found that vehicular turbulence effectively removes particulates from paved highway surfaces during extended dry periods. The University of Washington researchers also found positive correlations between the cumulative constituent loads and the cumulative vehicles during the storm. Both the Rexnord and University of Washington studies were near completion when the Caltrans highway storm runoff study was being done.

Before the Caltrans project for developing a predictive procedure for constituent loads in highway runoff began, there were two major studies performed concurrently by the Caltrans Transportation Laboratory in which highway runoff was addressed. One study is reported in Effects of Roadway Runoff on Algae, [Winters and Gidley, 2], in which the response of algae to various concentrations of highway runoff was investigated. Basically it was found that inhibition or stimulation to algal growth depended on the chemical composition, especially heavy metals, of the runoff water. The other study is reported in Water Pollution Aspects of Particles Which Collect on Highway Surfaces, [Howell, 1]. Thirty-four different physical and chemical water quality parameters were measured. Discrete water samples were collected at three sites: I-405 in Los Angeles County (Los Angeles), I-680 in Contra Costa County (Walnut Creek), and U.S. 50 in El Dorado County (Placerville). California experienced severe back-to-back droughts during the sampling periods of 1975 through 1978. Because of the drought and the sampling technique, the data were found to be insufficient for developing an acceptable set of regression equations for quantifying constituent loads. Therefore, in September of 1978, Caltrans initiated a research project, "Modeling Transportation Pavement Runoff," to quantify and forecast concentrations and loads of selected constituents from highway (pavement) runoff.

For the "runoff" project, it was required that both quantitative and qualitative water data be collected "continuously" instead of "discretely." Data were obtained from the I-405 and I-680 sites during the 1980-81 wet season. Additionally, in cooperation with Rexnord and under the sponsorship of FHWA, data for evaluation of regression equations were obtained from U.S. 50 in Sacramento County (Sacramento) during the 1979-80 and 1980-81 wet seasons. Figure 1 shows the location of the runoff sites. The highways are in urban settings and the data were collected under normal highway operating conditions during storms. Specific site information is reported in the Appendix.

This report documents the development of the Caltrans regression equations for quantifying the loads of constituents in highway pavement storm runoff. Because of the complex interactions among rainfall, runoff, highway design, surrounding land use, operating vehicles, and maintenance practices, regression analysis by the method of least squares was used to construct the lines. Dependent variables were selected from the data reported in Water Pollution Aspects of Particles Which Collect on Highway Surfaces, [Howell, 1]. A suitable independent variable was sought to forecast constituent loads and concentrations.

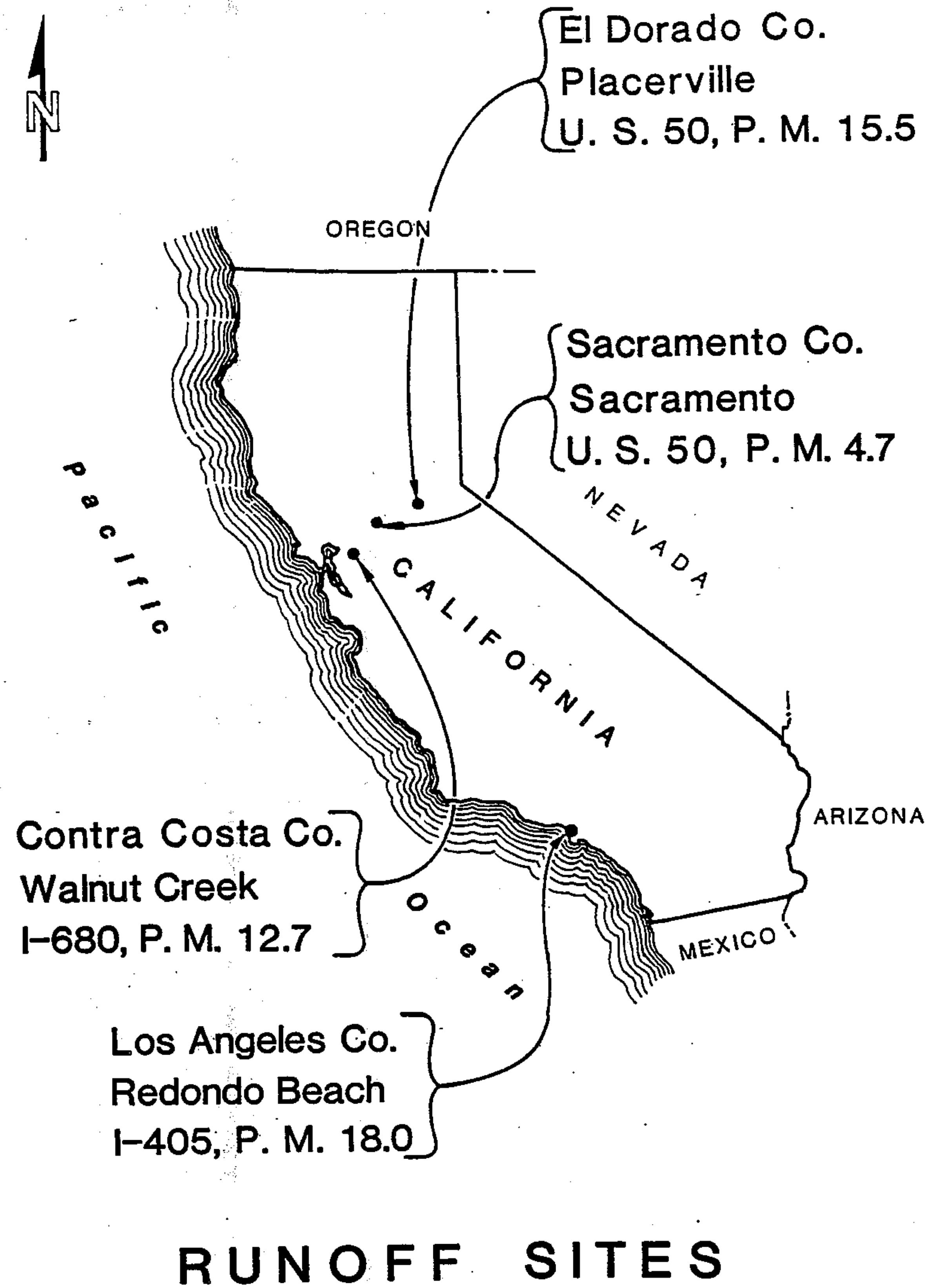

El Dorado Co.
Placerville
U. S. 50, P. M. 15.5
OREGON
Sacramento Co.
Sacramento
U. S. 50, P. M. 4.7
NEVADA
Pacific
CALIFORNIA
ARIZONA
Contra Costa Co.
Walnut Creek
I-680, P. M. 12.7
Ocean
MEXICO
Los Angeles Co.
Redondo Beach
I-405, P. M. 18.0
RUNOFF SITES

Figure 1

2. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached:

1 a) Equations to estimate the cumulative loads of the following pollutants were found to be statistically significant at the .05 level, on a storm event basis when:

- Correlated with vehicles during the storm:

  Chemical Oxygen Demand (COD)
  Filterable Residue (Dissolved Solids)
  Lead (Total)
  Total Kjeldahl Nitrogen (TKN)
  Zinc (Total)

- Correlated with total residue:

  Chemical Oxygen Demand (COD)
  Nonfilterable Residue (Suspended Solids)
  Zinc (Total)

b) The number of dry days between storm events and the corresponding cumulative traffic volume before the storm were found to be not statistically significant for quantifying cumulative constituent loads. Apparently, traffic-generated turbulence tends to "sweep" the traveled lanes and shoulders, continuously.

c) After the initial pavement and gutter loads are washed off, vehicles travelling on the highway will continue to emit constituents. Because constituents are continuously being added to the runoff, the use of an exponential washoff equation is not adequate. Instead, a linear approximation is appropriate.

2 a) No statistically significant correlations at the 0.05 level of significance were found with any of the independent variables examined for the following constituent loads:

boron, cadmium, nitrate nitrogen, ammonia nitrogen, total phosphorus, dissolved orthophosphate, oil and grease.

b) The following constituents exhibited a "first flush" pattern with relatively insignificant loads and concentrations:

sulfate, iron, chromium, copper, manganese, nickel, bicarbonate ion, carbonate ion, calcium, magnesium, chloride, mercury, molybdenum, potassium, silica, and sodium.

3 Urban highways in California operating under normal conditions, i.e., no accidents or chemical spills, do not produce large masses of constituents during storm runoff events. The findings of the research indicate that for highway segments which drain less than 3.5 acres of completely paved areas, and have six to eight travelled lanes, the constituent loads in runoff water are sufficiently low so that costly treatment facilities are not needed to meet water quality objectives.

The following recommendations are made:

1 Determination of constituent loads for chemical oxygen demand, filterable residue, total Lead, total

Kjeldahl nitrogen, and total zinc from pavement highway surfaces, using the regression equations shown in the Results section of this report, should be made for proposed highway projects where anticipated traffic volumes are at least 30,000 Average Daily Traffic (ADT) and a nearby sensitive environmental receptor, such as a stream, river or lake, exists.

a) The regression equations developed in this research can be used for calculating constituent loads from the paved travelled way and shoulder area. In order to assess the effects of the constituent load on nearby receiving waters, the load must be routed through the drainage system and ultimately to the receiving water. Along the way, runoff from other sources may be encountered. In order to conduct an environmental assessment, these other sources must be included along with dilution factors for the highway runoff in terms of the receiving water source.

b) This study did not address constituents in road slope (unpaved) runoff. Dustfall from various adjacent land uses and regional pollutant burdens from stationary sources can contribute to the loads via rainfall itself. The technical water quality study for the environmental assessment should include a section discussing this analysis. A qualitative evaluation of the possible environmental effect on the receiving water aquatic ecosystem should be made from this information.

c) The FHWA is concluding several research projects nationwide on the constituents in highway pavement storm runoff and its effects on receiving water quality. No further research by Caltrans should be undertaken pending the outcome of these studies; however, the constituent regression coefficients of the equations should be reevaluated in the future, as alternative fuel sources and transportation designs, modes, and operations change. Besides quantifying constituent loads, a future monitoring study of transportation runoff waters should include monitoring of vegetation and aquatic life so that mitigation measures, which are compatible with transportation facilities, can be designed.

2 Inclusion of mitigation measures in transportation projects to reduce the influence of pollutants from paved highway surfaces should be based on the findings from analyses performed in Recommendation #1.

a) Arbitrary inclusion of mitigation measures on projects should be avoided to reduce unnecessary costs.

b) Where measures are needed, proper designs should be based on loading analyses to provide a cost-effective measure to protect the aquatic receptor.

3. IMPLEMENTATION

Copies of this report will be distributed to FHWA, Caltrans Districts, and appropriate Headquarters Offices for their use. The regression equations reported in the "Results" may be used by the Districts to quantify the constituent loads and flow weighted concentrations found in storm water runoff from the paved travelled lanes and paved shoulders of highways. The Water Quality and Solid Waste Section of TransLab can assist the Districts in applying the equations to address potential environmental impacts.

4. DEVELOPMENT OF REGRESSION EQUATIONS

4.1 Background

The objective of the research was to develop regression equations for estimating concentrations of selected pollutants in storm runoff from paved highway surfaces. Because of the complexity of interactions among pollutants, rainfall, runoff, highway design, operating vehicles, surrounding land use, and maintenance practices, regression analysis by the method of least squares was the technique chosen for building the equations. The main thrust of the regression analysis was to find a suitable independent variable, which could be used to quantify the response variables. The response variables are the selected pollutants which have already been identified in past research by Caltrans and others and can be generally classified as heavy metals, oil and grease, nutrients, and residue (particulate material). The following discussions document our efforts.

4.2 Data Sources

There were three sets of data used for developing the regression equations. The first set of data was collected by Caltrans from 1975 through 1978. The data consist mainly of instantaneous flow observations and water quality measurements of manually obtained samples. These data were screened to select constituents for additional sampling in the current study. The data were also used for preliminary investigations. The runoff sites were at I-405 in Los Angeles, I-680 in Walnut Creek, and U.S. 50 in Placerville. The second set of data was collected by Caltrans specifically for this study at I-405 in Los Angeles, and I-680 in

Walnut Creek during the 1980-81 wet season. The data consist mainly of continuous flow observations and water quality measurements of composited samples of entire storms. These data were used to build the "tentative" regression equations.

The third set of data was collected by Caltrans, but was analyzed and reported by Rexnord in cooperation with FHWA. The runoff site was at U.S. 50 in Sacramento. Data were collected from 1979 through 1981. The data consist mainly of continuous flow observations and water quality measurements of composited samples of entire storms. These data were used to evaluate the tentative regression equations based on Los Angeles and Walnut Creek data.

4.3 Analytical Tools

Scatter plots of raw and transformed data were used extensively to detect relationships between variables. The regression test results included values of the statistical parameters:

F-ratio (F), T-test of regression coefficient (t), and the index of determination (r^2), which were used to evaluate the goodness of fit of the regression equations. In all tests of hypotheses, the 0.05 level of significance was selected.

4.4 Selection of Constituents to Sample: Dependent Variables

The water quality data collected from 1975 through 1978 were stored in the California State Water Resources Control Board's version of STORET, a computerized storage and retrieval system for water quality data. In accordance with the STORET "Quality Assurance of Stored Data" policy, the data were thoroughly checked and edited. A few outliers were found and were excluded from subsequent analyses.

Seven storms were evaluated to determine whether significant concentrations of any of 31 constituents existed before entering receiving waters, where further dilution would reduce concentration levels. The significance criteria were based on the maximum observed concentration which had to be within 50% of critical concentration reported in the U.S. Environmental Protection Agency "Quality Criteria for Water", July 1976 or the California Water Resources Control Board publication "Water Quality Criteria", 1963. Table 1 shows the constituents which were considered for futher study. Table 2 shows those constituents which were not.

Table 1 also shows the constituents selected for 1980-81 sampling program. The selected constituents are the dependent variables. Lead, zinc, cadmium, and oil and grease were chosen to study, because they are vehicle related. Total residue was selected, because it is associated both with vehicles and with local air particulate deposition. Nitrate-nitrogen, ammonia-nitrogen, total Kjeldahl nitrogen, total phosphorus, and ortho-phosphate were studied, because the traveled surfaces and shoulders are surfaces on which these constituents may collect. Boron was studied because of its potential impact on vegetation. Cadmium was selected for the 1980-81 sampling program; however, Cadmium testing at the Walnut Creek site was discontinued after the first major storm in December 10, 1980, because values dropped below detection limits after the intitial runoff. A "first flush" pattern was observed in the 1975 through 1978 data for sulfate, chromium, copper, manganese, and nickel; therefore, these constituents were not sampled in the 1980-81 sampling program.

TABLE 1

CONSTITUENTS CONSIDERED FOR FURTHER STUDY

Constituent	Criterion	Critical Value
*Boron	Crops	750 μg/l
Sulfate	Water supply	250 mg/l
Iron	Water supply	300 μg/l
*Lead	Water supply	50 μg/l
*Zinc	Salmo gairdneri	10 μg/l
*Nitrate Nitrogen	Aquatic growth	300 μg/l
*Total Kjeldahl Nitrogen	Aquatic growth	600 μg/l
*Ammonia	Aquatic life	20 μg/l
*Total Phosphorus	Aquatic growth	10 μg/l
*Dissolved Ortho Phosphate	Aquatic growth	10 μg/l
*Oil & Grease	Water supply	Virtually free from oil and grease
*Total Residue	Water supply	250 mg/l for Cl
*Total Nonfilterable Residue	Water Supply	Variable
*Chemical Oxygen Demand	Treatment Plant Effluent	50 mg/l
*Conductivity	Aquatic Life	1000 μ mhos
*pH	Special Treatment Required	
*Cadmium	Salmonid	0.4 μg/l
Chromium	Water supply	50 μg/l
Copper	Salmo gairdneri	2.0 mg/l
Manganese	Water supply	50 μg/l
Nickel	Water supply	100 μg/l

*Constituent was selected for 1980-81 sampling program, because the observed concentrations were within 50% of the critical value shown.

TABLE 2

CONSTITUENTS OF NO SIGNIFICANT IMPACT POTENTIAL

Bicarbonate ion

Carbonate ion

Calcium

Magnesium

Chloride

Mercury

Molybdenum

Potassium

Silica

Sodium

4.5 Preliminary Studies

Before the 1980-81 data were available, preliminary studies were performed using the 1975 through 1978 data.

From Table 1, six "indicator" constituents, which are either unique or which represent a category, were chosen to guide formulation of equations. These "indicator" constituents were boron, iron, lead, ammonia, total phosphorus, and oil and grease. The selection of independent variables was guided by ongoing and recent research in runoff modeling [Shaheen 3, Agnew, et al, 4, and Sartor and Boyd 5]. It was postulated that pollutants accumulate on paved surfaces during the dry period before storms. Major sources can be from atmospheric fallout and vehicles traveling on the highways. Thus, two of the independent variables were the number of dry days before the storm and the number of vehicles. It was further postulated by TransLab that the maximum rainfall intensity of a storm could remove potential pollutants quickly; thus, the third independent variable, maximum rainfall intensity. Since regulatory agencies specify critical concentrations of potential pollutants, the dependent variable chosen was maximum observed concentration. The regression equation is formulated as follows:

Equation 1

$$OMC = a + b(DD) + c(MRI) + d(V),$$

where OMC is observed maximum concentration,
DD is the number of dry days before the storm,
V is the product of dry days before the storm and average daily traffic (ADT),
MRI is the maximum rainfall intensity,

and a, b, c, and d are the regression coefficients. (Note: The units for the regression coefficients are not presented because this regression equation was rejected. In subsequent presentations of regression equations, the units of the regression equation are presented only if the equation was considered for evaluation.)

Equation 1 was tested using data from only six storms of the 1975-78 data for the six indicator constituents. The data for both dependent and independent variables were extracted from [Howell, 1]. Results of the test are shown in the Appendix, Table I. Regression coefficients for the independent variables, dry days and maximum rainfall intensity were negative, indicating that the observed maximum concentrations decreased as the independent variables increased. A closer examination of the independent variables showed that vehicles and dry days were redundant terms, since vehicles = Average Daily Traffic (ADT) x dry days. Removal of the dry days term and maximum rainfall intensity resulted in regression equation 2.

<u>Equation 2</u>

$$OMC = a + b(V)$$

where OMC is observed maximum concentration,
V is the product of average daily traffic and dry days before the storm,
and a and b are the regression coefficients.

Simple correlations using equation 2 were tried for each site using the six indicator constituents. The numbers of observations at Los Angeles, Walnut Creek, and Placerville were 10, 10, and 9, respectively. Results are shown in the

Appendix, Table II. The only significant correlation was at Los Angeles for ammonia. By eliminating one observation, which had less than one dry day, from the Los Angeles data such that n=9, the results for lead showed marginal improvement, while results of the remaining five constituents did not show much change. At each of the three sites (and with the exception of ammonia at Los Angeles) the r^2 values were less than .52; plots of concentration vs. vehicles confirmed the wide scatter of data. Without attempting to normalize the data, all 28 observations were tested using equation 2. Positive correlations were found for boron, lead, and ammonia; however, the scatter was still very wide as evidenced by the r^2 values. Based on the wide scatter of the data and the fact that the storms were not sampled from start to end of runoff, perhaps missing the actual peak concentrations, it was decided to discontinue trying to forecast maximum concentrations. Equations 1 and 2 were rejected. Instead, it was decided to compute the total load of each constituent and use the load as a dependent variable. However, before computing loads and before combining the 1975 through 1978 data with the 1980-81 data, a comparison was made between the data sources and sampling procedures of the 1975 through 1978 data and the 1980-81 data.

4.6 Comparison of Data Sources and Sampling Procedures

The data sources and sampling procedures of the 1975 through 1978 data were reviewed using the field notebooks, memoranda to files, equipment maintenance records, and personal interviews with sampling personnel. The findings of the review are presented below:

1. Onsite precipitation records generally were not available. Nearby gaging stations (in excess of two miles distant from the sampling locations) were used to fill gaps in precipitation records due to onsite gage malfunction and lost data.

2. The entire storm was sampled in only 5 of 28 storms. Samples for the majority of storms covered only the latter portions of the runoff hydrograph.

3. Continuous flow records were not available (except in one storm at Los Angeles). Because of the lack of continuous flow traces and onsite precipitation data, storm hydrographs could not be simulated. In-line flow measurements were instantaneous and infrequent which compounded the problem of producing a reliable storm hydrograph. It was found that runoff volume estimates two to four times greater than actual rainfall volume were produced in Walnut Creek and Placerville.

4. The pipe flows at Walnut Creek and Placerville were supercritical.

5. The sampling technique was manual.

The knowledge gained from the 1975 through 1978 data collection program prompted changes for collecting data in 1980-81. Rain gage inspections were more frequent than in the past. At Walnut Creek a channel modification was constructed to produce subcritical flows. Bubbler flow meters were installed for recording the entire storm hydrograph. Additionally, the flow meters triggered automatic sequential samplers, which were set to collect runoff samples at short time (15 minutes) or volume (100 cubic feet) intervals.

Comparison of sample concentrations for lead demonstrates the variation between composited automatic samples (W-11-1) and manual samples (W-11-5). Sample (W-11-5) represents a manual sample which was collected in the same manner as during the 1975 through 1978 data collection program, while sample (W-11-1) represents a composited automatic sample, typical of the 1980-81 data. The actual sample volume collected in each case was 2000 ml, however, the time spans over which they were collected were 4-1/2 hours for (W-11-1) and 20 minutes for (W-11-5). Load computations and differences are shown in Table 3.

TABLE 3

COMPARISON OF LEAD CONCENTRATIONS

Sample ID	Pb Conc. Mg/1	Volume of Runoff Which Sample Represents (liters)	Load (grams)	Sampling Technique
W-11-5	.08	28,317	2.27	Manual
W-11-1	.26	28,317	7.36	Automatic Composited

Since (W-11-1) was sampled at equal volume intervals of 100 cubic feet throughout the entire 4-1/2 hour period of run-off for which the concentration is to represent, it is a satisfactory sample. The load computed using (W-11-5) is 69.2% lower than the load computed using (W-11-1).

Because of the uncertainties revealed in the comparison of data sources and sampling procedures in the 1975 through 1978 data, it was decided that combining the observations with the 1980-81 data would be inappropriate, and, therefore, observations of the 1975 through 1978 data would not be used for development of the regression equations.

4.7 Load Computations

The procedure for computing loads using data collected during the 1980-81 season directly paralleled the sample compositing scheme. At Los Angeles, discrete samples were collected automatically at equal time intervals of 15 minutes; at Walnut Creek discrete samples were collected automatically at equal volume intervals of 100 cubic feet. The discrete samples were then sequentially composited to characterize concentrations and loadings for rising segments, relative peaks, and receding segments of the runoff hydrographs. Normally, $\pm$2000 ml of runoff was the composite sample volume needed to test for the 15 constituents singly asterisked in Table 1. One composite typically was composed of four 500 ml discrete samples. For storms which had many discrete samples on either the rising or falling segments of the hydrograph, the samples were split volumetrically to obtain the $\pm$2000 ml composite volume for testing. Samples for oil and grease were taken manually throughout storms, using 1.0 liter glass jars, whenever field personnel were at the runoff sites.

At Los Angeles, runoff volumes were computed from the continuous storm hydrographs for the intervals which corresponded to each composite sample. The circular Bristol bubbler chart traces were replotted on orthogonal grid paper using a resolution of 5 minutes and 0.1 inch. Level was converted to flow rate, Q, using the one-foot cutthroat flume equation:

$$Q = 3.5\ H^{1.56}$$

where H is the water level in feet and
Q is the flow rate in cubic feet per second.

The flow rate was then integrated for the corresponding time interval of the composite sample to arrive at the runoff volumes. At Walnut Creek, the flow recorder (ISCO 1870) produced an event mark for each discrete sample on the hydrograph, so that the number of event marks times 100 cubic feet equaled the runoff volume for the composite sample. Initial and final segments of hydrographs were computed by hand. Oil and grease samples were taken manually.

Tables 4A and 4B chronologically summarize the composite concentrations and corresponding runoff volumes for all constituents except oil and grease for Los Angeles and Walnut Creek, respectively.

Table 4C chronologically summarizes the manually collected sample concentrations of oil and grease and corresponding runoff volumes for Los Angeles and Walnut Creek.

Loads were computed using the equation below, in which "i" represents a composited sample and "n" represents the number of composites.

$$\text{Cumulative Constituent Load} = \sum_{i=1}^{n} \left[\begin{array}{l} \text{constituent} \\ \text{Concentration} \\ \text{of composite} \\ \text{sample} \end{array} \times \begin{array}{l} \text{runoff} \\ \text{volume} \end{array} \right]$$

By reporting all constituent concentrations in milligrams per liter and specifically not reporting heavy metals or boron in micrograms per liter, the possibility of errors of an order of magnitude of 10^3 were avoided. The use of metric units was preferred for runoff, for ease of computing and checking loads.

----- TABLE 4A -----

SUMMARY OF CONCENTRATIONS OF CONSTITUENTS (MILLIGRAMS/LITER). COMPID = COMPOSITE NUMBER. RUNOFF = LITERS. CD = CADMIUM. PB=LEAD. ZN=ZINC. SUSSOL = NONFILTERABLE RESIDUE. DISSOL = FILTERABLE RESIDUE. NO3 = NITRATE NITROGEN. NH4 = AMMONIA NITROGEN. TKN = TOTAL KJELDAHL NITROGEN. PO4 = ORTHOPHOSPHATE. TOTP=TOTAL PHOSPHORUS. B=BORON. DATA ARE FROM LOS ANGELES. L-1-1:810111. L-2-1/L-2-3:810123. L-3-1/L-3-6:810127-28. L-4-1/L-4-5:810208. L-5-1/L-5-6:810225. L-6-1/L-6-6:810304-05. L-8-1/L-8-5:810319.

COMPID	RUNOFF	CD	PB	ZN	SUSSOL	DISSOL	COD	NO3	NH4	TKN	PO4	TOTP	B
L-1-1	6440	0.02	0.71	2.20	166	417	478	1.30	4.60	1.7	0.00	0.73	0.9
.	.	.	.	.	.	.	.	.	.	.	.	.	.
L-2-1	15240	0.01	0.96	1.60	398	373	.	.	.	.	.	.	.
L-2-2	10160	0.00	0.36	0.74	176	164	.	.	.	.	.	.	.
L-2-3	24300	0.00	0.29	0.62	86	150	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
L-3-1	58698	0.01	2.80	1.60	2660	92	724	1.70	1.20	14.0	0.02	1.20	0.2
L-3-2	91645	0.01	1.70	0.77	13600	45	217	0.44	0.38	8.4	0.04	1.50	0.2
L-3-3	10258	0.01	1.80	0.84	15800	83	144	0.77	0.43	6.0	0.04	1.70	0.2
L-3-4	14098	0.00	0.48	0.35	4820	71	112	0.87	0.48	1.5	0.03	0.17	0.2
L-3-5	6316	0.00	0.20	0.26	18	71	45	0.89	0.49	1.2	0.03	0.11	0.2
L-3-6	3262	0.00	0.28	0.38	275	.	55	1.10	0.54	1.4	0.05	0.13	0.3
.	.	.	.	.	.	.	.	.	.	.	.	.	.
L-4-1	2801	0.01	0.42	1.20	92	320	270	5.90	2.50	6.0	0.07	0.44	0.7
L-4-2	6522	0.01	0.25	0.62	63	143	173	2.20	1.50	3.0	0.06	0.28	0.3
L-4-3	10322	0.01	0.17	0.36	38	84	90	1.20	0.91	1.7	0.05	0.19	0.2
L-4-4	22654	.	0.48	0.24	328	16	111	0.09	0.06	2.4	0.04	0.47	0.1
L-4-5	58698	0.01	2.80	1.60	2660	92	724	1.70	1.20	14.0	0.02	1.20	0.2
.	.	.	.	.	.	.	.	.	.	.	.	.	.
L-5-1	21100	0.01	4.10	0.86	208	165	281	2.70	1.40	10.0	0.05	1.30	0.6
L-5-2	28000	0.01	1.00	0.34	102	78	111	1.00	0.80	2.4	0.06	0.30	0.3
L-5-3	80770	0.00	2.20	0.19	35	63	50	0.69	0.52	1.5	0.05	0.15	0.2
L-5-4	4651	0.00	0.54	0.22	29	98	67	1.10	0.60	1.8	0.05	0.16	0.2
L-5-5	17550	0.00	0.19	0.82	27	64	62	0.82	0.50	1.4	0.05	0.13	0.2
L-5-6	3105	0.00	0.64	0.30	37	87	74	1.10	0.63	1.9	0.05	0.15	0.3
.	.	.	.	.	.	.	.	.	.	.	.	.	.
L-6-1	1300	0.01	1.70	0.75	142	240	337	3.10	0.71	5.1	0.04	0.25	0.4
L-6-2	3920	0.01	0.98	0.50	67	182	162	1.70	0.92	2.5	0.04	0.17	0.2
L-6-3	45710	0.01	3.40	0.55	238	92	146	0.90	0.50	2.9	0.04	0.43	0.1
L-6-4	70270	0.00	0.48	0.16	44	39	53	0.26	0.25	0.9	0.03	0.11	0.0
L-6-5	81230	0.00	0.52	0.13	51	44	38	0.17	0.18	2.3	0.02	0.12	0.0
L-6-6	35940	0.00	0.18	0.10	22	26	23	0.17	0.18	0.6	0.02	0.06	0.0
.	.	.	.	.	.	.	.	.	.	.	.	.	.
L-8-1	4511	0.01	0.82	1.80	146	461	550	8.40	2.10	11.0	0.00	0.54	4.3
L-8-2	32608	0.00	0.76	0.55	124	112	220	1.40	0.66	4.8	0.00	0.43	0.6
L-8-3	89619	0.00	0.40	0.30	114	46	132	0.39	0.31	1.8	0.01	0.21	0.3
L-8-4	103722	0.00	0.23	0.18	48	35	44	0.25	0.24	0.9	0.01	0.11	0.2
L-8-5	4825	0.00	0.21	0.25	28	63	61	0.49	0.34	1.3	0.01	0.12	0.3
MIN	1300	0.00	0.17	0.10	18	16	23	0.09	0.06	0.6	0.00	0.06	0.0
MAX	103722	0.02	4.10	1.80	15800	461	724	5.90	4.60	14.0	0.07	1.70	4.3

L-3 series excluded from analyses.

----- TABLE 4B -----

SUMMARY OF CONCENTRATIONS OF CONSTITUENTS (MILLIGRAMS/LITER). COMPID = COMPOSITE NUMBER. RUNOFF = LITERS. CD = CADMIUM. PB=LEAD. ZN=ZINC. SUSSOL = NONFILTERABLE RESIDUE. DISSOL = FILTERABLE RESIDUE. NO3 = NITRATE NITROGEN. NH4 = AMMONIA NITROGEN. TKN = TOTAL KJELDAHL NITROGEN. PO4 = ORTHOPHOSPHATE. TOTP=TOTAL PHOSPHORUS. B=BORON. DATA ARE FROM WALNUT CREEK. W-1-1/W-9-1:801203-4. W-2-1/W-2-2:810122. W-3-1/W-3-7:810126-28. W-5-1:810224. W-6-1:810224. W-7-1:810226. W-8-1:810304. W-11-1/W-11-5:810315. W-12-1:810318. W-13-1/W-13-2:810325.

COMPID	RUNOFF	CD	PB	ZN	SUSSOL	DISSOL	COD	NO3	NH4	TKN	PO4	TOTP	B
W-1-1	18250	0.01	0.42	0.33	182	186	229	1.20	1.40	6.3	1.10	1.80	0.1
W-1-2	38810	0.00	0.37	0.21	160	108	133	0.67	0.62	2.0	0.25	0.51	0.1
W-1-3	21370	0.00	1.60	0.43	436	156	272	1.10	0.57	4.0	0.15	0.78	0.1
W-1-4	36700	0.00	1.30	0.39	402	68	184	0.50	0.40	1.8	0.11	0.56	0.0
W-1-5	24300	0.00	0.70	0.25	196	60	128	0.51	0.40	1.3	0.09	0.37	0.0
W-1-6	26750	0.00	0.85	0.34	248	62	183	0.61	0.30	1.5	0.07	0.44	0.0
W-1-7	1,3200	0.00	0.43	0.22	130	64	97	0.57	0.35	1.2	0.07	0.31	0.0
W-1-8	17000	0.00	0.55	0.23	194	108	153	0.75	0.28	1.8	0.08	0.41	0.0
W-1-9	23700	0.00	0.22	0.10	75	62	73	0.38	0.23	0.9	0.09	0.23	0.0
W-2-1	30300	.	0.72	0.42	430	91	166	0.49	0.08	2.1	0.01	0.44	0.2
W-2-2	26335	.	0.63	0.34	317	77	158	0.51	0.11	1.9	0.01	0.39	0.1
W-3-1	65130	.	0.33	0.15	139	30	70	0.18	0.08	0.7	0.03	0.20	0.1
W-3-2	22654	.	0.48	0.24	328	16	111	0.09	0.06	2.4	0.04	0.47	0.1
W-3-3	31149	.	0.30	0.08	77	20	22	0.14	0.09	0.1	0.04	0.09	0.1
W-3-4	39644	.	0.51	0.25	423	35	76	0.22	0.09	3.5	0.02	0.44	0.1
EST	56634	.	0.40	0.20	338	35	85	0.18	0.07	2.8	0.02	0.35	0.1
W-3-5	35397	.	1.10	0.48	526	43	140	0.23	0.11	1.7	0.04	0.49	0.1
W-3-6	42476	.	0.70	0.29	280	53	108	0.21	0.10	1.1	0.04	0.26	0.1
W-3-7	35963	.	0.45	0.23	1110	38	68	0.09	0.08	1.2	0.07	0.61	0.1
W-5-1	14159	.	1.80	0.46	93	197	27	1.00	0.92	4.9	0.18	0.78	0.3
W-6-1	5664	.	3.30	0.67	.	.	.	.	.	.	.	.	.
W-7-1	17557	.	2.20	0.52	587	106	282	.	.	.	.	.	.
W-8-1	16141	.	1.60	0.41	112	95	215	0.46	0.36	2.1	0.06	0.48	0.2
W-11-1	28317	.	0.26	0.18	142	76	141	0.55	0.39	1.6	0.08	0.29	0.3
W-11-2	28317	.	0.32	0.18	161	47	106	0.28	0.26	1.2	0.05	0.22	0.0
W-11-3	28317	.	0.24	0.18	129	39	85	0.33	0.24	1.0	0.04	0.19	0.0
W-11-4	31715	.	0.21	0.14	111	36	92	0.31	0.24	0.8	0.04	0.16	0.0
W-11-5	28317	.	0.08	0.13	66	74	113	0.60	0.43	1.3	0.10	0.20	0.1
W-12-1	30299	.	0.78	0.36	262	86	169	0.42	0.29	1.8	0.03	0.38	0.3
W-13-1	78155	.	0.32	0.21	154	.	115	0.52	0.25	1.7	0.05	0.29	.
W-13-2	78155	.	0.43	0.25	188	.	116	0.13	0.14	1.4	0.03	0.31	.
MIN	5664	0.00	0.08	0.10	66	16	27	0.09	0.07	0.1	0.01	0.09	0.0
MAX	78155	0.01	3.30	0.67	1100	197	282	1.20	1.40	6.3	1.10	1.81	0.3

----- TABLE 4C -----
SUMMARY OF OIL AND GREASE SAMPLES.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.
SAMPID = SAMPLE IDENTIFICATION.
DATE = YEAR MONTH DAY.
RUNOFF = LITERS.
CONC = CONCENTRATION IN MILLIGRAMS PER LITER.

SITE	SAMPID	DATE	RUNOFF	CONC
LA	Z	810127	6533	9
LA	Y	810127	3038	5
.	.	.	.	.
.	.	.	.	.
LA	AA	810208	297	32
LA	AB	810208	302	29
LA	AC	810208	629	24
LA	AD	810208	1212	31
LA	AE	810208	4098	26
LA	AF	810208	7878	19
LA	AG	810208	11698	4
LA	AH	810208	25737	8
.	.	.	.	.
LA	CA	810225	2583	12
LA	CB	810225	8253	8
LA	CC	810225	7476	8
LA	CD	810225	5433	7
LA	CE	810225	30935	13
LA	CF	810225	56253	4
LA	CG	810225	4965	3
LA	CH	810225	16926	5
LA	CI	810225	2145	5
.	.	.	.	.
LA	FA	810304	1767	4
LA	FB	810304	1461	8
LA	FC	810304	1614	9
.	.	.	.	.
LA	LA	810319	467	6
LA	LB	810319	2190	4
LA	LC	810319	1415	6
LA	LD	810319	5857	8
LA	LE	810319	9004	8
LA	LF	810319	52898	8
LA	LG	810319	79061	11

SITE	SAMPID	DATE	RUNOFF	CONC
WK	B	801203	1420	77
WK	C	801203	4500	31
WK	D	801203	2740	20
WK	E	801203	680	17
WK	F	801203	12040	4
WK	G	801203	49990	10
WK	H	801203	10970	6
.	.	.	.	.
WK	A	810122	13310	18
WK	B	810122	5664	17
WK	C	810122	5664	19
WK	D	810122	8495	6
WK	E	810122	2832	7
WK	F	810122	20672	14
.	.	.	.	.
WK	P	810126	16707	20
WK	Q	810126	1416	31
WK	R	810126	1699	26
.	.	.	.	.
WK	S	810127	5663	36
WK	T	810127	2832	16
WK	U	810127	2832	14
WK	V	810127	4248	14
WK	W	810127	22370	10
WK	X	810127	8778	9
.	.	.	.	.
WK	EA	810304	57	9
WK	EB	810304	1926	15
WK	EC	810304	5097	12
WK	ED	810304	2832	14
WK	EE	810304	2832	6
WK	EF	810304	1982	4
.	.	.	.	.
WK	HA	810315	7079	3
WK	HB	810315	2265	7
WK	HD	810315	3398	6
WK	HF	810315	5663	7
WK	HH	810315	9911	4
WK	HI	810315	8495	4
WK	HJ	810315	8495	11
WK	HK	810315	11327	4
WK	HL	810315	8495	5
WK	HM	810315	14159	7
WK	HN	810315	15008	7
WK	HO	810315	23220	5

4.8 'Vehicles Before the Storm' as an Independent Variable

Hypothesis testing of regression equations using vehicles before the storm as an independent variable and constituent load as a dependent variable showed no statistical significance. The results of sweeping/flushing studies performed at the U.S. 50 site in Sacramento by Rexnord show that the active freeway lanes do not retain significant amounts of constituents. Furthermore, Rexnord's dustfall transect study in Sacramento demonstrates that particulates are blown off the traveled lanes to the shoulders and beyond. Evidently, during the antecedent dry period, the freeways are continuously swept by the traffic-generated turbulence; thus it was not surprising that correlating loads using traffic before the storm (ADT x dry days) showed no statistical significance.

4.9 'Vehicles During the Storm' as an Independent Variable

Because the study of "Lead Emissions and Washoff", in the Appendix, showed that a significant fraction of lead emitted from vehicles during the storm correlated well with lead in runoff, further studies using vehicles during storm as the independent variable were made using equation 3. Vehicles were counted on an hourly basis to match, as closely as possible, the times from start to end of runoff. Vehicle counts were obtained from the Traffic Operations Branches from the respective Districts in which the sampling was performed.

Equation 3

$$CL = a + b(VDS)$$

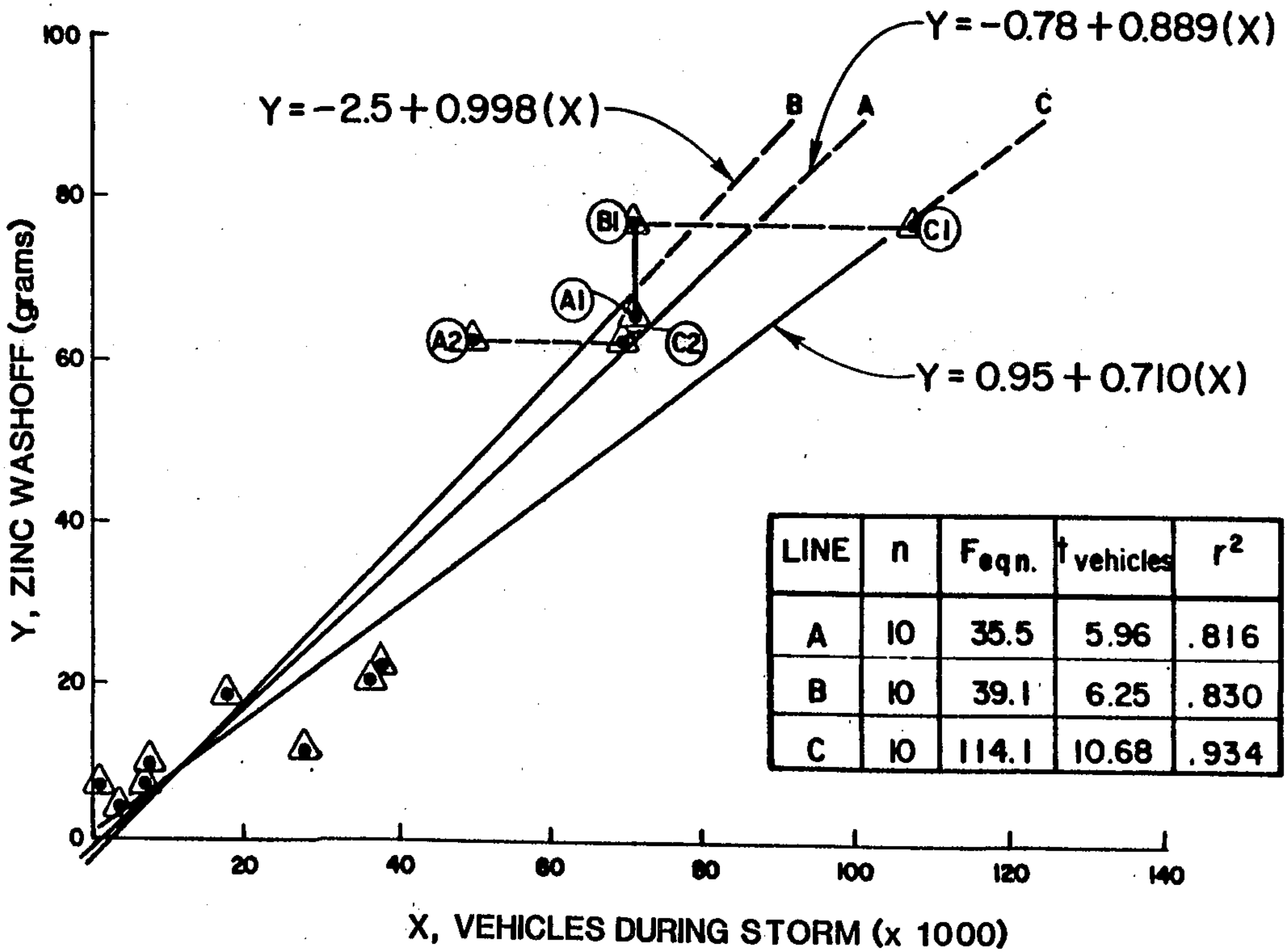
where CL is the cumulative constituent load,
VDS is the number of vehicles during the storm,
and "a" and "b" are regression coefficients, in which "a" represents the gutter load in grams and "b" represents a constituent washoff rate coefficient per vehicle in grams per vehicle.

Equation 3 was executed using the Los Angeles site data. Table XI-A in the Appendix shows the statistical results when the "outlier" storm of January 27-28, 1981 was included. None of the constituent equations showed statistical significance and none of the coefficients, b, were significant. After removing the outlier observation, the data were refitted to equation 3. Table XI-B in the Appendix indicates some improvement in the scatter of data; only boron and chemical oxygen demand produced statistically significant linear fits of equation 3. Since n = 6 or less, no conclusions could be made.

Next, the Walnut Creek data were tested using equation 3. The positive results shown in Appendix Table XI-C could have been due partially to summing the three periods of flow for the two large storms of December 3-4, 1980 and January 26-28, 1981. The magnitudes of the two large storms are such that a regression line is drawn between the eight smaller storms clustered near the origin (<25 grams) and the two larger storms (>60 grams); i.e., a "dogbone" regression line. See section 4.9.1 for further explanation.

4.9.1 Long Duration Storms with Intermittent Dry Periods

Preliminary sensitivity scenarios were done to test the effects of summing or not summing traffic during intermittent dry periods of long duration storms. Figure 2 shows three lines labeled A, B, and C. Line A represents the initial regression equation which is "fixed" by data points A1 and A2. Points A1 and A2 were "storms" which both had three distinct periods of runoff separated by two distinct periods of no runoff; whereas the remaining eight data points had only one distinct period of runoff. Line B was generated by modifying point A1 to B1, in which $\pm$11 grams of zinc washoff were estimated for 2000 cubic feet of runoff which was not sampled because the automatic sampler completed its cycle. The statistics did not change very much. However, by modifying point B1 to C1, and A2 to C2, in which traffic was counted for the two intermittent periods of no runoff, the linear fit "improved" as evidenced by the statistics. Table XI-D and XI-E in the Appendix show the statistical results for Total Kjeldahl Nitrogen which also showed improvement, while dissolved orthophosphate did not. The significance of these scenarios is that by summing events closely spaced in time, the line is given "direction", rather than having a cluster of data points near the origin for constituents which are vehicle related. Deciding which events should be summed or not summed appeared to be very subjective, and ultimately, the regression equations were developed by considering each period of runoff as a separate event (data point).



LINE	n	$F_{eqn.}$	$t_{vehicles}$	r^2
A	10	35.5	5.96	.816
B	10	39.1	6.25	.830
C	10	114.1	10.68	.934

SENSITIVITY SCENARIOS OF ZINC WASHOFF AND VEHICLES DURING STORM

Figure 2

4.10 Combining Data from Sites by Normalizing Loads

When data are fit using regression techniques, they must be of the same kind. To standardize or normalize the data from Los Angeles, Walnut Creek, and Sacramento, the physical characteristics of area (A), lane-miles (LM) and gutter-miles (GM), in Table 5 were applied to the constituent loadings. Initial studies in which data were not normalized presumed that the runoff sites are identical. Table XI-F in the Appendix shows the statistical results of fitting oil and grease loads to equation 3 without normalizing data for Los Angeles and Walnut Creek. On an individual site basis, Los Angeles showed a linear fit, while Walnut Creek did not. Combining the 11 observations, from both sites without normalizing the loads also produced a linear fit. The results for both Los Angeles and Walnut Creek using only nine observations produced a linear fit, after omitting two observations of small magnitude.

Since the number of observations was small, Sacramento data were introduced in various combinations with Walnut Creek and Los Angeles to test the effect of normalizing the loads. Tables XI-G, XI-H, and XI-I in the Appendix display the statistical results of fitting oil and grease loads to equations 4, 5, and 6.

Equation 4

$$\frac{CL}{A} = a + b(VDS),$$

Equation 5

$$\frac{CL}{LM} = a + b(VDS),$$

TABLE 5

PHYSICAL CHARACTERISTICS FOR INTERSITE COMPARISONS

	LOS ANGELES	WALNUT CREEK	SACRAMENTO
AREA (Acres)	3.2	2.1	2.0
LANE-MILES	1.4	1.0	1.1
GUTTER-MILES	0.70	0.56	0.27

Equation 6

$$\frac{CL}{GM} = a + b(VDS)$$

where CL is the cumulative constituent load,
VDS is number of vehicles during the storm,
a and b are the regression coefficients,
and the normalizing factors are A (acres), LM (lane-miles), and GM (gutter-miles).

In equations 4, 5, and 6, the "a" regression coefficient represents the dry load in grams per normalizing factor. The coefficient "b" represents a washoff rate of constituent; the units for "b" are grams per vehicle during storm per normalizing factor. This "hybrid" unit (mixed metric/English) was chosen because load computations are facilitated when runoff is expressed in liters.

Equation 4 produced results of no statistical significance, because oil and grease is not uniformly distributed over the drainage area. Equation 5 produced linear fits of statistical significance and so did equation 6; however, whether or not results were significant depended on the site combinations. Los Angeles and Walnut Creek showed good results using equation 6, while equation 5 produced positive results when the three sites were combined.

Three more equations were formulated to test normalizing the oil and grease loads per gutter-mile. Equation 7 yielded satisfactory results since loads are computed by using runoff volumes. Table XII in the Appendix shows the results for Los Angeles and Walnut Creek.

Equation 7

$$\frac{OG}{GM} = a + b(R)$$

where OG is the oil and grease load,
R is the cumulative runoff volume,
a and b are the regression coefficients,
and G is gutter-miles, the normalizing factor.

Equations 8 and 9 did not produce significant results. Tabulations are in Appendix Tables XIII-A and XIII-B.

Equation 8

$$\frac{OG}{GM} = a + b(R) + c(VDS)$$

Equation 9

$$\frac{OG}{GM} = a + b(RxVDS) + c(VDS)$$

where OG is the oil and grease load,
R is the runoff volume,
VDS is vehicles during the storm,
a,b, and c are the regression coefficients,
and GM is gutter-miles, the normalizing factor.

No further equations were formulated to test normalizing oil and grease or other constituent loads. Although the Sacramento data did not fit equation 6 well when loads were normalized on a per gutter-mile basis, it was felt that equation 6 should be evaluated. As with the other vehicle related constituents, oil and grease did not display an exponential washoff pattern. Vehicles during the storm contributed constituent loadings as long as the pavement was wet and producing runoff, which was conveyed to the gutters.

Since the "nutrient" constituents (NO_3-N, NH_4-N, TKN, PO_4, P total) are not necessarily 100% vehicle related, a comparison between loads per acre and loads per gutter-mile was made. Tables XIV and XV in the Appendix display the results of fitting data to equations 4 and 6, respectively. The scatter of data "improved" by using equation 6 as compared to equation 4 for NH_4, TKN, PO_4, and P total. However, PO_4 and P total did not produce linear fits in either equations 4 or 6. NO_3-N per acre produced a slightly tighter fit ($r^2 = 0.67$) than NO_3-N per gutter-mile ($r^2 = 0.41$).

4.11 Correlations With Residue

At this point, six more equations were formulated to study the interrelationships of each constituent load to non-filterable, filterable, and total residue loads on a per acre and per gutter-mile basis. The equations are:

Equation 10A

$$\frac{CL}{A} = a + b\left(\frac{NR}{A}\right),$$

Equation 10B

$$\frac{CL}{GM} = a + b\left(\frac{NR}{GM}\right),$$

Equation 11A

$$\frac{CL}{A} = a + b\left(\frac{FR}{A}\right),$$

Equation 11B

$$\frac{CL}{GM} = a + b\left(\frac{FR}{GM}\right),$$

Equation 12A

$$\frac{CL}{A} = a + b\left(\frac{TR}{A}\right),$$

Equation 12B

$$\frac{CL}{GM} = a + b\left(\frac{TR}{GM}\right),$$

where NR is nonfilterable residue,
FR is filterable residue,
TR is total residue,
a and b are the regression coefficients,
and the normalizing factors are A (acres) and GM (gutter-miles).

Tables XVI through XXI in the Appendix show the statistical results for the above equations. The data were from the Walnut Creek and Los Angeles sites; not all constituents were fitted to lines in all cases. Further discussion of these results is withheld because of the way in which a "data point" was treated. At Walnut Creek there were two "storms" with three periods of runoff and two intermittent periods of no runoff of short duration (4 hours or less). Instead of treating the data as six "data points", the loads and vehicle counts were summed to give only two data points. As described in Section 4.9.1, summing loads (and counting vehicles) when there are short durations of no runoff is subjective. To remain objective in subsequent studies, one data point corresponds (uniquely) to each period of runoff and is called a "singular event".

Table XXII in the Appendix gives the statistical results of fitting data using the "singular event" definition to equation 6. Only the Los Angeles and Walnut Creek constituent loads were used to develop the linear regression equations. The constituents which did not produce a linear equation were nonfilterable residue, total residue, orthophosphate, and total phosphorus.

By using the "singular event" definition, data from Los Angeles and Walnut Creek were fitted to equations 10B, 11B, and 12B. The statistical results are in Appendix Tables XXIII through XXV. It was envisioned that the interrelationships could be used by Districts in the following manner. When a project requires that "nonpoint source pollution" via runoff be addressed, the relatively inexpensive tests of total, nonfilterable, and filterable residue could be performed and estimates of the other constituents could be made. Subsequent evaluation studies led to the formulation of Equations 13 and 14 in which no transformations were applied to the data and in which the "singular event" definition was used.

Equation 13

$$CL = a + b(TR),$$

Equation 14

$$DOL = a + b(FR),$$

where CL is cumulative constituent load,
TR is total residue,
DOL is dissolved orthophosphate load,
FR is filterable residue,

and a and b are regression coefficients, where "a" represents an initial load in grams, and "b" is the fraction of constituent washed off the highway during a storm.

Equation 13 produced linear fits for zinc, nonfilterable residue, chemical oxygen demand, and Total Kjeldahl Nitrogen. Equation 14 did not produce a linear fit. Equations 13 and 14 are discussed in greater detail under section 6.3, Evaluation of Equations 3, 13, and 14 Using Loads With No Transformations.

Table 6 shows each equation number, and the dependent and independent variables, for ease of cross referencing to the tables of statistical results in the Appendix.

TABLE 6

Equation Variables

Equation Number	Dependent Variable	Independent Variable(s)
1	observed maximum concentration	dry days maximum rainfall intensity (ADT x dry days)
2	observed maximum concentration	(ADT x dry days)
3	constituent load	vehicles during storm
4	(constituent load/acre)	vehicles during storm
5	(constituent load/lane-mile)	vehicles during storm
6	(constituent load/gutter-mile)	vehicles during storm
7	(oil and grease/gutter-mile)	runoff
8	(oil and grease/gutter-mile)	runoff vehicles during storm
9	(oil and grease/gutter-mile)	(runoff x vehicles during storm) vehicles during storm
10A	(constituent load/acre)	(nonfilterable residue/acre)
10B	(constituent load/gutter-mile)	(nonfilterable residue/gutter-mile)
11A	(constituent load/acre)	(filterable residue/acre)
11B	(constituent load/gutter-mile)	(filterable residue/gutter-mile)
12A	(constituent load/acre)	(total residue/acre)
12B	(constituent load/gutter-mile)	(total residue/gutter-mile)
*13	constituent load	total residue
14	dissolved orthophosphate load	filterable residue

*except dissolved orthophosphate

5. RESULTS

Linear regression equations were tested and were evaluated by using vehicles during the storm as an independent variable to quantify the loads of the following constituents: lead, zinc, filterable residue, chemical oxygen demand, and Total Kjeldahl Nitrogen. Equation 3 is the general form of the line:

Equation 3

$$CL = a + b(VDS)$$

where CL is the cumulative constituent load,
VDS is the number of vehicles during the storm,
and a and b are the regression coefficients.

In addition, linear regression models were tested and were evaluated by using total residue as an independent variable to quantify the loads of the following constituents: zinc, nonfilterable residue, and chemical oxygen demand. Equation 13 is the general form of the line:

Equation 13

$$CL = a + b(TR)$$

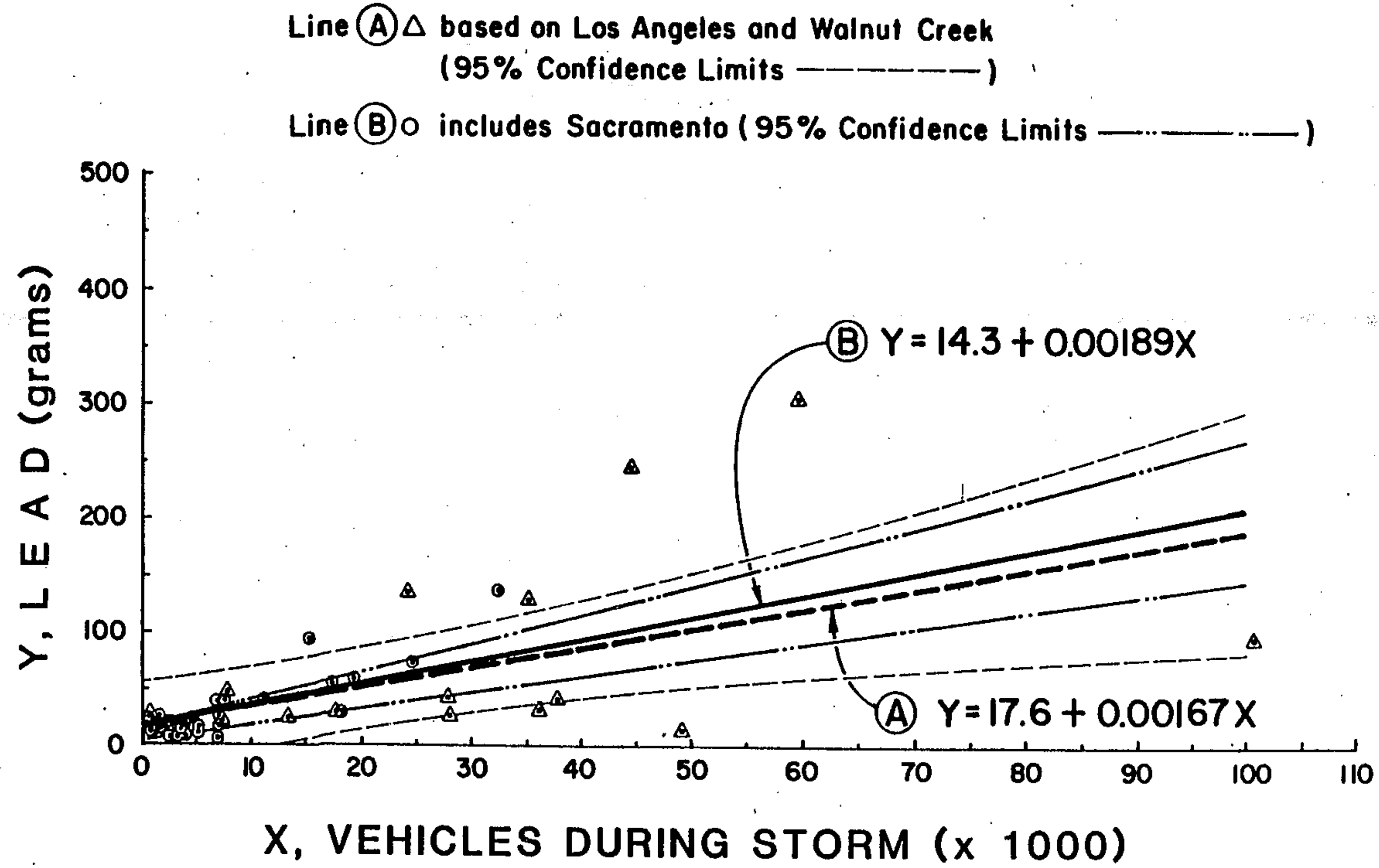
where CL is the cumulative constituent load,
TR is total residue,
and a and b are the regression coefficients.

The equations for each constituent are shown in Figures 3 through 10. Each figure shows a plot of the "tentative" equation (Line A), which was based on observations from

Los Angeles and Walnut Creek in addition to the "pooled" equation (Line B) which included observations from Sacramento. The 95% confidence limits are plotted for each line. The equations are statistical representations which were based on "continuous" observations for each storm event of constituents found in runoff from urban highways in California.

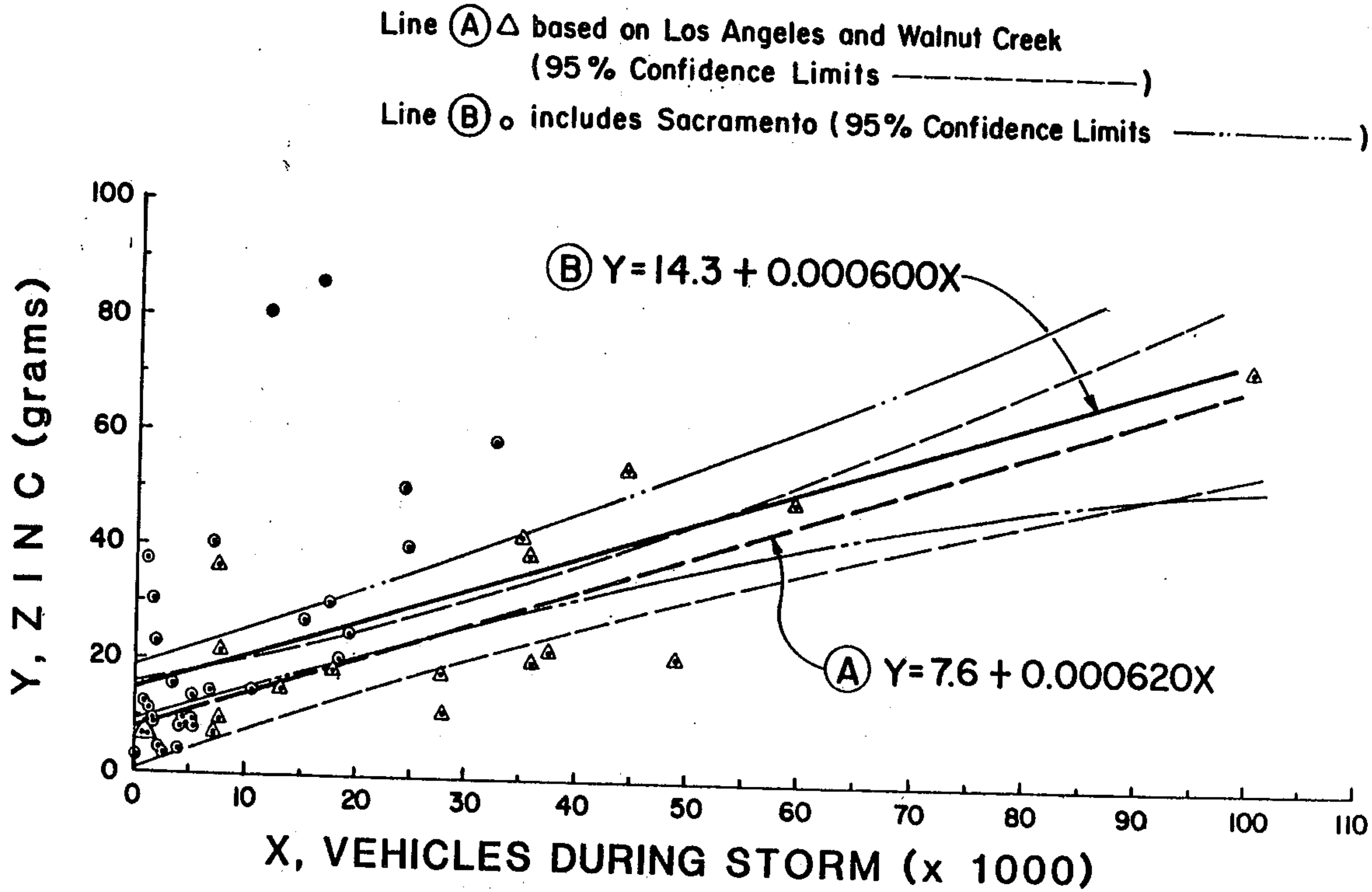
The equations may be applied for 100% paved highways which have the general site characteristics similar to the sites from which the observations were obtained. Figure 11 shows a simplified plan view of each of the completely paved test sites. Longitudinal slopes were generally less than 2%, such that the times of travel of runoff originating at the farthest point on the drainage catchment to the sampling location were less than 30 minutes. See section 7, "Explanation and Procedures for Using the Regression Equations".

The constituents for which no linear relationship was found by using Equation 3 are boron, cadmium, nitrate nitrogen, ammonia nitrogen, total phosphorus, dissolved orthophosphate, nonfilterable residue, total residue and oil and grease. In addition, no correlations were found by using Equation 13 for the following constituents: boron, cadmium, lead, nitrate nitrogen, Total Kjeldahl Nitrogen, ammonia nitrogen, total phosphorus, dissolved orthophosphate, filterable residue, and oil and grease.



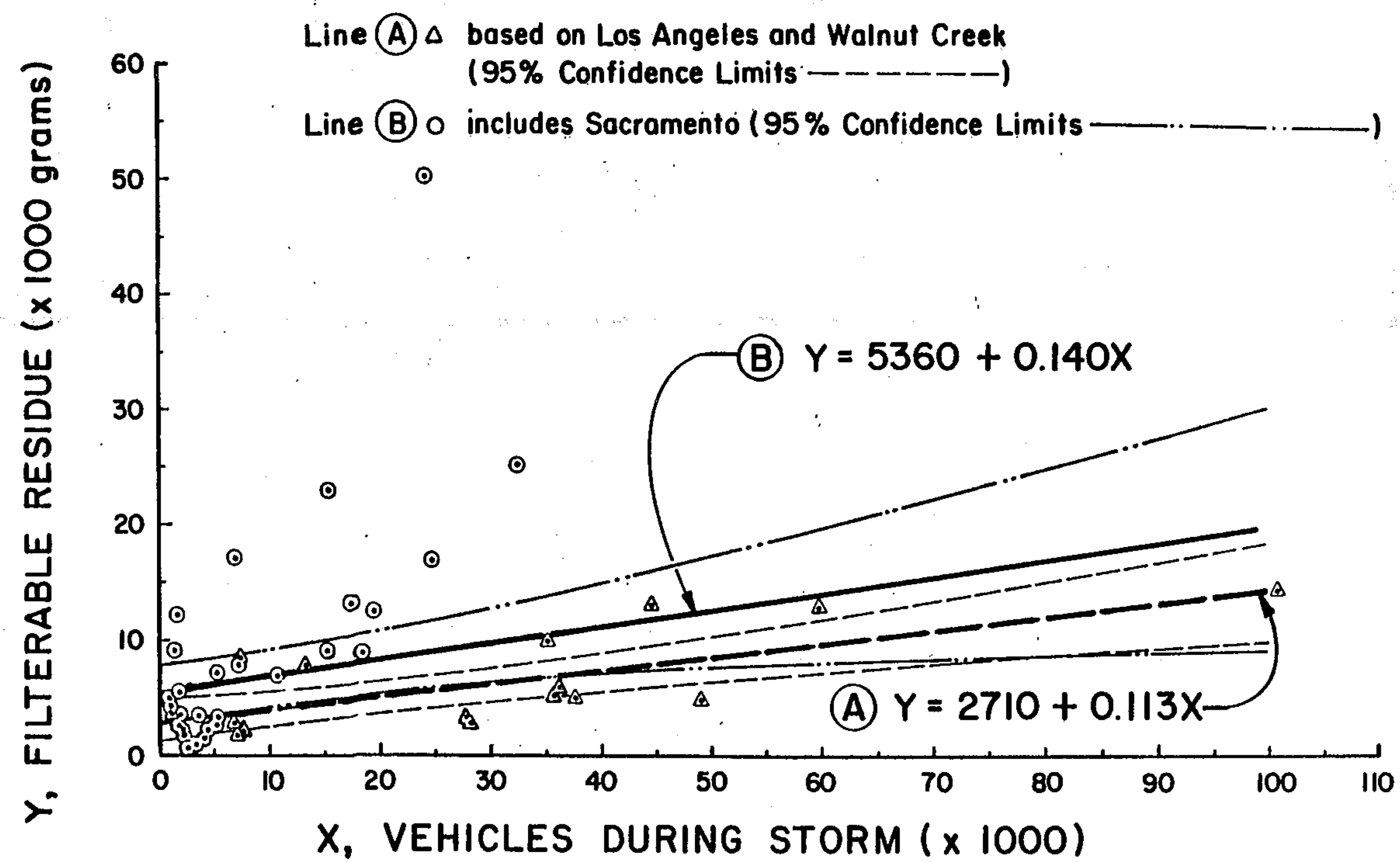
LEAD vs VEHICLES DURING STORM

Figure 3



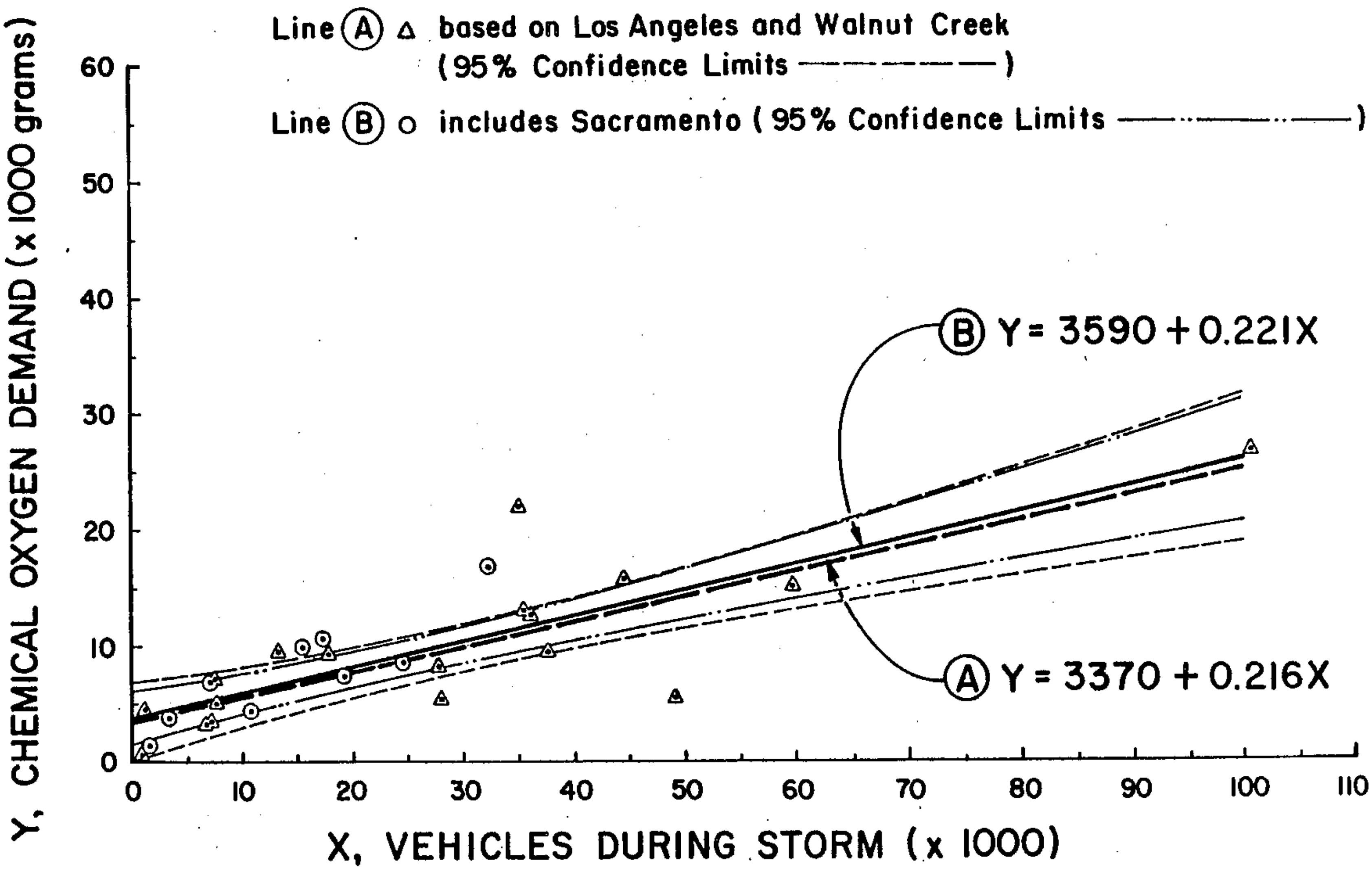
ZINC vs VEHICLES DURING STORM

Figure 4



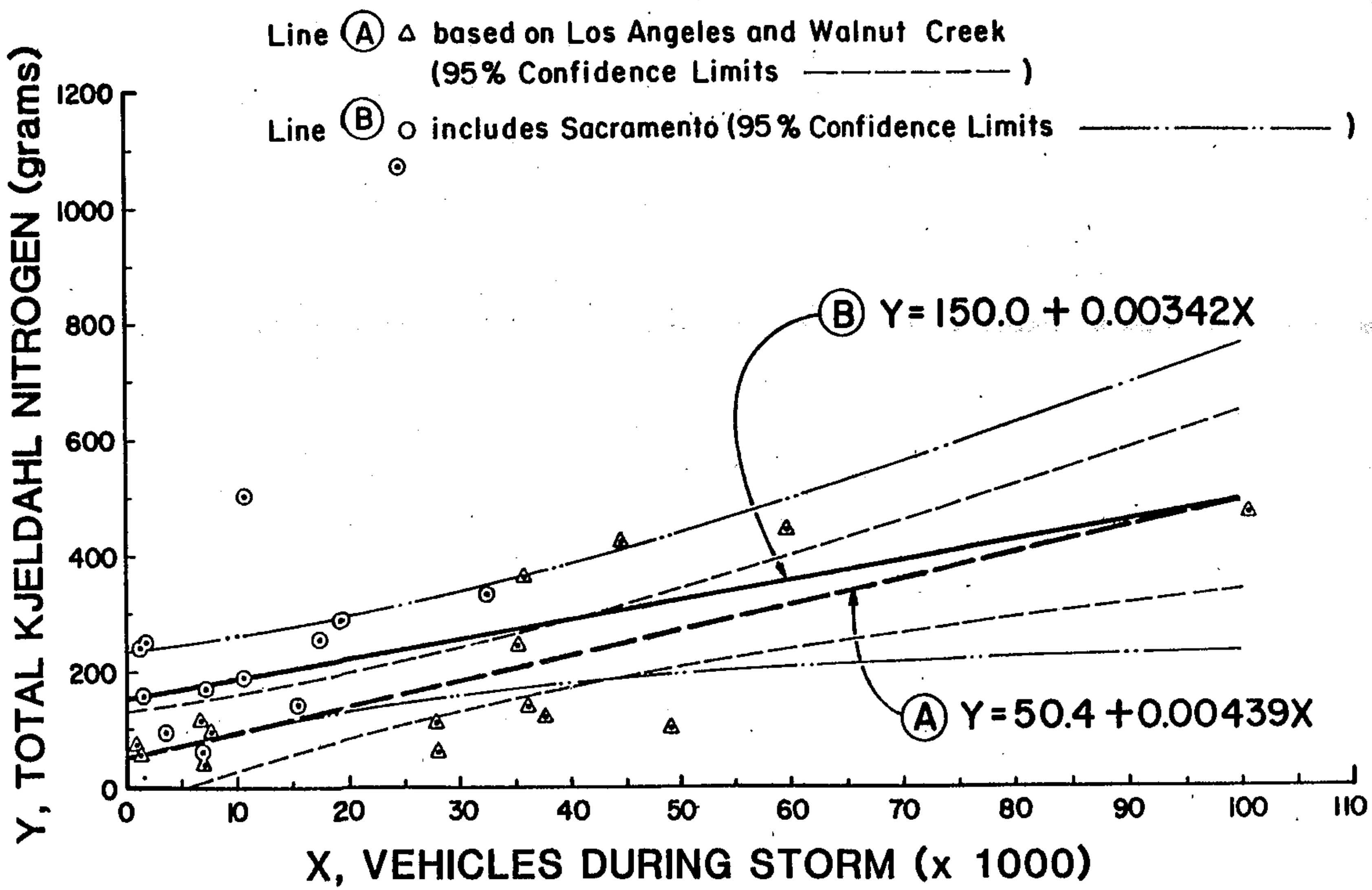
FILTERABLE RESIDUE vs VEHICLES DURING STORM

Figure 5



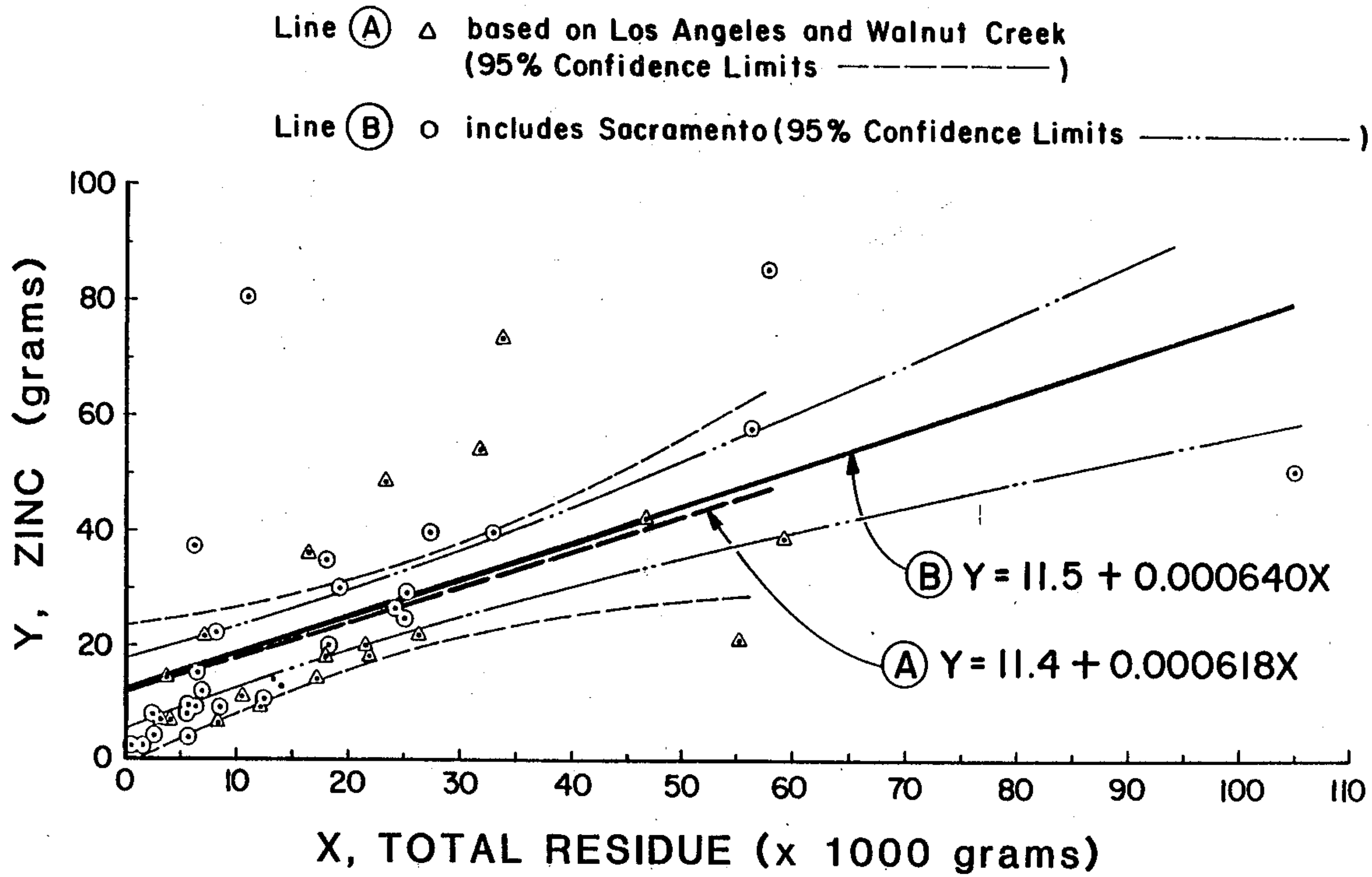
CHEMICAL OXYGEN DEMAND vs VEHICLES DURING STORM

Figure 6



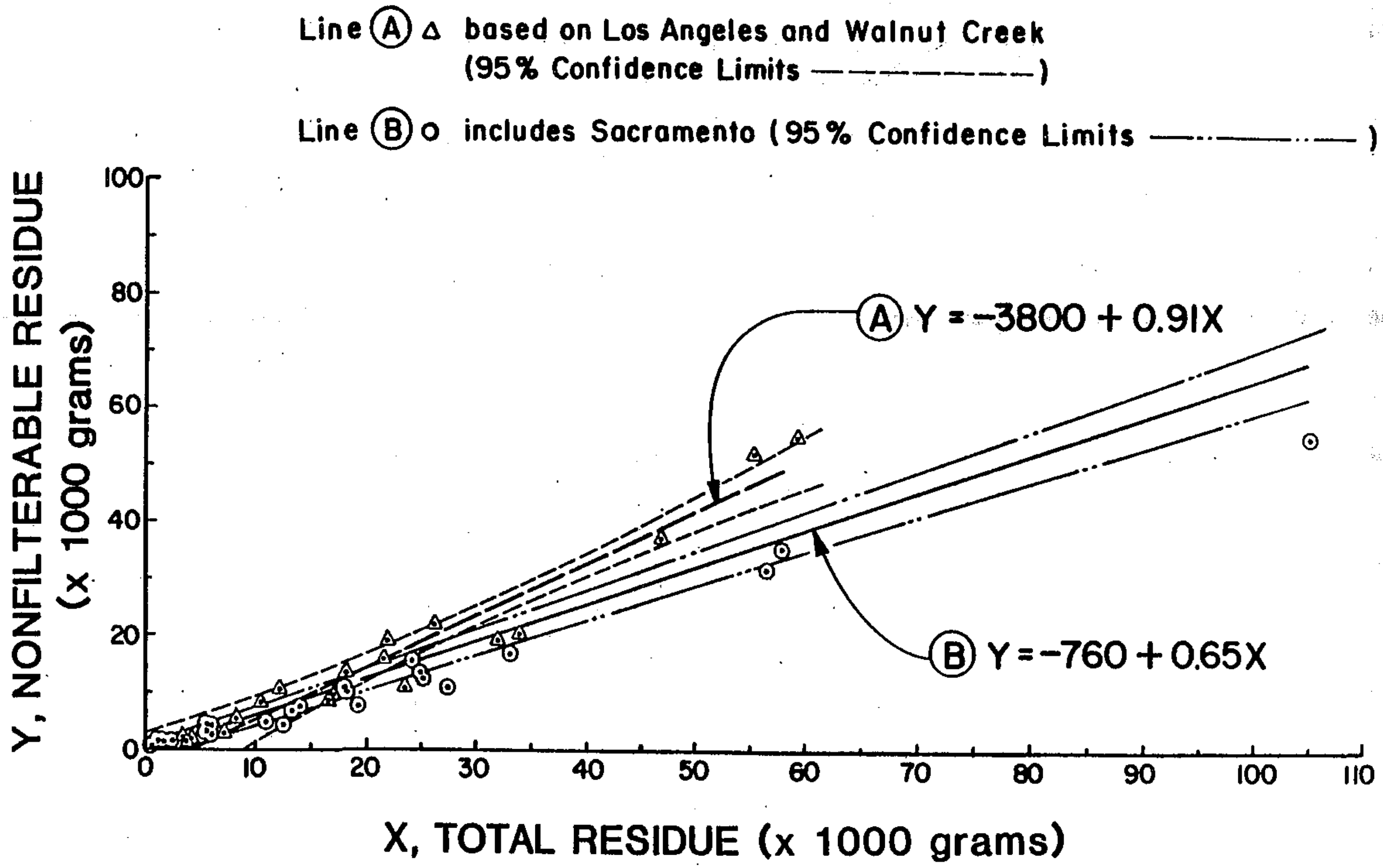
TOTAL KJELDAHL NITROGEN vs VEHICLES DURING STORM

Figure 7



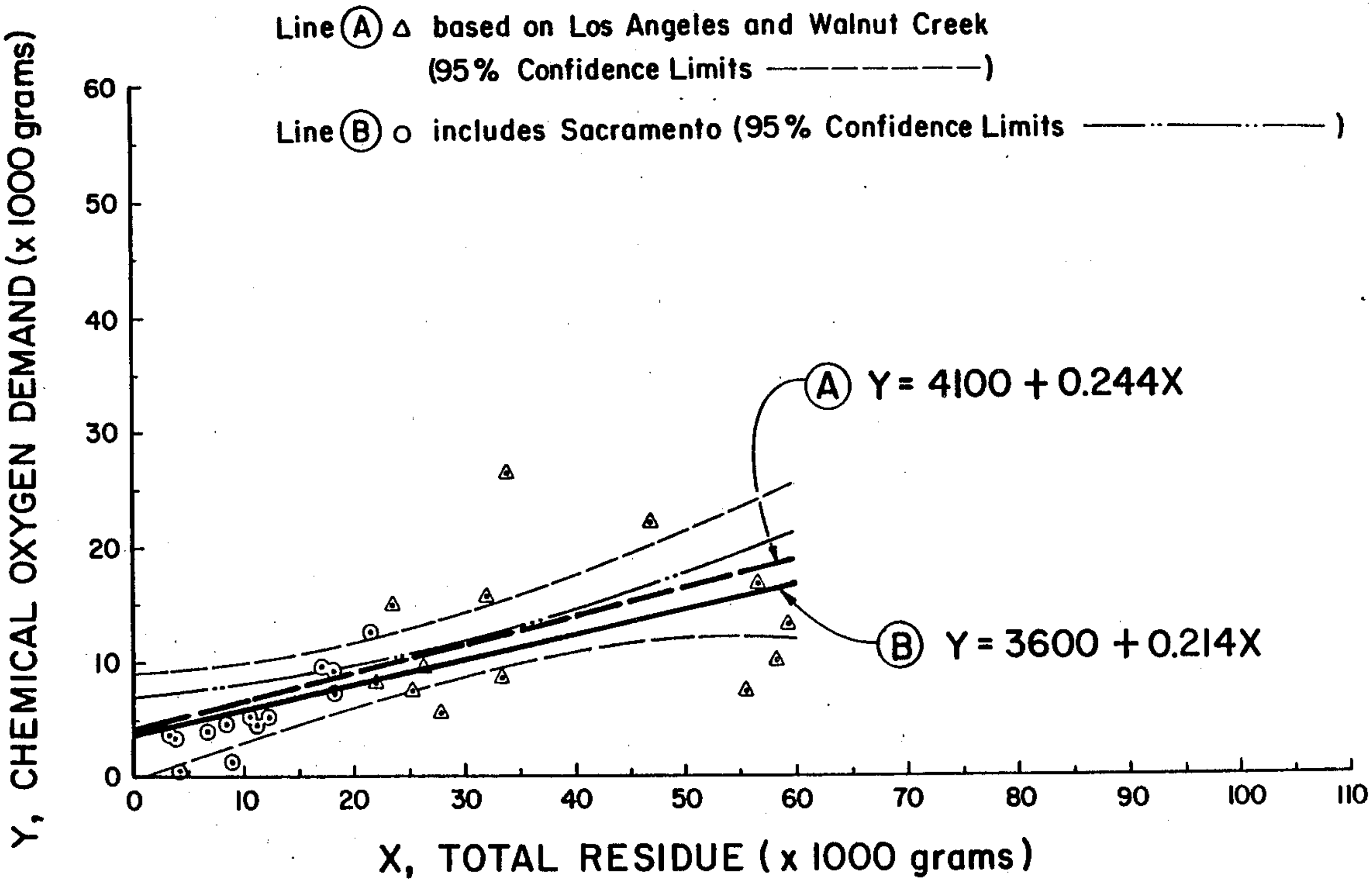
ZINC vs TOTAL RESIDUE

Figure 8



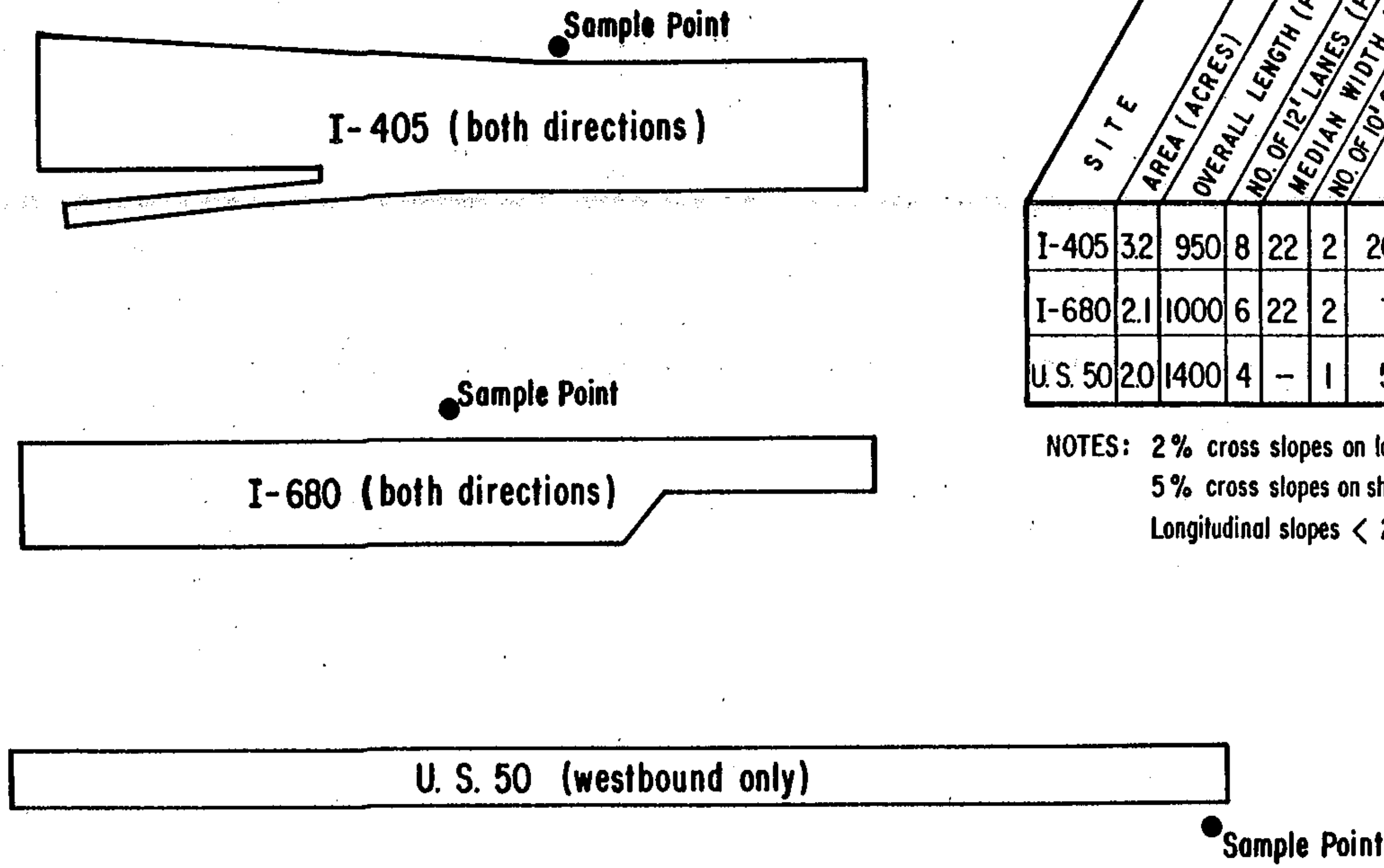
NONFILTERABLE RESIDUE vs TOTAL RESIDUE

Figure 9



CHEMICAL OXYGEN DEMAND VS TOTAL RESIDUE

Figure 10



SITE	AREA (ACRES)	OVERALL LENGTH (FEET)	NO. OF 12' LANES (PCC)	MEDIAN WIDTH (FEET)	NO. OF 10' OUTSIDE SHOULDERS (AC)	AVERAGE DAILY TRAFFIC 1980
I-405	3.2	950	8	22	2	200,000
I-680	2.1	1000	6	22	2	70,000
U.S. 50	2.0	1400	4	–	1	50,000

NOTES: 2% cross slopes on lanes
5% cross slopes on shoulders
Longitudinal slopes < 2%

SIMPLIFIED PLAN VIEWS OF RUNOFF SITES

Figure 11

6. EVALUATION OF REGRESSION EQUATIONS

6.1 Evaluation Procedure

The procedure normally exercised to evaluate regression equations is called verification. Verification consists of a mathematical comparison of measured quantities and calculated quantities for the same locations and times. "Validation might best be reserved for use such as a second verification that substantiates a previous verification." The above definitions of verification and validation are found in [Turner, D.B., 17]. The "tentative" regression equations to be "verified" were based on observations from urban freeways in Los Angeles and Walnut Creek. Generally, the high values for the independent variables occurred at Los Angeles, while low and intermediate values of the independent variable occurred at Walnut Creek. Data from Sacramento were to be used for "verifying" the tentative regression equations. However, because only low and intermediate values of the independent variables occurred at Sacramento, an alternative procedure described below was adopted to evaluate the regression equations. Since the regression equations are linear, we are simply evaluating whether or not the independent variables show the same trend and regression line characteristics using the Sacramento data. Recall that the intended application of the regression equations is to quantify constituent loads and the flow weighted concentrations for proposed urban highway before runoff enters a "sensitive" receiving body of water. Thus, the values calculated from the regression equations will be used for comparing the relative increases or decreases of constituent loads due to a proposed project. The criteria for accepting the regression equations are not limited to the "goodness of fit" or other regression characteristics because there are assumptions and restrictions on using the equations in a procedure which are not reflected in the statistics. Some of the more subjective criteria considered for accepting a regression equation are clarified in the following questions. First, is the relationship between the dependent and independent variables physically sound? Second, can future values ("good estimates") of the independent variables be obtained easily?

The alternative procedure adopted for evaluating the tentative regression equations based on observations from Los Angeles and Walnut Creek was to include the Sacramento observations and generate a "pooled" regression line. The slope of the "pooled" regression line was compared to the slope of the tentative regression line using a t-test. The procedure for testing the equality of the slopes of two regression lines is documented in reference (15). The underlying concept of the procedure is that if the slopes of the tentative and pooled regression lines remain the "same" (statistically), then the basic relationship between the dependent and independent variables has not changed, and the linear equation is then acceptable with restrictions. Changes in the ordinate-intercept would be tolerated since it is not expected that the initial dry loads among the three sites would be identical. However, with similar vehicle mixes and operating modes, the washoff rates of constituents may be similar after sufficient rainfall has removed the gutter load. Furthermore, the average annual rainfall at the three study sites is similar (less than 24 inches) and the rainfall occurs generally from October through April. The Los Angeles site may be considered arid (average rainfall = 12 inches) while Walnut Creek and

Sacramento may be considered semiarid (average rainfall = 20 inches and 18 inches, respectively). For constituents which exhibited a linear relationship for the tentative equation and no linear relationship for the pooled equation, the tentative equation is not acceptable, and perhaps another equation is needed.

6.2 Evaluation of Equation 6 Using Normalized Loads

Equation 6 appeared to yield satisfactory results for the tentative equation based on observations from Los Angeles and Walnut Creek. Next the Sacramento observations were normalized by dividing the constituent mass loads by the gutter length. Maximum values for all the normalized constituent loads (dependent variable) occurred at Sacramento. Table XXVI in the Appendix displays the statistical results of pooling the data from all sites and fitting the data to equation 6. Only lead and chemical oxygen demand showed linear fits with wide scatter ($r^2 = 0.23$). Comparison of Table XXII with Table XXVI in the Appendix indicates that by pooling the normalized Sacramento data with Los Angeles and Walnut Creek, equation 6 was not acceptable.

It appears that the technique of normalizing loads on a per gutter-mile basis is not entirely acceptable, since at the Sacramento site there was only one 0.27 mile gutter, which causes the normalized constituent mass loads to be almost four times the "raw" magnitudes. The next series of validation studies involved using no transformations of the "raw" data. Further attempts at validating equations 10A, 10B, 11A, 11B, 12A and 12B were abandoned in favor of evaluating equations in which the loads are not transformed by normalizing factors.

6.3 Evaluation of Equations 3, 13, and 14 Using Loads With No Transformations

By not applying transformations to the observed washoff values, it is presumed that there are no large differences among the runoff sites. Rexnord's "raw" data values from the Sacramento site were increased uniformly by 15 percent, because Rexnord computed runoff values by reducing ISCO 1870 flow traces. In contrast, Caltrans obtained runoff volumes by the ISCO 1870 flow meter totalizer readings(16). The data set used for evaluation with no data transformations is shown in Table 7.

The Los Angeles and Walnut Creek observations were fitted to equation 3 using no transformations, thereby providing the tentative regression equations. Statistical results are displayed in the Appendix Table XXXI. Constituents for which a linear relationship was found are lead, zinc, filterable residue, chemical oxygen demand, and Total Kjeldahl Nitrogen. Constituents for which no linear relationship was found are nonfilterable residue, total residue, and orthophosphate.

The statistical results of "pooling" the Sacramento observations with the Los Angeles and Walnut Creek observations and fitting equation 3 are displayed in Appendix Table XXXII. Comparison of the scatter plots and statistical results revealed that nonfilterable and total residue produced linear fits for the pooled equations, whereas there was no fit for the tentative equations. Except for orthophosphate the other constituents produced linear fits. There was more scatter in the pooled equations than in the tentative equations of zinc, filterable residue, and Total Kjeldahl Nitrogen. In Figures 4, 5, and 7, the scatter of

----- TABLE 7 -----
CONSTITUENT LOADS (GRAMS) NOT NORMALIZED.
SITE : LA=LOS ANGELES, WK=WALNUT CREEK, SO=SACRAMENTO.
DATE=YEAR MONTH DAY. TRAFFIC=VEHICLES DURING STORM.
ZINC=ZINC. TKN=TOTAL KJELDAHL NITROGEN. COD=CHEMICAL OXYGEN
DEMAND. TOTSOL=TOTAL RESIDUE. SUSSOL=NONFILTERABLE RESIDUE.
PO4=ORTHOPHOSPHATE. LEAD=LEAD. DISSOL=FILTERABLE RESIDUE.

SITE	DATE	TRAFFIC	ZINC	TKN	COD	TOTSOL	SUSSOL	PO4	LEAD	DISSOL
LA	810111	6882	14	110	3078	3754	1069	.	5	2685
LA	810123	7428	35	.	.	16563	8349	.	20	8214
LA	810208	49048	21	97	5185	7237	2708	2	12	4529
LA	810225	59731	48	439	14706	23400	10795	8	304	12605
LA	810304	44568	53	421	15386	31832	18975	6	244	12857
LA	810319	100746	73	467	26344	33821	20033	2	89	13788
WK	801203	13289	14	193	9341	17118	9532	30	22	7586
WK	801203	35136	42	239	21851	46975	37183	12	127	9792
WK	801203	1246	6	52	4331	8381	5076	3	15	3305
WK	810122	37619	22	114	9191	26162	21377	.6	38	4785
WK	810126	27763	18	103	7954	21821	18882	4	42	2939
WK	810127	35678	38	358	12783	59422	54530	3	82	4892
WK	810128	7766	21	90	7032	55430	51812	4	46	3618
WK	810224	830	7	70	382	4107	1317	3	25	2790
WK	810224	4043	4	.	.	.	.	.	19	.
WK	810226	7628	9	.	4951	12167	10306	.	39	1861
WK	810304	7159	7	34	3470	3342	1808	1	26	1534
WK	810315	36116	20	133	12320	21482	15753	6	30	5729
WK	810318	27995	11	55	5121	10544	7938	.9	24	2606
WK	810325	17755	18	122	9027	18054	13364	3	29	4689
SO	791219	15280	26	.	.	24254	15408	.	43	8846
SO	800109	32410	58	328	16563	56624	31393	40	135	25231
SO	800110	6980	39	56	5260	27612	10706	6	38	16906
SO	800111	15520	84	137	9586	58208	35381	14	91	22827
SO	800115	4460	9	.	.	6063	3958	.	21	2105
SO	800116	930	12	.	.	7103	2413	.	21	4690
SO	800117	24670	39	1070	8381	33170	16584	.	71	16586
SO	800214	5430	8	.	.	5717	3119	.	11	2598
SO	800214	2330	4	.	.	2853	1341	.	6	1512
SO	800214	5360	9	.	.	6563	3538	.	11	3025
SO	800215	1140	37	.	.	6373	2282	.	10	4090
SO	800215	18330	20	.	.	18354	9803	.	29	8551
SO	800215	5260	13	.	.	14267	7323	.	14	6944
SO	800216	10900	80	500	4194	11185	4593	7	.	6592
SO	800216	3620	15	91	3750	6686	3387	4	14	3298
SO	800216	1910	8	.	.	3596	1233	.	.	2363
SO	800217	160	2	.	.	844	143	.	.	701
SO	800217	19380	24	285	7133	25109	12840	16	57	12269
SO	800218	24240	50	.	.	105526	55259	.	133	50267
SO	800220	10790	14	186	.	13539	6676	9	37	6862
SO	800221	1340	11	238	.	12720	3804	10	12	8916
SO	800227	4180	8	.	.	2711	1326	.	6	1385
SO	800227	1710	30	152	.	19403	7456	11	23	11947
SO	800304	1810	9	148	1179	8845	3759	11	15	5086
SO	800305	3390	2	.	.	1876	1120	.	4	756
SO	800305	2230	4	.	.	5866	3980	.	10	1886
SO	800305	2710	3	.	.	1555	1127	.	4	428
SO	800305	1930	22	247	.	8408	4946	23	12	3462
SO	800325	17400	29	252	10334	25330	12349	25	50	12980
SO	800404	7290	34	164	6891	18211	10500	11	16	7711

data outside the confidence limits of the "pooled" regression equations indicates that effects other than vehicles during the storm are causing elevated loads. The elevated loads generally occurred at Sacramento when "vehicles during the storm" was less than 30,000. No speculative explanations will be offered for these data since other possible independent variables were not measured during the experiment. The t-tests for the equality of the slopes of the tentative and pooled regression lines were positive, i.e., the slopes of the lines show no significant difference, for lead, zinc, filterable residue, chemical oxygen demand, and Total Kjeldahl Nitrogen. The "pooled" regression equations in Figures 3 through 7 are acceptable, but some restrictions on their usage must be imposed. Briefly, only long duration storms should be used. The linear equations depict the intercept as an initial gutter load, while the relatively mild slopes of the lines depict the contribution of constituent loads from vehicles that travel through the site during the storm. Detailed comments for using the regression equations with restrictions and assumptions are presented in sections 7.0 and 7.1.

Next, the evaluation procedure was exercised using equation 13 for the following constituents with no data transforms: lead, zinc, nonfilterable residue, filterable residue, chemical oxygen demand, Total Kjeldahl Nitrogen. The evaluation procedure was exercised using equation 14 for dissolved orthophosphate using no data transforms.

Constituents were fit to equations 13 and 14 based on the chemical/analytical test procedure; e.g., total lead was tested, therefore it is appropriate to use equation 13.

The statistical results of the tentative equations are shown in Appendix Table XXXIII. Statistical results of pooled equations are shown in the Appendix Table XXXIV. Equation 14 was not accepted for dissolved orthophosphate because there was no linear relationship for the tentative equation. The regression equations shown in Figures 8 through 10 for zinc, nonfilterable residue, and chemical oxygen demand are acceptable with restrictions on usage as explained in sections 7.0 and 7.1.

6.4 Summary of Evaluations

Equation 3 was found to be acceptable by t-testing the equality of slopes of tentative and pooled equations for the following constituents:

Total Lead
Total Zinc
Filterable Residue
Chemical Oxygen Demand
Total Kjeldahl Nitrogen

Equation 13 was found to be acceptable by t-testing the equality of the slopes of tentative and pooled equations for the following constituents:

Total Zinc
Nonfilterable Residue
Chemical Oxygen Demand

Sections 7.0 and 7.1 delineate the restrictions, assumptions, and procedure for using the regression equations.

7. EXPLANATION AND PROCEDURE FOR USING THE REGRESSION EQUATIONS

Before using the regression equations to compute constituent loadings, there are three criteria to examine. First, there must be a sensitive receptor nearby, e.g., a stream which supports aquatic life. Second, the average daily traffic must exceed 30,000 vehicles. Third, the average annual rainfall in the area must be less than 24 inches.

Because the drainage details are not known in the advance stages of a project, the following assumptions and procedures are used to forecast constituent loads and flow-weighted concentrations.

1. The future California vehicle fleet and fuels used are the same (or nearly) as in the years of actual data collection (1979 through 1981). The highway is in an urban setting.

2. The median, traveled lanes, and shoulders are 100% paved.

3. The assumed drainage area is the actual proposed width of pavement times an assumed length, such that the area is 2 acres. The drainage area should be between 2 and 3 acres to correspond to the drainage areas used for the research sites. See Figure 11 for the actual site configurations.

4. Runoff from the assumed drainage area is conveyed via open channels to a single point of discharge. (Runoff quantity and quality from the unpaved area adjacent to the paved area was excluded from the research.)

5. A runoff coefficient of 0.90 is used to compute the cumulative runoff volume because the drainage area is completely paved.

6. The storm chosen is the annual one day rainfall event (two-year return interval). A 24-hour storm is chosen as the storm duration for two reasons. First, a storm lasting 24-hours will be sufficient to wash off the gutter load and both the AM and PM peak traffic will travel through the site and contribute to the runoff load. Second, a 24-hour storm is used because the future traffic prediction is a 24-hour value. Rainfall depth (amount) can be obtained from Goodridge, J. D, et al, Rainfall Analysis for Drainage Design, Vol. II, Long Duration Precipitation Frequency Data, California Department of Water Resources, Bulletin No. 195, October 1976.

7. Since the storm duration is 1 day, the projected average daily traffic (ADT) is used to compute constituent loads using the linear regression equations below which were evaluated and found to be acceptable. See section 6 for an explanation of the evaluation procedure.

(3A) Pb = 14.3 + 0.00189 (ADT)
(3B) Zn = 14.3 + 0.00060 (ADT)
(3C) F.R. = 5360 + 0.140 (ADT)
(3D) C.O.D. = 3590 + 0.221 (ADT)
(3E) T.K.N. = 150 + 0.00342 (ADT)

where Pb, Zn, F.R., C.O.D., and T.K.N. are the cumulative loads in grams for lead, zinc, filterable residue, chemical oxygen demand, and total Kjeldahl nitrogen, respectively. The intercepts represent initial dry loads in grams, while the slopes represent the washoff rate of constituent in grams per ADT during storm.

8. To forecast an annual load, divide the depth (amount) of the total annual rainfall (2-year return interval, 365-day value) for the station by the 1-day depth. The result is the theoretical number of 1-day events per year. Then simply multiply each of the daily loads by the number of 1-day events to arrive at an annual load.

9. The flow weighted concentration is computed by dividing the daily event load in 7 (above) by the 1-day cumulative runoff volume.

10. The following linear regression equations are used to calculate nonfilterable residue loads:

(13A) Zn = 11.5 + 0.00064 (TR)
(13B) C.O.D. = 3600 + 0.214 (TR)
(13C) N.R. = -760 + 0.65 (TR)

where TR is total residue in grams, Zn, C.O.D., and N.R. are the cumulative loads in grams for zinc, chemical oxygen demand, and nonfilterable residue, respectively. The intercepts represent the initial dry loads in grams, while the slopes represent the fraction of constituent found in the total residue load which is washed from the pavement during the storm.

Because total residue is an independent variable for which no easy future value can be obtained, the following procedure should be executed. Substitute values of the total zinc load computed from Equation (3B) and the chemical oxygen demand load computed from Equation (3D) in Equations (13A) and (13B) and compute two values of total residue. Then use the average value of total residue to compute the nonfilterable residue load using equation (13C). Compute the flow-weighted concentration as in 9. above.

11. The final step of the procedure is to check the computed loads and flow-weighted concentrations. The check is to make sure that the computed values are bounded by the field observations. Table 8 shows the limits of the observed concentrations and loads.

An example is presented it the next section to clarify the computational procedures.

Final water quality assessment must be made using the values of loads and concentrations in a "receiving" water analysis. This is beyond the scope of this research.

TABLE 8

LIMITS OF OBSERVED CONCENTRATIONS AND LOADS OF SINGLE EVENTS

Constituent	Concentration (mg/l) Low	Concentration (mg/l) High	Load (grams) Low	Load (grams) High
Total Lead	0.17	4.10	4.0	304
Total Zinc	0.10	1.80	2.0	84
Filterable Residue	16	461	428	50,167
Chemical Oxygen Demand	23	724	382	26,344
Total Kjeldahl Nitrogen	0.1	14.0	34	1,070
Nonfilterable Residue	18	2660	143	55,259

7.1 Example Computations

Given:

1. The average annual rainfall for the proposed project is 22 inches.

2. Average Daily Traffic (ADT)(year 2005) = 56,800

3. There is a river which crosses the proposed project. The river is used for recreation and supports Salmo gairdneri (trout).

4. Proposed urban freeway in year (2005) with:

46 feet of paved median	=	46'
2, 10 foot wide shoulders	=	20'
4, 12 foot wide lanes	=	48'
		114' width

Assumptions:

1. The paved width of 114' and each 750' of freeway length will be drained to a single discharge point.

2. Runoff coefficient is 0.90; thus, .90 x rainfall volume = runoff volume.

3. A 24-hour storm delivers 2.06 inches of continuous rainfall (see Reference in Item 6 on page 57).

4. The California vehicle fleet (and fuel used) will be the same in 2005 as it was in 1980. The vehicles are operating "normally", i.e., at speeds of 55 miles per hour with no accidents or spills.

Compute:

1. The area of the assumed catchment.

2. The cumulative volume of runoff (in liters).

3. The loads and flow-weighted concentrations of the constituents: lead (Pb), Zinc (Zn), filterable residue (F.R.), chemical oxygen demand (C.O.D.), and total Kjeldahl nitrogen (T.K.N.), and nonfilterable residue, using equations 3A through 3E and 13A, 13B, and 13C.

Computations:

1. Area = length (ft) x width (ft)$\left(\frac{1 \text{ acre}}{43,560 \text{ ft}^2}\right)$ = acres

$$= 750 \times 114 \times \frac{1}{43,560} = 1.96 \text{ acres}$$

Say O.K. 1.96 acres approaches the lower limit of 2.0 acres, the smallest area from which data were collected to build the equations.

2. Cumulative Runoff Volume = runoff coefficient x rainfall volume

= [0.90] x [2.06"] x [1.96 ac] x [3630 ft^3/ac-in] [28.32 l/ft^3]

= 373,564 call 373,500 liters

3. First compute the load in grams using the appropriate regression equation, then compute the flow-weighted concentration ($\overline{\text{conc.}}$) in milligrams per liter:

$$\overline{\text{conc.}}(\text{mg/l}) = \frac{\text{Load (grams)}}{\text{cumulative runoff volume (liters)}} \times \frac{1000 \text{ milligrams}}{1 \text{ gram}}$$

(3A) Pb = 14.3 + 0.00189 (56,800)
= 121.65 122 grams
$\overline{\text{conc.}}$ = 121.65/373,500 x 1000
= 0.326 0.33 mg/l

(3B) Zn = 14.3 + 0.00060 (56,800)
= 48.38 48 grams
$\overline{\text{conc.}}$ = 48.38/373,500 x 1000
= 0.129 0.13 mg/l

(3C) F.R. = 5360 + 0.140 (56,800)
= 13,312 — 13,300 grams

$\overline{\text{conc.}}$ = 13,312/373,500 x 1000
= 35.64 — 35.6 mg/l

(3D) C.O.D. = 3590 + 0.221 (56,800)
= 16,142 — 16,150 grams

$\overline{\text{conc.}}$ = 16,142/373,500 x 1000
= 43.22 — 43.2 mg/l

(3E) T.K.N. = 150 + 0.00342 (56,800)
= 344.26 — 344 grams

$\overline{\text{conc.}}$ = 344.26/373,500 x 1000
= 0.922 — 0.92 mg/l

Using the forecasted values of zinc (48 grams) and chemical oxygen demand (16,150 grams), an average value of total residue (T.R.) can be calculated using equations 13A and 13B.

(13A) Zn = 11.5 + 0.000640 (T.R.)

(13B) C.O.D. = 3600 + 0.214 (T.R.)

Solve for total residue (T.R.):
Using (13A) T.R. = 57,031 grams
Using (13B) T.R. = 58,645 grams
Sum = 115,676 grams
Avg = 57,838 — 57,840 grams

Using equation (13C) and the average value of 57,840 grams for total residue (T.R.), solve for nonfilterable residue (N.R.):

(13C) N.R. = -760 + 0.65 (57,840)

= 36,836 grams <u>36,840 grams</u>

$\overline{\text{conc.}}$ = 36,836/373,500 x 1000

= 98.62 <u>98.6 mg/l</u>

<u>Check</u>:

The computed values are within the limits of the values in Table 8.

The results must be compared to established water quality criteria, and if any excessive values are found, mitigation measures (or transportation alternatives) may be needed. This assessment was beyond the scope of this research.

REFERENCES

1. Howell, R. B., Water Pollution Aspects of Particles Which Collect on Highway Surfaces, Caltrans, publication No. FHWA-CA-TL-78-22, July 1978.

2. Winters, G. R. and Gidley, J. L., Effects of Roadway Runoff on Algae, Transportation Laboratory of Caltrans, FHWA/CA/TL-80/24, June 1980.

3. Shaheen, Donald G., Contributions of Urban Roadway Usage to Water Pollution, Biospherics, Inc., Maryland, March 1975.

4. Agnew, R. W.; T. L. Meinholz, and V. Novotny, A Preliminary Model for Determining the Water Quality Impact of Highway Systems, Envirex, Inc., July 1975, Interim Report.

5. Sartor, James D., and Gail B. Boyd, Water Pollution Aspects of Street Surface Contaminants, Municipal Pollution Control Branch, Environmental Protection Agency, Washington, D.C., November 1972, EPA-R2-72-081.

6. U.S. Environmental Protection Agency, Water Quality Management Planning for Urban Runoff, Office of Water Planning and Standards, Washington, D.C. EPA 440/9-75/004, December 1974, p. I-8.

7. Personal communication between Dr. Kenneth Kerri (consultant, California State University, Sacramento) and J. Racin (Transportation Laboratory), February 29, 1980.

8. Diniz, E. V., and W. H. Espey, Jr., Maximum Utilization of Water Resources in a Planned Community, Application of the Storm Water Management Model, Vol. I., US. EPA, Cincinnati, Ohio, July 1979, EPA-600/2-79-050c, pp. 66-69.

9. Ibid. p. 84

10. Asplund, Randy; Ferguson, John F.; and Mar, Brian; Characterization of Highway Runoff in Washington State, University of Washington, December 1980, p. 28.

11. Transportation Laboratory, User Manual, LEAD1, Motor Vehicle Lead Emission Rates, Caltrans Transportation Laboratory, Sacramento, California, July 1979.

12. Laxen, D.P.H., and R. M. Harrison, The Highway As a Source of Water Pollution: An Appraisal With the Heavy Metal Lead, "Water Research", Vol. II, pp. 1-11, Pergamon Press, Great Britain, 1977.

13. Ibid., pp. 1, 2.

14. Coats, D. M., C. R. Sundquist, E. C. Shirley, Lead Emissions From Roadway Vehicles, Caltrans, Transportation Laboratory CA-TL-7254-77-24, August 1977, p. 7.

15. Bhattacharyya, Gouri K., and Richard A. Johnson, Statistical Concepts and Methods, Wiley and Sons, New York, 1977, pp. 363, 364.

16. Personal Communication between N. Kobriger (Envirex soil scientist) and J. Racin (Transportation Laboratory) January 5, 1981.

17. Turner, D. B., "Atmospheric Dispersion Modeling - A Critical Review," Journal of the Air Pollution Control Association, Vol. 29, No. 5, May 1979, pp. 511, 512.

9.0 APPENDIX

9.1 Pavement Runoff Site Information

9.2 Summaries of Statistical Results of the Regression Equations

9.3 Lead Emissions and Washoff

9.1 Pavement Runoff Site Information

PAVEMENT RUNOFF SITE INFORMATION

Site Description

Dist 07 Co. LA Rte I-405 P.M. 18.0 Name Los Angeles

Average Daily Traffic 200,000 (1981)

Area of Runoff 3.2 acres Average Annual Rainfall: 12"

Culvert: 36-inch reinforced concrete pipe

Type of pavement: Concrete Shoulders: A.C. Curb and Gutter: Type E

No. of lanes: 4 NB, 4 SB Date of last construction: March 1963

Type of median barrier: Jersey Barrier (concrete)

Equipment

1975-78 - manually sampled

1980-81 Sampler - ISCO Automatic water sampler (Model 1680) with high speed pump

Flow monitoring device: 1 foot cutthroat flume (a modified PARSHALL)
1980-81 Bristol Level Recorder - 7 day clock
NOTE: 1975-78 Unisonic flow level recorder used.
Precipitation equipment:
Weather Measure P501 tipping bucket & P522 recorder.

Data

No. of storms sampled by year

Year	No. of Storms	Samples/Storm
75-76	2	6, 3
76-77	3	12, 8, 8
77-78	5	6, 9, 8, 8, 10
80-81	7 (composites)	1, 3, 6, 5, 6, 6, 5

Dustfall

Location	Period of sampling	Sample scheme	Met Sta
Adjacent freeway, median, background (500')	a. July 27 to Aug. 26, 1976 b. Feb. 2 to Mar. 3, 1977 c. Nov. 7, 1980 to Sept. 15, 1981	Total solids, Pb, Cr, PO4, NO_3-N (monthly, total solids only) 10 sets (set 7 included Pb[dissolved + suspended])	yes

---

PAVEMENT RUNOFF SITE INFORMATION

Site Description

Dist 04 Co. CC Rte I-680 P.M. 12.7 Name Walnut Creek

Average Daily Traffic 70,000 (1981)

Area of Runoff 2.1 acres Average Annual Rainfall: 20"

Culvert: 18-inch reinforced concrete pipe

Type of pavement: Concrete Shoulders: A.C. Curb and Gutter: Type E
AC Dike: Type A

No. of lanes: 3 NB, 3 SB Date of last construction: Aug. 1966

Type of median barrier: Jersey Barrier (concrete)

Equipment

1975-78 - ISCO sampler-malfunction-all samples taken manually
1980-81-water sampler-ISCO automatic water sampler (Model 1680) with high speed pump.

Flow monitoring device: 9" PARSHALL flume and Bristol water level recorder- 7 day clock (1980-81)
NOTE: For storms 1975-76, 76-77, 77-78 staff gage was used in 18"RCP
Precipitation equipment: MRI 304 tipping bucket with drum recorder
1980-81 winter Weather Measure recorder (Model P522A) w/tipping bucket gage, P501-I.

Data

No. of storms sampled by year

Year	No. of Storms	Samples/Storm
75-76	4	5, 5, 1, 3
76-77	3	5, 10, 14
77-78	4	5, 13, 10, 5
80-81	10 (composites)	9, 2, 7, 1, 1, 1, 1, 4, 1, 1

Dustfall

Location	Period of sampling		Sample scheme	Met Sta
4 bucket adjacent freeway +2 background	Nov. 6, 1980 to Sept. 3, 1981	10 sets	total solids, (monthly) (set 7 included Pb [dissolved + suspended])	yes

PAVEMENT RUNOFF SITE INFORMATION

Site Description

Dist 03 Co. SAC Rte US 50 P.M. 4.7 Name Sacramento

Average Daily Traffic 100,000 (1981)

*Area of Runoff 2.0 acres Average Annual Rainfall: 18"

Open channel: asphalt concrete "V" ditch, 2:1 sides, 3' maximum depth

Type of pavement: Concrete Shoulders: A.C. AC Dike = Modified Type A

No. of lanes: 5 EB, 4 WB Date of last construction: Nov. 1971
Sampling 4 WB, no sampling of EB lanes*
Type of median barrier: DMBB (double metal beam barrier)
*west bound lanes + outside shoulder

Equipment

Water samplers (1979-81) - 2 ISCO automatic water samplers (Model 1680 high speed pumps. One used in flow mode, the other in time mode. One ISCO automatic water sampler (Model 1392) used in time mode.

Flow monitoring device (1979-81) - 9" Parshall flume, ISCO 1870 bubbler flow meter (paved).
2" Parshall flume, ISCO 1870 bubbler flow meter (unpaved).

Precipitation equipment:
a) Belford weighing bucket w/drum recorder(1979-80)
b) P501 tipping buck w/P522 recorder (1980-81)

Data

No. of storms sampled by year

Year	No. of Storms	Samples/Storm
79-80	14	5, 19, 20, 24, 11, 22 23, 25, 37, 21, 9, 22, 32, 19

Dustfall

Location	Period of sampling	Sample scheme	Met Sta
transect adjacent freeway + background	Dec. 79 to Dec. 15, 1980	Total solids, occasionally Pb other heavy metals (semi-monthly)	yes

9.2 Summaries of Statistical Results of the Regression Equations

----- TABLE I -----

SUMMARY OF STATISTICAL RESULTS FOR EQUATION (1) :

| OBSERVED MAXIMUM A + B (DRY DAYS) + |
| CONSTITUENT CONCENTRATION = C (MAXIMUM INTENSITY) + |
| IN MILLIGRAMS PER LITER D (VEHICLES) |

N = NUMBER OF OBSERVATIONS. F IS F-TEST FOR MODEL.
TD,TI, & TV ARE T-TEST VALUES FOR THE COEFFICIENTS B,C, & D.
RSQ IS THE INDEX OF DETERMINATION. FSIG, TDSIG, TISIG, &
TVSIG ARE RESULTS AT THE .05 LEVEL OF SIGNIFICANCE FOR THE
EQUATION AND THE COEFFICIENTS B,C, AND D.

SITE	CONSTIT	N	F	TD	TI	TV	RSQ	TDSIG	TRSIG	TVSIG
LA+WK+PV	BORON	6	5.08	-3.53	-3.12	1.55	0.88	NO	NO	NO
LA+WK+PV	IRON	6	56.79	-11.40	-10.50	4.33	0.99	YES	YES	YES
LA+WK+PV	LEAD	6	1.47	-1.48	-0.07	0.60	0.69	NO	NO	NO
LA+WK+PV	AMMONIA NITROGEN	6	4.82	-3.41	-3.26	1.64	0.88	NO	NO	NO
LA+WK+PV	TOTAL PHOSPHORUS	6	3.09	-2.81	-1.32	1.45	0.82	NO	NO	NO
LA+WK+PV	OIL AND GREASE	6	1.58	-2.07	-0.78	1.48	0.70	NO	NO	NO

----- TABLE II -----

SUMMARY OF STATISTICAL RESULTS FOR EQUATION (2) :

| OBSERVED MAXIMUM |
| CONSTITUENT CONCENTRATION = A + B (VEHICLES) . |
| IN MILLIGRAMS PER LITER IN ADT X DRY DAYS |

N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS T-TEST VALUE FOR THE COEFFICIENTS B. RSQ IS THE INDEX
OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT THE .05 LEVEL
OF SIGNIFICANCE FOR THE F-TEST AND THE T-TEST OF THE COEFFICIENT
B. SITE CODES:LA=LOS ANGELES,WK=WALNUT CREEK,PV=PLACERVILLE.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA	BORON	10	4.20	2.05	0.34	NO	NO
LA	IRON	10	0.64	-0.80	0.07	NO	NO
LA	LEAD	10	8.79	2.97	0.52	YES	NO
LA	AMMONIA NITROGEN	10	25.24	5.02	0.76	YES	YES
LA	TOTAL PHOSPHORUS	10	0.23	0.48	0.03	NO	NO
LA	OIL AND GREASE	10	0.00	0.06	0.00	NO	NO
LA	BORON	9	3.42	1.85	0.33	NO	NO
LA	IRON	9	0.41	-0.64	0.06	NO	NO
LA	LEAD	9	8.36	2.89	0.54	YES	YES
LA	AMMONIA NITROGEN	9	20.54	4.53	0.76	YES	YES
LA	TOTAL PHOSPHORUS	9	0.31	0.56	0.04	NO	NO
LA	OIL AND GREASE	9	0.00	-0.07	0.00	NO	NO
WK	BORON	10	0.12	-0.35	0.02	NO	NO
WK	IRON	10	0.24	0.49	0.03	NO	NO
WK	LEAD	10	1.12	1.06	0.12	NO	NO
WK	AMMONIA NITROGEN	10	0.04	-0.20	0.00	NO	NO
WK	TOTAL PHOSPHORUS	10	0.01	-0.10	0.00	NO	NO
WK	OIL AND GREASE	10	0.52	0.72	0.06	NO	NO
PV	BORON	9	0.01	0.11	0.00	NO	NO
PV	IRON	9	1.80	1.34	0.20	NO	NO
PV	LEAD	9	1.49	1.22	0.18	NO	NO
PV	AMMONIA NITROGEN	9	0.00	-0.06	0.00	NO	NO
PV	TOTAL PHOSPHORUS	9	0.03	-0.17	0.00	NO	NO
PV	OIL AND GREASE	9	1.94	1.39	0.22	NO	NO
LA+WK+PV	BORON	28	12.81	3.58	0.33	YES	YES
LA+WK+PV	IRON	28	0.65	-0.81	0.02	NO	NO
LA+WK+PV	LEAD	28	12.85	3.58	0.33	YES	YES
LA+WK+PV	AMMONIA NITROGEN	28	34.76	5.90	0.57	YES	YES
LA+WK+PV	TOTAL PHOSPHORUS	28	0.15	0.39	0.00	NO	NO
LA+WK+PV	OIL AND GREASE	28	0.46	0.68	0.02	NO	NO

-----TABLE XI-A -----
STATISTICAL RESULTS OF EQUATION (3) :
CONSTITUENT = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM.
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE
FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA	LEAD	7	0.02	0.15	0.01	NO	NO
LA	ZINC	7	0.03	-0.18	0.01	NO	NO
LA	BORON	6	4.62	2.15	0.53	NO	NO
LA	NONFILTERABLE RESIDUE	7	0.72	-0.85	0.13	NO	NO
LA	FILTERABLE RESIDUE	7	2.10	1.45	0.29	NO	NO
LA	CADMIUM	7	0.60	-0.77	0.11	NO	NO
LA	CHEMICAL OXYGEN DEMAND	6	0.12	-0.34	0.03	NO	NO
LA	NITRATE NITROGEN	6	0.21	0.46	0.05	NO	NO
LA	AMMONIA NITROGEN	6	0.15	0.38	0.04	NO	NO
LA	TOTAL KJELDAHL NITROGEN	6	0.36	-0.60	0.08	NO	NO
LA	ORTHOPHOSPHATE	5	0.95	-0.97	0.24	NO	NO
LA	TOTAL PHOSPHORUS	6	0.45	-0.67	0.10	NO	NO

----- TABLE XI-B -----
STATISTICAL RESULTS OF EQUATION (3) :
CONSTITUENT = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM.
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE
FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA	LEAD	6	0.66	0.81	0.14	NO	NO
LA	ZINC	6	6.65	2.58	0.62	NO	NO
LA	BORON	5	10.90	3.30	0.79	YES	YES
LA	NONFILTERABLE RESIDUE	6	3.15	1.77	0.44	NO	NO
LA	FILTERABLE RESIDUE	6	3.75	1.94	0.49	NO	NO
LA	CADMIUM	6	0.01	0.08	0.01	NO	NO
LA	CHEMICAL OXYGEN DEMAND	5	11.58	3.40	0.79	YES	YES
LA	NITRATE NITROGEN	5	2.21	1.49	0.42	NO	NO
LA	AMMONIA NITROGEN	5	3.15	1.77	0.52	NO	NO
LA	TOTAL KJELDAHL NITROGEN	5	2.85	1.69	0.49	NO	NO
LA	ORTHOPHOSPHATE	4	0.64	-0.80	0.24	NO	NO
LA	TOTAL PHOSPHORUS	5	3.43	1.85	0.53	NO	NO

----- TABLE XI-C -----
STATISTICAL RESULTS OF EQUATION (3) :
CONSTITUENT = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM.
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE
FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
WK	LEAD	10	13.70	3.70	0.62	YES	YES
WK	ZINC	10	35.48	5.96	0.81	YES	YES
WK	BORON	9	13.71	3.70	0.66	YES	YES
WK	NONFILTERABLE RESIDUE	9	27.41	5.24	0.79	YES	YES
WK	FILTERABLE RESIDUE	9	5.57	2.36	0.45	NO	NO
WK	CHEMICAL OXYGEN DEMAND	9	12.44	3.53	0.64	YES	YES
WK	NITRATE NITROGEN	8	2.69	1.64	0.31	NO	NO
WK	AMMONIA NITROGEN	8	1.43	1.20	0.18	NO	NO
WK	TOTAL KJELDAHL NITROGEN	8	10.54	3.25	0.64	YES	YES
WK	ORTHOPHOSPHATE	8	1.75	1.32	0.21	NO	NO
WK	TOTAL PHOSPHORUS	8	9.02	3.00	0.58	YES	YES

----- TABLE XI-D -----

STATISTICAL RESULTS OF EQUATION (3) :
CONSTITUENT = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM. N = NUMBER OF OBSERVATIONS. F = F-TEST FOR MODEL. TV = T-TEST VALUE FOR THE COEFFICIENT B. RSQ = INDEX OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST & T-TEST OF THE COEFFICIENT B. SITE CODES : LA=LOS ANGELES, WK= WALNUT CREEK. RERUNS OF SELECTED CONSTITUENTS : LOAD ESITMATE INCLUDED FOR 56,634 LITERS (2000 CUFT) NOT SAMPLED.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
WK	ZINC	10	39.09	6.25	0.83	YES	YES
WK	TOTAL KJELDAHL NITROGEN	8	16.36	4.05	0.74	YES	YES
WK	ORTHOPHOSPHATE	8	1.93	1.39	0.24	NO	NO

----- TABLE XI-E -----

STATISTICAL RESULTS OF EQUATION (3) :
CONSTITUENT = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM. N = NUMBER OF OBSERVATIONS. F = F-TEST FOR MODEL. TV = T-TEST VALUE FOR THE COEFFICIENT B. RSQ = INDEX OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST & T-TEST OF THE COEFFICIENT B. SITE CODES : LA=LOS ANGELES, WK= WALNUT CREEK. RERUNS OF SELECTED CONSTITUENTS : TRAFFIC ESITMATE INCLUDED FOR TWO INTERMITTENT PERIODS OF NO RUNOFF.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
WK	ZINC	10	114.20	10.68	0.94	YES	YES
WK	TOTAL KJELDAHL NITROGEN	8	39.40	6.28	0.86	YES	YES
WK	ORTHOPHOSPHATE	8	2.44	1.56	0.29	NO	NO

----- TABLE XI-F -----

STATISTICAL RESULTS OF EQUATION (3) :
OIL AND GREASE = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM. N = NUMBER OF OBSERVATIONS. F = F-TEST FOR MODEL. TV = T-TEST VALUE FOR THE COEFFICIENT B. RSQ = INDEX OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST & T-TEST OF THE COEFFICIENT B. SITE CODES : LA=LOS ANGELES, WK= WALNUT CREEK, SO=SACRAMENTO. DATA WERE NOT NORMALIZED. FOR N=9, LA+WK TWO EVENTS OF SMALL MAGNITUDE WERE OMITTED.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
WK	OIL AND GREASE	6	3.26	1.81	0.45	NO	NO
LA	OIL AND GREASE	5	16.49	4.06	0.85	YES	YES
LA+WK	OIL AND GREASE	11	12.70	3.56	0.59	YES	YES
LA+WK	OIL AND GREASE	9	8.75	2.87	0.54	YES	YES

----- TABLE XI-G -----

STATISTICAL RESULTS OF EQUATION (4) :
O & G / ACRE = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM. N = NUMBER OF OBSERVATIONS. F = F-TEST FOR MODEL. TV = T-TEST VALUE FOR THE COEFFICIENT B. RSQ = INDEX OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST & T-TEST OF THE COEFFICIENT B. SITE CODES : LA=LOS ANGELES, WK= WALNUT CREEK, SO=SACRAMENTO. FOR (N=18 LA+WK+SO) ONE LARGE SO VALUE OMITTED. FOR (N=14 WK+SO) THE HIGH VALUE WAS KEPT.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	OIL AND GREASE	11	3.67	1.92	0.29	NO	NO
LA+WK+SO	OIL AND GREASE	19	0.16	0.40	0.01	NO	NO
LA+WK	OIL AND GREASE	18	2.94	1.71	0.16	NO	NO
WK+SO	OIL AND GREASE	14	0.53	0.73	0.04	NO	NO

----- TABLE XI-H -----

STATISTICAL RESULTS OF EQUATION (5) :
O & G / LANE MILE = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM. N = NUMBER OF OBSERVATIONS. F = F-TEST FOR MODEL. TV = T-TEST VALUE FOR THE COEFFICIENT B. RSQ = INDEX OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST & T-TEST OF THE COEFFICIENT B. SITE CODES : LA=LOS ANGELES, WK= WALNUT CREEK, SO=SACRAMENTO. FOR (N=18 LA+WK+SO) ONE LARGE SO VALUE OMITTED.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	OIL AND GREASE	11	4.69	2.17	0.34	NO	NO
WK+SO	OIL AND GREASE	14	9.82	3.13	0.45	YES	YES
LA+WK+SO	OIL AND GREASE	19	10.06	3.17	0.37	YES	YES
LA+WK+SO	OIL AND GREASE	18	4.62	2.15	0.22	YES	YES

----- TABLE XI-I -----

STATISTICAL RESULTS OF EQUATION (6) :
O & G / GUTTER MILE = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM. N = NUMBER OF OBSERVATIONS. F = F-TEST FOR MODEL. TV = T-TEST VALUE FOR THE COEFFICIENT B. RSQ = INDEX OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST & T-TEST OF THE COEFFICIENT B. SITE CODES : LA=LOS ANGELES, WK= WALNUT CREEK, SO=SACRAMENTO. FOR (N=18 LA+WK+SO) ONE LARGE SO VALUE OMITTED. FOR (N=10 LA+WK) ONE LOW LA VALUE OMITTED.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	OIL AND GREASE	11	6.82	2.61	0.43	YES	YES
LA+WK	OIL AND GREASE	10	7.13	2.67	0.47	YES	YES
WK+SO	OIL AND GREASE	14	0.07	0.27	0.01	NO	NO
LA+WK+SO	OIL AND GREASE	19	0.00	-0.06	0.01	NO	NO
LA+WK+SO	OIL AND GREASE	18	0.56	0.75	0.03	NO	NO

----- TABLE XII -----

STATISTICAL RESULTS OF EQUATION (7) :
O & G / GUTTER MILE = A + B (RUNOFF),
WHERE RUNOFF = LITERS OF RUNOFF. N = NUMBER OF OBSERVATIONS. F = F-TEST FOR MODEL. TV = T-TEST VALUE FOR THE COEFFICIENT B. RSQ = INDEX OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST & T-TEST OF THE COEFFICIENT B. SITE CODES : LA=LOS ANGELES, WK= WALNUT CREEK, SO=SACRAMENTO. FOR (N=10 LA+WK) ONE LOW LA VALUE WAS OMITTED.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	OIL AND GREASE	11	13.57	3.68	0.60	YES	YES
LA+WK	OIL AND GREASE	10	8.60	2.93	0.52	YES	YES

----- TABLE XIII-A -----

STATISTICAL RESULTS OF EQUATION (8) :
O & G / GUTTER MILE = A + B (RUNOFF) + C (VEHICLES) ,
WHERE VEHICLES = VEHICLES DURING STORM AND RUNOFF = LITERS.
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TR & TV ARE T-TEST VALUES FOR THE COEFFICIENTS B AND C.
RSQ IS THE INDEX OF DETERMINATION.
FSIG, TRSIG, & TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST AND T-TESTS OF THE COEFFICIENTS B AND C.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TR	TV	RSQ	FSIG	TRSIG	TVSIG
LA+WK	OIL AND GREASE	11	6.80	1.93	0.46	0.61	YES	NO	NO
LA+WK	OIL AND GREASE	10	4.36	1.14	0.76	0.55	NO	NO	NO

----- TABLE XIII-B -----

STATISTICAL RESULTS OF EQUATION (9) :
O & G / GUTTER MILE = A + B (RUNOFF X VEHICLES) + C (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM AND RUNOFF = LITERS.
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL. TR & TV ARE T-TEST VALUES FOR THE COEFFICIENTS B AND C. RSQ = INDEX OF DETERMINATION. FSIG, TRSIG, & TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST AND THE T-TESTS OF THE COEFFICIENTS B AND C. SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK. TEST FOR INTERACTION VARIABLE.

SITE	CONSTIT	N	F	TR	TV	RSQ	FSIG	TRSIG	TVSIG
LA+WK	OIL AND GREASE	11	3.42	0.66	0.54	0.46	YES	NO	NO

----- TABLE XIV -----

STATISTICAL RESULTS OF EQUATION (4) :
CONSTITUENT / ACRE = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM. N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL. TV IS THE T-TEST VALUE FOR THE COEFFICIENT B. RSQ = THE INDEX OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT THE .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST AND T-TEST OF THE COEFFICIENT, B. SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK. AT WK TWO STORMS WITH THREE INTERMITTENT PERIODS OF NO FLOW WERE SUMMED.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	NITRATE NITROGEN	13	6.44	2.54	0.67	YES	YES
LA+WK	AMMONIA NITROGEN	13	4.48	2.12	0.29	NO	NO
LA+WK	TOTAL KJELDAHL NITROGEN	13	10.39	3.22	0.49	YES	YES
LA+WK	ORTHOPHOSPHATE	12	0.25	0.50	0.02	NO	NO
LA+WK	TOTAL PHOSPHORUS	13	2.88	1.70	0.21	NO	NO

----- TABLE XV -----

STATISTICAL RESULTS OF EQUATION (6) :
CONSTITUENT / GUTTER MILE = A + B (VEHICLES),
WHERE VEHICLES = VEHICLES DURING STORM. N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL. TV IS THE T-TEST VALUE FOR THE COEFFICIENT B. RSQ = THE INDEX OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT THE .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST AND T-TEST OF THE COEFFICIENT, B. SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK. AT WK TWO STORMS WITH THREE INTERMITTENT PERIODS OF NO FLOW WERE SUMMED.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	NITRATE NITROGEN	13	7.66	2.77	0.41	YES	YES
LA+WK	AMMONIA NITROGEN	13	5.80	2.41	0.35	YES	YES
LA+WK	TOTAL KJELDAHL NITROGEN	13	13.88	3.73	0.56	YES	YES
LA+WK	ORTHOPHOSPHATE	12	0.29	0.54	0.03	NO	NO
LA+WK	TOTAL PHOSPHORUS	13	3.79	1.95	0.26	NO	NO

----- TABLE XVI -----

STATISTICAL RESULTS OF EQUATION (10-A) :
CONSTITUENT / ACRE = A + B(NONFILTERABLE RESIDUE / ACRE)
N = NUMBER OF OBSERVATIONS.
F IS F TEST FOR MODEL. TV IS THE T-TEST VALUE FOR THE COEFFICIENT B. RSQ = THE INDEX OF DETERMINATION. FSIG & TVSIG ARE RESULTS AT THE .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST AND T-TEST OF THE COEFFICIENT, B. SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK. AT WK TWO STORMS WITH THREE INTERMITTENT PERIODS OF NO FLOW WERE SUMMED.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	NITRATE NITROGEN	13	0.80	0.90	0.07	NO	NO
LA+WK	AMMONIA NITROGEN	13	0.63	0.79	0.05	NO	NO
LA+WK	TOTAL KJELDAHL NITROGEN	13	10.39	3.22	0.49	YES	YES
LA+WK	ORTHOPHOSPHATE	12	3.06	1.75	0.23	NO	NO
LA+WK	TOTAL PHOSPHORUS	13	23.17	4.81	0.68	YES	YES

----- TABLE XVII -----

STATISTICAL RESULTS OF EQUATION (10-B) :
CONSTITUENT/GUTTER MILE = A+B(NONFILTERABLE RESIDUE/GUTTER MILE)
N = NUMBER OF OBSERVATIONS.
F IS F TEST FOR MODEL. TV IS THE T-TEST VALUE
FOR THE COEFFICIENT B. RSQ = THE INDEX OF DETERMINATION.
FSIG & TVSIG ARE RESULTS AT THE .05 LEVEL OF SIGNIFICANCE FOR
THE F-TEST AND T-TEST OF THE COEFFICIENT, B. SITE CODES :
LA=LOS ANGELES, WK=WALNUT CREEK. AT WK TWO STORMS WITH THREE
INTERMITTENT PERIODS OF NO FLOW WERE SUMMED.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	NITRATE NITROGEN	13	0.43	0.66	0.04	NO	NO
LA+WK	AMMONIA NITROGEN	13	0.39	0.62	0.03	NO	NO
LA+WK	TOTAL KJELDAHL NITROGEN	13	7.16	2.67	0.39	YES	YES
LA+WK	ORTHOPHOSPHATE	12	2.92	1.71	0.23	NO	NO
LA+WK	TOTAL PHOSPHORUS	13	21.54	4.64	0.66	YES	YES

----- TABLE XVIII -----

STATISTICAL RESULTS OF EQUATION (11-A) :
CONSTITUENT / ACRE = A + B(FILTERABLE RESIDUE / ACRE)
N = NUMBER OF OBSERVATIONS.
F IS F TEST FOR MODEL. TV IS THE T-TEST VALUE
FOR THE COEFFICIENT B. RSQ = THE INDEX OF DETERMINATION.
FSIG & TVSIG ARE RESULTS AT THE .05 LEVEL OF SIGNIFICANCE FOR
THE F-TEST AND T-TEST OF THE COEFFICIENT, B. SITE CODES :
LA=LOS ANGELES, WK=WALNUT CREEK. AT WK TWO STORMS WITH THREE
INTERMITTENT PERIODS OF NO FLOW WERE SUMMED.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	NITRATE NITROGEN	13	29.91	5.47	0.73	YES	YES
LA+WK	AMMONIA NITROGEN	13	40.50	6.43	0.79	YES	YES
LA+WK	TOTAL KJELDAHL NITROGEN	13	71.05	8.43	0.87	YES	YES
LA+WK	ORTHOPHOSPHATE	12	44.40	6.66	0.82	YES	YES
LA+WK	TOTAL PHOSPHORUS	13	56.37	7.51	0.84	YES	YES

----- TABLE XIX -----

STATISTICAL RESULTS OF EQUATION (11-B) :
CONSTITUENT/GUTTER MILE = A+B (FILTERABLE RESIDUE/GUTTER MILE).
TWO STORMS WITH THREE INTERMITTENT NO FLOW PERIODS WERE SUMMED
AT WK. N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE
FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	LEAD	15	13.97	3.74	0.51	YES	YES
LA+WK	ZINC	15	45.21	6.72	0.78	YES	YES
LA+WK	BORON	14	2.02	1.42	0.14	NO	NO
LA+WK	NONFILTERABLE RESIDUE	15	5.03	2.24	0.28	YES	YES
LA+WK	CHEMICAL OXYGEN DEMAND	14	91.44	9.56	0.88	YES	YES
LA+WK	NITRATE NITROGEN	13	25.77	5.08	0.70	YES	YES
LA+WK	AMMONIA NITROGEN	14	39.08	6.25	0.78	YES	YES
LA+WK	TOTAL KJELDAHL NITROGEN	13	73.72	8.59	0.87	YES	YES
LA+WK	ORTHOPHOSPHATE	12	26.10	5.11	0.72	YES	YES
LA+WK	TOTAL PHOSPHORUS	13	43.56	6.06	0.80	YES	YES

----- TABLE XX -----

STATISTICAL RESULTS OF EQUATION (12-A) :
CONSTITUENT/ ACRE = A + B (TOTAL RESIDUE/ ACRE).
TWO STORMS WITH THREE INTERMITTENT NO FLOW PERIODS WERE SUMMED AT WK. N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	LEAD	15	6.80	2.61	0.34	YES	YES
LA+WK	ZINC	15	36.47	6.04	0.74	YES	YES
LA+WK	BORON	14	1.03	1.02	0.08	NO	NO
LA+WK	NONFILTERABLE RESIDUE	15	733.04	27.07	0.98	YES	YES
LA+WK	FILTERABLE RESIDUE	15	10.84	3.29	0.45	YES	YES
LA+WK	CHEMICAL OXYGEN DEMAND	14	23.73	4.87	0.66	YES	YES
LA+WK	NITRATE NITROGEN	13	1.75	1.32	0.14	NO	NO
LA+WK	AMMONIA NITROGEN	14	1.54	1.24	0.12	NO	NO
LA+WK	TOTAL KJELDAHL NITROGEN	13	16.61	4.08	0.60	YES	YES
LA+WK	ORTHOPHOSPHATE	12	5.07	2.25	0.34	YES	YES
LA+WK	TOTAL PHOSPHORUS	13	40.63	6.37	0.77	YES	YES

----- TABLE XXI -----

STATISTICAL RESULTS OF EQUATION (12-B) :
CONSTITUENT/GUTTER MILE = A + B (TOTAL RESIDUE/GUTTER MILE).
TWO STORMS WITH THREE INTERMITTENT NO FLOW PERIODS WERE SUMMED AT WK. N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	LEAD	15	4.83	2.20	0.27	YES	YES
LA+WK	ZINC	15	23.99	4.90	0.65	YES	YES
LA+WK	BORON	14	0.80	0.90	0.06	NO	NO
LA+WK	NONFILTERABLE RESIDUE	15	619.70	24.89	0.98	YES	YES
LA+WK	FILTERABLE RESIDUE	15	9.23	3.04	0.42	YES	YES
LA+WK	CHEMICAL OXYGEN DEMAND	14	21.05	4.59	0.64	YES	YES
LA+WK	NITRATE NITROGEN	13	1.21	1.10	0.10	NO	NO
LA+WK	AMMONIA NITROGEN	14	1.19	1.09	0.10	NO	NO
LA+WK	TOTAL KJELDAHL NITROGEN	13	11.92	3.45	0.52	YES	YES
LA+WK	ORTHOPHOSPHATE	12	4.83	2.20	0.33	NO	NO
LA+WK	TOTAL PHOSPHORUS	13	38.68	6.22	0.78	YES	YES

----- TABLE XXII -----

STATISTICAL RESULTS OF EQUATION (6) :
CONSTITUENT / GUTTER MILE = A + B (VEHICLES) ,
WHERE VEHICLES = VEHICLES DURING RUNOFF (START TO END OF FLOW).
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	LEAD	20	6.52	2.55	0.27	YES	YES
LA+WK	ZINC	20	35.56	5.96	0.66	YES	YES
LA+WK	BORON	17	33.36	5.78	0.69	YES	YES
LA+WK	NONFILTERABLE RESIDUE	19	0.33	0.58	0.02	NO	NO
LA+WK	FILTERABLE RESIDUE	19	15.74	3.97	0.48	YES	YES
LA+WK	TOTAL RESIDUE	19	1.23	1.11	0.06	NO	NO
LA+WK	CHEMICAL OXYGEN DEMAND	18	17.22	4.15	0.52	YES	YES
LA+WK	NITRATE NITROGEN	17	18.82	4.34	0.57	YES	YES
LA+WK	AMMONIA NITROGEN	17	13.42	3.66	0.47	YES	YES
LA+WK	TOTAL KJELDAHL NITROGEN	20	15.99	4.00	0.52	YES	YES
LA+WK	ORTHOPHOSPHATE	16	0.34	-0.58	0.02	NO	NO
LA+WK	TOTAL PHOSPHORUS	17	2.27	1.51	0.13	NO	NO

----- TABLE XXIII -----

STATISTICAL RESULTS OF EQUATION (10-B) :
CONSTITUENT/GUTTER MILE=A+B(NONFILTERABLE RESIDUE/GUTTER MILE)
A DATA POINT WAS DEFINED FROM START TO END OF FLOW.
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE
FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	LEAD	19	1.01	1.01	0.06	NO	NO
LA+WK	ZINC	19	4.07	2.02	0.19	NO	NO
LA+WK	BORON	17	0.00	0.02	0.01	NO	NO
LA+WK	FILTERABLE RESIDUE	19	0.67	0.82	0.04	NO	NO
LA+WK	CHEMICAL OXYGEN DEMAND	18	5.32	2.29	0.25	YES	YES
LA+WK	NITRATE NITROGEN	17	0.14	-0.37	0.01	NO	NO
LA+WK	AMMONIA NITROGEN	17	0.26	-0.51	0.02	NO	NO
LA+WK	TOTAL KJELDAHL NITROGEN	17	2.54	1.59	0.14	NO	NO
LA+WK	ORTHOPHOSPHATE	16	0.01	0.09	0.01	NO	NO
LA+WK	TOTAL PHOSPHORUS	17	12.11	3.48	0.45	YES	YES

----- TABLE XXIV -----

STATISTICAL RESULTS OF EQUATION (11-B) :
CONSTITUENT/GUTTER MILE=A+B(FILTERABLE RESIDUE/GUTTER MILE)
A DATA POINT WAS DEFINED FROM START TO END OF FLOW.
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE
FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	LEAD	19	17.01	4.19	0.51	YES	YES
LA+WK	ZINC	19	53.84	7.34	0.76	YES	YES
LA+WK	BORON	17	6.77	2.60	0.31	YES	YES
LA+WK	CHEMICAL OXYGEN DEMAND	18	41.68	6.46	0.72	YES	YES
LA+WK	NITRATE NITROGEN	17	31.23	5.59	0.68	YES	YES
LA+WK	AMMONIA NITROGEN	17	48.38	6.96	0.76	YES	YES
LA+WK	TOTAL KJELDAHL NITROGEN	17	42.45	6.52	0.74	YES	YES
LA+WK	ORTHOPHOSPHATE	16	2.25	1.50	0.14	NO	NO
LA+WK	TOTAL PHOSPHORUS	17	16.34	4.04	0.52	YES	YES

----- TABLE XXV -----

STATISTICAL RESULTS OF EQUATION (12-B) :
CONSTITUENT / GUTTER MILE = A + B (TOTAL RESIDUE / GUTTER MILE)
A DATA POINT WAS DEFINED FROM START TO END OF FLOW.
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE
FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	LEAD	19	2.48	1.57	0.13	NO	NO
LA+WK	ZINC	19	8.51	2.92	0.33	YES	YES
LA+WK	BORON	17	0.18	0.43	0.01	NO	NO
LA+WK	NONFILTERABLE RESIDUE	19	498.00	22.34	0.97	YES	YES
LA+WK	FILTERABLE RESIDUE	19	2.69	1.64	0.14	NO	NO
LA+WK	CHEMICAL OXYGEN DEMAND	18	10.31	3.21	0.39	YES	YES
LA+WK	NITRATE NITROGEN	17	0.05	0.22	0.01	NO	NO
LA+WK	AMMONIA NITROGEN	17	0.02	0.13	0.01	NO	NO
LA+WK	TOTAL KJELDAHL NITROGEN	17	5.45	2.33	0.27	YES	YES
LA+WK	ORTHOPHOSPHATE	16	0.12	0.34	0.01	NO	NO
LA+WK	TOTAL PHOSPHORUS	17	21.09	4.59	0.58	YES	YES

----- TABLE XXVI -----

STATISTICAL RESULTS OF EVALUATION TESTING OF EQUATION (6):
CONSTITUENT / GUTTER MILE = A + B (VEHICLES) ,
WHERE VEHICLES = VEHICLES DURING RUNOFF (START TO END OF FLOW).
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE
FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK, SO=SACRAMENTO.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK+SO	LEAD	47	13.60	3.69	0.23	YES	YES
LA+WK+SO	ZINC	50	2.52	1.59	0.05	NO	NO
LA+WK+SO	NONFILTERABLE RESIDUE	49	3.70	1.92	0.07	NO	NO
LA+WK+SO	FILTERABLE RESIDUE	49	0.90	0.95	0.02	NO	NO
LA+WK+SO	TOTAL RESIDUE	49	2.44	1.56	0.05	NO	NO
LA+WK+SO	CHEMICAL OXYGEN DEMAND	28	7.96	2.82	0.23	YES	YES
LA+WK+SO	TOTAL KJELDAHL NITROGEN	31	0.14	0.37	0.01	NO	NO
LA+WK+SO	ORTHOPHOSPHATE	29	1.21	-1.10	0.04	NO	NO

----- TABLE XXXI -----

STATISTICAL RESULTS OF EVALUATION TESTING OF EQUATION (3) :
CONSTITUENT = A + B (VEHICLES) , USING NO DATA TRANSFORMS,
WHERE VEHICLES = VEHICLES DURING RUNOFF (START TO END OF FLOW).
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE
FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK, SO=SACRAMENTO.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	LEAD	20	6.91	2.63	0.28	YES	YES
LA+WK	ZINC	20	40.74	6.38	0.69	YES	YES
LA+WK	NONFILTERABLE RESIDUE	19	0.67	0.82	0.03	NO	NO
LA+WK	FILTERABLE RESIDUE	19	18.78	4.33	0.52	YES	YES
LA+WK	TOTAL RESIDUE	19	2.35	1.53	0.12	NO	NO
LA+WK	CHEMICAL OXYGEN DEMAND	18	30.06	5.48	0.65	YES	YES
LA+WK	TOTAL KJELDAHL NITROGEN	17	20.56	4.53	0.58	YES	YES
LA+WK	ORTHOPHOSPHATE	16	0.20	-0.45	0.01	NO	NO

----- TABLE XXXII -----

STATISTICAL RESULTS OF EVALUATION TESTING OF EQUATION (3) :
CONSTITUENT = A + B (VEHICLES) , USING NO DATA TRANSFORMS,
WHERE VEHICLES = VEHICLES DURING RUNOFF (START TO END OF FLOW).
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE
FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK, SO=SACRAMENTO.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK+SO	LEAD	47	28.03	5.29	0.38	YES	YES
LA+WK+SO	ZINC	50	22.13	4.70	0.32	YES	YES
LA+WK+SO	NONFILTERABLE RESIDUE	49	9.63	3.10	0.17	YES	YES
LA+WK+SO	FILTERABLE RESIDUE	49	5.40	2.32	0.10	YES	YES
LA+WK+SO	TOTAL RESIDUE	49	10.01	3.16	0.18	YES	YES
LA+WK+SO	CHEMICAL OXYGEN DEMAND	28	49.32	7.02	0.65	YES	YES
LA+WK+SO	TOTAL KJELDAHL NITROGEN	31	4.45	2.11	0.13	YES	YES
LA+WK+SO	ORTHOPHOSPHATE	29	0.60	-0.77	0.02	NO	NO

----- TABLE XXXIII -----

STATISTICAL RESULTS OF EVALUATION TESTING USING NO TRANSFORMS OF EQUATION (13) : CONSTITUENT = A + B(TOTAL RESIDUE) , AND EQUATION (14) : ORTHOPHOSPHATE = A + (FILTERABLE RESIDUE) .
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK, SO=SACRAMENTO.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK	LEAD	19	2.82	1.68	0.14	NO	NO
LA+WK	ZINC	19	8.00	2.83	0.32	YES	YES
LA+WK	NONFILTERABLE RESIDUE	19	312.41	17.68	0.95	YES	YES
LA+WK	FILTERABLE RESIDUE	19	3.12	1.77	0.08	NO	NO
LA+WK	CHEMICAL OXYGEN DEMAND	18	10.23	3.20	0.39	YES	YES
LA+WK	TOTAL KJELDAHL NITROGEN	17	5.60	2.37	0.27	YES	YES
LA+WK	ORTHOPHOSPHATE	16	1.54	1.24	0.10	NO	NO

----- TABLE XXXIV -----

STATISTICAL RESULTS OF EVALUATION TESTING USING NO TRANSFORMS OF EQUATION (13) : CONSTITUENT = A + B(TOTAL RESIDUE) , AND EQUATION (14) : ORTHOPHOSPHATE = A + (FILTERABLE RESIDUE) .
N = NUMBER OF OBSERVATIONS. F IS F TEST FOR MODEL.
TV IS THE T-TEST VALUE FOR THE COEFFICIENT B.
RSQ IS THE INDEX OF DETERMINATION.
FSIG AND TVSIG ARE RESULTS AT .05 LEVEL OF SIGNIFICANCE FOR THE F-TEST AND T-TEST OF THE COEFFICIENT B.
SITE CODES : LA=LOS ANGELES, WK=WALNUT CREEK, SO=SACRAMENTO.

SITE	CONSTIT	N	F	TV	RSQ	FSIG	TVSIG
LA+WK+SO	LEAD	46	19.02	4.36	0.30	YES	YES
LA+WK+SO	ZINC	49	31.18	5.58	0.40	YES	YES
LA+WK+SO	NONFILTERABLE RESIDUE	49	377.07	19.42	0.89	YES	YES
LA+WK+SO	FILTERABLE RESIDUE	49	107.57	10.37	0.70	YES	YES
LA+WK+SO	CHEMICAL OXYGEN DEMAND	28	16.41	4.05	0.39	YES	YES
LA+WK+SO	TOTAL KJELDAHL NITROGEN	31	2.74	1.66	0.09	NO	NO
LA+WK+SO	ORTHOPHOSPHATE	29	12.02	3.47	0.31	YES	YES

9.3 Lead Emissions and Washoff

TABLE OF CONTENTS

FIGURES

TABLES

9.3 LEAD EMISSIONS AND WASHOFF

9.3.1 Estimated Source Strength of Lead

Using the "LEAD1" computer program, the total lead emitted from vehicle exhaust systems during the quarterly periods was computed for the westbound traffic which traveled through the 0.265 mile drainage catchment along Highway 50 in Sacramento. Detailed documentation of the "LEAD1" computer program is found in Reference (11). The inputs used for the program are summarized below:

Average daily vehicle miles traveled (westbound)		11,000
Average speed at cruise mode (mph)		55
California Vehicle mix (percentage of fleet):		
Light duty auto	81.5	
Light duty truck	12.1	
Medium duty truck	1.3	
Heavy duty gas	4.6	
Heavy duty diesel	0.5	
Inventory year		1980

The average daily emission rate of lead was 166 grams per day, which when multiplied by the days elapsed since the last sweeping/flushing, provides an estimate of the total lead emitted. By using the Rexnord data, dry lead loads resident on the freeway drainage catchment were computed. Table A-1 compares the total lead emitted quarterly with the resident dry load found by Rexnord. The dry lead load resident on the Sacramento Freeway surface (traveled lanes and shoulders) is less than 50 grams. The value of 41 grams from July to October represents the summer (no rain) lead

TABLE A-1

SACRAMENTO SWEEPING/FLUSHING - 'LEAD 1' COMPARISON

DATE OF SWEEPING/FLUSHING	DAYS	Pb EMITTED USING 'LEAD 1' (grams)	RESIDENT DRY LOAD FOUND BY SWEEPING/FLUSHING (grams)
December 12, 1979	---	---	43
March 27, 1980	106	17,596	30
July 23, 1980	118	19,588	28
October 22, 1980	91	15,106	41

load. The resident dry load on the traveled lanes and shoulders is several orders of magnitude less than quarterly emissions. A dustfall transect study performed by Rexnord at the Sacramento site also demonstrates the mass leaving the traveled surfaces. The majority of particles fall within the first ±30 feet in the unpaved areas from the edge of shoulder to the righ-of-way fence, not on the active, paved highway surfaces.

9.3.2 Correlations of Lead Washoff and Lead Emitted

Perusal of lead washoff values obtained from Rexnord at the Highway 50 Sacramento site indicate that for runoff events which are spaced closely in time, the washoff magnitudes are of the same order as the resident dry loads; however, for several events, the values of washoff exceed the observed dry load of ±50 grams.

Since lead from vehicle exhaust is in aerosol/particulate forms [Laxen and Harrison, 12], it is reasonable to postulate that during a rainfall/runoff event (rainfall, vehicle spray) a fraction the lead aerosol/particulate can be captured on the highway drainage catchment, instead of being dispersed as in dry periods to the adjacent lands. Therefore, linear correlations between lead (Pb) emissions and Pb washoff were tried using the equation below:

$$PbW = a + b\,(PbE),$$

where PbW is the lead (in grams) washed off the pavement,
PbE is the emitted lead (in grams) from vehicles during the storm,
and "a" and "b" are regression coefficients.

The "a" represents the dry gutter load, and "b" is the fraction of emitted lead which was washed off.

Initially, Sacramento data were studied. The Pb emissions (PbE) were computed using the "LEAD1" computer program. The inputs were the same as noted above except for vehicle miles traveled. Vehicle miles traveled were computed for the westbound, actual traffic counts during the runoff events. The starting and ending times were rounded to the nearest whole hour. Field personnel felt that the assumption, cruise speed at 55 mph, was reasonable. The results were statistically significant at the .05 level or better. Figure A-1 displays the scatter diagram, the equation of the line, number of observations, coefficient of correlation and F-test. The 45° line is also drawn on the figure as a point of reference.

The value of 0.32 grams for the intercept (initial load appears to be low considering the $\pm$50 grams value obtained by the Rexnord sweeping/flushing studies; however, the explanation is simply that the linear form does not account for the time interval between events and the sequence of the runoff events. Also, the flushing was done with a commercial wet vacuum cleaner which probably was more efficient in removing particulates than many of the runoff events of low rainfall intensity. Assuming that the freeway catchment were initially cleaned by (hypothetical) event one, then immediately (say within 1 hour) followed by (hypothetical) event two, we would not expect all of the Pb emitted during event two to be washed off since there is loss due to cracks in the pavement, background and traffic winds, and splashing. Thus, the fraction, .558 of Pb emitted which is washed off is reasonable. The cluster of points near the origin which lie above the 45° line can indicate:

1. There was sufficient time for a gutter load to build up and that Pb emitted occurred during low traffic volume times (off peak hours).

or

2. The assumptions in applying the "LEAD1" program were not correct, i.e., vehicle mix, mode, speed.

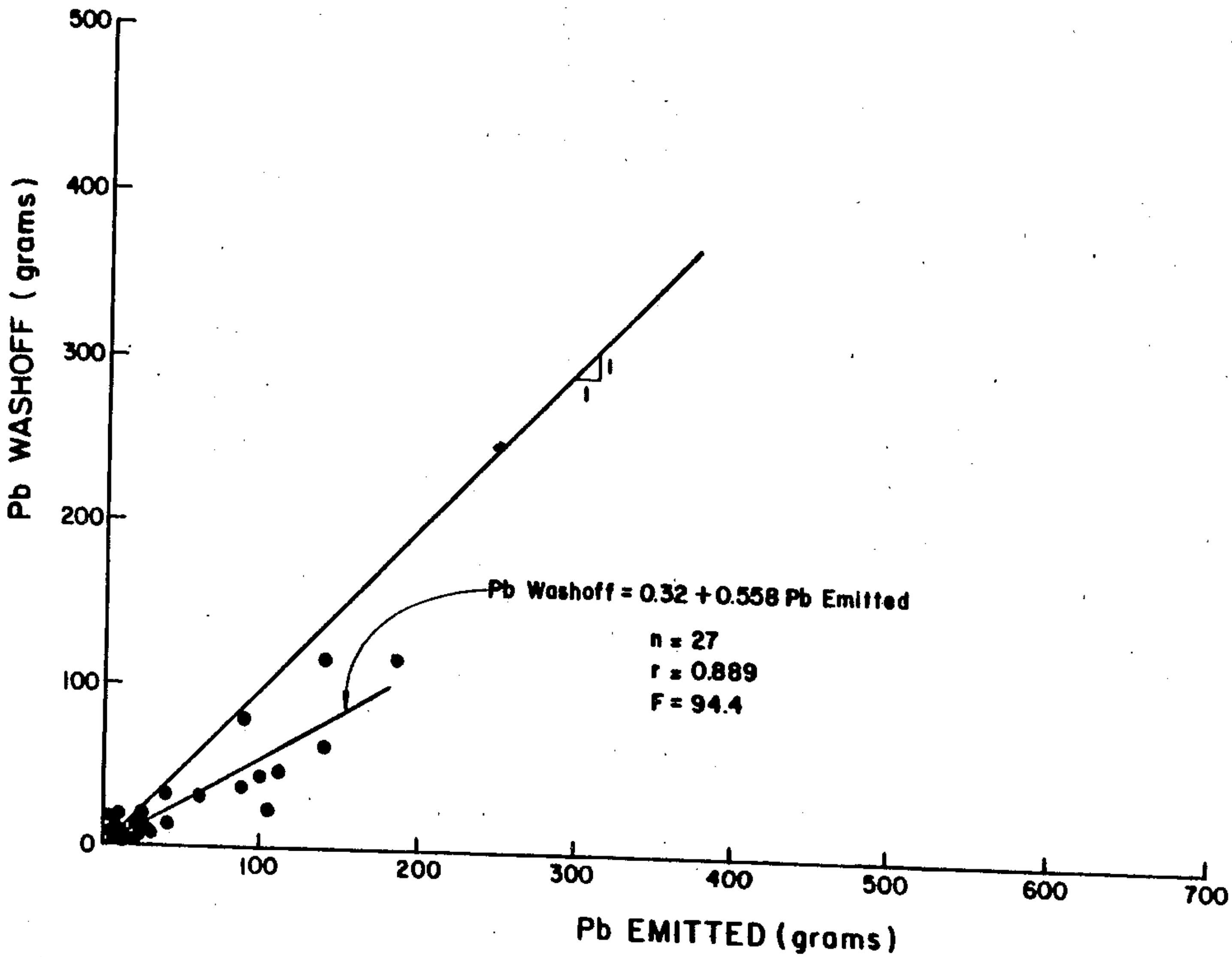
A traffic incident can cause erratic traffic patterns characterized by alternating acceleration/deceleration. The acceleration mode can cause Pb emission levels to exceed the Pb burned (input as fuel), because the Pb particulates trapped in the exhaust system can be resuspended [Laxen and Harrison, 13 and Coats, et al 14].

The Los Angeles washoff data were next correlated with the computed Pb emissions using the same assumptions for the "LEAD1" computer program (cruise mode at 55 mph ...) as those for Sacramento. Figure A-2 displays the scatter diagram and line characteristics. Since the seven data points display an erratic pattern by comparison to the Sacramento data, and since the slope of the line is negative, the program assumptions were reviewed, especially "cruise mode at 55 mph". As per discussions with the field sampling crew and as per later data obtained from the Los Angeles District Traffic Operations Unit on occupancy, volume, and speed algorithm, the traffic patterns through the freeway site are "stop-and-go" during peak hours at speeds less than 55 mph. Furthermore, the occupancy exceeds the theoretical design hourly volume of 1800 vehicles per hour; it is closer to 2200 vehicles per hour. The level of service would drop to a stop and go condition. A supplemental investigation of history of accidents within one mile on either side (northbound and southbound) of the runoff site showed 37 reported accidents occurred from October 1, 1980 to March 31, 1981 (time span of sampling). One accident in particular occurred during the sampling period of March 4-5, 1981 at Post Mile 17.5 at approximately midnight. Thus, it was presumed that "cruise mode at 55 mph" was not the operating condition during sampling; it was "stop-and-go" due to "rubbernecking" and normal slowing rather than "cruising" past an accident scene. Recognizing that the operating speeds are critical, and also recognizing that simulating daily or weekly traffic conditions in Los Angeles can be a Herculean task, the three data points (of Pb washoff) above the 45° line can be considered "typical of Los Angeles".

Another explanation for the three Los Angeles data points above the 45° line was attempted by looking at the storm hydrographs. It was observed that for low flows (<0.403 cfs or depth in 1' cutthroat flume less than three inches), low values of Pb washoff were observed; and conversely for large flows (>1.859 cfs of depths >8 inches) large values of Pb washoff were observed. This is analogous to trapped Pb particulates being exhausted from a vehicle exhaust system during rapid acceleration.

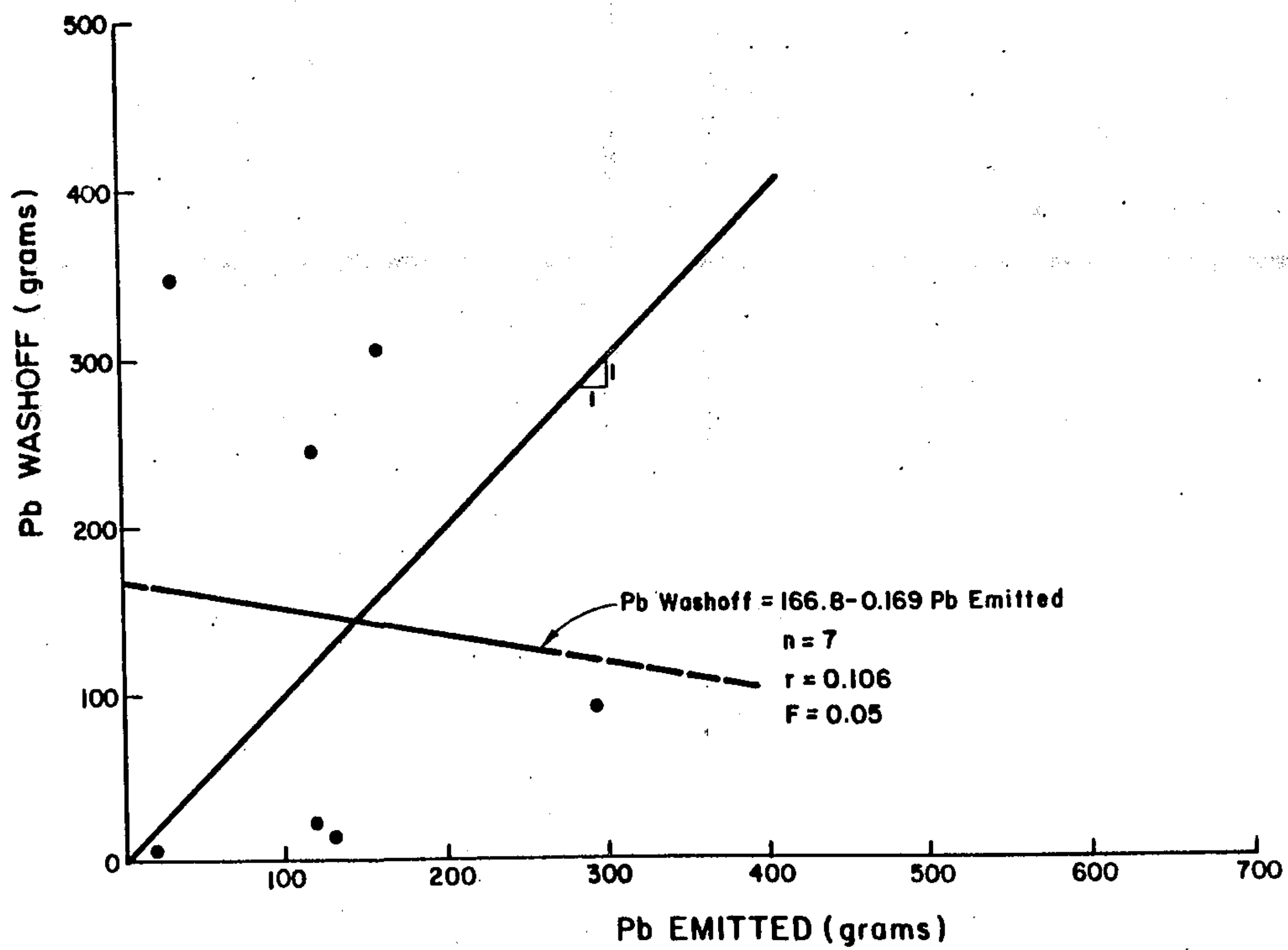
Similar linear correlations of Pb washoff vs. Pb emitted were done using the Walnut Creek data. However, several different treatments were tried. The statistical results (F-test) were marginal at the 0.05 level of significance. In Figure A-3, data from all 14 individual runoff events were correlated. Again, the statistical results were marginal, however, the Y-intercept value of 19.69 grams appeared to be reasonable (still low) as a "gutter load" and the coefficient 0.438 (of Pb emitted being washed off) also appeared to be reasonable, considering that the runoff coefficient values measured at Walnut Creek ranged from

0.39 to 0.80 for monitored events. When the Sacramento and Walnut Creek data were combined (not normalized), the Sacramento data appeared to "dominate" the results. (See Figure A-4 and compare Y-intercepts and slopes with Figure A-1; notice that the slopes and intercepts did not change very much.) In Figure A-5, the Los Angeles, Walnut Creek, and Sacramento data were combined (data not normalized), and although the equation shows significance at the .05 level with scatter (r = .49) due to the three Los Angeles data points above the 45° line, the Y-intercept and slope of the line appear reasonable.



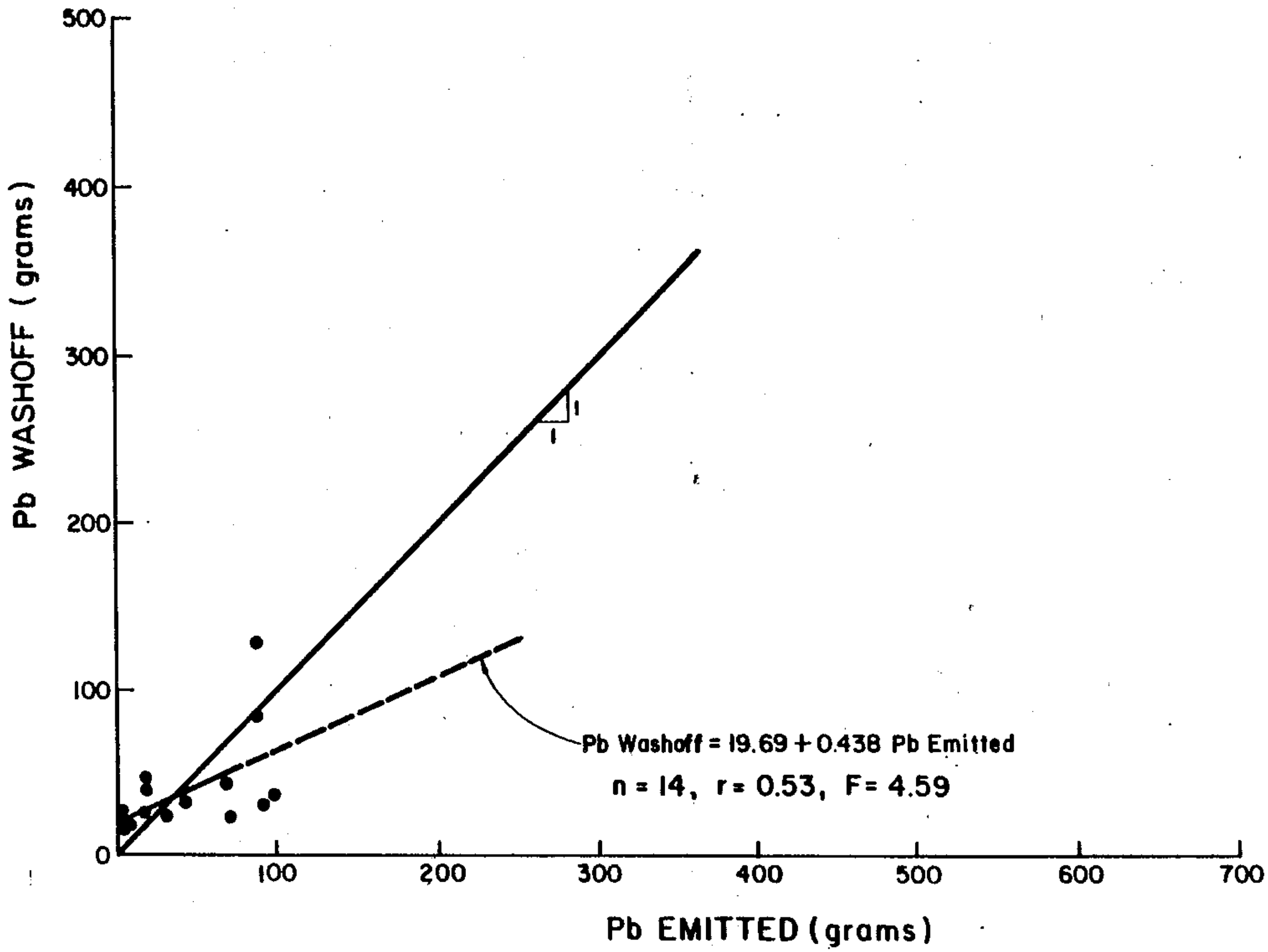
LEAD-SACRAMENTO

Figure A-1



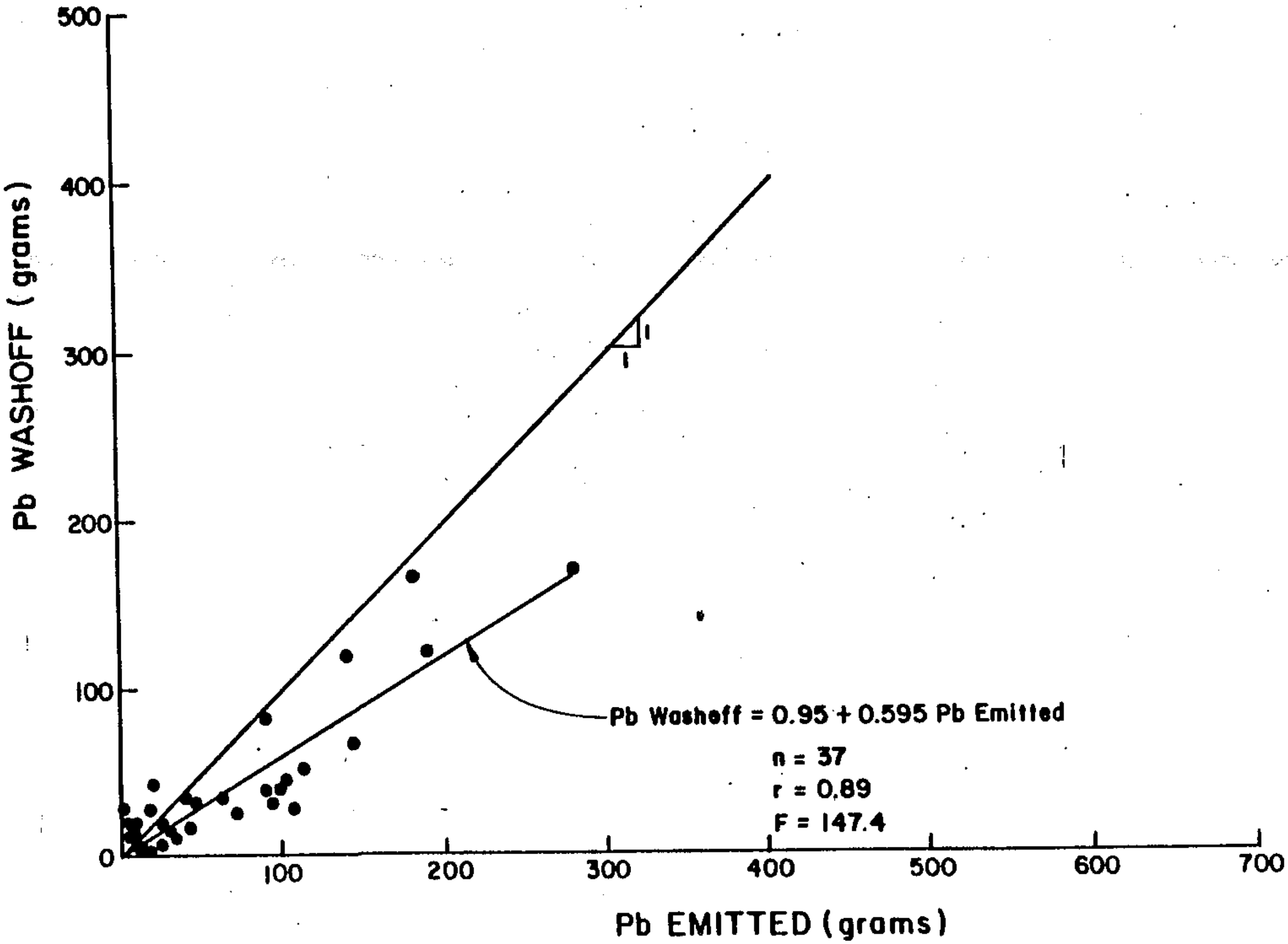
LEAD-LOS ANGELES

Figure A-2



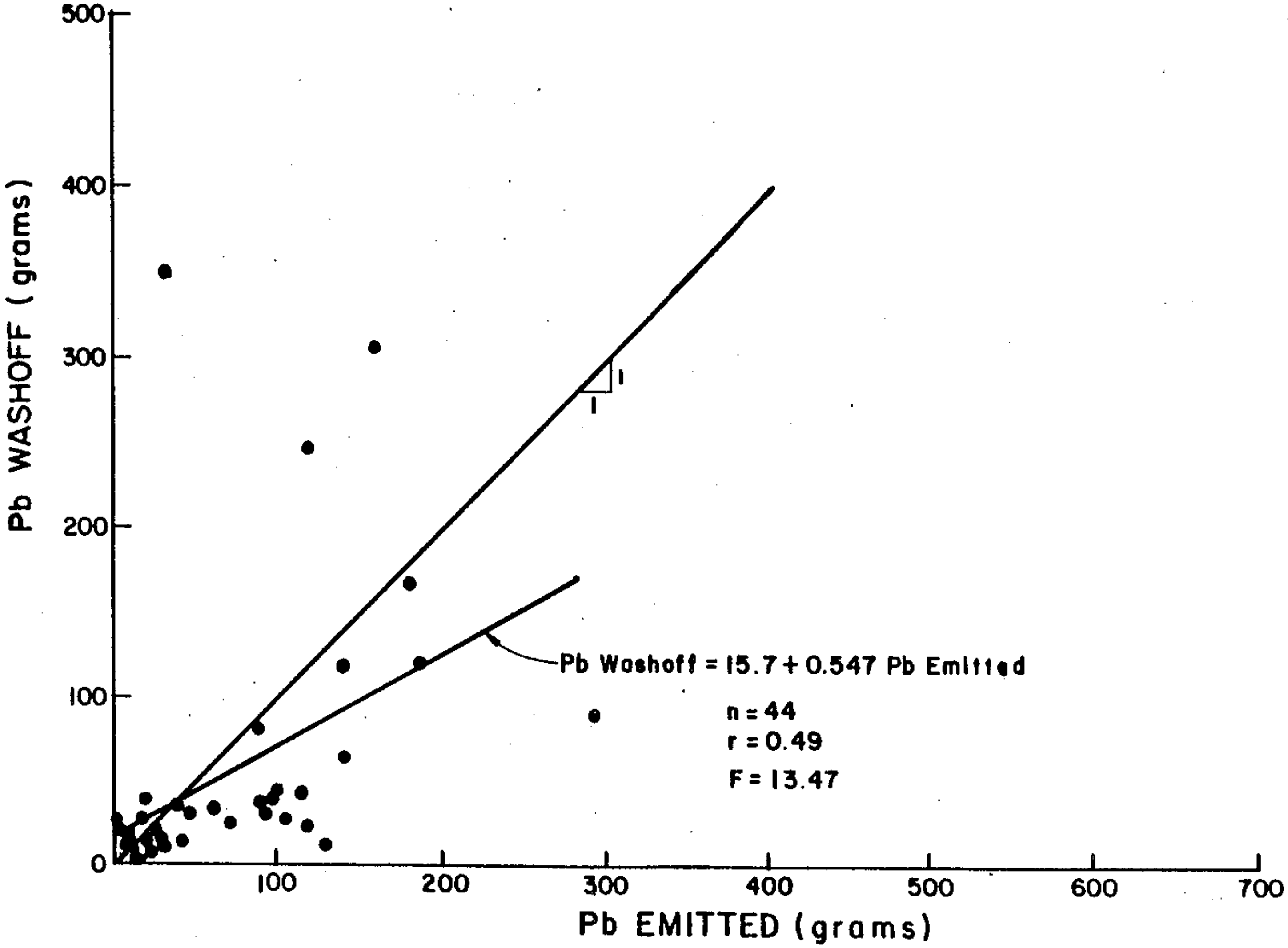
LEAD–WALNUT CREEK

Figure A-3



LEAD-SACRAMENTO and WALNUT CREEK

Figure A-4



LEAD–SACRAMENTO, WALNUT CREEK AND LOS ANGELES

Figure A-5