FHWA/NJ-91-007-7030

ARAN RUT DEPTH MEASUREMENT SYSTEM

FINAL REPORT

MARCH 1991

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In Cooperation With:

UNITED STATES DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/NJ-91-007-7030		

4. Title and Subtitle

ARAN Rut Depth Measurement System

5. Report Date
March 1991

6. Performing Organization Code

7. Author(s) Brian Margerum, Prin. Research Asst. & Ricardo Barros, Statistical Research Engineer

8. Performing Organization Report No.
91-007-7030

9. Performing Organization Name and Address
New Jersey Department of Transportation
1035 Parkway Avenue
Trenton, New Jersey 08625

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
NJ HPR Study 7030

12. Sponsoring Agency Name and Address

New Jersey Department of Transportation
1035 Parkway Avenue
Trenton, New Jersey 08625

13. Type of Report and Period Covered

Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

16. Abstract The results of a study to calibrate the acoustic rut measurement system of the New Jersey Department of Transportation's Automatic Road Analizer (ARAN) are presented.

Shortly after purchasing its ARAN unit, the NJDOT collected roughness, rut depth and distress data on New Jersey's Interstate highway system. The rut data was collected using the ARAN without extension wings. After processing this data using the software supplied with the ARAN, the rut measurements indicated virtually no rutting. Since these results were in direct contrast to data obtained manually for ongoing research projects, an evaluation of the ARAN rut depth measurement system was initiated.

The software, which computes rutting based on accoustic sensor readings, was modified to more accurately calculate rut depths with extension wings installed on the rut bar. In addition, a procedure for calculating rut depths from data collected without extension wings was developed.

Due to these modifications, the ARAN (with or without extension wings) is now capable of determining rut depths within 0.10 inches of standard (manual) measurements. Rutting values are averaged for 0.20 mile section lengths in New Jersey's Pavement Management System.

17. Key Words
ARAN, Rut Depth, Rutting
Acoustical Sensors

18. Distribution Statement

Copies available on request

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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IMPLEMENTATION

The rut depth measurement software modifications developed during the course of this study have provided the ability to accurately measure rutting with the New Jersey Department of Transportation's ARAN.

Implementation has been achieved by providing a copy of the modified software to the Bureau of Maintenance.

Periodic equipment operational prechecks have been established and will be performed by the Bureau of Maintenance to verify that proper system operation is accomplished.

ACKNOWLEDGMENTS

The authors wish to thank the Pavement Management Section of the Bureau of Maintenance for their assistance in this study.

A special note of thanks is extended to the ARAN crew members who enthusiastically configured the ARAN and drove in seemingly endless circles to collect the data required for this study.

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1.0 Research Objective

The purpose of this research study was to determine the ability of the New Jersey Department of Transportation's ARAN unit to replicate conventional manual rut depth measurements obtained on our bituminous pavements and to develop a plan for calibrating the rut measurement equipment.

2.0 Introduction

In 1986, the New Jersey Department of Transportation purchased an ARAN unit equipped with roughness, speed, distance, rut depth and gyro-based orientation measurement systems. In addition, the ARAN is equipped with distress rating keyboards and a videolog system. The data collected by the various systems is captured by an on-board computer and transferred to diskettes for further processing on a PC in the office. Software, provided by the ARAN manufacturer, is used to process this data and produce standard reports for each measurement system.

The Department's ARAN is configured to collect data in

.01 mile increments (every 52.8 feet). This data is averaged for each .20 mile section (1056 feet) for inventory reporting in NJ's Pavement Management System, however, the raw data is retained in .01 mile increments for more detailed reports and analysis if required.

2.1 Background

When New Jersey received the ARAN unit in the fall of 1986 a plan for verifying the output of each system (e.g., roughness, rut, geometrics, etc.) was adopted. The first step in this plan was to correlate the ARAN roughness measurement system with the Department's Mays Meters and a panel of users. At the time the ARAN was received, a panel study (correlation of user opinion with Mays meter roughness measurements) was being concluded.[1] Supplemental ARAN roughness measurements were obtained to correlate the ARAN with user opinion.

To establish a calibration procedure for the ARAN, data was also collected on six test sites to determine its repeatability and the effect of test speed and temperature on ARAN

[1] Vittilo N., Margerum B., Correlation of User Perceived Pavement Roughness (PSR) with Physical Roughness Measurements. NJDOT Research Report 89-007-7060 (July 1987)

roughness values. This data was also used to estimate the correlation of the ARAN and Mays units.

After the ARAN was calibrated for roughness, it was used to collect roughness, distress and rutting data on New Jersey's Interstate System in the Spring of 1988. The use of either the long or short extension wings on the rut bar make the vehicle excessively wide and difficult to negotiate in narrow, high traffic areas. This is particularly undesirable since it increases the possibility of an accident. Due to this safety problem, the Department's Pavement Management Section decided to eliminate the use of extension wings while collecting inventory data. However, subsequent ARAN data collected without wings indicated virtually no rutting. It was highly unlikely that the latter data was valid since it was in direct contrast to data obtained manually for then ongoing research activities concerning rutting of New Jersey's roads. In fact, because rutting is considered a relatively severe problem in New Jersey, it is a key element in determining rehabilitation needs. These obviously erroneous ARAN results prompted an immediate investigation of the unit's rut measurement system.

2.2 Rut Test Equipment

The ARAN comes equipped with a 7 foot rut bar mounted in place of the front bumper as shown in Figure 1. Seven acoustical sensors are mounted on the bottom of the rut bar at twelve inch intervals. A calibration sensor is mounted on the rear of the rut bar at a fixed distance from a target. This calibration sensor is used to adjust the rut bar sensor measurements for variation in air density identified by changes in the measured distance to the target. Short extension "wings" can be attached to either end of the rut bar increasing the number of sensors to eleven and the length of the bar to approximately 11 feet. Longer wings, containing 3 sensors each, can increase the total number of sensors on the rut bar to thirteen and the length to approximately 13 feet.

The manual rut measurement equipment historically used by the Department consists of a 10 foot long wood straightedge approximately one inch thick and five inches high. The narrow edge, which is placed on the pavement surface, is level across the entire length. Measurements are made by placing it across a wheelpath to traverse the entire width of the rut. Rut depth measurements are typically taken at fifty foot intervals along the roadway. The rut depth measurement is defined as the maximum distance from the bottom of the straightedge to the pavement surface. This device may

ARAN RUT MEASUREMENT SYSTEM

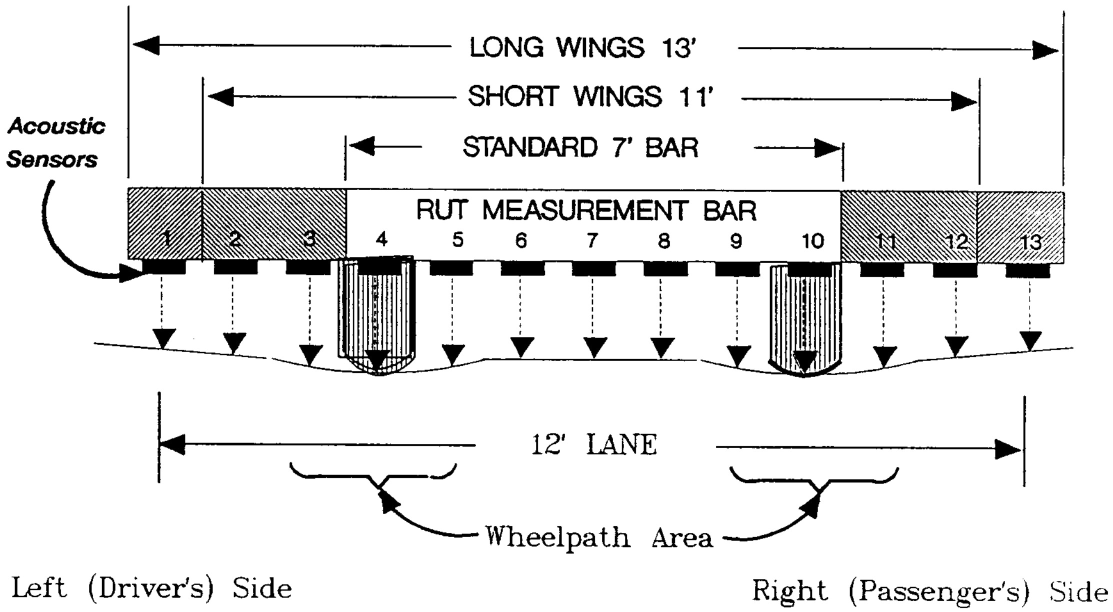

FIGURE 1

differ in design or size from state to state, however, the results produced by the straightedge method are comparable. In addition to the basic need for accurate data, it is important that the ARAN rut measurement results correlate with the manual measurements for historical perspective.

2.3 Other Agencies Operation/Calibration Procedures

Highway Products International, the manufacturer, of the ARAN, was contacted to determine if the problem was software related. They indicated that the ARAN is unable to generate rut measurements without either the long or short extension wings in place. The manufacturer's software relies on data from the outermost sensors (using the numbering system shown in Figure 1, these are sensors 1 or 2 and 12 or 13, depending on which extension wings are used) to calculate the rut depths in each wheelpath. Thus, without this input, their software package will not compute rut depths.

Five other transportation agencies using ARAN units were contacted to determine their testing procedures and methods for calibrating and verifying the accuracy of their rut bar output. Most indicated they have not had their ARAN units long enough to conduct a thorough evaluation of each system. However, most do use long wings when measuring rutting.

One agency employs one or two short wings in high volume locations or in areas with narrow lanes. These measurements are utilized in estimating the rut depths in at least one wheelpath.

Those agencies planning to verify the accuracy of the ARAN's rut measurement system anticipate using a calibration procedure that requires a water trough as recommended by the manufacturer. Using this method, the ARAN is placed on a level surface with the rut bar positioned over the water trough. The manually measured vertical distance from each sensor to the surface of the water can be compared to values measured by the ARAN software to verify that each sensor is functioning properly. Since the water surface is truly horizontal, the ARAN would be considered to be operating properly if no rut depths are calculated/reported.

3.0 Research Approach

Out of concern for safety, the ARAN software was examined to determine if, with modifications, rut depths could be calculated when the unit is operating without wings. Operation without wings was believed to be a necessity, particularly on multiple lane, high traffic areas common to New Jersey's road network.

In lieu of using a water trough, a simple method was developed to make preliminary (static) checks of the accuracy and repeatability of the ARAN's rut depth measurements using short wings, long wings and no wings.

These static tests were followed by field tests on three field sites (0.20 miles in length to match the section length reported in the Pavement Management System) with rut depths ranging from .2 to 1.0 inches. The results from these tests were compared to manual measurements as the standard or control.

3.1 Equipment Checks

The ARAN unit was placed on a level concrete slab (within 0.05" over 12' measured with a rod and surveyor's level) and each sensor was fired to determine the distance from the sensor to the floor. These distances were also measured with a ruler. In addition, wood blocks, ranging in thicknesses from one eighth of an inch to two inches, were placed on the floor below each sensor. The unit's sensors were then fired to determine the distance from each to the top of the blocks.

While checking the operation of the rut bar sensors, a 1.5 inch height differential or tilt was found across the length of the rut bar with the long wings installed and the vehicle unoccupied. The distance from sensor number 1 on the driver's side of the vehicle was 16.1 inches from the floor while sensor 13 on the passenger's side was 17.6 inches from the floor. The differential was attributed to the fact that most of the equipment (computer, video equipment, work table, etc.) is located on the driver's side of the vehicle. This differential was found to increase to over 2.0 inches or decrease to less than 1.0 inch depending on the weight and location of the operating crew.

The acoustical sensors were found to accurately measure the distance from the sensor to the floor and accurately detected the changes in the thickness of the blocks placed beneath them. The readings, which were observed on the monitor in the ARAN during testing, varied about 0.10 inch with the ARAN unit unoccupied and the motor off.

3.2 Software Checks

To determine how the sensor values were used to calculate rut depths, the ARAN software was investigated. From several discussions with the manufacturer's representative, the following procedure is used to determine the rut depth with the long wings installed:

For the left wheelpath, the program examines the values from sensors 1 and 2 and selects the smallest value (closest to the pavement)* as the height at the edge of the lane. The program then examines the readings from sensors 3, 4 and 5 and selects the largest value (farthest from the pavement). Finally, sensors 6 and 7 are evaluated to determine which is the closest to the pavement. The value from this sensor is used as the height at the middle of the lane. Data from the three sensors selected are combined to determine the slope of the line between the middle and outer high points and the distance from this line to the pavement surface based on the distance obtained from the sensor in the wheelpath. This is stored as the left rut depth. The same procedure is used to determine the rut depth in the right wheelpath using sensors 7 through 13.

The original software requires input from sensors 1 or 2 and 12 or 13 in order to calculate rut depths. This is the reason the ARAN reported no rutting when the Interstate system was measured without wings.

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* Refer to Figure 1 for sensor locations.

4.0 Development of Modified Rut Depth Calculation Method

During the analysis of the original ARAN software, a procedure was developed that improved the accuracy of estimating rut depths with either the short or long wings installed. The procedure checks the distance from all possible projected lines to the sensor values in the wheelpath to calculate the maximum rut depth. The upper portion of Figure 2 presents these modified procedures graphically.

Since we intended to utilize the ARAN without wings, due to safety, it was necessary to develop software to calculate rut depths based on the data from sensors 4 thru 10 on the main rut bar.

The modified software finds the smallest (shallowest) sensor value from sensors 6 or 7 on the left side and 7 or 8 on the right side (the center of the lane) and the greatest (deepest) from sensors 4 or 5 on the left side and 9 or 10 on the right side of the bar. The greatest value minus the smallest value is considered the rut depth. This procedure is presented in the lower portion of Figure 2.

The rut depths calculated by the modified ARAN software were not expected to exactly replicate manual measurements. Basically, this is due to the fact that the ARAN measures at fixed 12 inch intervals across the pavement while the manual measurements are determined by sliding a scale along the

ARAN Rut Calculations

LONG AND SHORT WINGS

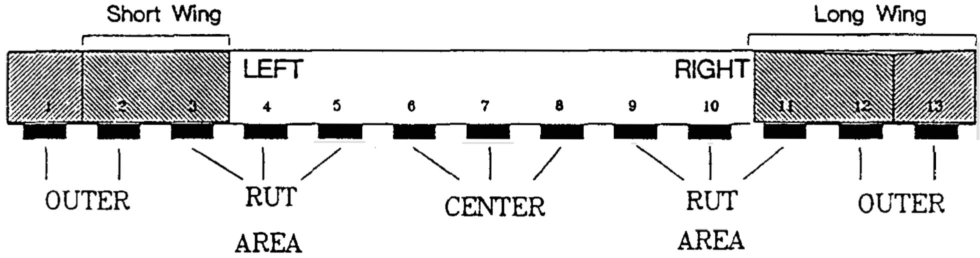
To calculate the left wheelpath rut :

A. Determine the slope between all combinations of center and outer sensor readings on the left side of the rut bar. (Only one outer sensor with short wings.)

B. Find the distance between each slope found in A and each of the rut area sensors on the left side.

C. Retain the greatest distance.

The right wheelpath rut is found by the same procedure using sensors 6 through 13.



NO WINGS

To calculate the left wheelpath rut :

A. Find the smallest center sensor value from sensors 6 or 7

B. Find the larger sensor value from sensors 4 or 5.

C. The left rut depth equals A - B.

The right wheelpath rut is found by the same procedure using sensors 7, 8, 9 and 10.

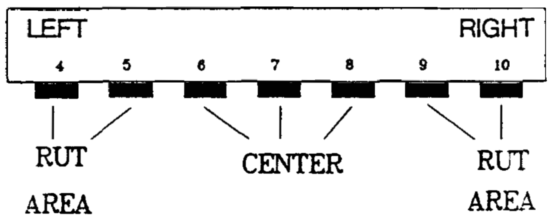


Figure 2

straightedge across the wheelpath until the deepest reading is located. In addition, the straightedge is positioned to span from the center of the lane to the outer edge of the lane while the ARAN, without wings, measures from the center of the lane to the approximate center of the wheelpath. If the outer edge of the lane is higher than the center of the lane, the ARAN will underestimate the rut. Conversely, if the center if the lane is higher than the outer edge of the lane, the ARAN will overestimate the rut.

4.1 Follow-up Static Tests

Once the modified software was developed, a second series of static tests were conducted with the ARAN again positioned on a level concrete floor. One test was run with nothing below the sensors to simulate a no rut condition. Blocks of wood were then placed on the floor beneath sensors 2, 7, and 12 to create ruts of .125, .250, .50, .75, 1.00, 1.50 and 2.00 inches.

4.1.1 Long and Short Wing Static Measurements

The upper portion of Table 1 presents the results calculated from the data collected on the wood blocks. Both the long wing and short wing results show a rut depth ranging from 0.1 to 0.2 inches greater than the actual rut on the left (driver's) side and within 0.1 inches of the actual rut on the right (passenger's) side.

TABLE 1

Difference Between Actual and Static ARAN Measured Rut Depths

NJ Modified Software

Rut Created With Blocks	Long Wings Left	Long Wings Right	Short Wings Left	Short Wings Right	No Wings Left	No Wings Right
0.0	+.2	+.1	+.2	0	-.1	+.3
0.125	+.1	+.1	+.2	+.1	-.2	+.3
0.25	+.1	0	+.1	0	-.2	+.3
0.50	+.2	0	+.2	0	-.2	+.4
0.75	+.1	-.1	+.1	-.1	-.2	+.3
1.00	+.2	+.1	+.2	+.1	-.2	+.4
1.50	+.1	0	+.1	0	-.2	+.3
2.00	+.1	0	+.1	0	-.2	+.3

Average of 50 measurements for each rut configuration.

NJ Modified Software With Correction Factors Applied

Rut Created With Blocks	No Wings Left	No Wings Right
0.0	+.1	0
0.125	0	0
0.25	0	0
0.50	0	+.1
0.75	0	0
1.00	0	+.1
1.50	-.1	0
2.00	0	0

4.1.2 No Wing Static Measurements

The results of the no wing measurements are also presented in the upper portion of Table 1. As can be seen, the left side generally calculates a rut 0.2 inches less than the actual rut and the right side is generally 0.3 inches greater than the actual rut.

Some disparity was expected since the rut bar, as discussed in section 3.1, is tilted. To correct for this, the software was modified (only for no wing mode) to include the average correction found during the tests on the blocks (+0.2 inches for left rut and -0.3 inches for the right rut). The lower portion of Table 1 shows the results of this modification on rut measurements obtained without wings.

4.2 Dynamic Tests (No Wings)

Three field test sites were established to gauge the accuracy of the ARAN rut measurement system when collecting data at the normal test speed (40 M.P.H.) with no wings on the rut bar. These sites were 0.20 miles (1056 feet) in length (replicating the section length used by the Pavement Management System), with individual rut depths ranging from 0.2 to 1.7 inches measured manually. As previously mentioned, the ARAN is configured to collect data every 52.8 feet, therefore twenty measurements are taken in each wheelpath in a given .20 mile section. The average of these measurements would be reported as the ARAN rut depth for the given section.

As can be seen in Table 2, for any single pass, the ARAN data is generally within 0.2 inches of the known (manual) value. If the rut is defined to be the average of the left and right wheelpaths -- as presently reported in the Department's pavement management data base -- the average for any given pass is within 0.1 inches of the average known value.

Similar results were obtained when the static ARAN data was collected. The static ARAN measurements can be found in Appendix A.

For practical purposes these results qualify our ARAN unit, without extension wings, with the modified software, as a reasonably precise instrument with which to collect network-level rut data. Not only will it efficiently characterize the overall rut condition of the roadway system, but it will also identify those particular roadway sections having a severe rutting problem.

A more detailed statistical analysis of the rut measurements collected during this study can be found in Appendix B.

Table 2

Dynamic Rut Measurements

No Wings

Site 1

Manual Left	Manual Right	Manual Avg	Pass	ARAN with No Wings Left	Right	Avg	Diff
0.5	0.5	0.5	1	0.5	0.6	.55	+.05
			2	0.5	0.6	.55	+.05
			3	0.6	0.5	.55	+.05
			4	0.5	0.4	.45	-.05
			5	0.5	0.3	.40	-.10

Site 2

Manual Left	Manual Right	Manual Avg	Pass	ARAN with No Wings Left	Right	Avg	Diff
1.0	1.0	1.0	1	1.1	0.9	1.0	0
			2	1.1	0.7	0.9	-0.1
			3	1.0	0.8	0.9	-0.1
			4	1.1	0.9	1.0	0
			5	1.0	0.9	0.95	-0.05

Site 3

Manual Left	Manual Right	Manual Avg	Pass	ARAN with No Wings Left	Right	Avg	Diff
0.4	0.3	0.35	1	0.5	0.2	.35	+.05
			2	0.4	0.2	.30	+.05
			3	0.4	0.1	.25	+.05
			4	0.4	0.2	.30	-.05
			5	0.4	0.1	.25	-.10

* Standard test speed of 40 MPH.

5.0 Conclusions

1. The Pavement Management System used by the Department will report rutting as the average of the left and right wheelpaths for a 0.20 mile section. The ARAN rut measurement system, when data is collected in the no-wing mode and averaged between wheelpaths, has demonstrated the ability to estimate known rut values (measured with a straightedge) to within approximately 0.1 inches.

2. Occasions may arise in which the rut depth of a single wheelpath is desired. The potential for error associated with a single pass is approximately 0.2 inches, therefore, replicate passes over each site are suggested for optimum results.

3. When calibrating the rut measurement system, a major concern is the effect of the weight of crew members. If one or more of the crew members are substantially heavier or lighter than the average crew weight, their placement in the unit may require that a different correction factor be applied to the data based on their position in the unit. These correction factors must be established and included in the modified software. Prior to testing, the crew members identification numbers are entered (in a predetermined order indicating their position in the unit) into the header record via the main keyboard in the ARAN. When the data is processed by the modified software, the appropriate adjustment is made to the rut measurements based on the crew information contained in the header record.

6.0 RECOMMENDATIONS

Due to safety considerations, the ARAN should be used without extension wings during inventory testing. If more detailed rut measurements are required for analysis of specific projects, replicate measurements should be obtained and averaged.

Until a permanent calibration facility is available, a level surface similar to that used for calibration during this study should be used for static calibration. A series of tests can be conducted using wood blocks to verify the adjustments. A log, containing the date and sensor readings must be kept to document changes in the rut bar/pavement surface relationship. The rut depth adjustment factors contained in the modified software will be adjusted as required by the Pavement Management Engineer responsible for the ARAN data processing.

LIST OF APPENDICIES

APPENDIX A

STATIC RUT MEASUREMENTS

ON FIELD TEST SITES

Manual and No Wing ARAN Static Rut Measurements

Site 1

Location on Site	Left Wheelpath Manual	Left Wheelpath ARAN	Right Wheelpath Manual	Right Wheelpath ARAN
1	0.6	0.7	0.3	0.4
2	0.4	0.8	0.6	0.4
3	0.6	0.7	0.6	0.4
4	0.5	0.6	0.5	0.4
5	0.5	0.7	0.4	0.3
6	0.4	0.6	0.5	0.3
7	0.4	0.5	0.3	0.2
8	0.4	0.6	0.4	0.4
9	0.5	0.4	0.4	0.4
10	0.6	0.5	0.6	0.7
11	0.6	0.8	0.6	0.4
12	0.4	0.6	0.6	0.5
13	0.5	0.6	0.8	0.6
14	0.4	0.4	0.6	0.4
15	0.4	0.5	0.4	0.4
16	0.4	0.7	0.4	0.5
17	0.4	0.5	0.6	0.5
18	0.5	0.7	0.5	0.5
19	0.6	0.9	0.8	0.9
Avg.	0.5	0.6	0.5	0.5

Note: Data was not available for one location on this site.

Manual and No Wing ARAN Static Rut Measurements

Site 2

Location on Site	Left Wheelpath Manual	Left Wheelpath ARAN	Right Wheelpath Manual	Right Wheelpath ARAN
1	0.9	0.9	0.9	0.8
2	1.0	1.2	0.9	0.8
3	0.9	1.0	1.0	0.8
4	1.0	1.2	1.2	1.2
5	1.1	1.1	1.0	1.0
6	0.7	0.8	0.6	0.7
7	0.9	0.9	0.7	0.8
8	1.0	1.0	1.0	1.0
9	1.1	1.1	1.1	1.0
10	1.0	1.0	1.0	0.8
11	1.0	0.9	0.9	0.8
12	0.9	0.9	0.9	0.9
13	1.0	0.9	1.0	0.8
14	1.2	1.2	1.4	1.3
15	1.0	1.0	1.7	1.6
16	0.9	0.7	1.0	1.1
17	1.1	1.2	1.1	1.0
18	1.4	0.7	0.9	0.7
19	1.0	0.9	1.0	0.7
20	1.2	0.9	1.0	0.6
Avg.	1.0	1.0	1.0	0.9

Manual and No Wing ARAN Static Rut Measurements

Site 3

Location	Left Wheelpath		Right Wheelpath	
on Site	Manual	ARAN	Manual	ARAN
1	0.3	0.2	0.3	0.1
2	0.3	0.3	0.3	0.0
3	0.3	0.4	0.3	0.0
4	0.3	0.3	0.3	0.1
5	0.3	0.4	0.3	0.1
6	0.4	0.3	0.2	0.2
7	0.4	0.4	0.3	0.2
8	0.4	0.4	0.3	0.2
9	0.3	0.3	0.2	0.1
10	0.5	0.4	0.5	0.4
11	0.4	0.4	0.2	0.1
12	0.4	0.4	0.3	0.1
13	0.4	0.4	0.3	0.3
14	0.4	0.5	0.3	0.2
15	0.5	0.5	0.3	0.3
16	0.4	0.4	0.3	0.3
17	0.4	0.5	0.3	0.2
18	0.4	0.5	0.3	0.3
19	0.5	0.5	0.3	0.3
20	0.4	0.4	0.3	0.2
Avg.	0.4	0.4	0.3	0.2

APPENDIX B

STATISTICAL ANALYSIS OF
ARAN RUT CALIBRATION DATA

Statistical Analysis of Aran Rut Calibration Data

This appendix summarizes selected statistical analyses performed in calibrating the Department's ARAN device. It concludes that the ARAN is capable of measuring individual wheelpath rut depths to within approximately ± 0.20 inches in both the long wing and in the no wing mode over the 0.2 mile pavement section lengths used in the Department's pavement management program. When the average of the left and right wheelpath is reported, this precision reduces to, approximately, ± 0.14 inches. Short wing mode measurements are not recommended. Specific findings follow.

1) **Controlled, Laboratory Tests of Individual Sensor Readings.**

On August 24, 1989, the ARAN was parked on a smooth concrete floor in the Fernwood building and the sensors fired in several replicates of 100 shots each. Wooden blocks of several known thicknesses were shuffled in turn beneath each of the sensors. For each sequence of measurements, the average sensor reading was observed to be within 0.05 inches or less of the correct value. The sensor standard deviations were homogeneous and the pooled value was estimated to be 0.05 inches, as shown in Table B1. Under ideal conditions, this precision indicates that the minimum standard deviation to be expected from calculated ruts is approximately 0.07 inches.

It was observed and confirmed that the ARAN rut bar is not parallel with the ground. The degree of tilt is dependent upon the vehicle loading but, generally, conforms to a slope of approximtely 1.5 inches over the rut bar's 12 foot length.

2) **Field Tests of Individual Sensor Readings**

The ARAN was parked at twenty locations on each of three sites and each sensor was fired 50 times at each location. While the actual distance between each of the sensors and the pavement beneath was "uncontrolled", for each location this distance was fixed and allowed the sensor precisions to be determined. It was observed that the precision of the right sensors (nos. 7-13) tended to be nearly double that of the left sensors (nos. 1-6) on two of the three sites. A satisfactory explanation for this observation was not produced. The estimated pooled precision values are also presented in Table B1.

Using the overall pooled sensor standard deviation of 0.1 inches, the expected standard deviation for the calculated rut is estimated to be approximately 0.12 inches. The corresponding 95 percent confidence limits on reported ruts is approximately ± 0.20 inches. According to the central limit theorem, averaging two ruts (i.e., the left and right wheelpaths) will reduce this confidence band to ± 0.14 inches.

3) **Controlled Field Tests**

Controlled, dynamic field tests were conducted in which replicate passes were made with the ARAN over pavements of known rut depths. (Reference Section 4.2 in the main body of this report.) As indicated in Table B2, the maximum discrepancy observed in the long wing mode was 0.17 inches on Site 2 for the right rut. This observation is consistent with (2) above. For the no wing mode, it had been empirically determined that a -0.3 inch adjustment to the right rut and a +0.2 inch adjustment to the left rut would generally compensate for the bias attributed to rut bar tilt. The maximum discrepancy observed after these adjustments had been made is seen to be 0.19 inches, also for the Site 2 right rut. On Site 3, where the rut magnitude is smaller, the right rut errs by 0.14 inches. If the left and right ruts are averaged, the grand mean for this data set agrees to within 0.10 inches for both the long wing and no wing modes.

4) **Simulation Check of Rut Calculation Procedure**

A computer simulation analysis was performed to determine whether biased rut measurements result when the ARAN's rut bar is used to profile wheelpath elevation. Unlike use of the straightedge, the fixed sensor spacing of the rut bar may unavoidably bias the maximum depth readings towards a smaller magnitude. The simulation analyses demonstrated that this consideration, although real, is practically negligible for the long wing mode measurement procedure.

Simulation analysis also demonstrated that the effect of rut bar tilt is also negligible for ruts calculated in the long wing mode.

The average simulated long wing ruts were typically within 0.05 inches of the average simulated straightedge measurement under a variety of conditions tested. This accuracy potential is considered to be very satisfactory for the purposes of pavement management, confirming the appropriateness of the rut calculation procedure.

5) **ARAN Short Wing Rut Measurements**

The advantages offered by the ARAN's short wing mode of operation are of dubious benefit. The width of these wings are only marginally less than that of the long wings, while computer simulation indicates a systematic bias of up to 0.40 inches may result for certain rut configurations due to the procedure alone. Thus it is recommended that the ARAN not be operated in the short wing mode.

6) **Average of Left/Right Wheelpath Rut Reported**

For the purposes of pavement management, the average of the left and right rut over a 0.2 mile pavement section is reported. Despite the apparently small, unexplained discrepancies in measuring individual ruts, this data suggests that the mean of the left and right wheelpath rut measurements may satisfactorily represent the mean manually measured for the Department's network-level pavement management purposes.

Table B1. Pooled Precision Estimates of Individual Sensors.

	Sensor Standard Deviation in Static Mode												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Laboratory	0.06	0.05	0.06	0.04	0.04	0.05	0.06	0.05	0.07	0.05	0.04	0.05	0.05
Field	0.10	0.09	0.10	0.07	0.10	0.11	0.13	0.16	0.18	0.17	0.16	0.17	0.16

Overall pooled laboratory precision: 0.05
Overall pooled field precision: 0.14
Field, sensors 1-7: 0.10
Field, sensors 8-13: 0.17

Table B2. Field Measured Dynamic Ruts.

	LONG WING DYNAMIC RUT						NO WING DYNAMIC RUT ADJUSTED FOR RUT BAR TILT					
	Left		Right		Average		Left		Right		Average	
Site	Manual	ARAN	Manual	ARAN	Manual	ARAN	Manual	ARAN	Manual	ARAN	Manual	ARAN
1, Rt 29	0.48	0.54	0.52	0.40	0.50	0.47	0.48	0.52	0.52	0.48	0.50	0.50
2, Rt 1	1.02	0.92	1.03	0.86	1.03	0.89	1.02	1.06	1.03	0.84	1.03	0.95
3, Rt 195 South	0.39	0.33	0.30	0.20	0.35	0.27	0.39	0.42	0.30	0.16	0.35	0.29
Grand Average					0.63	0.54					0.63	0.58