Evaluation of Retroreflectometers

for

The Alabama Department of Transportation

By

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16. Abstract

This project performed field-testing and analysis of two pavement marking retroreflectometers: the Laserlux and the LTL2000. The Laserlux is a vehicle–mounted device that takes readings at driving speed and produces computerized output. The LTL2000 is a hand-held device that also provides computerized output. The Federal Highway Administration (FHWA) may soon establish standards for pavement marking retroreflectivity, so the Alabama Department of Transportation (ALDOT) wished to establish which of the two devices would be most useful in complying with future standards.

The cost analysis of the two retroreflectometers clearly indicated that the Laserlux is the more cost effective retroreflectometer when measuring the approximately 11,000-centerline miles of the ALDOT system for an analysis period of eight years. The cost to test pavement markings for those circumstances is approximately $5/mile of marking per year for the Laserlux and approximately $35/mile of marking per year for the LTL2000. Only one Laserlux and one crew would be required to perform the testing. Eight LTL2000s and eight crews would be required to perform the same task.

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Executive Summary

This project performed field-testing and analysis of two competing pavement marking retroreflectometers: the Laserlux and the LTL2000. The Laserlux is a vehicle–mounted device, costing roughly $200,000 per unit that takes readings at driving speed and produces computerized output. The LTL2000 is a hand-held device costing approximately $20,000 that also provides computerized output. The Federal Highway Administration (FHWA) may soon establish standards for pavement marking retroreflectivity, so the Alabama Department of Transportation (ALDOT) wished to establish which of the two devices would be most useful in complying with the standards. The project was conducted to evaluate the relative usefulness and productivity of the two devices and to outline a methodology to implement the expected FHWA standards using the most suitable device.

The cost analysis of the two retroreflectometers clearly indicates that the Laserlux is the more cost effective retroreflectometer when measuring approximately 11,000 centerline miles (33,000 miles of pavement marking) for an analysis period of eight years. The cost to test pavement marking for those circumstances is approximately $5/mile of marking per year for the Laserlux and approximately $35/mile of marking per year for the LTL2000. Only one Laserlux and one crew would be required to perform the testing. Eight LTL2000s and eight crews would be required to perform the same job. (The Laserlux requires an LTL2000 to perform daily control sections. The cost of an LTL2000 was not included in the Laserlux analysis because ALDOT already possesses these instruments.) Appendix A contains a detailed summary of the cost analysis.

Appendix B, Monitoring Procedures of Pavement Markings, outlines a methodology for annually measuring the retroreflectivity of the pavement markings on all ALDOT-controlled roads. The work will require one Laserlux van and a crew of two technicians for approximately eight months per year of fieldwork. Tests will be performed on dry roads at highway speeds; no traffic control will be required. The Appendix also describes the calibration and control section procedures that must be done each day before work can begin. It ends with a brief methodology for selecting and confirming those sections of marking that should be replaced or maintained each year.

Section 1.0
Introduction

Pavement markings are important elements of the roadway system. Markings are retroreflectorized so they can function in both day and night conditions. Such markings redirect light from vehicle headlights back to drivers, so they can see the markings at night.

The American Society of Testing and Materials (ASTM) test E 1710-97 established standard retroreflectivity measurement geometries for pavement markings by adopting the "30-meter geometry." Tests using this geometry measure the performance of a marking that is located 30 meters in front of a standard vehicle. The European Committee on Standardization specifies this same geometry.

This project involved field-testing two competing 30-meter geometry pavement marking retroreflectometers: the Laserlux and the LTL2000. The Laserlux is a vehicle–mounted device, costing roughly $200,000 per unit, which takes readings at driving speed and produces computerized output. The LTL2000 is a hand-held device costing approximately $20,000 that also provides computerized output. The Federal Highway Administration (FHWA) may soon establish standards for pavement marking retroreflectivity, so the Alabama Department of Transportation (ALDOT) wishes to establish which of the two devices would be most useful in complying with the standards. This project included evaluating the relative usefulness and productivity of the two devices and writing a methodology to implement the expected FHWA standards using the more suitable device.

The research presented herein provided the following results:

- An evaluation of the usability, production rates, and life cycle costs of the two devices based on field tests with both flat thermoplastic and profiled thermoplastic markings.

- An outline of personnel requirements, frequency of testing, test procedures, and minimum retroreflectivity results to implement the expected FHWA requirements.

Section 2.0
Background

The following discussion provides background information concerning the retroreflectivity of pavement markings and the two test devices contrasted in this report.

Retroreflectivity

Retroreflectivity is the portion of incident light from a vehicle's headlights that is reflected back toward the eye of the driver. Retroreflectivity is provided in pavement marking materials by glass or ceramic beads that are partially embedded in the surface of the material. The beads are transparent and round, and they act like lenses. As light enters a bead, it is refracted or focused down through the bead, and reflected back toward the path of entry (see Figure 2-1). In a highway environment, retroreflectivity promotes efficient traffic flow, driving comfort, and highway safety.

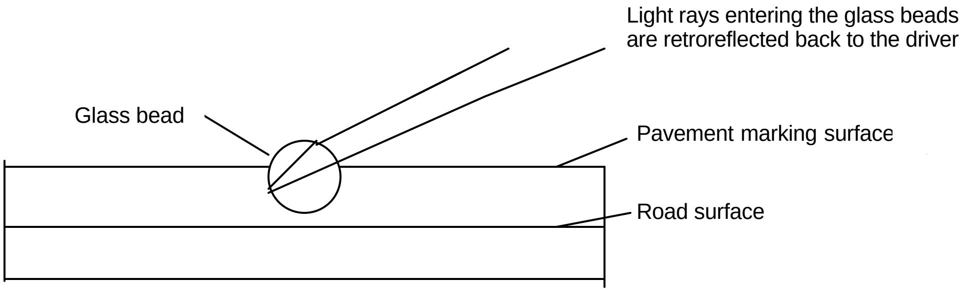

Figure 2-1: Glass bead retroreflection

ASTM E 1710 – 95a makes the following comments regarding retroreflectivity:

- The coefficient of retroreflected luminance, R_L, is defined as "the ratio of the luminance, L, of a projected surface to the normal illumination, E, at the surface on a plane normal to the incident light, expressed in candelas per square meter per lux" [(cd/m^2)/lx]. "Because of the low luminance of pavement markings, the units commonly used are millicandelas per square meter per lux" [(mcd/m^2)/lx].
- "The quality of the (pavement) stripe is determined by the coefficient of retroreflected luminance, R_L, and depends on the materials used, age, and wear pattern."
- "Under the same conditions of illumination and viewing, larger values of R_L correspond to higher levels of visual performance."
- "Retroreflectivity of pavement (road) markings degrades with traffic wear and requires periodic measurement to ensure that sufficient line visibility is provided to drivers."

Mobile Retroreflectometer - Laserlux

The Laserlux is a mobile pavement marking retroreflectometer that utilizes 30-meter geometry. Roadware Corporation, Potters Industries, and Advanced Retro Technology developed it in cooperation with the FHWA (see Figure 2-2). It can take over 70,000 measurements per hour. The vehicle moves at highway speeds and performs its work without traffic control. Operators can monitor displays of retroreflectivity data in the vehicle in real time. Later, statistical analysis and graphical displays are generated at off-line workstations [HITEC 2000].

Roadware conducted tests at its Canadian facilities that typically demonstrated 5% repeatability for three consecutive runs on a two-kilometer test road using the same Laserlux unit [Maerz, et. al. 1999]. Independent tests conducted by the FHWA on three Laserlux units concluded that the Laserlux retroreflectometers are capable of achieving good levels of repeatability, within the limits of 10% tolerance. [FHWA 1996]

Portable Retroreflectometer - LTL2000

The LTL2000 is a handheld pavement marking retroreflectometer that is manufactured by Delta Light and Optics and distributed in United States by Flint Trading Inc. (see Figure 2-3). The LTL2000 also uses 30-meter geometry. Data stored automatically by the LTL2000 can be printed in the field using a built-in thermal printer or retrieved via an RS-232 serial port connected to an IBM-compatible computer. The Highway Innovative Technology Evaluation Center (HITEC) performed research that showed that repeatability and reproducibility of the LTL 2000 were within the limits of 10% tolerance for most conditions [HITEC 2000].

Figure 2-2: Laserlux

Figure 2-3: LTL2000

Section 3.0
Field Comparison

On March 21, 2002, The University of Alabama (UA) and ALDOT personnel conducted field tests in Montgomery, Alabama using the Laserlux and the LTL2000. Two sections were tested that day: US 231 from mile post 168 to mile post 169 and Taylor Road from mile post 0.52 to mile post 1.52. The tests were conducted on both dry and artificially–wetted pavement markings. The results were used to determine the usability and the productivity of the competing devices. Both sites involved blocking one-mile sections of the outside lane of multiple-lane roadways. Sections of white edge line 2,500-feet long were tested. The remainder of the mile-long work zone served as acceleration and deceleration space for the Laserlux. ALDOT provided traffic control and ancillary equipment such as water trucks.

Flat Pavement Marking

The morning test was conducted on the flat pavement marking on US 231 North. A "torch test" was performed to find whether the marking was dry enough to provide repeatable test results. To perform the torch test, a retroreflectivity reading of the pavement marking was taken with the LTL2000. Then, the marking was completely dried using a torch, and the reading was taken again (see Figure 3-1). The value before drying was 235.8 (mcd/m^2)/lx. The value after drying was 236 (mcd/m^2)/lx. (Ratio = 236/235.8= 1.004 ≈ 1). A ratio less than 1.05 indicates that the pavement is sufficiently dry from dew or rain to begin retroreflectivity testing. If it had been greater than 1.05, according to the manufacturer, the pavement marking would not have been dry enough to begin testing.

Figure 3-1: Torch test

After the torch test indicated that retroreflectivity testing could begin, calibration and control section tests were performed to prepare the Laserlux for testing:

- Calibration: The instrument was calibrated as specified by the owners' manual.
- Control Section: A control section consisting of 1,200 feet of pavement marking was established. One pass with the Laserlux and 39 readings with the LTL2000 were

performed on the section. The readings were compared, and they agreed within 5%, so field testing could begin.

Field testing began with dry pavement marking retroreflectivity testing by the Laserlux. The Laserlux took readings three times over the 2,500-foot test section. (Test values for both the Laserlux and the LTL2000 are given in the Field Test Results section of this report.)

Next, dry and wet readings were taken with the LTL2000. The instrument was calibrated as specified by the owners' manual. Then, researchers tested the same 2,500-foot section that had been tested by the Laserlux. In this section, readings were taken at points spaced 200 feet apart. At every point, four dry readings were taken 20-inches apart. The locations of the four tests were marked with chalk. Then, approximately a gallon of water was poured onto the pavement marking, and after 40 seconds (as specified in ASTM E 2177-01), a reading was taken at both of the locations where the first two dry readings were taken. It was important that only 40 to 50 seconds elapsed between pouring the water and taking readings, and only two readings could be taken in that time period. So, another gallon of water was poured on the area, and after 40 seconds, readings were taken at the positions where the last two dry readings had been taken.

Wet readings with the Laserlux completed the flat pavement marking tests. A water truck equipped with a special nozzle was used to spray water on the edge line in an approximately 3-foot wide strip at the rate of 100 gallons/mile (see Figure 3-2). The Laserlux followed the water truck after an interval of 45 seconds and took retroreflectivity readings. This process was repeated three times over the 2,500-foot test section.

Figure 3-2: Water truck

Profiled Pavement Marking

Tests were conducted in the afternoon on profiled pavement markings on Taylor Road. The procedure was similar to that used in the morning tests:

- Laserlux readings were taken three times on a 2,500-foot long section of dry pavement marking.
- The height of the profiled pavement marking was measured every 200 feet with the help of the micrometer (see Figure 3-3). These readings were taken due to reports that

marking thickness was sometimes insufficient during construction. The average height of the profiled marking was found to be 196 mils.
- Due to time constraints, the LTL2000 readings were performed on a 1,800-foot long section rather than a 2,500-foot long section as in the morning. This deviation was not significant because sufficient data was collected in 1,800 feet to compare production rates of the two meters. In the 1,800-foot section, readings were taken at points spaced 200 feet apart. At every point, four readings were taken 20-inches apart for both dry and wet pavement in the same manner employed in the morning test.
- The Laserlux van took readings three times on wet pavement markings on the 2,500-foot section in the same manner employed in the morning test.

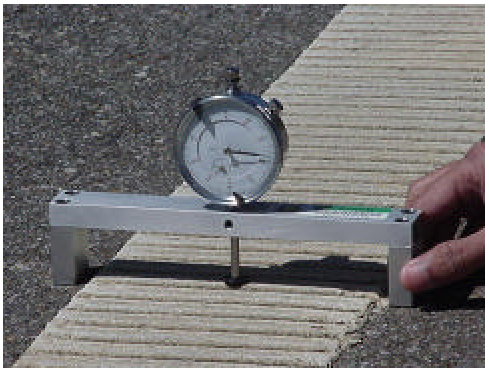

Figure 3-3: Micrometer readings

Applicable Standards

ASTM E 2177-01, *Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Wetness*, was used as a guide during the wet field tests. Important test procedures from the standard are described below:

- For the LTL2000, the retroreflectometer is placed directly over the pavement marking to be measured. The reading is taken, and then the retroreflectometer is moved 20 inches to another position on the pavement marking. The procedure is repeated four times, and the readings are recorded and averaged.

- For both retroreflectometers, wetting the pavement marking and waiting a certain time period after wetting for water to run off create the test condition:
    - Wet the pavement marking with water. Pour 1-2 gallons of water from a bucket.
    - Wait for 40-45 seconds for the water to drain.
    - Take reading with retroreflectometer.

- For both retroreflectometers, the test report should include the following:
    - “Average of the readings at each location, expressed as millicandelas per square meter per lux.”

- “Remarks concerning the overall condition of the line, such as rubber skid marks, carryover of asphalt, snowplow damage, and other factors that may affect the retroreflection measurement.”

Section 4.0
Field Test Results

The retroreflectivity values for the flat thermoplastic tests are shown in Table 4-1. The values shown for the Laserlux were calculated by averaging the composite values for each of the three runs. The LTL2000 values in the table represent the average of all readings taken over the 2,500-foot long section.

Table 4-1: Flat thermoplastic

Pavement Condition	Laserlux	LTL2000
	Retroreflectivity (mcd/m^2/lx)	Retroreflectivity (mcd/m^2/lx)
Dry	282	234
Wet	19	12

The average retroreflectivity reading with the Laserlux for dry flat thermoplastic pavement marking was 282 mcd/m^2/lx, while the average reading with the LTL2000 was 234 mcd/m^2/lx. The researchers had expected better agreement between the two devices. The control test (described on page four of this report) had already shown that the Laserlux and the LTL2000 agree within 5% when a large number of readings were taken over a 1,200-foot length of marking. It is possible that the limited readings taken at 200-foot intervals caused the greater differences shown in Table 4-1. The purpose of the tests was to compare production rates of the two devices, so agreement within 5% was not required in this portion of the testing. Table 4-1 also shows a difference in wet readings for the two devices, with the Laserlux again exhibiting higher retroreflectivity values.

The retroreflectivity values for the profiled thermoplastic marking are shown in Table 4-2. Agreement between the two meters was closer for this series of tests, i.e., 157 vs. 164 mcd/m^2/lx. In addition, dry readings were lower and wet readings were higher than the readings obtained while testing flat thermoplastic markings.

Table 4-2: Profiled thermoplastic

Pavement Conditions	Laserlux	LTL2000
	Retroreflectivity (mcd/m^2/lx)	Retroreflectivity (mcd/m^2/lx)
Dry	157	164
Wet	73	84

A research crewmember recorded the time required to take each LTL 2000 reading. The accumulated data for the different activities is shown in Table 4-3. The data was used later to calculate the production rate (the miles of pavement marking readings that could be taken per day) of the LTL2000 so that it could be compared to the production rate of the Laserlux.

Table 4-3: LTL2000 time requirements

Type Marking	Time per dry reading (sec)		Time for four dry readings per site (sec)		Time for two wet readings per site (sec)		Time to walk 200 ft (sec)	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Flat	6.5	2	26.2	4.6	46.1	2.4	51.1	4.7
Profiled	6	1.6	23.9	3.6	46.7	2.3	60.8	10.2

Section 5.0
Productivity and Cost Evaluation

Both retroreflectometers tested during the project have an estimated life of approximately 10 years. Researchers performed comparisons of the production rates (the miles per day of pavement marking that can be tested) and the associated costs of the two meters to determine which device to recommend for testing pavement marking on ALDOT's roughly 11,000 centerline miles of road.

ALDOT personnel supplied cost data for vehicles, personnel, and other pertinent factors, and requested an eight-year life cycle evaluation. That value was used in the analysis as well as a four percent discount rate. Detailed calculations are shown in Appendix A.

Time Analysis of Laserlux

The Laserlux production rate was calculated to determine the number of instruments required to take pavement-marking readings in Alabama each year. The number of available test days per year was set at 200, because the instrument cannot perform when the pavement is wet. The workday was considered as eight-hours/day. Thus, the total time available in a year for the instrument to take readings was 1,600 hours.

The total time lost to travel to and from the test area was set at one hour/day, and the time taken for calibration of the instrument was set at 45 minutes/day. Thus, the yearly lost time for traveling and calibration is 350 hours.

The average time taken for the Laserlux to test a 1-mile section is approximately 1.2 minutes/mile, assuming a driving speed of 50 mph. The 1.2 minutes/mile was multiplied by a factor of 1.25 to account for typical lost time. Thus, the total time taken to test a one-mile section is 1.5 minutes/mile. The analysis considered 11,000 centerline miles of road containing two edge lines and one centerline, resulting in 33,000 miles of pavement markings to be tested. The time required to measure 33,000 miles is 825 hours.

Three hundred fifty hours plus 825 hours results in 1,175 hours required to travel and test ALDOT pavement markings. Because 1,175 hours is less than the 1,600 work time hours available in a year, only one instrument is required to test 33,000 miles of pavement markings in Alabama in one year.

Time Analysis of LTL 2000

The LTL2000 was analyzed to determine the number of instruments required to test 33,000 miles of road markings. For the analysis, Alabama roads were broken into two zones based on pavement marking age:

- Zone 1 consists of roads with relatively new markings with retroreflectivity values that are well above the value at which markings must be replaced. 8,000 miles of roads were assumed to be in this zone. In this zone, crews will take LTL2000 readings every 1/10 of a mile and will ride between test sites.

- Zone 2 comprises 3,000 miles of remaining roads (those with pavement markings nearing replacement). In this zone, crews will take LTL2000 readings every 1/100 of a mile and will walk between test sites.

The number of working days available in a year was set at 200 days because the instrument cannot be used on wet markings. Time available in a day was set at eight-hours/day. Thus, the total time available in a year for the instrument to take readings is 1,600 hours.

The total time lost to travel to and from the test site was considered as one hour/day, and the time taken for calibration of the instrument was set at five minutes/day. Thus, the total lost time for traveling and calibration in a year is 217 hours, and yearly test time available for each LTL is 1,383 hours/year.

Time Used for Testing Zone 1

The total time used for testing Zone 1 was calculated considering the following circumstances:

- The total number of readings taken in this zone is 240,000. Researchers used the LTL2000 field test data to perform a regression analysis to estimate the time required per reading. The resulting equation is $y = 6.083x - 28.204$, where x is the number of readings and y is the time required to take x readings. The time required to take the readings in this zone is 406 hours per year.
- One crew will test both the centerline and edge line simultaneously. The time taken for the crewmember to move from edge line to centerline was set at 10 seconds. Thus, the required time to walk this distance per year is 222 hours. (The remaining edge line will be tested at another time.)
- Time taken to move the 528 feet from one test point to the next was set at 30 seconds. The person taking the reading is assumed to travel to the next test site by riding on a truck. The required time to drive between sites is 1,333 hours per year.

Adding the three items listed above results in a total time of 1,961 hours. This value was multiplied by a factor of 1.5 to consider typical lost time. (1.5 was used instead of the 1.25 used in the Laserlux analysis to account for more manual labor). Thus, the total time used for testing Zone 1 was 2,942 hours.

Time Used for Testing Zone 2

The total time for testing Zone 2 was calculated considering the following circumstances, using the same types of assumptions and factors that were applied to Zone 1:

- The total number of readings taken in this zone is 900,000 per year. Using the regression equation described for Zone 1, the time required to take the readings in this zone was calculated as 1,521 hours.
- One crew will test both the centerline and edge line simultaneously. Time taken to move from edge line to centerline was set at 10 seconds. The total time required in a year is 833 hours. (A separate crew will test the remaining edge line.)
- Time taken to walk 53 feet (from one test site to the next) was set at 15 seconds. Thus, the total required time in a year is 2,500 hours.

The sum of the times for testing Zone 2 is 4,854 hours. Multiplying by a factor of 1.5 to consider typical lost time results in total test time required in Zone 2 of 7,281 hours.

Thus, the total time used for testing Zone 1 and Zone 2 is 2,942 + 7,281 = 10,223 hours.

10,223 hours of testing per year requires at least eight instruments and eight crews to test ALDOT's roads each year, because as calculated earlier, each LTL2000 is available about 1,400 hours per year.

Cost Analysis of Laserlux

The results of a life cycle analysis of the Laserlux can be seen in Table 5-1. It shows an estimated cost to test pavement markings for the Laserlux of $5.05/mile of marking/year. Details of the analysis can be found in Appendix B.

Table 5-1: Cost analysis for the Laserlux for an eight-year period

		Laserlux
Capital Expenses	$	225,444
Operational Expenses	$	1,107,520
Total Cost	**$**	**1,332,964**
Cost per mile per year	$	5.05

Life cycle costs for the Laserlux were distributed into capital and operational expenses. Capital expenses include the initial cost of the Laserlux, initial cost of the vehicle, and training costs. Operational costs include items such as gasoline and insurance.

Cost Analysis of LTL 2000

The results of a life cycle cost analysis of the LTL2000 can be seen in Table 5-2. It shows an estimated cost for the LTL 2000 of $35.10/mile of marking/year. Details of the analysis can be found in the appendix A.

Table 5-2: Cost analysis for the LTL2000 for an eight-year period

		LTL2000
Capital Expenses	$	298,640
Operational Expenses	$	8,968,990
Total Cost	**$**	**9,267,630**
Cost per mile per year	$	35.10

Life cycle costs for the LTL 2000 were distributed into capital and operational expenses. Capital expenses include the cost of the LTL 2000 and the vehicle. Operational costs include such items as gasoline, insurance, and traffic control.

Mileage Break-Point

The initial capital expense of the LTL2000 is less than that of the Laserlux. However, operational costs per mile are higher for the LTL2000. Thus, as more miles of pavement marking stripe per year are measured, Laserlux becomes more cost efficient. Figure 5-1 shows the point at which use of the Laserlux becomes less costly (approximately 580 miles of two-lane road system per year). Thus, for a city or county in Alabama with less than 550 centerline miles of road to maintain, the LTL2000 may be more cost effective than the Laserlux.

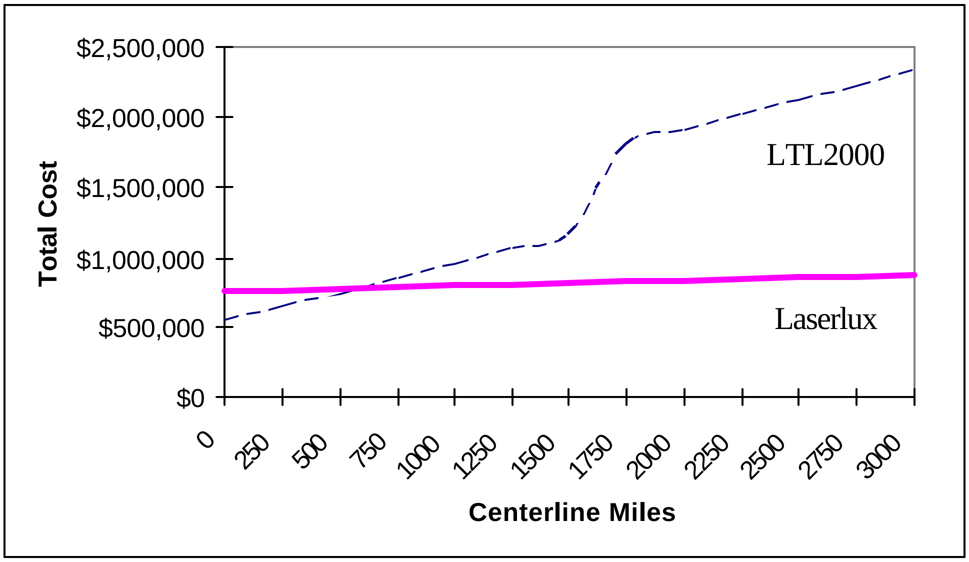

Figure 5-1: Comparison of retroreflectometers

Section 6.0
Conclusions

The cost analysis of the two retroreflectometers clearly indicates that the Laserlux is the more cost-effective retroreflectometer when measuring approximately 11,000 centerline miles (33,000 miles of pavement marking) for an analysis period of eight years. The cost to test pavement marking for those circumstances is approximately $5/mile of marking/year for the Laserlux and approximately $35/mile of marking/year for the LTL2000.

There appear to be circumstances where the LTL2000 may be more cost effective than the Laserlux. If a municipality or county in Alabama desires to perform retroreflectivity tests and desires to test less than approximately 550 miles of two-lane road, then the LTL2000 may be more cost effective than the Laserlux.

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Appendix A
Life Cycle Cost Analysis

The researchers used life cycle cost analysis to compare the Laserlux and LTL2000 retroreflectometers. This analysis considers initial costs and discounted future costs for each test plan, including manpower, maintenance, vehicle operation, and vehicle ownership costs. In this study, the discount rate and the analysis period are four percent and eight years, respectively.

Cost Estimates

This section presents estimates of cost components related to life cycle cost analysis in the report. ALDOT provided cost information for the analysis. The expenses were distributed into two major categories: capital expenses and operating expenses.

Capital Expenses:
Capital expenses are investments for buying equipment, buying vehicles, and training crews at the start of the project. Cost components belonging to this category are listed below.

- *Equipment Cost:* The Laserlux retroreflectometer costs $206,000 including a vehicle and installation. The LTL2000 retroreflectometer costs $17,330.

- *Vehicle Cost:* The cost of a vehicle is $20,000.

- *Training Cost:* Due to differing complexities of operation, only the Laserlux retroreflectometer requires training. Training cost for each person was set at three months of civil engineer (CE) salary – $9,722 per person.

Operational Expenses:
Operational expenses occur during field-testing. ALDOT suggested an analysis period of eight years and provided values of operational expenses corresponding to that time period. Cost components belonging to this category are listed below.

- *Manpower Cost:* Manpower costs are salaries and benefits of the crews working on the testing. The salary of a middle-grade ALDOT CE is $38,888 per year. Benefits add 50 percent of the annual gross salary, i.e., $19,444 per year. The annual rate of increase of salaries and benefits is taken as three percent. Personal expenses incurred during field-testing, such as hotel expenses and meals, are set at $75 per day per person.

- *Vehicle Operating Cost:* Gas, oil, and tire expenditures are the operating costs considered in the report. Vehicle operating cost was set at 15 cents per mile.

- *Vehicle Ownership Cost:* Taxes, registration, insurance, depreciation, and license fees are ownership costs. These costs are incurred regardless of how much a vehicle travels. ALDOT provided ownership figures of \$3,150 per year per vehicle.

- *Maintenance and Repair Cost:* Maintenance and repair costs are the labor and material expenses required to maintain the retroreflectometer in a suitable condition. The maintenance cost for the LTL2000 retroreflectometer is \$175 per year [HITEC 2000]. Laserlux maintenance should not be required during its service life [HITEC 2000].

- *Traffic Control Cost:* According to the Manual on Uniform Control Devices (MUTCD) Millennium Edition, the traffic control selected for the LTL2000 testing plan is Typical Application 17 – mobile operation on two-lane road. The traffic control consists of a truck-mounted attenuator with a "ROAD WORK AHEAD" sign and arrow panel. The traffic control costs approximately \$2.8 per mile [Trimac Logistics Ltd. 2002].

Detailed Calculation of Expenses

Present Value (PV) is the economic indicator used for cost comparison in the report. Sometimes, present value is called Present Worth (PW). PV is computed by bringing future costs to present costs using an appropriate discount rate and discount factor, then adding up the total of the present costs. For this analysis, constant dollars are used to estimate future costs. The costs of equipment and operating activities will not change as a function of the future year in which they will be accomplished.

Table A-1 shows discount factors for a single payment and an annual future payment at four percent discount rate for up to eight years in the future. Several discount factors are important to the calculations. Three main equations are listed below.

- Equation (1) is used to convert a single future cost to a present cost.

$$\text{PV} = F \times (P/F, n, i) \qquad (1)$$

- Equation (2) is used to convert a uniform series of future cost to a present cost.

$$\text{PV} = A \times (P_u / A, n, i) \qquad (2)$$

- Equation (3) is used to convert a uniform-rate series of future cost to a present cost.

$$\text{PV} = H_1 \times \frac{[(F/P, n, s)(P/F, n, i) - 1]}{s - i} \qquad (3)$$

Where: PV = present value of a series
P = present value of a given sum of money
F = future value of a given sum of money
A = annual payment in a uniform series
H_1 = first payment in a series
n = number of payments in a series

i = discount rate
s = rate of increase of payments in a uniform-rate series

Table A-1: Discounted factors with discount rate = 4% and rate of increase = 3%

n	Single Payment		Annual Payment
	(P/F,n,i)	(F/P,n,s)	(P_u/A,n,i)
1	0.9615	1.0300	0.9615
2	0.9246	1.0609	1.8861
3	0.8890	1.0927	2.7751
4	0.8548	1.1255	3.6299
5	0.8219	1.1593	4.4518
6	0.7903	1.1940	5.2421
7	0.7599	1.2299	6.0020
8	0.7307	1.2668	6.7327

Where: (P/F,n,i) = Factor for converting a single future payment to a single present payment with given year and discount rate
(F/P,n,s) = Factor for converting a single present payment to a single future payment with given year and rate of increase
(P_u/A,n,i) = Factor for converting a single future payment to a single present payment with given number of payments and discount rate

From the equations listed previously, researchers calculated the cost components for both retroreflectometers.

For the Laserlux Retroreflectometer

The calculations of each factor for the Laserlux testing plan are listed below.

- *Equipment Cost:*
  A Laserlux retroreflectometer including a vehicle and installation costs $206,000.

  $PV_{equipment}$ = $206,000
  Note: the Laserlux requires an LTL2000 to perform daily control tests. However, the cost of an LTL2000 was not included in the analysis because ALDOT already owns one.

- *Training Cost:*
  The PV of training costs $19,444. This represents three months of salaries of two civil-engineer trainers. Considering the rate of increase of three percent, an additional training cost estimated for four years from the beginning of the project when new employees may be trained will be $19{,}444 \times (F/P, 4, 3\%)$ = $21,884.

$$PV_{\text{1st training}} = \$19{,}444$$

$$\begin{aligned} PV_{\text{2nd training}} &= 21{,}884 \times (P/F, 4, 4\%) \\ &= 21{,}884 \times 0.8548 \\ &= \$18{,}706 \end{aligned}$$

- *Manpower Cost:*
  The salary of middle-grade civil engineer is \$38,888 per year. Salaries are normally raised three percent per year. Benefits are 50 percent of salary. Personal expenses are \$75 per day per person. ALDOT will use two persons working 132 days per year in the Laserlux testing plan.

$$\begin{aligned} PV_{\text{salaries}} &= 2 \times 38{,}888 \times \frac{[(F/P, 8, 3\%)(P/F, 8, 4\%) - 1]}{3\% - 4\%} \\ &= 2 \times 38{,}888 \times \frac{[(1.2668)(0.7307) - 1]}{0.03 - 0.04} \\ &= 2 \times 38{,}888 \times 7.4349 \\ &= \$578{,}257 \end{aligned}$$

$$\begin{aligned} PV_{\text{benefits}} &= 50\% \times 578{,}257 \\ &= \$289{,}129 \end{aligned}$$

$$\begin{aligned} PV_{\text{expenses}} &= 2 \times 75 \times 132 \times (P_u / A, 8, 4\%) \\ &= 2 \times 75 \times 132 \times 6.7327 \\ &= \$133{,}307 \end{aligned}$$

- *Vehicle Cost:*
  A vehicle costs \$20,000. There are approximately 11,000 miles of roads in Alabama to be tested. Assuming that the roads have three stripes of pavement markings, the vehicle will be driven 33,000 miles per year. Therefore, the vehicle may be replaced every three years, which is at the end the third year and the sixth year.

$$\begin{aligned} PV_{\text{vehicle}} &= [20{,}000 \times (P/F, 3, 4\%)] + [20{,}000 \times (P/F, 6, 4\%)] \\ &= [20{,}000 \times 0.8890] + [20{,}000 \times 0.7903] \\ &= \$33{,}586 \end{aligned}$$

- *Vehicle Operating Cost:*
  The operating cost of the vehicle is set at 15 cents per mile, and the vehicle will be driven 33,000 miles per year.

$$\begin{aligned} PV_{\text{veh operation}} &= 0.15 \times 33{,}000 \times (P_u / A, 8, 4\%) \\ &= 0.15 \times 33{,}000 \times 6.7327 \\ &= \$33{,}327 \end{aligned}$$

- *Vehicle Ownership Cost:*
  The ownership cost of the vehicle is set at $3,150 per year.

$$\begin{aligned} PV_{\text{veh ownership}} &= 3{,}150 \times (P_u / A, 8, 4\%) \\ &= 3{,}150 \times 6.7327 \\ &= \$21{,}208 \end{aligned}$$

- *Maintenance and Repair Cost:*
  Laserlux maintenance is not required.

- *Traffic Control Cost:*
  Traffic control is not required for the Laserlux retroreflectometer.

For the LTL2000 Retroreflectometer

The calculations of each factor for the LTL2000 testing plan are listed below.

- *Equipment Cost:*
  The LTL2000 retroreflectometer costs $17,330. According to the analysis presented previously, eight LTL2000s are used in the testing plan.

$$PV_{\text{equipment}} = 8 \times 17{,}330 = \$138{,}640$$

- *Training Cost:*
  Training is not required for the LTL2000 due to its simple operation.

- *Manpower Cost:*
  The salary of middle-grade civil engineer is $38,888 per year. Salaries are normally raised three percent per year. Benefits are 50 percent of the salary. Personal expenses are $75 per day per person. ALDOT will use sixteen persons working 175 days per year in the LTL2000 testing plan.

$$\begin{aligned} PV_{\text{salaries}} &= 2 \times 8 \times 38{,}888 \times \frac{[(F/P, 8, 3\%)(P/F, 8, 4\%) - 1]}{3\% - 4\%} \\ &= 2 \times 8 \times 38{,}888 \times \frac{[(1.2668)(0.7307) - 1]}{0.03 - 0.04} \\ &= 2 \times 8 \times 38{,}888 \times 7.4349 \\ &= \$4{,}626{,}054 \end{aligned}$$

$$
\begin{aligned}
\text{PV}_{\text{benefits}} &= 50\% \times 4{,}626{,}054 \\
&= \$2{,}313{,}027
\end{aligned}
$$

$$
\begin{aligned}
\text{PV}_{\text{expenses}} &= 2 \times 8 \times 75 \times 175 \times (P_u / A, 8, 4\%) \\
&= 2 \times 8 \times 75 \times 175 \times 6.7327 \\
&= \$1{,}413{,}867
\end{aligned}
$$

- *Vehicle Cost:*
  A vehicle costs $20,000. Due to limitations of traffic control, only two stripes are tested at a time. For 11,000 miles of roads in Alabama, the technicians must drive 22,000 miles to test 33,000 miles of pavement markings. ALDOT must use eight crews in this plan, so each vehicle will be driven one-eighth of 22,000 miles each year. All vehicles are assumed to be used only for the testing of pavement marking retroreflectivity. Therefore, the vehicles need not be replaced during the eight-year analysis period.

$$\text{PV}_{\text{vehicle}} = 8 \times 20{,}000 = \$160{,}000$$

- *Vehicle Operating Cost:*
  The operating cost of the vehicle is set at 15 cents per mile, and the vehicles will be driven 22,000 miles per year.

$$
\begin{aligned}
\text{PV}_{\text{veh operation}} &= 0.15 \times 22{,}000 \times (P_u / A, 8, 4\%) \\
&= 0.15 \times 22{,}000 \times 6.7327 \\
&= \$22{,}218
\end{aligned}
$$

- *Vehicle Ownership Cost:*
  The ownership cost of the vehicle is taken as $3,150 per year.

$$
\begin{aligned}
\text{PV}_{\text{veh ownership}} &= 8 \times 3{,}150 \times (P_u / A, 8, 4\%) \\
&= 8 \times 3{,}150 \times 6.7327 \\
&= \$169{,}664
\end{aligned}
$$

- *Maintenance and Repair Cost:*
  The manufacturer suggests that regular maintenance be performed on the LTL2000s once a year. The fee for this maintenance is $175 per year.

$$
\begin{aligned}
\text{PV}_{\text{maintenance}} &= 8 \times 175 \times (P_u / A, 8, 4\%) \\
&= 8 \times 175 \times 6.7327 \\
&= 49{,}426
\end{aligned}
$$

- *Traffic Control Cost:*
  Traffic control for the LTL2000 testing costs $2.8 per mile, and the vehicles will be driven 22,000 miles per year.

$$
\begin{aligned}
\mathrm{PV}_{\text{traffic control}} &= 2.8 \times 22{,}000 \times (P_u / A, 8, 4\%) \\
&= 2.8 \times 22{,}000 \times 6.7327 \\
&= \$414{,}734
\end{aligned}
$$

Results

The estimated life cycle costs for Laserlux and LTL2000 are summarized in Tables A-2 and A-3. Figures A-1 and A-2 show expenditure stream diagrams for the alternatives.

Table A-2: Life cycle cost for the Laserlux

Expenses	Present Value
Capital Expenses	
Initial Investment Cost (one time start-up costs)	
- Laserlux + Vehicle	$206,000
- 1st Training	$19,444
Operational Expenses	
Manpower Cost (annual costs)	
- Salaries	$578,257
- Benefits	$289,129
- Expenses	$133,307
2nd Training (at the end of year 4)	$18,706
Vehicle (at the end of years 3 and 6)	$33,586
Vehicle Operations Cost (annual costs)	$33,327
Vehicle Ownership Cost (annual costs)	$21,208
Total Present Value	**$1,332,964**

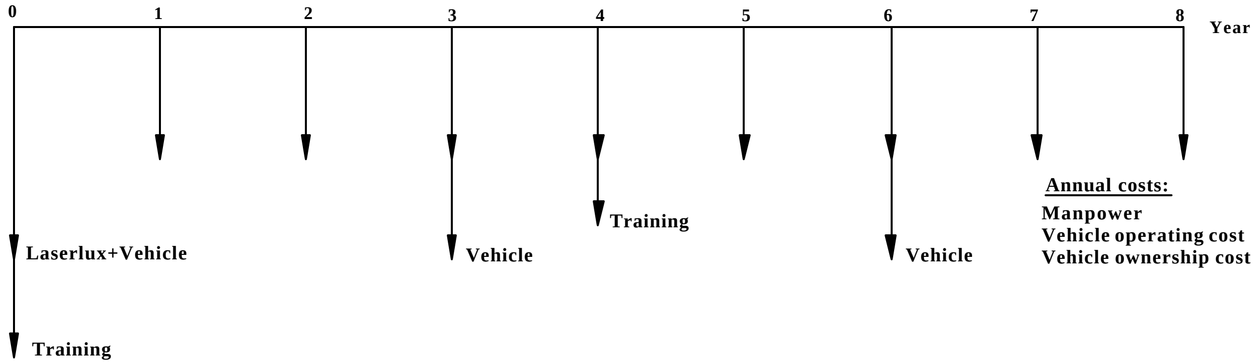

Figure A-1: Expenditure stream diagram for the Laserlux

Table A-3: Life cycle cost for the LTL2000

Expenses	Present Value
Capital Expenses	
Initial Investment Cost (one time start-up costs)	
LTL2000	$138,640
Vehicles	$160,000
Operational Expenses	
Manpower Cost (annual costs)	
Salaries	$4,626,054
Benefits	$2,313,027
Expenses	$1,413,867
Vehicle Operations Cost (annual costs)	$22,218
Vehicle Ownership Cost (annual costs)	$169,664
Maintenance & Repair Cost (annual costs)	$9,426
Traffic Control Cost	$ 414,734
Total Present Value	**$ 9,267,630**

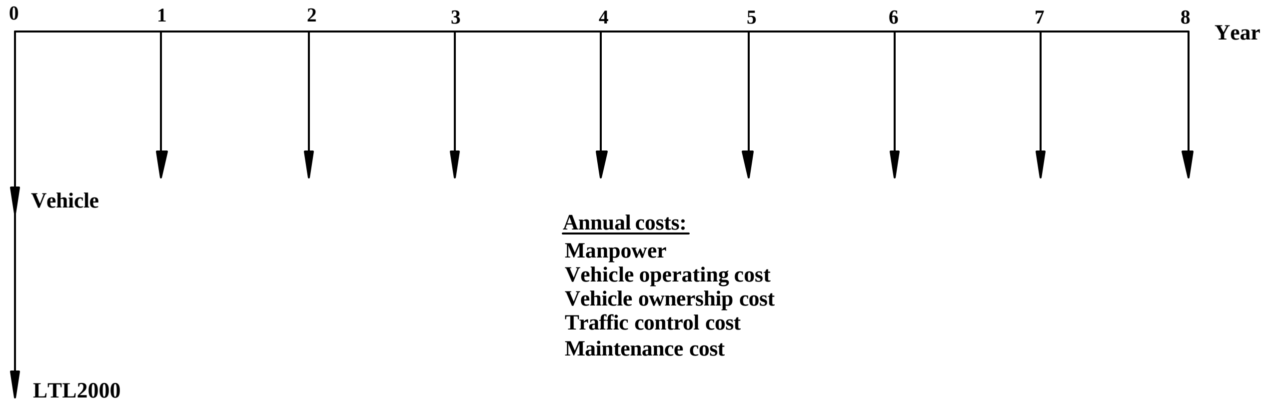

Figure A-2: Expenditure Stream Diagram for the LTL2000

Appendix B
Suggested Monitoring Procedures of Pavement Marking

Introduction

This appendix describes how the Alabama Department of Transportation may measure annually the retroreflective properties of horizontal pavement markings in its 11,000-centerline mile system. Retroreflectivity describes the portion of light from a vehicle's headlights that a marking reflects back toward the eye of the driver at night. The quality of the marking is determined by the retroreflectivity value (which is also known as the coefficient of retroreflected luminance, R_L) and depends on the marking materials used, age, and wear pattern. Under the same conditions of illumination and viewing, larger values of R_L correspond to higher levels of visual performance.

The FHWA may soon introduce requirements that pavement markings be replaced when their R_L values fall below a certain level. The replacement level is expected to vary with traffic volume, marking color, and other factors. Table B-1 presents the current best estimate of replacement values that may apply when markings are tested dry [Migletz, et. al. 2001].

To comply with the expected FHWA standards, ALDOT measures the retroreflectivity of yellow and white longitudinal pavement markings once per year with a van-mounted Laserlux device that gathers pavement marking R_L data at highway speeds. The readings are used to upgrade or replace selected pavement markings.

Table B-1: Sample replacement retroreflectivity values

Color of Marking	Roadway Type/Speed Classification		
	Non-freeway = 64 km/h	Non-freeway = 72 km/h	Freeway = 89 km/h
White	85	100	150
White with RPMs and/or Lighting	30	35	70
Yellow	55	65	100
Yellow with RPMs and/or Lighting	30	35	70

Note: 1 km = 0.6 miles. All retroreflectivity values are in mcd/m^2/lux.

Glossary of Terms

Retroreflectivity test devices direct a laser at the pavement marking and measure the proportion of light that is returned (see Figure B-1). The test conditions simulate light emitted from headlights mounted 0.65 m above the ground that reflects from the pavement marker 30 m ahead and is returned to the driver's eyes located 1.2 m above the ground. That set of test conditions is called “30 meter geometry”. ASTM E 1710 – 95a provides definitions of technical terms from Figure B1 below:

Coefficient of Retroreflected Luminance, R_L - the ratio of the luminance, L, of the projected surface to the normal illumination, E, at the surface on a plane normal to the incident light is defined as the coefficient of retroreflected luminance, R_L, expressed in candelas per square meter per lux [(cd/m^2)/lx]. Because of the low luminance of pavement markings, the units commonly used are millicandelas per square meter per lux [(mcd/m^2)/lx].

Entrance angle, β - The angle between the illumination axis and the retroreflector axis.

Viewing angle, α - The angle between the retroreflector axis and the receiver axis.

Co-entrance angle, β_c –The complement of the entrance angle.

Co-viewing angle, ν_c – The complement of the viewing angle.

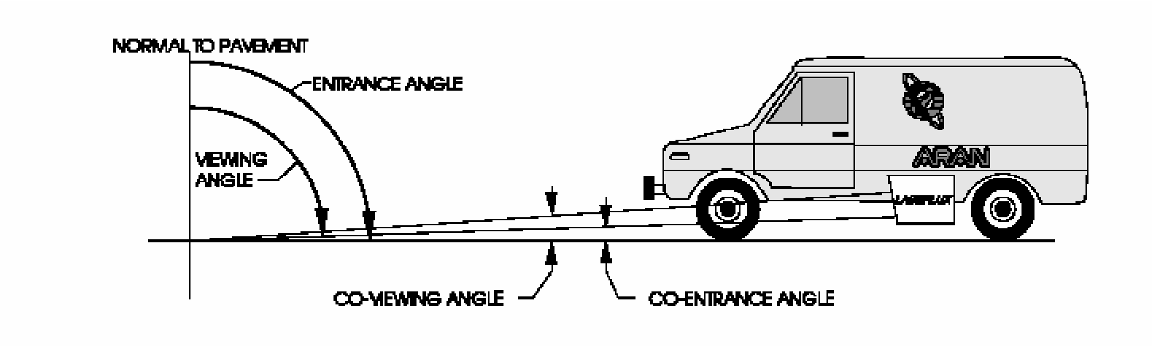

Figure B1: Laserlux geometry
Source: [Roadware Group Inc. 2002]

Instrument Description

The Laserlux is a mobile retroreflectometer that can make over 70,000 measurements per hour while moving at high speeds without disrupting the flow of traffic (see Figure B-2). Seventy thousand measurements per hour is normally too much data to comprehend, so the system summarizes and displays the data in the vehicle in real time but stores all the data on computer. Normally, the vast amounts of R_L values are combined and presented as averages over 0.1 or 0.01 mile sections. Statistical analysis and graphical displays can be generated at off–line workstations.

Figure B-2: Laserlux

In operation, a video camera is focused on the target marking stripe. The camera "is used to set the vertical aim of the Laserlux unit before the start of data acquisition and as a driving guide. The video image is displayed on a monitor inside the vehicle with a white indicator dot to help the driver steer the vehicle to keep the lane stripe centered in the sampling window" [HITEC 2000].

The Laserlux projects a 10 mW helium-neon laser beam that sweeps a 1.07-meter wide area in front of the vehicle. "The intensity of the returning laser signal is measured by an optical sensor, amplified by a special high gain amplifier, and digitized using a high speed analog to digital converter" [HITEC 2000]. Data is stored onboard in a high-speed computer. The data is output in standard ASCII format and can be printed directly or brought into any spreadsheet program for further analysis.

Test Overview

To test all pavement markings under ALDOT control annually requires one Laserlux system plus a crew of two trained persons. One person drives, and one person controls the laser and computer systems. Discussions with technicians from a private retroreflectivity test firm indicate that three to six months of training/practice are required to gain proficiency with the Laserlux. No traffic control is required. Tests are performed at highway speeds on dry roads, so several hundred miles per day of pavement marking can be tested.

Testing cannot begin in the morning until the laser is mounted on the van and reaches a minimum ambient temperature. Testing also may not begin until the pavement markings are sufficiently dry of dew or rain. These two factors mean calibration and control procedures (described below) probably cannot start until 8:30 to 9:30 a.m., depending on the season. The calibration and control procedures take approximately one hour, so actual testing may not begin until 9:30 or 10:30 a.m. This condition may allow the crew to work out of a central location for much of the test year, because it allows the crew time each morning to drive to the road section to be tested.

Tests on edge lines and lane lines may be accomplished with the laser mounted on the right side of the van, away from oncoming vehicles. However, centerlines must be measured with the laser mounted on the left side of the vehicle. The laser is easily shifted from one side to the other, but the entire shifting operation takes approximately one hour. The laser must be re-calibrated and a control section performed before it may be used again. Thus, the test crew may wish to arrange its test schedule so that the laser is not shifted in the middle of the test day.

Procedure

The manufacturer lists controls that should be followed at the time of testing:

- Take measurements on a clean, dry roadway.
- Collect data in the direction of traffic flow. For centerlines, the readings can be taken in any direction.
- Wait at least two weeks from date of placement of the markings before taking initial readings.
- Measure each line separately. The exception is the centerline when there is more than one marking. The Laserlux can simultaneously measure the R_L of two centerlines and provide separate values for the two lines.
- Put Plexiglas over the laser when not in use to prevent damage by rocks and grit from the road during travel.

Tests can be started any time in the morning that the pavement marking is dry enough to measure (see Torch Test in the list below) and the air temperature is high enough for the laser to operate. The following procedure should be followed each morning:

- Calibration of LTL2000: An LTL2000 retroreflectometer is used as part of the morning start-up procedure, and it should be calibrated as specified by the users' manual. According to the manufacturer, a proficient user can calibrate the LTL2000 in less than 1 minute.
- Torch Test: This test should be conducted to determine whether the pavement marking is dry enough to begin taking readings or not. The retroreflectivity of the pavement marking should be measured with the LTL2000. Then, the marking should be completely dried using a hand torch, and the measurement should be taken again. If the ratio between the retroreflectivity value after drying and the value before drying is close to one, multiply the Laserlux values taken subsequently by the ratio. If the ratio equals one, continue testing but do not adjust Laserlux readings. If the ratio is greater than 1.05, the manufacturer states that the pavement marking is not dry enough to take Laserlux readings. This test takes approximately 10 minutes.
- Calibration of Laserlux: Calibration of the Laserlux should be done at the beginning and end of the day. After the laser is mounted on the van, its temperature must reach at least 20° C before the Laserlux can be calibrated. The time it takes to reach this temperature can vary depending on weather conditions. Once the laser reaches this temperature, it will take approximately 15 – 20 minutes to calibrate. The Laserlux is calibrated using the instruction manual. In this procedure, a factory-provided calibrated metal panel with reflective coating is placed 10 meters in front of the unit. The operator aims the laser

beam onto the panel and gets a retroreflectivity reading. The operator compares the reading from the Laserlux with the calibrated value marked on the panel. If they agree within 5%, calibration is complete. If the readings deviate by more than 5%, re-calibration must be performed. If the evening readings on the reference standard deviate by more than 10% from the morning readings, recalibrate and re-measure previous measurements made on the same day.

- Control Section: The manufacturer also suggests performing a control section in which the Laserlux readings are checked with the readings of the LTL2000. A control section consisting of 1,200-feet of pavement marking is established. One pass with the Laserlux and approximately 40 randomly spaced readings with the LTL2000 are performed on the section. The readings are compared; if they agree within 5%, field-testing can begin. This procedure takes approximately 30 minutes.
- Field Tests Begin.

Inputs/Outputs

Some of the input parameters required by the Laserlux software can be altered from their default values to take into account special situations. A Highway Innovative Technology Evaluation Center (HITEC) report concerning the Laserlux system provides a list of those parameters [HITEC 2000]:

- Validation Threshold – The minimum level of retroreflectance acceptable for a valid scan (to reject extraneous road reflectance). For example, if the crew is measuring a skip line, the computer rejects the data from the un-marked pavement sections because the values are too low.
- Rejection Threshold – The maximum level of retroreflectance acceptable for a valid scan. For example, if the crew is measuring a pavement marking lined with raised pavement markers (RPMs), the computer rejects the extremely high readings caused by the RPMs.
- Display Range – The scale in retroreflectivity units of the screen plot displaying the retroreflectivity profile of the current stripe.
- Graph Range – The scale in retroreflectivity units of the hardcopy graph of retroreflectivity plotted against chainage (distance traveled).
- Console Colors – The colors to be displayed on the video monitor for use with the video overlay feature.
- Station Interval – The distance over which peak retroreflectivity measurements are summarized. For example, readings can be summarized for every 1/10 of a mile or for every 1/100 of a mile.
- Start Chainage – The mileage reference at the beginning of the sample (to match mileage reference markers).
- Distance Measurement Instrument (DMI) Selection – Units for measuring the distance (kilometers or miles).
- White/Yellow Lines – Selection of a white or yellow pavement marking color, at the start or during data collection.
- One/Two Lines – Selection of single vs. double stripes, at the start or during data collection.

- Skip/Cont Lines – selection of continuous vs. skip stripes, at the start or during data collection.
- Length (Stripe) – specification of the design length of the stripe, as required by the statistical algorithm used to summarize skip lines.

The Laserlux system provides utility programs to generate graphical output or a text report. The report summarizes the parameters in use and provides the overall mean retroreflectivity and standard deviation of the runs as well as the following information [HITEC 2000]:

- The chainage (distance traveled);
- The number of valid scans;
- The number of invalid scans;
- The number of valid scans of double stripes;
- The average retroreflectivity of the right stripe (if double lines are present);
- The average retroreflectivity of the left stripe (if double lines are present);
- The contrast ratio between the stripe and the pavement;
- The average vehicle speed;
- The average retroreflectivity of all stripes detected;
- The standard deviation of the right stripe (if double lines are present);
- The standard deviation of the left stripe (if double lines are present)
- The number of invalid scans due to raised pavement markers; and
- The temperature inside the Laserlux unit.

Test Report

The final test report contains the following items:

- Project identifier/number
- Test date
- Test crew names
- Geographical location of the test site, which may consist of milepost references or the distance from the nearest permanent site identification.
- Pavement marking material tested: type, color, age, and location on road (edge line, center line, etc).
- Remarks concerning the overall condition of the line, dirt or debris on the marking, uneven distribution of beads, etc.
- Ambient temperature.

Analysis

ALDOT uses databases in other areas to perform management functions. The list below outlines a method that could be used to identify markings for replacement or maintenance, loosely based on ALDOT's Pavement Management system:

- Data is downloaded from the Laserlux to the database management software. The downloaded data has been previously summarized in 0.1 or 0.01 mile increments and linked to a reference system (most often mileposts.) If desired, the software may use historical data for each road section to project retroreflectivity values for future months.
- Computer identifies marking sections with values below established boundaries for each color of marking.
- Identified sections are collated by road and by Division and sent to Division Offices.
- Divisions perform site visits to confirm the findings. Supplementary readings by handheld LTL2000 retroreflectometers may be used at this stage.
- Divisions schedule replacement/maintenance of pavement markings as appropriate.

Input from Division personnel or the public can be added to the sections identified by the computerized data management system.