Characteristics and Needs for Overhead Guide Sign Illumination from Vehicular Headlamps

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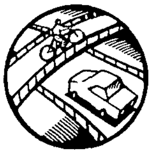

FOREWORD

This report represents the results of a study which investigated to what degree light from automobile headlamps contributes to the visibility of non-illuminated, retroreflective traffic signs. With the ongoing shift in headlamp designs from sealed-beam types to composite/ aerodynamic types, along with a trend toward world-wide beam harmonization, light above the horizontal and to the left is being reduced. Locations of overhead guide and left shoulder mounted signs are primarily affected by this trend. Retroreflective signs depend on light from the vehicles' headlamps to be visible and legible.

A field study evaluated the light from headlamps toward left and right shoulder and overhead mounted signs. Over 1,500 randomly observed vehicles, plus a group of 50 known cars, form the basis which led to the following conclusions: Based on a minimum sign legend luminance of 3.2 cd/m^2 and relatively new Type III signing material, practically all cars provided sufficient illumination for right-shoulder mounted signs, better than 90 percent of these vehicles provided sufficient light for left-shoulder mounted signs, but only about 50 percent of them provided sufficient light toward overhead signs. For signing material of Type II, quite commonly used in many sign applications, about 90 percent of the vehicles provided sufficient light toward right-shoulder mounted signs, about 45 percent provided sufficient light toward left-shoulder mounted signs, and only about 10 percent of these vehicles provided sufficient illumination for overhead mounted signs.

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16. Abstract

The Federal Highway Administration (FHWA) is concerned about changes in headlamp performance of the present fleet of vehicles in the US relative to its ability to properly illuminate traffic signs, especially overhead guide signs. If this is true, overhead guide sign luminance, a function of the type of sign sheeting and headlamp illumination, may be marginal or insufficient for a motorist to read and comprehend the sign in sufficient time to take proper action. A team of Kansas State University researchers was given a contract to determine the minimum luminance requirements for overhead guide signs and to determine if the illuminance from vehicle headlamps on highways was sufficient to provide drivers with this required minimum luminance. This report covers a literature review to determine the minimum luminance value needed, an overview of the equipment developed for field studies of vehicle headlamp illuminance, results of a small laboratory study to determine minimum luminance of highway guide signs, and the results of field studies to determine illuminance values from a sample of the fleet of vehicles on highways, and the results of a study of illuminance values obtained from the headlamps of 50 known vehicles of varying ages and types. Headlamp illuminance readings from samples of vehicles on the highway were taken at points where overhead and shoulder signs would be located. The report discusses minimum luminance values, the illuminance recording equipment, the conduct of the field studies and results, and the laboratory study and results. It concludes with calculations of sign luminance values based on the headlamp illuminance measurements and two assumed types of retroreflective material.

17. Key Words Headlight illuminance, sign luminance, sign luminance studies, vehicle headlamp illumination measurement, field studies of vehicle headlamp illuminance, minimum sign luminance		**18. Distribution Statement** No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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INTRODUCTION

The U.S. Federal Highway Administration (FHWA) has recently become concerned that low-beam illumination from the headlamps of vehicles on U.S. highways is resulting in inadequate luminance of roadway signs, particularly overhead guide signs. Controlled laboratory tests can be performed on vehicle headlamps and on the luminance of sign sheeting material; however, many real world factors cannot be accounted for in a laboratory setting. The FHWA wanted to determine the actual illuminance provided by a sample consisting of a typical mix of vehicles on U.S. highways.

To fully characterize a wide range of vehicular headlamps on vehicles traveling on highways, it was necessary to observe and record values of headlamp illuminance that was directed toward specified sign locations from key highway locations. The FHWA contracted with Kansas State University (KSU) to conduct a study that included a comprehensive literature review of the minimum luminance needs of drivers, designing and building suitable equipment for field data collection, conducting field studies with the equipment, and analyzing the data. On the basis of the illuminance values found in the field and retroreflectance properties of two grades of typical sign sheeting, theoretical luminance values were calculated for an overhead guide sign and for right and left shoulder signs.

LITERATURE REVIEW: MINIMUM OVERHEAD GUIDE SIGN LUMINANCE

The objective of the literature review was to determine, from the scientific literature, domestic and foreign, minimum overhead guide sign requirements. The KSU team reviewed the most current and relevant literature available. The data bases for Transportation Research Information System (TRIS) (1970-1994)/August, National Technical Information Service (NTIS) (1969-1994)/October, and Engineering Compendex (1970-1994)/October were searched. The section that follows summarizes the findings. The KSU team understands that there may be some more recent reports, but believes that the most relevant literature on minimum overhead guide sign luminance requirements is summarized below.

Summary of Studies of Minimum Guide Sign Luminance

Sivak and Olson (1983) reviewed applied research on sign legibility to obtain information regarding optimal and replacement luminance values of retroreflective traffic signs (Table 1). Their report presents tabular summaries of 18 experimental studies followed by a synthesis of findings in terms of luminance recommendations and corresponding retroreflectance values. Letters used in the studies were generally guide-sign style letters corresponding to FHWA series E letters. Assuming legibility criteria of 6 m/cm of letter height for younger drivers and 4.8 m/cm for older drivers, their data suggest that the replacement luminance for the median user is 2.4 candela per square meter (cd/m$^{2)}$ for light legends on dark backgrounds and for light backgrounds with black legends. From these studies they derived the optimal luminance requirement of 75 cd/m^2 to satisfy 99 percent of subjects and 2.4 cd/m^2 for median, 50th percentile drivers.

Table 1. Optimal and Replacement Sign Luminance Recommendations (Sivak and Olson, 1983).

Level	Sign Luminance
Optimal	75 cd/m^2
Replacement:	
•85th Percentile	16.8 cd/m^2
•75th Percentile	7.2 cd/m^2
•50th Percentile	2.4 cd/m^2

The International Road Federation (IRF) publication *Retroreflective Road Traffic Signs* (1991) reports sign luminance of 20 cd/m^2 as the optimum level for dark conditions and 50 cd/m^2 for glare conditions created by one oncoming vehicle using lower beams.

For a sign to be noticed by a road user, it must have sufficient contrast ("external contrast") between itself and the surroundings, and the contrast between the sign legend and its background ("internal contrast") must be sufficient. The levels of internal contrast found are a function of both the type and the color of the sign materials. Laboratory experiments were conducted by

Jenkins and Gennaoui (1992) to determine the minimum required contrast and luminance for traffic signs at night. The experiment used slides of nighttime traffic scenes with a superimposed target. The target was either a black Landolt ring on a yellow background (resembling a warning sign) or a white Landolt ring on a green background (resembling a guide sign). The experiment was divided into two parts. First, out of four possible locations, the subject had to choose where the target was when the stimulus slide was presented for 250 ms. For the second experiment, the subject had to nominate which of four orientations the gap in the Landolt ring was positioned at when the stimulus slide was presented for 3000 ms. The two tasks represented a conspicuity task and a legibility task, respectively. The subjects found the conspicuity task difficult, and probability of correct responses did not rise above 80 percent. The optimal luminance was taken at the point where the subject's correct responses began to plateau. This was 18 cd/m^2 for the guide signs and 23 cd/m^2 for warning signs. The threshold luminance (taken at the proportion of correct responses 0.56) was 3.2 cd/m^2 for guide signs and 9.7 cd/m^2 for warning signs.

The minimum values required for guide sign luminance, according to Jenkins and Gennaoui, and corresponding retroreflectivity levels (at entrance angle of 4° and observation angle of 0.2°) are provided for two different guide signs in Tables 2 and 3. Retroreflectivity levels are determined for the use of ECE type headlamps, the type prevailing in Australia.

White on Green Guide Signs: Key Variables

Traffic Speed: Although guide signs generally do not require a maneuver prior to reaching the sign, vehicle speed does affect the amount of time available for reading the sign and ultimately the distance at which the sign must be seen. Therefore, traffic speed was selected as a critical variable.

Sign Size: Since there are no standard sizes for most green on white guide signs, it was felt that specifying different values for different sign sizes would not be practical. Therefore, size was not selected as a critical variable.

Sign Legend: Given the wide variation in the type and amount of legend on guide signs, it was not reasonable to capture this variable in a practical implementable manner. Therefore, sign legend was not selected as a critical variable.

Material Type: Since the Minimum Required Visibility Distance (MRVD) for this group of guide signs generally falls in the 0.4° to 0.2° observation angle range (91 to 152 m), the effect of correcting the minimum retroreflectivity values back to the standard of 0.2° observation angle and -4° entrance angle is minimal. Therefore, material type was not selected as a critical variable.

Sign Placement: Since guide signs are often located overhead, sign placement was selected as a critical variable.

Table 2. Minimum Required Photometric Performance of Traffic Signs (IRF 1991)

Type of Sign: Guide	Colors: Legend: White Background: Green
Minimum Luminance: 3.2 cd/m sq	Contrast: 7:1
Number of Words on Sign: 4 except for street name signs (2 words)	

Environ-ment	Sign Position	Carriage-way	Speed Limit km/h	Maneuver	Minimum Distance m	Sign Illuminance lux	Minimum Retroreflectance $cd.lx^{-1}.m^{-2}$		
								For	
							Sign R_A	Legend R_A	Background R_A
Rural	Left[1]	2 lanes	100	No	64[4]	0.0927	34.4	100.0	12.5
Rural	Left	4 lanes	100	Yes[3]	77	0.0877	36.4	106.4	13.0
Rural	Left	4 lanes	100	No	73	0.0927	34.5	100.8	12.6
Urban	Left	4 lanes	60	Yes	55	0.1533	20.8	60.8	7.6
Highway	Right[2] on median	6 divided car in median lane	80	Yes	41	0.0577	55.4	161.6	20.2
Highway	Right on median	6 divided car in center lane	80	Yes	50	0.0604	52.9	154.4	19.3
Freeway	Overhead center lane	6 divided car in curb lane	110	Yes	44	0.0444	72.0	209.6	26.2
Freeway	Overhead center lane	6 divided car in center lane	110	Yes	39	0.0624	51.2	148.8	18.6
Freeway	Overhead center lane	6 divided car in median lane	110	Yes	56	0.0357	89.5	260.8	32.6

1. Left side is near shoulder.
2. Right is far shoulder.
3. Change one lane.
4. Five m distance per cm of letter height is an approximation of the required letter height.

Table 4 illustrates the final framework and values for this group of guide signs. It includes two critical variables: traffic speed and sign placement. The values for this table were developed using "typical" guide signs. Since both the legend and the background of these signs are retroreflective, a minimum contrast ratio of 4:1 has also been established. If the retroreflectivity (R_A) value for the white material divided by the retroreflectivity value of the green material is less than four, the sign should be replaced.

Traffic sign luminances under real traffic conditions must be carefully considered according to several important and influential criteria in order to define the minimum luminance requirements. (IRF, 1991). These criteria range from the type and colors of the retroreflective materials used, the worst case of sign illumination geometry that depends on the geometry of the road, and the type of vehicle. Car/sign geometry compared with truck/sign geometry gives

Table 3. Minimum Required Photometric Performance of Traffic Signs (IRF, 1991).

Type of Sign: Guide	Colors: Legend: White Background: Green, Blue
Minimum Luminance: Legend: 16.2 cd/m sq Background: 2.3 cd/m sq	Minimum Contrast: 7:1
Number of Words on Sign: 4 except for street name signs (2 words)	

Environ-ment	Sign Position	Roadway	Speed Limit km/h	Maneuver Change One Lane	Minimum Distance m	Minimum Retroreflectance $cd.lx^{-1}.m^{-2}$	
						For	
						Legend R_A	Background R_A
Rural	Near Shoulder	2 lanes	100	No	64[1]	100	13
Rural	Near Shoulder	4 lanes	100	Yes	77	107	13
Rural	Near Shoulder	4 lanes	100	No	73	100	13
Urban	Near Shoulder	4 lanes	60	Yes	55	61	8
Highway	Far Shoulder or Median	6 divided car in median lane	80	Yes	41	162	20
Highway	Far Shoulder	6 divided car in curb lane	80	Yes	50	155	20
Freeway	Overhead Center Lane	6 divided car in curb lane	110	Yes	44	210	26
Freeway	Overhead Center Lane	6 divided car in median lane	110	Yes	56	260	33

[1] 5 m distance per cm of letter height is an approximation of the required letter height.

different luminances. The worst case should be taken into account for the choice of sign design criteria for optimal performance (Tables 2 and 3).

To describe the luminances of traffic signs under real traffic conditions, and because of the wide spread of luminous intensities of vehicle headlamps as well as the choice of retroreflective materials, it is necessary to consider a typical headlamp and a typical retroreflective material.

Table 4. Minimum Retroreflectivity Guidelines R_A (cd·lx^{-1}m^{-2}) (Paniati and Mace, 1993).

Type of Sign: Guide	Colors: Legend: White Background: Green			
Minimum Contrast Ratio: 4:1				
Traffic Speed:	72 km/h or greater		64 km/h or less	
	White	Green	White	Green
Ground-Mounted	35	7	25	5
Overhead-Mounted	110	22	80	16

Figure 1 shows the luminance values (L) for two different retroreflective materials (Types I and II) and for two colors (white and blue) in relation to observation distance (d).

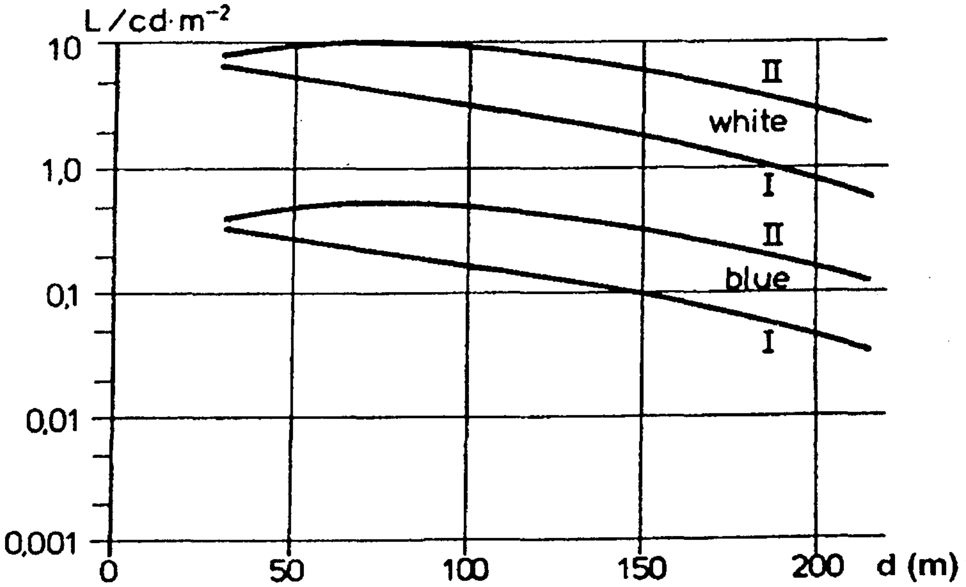


Figure 1. Luminance (L) of White and Blue Retroreflective Materials (Types I and II) When Illuminated by a Typical Low Beam Headlamp System at Different Distances (d) (IRF, 1991).

These curves are the readings of a shoulder mounted traffic sign on the right-hand side of the road when illuminated by the correctly aimed headlamps of a passenger car.

The luminance (L) also changes according to the mounting height of a traffic sign (IRF, 1991). Figure 2 shows the variation of the luminance value (L) at the observation distances (d) of a shoulder mounted sign versus an overhead mounted sign.

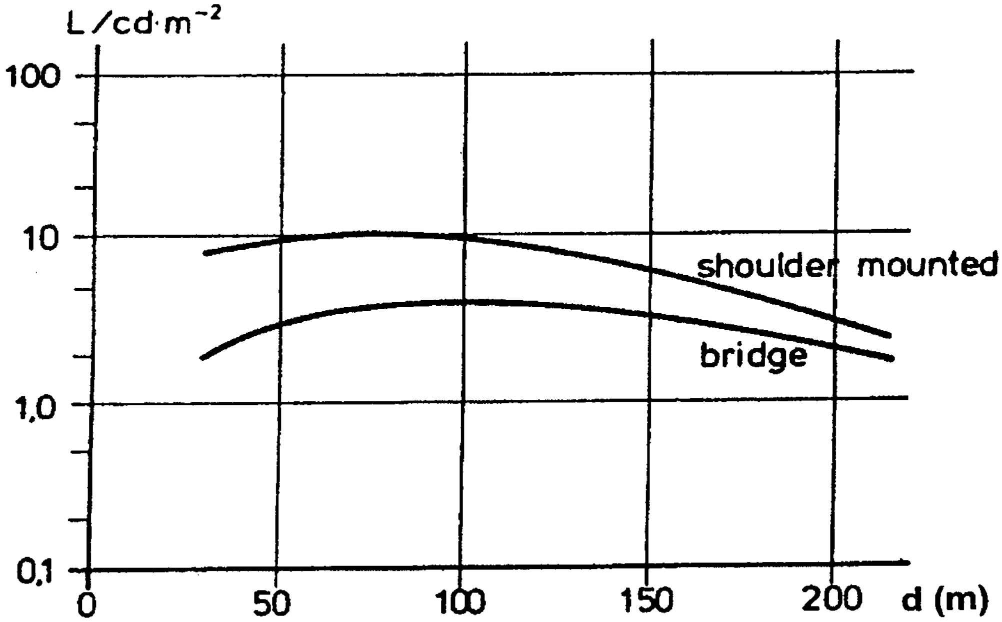
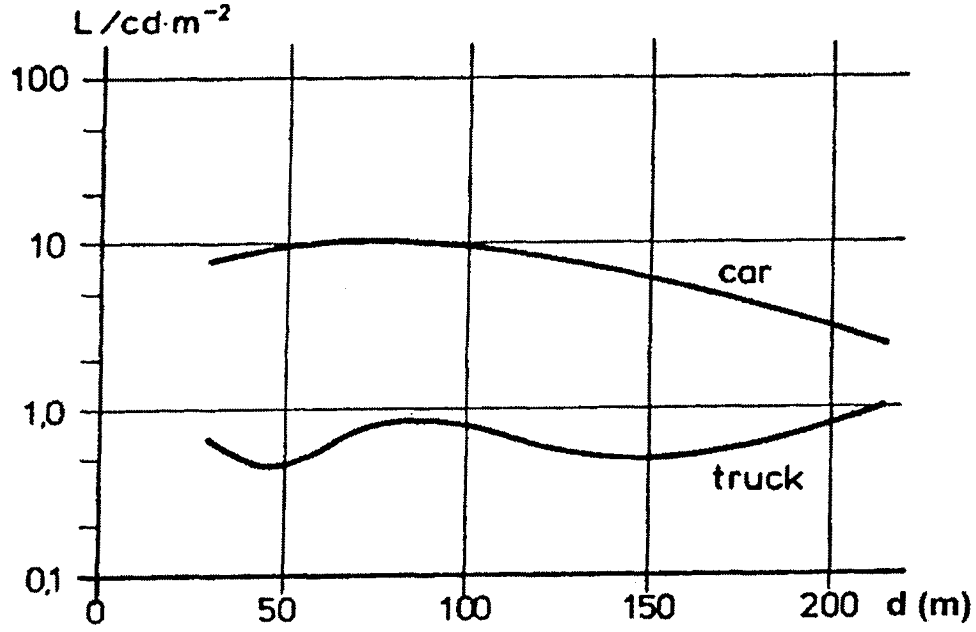


Figure 2. Luminances (L) of Traffic Signs in Different Positions When Illuminated by a Low Beam Headlamp System as Mounted on a Car (IRF, 1991).

At close distances from the sign, e.g., 50 m, the luminance values differ by a factor of 3, whereas at longer distances from a sign, the difference factor decreases.

Regarding the different mounting heights of traffic signs and the aiming of low beam headlamps and their influence on the luminance values, one can also note that different relations between the signs and the types of vehicles illuminating them are of importance (IRF, 1991). Figure 3 shows the comparison of the following scenarios of two extreme cases:

> A passenger car illuminating a shoulder mounted sign compared with a truck illuminating an overhead sign.



Car: shoulder mounted sign
Truck: bridge sign

Figure 3. Luminances (L) of Traffic Signs Illuminated in Different Geometries (IRF, 1991).

One can note that for observation distances of up to 150 m, the difference in luminance is roughly a factor of 10. In other words, a truck driver will not see the sign in the same way as a passenger car driver. The truck driver's rating would be at least two steps lower.

These cases illustrate the need to define clearly the minimum values for different traffic situations and, in cases of doubt, the worst case should be taken into account to define the necessary requirements for traffic sign performance.

Older Drivers

It is anticipated that in the year 2020, 17 percent of the U.S. population will be 65 or older, resulting in more than 50 million persons in this age group eligible to drive (Transportation Research Board (TRB), 1988). Figure 4 and Table 5 show the trends in age changes in the U.S. population structure. Given such a significant proportion of older people in the population, considering their greater need for better signing cannot be overstated.

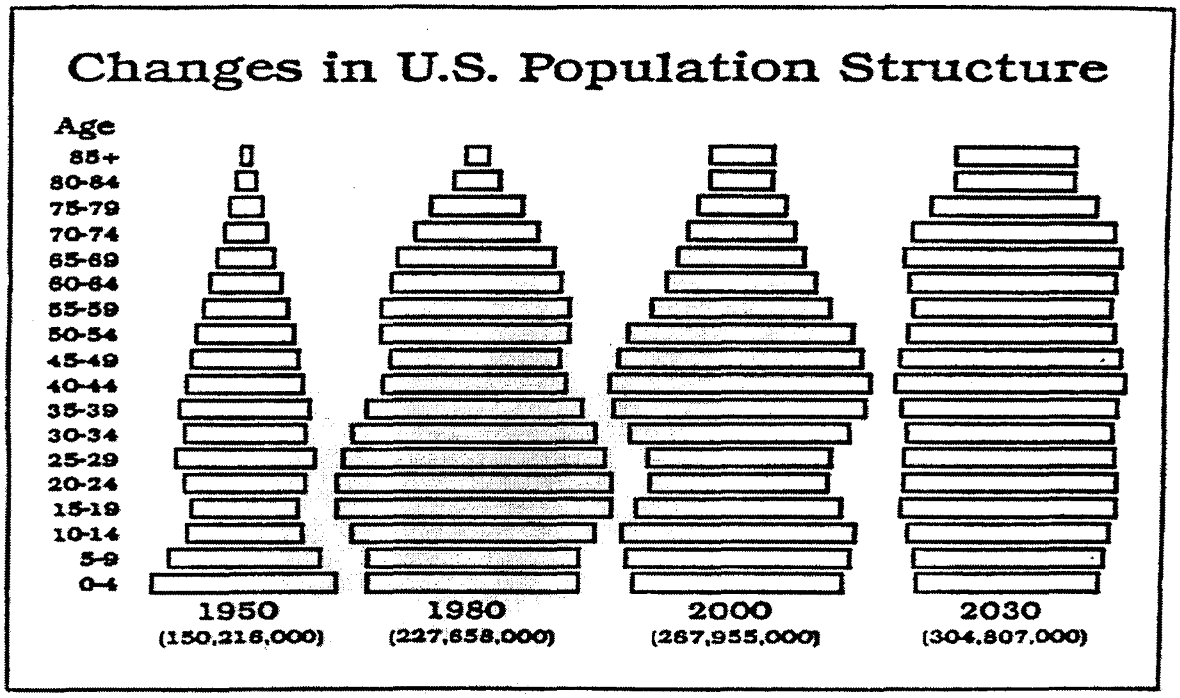


Figure 4. Changes in U.S. Population Structure (TRB, 1988).

Driving can become a problem for the older driver because, with aging, certain deficits occur in the sensory, perceptual, cognitive, and physical abilities. Each factor will be discussed separately below.

Vision: It is estimated that 90 percent of all information necessary for driving is acquired visually. Thus, any visual problems are cause for concern. Age-related changes include:

- loss of lens elasticity and ability of the eye to accommodate or change focus.
- loss of transparency in the lens and yellowing of the lens.
- loss of dynamic range fixed at 2 to 4 mm.
- increased scattering in the eye due to aging.

A significant decline in vision begins in the mid-fifties. Visual acuity (the ability to see clearly) begins a rapid decline. It becomes harder to focus on objects and to change focus quickly. It takes a 52-year-old driver about 1 s longer than a 20-year-old driver to switch focus from the road to the instrument panel. Depth perception weakens. Peripheral vision gradually worsens. After the age of 20, a person's illumination needs double every 13 years. Older people need more illumination to see clearly.

Older persons' need for more light conflicts with their problem in adjusting to glare. The glare from the headlamp beams of an approaching car can cause a temporary blind spot that blocks vision of objects directly in a driver's line of sight, even after the vehicle has passed. Sensitivity to such glare becomes more pronounced with age. Older people begin to experience difficulty with glare at light intensities that previously did not affect them, and its after-effects begin to remain longer. It has been said that resistance to glare deteriorates about 50 percent every 12 years after age 17.

Some ways visual problems of older people are manifested on the highway include:

- slow response to signals, signs, and complex driving situations.
- problems in determining the distance of oncoming vehicles.
- reduced ability to detect cars and crossing pedestrians.

The older driver is at a greater disadvantage reading signs at night because of poorer acuity under low illumination. Sivak and Olson, 1985, determined that older drivers (age 62 to 79) had a legibility distance only 65 to 77 percent of that of drivers 18 to 24 years old. It should be noted here that letter height for signs is based on the assumption that a 1-cm-high[1] letter is visible from 6.0 m, which assumes a visual acuity of roughly 20/25. However, 40 percent of the drivers between 65 and 74 do not see that well.

It is recommended (Sivak and Olson, 1985) to increase letter height based on the assumption that a 1-cm-high letter can be read at 4.8 m rather than 6.0 m. If a minimum legibility distance of 270 m is assumed, this revised standard would result in 57-cm letters. North Carolina is experimenting with larger letter sizes on guide signs. It was determined that the larger size legend increases the sign panel by a factor of 1.5, which substantially increases the cost of the total sign and support structure.

Another way of improving sign performance is to increase conspicuity and/or install multiple signs. (TRB, 1988) Sign conspicuity can be enhanced by using Type III or micro-prismatic retroreflective sheeting, especially in urbanized areas where visual clutter occurs.

Hearing: It is estimated that about 30 percent of the over 65 population has some hearing loss. Generally, high-pitched sounds become less audible long before low-pitched ones. Since high-pitched sounds are less audible to older people, they have difficulty hearing and reacting to horns, motors, sirens and train whistles. Thus, they are more dependent on visual clues for some driving decisions.

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[1] *In the English system, we usually refer to legibility distances in terms of a given distance (in ft) at which a sign can be read per one-in letter height. We used to generally use a figure of 50 ft distance for a letter height of one in, or, in the case of older drivers, 40 ft/in. To use SI terminology, the standard nomenclature used by several international organizations is m of distance per 1 cm letter height. The most commonly used English ratios then translate as follows: 60 ft/in - 7.2 m/cm; 50 ft/in = 6.0 m/cm; 40 ft/in = 4.8 m/cm; and 30 ft/in = 3.6 m/cm. The SI units are used in this report.*

Table 5. Percentage of U.S. Population 65+ (1988). (Professional Development Seminar Institute of Transportation Engineers, 1991).

STATE	TOTAL	URBAN (Metro)	RURAL
Alabama	12.5%	10.5%	12.6%
Alaska	3.8%	2.0%	3.5%
Arizona	12.8%	11.6%	10.4%
Arkansas	14.6%	10.7%	15.5%
California	10.6%	10.1%	11.8%
Colorado	9.5%	8.0%	11.0%
Connecticut	13.4%	11.7%	12.7%
Delaware	11.6%	9.4%	11.1%
Florida	17.8%	17.2%	18.5%
Georgia	10.0%	8.2%	11.6%
Hawaii	10.4%	7.3%	10.3%
Idaho	11.7%	8.6%	10.2%
Illinois	12.2%	10.2%	14.7%
Indiana	12.2%	9.9%	12.2%
Iowa	14.9%	10.4%	15.4%
KANSAS	**13.5%**	**9.9%**	**15.9%**
Kentucky	12.4%	10.3%	12.0%
Louisiana	10.9%	8.7%	11.6%
Maine	13.4%	12.0%	12.9%
Maryland	10.8%	9.1%	12.5%
Massachusetts	13.7%	12.4%	18.5%
Michigan	11.7%	9.3%	12.3%
Minnesota	12.5%	9.9%	15.1%
Mississippi	12.3%	8.6%	12.6%
Missouri	13.8%	11.7%	16.1%
Montana	12.8%	9.4%	11.2%
Nebraska	13.8%	9.5%	16.0%
Nevada	10.7%	7.8%	9.9%
New Hampshire	11.3%	9.9%	13.1%
New Jersey	13.1%	11.7%	NA
New Mexico	10.3%	8.0%	9.7%
New York	13.0%	12.3%	12.7%
North Carolina	11.9%	9.3%	11.4%
North Dakota	13.5%	9.0%	14.2%
Ohio	12.6%	10.6%	11.7%
Oklahoma	13.0%	10.0.%	15.7%
Oregon	13.8%	11.3%	11.9%
Pennsylvania	14.9%	12.8%	13.3%
Rhode Island	14.7%	13.6%	11.4%
South Carolina	10.9%	8.5%	10.2%
South Dakota	14.0%	10.6%	13.7%
Tennessee	12.5%	10.4%	12.9%
Texas	9.9%	8.2%	15.4%
Utah	8.4%	7.0%	9.0%
Vermont	11.8%	7.6%	11.6%
Virginia	11.8%	10.0%	12.0%
Washington	11.8%	10.0%	12.4%
West Virginia	14.3%	12.2%	12.2%
Wisconsin	13.2%	10.8%	14.4%
Wyoming	9.4%	6.3%	8.2%
UNITED STATES	**12.3%**	**10.7%**	**13.0%**

Cognitive Deficiencies: Cognitive deficiencies associated with older people include confusion, inattention, slowed reaction time, slowed decision time and forgetfulness. It is estimated that two-thirds of older people have some cognitive deficiency.

Physiological Changes: Physiological changes resulting from the normal aging process are estimated to affect 3 out of 5 people aged 75 and older (TRB, 1988). It has been postulated that to drive safely, a person needs adequate muscle strength, range of motion, good reaction, perception, localization, endurance, and coordination. A decrease in muscle strength, stiffness of joints, slowing of reflex action, and general bone deterioration will compromise coordination and reaction abilities. These physiological changes affect perception reaction time, decision sight distance, and minimum required visibility distance. A decrease in sensation, coordination, and reaction skills may result in less than adequate accelerating, braking, steering, and general maneuvering of the vehicle. Driving often becomes a greater chore because of the difficulty in getting in and out of a vehicle, turning around to see behind the car, and being able to respond to several things at once. Older drivers are at a disadvantage in two ways. Because of decreased reaction time, they need more warning for critical maneuvers; because of decreased visual acuity, they are getting less.

Susceptibility to Injury: Sommons (TRB, 1988) noted that older persons are more likely than younger people to be injured or killed in a crash because their bones are weaker and more brittle. From Table 6 it can be seen that drivers over the age of 65 are the ones at greater risk when involved in accidents with drivers of other younger age groups. This increase in the fatality rate and the number of accidents will increase the cost of accidents.

Table 6. Risk of Older Driver Fatality in Collisions with Drivers of Other Ages (Patryka, 1984).

Over 65 Group vs. Other Age Groups	Risk Factor
Over 65 vs. 15-19	4.97
Over 65 vs. 20-24	4.13
Over 65 vs. 25-34	3.51
Over 65 vs. 35-49	2.79
Over 65 vs. 50-64	2.41

Drugs: Drugs are a serious problem among older people. However, their "problem" refers primarily to the misuse of prescription and over-the-counter drugs or improper mixing with other drugs. This can create a confused mind.

Mobility is essential to the quality of life of older people, and all trends indicate that a majority of the transportation needs of older citizens into the next century will be met by the private automobile. Persons 65 and over today make over 80 percent of their trips by car, either as drivers or passengers, and this percentage will increase.

According to the Federal Highway Administration's (FHWA) Highway Statistics 1988, 80 percent of the population age 65-69 has a driver's license. Figure 5, based on 1979, 1983, and 1987, illustrates the percentages of each age group with a driver's license and how the percentages have changed over the years. The 1983 NPTS data indicate that individuals aged 65 and over take an average of 1.8 person trips per day for an average trip length of 10.7 km, which results in 20 average daily person km of travel. This can be compared with data for all individuals who take an average of 2.7 person trips per day for an average trip length of 14 km and 39 average daily person km of travel.

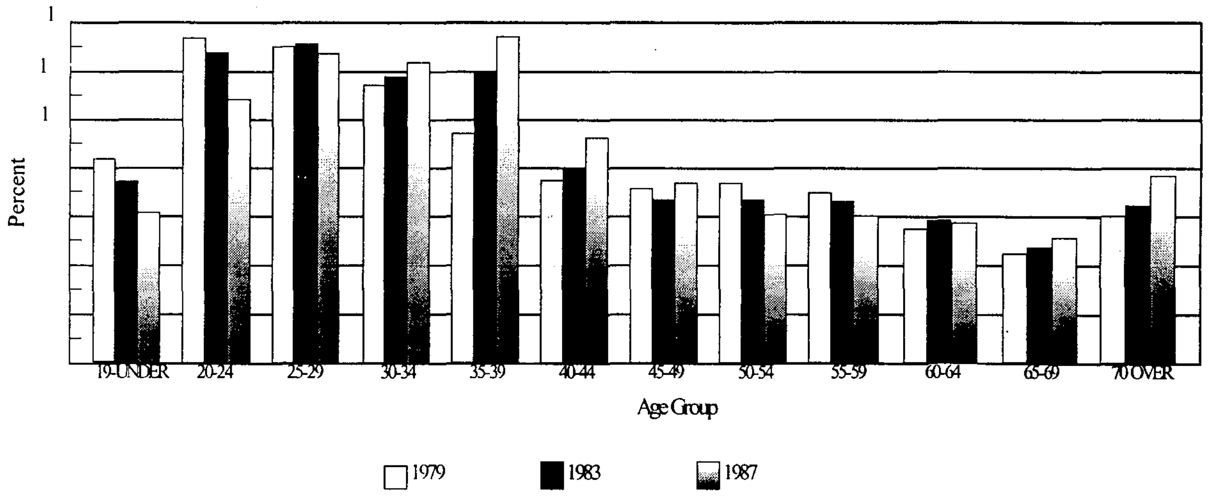

Figure 5. Percentage of Licensed Drivers (Older Driver Pilot Program, 1990)

On the basis of distance driven, older drivers are involved in fatal crashes more frequently than any other age group except teenage drivers (Figure 6 and Figure 7).

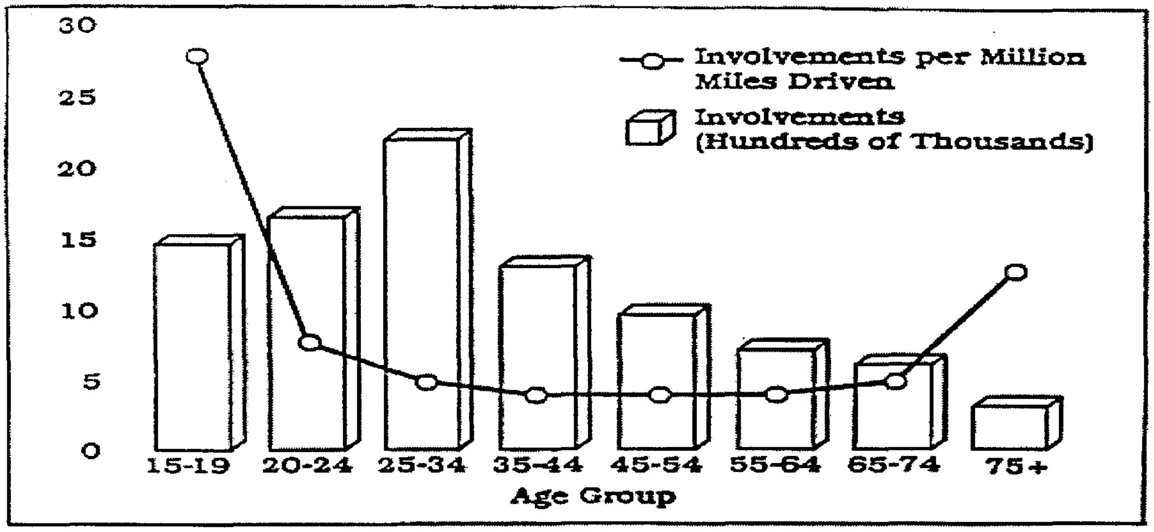

Figure 6. Driver Involvement in Crashes and Involvement Rates by Age (Professional Development Seminar Institute of Transportation Engineers, 1991).

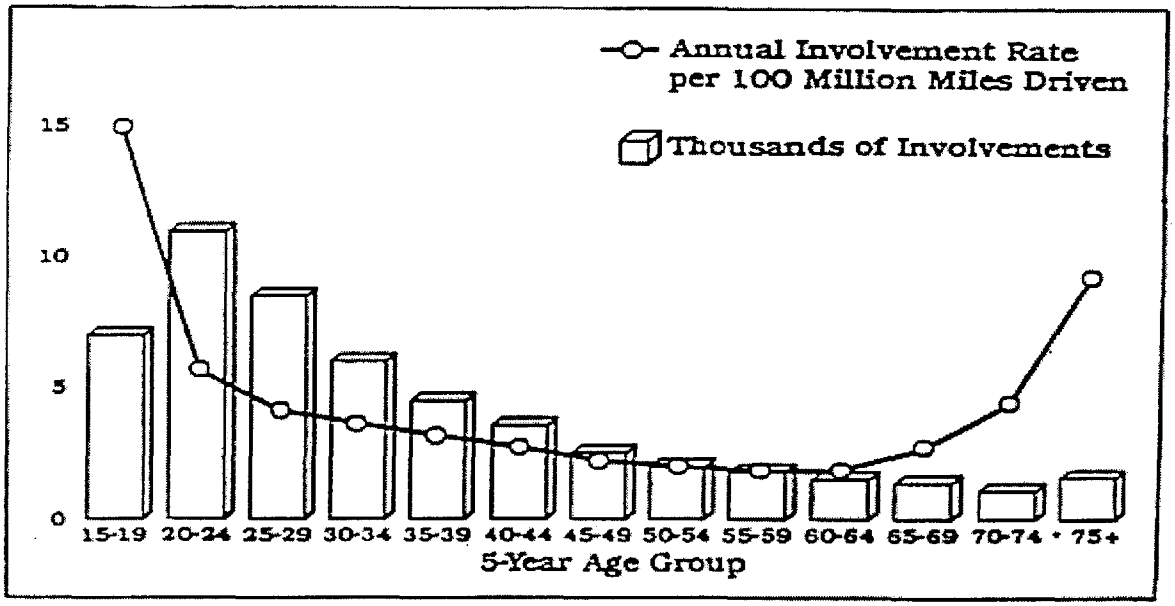

Figure 7. Driver Involvement in Fatal Crashes and Fatal Involvement Rates by Age (Professional Development Seminar Institute of Transportation Engineers, 1991)

The research conducted by Mace et al. (1994) on "Relative Visibility of Increased Legend Size vs. Brighter Materials for Traffic Signs" resulted in a number of findings (summarized in Table 7). With regard to older drivers, the studies resulted in two findings that were generally unexpected. First, sign legibility is not a bigger problem for older drivers at night than it is during daylight. The legibility index (LI[1] is the distance in ft at which a letter is legible per 2.5 cm of letter height) for older drivers is very low both day and night. One likely explanation for this is that the farthest distance at which the older drivers are capable of discerning the critical detail of the signs in the daytime is within the limits of the headlamp/retroreflective system at night. That is visual resolution, not the lighting system (sunlight or headlamps) is the limiting factor for older observers. This is not the case for younger drivers, who are reading 20 cm letters in the daylight at distances in excess of 183 m.

Table 7. Summary of Results (Mace et al., 1994).

INDEPENDENT VARIABLES	RESULTS
Driver Age	LI of younger drivers is 5 to 20 ft/in>older drivers at night and 20 to 30 ft/in>drivers during the day. The LI of older drivers is the same during the day or night.
Color	W/G E(M) is 5 to 10 ft/in > negative-contrast sign day and night. B/W is more legible than B/O.
Material	Positive high-contrast (type I on type VII) gave poor results. The LI with negative-contrast type VII is about 5 ft/in > type I with series C or D letters.
Letter Series	LI of series D is 5 to 8 ft/in > series C.
Letter Height	Legibility distance is less than proportional to letter height, particularly for younger drivers and signs legible at longer distances, e.g., with series D letters or type VII material.
Stroke Width	Avoid high positive-contrast signs so that normal stroke width may be effective day and night. Use normal stroke width on negative-contrast signs.
Letter Spacing	Wider spacing produced some improvement with positive-contrast signs. The narrow spacing equal to stroke width reduced the LI by 8 to 14 percent.
Font	No significant difference between Clarendon and Highway font.

1 ft/in = 0.12 m/cm

The materials with ASTM-type numbers in parentheses were used in this study: Avery's engineering-grade sheeting (*), Seibulite's super engineering-grade sheeting (II), Stimsonsite's cube-corner, high-performance sheeting (V), 3M Company's diamond-grade sheeting (VII).

W/G = white letters on the green background
B/W = black letters on the white background
B/O = black letters on the orange background

The second finding regarding older drivers is that increasing letter size is more likely to produce a proportionate increase in legibility distance among older drivers than among younger drivers up to about 30-cm letters. This was observed during both daytime and nighttime conditions. At night, the reduction of sign luminance at distances beyond 183 m would explain this discrepancy between old and young drivers; however, another explanation is needed for the daytime results. The flattening of the legibility distance curves between 30-cm and 41-cm letters for both young and old drivers suggests that further increases in letter height beyond 41 cm might not produce the expected increases in legibility distance.

Although the legibility of signs for older drivers is almost as poor in daylight as at night, the fact that it is no worse during the day suggests that, for the purpose of establishing the letter size required for any MRVD, only nighttime performance needs to be considered.

The data collected in this study seem to suggest that there is no strong basis to argue to change the stroke width of the series C, D, or E letters. Although a narrower stroke width improves legibility for high-contrast combinations of positive-contrast materials, the results suggest that the nominative series E(M) font is best as long as high-contrast combinations of materials are avoided.

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[1] The LI is important to the determination of the size requirements for a sign in a specific application.
MRVD-Minimum Required Visibility Distance
Required Letter Size = MRVD/LI
Required LI = MRVD/Letter Size
Either the letter size or the LI may be manipulated to satisfy the basic distance requirement.

With the exception of high-contrast signs using type VII on type I material, the range of contrast tested had little impact on legibility, suggesting that the materials used on positive-contrast signs (legend brighter than background) may be chosen based upon the needs for conspicuity and cost factors. On the basis of legibility alone, the data would suggest the use of uppercase letters; although with letters smaller than 30 cm (12 in), there was no performance difference. Whether or not lower case aided the search for place name information was not investigated.

With negative-contrast signs' (background brighter than legend), type VII material consistently provided greater legibility than type I materials, with the exception of B/O with series C letters. With B/W signs, type II and IV materials resulted in legibility similar to type VII material.

Standard highway letter spacing should be maintained unless sufficient space exists on the sign to increase spacing without increasing the size of the sign. Spacing less than standard should be avoided. Type VII material should be used when other factors, such as letter series or sign size, tend to reduce the legibility distance.

The nominative LI of 6 m/cm of letter height corresponds to a visual acuity of 20/25 (1.25 min of arc), which has been estimated to exceed the visual ability of 40 percent of the drivers over age 65. This reflects the fact that the data from which the 5 m/cm standard was obtained using young subjects with better-than-average vision. A more conservative standard would provide drivers with 2 min of arc, which corresponds to 20/40 vision and a 3.6 m/cm LI. On the basis of the findings of this research, and without consideration of the cost trade-offs involved with making larger signs or choosing brighter materials, the following guidelines that will, in general, provide the letter size needed to accommodate 75 to 80 percent of older drivers and 95 percent or more of younger drivers were recommended. (Mace et al., 1994)

- For B/W and B/O signs, assume an LI of 3.6 m/cm with series C letters on any retroreflective material, and with series D letter on Type I or II sheeting. With series D letters on Type III or Type IV sheeting, assume an LI of 4.8 m/cm.

- For W/G signs, assume an LI of 5.4 m/cm with 20-cm letters, and LI of 4.8 m/cm with 30-cm letters.

With regard to conspicuity of B/W signs, the results of the research (Mace et al., 1994) suggest that there is probably no advantage to using brighter materials, although there may be an advantage with smaller signs. A 0.91-m sign with type I sheeting was noticed from about the same distance as the same size sign with type VII sheeting. Among B/O and W/G signs, type VII material increased detection distances by 30.5 to 61 m for both 0.61- and 0.91-m signs and in low- and high-complexity situations. The brighter materials on 0.61-m signs resulted in similar detection distances as type I material on 0.91-m signs, and the combination of increased size and brightness resulted in even greater detection distances for younger, but not older, observers.

LITERATURE REVIEW TO ASSESS POTENTIAL IMPACTS ON SAFETY AND TRAFFIC OPERATIONS DUE TO INSUFFICIENT SIGN VISIBILITY

The KSU Team was unable to locate any published literature that directly addresses this issue. A number of colleagues with considerable expertise in accident studies were contacted but they are currently unaware of any studies available. The consensus of those contacted is that this is an impossible task that cannot be answered directly from any field source. Relevant crash data and exposure are non-existent. The Kansas Department of Transportation (KDOT), Bureau of Traffic, is interested in this topic. They sent a questionnaire to all 50 State traffic organizations seeking information on the subject but received little relevant information. This confirms the KSU Team's conclusion that none exists. This issue is addressed from a theoretical basis later in this report. An example of this KDOT questionnaire can be found in Appendix A.

REVIEW OF VISIBILITY AND LEGIBILITY DISTANCES OF OVERHEAD GUIDE SIGNS AND MEASURES OF EFFECTIVENESS

This section reviews methodology and models to determine visibility and legibility distances of overhead guide signs illuminated at less than recommended luminance and measures of effectiveness (MOE).

Visibility Distance Determination

A number of visibility models have been proposed. The most familiar to those working on roadway and sign visibility are:

> CIE 19/2. "An Analytic Model for Describing the Influence of Lighting Parameters Upon Visual Performance." This appears in CIE publication 19/2, 1980. The Chairman of the CIE committee who prepared this was H. Richard Blackwell and it is often referred to as the Blackwell Model.
>
> PC-Detect. This model was first used in the Ford Motor Co. headlighting program CHESS and has been revised and named PC-Detect. There are several variations of this model, one of them is used in the FHWA program CARTS (Computer Analysis of Retroreflective Traffic Signs). The original model appears in "Predicting Target-Detection Distance With Headlights," which was presented at a TRB meeting (date not shown on the publication reviewed). The authors were Bhise, Farber, and McMahan.
>
> VL-Adrian. This model is used by the IESNA Roadway Lighting Committee in RP-8, 1990, to calculate the visibility of targets on the road to determine the STV (Small Target Visibility) ratings of fixed roadway lighting systems. The model is found in a paper "Visibility of Targets: Model for Calculation" by Adrian, published in Lighting Res. Technol. 21(4) pg. 181-188, Great Britain, 1989.

All three of these models are based on the work of Blackwell plus that of others. The primary differences are with regard to observer age, time of vision (duration of fixation), influence of glare, and the method of handling low levels of visual adaptation. The models all utilize the concept of Visibility Level. Visibility Level (VL) is the result of dividing the luminance contrast of a task by the luminance contrast of that same task at the observer's visibility threshold. VL can be measured with a contrast reducing visibility meter. By definition, the value of VL equals 1 at the visibility threshold.

Visibility predictions in the field, as opposed to those in the laboratory, are complicated by non-uniform backgrounds, visual fixation variations, visual acuity, and by variations in the contrast sensitivity and disability glare effects, which are not age related.

For other work, a member of the team wrote a computer program utilizing three "visibility models" found in the literature. This program, 3VL-LOOP, provided for keyboard input and an iterative (loop) technique to move the observer and calculate the visibility level at each distance. The output, observer distance and VL, are written to disk in a format that can be imported to a spreadsheet program (Lotus 123) for evaluation and the plotting of graphs.

The program was modified to provide for the following default conditions relative to overhead guide signs and named 3VL-KSU.

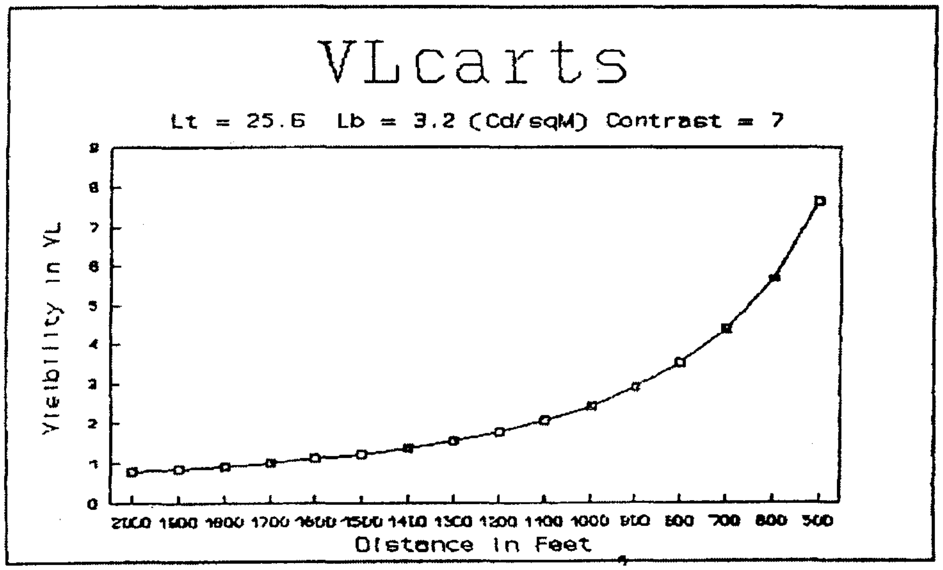
- Sign detail centered over vehicle lane and 7.6 m above lane.
- Driver eye height 1 m, 0.46 m.
- Distance from front of car to driver 1.4 m.
- Detail size for legibility 7.1 cm.
- Detail size for conspicuity 2.4 x 1.8 m.

The program was validated for consistency with the CARTS program by using sign OG-2 in the CARTS program and entering its output, age of the driver, percentile that determines the visual acuity of the driver, detail size, recognition distance, background luminance, and legend luminance into 3VL-KSU to find the VL of 1.2 which represents fair agreement with CARTS VL of 1.0.

From the literature study the base value of 3.2 cd/m^2 for sign luminance and a contrast of seven were chosen. The program 3VL-KSU was then exercised to produce the following information presented in the next section, "Results."

Results

In all cases, the defaults listed above were used. By starting the car from 610 m and moving it forward to the sign in increments of 30 m, the data and curve of Fig. 8 was produced. The visibility distance for this luminance level is determined by the location of the intersection of the curve with a VL of 1. This cannot be done with accuracy from the graph but can be done with any accuracy desired by changing the increment distance and evaluating the values on the spread sheet. In this case the visibility distance is 521 m. For these data the CARTS median observer, age 46.5 with a vision percentile of 65.9, was used.



VL = visibility level
L_b = luminance background
L_t = luminance of task

Figure 8. VL Carts Output: VL vs. Distance (L_b=3.2 cd/m^2; L_t=25.6 cd/m^2; Contrast=7:1).

Figure 9 shows a similar graph for five luminance ranges, three below and one above the base range of 3.2 cd/m^2 for the background luminance. The precise visibility distance for recognition with each range is shown in Table 8. From this it can be seen that even for a very low luminance of 0.4 cd/m^2 for the background, a 46.5-year-old observer is predicted to be able to read the legend (sign words) at a distance of 226 m. This luminance is far below the minimum recommended in any publications found in the literature search while the distance is more than twice the 66 m that CARTS gives as the minimum required visibility distance for legibility of sign OG-2.

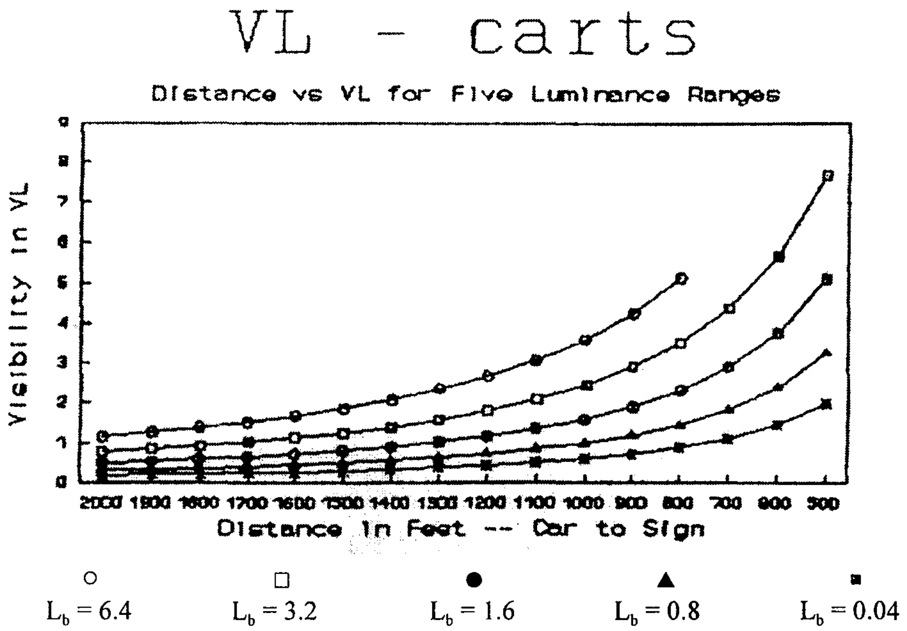


Figure 9. VL vs. Distance for Five Visibility Ranges (Contrast=7:1).

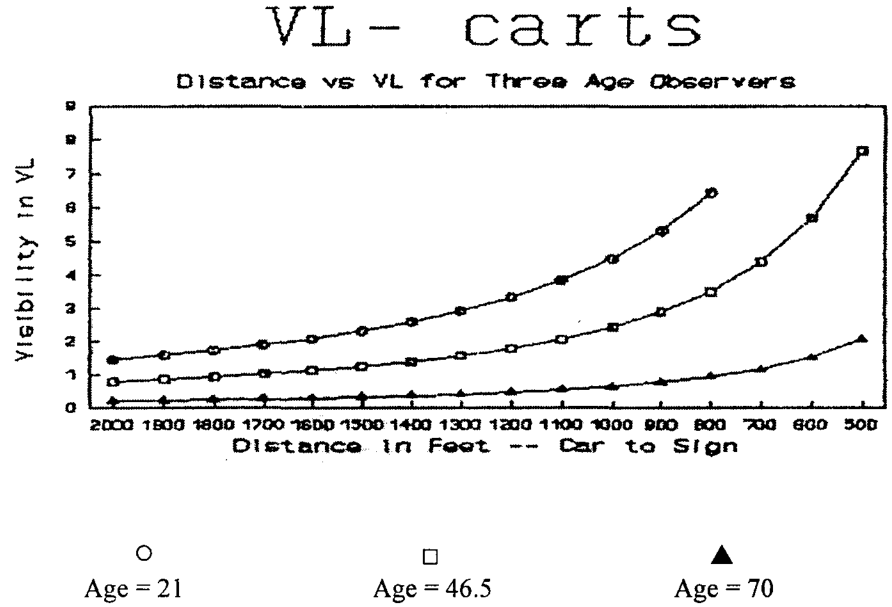


Figure 10. VL vs. Distance (using the base luminance range of L_b=3.2 cd/m^2; plotted for observers of three ages: 21, 46.5 and 70 years).

Observer age is the variable shown in Figure 10. The effects of age vary between visibility models, as do the effect of contrast, glare luminance, and size of critical detail.

The same approach, using program 3VL-KSU, has been applied to the prediction of the distance at which the presence of a sign can be detected. In this case the VL used by CARTS is 10 rather than 1 and the critical detail size is determined by using a circle whose area is equal to that of the sign, with the size expressed in minutes subtended by that circle. Graphs of this are not shown; however, the visibility distances are shown in Table 8.

As a vehicle approaches a retroreflective sign, the luminance of both the panel background and the legend change as the illuminance from the headlights varies. The contrast between them remains constant. The background against which the sign is seen, most frequently the sky but sometimes distant trees or buildings, is not retroreflective. In any event the changing illuminance from the vehicle has little, if any, effect on the luminance of the background against which the total sign is viewed. As the vehicle approaches the sign and only the sign luminance increases, the contrast between the sign and its background changes. For this reason, the approach to the calculation of detection distance is somewhat different than the calculation of the recognition distance.

With the very low 0.01 background luminance assumed by CARTS, the visibility distance with a panel luminance of 3.2 cd/m^2 is more than 4600 m. Since headlights are incapable of producing this level of luminance at this distance, the calculations are started at a much lower sign luminance level.

Table 8. Summary of Detection and Recognition Distance Calculations.

Detection Distance				Recognition Distance		
Sign Luminance	Background Luminance	Dist. Meters		Legend Luminance	Panel Luminance	Dist. Meters
0.8	0.01	1545		51.2	6.4	668
0.4	0.01	1067		25.6	3.2	521
0.2	0.01	664		12.8	1.6	400
0.1	0.01	202		6.4	0.8	300
0.05	0.01	90		3.2	0.4	225

Measurement of Effectiveness

The study called for the KSU Team to develop a Measure of Effectiveness (MOE) resulting from less than minimal overhead guide sign visibility.

Nothing was found in the literature to indicate that prior studies or investigations have determined or recommended such an MOE. The purpose of an overhead guide sign is to provide sufficient information to drivers to enable them to select the desired exit ramp so that they may reach their destination quickly and safely. The effectiveness may be measured in terms of accidents caused by maneuvers intended to place drivers in the exit lane. The effectiveness can also be measured in terms of the time lost by drivers exiting at other than the desired location and then having to retrace their path or take a longer route to their destination. Since neither the accident data nor the time lost data are available, another means must be selected.

The FHWA program CARTS provides a means of calculating the Minimum Required Visibility Distance (MRVD) for recognition of the meaning of a sign legend in sufficient time to safely maneuver. We propose that the MOE be calculated from the equation:

$$\text{MOE} = \frac{\text{Visibility Distance}}{\text{MRVD for Recognition}} \qquad \text{- - - - - - - - -} \ \textbf{\textit{(Equation 1)}}$$

An MOE value of less than 1 would indicate the sign effectiveness at night is unsatisfactory. Values greater than 1 would indicate the relative effectiveness of the sign visibility.

The MRVD for Recognition is to be calculated from the existing computer program CARTS. This research project does not provide for an investigation of the validity of the MRVD model used in CARTs.

The Visibility Distance is to be calculated using a visibility model selected and used in accordance with the techniques determined from the laboratory study of this project. To calculate Visibility Distance, it is necessary to choose not only a visibility model and the techniques for its use but also minimum headlight intensity values at angles appropriate to the required MRVD distances.

This project did not result in a new computer program to determine the MOE or a revision of the supply portion of CARTS. It did, however, result in headlight intensity values that may be used in the program CARTS or a similar program. It also provided the headlight intensity values that can be considered for a National Standard specifying above-the-beam, minimum light intensities.

MINIMUM LEGIBILITY DISTANCE UNDER REDUCED SIGN LUMINANCE

Introduction

The purpose of this task was to determine in the laboratory the effect on legibility distance of a reduction in sign luminance.

It is well known that the legibility distance of a word (or any letter) is a function of the size of the letters, the contrast between the letter stroke and its background, the luminance level of the stroke and background, the amount of disability glare present, and the differing visual capability of each observer. The complex relationship among these factors has been determined in terms of mathematical equations by previous research. When these equations are grouped together, the result is a visibility model.

Motorists approaching a sign during the daylight hours will first determine that a sign exists; this normally occurs at a much greater distance than that at which the legend can be read. During daylight the only variable is the size of the letters on the retina of the eye (visual angle), which increases as motorists approach the sign. This increase will continue until the legend can be read. Motorists have other visual tasks during the period of time after they recognize that a sign exists until they can read the legend. This results in motorists fixating their line of sight on the sign and onto other things such as the edge of the roadway, other traffic, etc. Under normal conditions these individual fixations have a duration of about 0.2 s. Fixations are sequential, with the sequence determined by the needs of the entire driving task.

Motorists approaching a sign during the nighttime hours follow the same procedure. The primary difference is that, if the light that produces the sign luminance originates from the vehicle headlights, then the luminance of the stroke and background will vary as the vehicle approaches, due to the constantly changing angular relationships between the vehicle's headlamps, the sign, and the driver's eye location. At night and day the contrast between the letter stroke and its background is similar. It is quite possible that as the motorist approaches to where words become barely legible, then approaches still closer and the luminance level drops, the words also drop below threshold even though they have increased in size.

The relationship between size and luminance level of the sign and age of the driver is predictable from visibility models, but it should be verified, since the visibility models are based on certain assumptions such as a constant angular, critical detail while the critical detail between different words and letters varies.

The experimental data for this task were taken in the FHWA Visibility Laboratory at Turner-Fairbank, which is 37 m long by 4 m wide, has no windows, and with black floors, walls, and ceilings. At one end of the laboratory was placed a simple sign with a familiar five letter word. At the other end the observer was seated in a small electric vehicle with a maximum speed of 8 km/h. The observer drove toward the sign at 8 km/h and, when the word became legible, pushed a button that turned off the lighted sign and recorded the distance traveled by the vehicle. The observer then stopped the vehicle and reported what word was on the sign. The sign was lighted by means of a fixed projector whose light output could be controlled.

There was never any doubt that the distance at which the word became legible would vary as the light level on the sign was changed - the purpose of the experimental work was to determine if the distance could be predicted accurately by means of a visibility model and, if so, what level would be appropriate for a given percentile of the population.

Observers

Thirty-three observers were used, ages 22 to 78, 21 male and 12 female. Each observer was tested for visual acuity and the length of time required to read a standard paragraph of information. Visual acuity ranged from 20/17 to 20/30 with the corrective lenses they used for driving. Reading times varied from 45 to 212 s. A three question quiz was used to ensure that the information read had been understood.

Stimulus

At one end of the laboratory was placed a stimulus holder that was 25.4 x 35.5 cm, faced with green, engineering grade, retroreflective sheeting. The stimulus holder had a white border, 0.64 cm wide, of the same type of material. On this holder could be placed either a plaque carrying a five letter word or one with two Landolt rings of the white material. The letter height was 3.8 cm with a stroke of 0.79 cm. The ring diameter was equal to the letter height and the stroke the same as that for the letters. The ring gap positions were adjustable and set either up, down, right, or left. The words were SPEED, ROUTE, SOUTH, NORTH, DELAY, and RIGHT.

The stimulus was at one end of the laboratory, mounted on a flat black wall, and lighted by a framing projector located at the same height as the stimulus and 40° from the centerline of the laboratory. Engineering grade retroreflective material exhibits diffuse reflectance characteristics when lighted from an angle greater than about 30° (entrance angle). The result was a uniformly lighted small sign (stimulus) whose luminance was constant regardless of distance and that was essentially lambertian for reasonable angles of view. The projector light passed through a filter wheel with 20 neutral density filters. The 20 filters mounted on the wheel could provide a range of luminance of approximately 100 to 1.

The contrast between the white legend and the green background was +8.3:1 as calculated from equation (2) and was constant during all data runs.

$$C = \frac{L_t - L_b}{L_b} \qquad \text{----------}(\textit{\textbf{Equation}}\ \textbf{2})$$

where:

C = Contrast
L_t = Luminance of white stroke
L_b = Luminance of green background

Luminance levels are listed for L_t in Appendix B and values for L_b may be determined from the above equation.

Vehicle

At the other end of the laboratory, 32 m from the stimulus, the observer was seated in a small electric vehicle, similar to a golf cart, which had a maximum speed of 8 km/h. The vehicle was equipped with a device on one wheel that emitted a pulse after each 10 cm of travel. The pulse was recorded by the onboard computer to determine the distance traveled.

On the steering wheel of the vehicle were two buttons. The right button was used to indicate that the observer recognized the word or the gap location of the rings. When this button was pushed a signal was transmitted to the onboard computer and by radio to the projector shutter which then closed, making the stimulus invisible while the observer stopped the vehicle. The left button was used by the subject to respond to a "loading" or "distraction" task. This task consisted of three low intensity LED's (Light Emitting Diodes) mounted on the left windshield support. The three LED's (one green, one yellow, one red) were on a small panel and were about 2.54 cm apart. The yellow lamp burned continuously while the green and red LED's were controlled by the computer. The concept was that these LED's would be in the subjects' peripheral field where color can not be detected by the rods in the eye, and when either the red or green LED came on it would force the observer to fixate on the lamp panel, thus simulating fixations normal to the task of driving. If the green LED was on, the subject was to do nothing. If the red LED was on, the observer was to push the left button. Both the energization of the red and green LED's and the left button push were recorded by an onboard computer.

The path between the vehicle and the stimulus was outlined with low intensity white LED's and was 1.5 m wide. An infrared beam across the path, 6 m ahead of the wall that held the stimulus, turned on a red stop sign. When broken, this indicated that the vehicle must be stopped immediately regardless of whether the sign was legible or not.

Experimental Procedure

Test subjects (observers) were selected and contacted from an FHWA list of volunteers and an appointment time agreed upon. Upon arrival at the laboratory, they were given a verbal overview of the experimental task, tested for visual acuity, and timed while reading the standard paragraph. The observers' ages were recorded, and they were given a written set of instructions.

The observers were then taken into the lighted laboratory, shown the vehicle, and its operation was carefully explained. The observers were then required to drive down the laboratory to the stimulus end, with a low level of ambient light in the laboratory. The concept of a Landolt ring with a movable gap position was explained. If the observers had never driven a golf cart, they were allowed to drive in the lighted lab several times. When the observers indicated that they were comfortable driving the vehicle, the laboratory lights were turned off.

While the subject became dark adapted for 5 minutes, six practice runs were completed, with the computer and loading task operating. One experimenter rode with the observer, operated the computer, and if necessary, backed the vehicle up at the end of each run. All practice runs were made using Landolt rings as a stimulus. The subjects understood that they were to press the accelerator on the command "go" of the sequence, "ready, set, go." Then, as the vehicle moved forward, they were to drive, watch the stimulus, and when one of the LED's was energized in their peripheral field, they were to glance at it and determine if it was red or green. If red, then they were to press the left button, the LED would go out, and they would continue to drive toward the stimulus until they could either read the word or determine the position of the gaps of the rings. As soon as they could recognize the word or gap position, the subjects were to press the right button, stop the vehicle, and say aloud the word or the gap positions. The experimenter who rode with the subject entered into the computer the word name or ring settings, issued the "ready, set, go" command, and entered into the computer whether the response was correct or not. The computer counted the pulses from the wheel and entered this number into the record when the right button was pushed. If the response was incorrect, the experimenter so advised the observer and flipped a switch that lighted an LED on the front of the vehicle which was invisible to the subject. This light could be seen by the other experimenter at the stimulus end of the lab.

The experimenter at the stimulus end of the lab placed the proper word or rings on the stimulus board, set the proper filter on the projector, and pressed a button to open the shutter when he heard the word "go" from the experimenter in the vehicle. The experimenter recorded each run as "correct" or "incorrect" on his data sheet, and after the entire set of 25 runs had been completed, reran the incorrect responses using the same word and filter options.

After the practice runs using the rings were complete and the subject was fully adapted to the dark, a "calibration run" was made. This run used the word "SPEED," and the same filter setting (same luminance level) was used for all subjects. On the basis of the distance (calibration distance) at which the subject recognized the word "SPEED," the experimenter determined, using a set of standard rules, the luminance levels that would be used for the balance of the runs with that subject. Two luminance levels were used for rings and three for words. The concept was to select a high luminance level that would permit the stimulus to be recognized at a distance greater than 24 m, and a low level that would permit recognition at less than 12 m. A medium level was also used when words were used as the stimulus.

After the calibration run, each subject made five runs using different words, five runs using Landolt rings with variable gap locations, five runs using words, five runs using rings, and a final five runs using words. Three light levels were used with words and two light levels with rings. Six different sequences of words, gap positions, and light levels were used. The average of the runs at each light level was used as the recognition distance for the individual. No two successive runs ever used the same word or gap position. Reruns of incorrect responses were made at the conclusion of the normal runs.

At the conclusion of test runs, the observer was told the approximate difference in light levels, asked if he had any comments or questions, and paid $25 for his participation. The testing period averaged about 1 hour. No observers indicated that they were tired or needed a break during the test runs or afterward.

Data Reduction and Analysis

Pilot runs indicated that it would be impossible, due to the limited length of the laboratory, for all observers to use the same three light levels for word legibility, or the same two light levels for ring gap recognition. The choice of a calibration stroke luminance level of 8.3 cd/m^2 was made as a result of data taken during the pilot runs and barely accommodated the 33 observers.

The experiment was designed with the expectation that a "visibility model" could be used to predict the distance at which observers, average for their age group, would recognize a word under different luminance levels. It was expected that there would be a greater variation in the prediction for words than for the Landolt rings. This is because the critical detail for ring gap recognition is precisely known but the critical detail to recognize a word is unknown since it varies between words and letters.

To use a visibility model to predict legibility, it is necessary to "calibrate" the model as to the visibility level (VL) that the human visual system uses for the task. The data used in developing such models assumes that threshold (VL=1) is the result of numerous trials with 50 percent accuracy. In normal tasks, such as reading signs, the accuracy level must be much higher than 50 percent.

The task of determining the gap position of the Landolt rings was used in the experiment to ensure that the model could be calibrated with a task where the critical detail is known. In theory, all observers will recognize the gap position at the same VL regardless of the luminance level, contrast, level of disability glare, or their age. This will be true only if each observer is a true average in terms of acuity, contrast sensitivity, and glare sensitivity of his/her age group of the population. Age is used in most visibility models to correct for normal changes in vision with age.

Taking the Landolt rings as an example, by using a visibility model and entering recognition distance, the observer's age, the luminance of the stimulus and its background, a VL could be calculated for each subject and each run. In theory, as stated above, these VL's should be exactly the same, while in practice it would be expected that they would be reasonably close. The average of these VL's would then represent what an average observer would need in terms of visibility to ensure reasonable accuracy in knowing the gap position.

This procedure was followed using four different visibility models as listed below.

1. Visibility Index as published in CIE Publication 19/2
2. Adrians VL model as published in "Lighting Research and Technology," Vol 21-4, 1989.
3. VL from the PC Detect model as extracted from the FHWA program CARTS.
4. VL from the Clear-Berman Model obtained by private communication.

An attempt was made to use the Reaction Time model of Mark Rae as distributed in 1990 to IES Committee Chairmen for evaluation. However, the values of luminance were too low and the critical detail too small, and the program would not accept them.

Of these four models, the Adrian and Clear models had the smallest, and nearly equal, deviation between the VL values produced for the Landolt ring observations. When the average VL for the high luminance ring gap task was used to predict the recognition distance for the low luminance gap position, there was no correlation. Similarly, when the average VL for all gap position luminances was used to predict the legibility distance for words, the results showed no correlation with the measured legibility distance.

When either of these two models were used by taking the average VL values of the word calibration run as the calibration VL, then a relatively poor correlation with an R^2 of 0.41 was found.

Considerable time was spent in trying to determine the reasons the four visibility models failed to correlate better. The following conclusions as to possible areas of failure were reached:

1. The effect of differences in visual acuity are not considered by any of the models. The models are based on the recognition of relatively large targets in the order of 5 to 15 minutes of visual angle. The ring gap critical detail was 0.89 minutes at 30 m and 1.79 minutes at 15 m.

2. The laboratory work was done with no external glare sources. The primary effects of age on the visual system relate to increasing the effect of glare. Many of the older observers were able to read the words under low luminance levels whereas they might not have been able to do so with external glare.

3. Visual system adaptation is the result of the average luminance in the foveal area, which covers from 1.5 to 2 degrees of the central visual field. At distances greater than 12 m, the 25.4 x 35.5 cm luminous stimulus area covered less than the normal foveal field.

None of the models covers this situation.

The process of using the recognition distance of the word "speed" to determine the luminance levels at which a particular observer's legibility distance would be evaluated leads naturally into a division of the 33 observers into groups, in which the individuals of the group were evaluated at the same luminance level. Table 9 provides interesting information as to the six groups that resulted from this procedure.

Groups 1 and 6 each contained only one observer. Group 1 was the observer who needed the highest light levels and group 6 was the one observer who needed the lowest light levels. Group 2 contained the largest number of observers, 15. The age span of group 2 included both a 22-year-old and a 78-year-old observer. The sole member of group 6 whom we called "eagle eyes," was tested using a high light level of 0.78 cd/m^2 as compared with the sole member of group 1, who was tested with a low light level of 0.65 cd/m^2. "Eagle eyes," who was a 47-year-old female, could read the words consistently at a distance of 7 m to 9 m with a low light level of 0.04 cd/m^2. The difference between individual abilities was quite large. "Eagle eyes" was tested as having a visual acuity of 20/17 while the 68-year-old observer in group 1 was tested as 20/30.

An evaluation of the data indicated that there was some correlation between the calibration distance and visual acuity, luminance level, and age but no correlation between the time required to read the standard paragraph and the calibration distance.

The data relative to the word calibration distances and the group results were evaluated by several statistical programs at Kansas State University and a predictor equation was developed for this set of data. The equation utilizes three variables: stroke luminance, visual acuity, and age. The equation is as follows:

$$\mathbf{LD = 153.57 + 19.76\,\log(stroke\ luminance) - 59.5\,\log(acuity) - .0048\,(age)^3} \quad \text{- - -} \ \textit{(Equation 3)}$$

where:

LD is the legibility distance in ft
stroke luminance is in cd/m^2
acuity is the denominator of 20/xx; i.e. 20/30
age is in years

This equation should not be used for signs other than those with a font, background size, contrast, and distance range equivalent to those in this laboratory experiment.

For this experiment, the $R^2 = 0.59$ when the equation was used to predict the distances for word legibility of all 33 observers under the luminance levels at which they were tested. If the two observers of groups 1 and 6 are not included, the R^2 rises to 0.61.

Because the signs used in the laboratory experiment are approximately 1/10 the scale of *Manual for Uniform Traffic Control Devices* (MUTCD) specified overhead guide signs, and the speed of the vehicle is also approximately 1/10 of vehicle speeds, the predictive results using the

KSU equation (Equation 3) should be reasonably accurate over a range of 90 to 300 m in terms of the distance per cm of letter height for overhead guide signs.

Table 9. Experimental Data.

Group No.	Number of Observers	Age Range	Acuity Range	Avg. Calib Dist.	Stroke Luminance		
					High	Med	Low
1	1	67	20/30	42.1	21.4	1.44	.65
2	15	22-78	20/18-20/30	66.8	13.2	1.27	.48
3	6	22-66	20/18-20/27	77.0	8.31	1.05	.39
4	4	29-43	20/17-20/22	91.0	3.25	.65	.23
5	6	27-59	20/17-20/20	98.0	1.44	.39	.13
6	1	47	20/17	102.4	.78	.22	.04

DEVELOPMENT OF AN INSTRUMENTATION PACKAGE AND DATA COLLECTION PROTOCOL FOR FIELD STUDIES

The KSU Team that is conducting this study conducted a previous NHSTA (DOT HS 807 736, 1991) study. The KSU team was intimately familiar with the study, the equipment, and the report. The final report, *Development of a Headlight Safety Database* documented several "problems" with a data collection system and suggestions for modification.

A decision was made to start from scratch and build new equipment. Details are included in a separate report available from FHWA upon request. An overview follows.

Summary of Changes

Software. Several modifications and additions were made to the software used in the Headlight Measurement System (HMS). The Quiklite program was corrected slightly, and modified to include three new features: an abort function for the data collection process; a calibrate function allowing for ambient light; and a remove calibration function. The abort function was added to the Quiklite program under the data collection routine, mode three, to allow the user to terminate the data collection process, if necessary, from the computer keyboard, instead of having to manually trigger the system to terminate the data collection. The calibration routinely measures the amount of ambient light and removes this value, in the software, from any collected data as they are taken, as opposed to removing the ambient light values manually after the data are taken. The remove calibration function disables the calibrate function.

To continue the development of the HMS, the software for the HMS was rewritten in C++ instead of QuickBasic. This allows for better portability and more efficient and faster code. Furthermore, the new software was developed in the Microsoft Windows environment, used in conjunction with Borland Quattro Pro 5.0, a graphical database and spreadsheet package.

Hardware. Many changes were made in the hardware of the HMS. The computer system for the HMS was upgraded to an 80486 portable computer with a 66 MHz clock and a 340 MB hard drive, replacing the older 80286 portable computer. This upgrade allowed the HMS to take readings at 0.5 s intervals, much faster than the old system, and gave the system a larger storage space for data. A new DC to AC power invertor was purchased to power the computer system. The old invertor did not provide a good sinusoidal AC output, and did not have a low battery indicator. These are two of the primary features in the new power invertor. Two additional items were added to the system, a serial I/O board and a trackball mouse, for use with the Microsoft Windows environment. The additional serial board allows the trackball to be connected to the computer, while still leaving serial ports that will eventually be used to interface with the SED033/Y/W photometers, mentioned below.

Seven photometers were connected to the system: five Minolta T-1's and two International Light SED033/Y/W photometers used with the IL1700 research photometer system.

The cables that were used to connect the infrared sensors to the computer during the NHTSA study (DOT HS 807 736, 1991) were replaced with two FM transceivers to allow placement of the infrared sensors a greater distance from the computer system. The FM transceivers are Radio Shack's model BTX-120, which operate well above the commercial broadcast FM band, preventing any interference with local radio stations. Slight modifications were made to the FM transceivers so that they could be used to transmit the signal from the infrared sensors. Connectors were added between the FM transceivers and the infrared sensors, to add to the portability and durability of these components.

Description of the Revised System

Development of the data collection system involved interfacing a portable '486 computer with five Minolta T- 1 illuminance meters, two International Light IL 1700 research photometers, and two infrared beam triggers. The Minolta meters and infrared beam triggers were interfaced to the computer with a Keithley DAS-HRES data acquisition board (DAQ), and the IL 1700's were connected to two of the computer's RS-232 compatible serial communications ports. Finally, software was written in "C" to provide a user interface to the system and store the photometric data collected by the system to a database file for later analysis.

The infrared beam triggers cause the system to collect data when the oncoming vehicles are certain distances away from the photometers. The infrared beam system consists of two pairs of infrared emitters and detectors. The infrared emitters are powered and placed on one side of the highway so as to project a beam of infrared light across the traffic lane to infrared detectors. The detectors provide a TTL-compatible signal, which is in the "high" state as long as the infrared beam is reaching the detector, and in a "low" state when the beam is broken, and not reaching the detector. As vehicles break the infrared beam the detector switches its logic states. This TTL signal is passed along to a tone encoder

Figure 11 shows the block diagram of the system, including the portable computer with the Keithly DAS-HRES DAQ installed, the infrared beam triggering system, and the two sets of photometers.

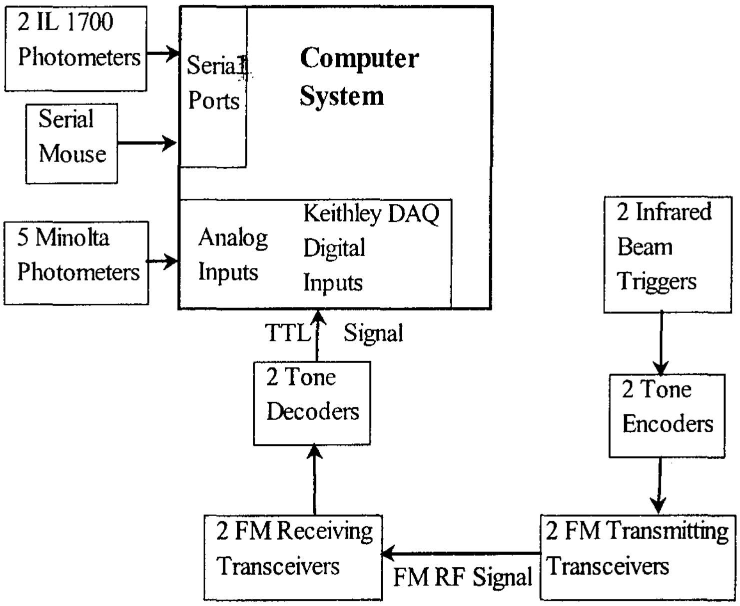


Figure 11. General Hardware Block Diagram for Field Data Collection.

When the detector switches its logic states, the tone encoder produces a 4.6875 kHz signal which is then modulated onto an FM carrier by an FM transceiver and transmitted to a detecting FM transceiver. The detecting FM transceiver demodulates the 4.6875 kHz signal and passes it along to a tone decoder. The decoder produces a TTL "low" signal which is passed along to one of the digital inputs in the Keithley DAQ. The software that controls the system then collects the photometric readings from the seven photometers.

The Minolta photometers provide their photometric readings through an external analog voltage output corresponding directly to their readings. To avoid loss of the analog voltage signal between the Minolta meter and the computer, the analog voltage signal is converted into a current from 4 to 20 mA proportional to the analog voltage and then transferred along 12 to 15 m of cable to a junction box near the computer where it is passed through a precision resistor, providing a voltage proportional to the photometric reading on the Minolta meter. The computer system then converts this voltage into a photometric measurement by using one of the Keithley DAQ's analog inputs to measure the voltage across the resistor, and then converts this voltage to the correct photometric measurement.

The Minolta meters were found to be not sensitive enough to measure headlight intensities at the highest vertical positions in which the FHWA was interested. Two International Light IL 1700 photometers were used in these two positions to measure the illuminance from the headlights, since they are almost 100 times as sensitive as the Minolta meters. The IL 1700's are interfaced to the computer through two of the computer's RS-232 compatible serial ports. To obtain the photometric readings from these two meters, the software in the system performs interrupt-driver serial communications. The photometric readings from the IL 1700's is transmitted across the serial lines as ASCII data, which are received by the computer and then displayed for the user.

FIELD STUDY

Two field studies were conducted under this contract. The following describes the experimental setup procedure used in data collection and the results obtained in these studies.

Overview of the First Field Study

After successfully completing development of the data collection equipment, the Headlight Measurement System (HMS) was used for field data collection of a sample of illuminance values from a typical fleet of vehicles traveling on U.S. highways.

The field data collection was done on a straight, flat, level section of Interstate 70 at Spring Creek Road (Exit 332), about 30 miles east of Manhattan, Kansas and on Interstate 435 in Missouri. Seven photometers (five Minolta T-1 illuminance meters and two International Light IL-1700 illuminance meters) were used to collect illuminance values. Four Minolta illuminance meters were located along the right shoulder at the heights of 0.61 m, 1.95 m, 3.26 m, and 4.6 m from the road surface. Two IL-1700's and one Minolta illuminance meter were located at an overhead sign location at heights of 8.62 m, 7.28 m, and 5.94 m, respectively (see Table 10). The illuminance values were collected only from vehicles traveling in the right-hand lane and operating with low-beam headlamps. A sign was positioned approximately 1.2 km (3/4 mi) ahead of the test site asking drivers to use their low-beam headlamps for the next mile. Along with the illuminance readings, the vehicle speed and the vehicle's rear license plate were recorded by using an infrared video camera system. The video imaging system included a 500-watt infrared lamp, an infrared video camera with a low-light level telephoto lens, a VCR and video monitor, and a gasoline-powered generator.

Table 10. Sensor Positions Used in the Field Study.

Sensor Designation	Location on Highway	Sensor Height (m)	Vertical Angle @152 m	Vertical Angle @114 m
IL 1700-1	Lane Ctr	8.6*	3.0	4.01
IL 1700-2	Lane Ctr	7.3*	2.5	3.34
Minolta 1	Lane Ctr	5.9	2.0	2.67
Minolta 2	Rt. Edge	4.6	1.5	2.0
Minolta 3	Rt. Edge	3.3	1.0	1.33
Minolta 4	Rt. Edge	1.9	0.5	0.67
Minolta 5	Rt. Edge	.61	0.0	0.00

*Denotes the more sensitive IL 1700 photometers

Measurements were taken at distances of 152 m and 114 m, plus a third reading 1.1 s after a vehicle passed the 114-m location (see Table 11). Infrared triggers were set up at 152 m and 114 m locations to activate a computer to collect the readings from the photometers. Because the third reading was time dependent, the exact location of each vehicle varied according to its speed. Figure 12 shows a top view of the setup of the system as it was used in this study.

Figure 12. Top View of the Instrumentation Setup of the First Field Study.

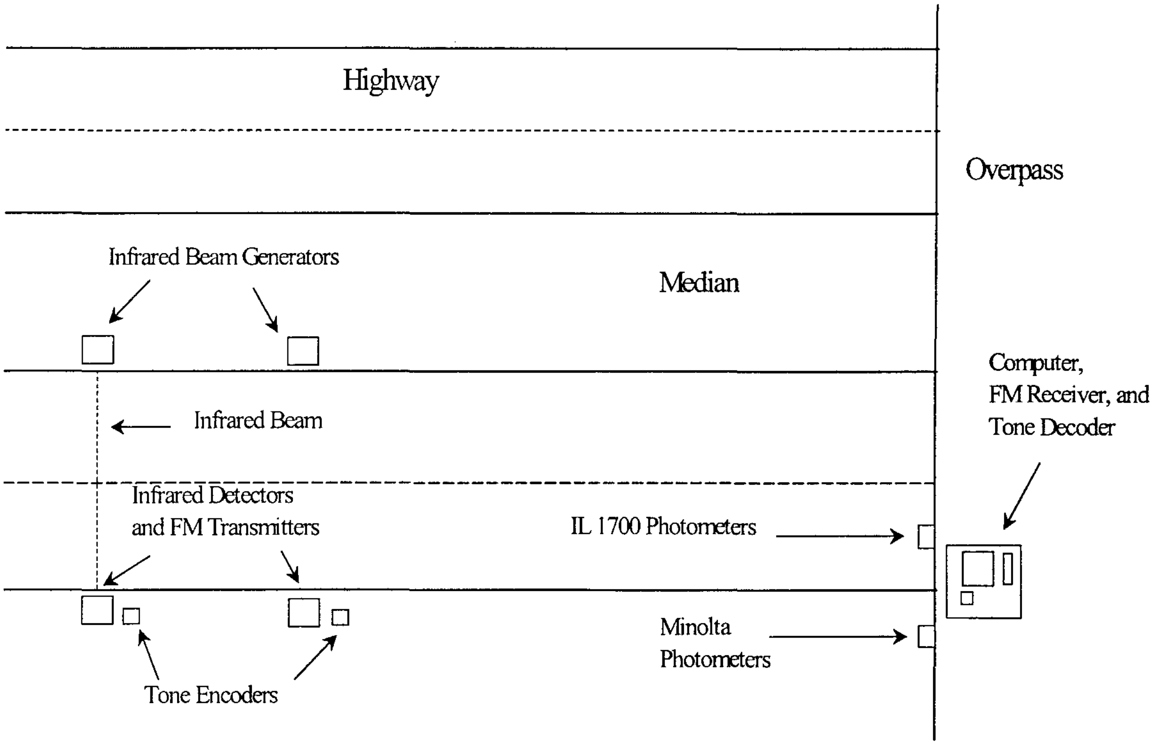


Table 11. Typical Set of Photometric Measurements (lux).

Record Number 116[1] Vehicle Type: Car[1] Sensor Number	Speed: 112 km/h			License Tag:[3]
	Illuminance (lx) at D_1 - 152 m	Illuminance (lx) at D_2 - 114 m	Illuminance (lx) at D_3[2]	
IL1700 #1	0.039	0.046	0.077	
IL1700#2	0.045	0.053	0.089	
Minolta 1	0.097	0.119	0.140	
Minolta 2	0.151	0.184	0.216	
Minolta 3	0.194	0.270	0.259	
Minolta 4	0.164	0.242	0.197	
Minolta 5	0.114	0.140	0.173	

[1] manual input
[2] distance relative to the car speed
[3] added manually after viewing video

Table 11 shows all of the data that were collected on each vehicle as it passed through the system. The data were entered in a spreadsheet format in a QuattroPro program as part of the data collection system. The topmost items in the data are the type (car, truck, etc.) and speed of the vehicle. The first column denotes whether the measurements are taken with the Minolta or IL 1700 photometer, and the next three columns show the photometric measurements taken as the first and second infrared beams are broken, and 1.1 s after the second infrared beam is broken, respectively. Table 11 is close to what is actually seen on the computer screen.

A sample of about 2,500 total vehicles was obtained from two locations during the months of April, May, and June (1996). Data were collected along Interstate highway I-70 in Kansas and along Interstate Highway I-435 in Missouri. License plate identification was possible on about 1,000 vehicles. The license tag numbers identified from the videotape were sent to the appropriate states' department of motor vehicles to obtain the make and model of the vehicles. This was done to determine whether or not headlamp illumination toward signs, especially overhead guide signs, changed gradually as headlamps designs changed from sealed-beam types to composite (aerodynamic) types over years.

Data Reduction Based on Vehicle Type as Determined by Make/Model

After the vehicle identification was obtained, it was incorporated into the database. At this point the "Car Type" field was modified based on the make, model, and type of the vehicle. Analysis of data by vehicle type is presented below.

Analysis of Data by Vehicle Type

The original data was sorted to create "car, "truck," "minivan," and "van" data bases. Statistical means and ranges were calculated for all data bases. Histograms were constructed for each vehicle type for every set of readings, i.e., each photometer and each distance. Figure 13 shows the histogram for cars obtained from Minolta number Ml (h = 5.9 m) at distance 152 m. The means of all data bases are shown in Table 12. An analysis of variance (ANOVA) procedure was used to check for statistical differences in illuminance between vehicle types. It was determined that there is no statistically significant difference between vehicle types.

The data from the complete data set, approximately 2,500 vehicles, was analyzed and delivered to FHWA. It was subsequently determined by the Contracting Officer Technical Representative (COTR) that: 1) the data contained too much reflected light from the pavement and 2) the random nature of the reflected light made adjusting the data base by applying some factor questionable.

Table 12. Summary of Vehicle Data.

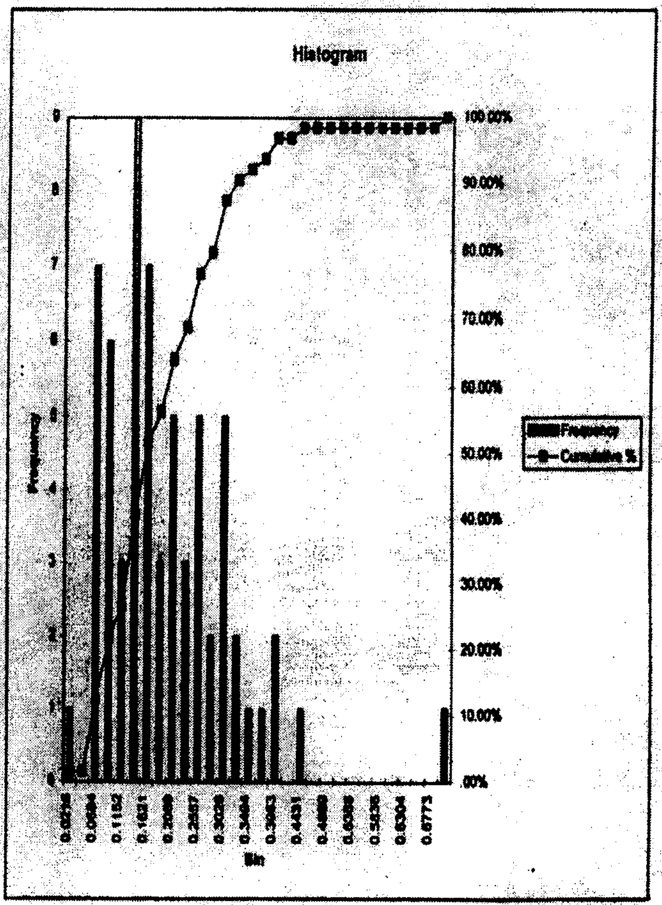
a.	Mean Illuminance Values (lux)					
	IL1700 1 (h - 8.6 m)			IL1700 2 (h = 7.3 m)		
Vehicle type	D1 152 m; θ = 3.0°	D2 114 m; θ = 4.01	D3 Variable; 1.1 s After D_2	D1 152 m; θ = 2.5°	D2 114 m; θ = 3.34°	D3 Variable; 1.1 s After D_2
Car	.0785	.0882	.1270	.0861	.0904	.1302
Minivan	.0516	.0699	.1108	.0656	.0850	.1280
Truck	.0742	.0904	.1345	.0893	.1022	.1506
Van	.0667	.0850	.1259	.0678	.0850	.1344
All Vehicles	.0761	.0877	.1275	.0843	.0924	.1349

b.	Mean Illuminance Values (lux)					
	MINOLTA 1 (h - 5.9 m)			MINOLTA 2 (h = 4.6 m)		
Vehicle type	D1 152 m; θ = 2.0°	D2 114 m; θ = 2.67°	D3 Variable; 1.1 s After D_2	D1 152 m; θ = 1.5°	D2 114 m; θ = 2.0°	D3 Variable; 1.1 s After D_2
Car	.1442	.1786	.2421	.2260	.2808	.3562
Minivan	.1420	.1775	.2421	.2378	.2948	.3701
Truck	.1506	.1937	.2625	.2464	.3120	.3981
Van	.1463	.1937	.2701	.2486	.3077	.4433
All Vehicles	.1453	.1817	.2467	.2311	.2881	.3674

c.	Mean Illuminance Values (lux)					
	MINOLTA 3 (h - 3.3 m)			MINOLTA 4 (h = 1.9 m)		
Vehicle type	D1 152 m; θ = 1.0°	D2 114 m; θ = 1.33°	D3 Variable; 1.1 s After D_2	D1 152 m; θ = 0.5°	D2 114 m; θ = 0.67°	D3 Variable; 1.1 s After D_2
Car	.3712	.5326	.7285	.6155	1.0706	1.8862
Minivan	.4013	.5724	.7521	.6994	1.2148	2.1316
Truck	.4304	.6230	.8630	.7532	1.3256	2.3963
Van	.3766	.5724	.8511	.6703	1.1556	2.2865
All Vehicles	.3837	.0513	.0704	.6469	1.1276	2.0054

d.	Mean Illuminance Values (lux)		
	MINOLTA 5 (h - 0.61 m)		
Vehicle type	D1 152 m; θ = 0.0°	D2 114 m; θ = 0.0°	D3 Variable; 1.1 s After D_2
Car	.1130	.1420	.1991
Minivan	.1130	.1420	.2001
Truck	.1194	.1506	.2087
Van	.1173	.1474	.2044
All Vehicles	.1143	.1437	.2010

Bin	Frequency	Cumulative %	Min (lx)	Max (lx)
0.0216	1	1.56%	0.0216	0.0449
0.0450	0	1.56%	0.0450	0.0683
0.0684	7	12.50%	0.0684	0.0917
0.0918	6	21.88%	0.0918	0.1151
0.1152	3	26.56%	0.1152	0.1386
0.1387	9	40.63%	0.1387	0.1620
0.1621	7	51.56%	0.1621	0.1854
0.1855	3	56.25%	0.1855	0.2088
0.2089	5	64.06%	0.2089	0.2322
0.2323	3	68.75%	0.2323	0.2556
0.2557	5	76.56%	0.2557	0.2791
0.2792	2	79.69%	0.2792	0.3025
0.3026	5	87.50%	0.3026	0.3259
0.3260	2	90.63%	0.3260	0.3493
0.3494	1	92.19%	0.3494	0.3727
0.3728	1	93.75%	0.3728	0.3962
0.3963	2	96.88%	0.3963	0.4196
0.4197	0	96.88%	0.4197	0.4430
0.4431	1	98.44%	0.4431	0.4664
0.4665	0	98.44%	0.4665	0.4898
0.4899	0	98.44%	0.4899	0.5133
0.5134	0	98.44%	0.5134	0.5367
0.5368	0	98.44%	0.5368	0.5601
0.5602	0	98.44%	0.5602	0.5835
0.5836	0	98.44%	0.5836	0.6069
0.6070	0	98.44%	0.6070	0.6303
0.6304	0	98.44%	0.6304	0.6538
0.6539	0	98.44%	0.6539	0.6772
0.6773	0	98.44%	0.6773	0.7006
More	1	100.00%	0.7007	0.7007



YEAR 1989 VEHICLE TYPE: CARS
METER HEIGHT: 5.94 m
DISTANCE: 152.48 m

M1D1

COUNT 64	MAX 0.7007	RANGE 0.6791
MEAN 0.1673	MIN 0.0216	BIN SIZE 0.0234

Bin size is the computer assigned interval width of the histogram.

**Illumination readings are in lux.*

Figure 13. Histogram and Cumulative Frequency of Illuminance Readings from Minolta 1 for Cars at 152 Meters.

Conclusions

The results from this study indicated considerably higher illuminance values than anticipated. It was concluded that a substantial amount of light reflected from the pavement was included in the readings. The illuminance reflected from the pavement does not contribute to sign luminance visible to drivers and must be eliminated from the readings and calculations for a proper analysis of sign luminance. Originally, provision had been made to eliminate some of the pavement reflection (a black rubber tube was attached to the two Minolta meters nearest to the road surface); however, the actual extent and magnitude of the expected reflection could not be accurately determined until data were collected and analyzed and, subsequently, additional studies on pavement reflectance were performed by FHWA personnel.

Based on these studies done by FHWA, it was concluded that the difference in the amount of light reflected from the pavement is a function of headlamp aim and headlamp photometric characteristics. Trying to quantify the magnitude of pavement reflection to modify the existing data base most likely would be unrealistic. Thus, in order to determine the correct luminance values of overhead guide signs, it was decided to conduct a second field study.

Overview of the Second Field Study

The second field study was conducted during the summer of 1997 in the same Kansas location as the first study: Interstate 70, Exit 332 (Spring Creek Road), about 30 miles east of Manhattan, Kansas. Equipment was modified in an attempt to eliminate pavement reflection from the illuminance readings.

Six photometers (four Minolta T-1 illuminance meters and two International Light IL-1700) were used to collect the illuminance data. Pairs of photometers were mounted on the right shoulder (coded Minolta "blue" and "clear"), the left shoulder (coded Minolta "yellow" and "green"), and over the center of the right driving lane (two IL-1700 at an overhead sign location) on the bridge structure. Figure 14 shows a plan view of the field data collection site. Figure 15 shows a cross section of the field data collection site.

To eliminate or reduce the amount of light reflected from the pavement and stray light,"optical occluders" (metal tubes lined with black velvet) were designed and constructed onto the photometers (see Figures 16 and 17). These tubes were permanently attached via a gimbal-mount to a support structure embedded either in the roadway (4x4 breakaway wooden post) or on the overhead (bridge) structure (1-inch-diameter metal pipe). Once securely in place and properly aimed, the photometers were attached to the tubes. Originally, it was planned that one IL-1700 and two Minolta illuminance meters would be aimed from the overpass at the roadway at 152 m and one IL-1700 and two Minolta Illuminance meters would be aimed from the overpass at the roadway at 114 meters. During trial runs it was determined that, due to the relatively low mounting height of the photometers, valid readings could be taken at both the 152 m and 114 m locations by the same photometer, while still keeping light reflected from the road surface to a minimum. Therefore, the two photometers at each of the three locations were aimed toward the same locations to allow double data collection. This dual data collection served as a check on the performance of each photometer pair.

The effectiveness of the optical occluders was verified by using a 1 ° luminance meter, measuring the luminance of selected parked cars' headlamps at the 152-m distance and converting the recorded value to luminous intensity. Extremely good agreement was found.

(John Arens, TRB presentation, 1998).

The experimental data consisted of illuminance values and the vehicle speed. The very labor- and cost-intensive part of identifying each vehicle's make, model, and year based on recorded license plate number was omitted. This was due in part to budgetory constraints. Also, since it would not be known how the headlights were aimed, the information would be of limited value. Instead data were collected on 50 known vehicles in addition to the data on about 1,500 vehicles that happened to travel through the data collection site on Interstate 70 during periods of data collection. No attempt was made to randomize the vehicles or the data collection periods.

The advertisement printed below appeared in the city newspaper "Manhattan Mercury" and in the student newspaper "Kansas State Collegian" to obtain 50 known vehicles.

> *Kansas State University research team is conducting a study to determine how much light from your car headlights is getting to the highway traffic control signs, specifically overhead guide signs. We would like to collect the data (headlamp type, headlamp aim, make, model, and year) on specific vehicles (cars only!) listed below:*
>
> *10 with old sealed beams (1980 to 1989)*
> *20 1990 to 1995*
> *20 1996 to 1997*
>
> *You will be asked to drive at nighttime through the data collection system located on I-70 and Spring Creek Road (Exit 332) 3 times. Prior to the field runs, you need to agree, that the headlamp aiming of your car will be checked and adjusted as necessary. To be able to participate in this experiment you need to have a valid license and proof of car insurance. The total time to complete the experiment will be approximately two-and-a-half hours. You will receive $55.00 for participation in the experiment.*

Table 13 contains a list of vehicles on which the illuminance data and vehicles' characteristics data (headlamp type, headlamp aim, make, model, year, voltage) were gathered. Prior to the field experiment, the headlamps of the cars listed in Table 13 were properly aimed by using a headlamp aimer provided to the Kansas State University research team at no cost by Hopkins Manufacturing Co., Emporia, Kansas. For a small number of selected cars, the voltage at the lamp terminals was checked during engine idle (see Table 14). In addition, FHWA provided three sets of calibrated headlamps that were installed in each of the following vehicles:

(1) 1985 Subaru GL (4 headlamp system)
(2) 1990 Ford Taurus
(3) 1996 Ford Taurus

The contract also called for one or two of the 1996-1997 vehicles used in the field experiment to be equipped with "projector type" headlamps. A 1994 Accura Integra equipped with "projector type" headlamp was tested in the field study. All cars were traveling in the right lane and with the low beam headlamps on. Again, as in the first field study, a sign was positioned 1.2 km (3/4 mi) ahead of the test site to remind drivers to use low-beam headlamps.

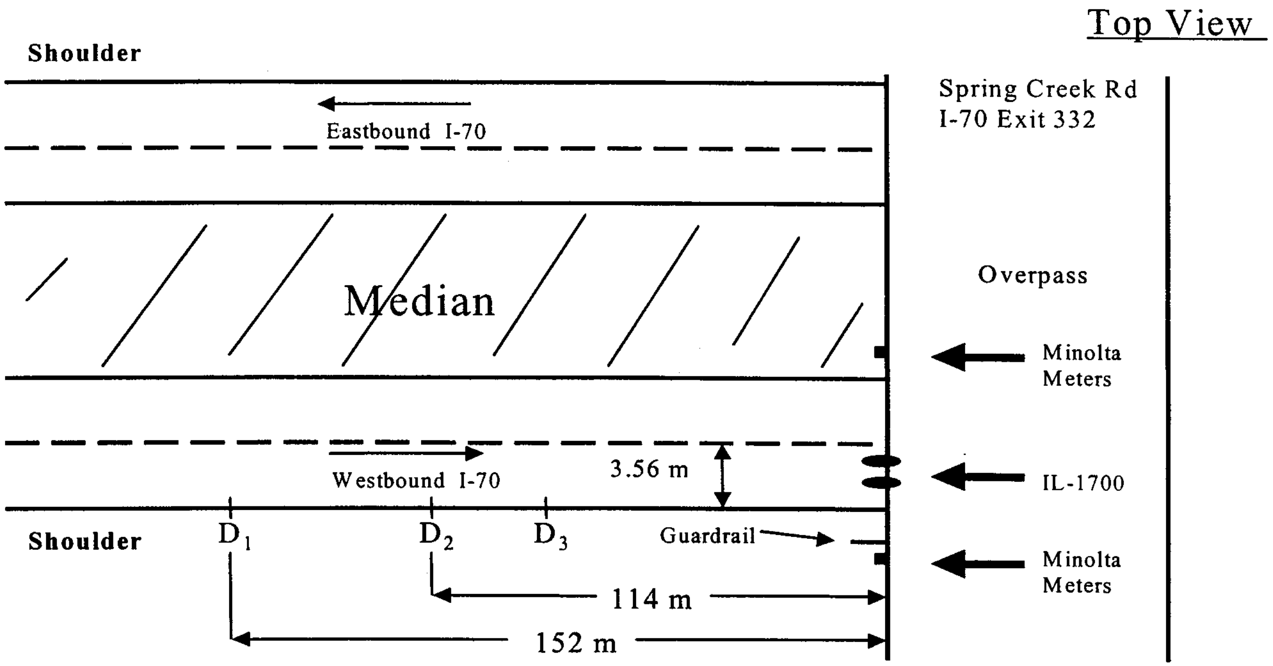
Table 13. Vehicles Tested in the Field Study.

Vehicle Type	Year	HeadlampType	Vehicle Type	Year	Headlamp Type
Ford Granada	1980	Sealed 2B1	Ford Taurus	1993	Hal. comp.
Chevy Cavalier	1983	Sealed 2B1	Honda Accord	1993	Hal. comp.
Mazda	1984	Sealed 2B1	Plymouth Acclaim	1993	Hal. comp.
Nissan Stanza	1984	Sealed 2B1	Plymouth Duster	1993	Hal. comp.
Buick Century	1985	Sealed 2A1	Pontiac Bonneville	1993	Hal. comp.
Ford Tempo	1985	Sealed 2B1	Acura Integra	1994	Projector
Pontiac Bonneville	1985	Sealed 2A1	Mercury Tracer	1994	Hal. comp.
Subaru GL	1985	Sealed 2A1	Ford Escort	1995	Hal. comp.
Subaru GL (1)	1985	Sealed 2A1	Ford Taurus	1996	Hal. comp.
Dodge Aries	1987	Sealed 2B1	Honda Accord	1996	Hal. comp.
Stanza	1987	Hal. comp.	Mazda Protege	1996	Hal. comp.
Buick Century Limited	1989	Hal. comp.	Mercedes	1996	Xenon comp.
Pontiac GrandAm	1989	Hal. comp.	Nissan Altima	1996	Hal. comp.
Buick LeSabre	1990	Hal. comp.	Nissan Maxima	1996	Hal. comp.
Buick Reatta	1990	Sealed 2B1	Pontiac GrandAm GT	1996	Hal. comp.
Cadillac	1990	Hal. comp.	Saturn	1996	Hal. comp.
Chevy Cavalier	1990	Hal. comp.	Camaro	1997	Sealed H90
Ford Taurus	1990	Hal. comp.	Chevy Cavalier	1997	Hal. comp.
Honda Accord	1990	Hal. comp.	Ford Aspire	1997	Hal. comp.
Plymouth Laser	1990	Sealed 2E1	Ford Taurus	1997	Hal. comp.
Pontiac GrandAm	1990	Hal. comp.	Ford Taurus	1997	Hal. comp.
Buick Century	1991	Hal. comp.	Ford Taurus	1997	Hal. comp.
Chevy Corsica	1992	Hal. comp.	Ford Taurus (1)	1997	Hal. comp.
Chevy Lumina	1993	Hal. comp.	Mazda Protege	1997	Hal. comp.
Chevy Lumina	1993	Hal. comp.	Pontiac GrandAm	1997	Hal. comp.

(1) Headlamps supplied by FHWA.

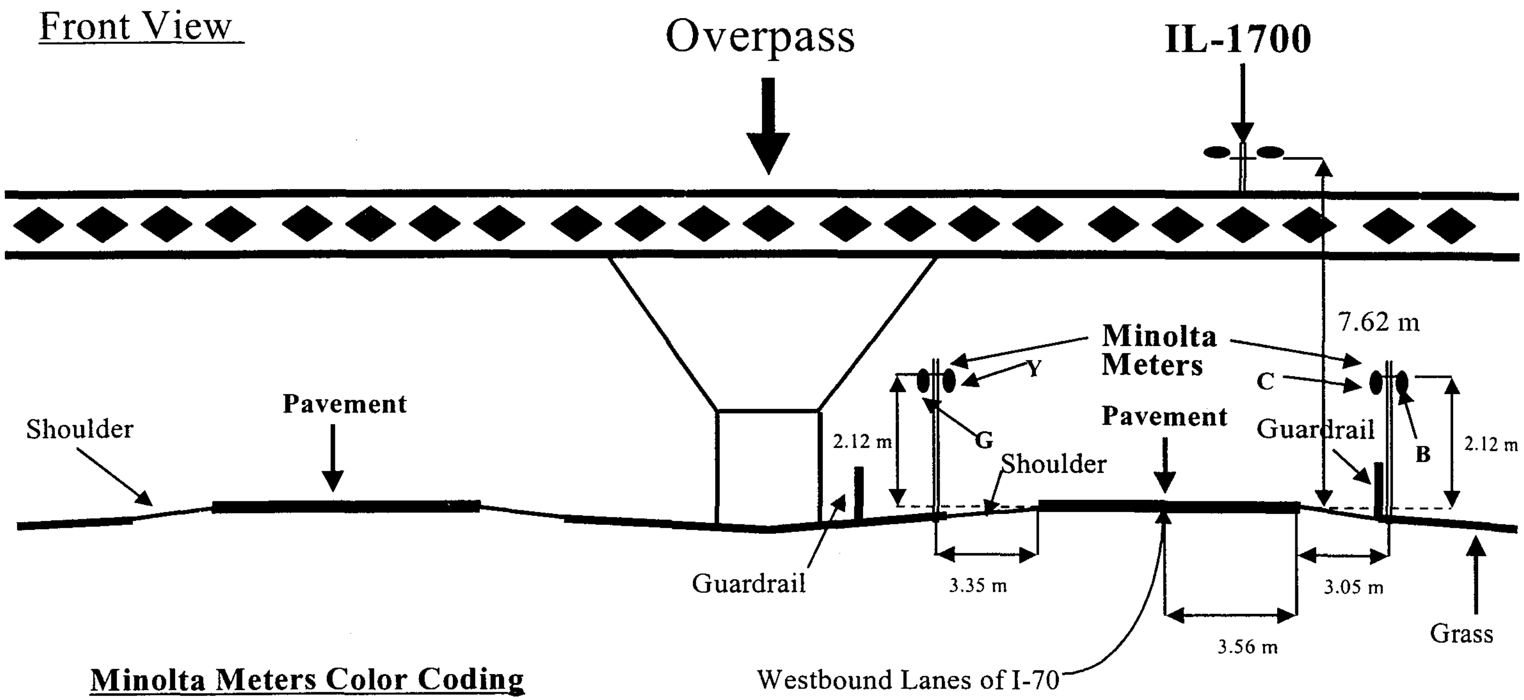
Table 14. Vehicles with Known Headlamp Voltages for Engines Idling.

Vehicle Type	Year	Headlamp Type	Headlamp Voltage, V	Headlamp Intensity, c	
				Passenger Side	Driver Side
Ford Granada	1980	Sealed 2B1	14.00	16000	16000
Chevy Cavalier	1983	Sealed 2B1	13.50	22000	24000
Mazda	1984	Sealed 2B1	13.56	22000	28000
Nissan Stanza	1984	Sealed 2B1	13.12	6000	6500
Ford Tempo	1985	Sealed 2B1	13.00	22000	21000
Dodge Aries	1987	Sealed 2B1	13.45	21000	13000



Note: Distance from D3 to the meters is relative to the car speed

Figure 14. Plan View of the Field Data Collection Site.



Minolta Meters Color Coding

B - **B**lue is positioned on right shoulder
C - **C**lear is positioned on right shoulder
Y - **Y**ellow is positioned on left shoulder
G - **G**reen is positioned on left shoulder

Figure 15. Cross Section of the Field Data Collection Site.

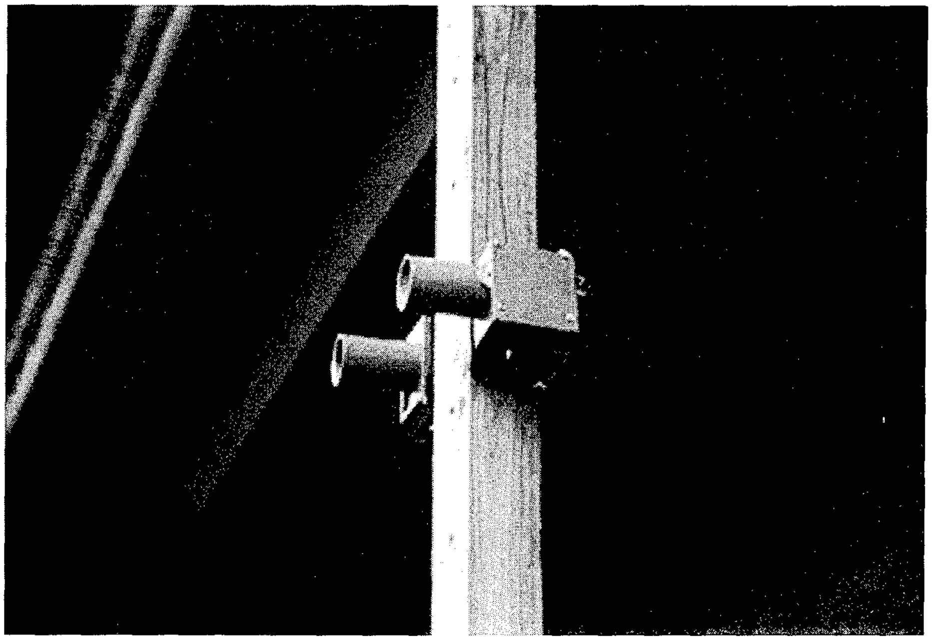


Figure 16. Optical Occluders.

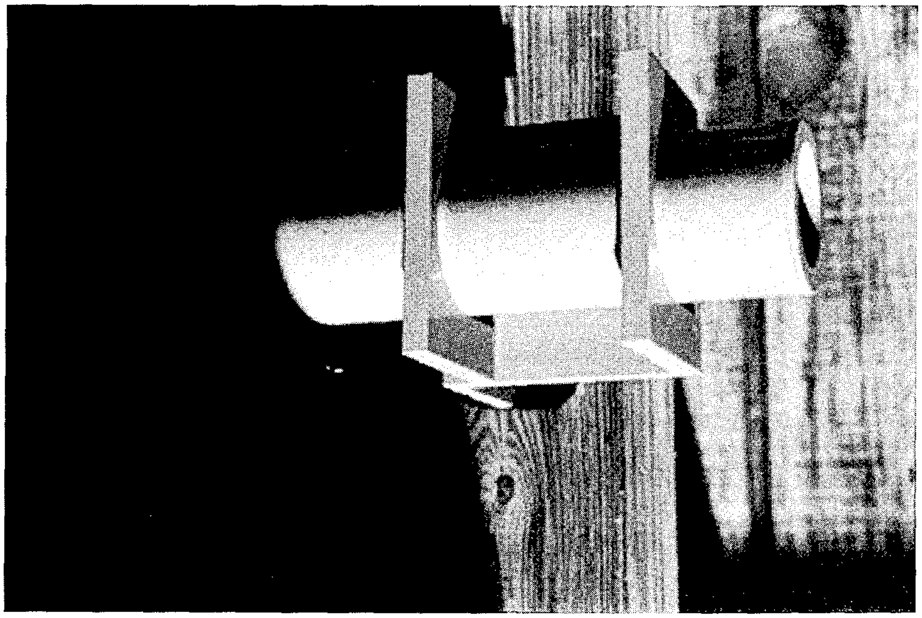


Figure 17. Minolta Photometer Mounted on the Optical Occluder.

Statistical Analyses

Separate statistical analyses were performed on the 50 known vehicles and 1,500 unidentified vehicles. The first section , “Statistical Analysis of the 50 Known Vehicles,” describes the tests used and the results obtained from the analysis of the illuminance data of the 50 known vehicles. The second section, “Statistical Analysis of 1,500 Vehicles,” describes the tests and results obtained from the analysis of the illuminance data of the 1,500 vehicles.

Statistical Analysis of the 50 Known Vehicles

Statistical analyses were performed on the illuminance data for each of the six independent variables. The independent variables obtained from the 50 vehicles were: *vehicle year, headlamp type, headlamp wattage, passenger-side headlamp intensity, driver-side headlamp intensity, and vehicle speed.* The dependent variables obtained in the field were the measurements of headlamps' illuminance in lux detected by each of six photometers, when vehicles were 152 m or 114 m away from the overpass (bridge). Two Minolta illuminance meters were mounted on the right shoulder of the highway (3.05 m from the edge of the lane and 2.12 m off the road surface) and designated as "blue" and "clear" in Figure 14 and Table 15. Two Minolta illuminance meters were mounted at the left shoulder of the highway (3.35 m from the edge of the left lane and 2.12 m off the road surface) and designated "green" and "yellow" in Figure 14 and Table 15. Two IL 1700 illuminance meters were positioned in the center of the right driving lane on a bridge structure at the height of 7.62 m above the road surface.

Below is a detailed description of the statistical analysis performed on one of the independent variables - *vehicle year*. The same type of analysis was performed for all other independent variables and the results of the analysis are summarized later in Table 17. The mean and standard deviation of the illuminance measurements corresponding to each vehicle year was calculated, the significance of the variable was determined, and, if vehicle year was significant, a Duncan Multiple Range test was performed.

Statistical Analysis System (SAS) version 3.11 was employed to perform the statistical analysis. The following is an example of the SAS code used: (Terms are explained below)

```
Proc GLM data = headlite;
Class vehicle-year;
Model blue = vehicle-year / ss3;
Means year / alpha = 0.05 Duncan;
```

The first line of code (*Proc GLM data = headlite*) means that SAS is to use a general linear model procedure on the data that is named headlite. (Using a general linear model procedure is standard for a one-way analysis of variance.) The second line tells SAS that *vehicle-year* is the independent variable in this analysis. *Model blue = vehicle-year / ss3* tells SAS that the dependent variable is the group of photometer readings taken by the Minolta illuminance meter that was coded "blue" when vehicles were 152 m away,and also that the significance of vehicle year on illuminance values (blue) is to be investigated. That line also has SAS form an analysis of variance (ANOVA) table giving means, sums of squares, degrees of freedom, p-values, etc. These values are summarized in Table 16. The last line of code, *means year/alpha = 0.05*

Duncan, causes SAS to form a Duncan grouping based on the mean of the photometer readings for each vehicle year. The alpha value was set at 0.05 to distinguish which vehicle years' means were significantly different. The value 0.05 is a common choice for this variable. The Duncan groupings for each independent variable are given in Appendix C (Table 1 through Table 18). In these tables the levels (means) with the same letter are not significantly different.

Table 15. Mean Illuminations (lux) for the 50 Known Vehicles.

			Minolta Illuminance Meters (2)								IL1700 Illum. Meters			
			Blue		Clear		Yellow		Green		#1		#2	
Vehicle Type	Year	Headlamp Type	152	114	152	114	152	114	152	114m	152	114	152	114
Ford Granada	1980	2B1-35	.250	.305	.245	.308	.052	.074	.056	.080	.031	.039		
Chevy Cavalier	1983	2B1-35	.148	.217	.147	.220	.060	.096	.065	.101	.033	.049	.038	.056
Mazda	1984	2B1-35	.349	.411	.343	.408	.150	.147	.130	.170	.079	.116	.081	.135
Nissan Stanza	1984	2B1-35	.102	.144	.104	.147	.051	.070	.057	.077	.026	.034	.028	.041
Buick Century	1985	2A1-35	.185	.242	.186	.251	.086	.115	.096	.127	.073	.084	.079	.090
Ford Tempo	1985	2B1-35	.089	.128	.092	.133	.052	.077	.069	.092	.020	.029	.020	.031
Pontiac Bonneville	1985	2A1-35	.126	.181	.126	.181	.055	.079	.060	.085	.025	.034		
Subaru GL	1985	2A1-35	.132	.201	.137	.207	.054	.086	.059	.066	.028	.035	.030	.037
Subaru GL (1)	1985	2A1-35	.126	.184	.133	.188	.054	.069	.050	.068	.020	.030		
Dodge Aries	1987	2B1-35	.123	.204	.081	.134	.057	.076	.053	.074	.036	.052		
Stanza	1987	Hal-45	.118	.182	.119	.183	.079	.119	.083	.119	.038	.053	.044	.059
Buick Century Limited	1989	Hal-55	.144	.225	.149	.225	.062	.097	.078	.111	.024	.061		
Pontiac GrandAm	1989	Hal-45	.090	.131	.094	.135	.059	.086	.064	.089	.020	.030	.025	.032
Buick LeSabre	1990	Hal-55	.146	.174	.147	.176	.060	.087	.067	.092	.025	.034		
Buick Reatta	1990	2B1-35	.251	.327	.251	.326	.060	.080	.063	.090	.039	.050	.042	.028
Cadillac	1990	Hal-45	.067	.097	.074	.102	.039	.059	.052	.066	.019	.027		
Chevy Cavalier	1990	Hal-55	.099	.158	.103	.163	.064	.096	.072	.103	.042	.061		.064
Ford Taurus	1990	Hal-45	.119	.199	.119	.200	.037	.058	.049	.068	.245	.195		
Honda Accord	1990	Hal-55	.172	.252	.169	.247	.096	.120	.098	.130	.054	.066	.060	.075
Plymouth Laser	1990	2E1-35	.134	.209	.135	.209	.055	.085	.063	.092	.031	.054	.041	.060
Pontiac GrandAm	1990	Hal-55	.132	.160	.068	.080	.065	.087	.061	.085	.020	.028		
Buick Century	1991	Hal-55	.157	.252	.157	.248	.075	.115	.082	.122	.047	.074		
Chevy Corsica	1992	Hal-55	.199	.255	.199	.256	.092	.129	.092	.125	.023	.032		
Chevy Lumina	1993	Hal-55	.122	.149	.126	.153	.060	.084	.068	.087	.029	.041	.033	.036
Chevy Lumina	1993	Hal-55	.144	.184	.137	.184	.068	.115	.068	.111	.022	.038		
Ford Taurus	1993	Hal-55	.222	.277	.219	.272	.089	.114	.085	.109	.029	.035		
Honda Accord	1993	Hal-55	.159	.242	.165	.244	.089	.121	.097	.130	.038	.053	.041	.058
Plymouth Acclaim	1993	Hal-45	.161	.244	.168	.254	.066	.107	.087	.112	.033	.054	.040	.054
Plymouth Duster	1993	Hal-45	.127	.226	.123	.222	.066	.099	.065	.098	.033	.051		
Pontiac Bonneville	1993	Hal-55	.060	.118	.065	.122	.057	.072	.061	.079	.023	.033	.024	.032
Acura Integra	1994	Proj-55	.085	.126	.092	.132	.034	.055	.050	.067	.024	.033		
Mercury Tracer	1994	Hal-45	.121	.183	.125	.185	.073	.104	.083	.107	.062	.088	.076	.097
Ford Escort	1995	Hal-45	.117	.170	.123	.171	.078	.110	.076	.103	.032	.049		
Ford Taurus	1996	Hal-55	.189	.279	.150	.220	.082	.110	.080	.106	.035	.044		
Honda Accord	1996	Hal-55	.286	.410	.283	.410	.128	.163	.135	.168	.075	.091	.077	.100
Mazda Protege	1996	Hal-55	.063	.109	.063	.105	.042	.068	.042	.070	.018	.027		
Mercedes	1996	Xen-35	.059	.092	.063	.094	.038	.058	.045	.067	.013	.021	.009	.018
Nissan Altima	1996	Hal-55	.097	.139	.104	.145	.051	.074	.061	.082	.028	.039	.031	.041
Nissan Maxima	1996	Hal-45	.160	.200	.168	.206	.065	.093	.075	.100	.030	.034	.033	.038
Pontiac GrandAm GT	1996	Hal-55	.206	.279	.202	.273	.085	.122	.086	.123	.032	.042	.036	.046
Saturn	1996	Hal-55	.137	.204	.135	.205	.081	.115	.083	.117	.052	.046		
Camaro	1997	H90-55	.058	.107	.050	.063	.043	.062	.049	.063	.015	.023		
Chevy Cavalier	1997	Hal-55	.144	.200	.155	.204	.036	.055	.057	.079	.014	.025		
Ford Aspire	1997	Hal-55	.156	.240	.153	.233	.079	.110	.084	.114	.025	.032		
Ford Taurus	1997	Hal-55	.138	.200	.141	.200	.063	.079	.068	.082	.024	.029		
Ford Taurus	1997	Hal-55	.137	.201	.143	.209	.049	.067	.061	.079	.019	.031		
Ford Taurus	1997	Hal-55	.126	.190	.132	.202	.055	.065	.058	.078	.011	.026		
Ford Taurus (1)	1997	Hal-55	.116	.192	.119	.190	.047	.067	.054	.075	.027	.038		
Mazda Protege	1997	Hal-55	.074	.115	.077	.116	.047	.075	.056	.081	.019	.030		
Pontiac GrandAm	1997	Hal-55	.314	.413	.311	.411	.144	.207	.142	.210	.055	.076		
Pontiac GrandAm	1997	Hal-55	.249	.369	.247	.364	.115	.171	.117	.170	.031	.038		

(1) Headlamps supplied by FHWA.

(2) **Minolta blue** - right shoulder / 2.12 m height **Minolta yellow** - left shoulder/ 2.12 m height
Minolta clear - right shoulder / 2.12 m height **Minolta green** - left shoulder/ 2.12 m height
IL 1700 #1 & #2 - center of the right driving lane / 7.62 m height

Table 16. Data Summary for 50 Known Vehicles (Mean, Standard Deviation, Max, Min, and Number of Readings).

Photometer (1)	Minolta Blue 152 m	Minolta Blue 114 m	Minolta Blue 1.1s	Minolta Clear 152 m	Minolta Clear 114 m	Minolta Clear 1.1s later	Minolta Yellow 152 m	Minolta Yellow 114 m	Minolta Yellow 1.1s later
Criteria	(lux)	(lux)	(lux)	(lux)	(lux)	(lux)	(lux)	(lux)	(lux)
Mean	0.143	0.205	0.287	0.142	0.202	0.284	0.068	0.096	0.135
Std dev	0.066	0.081	0.110	0.065	0.082	0.110	0.028	0.037	0.048
Max	0.349	0.413	1.016	0.343	0.411	1.009	0.150	0.207	0.337
Min	0.058	0.092	0.116	0.050	0.063	0.067	0.034	0.055	0.055
# of readings	198	199	196	198	199	195	196	197	194

Photometer	Minolta Green 152 m	Minolta Green 114 m	Minolta Green 1.1s	IL 1700 #1 152 m	IL 1700 #1 114 m	IL 1700 #1 1.1s later	IL 1700 #2 152 m	IL 1700 #2 114 m	IL 1700 #2 1.1s later
Criteria	(lux)	(lux)	(lux)	(lux)	(lux)	(lux)	(lux)	(lux)	(lux)
Mean	0.073	0.101	0.137	0.035	0.047	0.063	0.042	0.054	0.076
Std dev	0.027	0.035	0.044	0.040	0.034	0.036	0.027	0.033	0.038
Max	0.142	0.210	0.349	0.245	0.195	0.316	0.081	0.135	0.221
Min	0.049	0.063	0.071	0.011	0.021	0.003	0.009	0.018	0.031
# of readings	199	198	196	165	163	176	64	66	68

(1) **Minolta blue** - right shoulder / 2.12 m height **Minolta yellow** - left shoulder/ 2.12 m height
Minolta clear - right shoulder / 2.12 m height **Minolta green** - left shoulder/ 2.12 m height
IL 1700 #1 & #2 - center of the right driving lane / 7.62 m height

Significance of Each Independent Variable

Table 17 gives p-values from one-way AVOVA's for all six photometers at three distances for each independent variable. Independent variables are listed at the top of the table. Sets of photometer readings are listed on the left side of the column. For example, Minolta Blue @ 152 m corresponds to the group of photometer readings taken by the "blue" Minolta illuminance meter positioned on the right shoulder when the vehicle was 152 m from the overpass. The next line labeled "@ 114 m" corresponds to the set of photometer readings taken when vehicles were 114 m away from this same meter. The photometer readings taken 1.1 s after the vehicles broke the second infrared beam are reported as "1.1 s later." This type of labeling is repeated for the other photometers.

A p-value less than **0.05** (bold type) means that at least one level of the independent variable had significantly different photometer readings than the other levels. For example, the p-value of 0.0143 in the top left cell means at least one vehicle year had significantly different readings than the other years for photometer readings taken by the "blue" Minolta illuminance meter when the vehicles were 152 m from the overpass.

Conclusions

Based on the p-values, the following conclusions were reached about significance of each of the independent variables. *Vehicle year* was significant only for the "blue" and "clear" (right shoulder) Minolta illuminance meters when vehicles were 152 m from the overpass. Headlamp *type* was significant for the "blue" and "clear" Minolta (right shoulder) illuminance meters at all distances and for the yellow Minolta (left shoulder) illuminance meter when vehicles were 152 m and 114 m away. *Headlamp wattage* was only significant in two cases: (1) for the blue Minolta illuminance meter (right shoulder) when vehicles were 152 m away from the overpass and (2) for the yellow Minolta illuminance meter (left shoulder) when vehicles were 114 m away. *Headlamp intensity* for either the passenger side or driver side was significant for all five photometers except the IL1700 #1 photometer vehicles were 152 m away from the overpass. *Vehicle speed* was insignificant for all photometer readings.

Table 17. P-Values for One-Way ANOVA's of the Photometer Readings vs. Each Independent Variable. **(Bold Type Indicates Significance at p=0.05)**

				Intensity of Headlamps		
INDEPENDENT VARIABLE	Vehicle Year	Headlamp Type	Headlamp Wattage	Passenger Side	Driver Side	Vehicle Speed
METER						
Minolta Blue @152 m	**0.0143**	**0.0039**	**0.0157**	**0.0001**	**0.0001**	0.9234
@ 114m	0.1481	**0.0059**	0.0587	**0.0001**	**0.0001**	0.9137
1.1 s Later	0.2701	**0.0033**	0.0578	**0.0001**	**0.0001**	0.7008
Minolta Clear @ 152 m	**0.0106**	**0.0199**	0.0515	**0.0001**	**0.0001**	0.9661
@ 114m	0.0886	**0.0246**	0.1559	**0.0001**	**0.0001**	0.9612
1.1 s Later	0.1883	**0.0146**	0.1400	**0.0001**	**0.0001**	0.7756
Minolta Yellow @152 m	0.4045	**0.0187**	0.2149	**0.0001**	**0.0001**	0.7715
@ 114m	0.2756	**0.0162**	0.0412	**0.0001**	**0.0001**	0.4118
1.1 s Later	0.4157	0.0502	0.0912	**0.0001**	**0.0001**	0.1747
Minolta Green @ 152 m	0.7645	0.0567	0.1898	**0.0001**	**0.0001**	0.8658
@ 114m	0.6130	0.0520	0.1262	**0.0001**	**0.0001**	0.6286
1.1 s Later	0.4792	0.1232	0.2293	**0.0001**	**0.0001**	0.3017
IL1700 #1 @ 152 m	0.8690	0.8793	0.1920	0.2011	0.0904	0.9274
@ 114m	0.7811	0.6497	0.1236	**0.0140**	**0.0023**	0.7563
1.1 s Later	0.7198	0.4900	0.6194	**0.0002**	**0.0001**	0.4748
IL1700 #2 @ 152 m	0.6474	0.1264	0.9426	**0.0010**	**0.0034**	0.6786
@ 114m	0.5943	0.2659	0.8762	**0.0006**	**0.0004**	0.3529
1.1 s Later	0.3308	0.4790	0.8352	**0.0001**	**0.0001**	0.3866

Minolta blue - right shoulder / 2.12 m height **Minolta yellow** - left shoulder/ 2.12 m height
Minolta clear - right shoulder / 2.12 m height **Minolta green** - left shoulder/ 2.12 m height
IL 1700 #1 & #2 - center of the right driving lane / 7.62 m height

Histograms

The illumination data were represented graphically in the form of histograms. The histograms were constructed for each of the six photometers at three distances: 152 m, 114 m, and 1.1 s after the second beam was broken. The bin size used in construction of the histograms was 0.025 lux. See Appendix D for the histograms.

Overall Results

Independent variable - *vehicle year*. The vehicle year was a significant variable for readings obtained from Minolta illuminance meters "blue" and "clear" positioned on the right shoulder when the vehicles were 152 m away from the overpass. Duncan groupings for both "blue" and "clear" Minolta illuminance meters are similar, but there was less variation between vehicle years for the clear Minolta illuminance meter. For both meters, the year with the highest mean illuminance was 1980 and the lowest was 1994. Also, 1980, 1984, and 1992 were the groups with the highest mean illuminations, and the rest of the years were in a group with the lowest mean illuminations.

When vehicles were 114 m away from the overpass, vehicle year was not significant for any of the four Minolta illuminance meters, which means that there was no statistically significant difference between illuminance readings taken by any Minolta illuminance meter at that distance. For the two IL 1700 photometers, vehicle year was not significant.

Independent variable - *headlamp type.* When vehicles were 152 m and 114 m away from the overpass, headlamp type was significant for the "blue" (right shoulder/2.12 m high), "clear" (right shoulder/2.12 m high), and "yellow" (left shoulder/2.12 m high) Minolta illuminance meters. Vehicles with the 2B1 sealed beam headlamps had the highest mean illuminance values, followed by the vehicles with the other two types of sealed beam headlamps. Mercedes with xenon composite headlamps had the lowest illuminance value. For "blue," "clear," and "yellow" Minolta illuminance meters, vehicles with either sealed beam headlamps or halogen composite headlamps were in a group with the higher mean illuminance values. Vehicles with the projector headlamps (Acura) or xenon composite headlamps (Mercedes) were in a group with the lowest mean illuminance. For the two IL 1700 photometers, *headlamp type* was not significant at either of the two distances.

Statistical Analysis of 1,500 Vehicles

The following summary explains steps taken for creating the data base for the illuminance data taken on more than 2,000 vehicles in the second field study. The original data set included more than 2,000 vehicles: trucks, cars, and sport utility. The first step was to clean up the database. The data set was saved in a file called "litedata" by using Microsoft Excel (version 5.0). To clean up the data, the data set was sorted in ascending record number order. Then, the data collector looked back at the experimental log book to check whether there were any truck or jeep data recorded as car data or vice versa, or any other data recording mistakes. If there was a mistake, a correction was made. Upon correcting all the misrecorded data, Excel was used to sort the data set by the field "vehicle type." The records containing a word other than "car" were deleted, since FHWA was interested in illumination data for cars only. Then a second clean-up was performed on this new data set. A real data set always contains some unrealistic values, thus, the next step was to identify unrealistic values. For example, a recorded car speed exceeding 200 mi/h was considered unrealistic. The cells (in Excel) for these unrealistic values were left blank. Basically, a blank cell in this data set indicates that the cell used to be occupied by an unrealistic value. After identifying and deleting all the unrealistic values, mean and standard deviation were calculated for each of the six photometers at three distances (Minolta "blue" at 152, Minolta "blue" at 114, etc.). Because of the unrealistic values that were removed from each illumination data set, the data base contains different numbers of data points for each photometer/distance category. The mean and standard deviation were calculated based on the number of the illuminance data contained in the referred photometer/distance category (see Table 18).

Statistical Tests

The statistical analyses were performed on the data set to see if there was a significant difference between the illuminance means based on the location of the photometer and the distance from the overpass. Based on the analysis of variance (ANOVA) there was no significant difference between illuminance means for the photometers positions at the same side of the road (Minolta luminance meters "blue" and "clear" - right shoulder/2.12 m height; Minolta illuminance meter "yellow" and "green" - left shoulder/2.12 m height) for either of the three distances 152 m, 114 m, and 1.1 s after the second infrared beam was broken.

The same statistical test was performed on IL1700 #1 and IL1700 #2 (overhead sign location/7.62 m height). There was also no significant difference between illuminance means for these photometers. This indicates that the amount of light recorded by these photometers, which were in approximately the same location, was the same.

To see if there was a significant difference between the illuminance means based on the different location of the photometers, a statistical test (t-test) was conducted on the data for Minolta "clear" (right shoulder) and Minolta "green" (left shoulder). There was a statistically significant difference between the illumination means for the two photometers: Minolta clear and Minolta green. Thus, it can be concluded that there was a significant difference in amount of illuminance received and recorded by Minolta "green" and Minolta "clear." In fact, Minolta "clear" (mean=0.281 lux @ 152 m) received much more illumination than Minolta "green" (mean=0.114 lux @ 152 m). Based on this result, it can be concluded that signs positioned on the right shoulder received significantly more illuminance than the signs positioned on the left shoulder. The same type of test was performed to see if there was a significant difference between the four Minolta illuminance meters (blue/clear, green/yellow) and the IL 1700 photometers (#1, #2). Based on the results, it was concluded that there was a statistically significant difference between the illumination means for the four Minolta meters and the two IL 1700 photometers. The IL 1700's received and recorded the least amount of illumination (see Table 18).

Histograms

The next step in the statistical analysis of the data set was generating histograms for each of the six photometers at each of the three distances (see Appendix E). Microsoft Excel function (Wizard) was utilized to generate histograms. The histograms were constructed by using the bin size of 0.025 lux. The illumination data recorded by the Minolta illuminance meters appears to have a normal distribution. The illumination data recorded by the IL 1700 does not appear to have a normal distribution.

The histograms were used to identify and count "zero" values for each of the six photometers and the three distances. This "zero" value indicates that the photometer received little or no illuminance (i.e. an unrecordable amount). The Minolta meters cannot record values below 0.01 lux and the IL 1700 cannot record values below 1.7×10^{-4} lux. (Report on hardware used in this study is available from FHWA upon request.) Table 19 summarizes the findings. The table contains the number of "zeros," number of the data points, and the percentage of "zeros" in the data set for each of the six photometers at the three distances. Based on the results, it was concluded that IL 1700's have more "zeros" than Minolta illuminance meters.

Tables 20 and 21 show the number of readings and percentage of readings, for the three distances, below 0.05 lux, and 0.1 lux, respectively. More than half (55 percent) of the readings recorded by the IL 1700 # 1 were equal to or below 0.05 lux at the distance of 152 m from the photometer. For the same photometer there were 35 percent of readings equal to or below 0.05 lux at the distance of 114 m from the photometer.

Using the following equation, *Sign luminance* = R_A * *Mean headlamp illuminance*, the values of the mean headlamp illuminance could be calculated, assuming the two other variables are specified. The minimum overhead guide sign luminance from the literature review was determined to be 3.2 cd/m^2. R_A is the retroreflectivity value that is specific for each sign sheeting material and the entrance and observation angles for a specific vehicle location. This value was calculated for engineering type II material and specific sign and driver location by John Arens, FHWA. The values and details of calculations are given in the next section. Using the retroreflectivity value of $R_A = 63$ cd/lux/m^2 for engineering type II sheeting material at the distance 152 m from the sign, and the sign luminance of 3.2 cd/m^2, the calculated mean headlamp illuminance required to produce sign luminance of 3.2 cd/m^2 is equal to 0.05 lux.

Using the retroreflectivity value $R_A = 33$ cd/lux/m^2 for engineering type II sheeting material at the distance 84 m from the sign, and the sign luminance of 3.2 cd/m^2, the calculated mean headlamp illuminance required to produce sign luminance of 3.2 cd/m^2 is approximately equal to 0.1 lux (see Table 21).

Table 18. Data Summary (Mean, Standard Deviation, Max, Min, and Number of Readings)

Photometer(1) Criteria	Minolta Blue 152m (lux)	Minolta Blue 114m (lux)	Minolta Blue 1.1s later (lux)	Minolta Clear 152m (lux)	Minolta Clear 114m (lux)	Minolta Clear 1.1s later (lux)	Minolta Yellow 152m (lux)	Minolta Yellow 114m (lux)	Minolta Yellow 1.1s later (lux)
Mean	0.288	0.394	0.498	0.281	0.375	0.483	0.111	0.148	0.208
std dev	0.257	0.536	0.457	0.251	0.352	0.406	0.083	0.106	0.125
Max	3.367	16.374	8.661	3.347	4.389	3.920	1.556	2.014	2.194
Min	0.027	0.000	0.002	0.029	0.032	0.034	0.000	0.000	0.000
# of Readings	1553	1554	1554	1554	1554	1554	1553	1553	1553
Photometer(1) Criteria	Minolta Green 152m (lux)	Minolta Green 114m (lux)	Minolta Green 1.1s later (lux)	IL 1700 #1 152m (lux)	IL 1700 #1 114m (lux)	IL 1700 #1 1.1s later (lux)	IL 1700 #2 152m (lux)	IL 1700 #2 114m (lux)	IL 1700 #2 1.1s later (lux)
Mean	0.114	0.149	0.208	0.054	0.068	0.095	0.065	0.079	0.114
std dev	0.079	0.091	0.120	0.038	0.054	0.082	0.109	0.067	0.116
Max	1.508	1.914	2.063	0.470	1.029	1.881	2.980	1.038	2.180
Min	0.022	0.026	0.010	0.000	0.000	0.000	0.000	0.000	0.000
# of Readings	1554	1554	1554	1502	1508	1509	850	854	853

(1) **Minolta blue** - right shoulder / 2.12 m height **Minolta yellow**- left shoulder/ 2.12 m height
Minolta clear - right shoulder / 2.12 m height **Minolta green** - left shoulder/ 2.12 m height
IL 1700 #1 & #2 - center of the right driving lane / 7.62 m height

Table 19. Summary of "Zero" Readings

Distance	**Minolta Blue (1)**			**Minolta Clear (2)**		
	# of readings ≤0	# of data	%	# of readings ≤0	# of data	%
152 m	0	1553	0	0	1554	0
114 m	1	1554	0.06	0	1554	0
After 1.1 s	0	1554	0	0	1554	0
Distance	**Minolta Yellow (3)**			**Minolta Green (4)**		
	# of readings ≤0	# of data	%	# of readings ≤0	# of data	%
152 m	2	1553	0.13	0	1554	0
114 m	2	1553	0.13	0	1554	0
After 1.1 s	3	1553	0.19	0	1554	0
Distance	**IL 1700 # 1 (5)**			**IL 1700 #2 (5)**		
	# of readings ≤0	# of data	%	# of readings ≤0	# of data	%
152 m	30	1502	2.00	27	850	3.18
114 m	31	1508	2.06	24	854	2.81
After 1.1 s	34	1509	1.59	15	853	1.76

(1) **Minolta blue** - right shoulder / 2.12 m height (3) **Minolta yellow**- left shoulder/ 2.12 m height
(2) **Minolta clear** - right shoulder / 2.12 m height (4) **Minolta green** - left shoulder/ 2.12 m height
(5) **IL 1700 #1 & #2** - center of the right driving lane / 7.62 m height

Table 20. Summary of Readings Equal to or Below 0.05 lux that Result in Luminance Below 3.2 cd/m^2 for Type II Sheeting.

Distance	**Minolta Blue (1)**			**Minolta Clear (2)**		
	# of readings ≤0.05	# of data	%	# of readings ≤0.05	# of data	%
152 m	14	1553	0.9	12	1554	0.8
114 m	5	1554	0.3	2	1554	0.13
After 1.1 s	3	1554	0.2	2	1554	0.13
Distance	**Minolta Yellow (3)**			**Minolta Green (4)**		
	# of readings ≤0.05	# of data	%	# of readings ≤0.05	# of data	%
152 m	132	1553	8.5	68	1554	4.4
114 m	12	1553	0.8	6	1554	0.4
After 1.1 s	7	1553	0.5	4	1554	0.3
Distance	**IL 1700 # 1 (5)**			**IL 1700 #2 (5)**		
	# of readings ≤0.05	# of data	%	# of readings ≤0.05	# of data	%
152 m	826	1502	55	390	850	46
114 m	526	1508	35	218	854	26
After 1.1 s	210	1509	14	69	853	8.1

(1) **Minolta blue** - right shoulder / 2.12 m height (3) **Minolta yellow**- left shoulder/ 2.12 m height
(2) **Minolta clear** - right shoulder / 2.12 m height (4) **Minolta green** - left shoulder/ 2.12 m height
(5) **IL 1700 #1 & #2** - center of the right driving lane / 7.62 m height

Table 21. Summary of Readings Equal to or Below 0.1 lux.

Distance	**Minolta Blue (1)**			**Minolta Clear (2)**		
	# of readings ≤0.1	# of data	%	# of readings ≤0.1	# of data	%
152 m	164	1553	10.5	189	1554	12.1
114 m	43	1554	2.7	56	1554	3.6
After 1.1 s	5	1554	3	11	1554	0.7
Distance	**Minolta Yellow (3)**			**Minolta Green (4)**		
	# of readings ≤0.1	# of data	%	# of readings ≤0.1	# of data	%
152 m	875	1553	56.3	827	1554	53.2
114 m	427	1553	27.5	385	1554	24.8
After 1.1 s	95	1553	6.1	72	1554	4.6
Distance	**IL 1700 # 1 (5)**			**IL 1700 #2 (5)**		
	# of readings ≤0.1	# of data	%	# of readings ≤0.1	# of data	%
152 m	1387	1502	92.3	746	850	87.8
114 m	1273	1508	84.4	668	854	78.2
After 1.1 s	946	1509	62.7	430	853	50.4

(1) Minolta blue - right shoulder / 2.12 m height
(2) Minolta clear - right shoulder / 2.12 m height
(3) Minolta yellow- left shoulder/ 2.12 m height
(4) Minolta green - left shoulder/ 2.12 m height
(5) IL 1700 #1 & #2 - center of the right driving lane / 7.62 m height

Determination of Sign Luminance

The important value to the driver at night is sign luminance. For a single headlamp, sign luminance (L) is determined by the coefficient of retrofeflection of the signing material (R_A), the luminous intensity (I) of the headlamp toward the sign, the distance (d) between the headlamp and the sign, and the geometry between headlamp, sign, and driver's eye location (α, β_1, β_2, ϵ). The headlight output toward any point can be determined from a standard isocandela diagram of the headlamp if the angle between the headlamp axis and the point is known.

After the geometric angles (Woltman, 1998) are determined for a specific driving/viewing scenario, one application is to calculate the available luminance to the vehicle driver. For each distance, the available luminance is the sum of the luminance from the two headlamps based on the following equation:

$$L_T = \left[R_L \frac{I}{d^2}\right]_{Left} + \left[R_L \frac{I}{d^2}\right]_{Right} \text{------------------}(\textit{Equation 4})$$

where R_L is the coefficient of retroreflected luminance at the angles of concern, and I is the luminous intensity of the headlamp in the direction of the sign.

Since both retroreflectance and luminous intensity in the sign direction are angle-dependent quantities related to vehicle and sign placement, this calculation is very geometry specific. The coefficient of retroreflection is dependent on up to four angles, alpha, beta (beta one and beta two), and rotation. The luminous intensity pattern of the headlamp is dependent on vertical and horizontal angular components.

The usual method for expressing the geometry and these calculations is to locate the sign and vehicle in a local Cartesian coordinate system, usually with the z axis toward the azimuth, the y axis to the road curbside, and the x axis directed toward the vehicle. For the simple straight road situation, the x direction is a measure of test distance. Then in this local coordinate system, the x,y,z coordinates of the driver's eyes, each headlamp, and the sign retroreflector center may be described.

Vectors may be readily determined for the illumination axis, the observation axis, sign retroreflector axis and the sign datum axis, from the Cartesian coordinates. Using vector notation, as illustrated in Figure 11, the cosine of the observation angle is the dot product of the illumination and observation axis, and the cosine of the entrance angle is the dot product of the illumination and retroreflector axis. Alternate trigonometric methods may be used.

KEY:	R	Retroreflector Axis Vector
	D	Datum Axis Vector
	I	Illumination Axis Vector
	E	Viewing Axis Vector

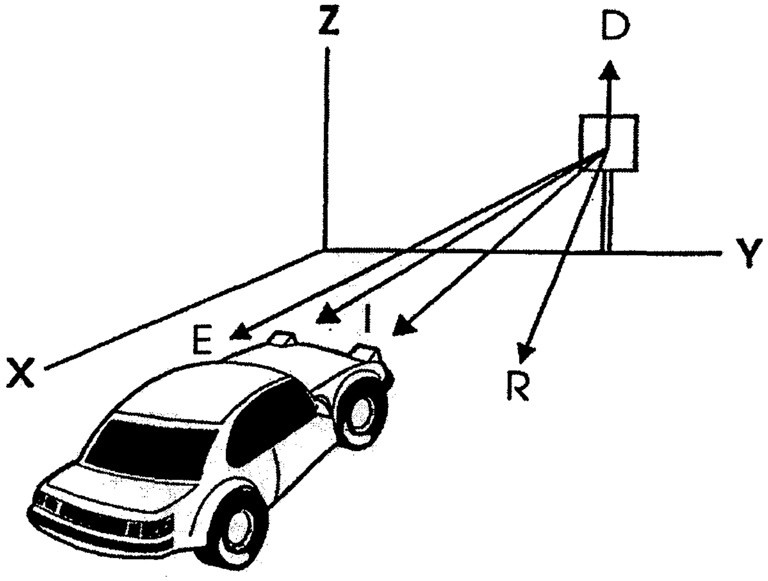


Figure 18. Geometric System for Calculation of Angle Components (Woltman, 1993).

Notes relating to Figure 18:

Using unit vectors R, D, E, I, the following apply:

Observation angle.

$\cos \alpha = E \times I$

Entrance angle.

$\cos \beta = R \times I$

and $\cos \beta = \cos \beta_1 \cos \beta_2$

Presentation angle.

$\cos \gamma = (I \times R) \times (I \times E)$

Rotation angle

$\cos \epsilon = D \times [I \times (I \times E)]$

When considering road sign performance, these angles are important because the geometry shown in Figure 19 must be taken into consideration. This standard geometry has been adopted by many national and international scientific bodies. Under entrance angle **β**, the headlamp illuminates a sign when it is looked at by a driver under the observation angle α. The sign is positioned at a rotation angle ϵ (assumed 0° in this study) at a height of h_2. Sign luminance from retroreflective sheeting is a function of: 1) the illuminance received at the sign surface from the headlamp and 2) the geometry shown, in Figure 19, particularly the observation angle. The relationship between observation angle, α, and sign sheeting coefficient of retroreflection, R_A, for several sheeting types is shown in Figure 20.

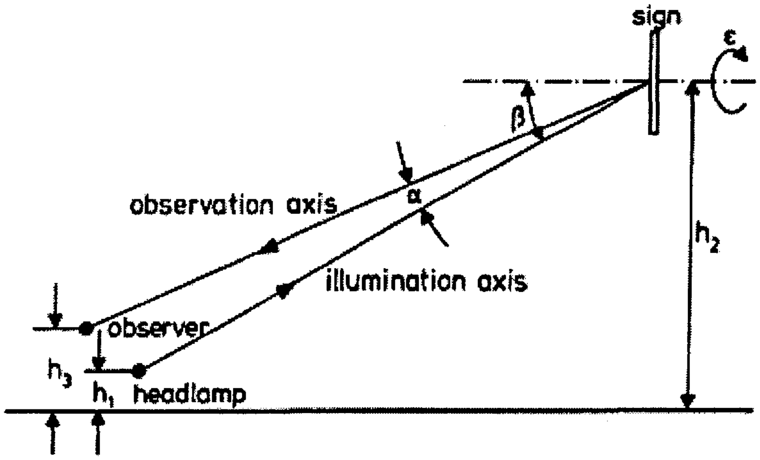


Figure 19. Geometry for an Overhead Traffic Sign Situation.

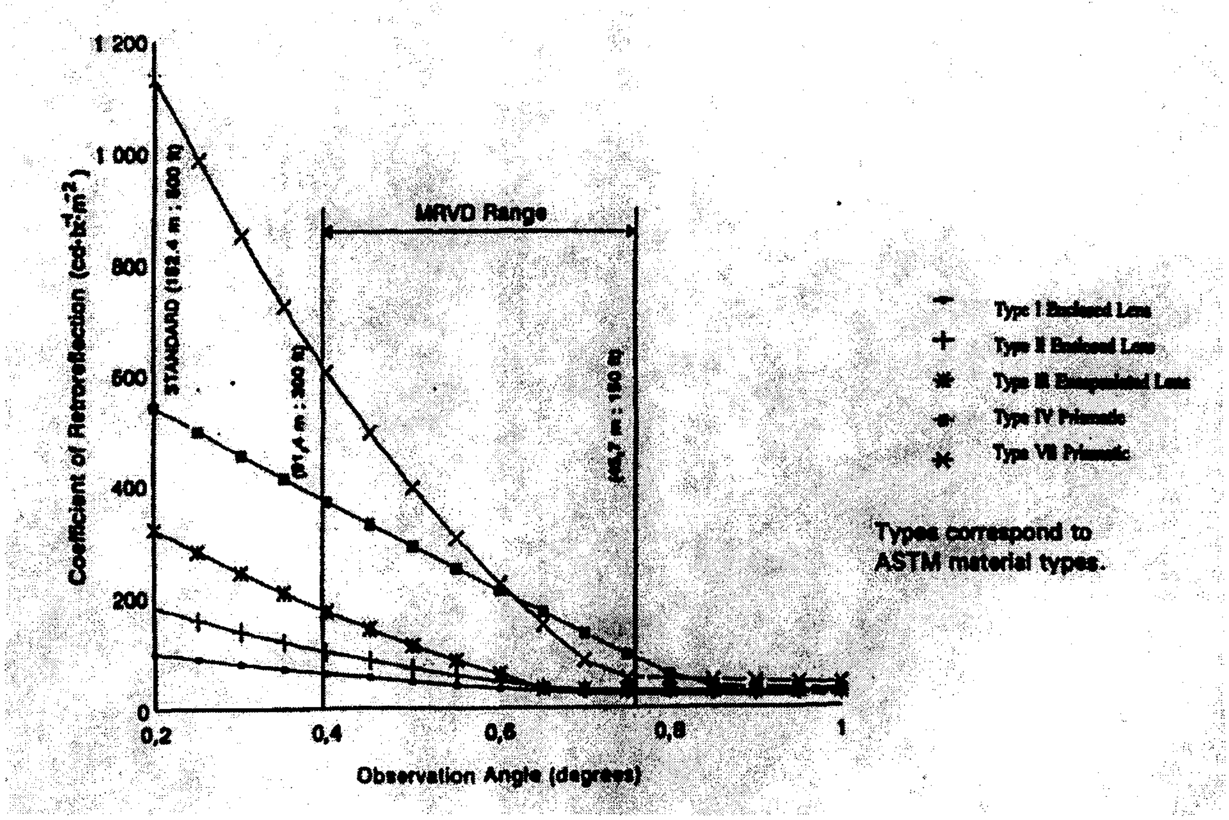


Figure 20. Relationship Between Coefficient of Retroreflection and Observation Angle for Common Types of White Sheeting (Paniati and Mace, 1993).

Use of the Data

The important value to the driver at night is sign luminance. A review of the literature found that *threshold* luminance of a sign was reported as low as 3.2 cd/m^2 (Jenkins and Gennaoui, 1992); however, optimal values as high as 75 cd/m^2 have been reported (Sivak and Olson, 1983). Laboratory experimentation in the KSU study found the minimum value to be around 13.2 cd/m^2, using white letters on a green background with a contrast ratio of 8:1.

To determine the actual sign luminance value, the retroreflectivity (R_A) of the signing material must be known. The values for R_A of the white type II sheeting (engineering grade) and the type III sheeting (high intensity) for the KSU field geometric parameters were obtained from FHWA and are listed in Table 22.

Table 22. R_A Values for White Type II (Engineering Grade) and Type III (High Intensity) Sheeting as a Function of Sign, Driver Location, and Standard Headlamp Placement for Sheeting with Values of 70 and 250 cd/lx/m^2 @ .2°/-4° Geometry.

Distance to Sign (m)	**Sign location**	**R_A (cd/lx/m^2) Type II**	**R_A (cd/lx/m^2) Type III**
152m	Right shoulder	63	209
"	Left shoulder	63	203
"	Overhead	63	201
114m	Right shoulder	54	167
"	Left shoulder	52	157
"	Overhead	49	147
~84m[1]	Right shoulder	39	104
"	Left shoulder	39	106
"	Overhead	33	81

[1] approximate location of cars at 1.1 s.

The sign luminance values were calculated based on drivers and sign geometrics (Sign luminance = R_A x Mean Headlight Illuminance) for some of the selected cars from the KSU database of the "50 Known Vehicles" (See Table 23 and Table 24).

After an analysis of selected cars (Table 23), such as the 1996 Mercedes with xenon composite headlamps, or the 1994 Acura Integra with project type of headlamps, it was found that there is a sufficient amount of light for the right and left shoulder mounted signs, but insufficient light for the overhead signs.

When looking at the same cars but using the engineering grade sheeting for the signs (Table 24), it was found that there is a sufficient amount of light (using 3.2 cd/m^2 as a minimum) only for the right shoulder mounted signs.

The highest sign luminance values were obtained for a Mazda 1984 with sealed 2B1 headlamps for both high intensity and engineering grade sheeting at three sign locations - right shoulder, left shoulder, and overhead. All values were above the minimum sign luminance values of 3.2 cd/m^2 found from the literature review.

Table 23. Calculated Sign Luminance for High Intensity Sheeting R_A Values Based on Driver, Standard Headlamp Placement, and Sign Geometrics for the KSU Study and Mean Illuminance Values for Selected Cars.

Car/Headlamp Type	Distance to Sign (m)	Sign Location	R_A[4] (cd/lux/m^2)	KSU Field Data Mean (lux)	Sign Luminance cd/m^2
Mercedes 1996 Xenon Composite Headlamp	152	right shoulder[1]	209	0.0610	12.7
	152	left shoulder[2]	203	0.0420	8.5
	152	Overhead[3]	201	0.0108	**2.2**
	114	right shoulder	167	0.0930	15.5
	114	left shoulder	157	0.0620	9.7
	114	overhead	147	0.0198	**2.9**
	84	right shoulder	104	0.1370	14.2
	84	left shoulder	106	0.1060	11.2
	84	overhead	81	0.0392	**3.2**
Acura Integra 1994 Projector Type Headlamp	152	right shoulder	209	0.0890	18.6
	152	left shoulder	203	0.0430	8.7
	152	overhead	201	0.0240	4.8
	114	right shoulder	167	0.1290	21.5
	114	left shoulder	157	0.0610	9.6
	114	overhead	147	0.0327	4.8
	84	right shoulder	104	0.1870	19.4
	84	left shoulder	106	0.0880	9.3
	84	overhead	81	0.0506	4.1
Ford Taurus 1996 Halogen Composite Headlamp	152	right shoulder	209	0.1690	35.3
	152	left shoulder	203	0.0780	15.8
	152	overhead	201	0.0349	7.0
	114	right shoulder	167	0.2500	41.8
	114	left shoulder	157	0.1080	17.0
	114	overhead	147	0.0439	6.5
	84	right shoulder	104	0.3470	36.1
	84	left shoulder	106	0.1460	15.5
	84	overhead	81	0.0578	4.7
Mazda 1984 Sealed 2B1 Headlamp	152	right shoulder	209	0.3460	72.3
	152	left shoulder	203	0.1380	28.0
	152	overhead	201	0.0798	16.0
	114	right shoulder	167	0.4090	68.3
	114	left shoulder	157	0.1590	25.0
	114	overhead	147	0.1253	18.4
	84	right shoulder	104	0.5740	59.7
	84	left shoulder	106	0.2010	21.3
	84	overhead	81	0.1614	13.1

[1] right shoulder - 3.05 m from the right lane / 2.12 m high

[2] left shoulder - 3.35 m from the left lane / 2.12 m high

[3] overhead - center of the right driving lane / 7.62 m high

[4] data provided by John Arens, FHWA lighting lab

Table 24. Calculated Sign Luminance for Engineering Grade Sheeting R_A Values Based on Driver, Standard Headlamp Placement, and Sign Geometrics for the KSU Study and Mean Illuminance Values for Selected Cars.

Car/Headlamp Type	Distance to Sign (m)	Sign Location	R_A[4] $(cd/lux/m^2)$	KSU Field Data Mean (lux)	Sign Luminance cd/m^2
Mercedes 1996 Xenon Composite Headlight	152	right shoulder[1]	63	0.0610	3.8
	152	left shoulder[2]	63	0.0420	**2.6**
	152	overhead[3]	63	0.0108	**0.4**
	114	right shoulder	54	0.0930	5.0
	114	left shoulder	52	0.0620	**3.2**
	114	overhead	49	0.0198	**1.0**
	84	right shoulder	39	0.1370	5.3
	84	left shoulder	39	0.1060	4.1
	84	overhead	33	0.0392	**1.3**
Acura Integra 1994 Projector Type Headlight	152	right shoulder	63	0.0890	5.6
	152	left shoulder	63	0.0430	**2.7**
	152	overhead	63	0.0240	**1.5**
	114	right shoulder	54	0.1290	6.9
	114	left shoulder	52	0.0610	**3.2**
	114	overhead	49	0.0327	**1.6**
	84	right shoulder	39	0.1870	7.3
	84	left shoulder	39	0.0880	3.4
	84	overhead	33	0.0506	**1.7**
Ford Taurus 1996 Halogen Composite Headlight	152	right shoulder	63	0.1690	10.6
	152	left shoulder	63	0.0780	4.9
	152	overhead	63	0.0349	**2.2**
	114	right shoulder	54	0.2500	13.5
	114	left shoulder	52	0.1080	5.6
	114	overhead	49	0.0439	**2.15**
	84	right shoulder	39	0.3470	13.5
	84	left shoulder	39	0.1460	5.7
	84	overhead	33	0.0578	**1.9**
Mazda 1984 Sealed 2B1 Headlight	152	right shoulder	63	0.3460	21.8
	152	left shoulder	63	0.1380	8.7
	152	overhead	63	0.0798	5.0
	114	right shoulder	54	0.4090	22.1
	114	left shoulder	52	0.1590	8.3
	114	overhead	49	0.1253	6.1
	84	right shoulder	39	0.5740	22.4
	84	left shoulder	39	0.2010	7.8
	84	overhead	33	0.1614	5.3

[1] right shoulder - 3.05 m from the right lane / 2.12 m high
[2] left shoulder - 3.35 m from the left lane / 2.12 m high
[3] overhead - center of the right driving lane / 7.62 m high
[4] data provided by John Arens, FHWA lighting lab

The large KSU field database (1,500 unidentified vehicles), based on mean values, suggests that there is sufficient light for the left and right shoulder mounted signs but, at best, marginal light available for the overhead signs (see Table 25).

The same data base, using mean values but using the engineering grade sheeting materials for the signs, suggests that there is sufficient amount of light available for right and left shoulder mounted signs and at best marginal amount for overhead mounted signs (see Table 26).

Sign luminance values of the overhead sign are slightly higher (3.7 cd/m^2 at 152 m, 3.6 cd/m^2 at 114 m, and 3.4 cd/m^2 at 84 m) than the minimum value suggested in the literature (3.2 cd/m^2). They are, however, considerably lower than the minimum sign luminance value obtained in the KSU laboratory study of 13 cd/m^2. Using the value of 13 cd/m^2 as a threshhold and engineering grade sheeting for the signs, there is not sufficient amount of light for the left shoulder mounted signs and overhead signs.

All the sign luminance values obtained from the KSU field study for the three sign locations (left and right shoulder and overhead) were below 75 cd/m^2, which Sivak and Olson (1983) reported as "optimum."

Table 25. Calculated Sign Luminance for High Intensity Sheeting R_A Values Based on Driver, Standard Headlamp Placement, and Sign Geometrics for the KSU Study Using Mean Values of Illuminance.

Distance to Sign (m)	Sign Location	R_A[4]	Mean KSU Field Data (lux)	Sign Luminance cd/m^2 Type III
152	right shoulder[1]	209	0.2845	59.5
152	left shoulder[2]	203	0.1125	22.8
152	overhead[3]	201	0.0595	12.0
114	right shoulder	167	0.3845	64.2
114	left shoulder	157	0.1485	23.3
114	overhead	147	0.0735	10.8
84	right shoulder	104	0.4905	51.0
84	left shoulder	106	0.2080	22.0
84	overhead	81	0.1045	8.5

[1] right shoulder - 3.05 m from the right lane / 2.12 m high
[2] left shoulder - 3.35 m from the left lane / 2.12 m high
[3] overhead - center of the right driving lane / 7.62 m high
[4] provided by John Arens, FHWA

Table 26. Calculated Sign Luminance Values for Engineering Grade Sheeting R_A Based on Driver, Standard Headlamp Placement, and Sign Geometrics for the KSU Study Using Mean Values of Illuminance.

Distance to Sign (m)	Sign Location	R_A[4]	Mean KSU Field Data (lux)	Sign Luminance cd/m² Type II
152	right[1]	63	0.2845	17.9
152	left shoulder[2]	63	0.1125	7.09
152	overhead[3]	63	0.0595	3.7
114	right	54	0.3845	20.8
114	left shoulder	52	0.1485	7.7
114	overhead	49	0.0735	3.6
84	right	39	0.4905	19.1
84	left shoulder	39	0.2080	8.1
84	overhead	33	0.1045	3.4

[1] right shoulder - 3.05 m from the right lane / 2.12 m high
[2] left shoulder - 3.35 m from the left lane / 2.12 m high
[3] overhead - center of the right driving lane / 7.62 m high
[4] data provided by John Arens, FHWA

THE EFFECTS OF REDUCED SIGN LUMINANCE ON SIGN RECOGNITION DISTANCE AND ON LEGIBILITY DISTANCE: AN INTUITIVE APPROACH

General Discussion

As an observer driving a motor vehicle at night approaches a retroreflective sign (overhead guide sign) illuminated by his/her own vehicle's headlights, a number of visibility factors change as the distance between the observer and the sign decreases. The driver of the vehicle is, of course, concerned with the task of safely driving his/her own vehicle. If we assume that there are no oncoming vehicles or other glare sources in the field of view and that there are no other vehicles moving in the same direction between the driver and the sign (all lighting comes from the driver's own vehicle), then the following things occur:

1. The driver detects that an overhead sign exists. The recognition that a sign exists is the result of a slowly increasing average sign luminance created by the headlamps of the driver's own vehicle. Contrast between the sign and its background increases until the sign is detected. The distance at which detection will occur is a function of the adaptation luminance (background around the sign), the sign luminance, and the angle between the line of sight and the sign location.

2. At the time of sign recognition the sign message is illegible. The sign location is, however, known; as the vehicle moves closer, the driver may fixate on the sign at any desired time and for any desired duration, subject of course to the other visual demands of the driving task.

3. Adaptation luminance is considered to be the result of the proportionally summed luminance within a 1.5° cone of the line of sight. At the time of sign recognition, this cone will encompass much more area than the sign alone. As the vehicle approaches the sign, its luminance will occupy an increasing proportion of the adaptation cone. At approximately 90 m, a 2.4-m sign will fill the adaptation cone.

4. During the interval between sign presence recognition and legend legibility, the luminance of the sign will continue to increase and the color of the sign background and the legend color will be determined by color-sensitive observers. The legend proportions (length and number of lines) will also be determined during this interval. Some symbols, such as arrows or route shields, may be recognized before the entire message can be read.

5. As the distance between the vehicle and the sign decreases, the average luminance of the sign will increase, the portion of the adaptation cone occupied by the average sign luminance also increases, and the contrast between the sign background and the legend will vary if the retroreflectance of the materials used for each are not identical in terms of the changing entrance and observation angles. The size of the visual angle of the legend critical details will increase and eventually the observer will be able to read the legend.

The purpose of the laboratory study was to isolate as many of the variables as possible and determine the relationship of background sign luminance to recognition and legibility distances.

There is a complex relationship between the luminance levels of the stroke and background, distance from the sign, and the size and spacing of the letters making up the message, which determines when a driver approaching a sign will find that the words are legible. One commonly used simplification is to use the distance divided by the letter height (ft per in) to represent one term, and the luminance level of the stroke as another. One might then say that, for a luminance level of 5 cd/m^2, the legibility distance is 5.1 m/cm of letter height. Such a simplification assumes the difference between the stroke luminance level and the background luminance level (contrast) to be constant and that the font and letter spacings have been standardized. Such a simplified statement is correct for only one font and one contrast.

In terms of an overhead guide sign created in accordance with the standards of the *Manual on Uniform Traffic Control Devices* (MUTCD), this is a reasonable approach. It must be remembered, however, that a sign using white letters on a brown background will have a different contrast than the usual white letters on a dark green background.

In the laboratory experiment, the sign letters were all capitals and were 3.8 cm high. In a standard OG-2 overhead sign (Overhead Destination Sign with two Destinations) the letter height is 40 cm or a ratio of 10.6667 to the letters used in the laboratory experiment. The speed of the electric vehicle used in the experiment was 8 km/h, which, at the same scale, would translate to 85 km/h.

Determination of Distance Range Over Which the Sign is to be Read

I. The first step is to determine the approximate distances at which the signs would be read by an approaching motorist.

    A. The minimum distance was determined from the MRVD model of the program "CARTS" as 78 m.

    B. The maximum distance was determined in this manner:

        1. If no lighting is provided after sundown, then it will be impossible to read the sign. Vehicle headlighting is required to be turned on x minutes before sunset, fixed sign lighting and fixed roadway lighting are also turned on at this time, usually by photoelectric devices that sense the amount of natural daylight. The standard setting for these devices is 10 lux (1 footcandle).

        2. White engineer grade retroreflective material has a luminance of 1.3 cd/lux/m^2/ at an entrance angle of 40° (normal for fixed sign lighting) and an observation angle of 2.5°(approximate angle for viewing an overhead sign from 122 m. This distance was chosen as the approximate midpoint between the minimum distance of 61 m and a frequently used distance of 183 m. From these two facts a sign stroke luminance of 13 cd/m^2 is used as the dusk and dawn stroke luminance.

3. Using the predictive equation from the laboratory study (Equation 3), the distance that each of the 33 observers in the laboratory test would find the words legible at 13 cd/m^2 was calculated. The 85th percentile observer would find the words legible at a distance of 22.48 m or 5.9 m/cm. For a 40 cm letter on an overhead sign this equals 240 m. This approximate distance of 236 m is thus considered the distance at which a minimum level of natural light will permit 85 percent of the population to find the words on a sign legible. At a vehicle speed of 96 km/h, the distance between 236 m and 76 m will be covered in 5.9 s. This time appears logical and normal for the motorist to comprehend the sign and determine if he/she wishes to take any action.

Determination of the Amount of Luminance Required by a Lighting System

I. A fixed lighting system, other than vehicle headlights, can easily provide for a minimum of 10 lux over the entire sign surface. The average lux level will exceed this minimum. Present and proposed recommendations by the Illuminating Engineering Society for a minimum maintained average lux level exceed this value.

II. The vehicle headlighting system is a more complex situation. The level of illumination depends on the distance the vehicle is from the sign as well as the angle between the center of aim of the vehicle headlights and the angle toward the center of the sign. This latter angle determines the candlepower directed towards the sign. In addition the closer the motorist is to the sign the less stroke luminance is required due to the larger visual angle subtended by the constant letter height. The method used to evaluate the headlighting requirements is as follows.

   A. We selected the 85th percentile observer from the laboratory test and, using the predictor equation (Equation 3), calculated the stroke luminance needed by that observer to make words legible from 60, 90, 120, 150, 180, 210, and 240 m. These distances scaled up by the 10.667 factor were then plotted and found to be a straight line when plotted on a semi-log scale. The values as well as the m/cm relationship for each distance are listed in Table 27.

   B. Because in several instances in the literature search the required luminance value of 3.2 cd/m^2 was found, and because this value would yield a visibility distance of approximately 198 m for our 85th percentile observer, we have decided to utilize this value rather than the 13 cd/m^2 value derived from the dusk or dawn natural light value as a requirement for vehicle headlighting. We believe that the reduction in about 1 s in reading and decision time at 96 km/h is not a sufficient penalty to require 4 times the luminance level.

   C. Next we have located a vehicle at each 30-m point from 60 m to 210 m and, using the criteria of producing 3.2 cd/m^2 in luminance, calculated the vertical footcandles and headlight candlepower required at each distance. The results are shown in Table 28.

D. In the field study, we have determined the vertical illuminance produced by the 1,500 vehicles that traveled through the field test area. We have listed in Table 12 the average values found at the following distances: 152, 114, and 1.1 s after the second beam was broken (approx. 84 m). From this summary we conclude that the present fleet of vehicles provides, on average, more than enough light to permit the 85th percentile driver to read overhead guide signs. However a significant number of vehicles fail to provide this value.

Potential Safety Effects

Overhead guide signs have been provided for the Federal Interstate System at a substantial cost so that motorists will be given sufficient information to decide which lane to use to exit the highway, or continue toward their desired destination. These guide signs are legible for a distance in excess of 210 m during all hours of daylight and dusk when there is no rain, fog, or snow. To deny this level of information and time to make decisions during the hours of darkness has serious potential safety effects and also would result in lost time for motorists to retrace their paths to reach their destinations.

Interviews with safety officials and drivers confirm that during periods of poor visibility, rain, snow, and fog, the number of accidents and delays near exit ramps increases. In many of these cases the atmospheric transmission reduces the legibility of the overhead guide signs (and other signs) significantly. This decrease in legibility distance is partially compensated for by a reduction in average speed, which gives the motorist more time to choose and reach the desired lane in order to exit or continue to his/her destination. In the event that the ability to read overhead guide signs were to be reduced at night under otherwise, clear, dry road conditions would result in no reduction in speed but would result in a much higher risk of accidents and delays.

Some vehicle manufacturers have adopted headlight optical designs that reduce the amount of light reaching overhead guide signs to far below the minimums indicated by these studies. We can expect the percentage of the fleet that fails to meet these minimums to increase each year. It is our recommendation that Federal requirements for headlight output include in their specifications sufficient light to meet these minimums. In lieu of this requirement it will be necessary to require that overhead guide signs be lighted with fail-safe fixed lighting equipment including batteries to supply emergency power. Such a requirement would result in the expenditure of millions of dollars nationwide but it would still be a small percentage of the total amount that has already been spent for overhead guide signs and their supporting bridges.

Table 27. Luminance of the Legend Required by 85th Percentile Observer for Various Distances from an Overhead Sign.

Distance From Sign (m)	Luminance Required (cd/m^2)	m/cm of Letter Height
61	.0215	1.5
91	.0687	2.25
122	.191	3.0
152	.567	3.75
183	1.69	4.5
213	5.046	5.25
244	15.04	6.0

Table 28. Observation Angle and Distance at Which Field Measurements Were Made.

Observation Angle	Distance Vehicle to Sign (m)	Illuminance Required for 3.2 cd/m^2 (lux)	Total Headlamp Luminous Intensity (cd)
0.5	646	0.0202	8430
0.67	482	0.0209	4855
1.0	323	0.0235	2452
1.33	243	0.0268	1582
1.5	215	0.0286	1322
2.0	162	0.0344	903
2.5	129	0.0423	704
2.67	121	0.0453	663
3.0	108	0.0522	609
3.34	97	0.0601	565
4.01	80	0.080	512

CONCLUSIONS

From the literature review it can be concluded that a luminance value of 3.2 cd/m^2 is the absolute minimum acceptable sign legend luminance for proper legibility of overhead guide signs. A limited laboratory study, conducted as part of this investigation, suggests a minimum luminance value of 13.0 cd/m^2, however, the sample was small and the data varied considerably. As noted in the literature review, several researchers indicate higher values, including one study which recommends an optimum value of 75 cd/m^2. Thus, the authors conclude that a sign legend luminance (white letters) of 3.2 cd/m^2 is a reasonably conservative, low value for signs located in an area with no ambient lighting and no oncoming traffic.

Based on this minimum sign legend luminance of 3.2 cd/m^2 and a retro reflectance characteristics for sheeting materials (R_A value) commonly used, we concluded that several cars evaluated in the field study did not provide sufficient illumination toward overhead and left-shoulder mounted signs for proper sign legibility, unless high-grade sheeting (Type III) would be used. One car, a 1996 Mercedes with HID composite headlamps, did not provide sufficient illumination to result in minimum sign luminance of overhead or left shoulder mounted signs even if those signs were made from Type III materials.

The following general conclusions can be drawn from the field study in which the lighting toward sign locations from the headlamps of over1,500 randomly observed vehicles was evaluated: Based on a suggested minimum sign legend luminance value of 3.2 cd/m^2, relatively new Type III sheeting material, and straight and level roadways, there is sufficient illumination toward right-shoulder mounted signs; barely sufficient illumination toward left-shoulder mounted signs, and marginal illumination toward overhead sign locations. Specifically, based on high performance sheeting (Type III), an observation distance of 152 meters, and a minimum sign luminance of 3.2 cd/m^2, better than 99 percent of the over 1,500 vehicles observed would provide sufficient illumination for right-shoulder mounted signs; more than 90 percent of these vehicles would provide sufficient light for the left-shoulder mounted signs; but only about 50 percent of them would provide sufficient light toward overhead signs. If the signing material would be Type II, quite commonly used in many sign applications, the percentages of signs having a sign luminance of 3.2 cd/m^2 or better would be slightly less than 90 percent for the right shoulder mounted signs, about 45 percent for the left shoulder mounted signs, and only about 10 percent for all overhead mounted signs. These conclusions are predicated on signing materials to be fairly new and meeting the R_A values used in converting the measured illuminance values to sign luminance values. Since many signs, especially some of the older overhead guide signs, are constructed from Type II materials, we expect the percentage of signs with marginal and/or insufficient luminance values under headlighting conditions to be higher than indicated above where the retroreflectance characteristics are based on fairly new materials.

It is obvious from the above that reduced headlamp illumination toward signs located to the left and overhead could reduce the conspicuity, visibility, and legibility of many of the presently installed signs. Although light from headlamps which renders signs located to the left and overhead can contribute to some glare toward oncoming traffic, headlamp performance must be such that it provides sufficient sign visibility while keeping glare to an acceptable level. While no direct hard evidence could be found relating poor sign visibility to accidents, it should need no justification to suggest traffic signs must be visible for a safe and comfortable driving environment.

APPENDIX A
OVERHEAD SIGN STRUCTURES, SIGNING, LIGHTING & ACCIDENT HISTORY
Bureau of Traffic Engineering
Kansas Department of Transportation

Questionnaire to all States

Statement: We are interested in determining minimum, acceptable luminance values to use on overhead guide signs, how best to achieve adequate (above minimum) luminance, and the adverse effects of having less than adequate or minimum luminance on overhead signs. We will summarize and send results back to all who respond, keeping sources anonymous and confidential. The results could be beneficial to all States.

Specifically, we would like to know:

1. What type of background sheeting and letters you use on overhead signs.
   Background ______________ Letters ______________

2. Do you use external illumination? Yes _____ No _____
   a. If so, do you have any standards or guidelines as to amount of illumination provided?
   b. If yes, please send any standards or guidelines
   c. If no, what do you consider adequate (professional opinion)?

3. Have you done, or do you know of any studies specifically relevant to question 2 above or any studies on the general question of having "adequate" luminance on overhead guide signs?
   ____
   ____
   ____

4. Have you done any studies, or know of any studies, that have estimated the accident potential of overhead guide signs with less than adequate illumination?
   ____
   ____
   ____

5. Do you have accident records that can identify accidents upstream from overhead guide signs, as to number, rate and type? We are particularly interested in lane-changing or ramp-entrance type of accidents, i.e., side swipe, rear-end, etc., that might be attributed to a late decision to exit at a particular exit ramp. If this is not possible, could you give us current accident rates on two typical freeway sections where you have overhead signs? If possible, we would like one route identified as a route on which there is a high percentage of through traffic; the other identified as a route having a high percentage of local (work trips, etc.) traffic.

6. Any additional comments you have on the subject of illumination overhead guide signs and minimum luminance requirements, or anything else on this subject would be appreciated.

PLEASE SEND ALL RESPONSES BY JULY 11, 1994 TO THE FOLLOWING ADDRESS

Mail: State Traffic Signing Engineer
Kansas Department of Transportation
Docking State Office Bldg.
Topeka, KS 66612-1568

APPENDIX B

Luminance Levels for L_t for the Laboratory Experiment

Summary of Data from July-Aug KSU -- Task C

NUMBER	NAME	AGE	CAL DIST	ACCUITY	R. TIME	RING HIGH	Lt	RING LOW
1	Anna	78	59.74026	20	96	44.4	21.4	36.6
5	Cheryl	33	69.30736	25	92	68	21.4	41.8
7	Dale	74	61.94805	20	82	46.2	21.4	32.6
8	Debora	40	67.8355	20	0	50.8	21.4	39.1
11	Hugh	67	42.07792	33	97	32.8	21.4	26.5
12	Janis	66	58.63636	23	97	52.2	21.4	35.4
13	Jim-F	52	75.56277	18	77	65.6	21.4	39.8
15	John-F	54	66.7316	30	109	66.5	21.4	45.3
17	Lloyd	68	67.09957	23	105	55.4	21.4	40.9
18	Lucie	50	74.82684	22	80	52.3	21.4	32.5
19	Lyle	54	60.84416	29	0	45.7	21.4	33.2
20	Madeline	55	75.93074	29	45	72.5	21.4	57.9
22	Marian	74	58.2684	25	112	46.8	21.4	35.7
28	Roberta	23	62.68398	29	150	49.8	21.4	44.8
29	Roj	22	67.8355	29	0	56.7	21.4	41.6
32	Tony	48	75.19481	22	78	53	21.4	47.2
3	Brian	41	77.03463	18	79	67.2	13.19	53
4	Charles	64	80.34632	20	212	70.6	13.19	33.2
10	Holbrook	66	81.45022	22	0	43.2	13.19	23.1
14	Joe-M	44	82.18615	27	121	78.5	13.19	50.6
27	Richard	29	79.24242	25	0	67.8	13.19	56.7
9	Frank	22	61.94805	20	0	63.3	8.31	54.4
16	John-S	43	91.01732	18	87	71.2	8.31	48.1
23	Mary-B	38	93.22511	19	96	66.7	8.31	61.7
24	Mike-G	30	91.38528	17	102	66.6	8.31	37.8
26	Rafael	29	88.80952	22	94	93.6	8.31	68.2
2	Baylin	52	95.4329	17	105	79	3.25	50.4
6	Christine	27	96.16883	27	0	64.7	3.25	48.1
25	Paul	32	98.37662	17	95	86.7	3.25	61.1
30	Sara	27	99.48052	19	113	73.3	3.25	48.8
31	Tom-G	52	97.64069	20	104	62.6	3.25	43.5
33	Vic	59	103.5281	18	64	77	3.25	42.7
21	Margaret	47	102.4242	17	49	74.5	1.27	42.7
	Max	78	103.5281	33	212	93.6	21.4	68.2
	Min	22	42.07792	17	0	32.8	1.27	23.1

Lt	|	WORDS HIGH	Lt	WORDS MED	Lt	WORDS LOW	Lt
1.05	|	69.8	13.19	47.7	1.27	35.4	0.48
1.05	|	76.1	13.19	56	1.27	47.7	0.48
1.05	|	64.8	13.19	40.5	1.27	34.1	0.48
1.05	|	75.7	13.19	56.3	1.27	50.2	0.48
3.25	|	45.5	21.4	27.4	1.44	27	0.65
1.05	|	80.1	13.19	58	1.27	42.4	0.48
1.05	|	86.6	13.19	63.2	1.27	41.1	0.48
1.05	|	78.4	13.19	63.9	1.27	45.8	0.48
1.05	|	73.6	13.19	53.1	1.27	45.8	0.48
1.05	|	75.6	13.19	68.2	1.27	54.7	0.48
1.05	|	71.4	13.19	51.4	1.27	41.9	0.48
0.78	|	82.8	13.19	76.9	1.27	62.6	0.48
1.05	|	64.2	13.19	45.5	1.27	38.1	0.48
1.05	|	71.3	13.19	54.7	1.27	46	0.48
1.05	|	78.3	13.19	56.9	1.27	48.9	0.48
1.05	|	78.7	13.19	64.6	1.27	57.2	0.48
0.78	|	86.5	8.31	79.6	1.05	62	0.39
0.78	|	88.7	8.31	56.6	1.05	39.9	0.39
0.78	|	57.2	8.31	41.4	1.05	34.2	0.39
0.3	|	98	8.31	76.5	1.05	57.1	0.39
0.78	|	81.8	8.31	69.4	1.05	58.2	0.39
0.48	|	83.5	8.31	59.9	1.27	55.9	0.48
0.65	|	89.3	3.25	65.5	0.65	46.9	0.23
0.65	|	93.8	3.25	78.3	0.65	68.4	0.23
0.65	|	87.6	3.25	67	0.65	48.1	0.23
0.65	|	98.5	3.25	88.9	0.65	83.3	0.23
0.39	|	74.6	1.44	54.9	0.39	43.5	0.15
0.39	|	78.9	1.44	70.5	0.39	51.7	0.15
0.39	|	98.2	1.44	84.5	0.39	59.2	0.15
0.39	|	80.5	1.44	62.4	0.39	47.2	0.15
0.39	|	83.2	1.44	63.1	0.65	44.5	0.15
0.39	|	92.9	1.44	65.8	0.39	44.5	0.15
0.22	|	101	0.78	69	0.22	28	0.04
							Total
3.25	0	101	21.4	88.9	1.44	83.3	0.65
0.22	0	45.5	0.78	27.4	0.22	27	0.04

APPENDIX C

DUNCAN MULTIPLE RANGE TEST

Interpretation of the Duncan Multiple Range Test

Following is an interpretation of the Duncan Multiple Range test for the independent variable *vehicle year* in Table 1. Starting with the levels in the "A" group, the years 1980, 1984, and 1992 have the highest mean illuminance values and aren't significantly different from one another. The "B" group, including 1984, 1992, 1991, 1996, 1997, 1983, 1990, 1993, and 1985, is the group of years with the next highest mean illuminance values that aren't significantly different from one another. The "C" group is the next group of years that aren't significantly different. That group includes the years 1992, 1991, 1996, 1997, 1983, 1990, 1993, 1985, 1989, 1987, and 1995. Finally, the "D" group includes 1991, 1996, 1997, 1983, 1990, 1993, 1985, 1989, 1987, 1995, and 1994. Of course, the groups "A", "B", "C", and "D" are significantly different from each other in descending order; i.e., "B" is significantly lower than "A", and "C" is significantly lower than "B" and so forth.

Other observations were made from this Duncan grouping. The year 1980 had the highest mean illuminance. It's significantly higher than all years except 1984 and 1992. The year 1994 had the lowest mean illuminance and is significantly lower than all years except the rest in the "D" group. Years other than 1980 and 1994 were included in two or more groups. A year in two or more groups can't be given a single label such as the year with the highest illuminance, the year with the second highest, or the year with the lowest. For example, the year 1984 can't be said to tie for the highest mean illuminance because its mean wasn't significantly higher than all the years in the "B" group while the mean for 1980 was. However, if there were two or more years in the "A" group that were exclusive to the "A" group only, then those years would tie for the highest illuminance, and any one would be the most desirable year. Likewise, two or more years in the very last group, the "D" group in this case, that are exclusive to the last group only would tie for the lowest mean illuminance. Any one would be the least desirable year.

Table 1. Duncan Groupings for One-Way ANOVA's for the Meter Minolta Blue (right shoulder) at 152 m.

```
Independent Variable    Duncan Grouping        Mean       N Level
=========================================================================================
Vehicle Year
                                 A           0.25000      3 1980
                         B       A           0.20757      7 1984
                         B       A   C       0.19867      3 1992
                         B       D   C       0.15700      3 1991
                         B       D   C       0.15270     27 1996
                         B       D   C       0.14784     37 1997
                         B       D   C       0.14767      3 1983
                         B       D   C       0.14524     25 1990
                         B       D   C       0.14328     25 1993
                         B       D   C       0.13710     20 1985
                                 D   C       0.11971      7 1989
                                 D   C       0.11872     25 1987
                                 D   C       0.11700      3 1995
                                 D           0.10057      7 1994

Headlight Type
                                 A           0.17688     26 Seal2B1
                         B       A           0.14906     16 Seal2A1
                         B       A           0.14197    142 Halcomp
                         B       A           0.13433      3 Seal2E1
                         B       C           0.08500      4 Projctor
                                 C           0.05875      4 Xencomp

Headlight Wattage
                                 A           0.15555     49 35
                                 A           0.14903    104 55
                                 B           0.11907     42 45

Passenger Side Intensity
                                 A           0.28625      4 29000
                                 B           0.19026     19 16000
                         C       B           0.18470     10 22000
                         C       B   D       0.17016     19 18000
                         C   E   B   D       0.15700      3 24000
                     F   C   E   B   D       0.14279     24 15000
                     F   C   E   B   D       0.14089      9 17000
                     F   C   E   B   D       0.14044     18 21000
                     F   C   E   B   D       0.13433      3 30000
                     F   C   E   B   D       0.13183     41 14000
                     F   C   E   B   D       0.12590     10 12000
                     F   C   E   B   D       0.12133      3 6000
                     F   C   E       D       0.11100     12 20000
                     F       E       D       0.10150      4 10000
                     F       E               0.09208     13 13000
                     F                       0.07400      3 25000

Driver Side Intensity
                                 A           0.34900      3 28000
                                 B           0.28625      4 31000
                                 C           0.21867      9 20000
                         D       C           0.18323     13 19000
                         D       E           0.15306     16 18000
                         D       E           0.15281     21 16000
                         D       E   F       0.14767      3 24000
                         D       E   F       0.14490     10 12000
                         D       E   F       0.13515     13 15000
                         D       E   F       0.13182     11 14000
                         D       E   F       0.13167      3 10000
                         D       E   F       0.12985     13 22000
                         D       E   F       0.12133      3 5000
                         D       E   F       0.12010     21 21000
                         D       E   F       0.11890     10 13000
                         D       E   F       0.11765     20 6000
                                 E   F       0.11560     15 17000
                                     F       0.08257      7 11000

Speed                 Not Significant at Alpha = 0.05
```

Table 2. Duncan Groupings for One-Way ANOVA's for the Meter Minolta Blue (right shoulder) at 114 m.

Independent Variable	Duncan Grouping			Mean	N	Level
Vehicle Year	Not Significant at Alpha = 0.05					
Headlight Type						
		A		0.23804	6	Seal2B1
	B	A		0.20900	3	Seal2E1
	B	A		0.20825	16	Seal2A1
	B	A		0.20601	143	Halcomp
	B	C		0.12600	4	Projctor
		C		0.09150	4	Xencomp
Headlight Wattage	Not Significant at Alpha = 0.05					
Passenger Side Intensity						
		A		0.40950	4	29000
		B		0.25200	3	24000
		B		0.24867	18	16000
		B		0.24168	19	18000
		B		0.23950	10	22000
	C	B		0.21644	18	21000
	C	B		0.21189	9	17000
	C	B		0.20900	3	30000
	C	B	D	0.19498	42	14000
	C	B	D	0.19204	25	15000
	C	B	D	0.19140	10	12000
	C	B	D	0.18333	3	6000
	C	B	D	0.16425	12	20000
	C		D	0.14400	4	10000
	C		D	0.14185	13	13000
			D	0.11500	3	25000
Driver Side Intensity						
		A		0.41100	3	28000
		A		0.40950	4	31000
		B		0.29844	9	20000
	C	B		0.24262	13	19000
	C	D		0.22038	16	18000
	C	D		0.21700	3	24000
	C	D		0.20346	13	22000
	C	D		0.20133	3	10000
	C	D		0.19952	21	16000
	C	D		0.19555	11	14000
	C	D		0.19040	10	13000
	C	D		0.18833	15	17000
	C	D		0.18700	9	12000
	C	D		0.18333	3	5000
	C	D		0.18246	13	15000
	C	D		0.18171	21	6000
	C	D		0.17848	21	21000
		D		0.13763	8	11000
Speed	Not Significant at Alpha = 0.05					

Table 3. Duncan Groupings for One-Way ANOVA's for the Meter Minolta Blue (right shoulder) 1.1 s After 114 m.

Independent Variable	Duncan Grouping				Mean	N	Level
Vehicle Year	Not Significant at Alpha = 0.05						
Headlight Type							
			A		0.35433	3	Seal2E1
			A		0.33531	26	Seal2B1
	B		A		0.28913	16	Seal2A1
	B		A		0.28697	140	Halcomp
	B		C		0.18350	4	Project
			C		0.13725	4	Xencomp
Headlight Wattage	Not Significant at Alpha = 0.05						
Passenger Side Intensity							
			A		0.64925	4	29000
			B		0.35433	3	30000
	C		B		0.34167	3	24000
	C		B		0.34130	10	22000
	C		B	D	0.32989	18	16000
	C		B	D	0.31644	18	18000
	C	E	B	D	0.30390	10	12000
	C	E	B	D	0.29688	17	21000
	C	E	B	D	0.28233	9	17000
	C	E	B	D	0.27493	41	14000
	C	E	B	D	0.25784	25	15000
	C	E	B	D	0.25733	3	6000
	C	E	B	D	0.23817	12	20000
	C	E		D	0.22125	4	10000
		E		D	0.20923	13	13000
		E			0.18467	3	25000
Driver Side Intensity							
			A		0.64925	4	31000
			A		0.58400	3	28000
			B		0.33871	7	20000
			B		0.33454	13	19000
	C		B		0.31646	13	22000
	C		B		0.31167	3	24000
	C		B		0.30713	16	18000
	C		B		0.29893	15	17000
	C		B		0.27400	10	13000
	C		B		0.27373	11	14000
	C		B		0.27010	20	16000
	C		B		0.26533	3	10000
	C		B		0.25733	3	5000
	C		B		0.25629	21	6000
	C		B		0.25589	9	12000
	C		B		0.24500	21	21000
	C		B		0.23569	13	15000
	C				0.21688	8	11000
Speed	Not Significant at Alpha = 0.05						

Table 4. Duncan Groupings for One-Way ANOVA's for the Meter Minolta Clear (right shoulder) at 152 m.

Independent Variable	Duncan Grouping	Mean	N	Level
Vehicle Year				
	A	0.24467	3	1980
	B A	0.20657	7	1984
	B A	0.19867	3	1992
	B C	0.15700	3	1991
	B C	0.15124	37	1997
	B C	0.14822	27	1996
	B C	0.14667	3	1983
	B C	0.14512	25	1993
	B C	0.13970	20	1985
	B C	0.13888	25	1990
	B C	0.12343	7	1989
	B C	0.12333	3	1995
	C	0.11176	25	1987
	C	0.10629	7	1994
Headlight Type				
	A	0.16877	26	Seal2B1
	A	0.15163	16	Seal2A1
	A	0.14164	142	Halcomp
	B A	0.13467	3	Seal2E1
	B A	0.09200	4	Project
	B	0.06300	4	Xencomp
Headlight Wattage	Not Significant at Alpha = 0.05			
Passenger Side Intensity				
	A	0.28325	4	29000
	B	0.19121	19	16000
	C B	0.18370	10	22000
	C B D	0.17474	19	18000
	C E B D	0.15700	3	24000
	F C E B D	0.13989	9	17000
	F C E B D	0.13688	24	15000
	F C E B D	0.13467	3	30000
	F C E B D	0.13322	41	14000
	F C E B D	0.13140	10	12000
	F C E B D	0.12533	3	6000
	F C E B D	0.12150	18	21000
	F C E D	0.11550	12	20000
	F E D	0.10425	4	10000
	F E	0.09508	13	13000
	F	0.07700	3	25000
Driver Side Intensity				
	A	0.34300	3	28000
	B	0.28325	4	31000
	C	0.21589	9	20000
	D C	0.18631	13	19000
	D E	0.15656	16	18000
	D E	0.15281	21	16000
	D E F	0.14730	10	12000
	D E F	0.14667	3	24000
	D E F	0.13667	3	10000
	D E F	0.13627	11	14000
	D E F	0.12533	3	5000
	D E F	0.12362	13	15000
	E F	0.11970	10	13000
	E F	0.11945	20	6000
	E F	0.11807	15	17000
	E F	0.11667	21	21000
	E F	0.11469	13	22000
	F	0.08671	7	11000
Speed	Not Significant at Alpha = 0.05			

Table 5. Duncan Groupings for One-Way ANOVA's for the Meter Minolta Clear (right shoulder) at 114 m.

Independent Variable	Duncan Grouping			Mean	N	Level
Vehicle Year	Not Significant at Alpha = 0.05					
Headlight Type						
		A		0.22588	26	Seal2B1
		A		0.21306	16	Seal2A1
		A		0.20867	3	Seal2E1
		A		0.20408	143	Halcomp
	B	A		0.13200	4	Project
	B			0.09350	4	Xencomp
Headlight Wattage	Not Significant at Alpha = 0.05					
Passenger Side Intensity						
		A		0.40950	4	29000
		B		0.25156	18	16000
		B		0.24800	3	24000
		B		0.24379	19	18000
		B		0.24130	10	22000
	C	B		0.20989	9	17000
	C	B	D	0.20867	3	30000
	C	B	D	0.19750	10	12000
	C	B	D	0.19562	42	14000
	C	B	D	0.18756	18	21000
	C	B	D	0.18467	3	6000
	C	B	D	0.18448	25	15000
	C	B	D	0.16750	12	20000
	C		D	0.14650	4	10000
	C		D	0.14208	13	13000
			D	0.11600	3	25000
Driver Side Intensity						
		A		0.40950	4	31000
		A		0.40767	3	28000
		B		0.29644	9	20000
	C	B		0.24777	13	19000
	C	B	D	0.22138	16	18000
	C	B	D	0.21967	3	24000
	C		D	0.20667	3	10000
	C		D	0.20138	21	16000
	C		D	0.19973	11	14000
	C		D	0.18920	10	13000
	C		D	0.18811	9	12000
	C		D	0.18680	15	17000
	C		D	0.18467	3	5000
	C		D	0.18329	21	6000
	C		D	0.17646	13	22000
	C		D	0.17305	21	21000
	C		D	0.16469	13	15000
			D	0.14225	8	11000
Speed	Not Significant at Alpha = 0.05					

Table 6. Duncan Groupings for One-Way ANOVA's for the Meter Minolta Clear (right shoulder) 1.1 s After 114 m.

Independent Variable	Duncan Grouping			Mean	N	Level
Vehicle Year	Not Significant at Alpha = 0.05					
Headlight Type						
		A		0.34633	3	Seal2E1
	B	A		0.31735	26	Seal2B1
	B	A		0.29281	16	Seal2A1
	B	A		0.28720	139	Halcomp
	B	C		0.19100	4	Project
		C		0.13600	4	Xencomp
Headlight Wattage	Not Significant at Alpha = 0.05					
Passenger Side Intensity						
		A		0.64300	4	29000
		B		0.34633	3	30000
		B		0.34010	10	22000
		B		0.33367	3	24000
		B		0.33128	18	16000
	C	B		0.32050	18	18000
	C	B	D	0.30740	10	12000
	C	B	D	0.28722	9	17000
	C	B	D	0.27888	40	14000
	C	B	D	0.26500	3	6000
	C	B	D	0.26229	17	21000
	C	B	D	0.24876	25	15000
	C	B	D	0.24683	12	20000
	C	B	D	0.22675	4	10000
	C		D	0.21046	13	13000
			D	0.18900	3	25000
Driver Side Intensity						
		A		0.64300	4	31000
		A		0.56467	3	28000
		B		0.34214	7	20000
		B		0.33792	13	19000
	C	B		0.31567	3	24000
	C	B		0.31113	16	18000
	C	B		0.30536	14	17000
	C	B		0.27777	13	22000
	C	B		0.27770	10	13000
	C	B		0.27582	11	14000
	C	B		0.27335	20	16000
	C	B		0.27200	3	10000
	C	B		0.26500	3	5000
	C	B		0.26044	9	12000
	C	B		0.25748	21	6000
	C	B		0.24533	21	21000
	C			0.22225	8	11000
	C			0.21300	13	15000
Speed	Not Significant at Alpha = 0.05					

Table 7. Duncan Groupings for One-Way ANOVA's for the Meter Minolta Green (left shoulder) at 152 m.

```
Independent Variable    Duncan Grouping        Mean      N  Level
==========================================================================================
Vehicle Year          Not Significant at Alpha = 0.05
------------------------------------------------------------------------------------------
Headlight Type        Not Significant at Alpha = 0.05
------------------------------------------------------------------------------------------
Headlight Wattage     Not Significant at Alpha = 0.05
------------------------------------------------------------------------------------------
Passenger Side Intensity
                                A            0.13525     4  29000
                                B            0.09089    19  18000
                          C     B            0.08600    10  22000
                          C     B            0.08333     3  6000
                          C     B            0.08167     3  24000
                          C     B            0.08005    19  16000
                          C     B            0.07617    41  14000
                          C     B            0.07156     9  17000
                          C     B            0.07020    10  12000
                          C     B            0.06511    18  21000
                          C     B            0.06492    25  15000
                          C     B            0.06333     3  30000
                          C                  0.05775    12  20000
                          C                  0.05675     4  10000
                          C                  0.05623    13  13000
                          C                  0.05600     3  25000
------------------------------------------------------------------------------------------
Driver Side Intensity
                                A            0.13525     4  31000
                                A            0.13000     3  28000
                                B            0.10378     9  20000
                          C     B            0.08375    16  18000
                          C     B            0.08333     3  5000
                          C     B            0.08255    20  6000
                          C     B            0.07962    13  19000
                          C                  0.07655    11  14000
                          C                  0.06924    21  16000
                          C                  0.06663     8  11000
                          C                  0.06467     3  24000
                          C                  0.06440    10  13000
                          C                  0.06340    10  12000
                          C                  0.06246    13  15000
                          C                  0.06210    21  21000
                          C                  0.06020    15  17000
                          C                  0.05985    13  22000
                          C                  0.05933     3  10000
------------------------------------------------------------------------------------------
Speed                 Not Significant at Alpha = 0.05
```

Table 8. Duncan Grouping for One-Way ANOVA's for the Meter Minolta Green (left shoulder) at 114 m.

```
Independent Variable    Duncan Grouping         Mean      N  Level
=========================================================================================
Vehicle Year          Not Significant at Alpha = 0.05

Headlight Type        Not Significant at Alpha = 0.05

Headlight Wattage     Not Significant at Alpha = 0.05

Passenger Side Intensity
                                 A           0.16775      4 29000
                                 B           0.12632     19 18000
                         C       B           0.12167      3 24000
                         C       B   D       0.11800     10 22000
                         C       B   D       0.10874     42 14000
                         C       B   D       0.10700     18 16000
                         C       B   D       0.10667      3 6000
                         C       B   D       0.10344      9 17000
                         C       B   D       0.09500     10 12000
                         C       B   D       0.09200      3 30000
                         C       B   D       0.08922     18 21000
                         C       B   D       0.08750     24 15000
                         C           D       0.08067      3 25000
                                     D       0.07838     13 13000
                                     D       0.07675      4 10000
                                     D       0.07592     12 20000

Driver Side Intensity
                                     A           0.17000      3 28000
                                     A           0.16775      4 31000
                             B       A           0.15011      9 20000
                             B       C           0.11881     21 6000
                                     C           0.11300     16 18000
                                     C           0.10667      3 5000
                                     C           0.10654     13 19000
                             D       C           0.10364     11 14000
                             D       C           0.10133      3 24000
                             D       C           0.09767     21 16000
                             D       C           0.09063      8 11000
                             D       C           0.09030     10 13000
                             D       C           0.08892     13 15000
                             D       C           0.08560     15 17000
                             D       C           0.08410     21 21000
                             D       C           0.08100      9 12000
                             D       C           0.08008     13 22000
                             D                   0.06600      2 10000

Speed                 Not Significant at Alpha = 0.05
```

Table 9. Duncan Grouping for One-Way ANOVA's for the Meter Minolta Green (left shoulder) 1.1s After 114 m.

Independent Variable	Duncan Grouping			Mean	N	Level
Vehicle Year	Not Significant at Alpha = 0.05					
Headlight Type	Not Significant at Alpha = 0.05					
Headlight Wattage	Not Significant at Alpha = 0.05					
Passenger Side Intensity						
		A		0.25300	4	29000
		B		0.16450	10	22000
		B		0.16095	19	18000
	C	B		0.15767	3	24000
	C	B		0.15733	3	6000
	C	B	D	0.14634	41	14000
	C	B	D	0.14144	18	16000
	C	B	D	0.14056	9	17000
	C	B	D	0.13870	10	12000
	C	B	D	0.13133	3	30000
	C	B	D	0.12967	3	25000
	C	B	D	0.12156	25	15000
	C		D	0.11000	16	21000
	C		D	0.10767	12	20000
			D	0.10646	13	13000
			D	0.10325	4	10000
Driver Side Intensity						
		A		0.25300	4	31000
	B	A		0.21800	3	28000
	B			0.20143	7	20000
		C		0.15967	3	24000
		C		0.15805	21	6000
		C		0.15733	3	5000
	D	C		0.14791	11	14000
	D	C		0.14569	13	19000
	D	C		0.14238	16	18000
	D	C	E	0.13363	8	11000
	D	C	E	0.13010	20	16000
	D	C	E	0.12923	13	15000
	D	C	E	0.12040	15	17000
	D	C	E	0.11652	21	21000
	D		E	0.11044	9	12000
	D		E	0.10892	13	22000
	D		E	0.10890	10	13000
			E	0.09367	3	10000
Speed	Not Significant at Alpha = 0.05					

Table 10. Duncan Grouping for One-Way ANOVA's for the Meter Minolta Yellow (left shoulder) at 152 m.

Independent Variable	Duncan Grouping	Mean	N	Level
Vehicle Year	Not Significant at Alpha = 0.05			
Headlight Type				
	A	0.07112	141	Halcomp
	B A	0.06638	16	Seal2A1
	B A	0.06348	25	Seal2B1
	B A	0.05467	3	Seal2E1
	B A	0.03825	4	Xencomp
	B	0.03350	4	Project
Headlight Wattage	Not Significant at Alpha = 0.05			
Passenger Side Intensity				
	A	0.12750	4	29000
	B	0.08258	19	18000
	C B	0.07622	9	22000
	C B	0.07533	3	24000
	C B	0.07417	18	16000
	C B	0.07300	3	6000
	C B	0.07198	41	14000
	C B	0.07000	9	17000
	C B	0.06494	18	21000
	C B	0.06252	25	15000
	C B	0.06122	9	12000
	C B	0.05467	3	30000
	C B	0.05050	4	10000
	C B	0.04975	12	20000
	C B	0.04731	13	13000
	C	0.04700	3	25000
Driver Side Intensity				
	A	0.15000	2	28000
	B A	0.12750	4	31000
	B C	0.10367	9	20000
	D C	0.07905	20	6000
	D C	0.07744	16	18000
	D	0.07300	3	5000
	D	0.07123	13	19000
	D	0.06560	10	14000
	D	0.06443	21	16000
	D	0.06310	10	12000
	D	0.06050	8	11000
	D	0.05967	3	24000
	D	0.05883	12	15000
	D	0.05680	10	13000
	D	0.05662	13	22000
	D	0.05510	21	21000
	D	0.05433	3	10000
	D	0.05247	15	17000
Speed	Not Significant at Alpha = 0.05			

Table 11. Duncan Grouping for One-Way ANOVA's for the Meter Minolta Yellow (left shoulder) at 114 m.

Independent Variable	Duncan Grouping			Mean	N	Level
Vehicle Year	Not Significant at Alpha = 0.05					
Headlight Type						
		A		0.10116	141	Halcomp
	B	A		0.09181	16	Seal2A1
	B	A		0.08688	26	Seal2B1
	B	A		0.08533	3	Seal2E1
	B	A		0.05775	4	Xencomp
	B			0.05525	4	Project
Headlight Wattage						
		A		0.105279	43	45
	B	A		0.097627	102	55
	B			0.086020	49	35
Passenger-Side Intensity						
		A		0.16325	4	29000
		B		0.11763	19	18000
	C	B		0.11500	3	24000
	C	B	D	0.10802	41	14000
	C	B	D	0.10380	10	22000
	C	B	D	0.10367	3	6000
	C	B	D	0.10233	9	17000
	C	B	D	0.09533	18	16000
	C	B	D	0.09110	10	12000
	C	B	D	0.08724	17	21000
	C	B	D	0.08608	25	15000
	C	B	D	0.08533	3	30000
	C	B	D	0.07500	3	25000
	C	B	D	0.07177	13	13000
	C		D	0.06975	4	10000
			D	0.06775	12	20000
Driver-Side Intensity						
		A		0.16325	4	31000
	B	A		0.14778	9	20000
	B	A		0.14700	3	28000
	B	C		0.11881	21	6000
	D	C		0.10506	16	18000
	D	C		0.10367	3	5000
	D	C		0.10000	11	14000
	D	C		0.09600	3	24000
	D	C		0.09592	13	19000
	D	C		0.09490	20	16000
	D	C		0.08600	3	10000
	D	C		0.08480	10	13000
	D	C		0.08388	8	11000
	D	C		0.08246	13	15000
	D	C		0.07922	9	12000
	D	C		0.07847	15	17000
	D	C		0.07762	13	22000
	D			0.07540	20	21000
Speed	Not Significant at Alpha = 0.05					

Table 12. Duncan Grouping for One-Way ANOVA's for the Meter Minolta Yellow (left shoulder) 1.1s After 114 m.

```
Independent Variable    Duncan Grouping         Mean      N  Level
==========================================================================================
Vehicle Year          Not Significant at Alpha = 0.05

Headlight Type        Not Significant at Alpha = 0.05

Headlight Wattage     Not Significant at Alpha = 0.05

Passenger-Side Intensity
                                 A           0.23725      4  29000
                                 B           0.15984     19  18000
                         C       B           0.15667      3  24000
                         C       B   D       0.15150     10  22000
                         C       B   D       0.14988     41  14000
                         C       B   D       0.14733      3  6000
                         C       B   D       0.14467      9  17000
                         C       B   D       0.13867      9  12000
                         C       B   D       0.13700     17  16000
                         C       B   D       0.12800      3  25000
                         C       B   D       0.12108     25  15000
                         C       B   D       0.11567      3  30000
                         C       B   D       0.10875     16  21000
                         C       B   D       0.10338     13  13000
                         C           D       0.10075     12  20000
                                     D       0.09400      4  10000

Driver-Side Intensity
                                 A           0.23725      4  31000
                         B       A           0.21843      7  20000
                         B       C           0.18467      3  28000
                         D       C           0.16390     21  6000
                         D       C   E       0.15400      3  24000
                         D       C   E       0.14733      3  5000
                         D       C   E       0.14336     11  14000
                         D       C   E       0.14287     15  18000
                         D   F   C   E       0.13792     13  19000
                         D   F       E       0.12831     13  15000
                         D   F       E       0.12825      8  11000
                         D   F       E       0.12660     20  16000
                         D   F       E       0.11933     15  17000
                         D   F       E       0.11288      8  12000
                             F       E       0.11110     21  21000
                             F       E       0.11030     10  13000
                             F       E       0.10354     13  22000
                             F               0.09067      3  10000

Speed                 Not Significant at Alpha = 0.05
```

Table 13. Duncan Grouping for One-Way ANOVA's for the Meter IL 1700 #1 (over the center of the right driving lane) at 152 m.

```
Independent Variable    Duncan Grouping         Mean       N  Level
==========================================================================================
Vehicle Year          Not Significant at Alpha = 0.05

Headlight Type        Not Significant at Alpha = 0.05

Headlight Wattage     Not Significant at Alpha = 0.05

Passenger-Side Intensity      Not Significant at Alpha = 0.05

Driver-Side Intensity         Not Significant at Alpha = 0.05

Speed                 Not Significant at Alpha = 0.05
```

Table 14. Duncan Grouping for One-Way ANOVA's for the Meter IL 1700 #1 (over the center of the right driving lane) at 114 m.

```
Independent Variable    Duncan Grouping         Mean      N  Level
==========================================================================================
Vehicle Year           Not Significant at Alpha = 0.05
------------------------------------------------------------------------------------------
Headlight Type         Not Significant at Alpha = 0.05
------------------------------------------------------------------------------------------
Headlight Wattage      Not Significant at Alpha = 0.05
------------------------------------------------------------------------------------------
Passenger-Side Intensity
                                 A           0.09108       4 29000
                         B       A           0.08805       2 6000
                         B       A   C       0.07410       3 24000
                         B   D   A   C       0.06898      13 21000
                         B   D   A   C       0.06253       7 22000
                         B   D   A   C       0.05350       3 30000
                         B   D   A   C       0.05296      15 18000
                         B   D   A   C       0.05260      12 16000
                         B   D   A   C       0.04593      37 14000
                         B   D       C       0.04436       7 12000
                             D       C       0.03995       8 17000
                             D       C       0.03748      21 15000
                             D       C       0.03443       4 10000
                             D       C       0.03008      13 13000
                             D       C       0.02960       3 25000
                             D               0.02640       9 20000
------------------------------------------------------------------------------------------
Driver-Side Intensity
                                 A           0.11590       2 28000
                         B       A           0.09108       4 31000
                         B       A           0.08805       2 5000
                         B       C           0.07232      12 22000
                         B       C           0.06003       7 19000
                         B       C           0.05756       7 20000
                         B       C           0.05326      20 6000
                         B       C           0.04907       3 24000
                         B       C           0.04778      13 18000
                                 C           0.04367      15 17000
                                 C           0.04299      15 16000
                                 C           0.03874       5 11000
                                 C           0.03698      10 14000
                                 C           0.03677       9 13000
                                 C           0.03523       3 10000
                                 C           0.03325      10 12000
                                 C           0.03139      14 21000
                                 C           0.02863      10 15000
------------------------------------------------------------------------------------------
Speed                  Not Significant at Alpha = 0.05
```

Table 15. Duncan Grouping for One-Way ANOVA's for the Meter IL 1700 #1 (over the center of the right driving lane) at 1.1 s later.

Independent Variable	Duncan Grouping				Mean	N	Level
Vehicle Year	Not Significant at Alpha = 0.05						
Headlight Type	Not Significant at Alpha = 0.05						
Headlight Wattage	Not Significant at Alpha = 0.05						
Passenger-Side Intensity							
			A		0.12970	4	29000
	B		A		0.11565	2	6000
	B		A	C	0.10003	3	24000
	B	D	A	C	0.09043	7	22000
	B	D	E	C	0.07980	3	30000
		D	E	C	0.07041	12	16000
		D	E	C	0.06966	18	18000
		D	E	C	0.06650	17	21000
		D	E	C	0.06466	8	12000
		D	E	C	0.06330	40	14000
		D	E		0.05142	9	17000
		D	E		0.05009	23	15000
		D	E		0.04963	3	25000
		D	E		0.04960	4	10000
		D	E		0.04441	13	13000
			E		0.03731	9	20000
Driver-Side Intensity							
			A		0.15845	2	28000
	B		A		0.12970	4	31000
	B		C		0.11565	2	5000
	D		C		0.08050	8	20000
	D		C		0.07717	13	22000
	D				0.07240	3	24000
	D				0.06847	9	19000
	D				0.06788	21	6000
	D				0.06501	15	17000
	D				0.06496	14	18000
	D				0.06155	11	14000
	D				0.05776	18	16000
	D				0.05398	6	11000
	D				0.04856	10	13000
	D				0.04790	10	15000
	D				0.04323	10	12000
	D				0.04257	3	10000
	D				0.04085	16	21000
Speed	Not Significant at Alpha = 0.05						

Table 16. Duncan Grouping for One-Way ANOVA's for the Meter IL 1700 #2 (over the center of the right driving lane) at 152 m.

```
Independent Variable    Duncan Grouping         Mean      N  Level
==========================================================================================
Vehicle Year          Not Significant at Alpha = 0.05

Headlight Type        Not Significant at Alpha = 0.05

Headlight Wattage     Not Significant at Alpha = 0.05

Passenger-Side Intensity
                                 A           0.07680     4  29000
                                 A           0.07610     2  6000
                         B       A           0.07134     5  16000
                         B       A   C       0.05342     6  22000
                         B       D   C       0.04161     9  14000
                         B       D   C       0.04130     3  30000
                         B       D   C       0.04023     3  12000
                         B       D   C       0.03644    10  18000
                                 D   C       0.03065     6  17000
                                 D   C       0.02843     8  15000
                                 D   C       0.02815     4  10000
                                 D           0.01230     5  20000

Driver-Side Intensity
                                 A           0.08057     3  28000
                         B       A           0.07680     4  31000
                         B       A           0.07610     2  5000
                         B       A   C       0.05311     7  19000
                         B       A   C       0.04416     7  6000
                         B       A   C       0.04352     9  18000
                         B           C       0.03810     1  24000
                         B           C       0.03733     4  22000
                         B           C       0.03607     3  20000
                                     C       0.03273     6  14000
                                     C       0.03270     2  16000
                                     C       0.03010     3  10000
                                     C       0.02815     4  12000
                                     C       0.02368     4  11000
                                     C       0.01280     6  21000

Speed                 Not Significant at Alpha = 0.05
```

Table 17. Duncan Grouping for One-Way ANOVA's for the Meter IL1700 #2 (over the center of the right driving lane) at 114 m.

```
Independent Variable    Duncan Grouping         Mean      N  Level
=========================================================================================
Vehicle Year          Not Significant at Alpha = 0.05

Headlight Type        Not Significant at Alpha = 0.05

Headlight Wattage     Not Significant at Alpha = 0.05

Passenger-Side Intensity
                                 A           0.10025      4  29000
                         B       A           0.09740      2  6000
                         B       A   C       0.08412      5  16000
                         B   D   A   C       0.07738      5  22000
                     E   B   D   A   C       0.05973      3  30000
                     E   B   D       C       0.05640      4  12000
                     E       D       C       0.05231     10  14000
                     E       D       C       0.04920     10  18000
                     E       D               0.04062      4  10000
                     E       D               0.04042      5  17000
                     E                       0.03278      9  15000
                     E                       0.02092      5  20000

Driver-Side Intensity
                                 A           0.13470      2  28000
                         B       A           0.10025      4  31000
                         B       A           0.09740      2  5000
                         B       C           0.05921      7  6000
                         B       C           0.05753      9  18000
                         B       C           0.05640      1  24000
                         B       C           0.05638      8  19000
                         B       C           0.05258      4  22000
                                 C           0.04593      3  20000
                                 C           0.04510      5  14000
                                 C           0.04062      4  12000
                                 C           0.03864      5  11000
                                 C           0.03667      3  10000
                                 C           0.03620      3  16000
                                 C           0.02243      6  21000

Speed                 Not Significant at Alpha = 0.05
```

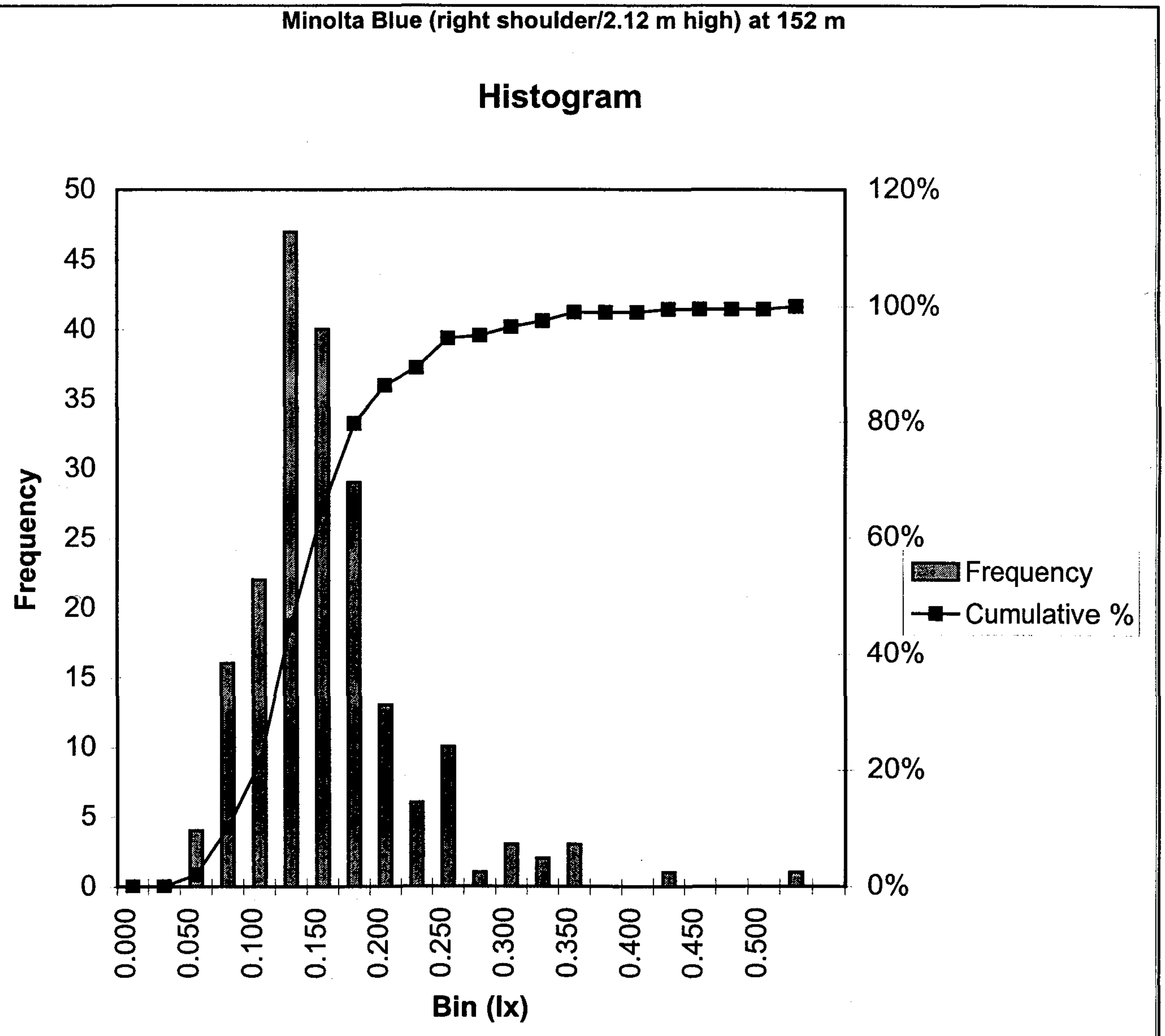
Table 18. Duncan Grouping for One-Way ANOVA's for the Meter IL 1700 #2 (over the center of the right driving lane) 1.1 s after 114 m.

```
Independent Variable    Duncan Grouping         Mean      N  Level
==========================================================================================
Vehicle Year           Not Significant at Alpha = 0.05

Headlight Type         Not Significant at Alpha = 0.05

Headlight Wattage      Not Significant at Alpha = 0.05

Passenger-Side Intensity
                                 A           0.13765     4  29000
                                 A           0.13710     2  6000
                         B       A           0.10028     5  16000
                         B       A   C       0.09790     4  12000
                         B       A   C       0.09317     6  22000
                         B           C       0.08910     3  30000
                         B       D   C       0.06994    10  18000
                         B       D   C       0.06526    10  14000
                         B       D   C       0.05780     4  10000
                         B       D   C       0.05608     5  17000
                                 D   C       0.05307    10  15000
                                 D           0.04224     5  20000

Driver-Side Intensity
                                 A           0.16435     2  28000
                                 A           0.13765     4  31000
                                 A           0.13710     2  5000
                                 B           0.07948     9  18000
                                 B           0.07693     4  22000
                                 B           0.07684     9  19000
                                 B           0.07444     5  14000
                                 B           0.07264     7  6000
                                 B           0.06310     2  24000
                                 B           0.06117     3  20000
                                 B           0.06108     5  11000
                                 B           0.05780     4  12000
                                 B           0.04803     3  16000
                                 B           0.04582     6  21000
                                 B           0.04517     3  10000

Speed                  Not Significant at Alpha = 0.05
```

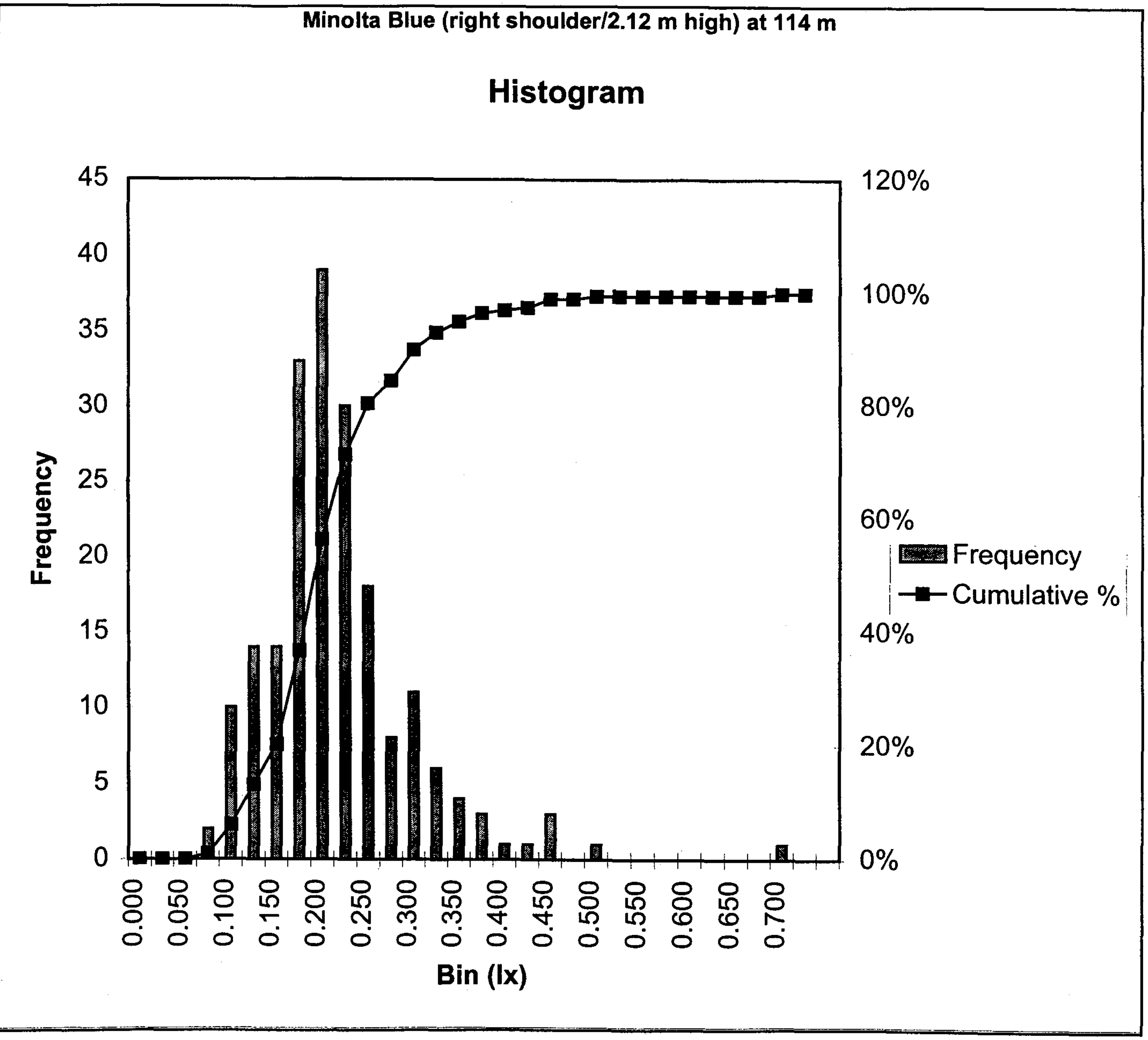
APPENDIX D

HISTOGRAMS FOR 50 KNOWN CARS

Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	0	.00%
0.050	4	2.02%
0.075	16	10.10%
0.100	22	21.21%
0.125	47	44.95%
0.150	40	65.15%
0.175	29	79.80%
0.200	13	86.36%
0.225	6	89.39%
0.250	10	94.44%
0.275	1	94.95%
0.300	3	96.46%
0.325	2	97.47%
0.350	3	98.99%
0.375	0	98.99%
0.400	0	98.99%
0.425	1	99.49%
0.450	0	99.49%
0.475	0	99.49%
0.500	0	99.49%
0.525	1	100.00%



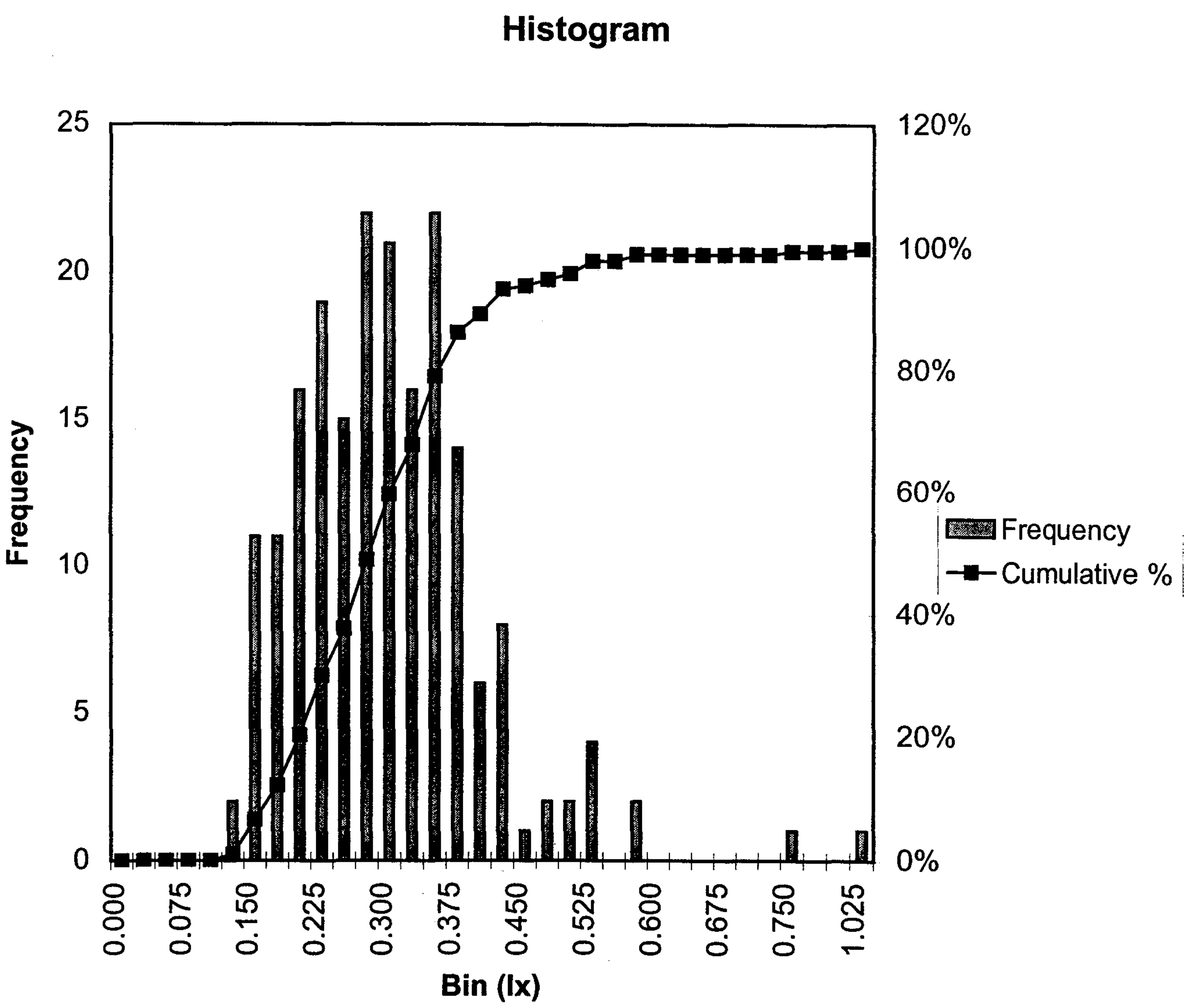
Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	0	.00%
0.050	0	.00%
0.075	2	1.01%
0.100	10	6.03%
0.125	14	13.07%
0.150	14	20.10%
0.175	33	36.68%
0.200	39	56.28%
0.225	30	71.36%
0.250	18	80.40%
0.275	8	84.42%
0.300	11	89.95%
0.325	6	92.96%
0.350	4	94.97%
0.375	3	96.48%
0.400	1	96.98%
0.425	1	97.49%
0.450	3	98.99%
0.475	0	98.99%
0.500	1	99.50%
0.525	0	99.50%
0.550	0	99.50%
0.575	0	99.50%
0.600	0	99.50%
0.625	0	99.50%
0.650	0	99.50%
0.675	0	99.50%
0.700	1	100.00%
0.725	0	100.00%


Minolta Blue (right shoulder/2.12 m high) at 114 m

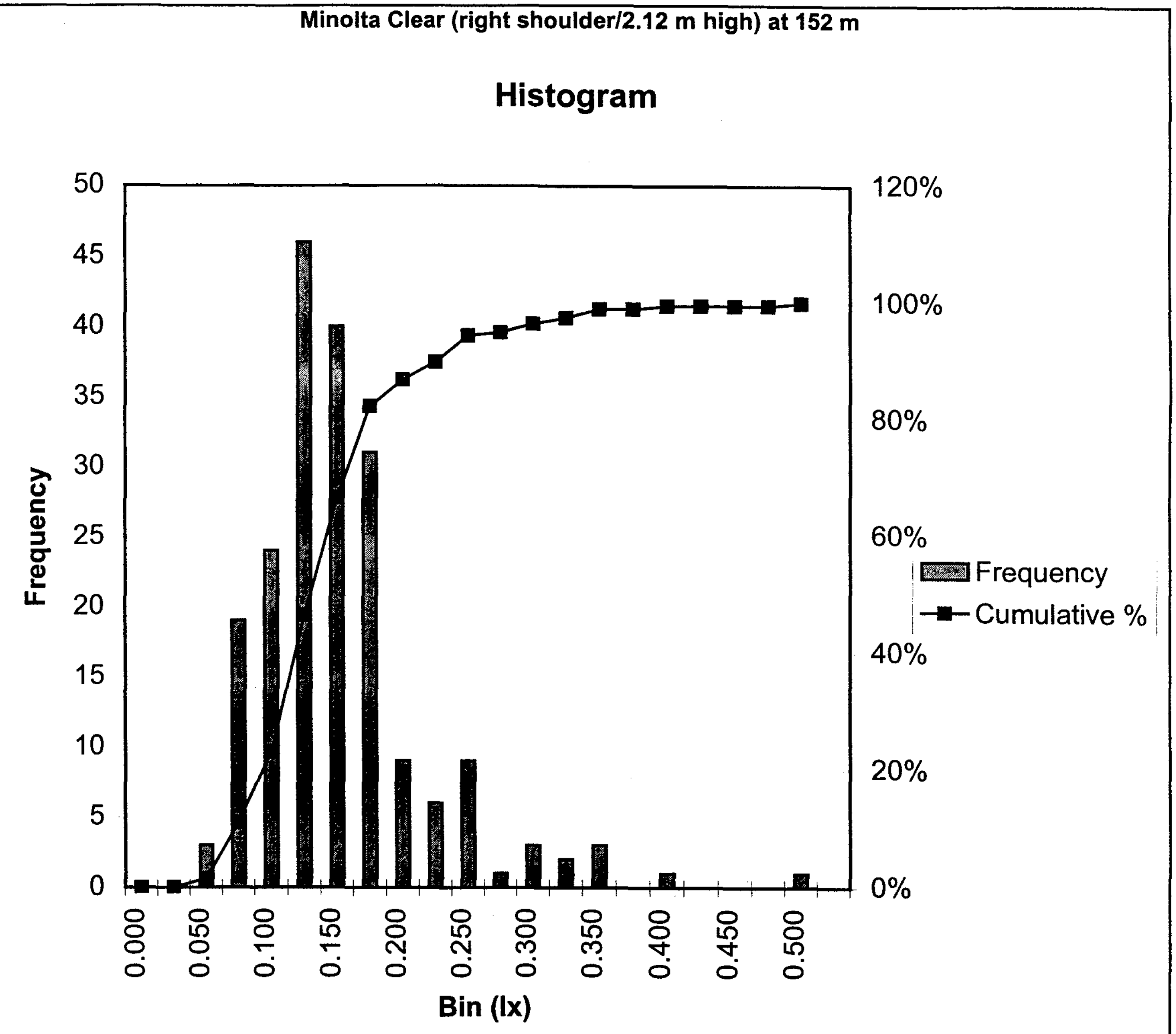
Histogram

Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	0	.00%
0.050	0	.00%
0.075	0	.00%
0.100	0	.00%
0.125	2	1.02%
0.150	11	6.63%
0.175	11	12.24%
0.200	16	20.41%
0.225	19	30.10%
0.250	15	37.76%
0.275	22	48.98%
0.300	21	59.69%
0.325	16	67.86%
0.350	22	79.08%
0.375	14	86.22%
0.400	6	89.29%
0.425	8	93.37%
0.450	1	93.88%
0.475	2	94.90%
0.500	2	95.92%
0.525	4	97.96%
0.550	0	97.96%
0.575	2	98.98%
0.600	0	98.98%
0.625	0	98.98%
0.650	0	98.98%
0.675	0	98.98%
0.700	0	98.98%
0.725	0	98.98%
0.750	1	99.49%
0.775	0	99.49%
0.800	0	99.49%
1.025	1	100.00%

Minolta Blue (right shoulder/2.12 m high) after 1.1s

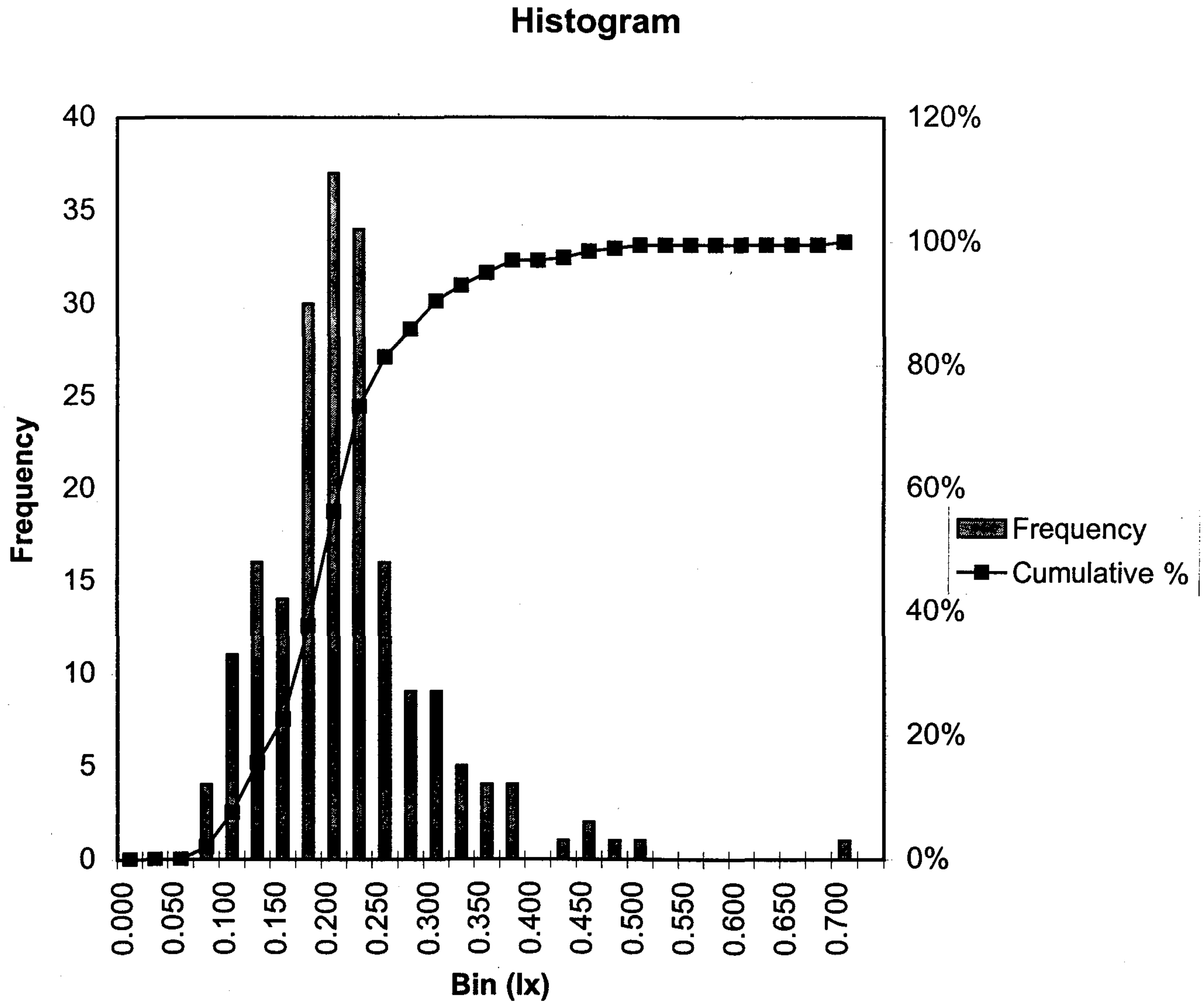


Bin (lx)	Frequency	Cumulative %
0.000	0	.00%
0.025	0	.00%
0.050	3	1.52%
0.075	19	11.11%
0.100	24	23.23%
0.125	46	46.46%
0.150	40	66.67%
0.175	31	82.32%
0.200	9	86.87%
0.225	6	89.90%
0.250	9	94.44%
0.275	1	94.95%
0.300	3	96.46%
0.325	2	97.47%
0.350	3	98.99%
0.375	0	98.99%
0.400	1	99.49%
0.425	0	99.49%
0.450	0	99.49%
0.475	0	99.49%
0.500	1	100.00%



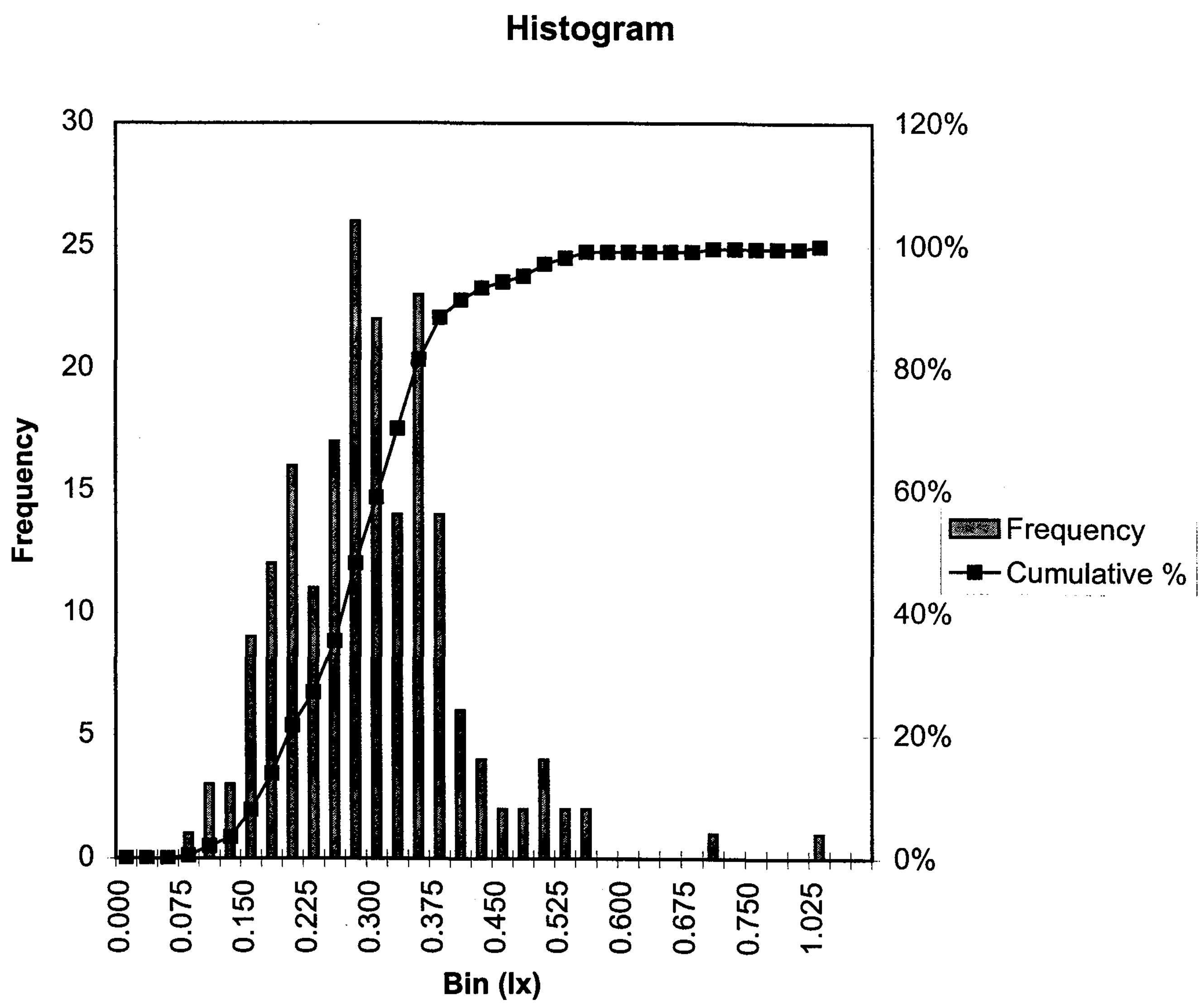
Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	0	.00%
0.050	0	.00%
0.075	4	2.01%
0.100	11	7.54%
0.125	16	15.58%
0.150	14	22.61%
0.175	30	37.69%
0.200	37	56.28%
0.225	34	73.37%
0.250	16	81.41%
0.275	9	85.93%
0.300	9	90.45%
0.325	5	92.96%
0.350	4	94.97%
0.375	4	96.98%
0.400	0	96.98%
0.425	1	97.49%
0.450	2	98.49%
0.475	1	98.99%
0.500	1	99.50%
0.525	0	99.50%
0.550	0	99.50%
0.575	0	99.50%
0.600	0	99.50%
0.625	0	99.50%
0.650	0	99.50%
0.675	0	99.50%
0.700	1	100.00%

Minolta Clear (right shoulder/2.12 m high) at 114 m



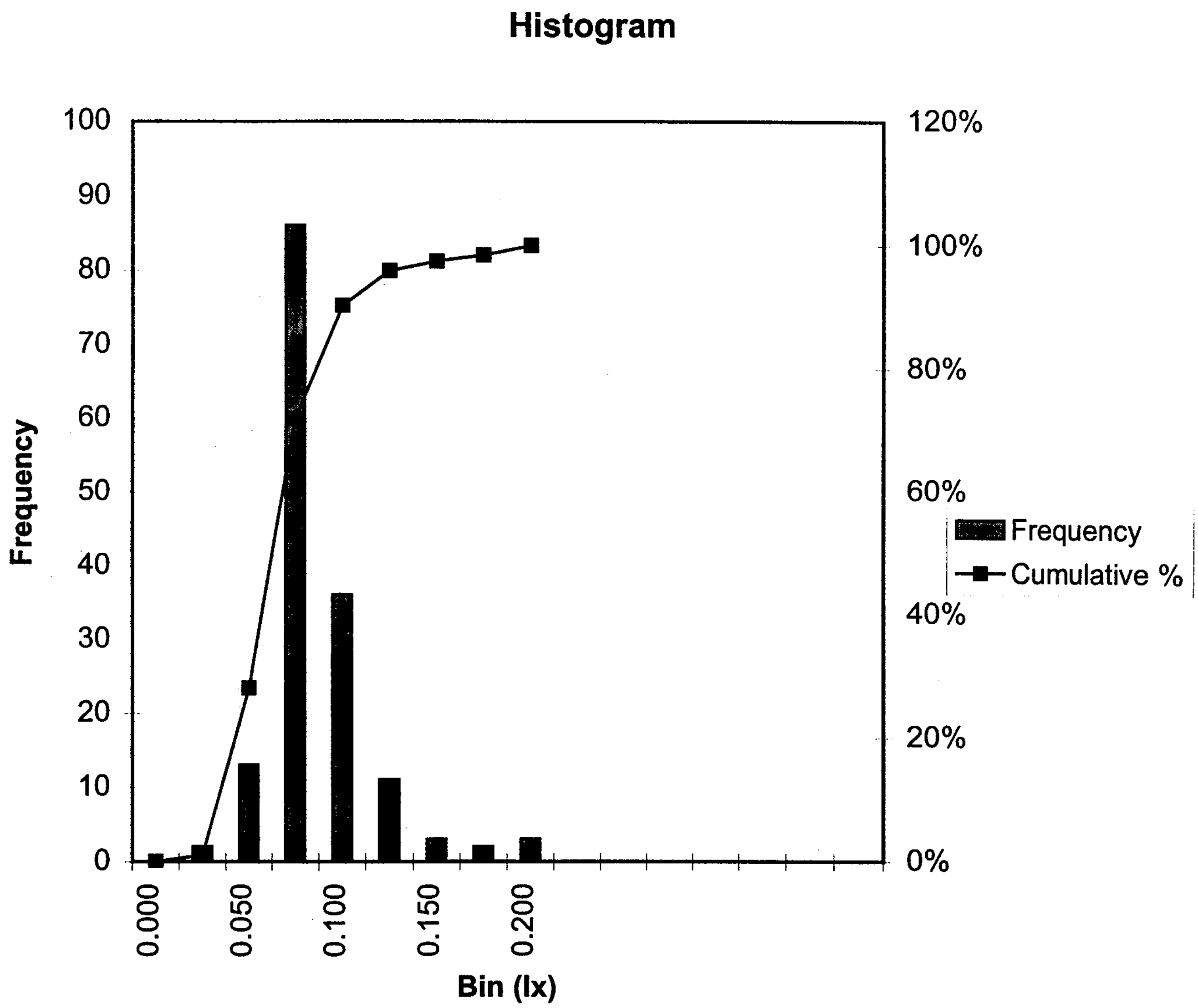
Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	0	.00%
0.050	0	.00%
0.075	1	.49%
0.100	3	1.96%
0.125	3	3.43%
0.150	9	7.84%
0.175	12	13.73%
0.200	16	21.57%
0.225	11	26.96%
0.250	17	35.29%
0.275	26	48.04%
0.300	22	58.82%
0.325	14	70.10%
0.350	23	81.37%
0.375	14	88.24%
0.400	6	91.18%
0.425	4	93.14%
0.450	2	94.12%
0.475	2	95.10%
0.500	4	97.06%
0.525	2	98.04%
0.550	2	99.02%
0.575	0	99.02%
0.600	0	99.02%
0.625	0	99.02%
0.650	0	99.02%
0.675	0	99.02%
0.700	1	99.51%
0.725	0	99.51%
0.750	0	99.51%
0.775	0	99.51%
0.800	0	99.51%
1.025	1	100.00%

Minolta Clear (right shoulder/2.12 m high) after 1.1s

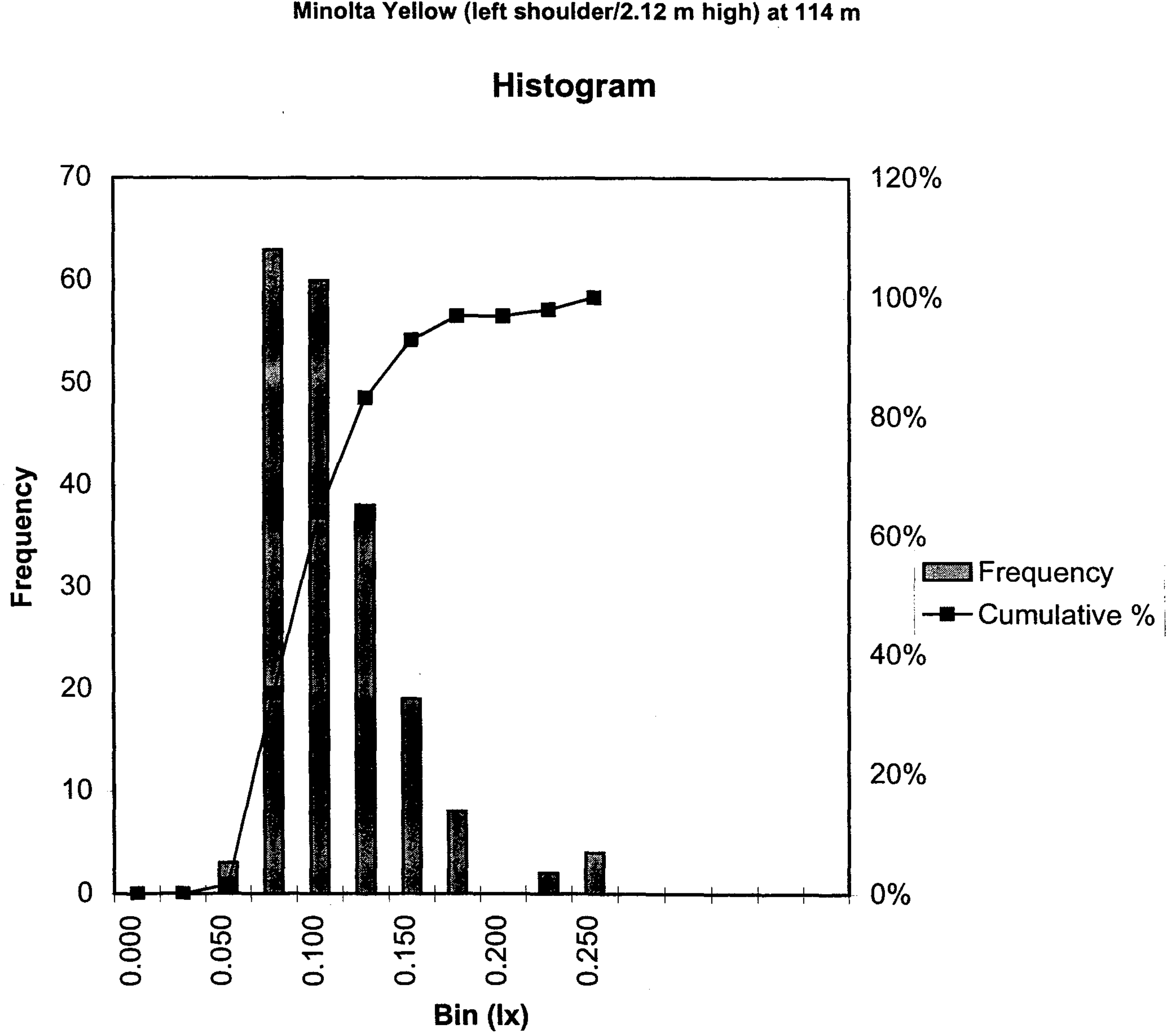


Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	2	1.02%
0.050	13	28.06%
0.075	86	71.94%
0.100	36	90.31%
0.125	11	95.92%
0.150	3	97.45%
0.175	2	98.47%
0.200	3	100.00%

Minolta Yellow (left shoulder/2.12 m high) at 152 m



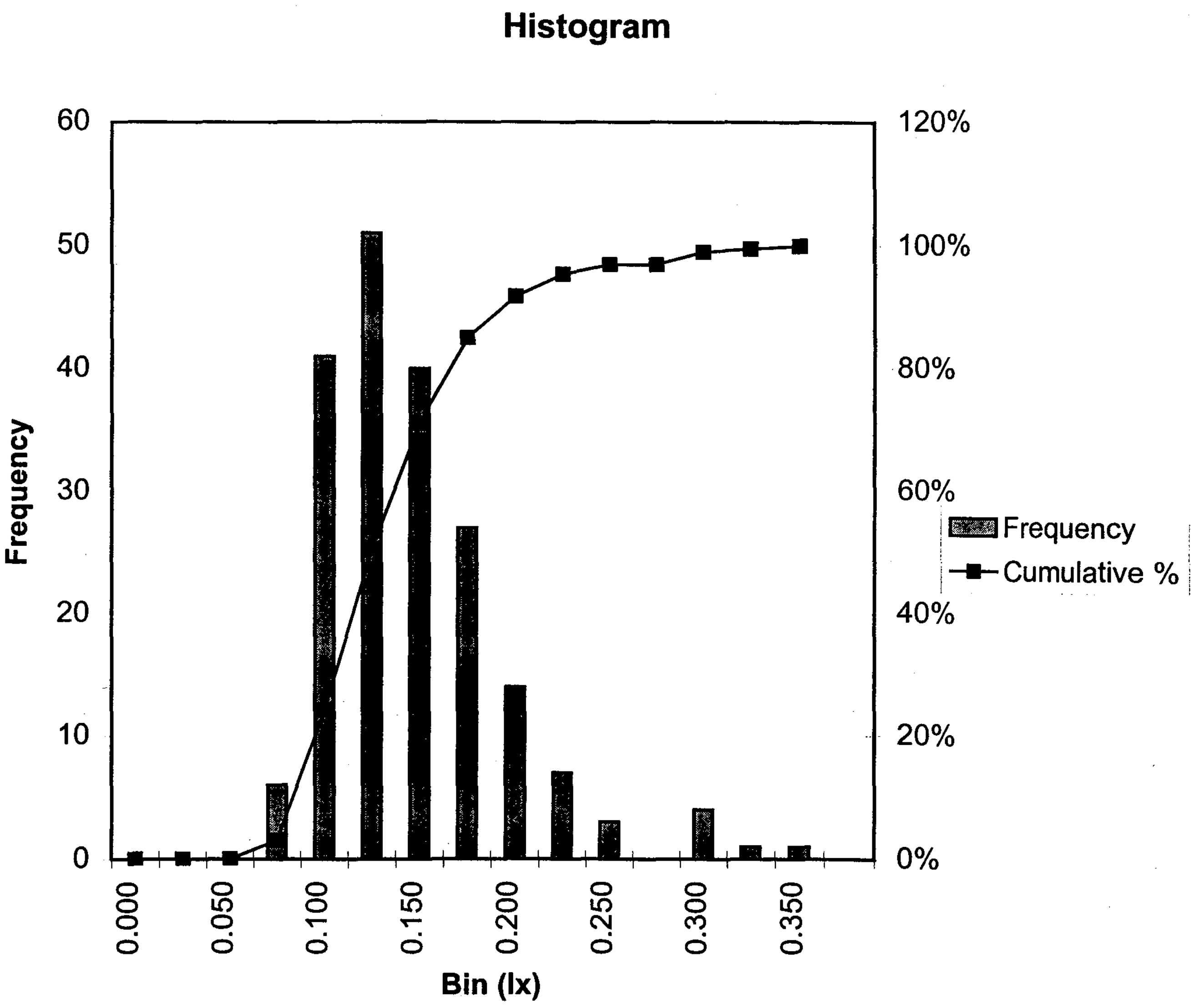
Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	0	.00%
0.050	3	1.52%
0.075	63	33.50%
0.100	60	63.96%
0.125	38	83.25%
0.150	19	92.89%
0.175	8	96.95%
0.200	0	96.95%
0.225	2	97.97%
0.250	4	100.00%


Minolta Yellow (left shoulder/2.12 m high) at 114 m

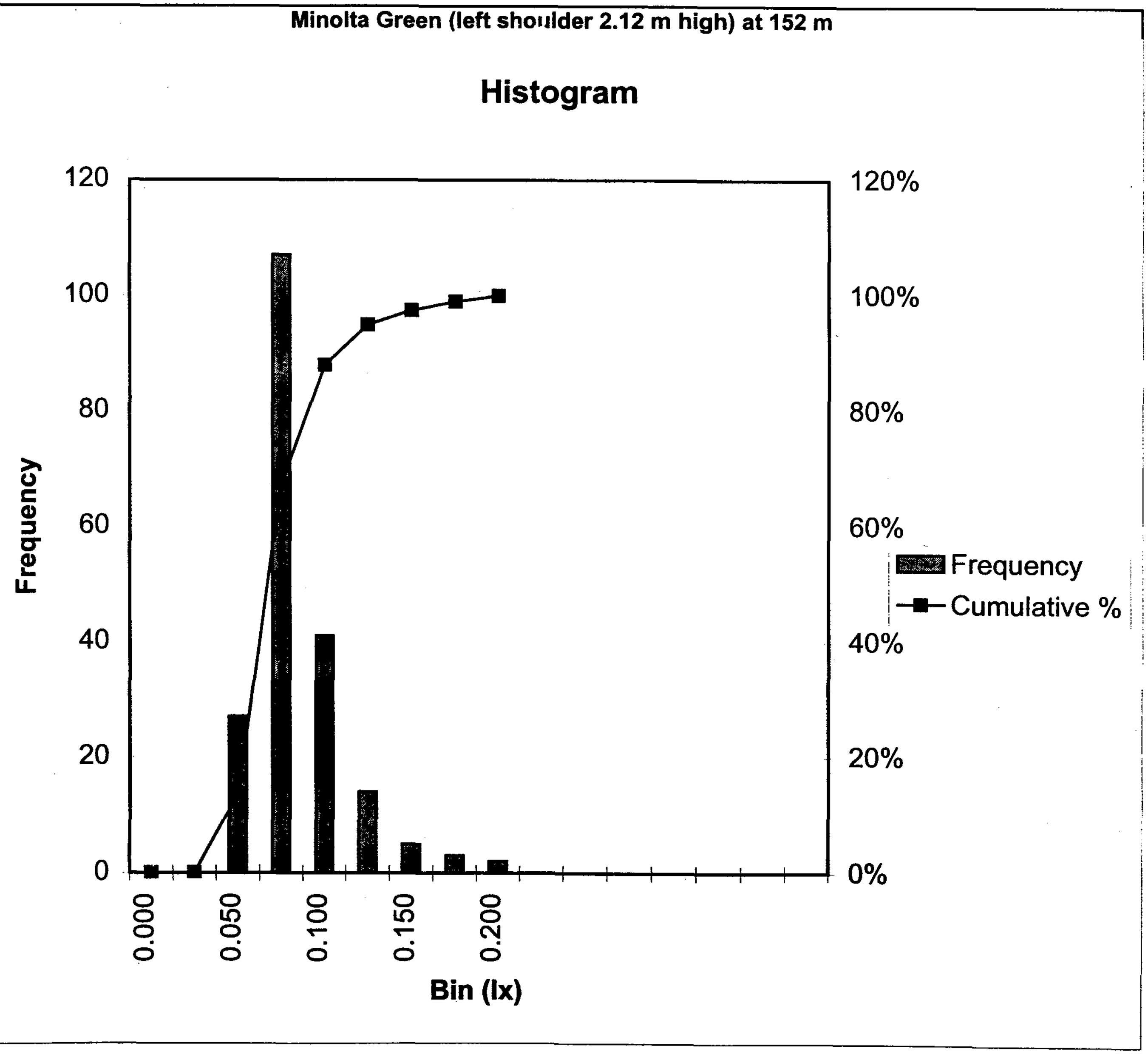
Histogram

Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	0	.00%
0.050	0	.00%
0.075	6	3.09%
0.100	41	24.23%
0.125	51	50.52%
0.150	40	71.13%
0.175	27	85.05%
0.200	14	91.75%
0.225	7	95.36%
0.250	3	96.91%
0.275	0	96.91%
0.300	4	98.97%
0.325	1	99.49%
0.350	1	100.00%

Minolta Yellow (left shoulder/2.12 m high) after 1.1s



Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	0	.00%
0.050	27	13.57%
0.075	107	67.34%
0.100	41	87.94%
0.125	14	94.97%
0.150	5	97.49%
0.175	3	98.99%
0.200	2	100.00%

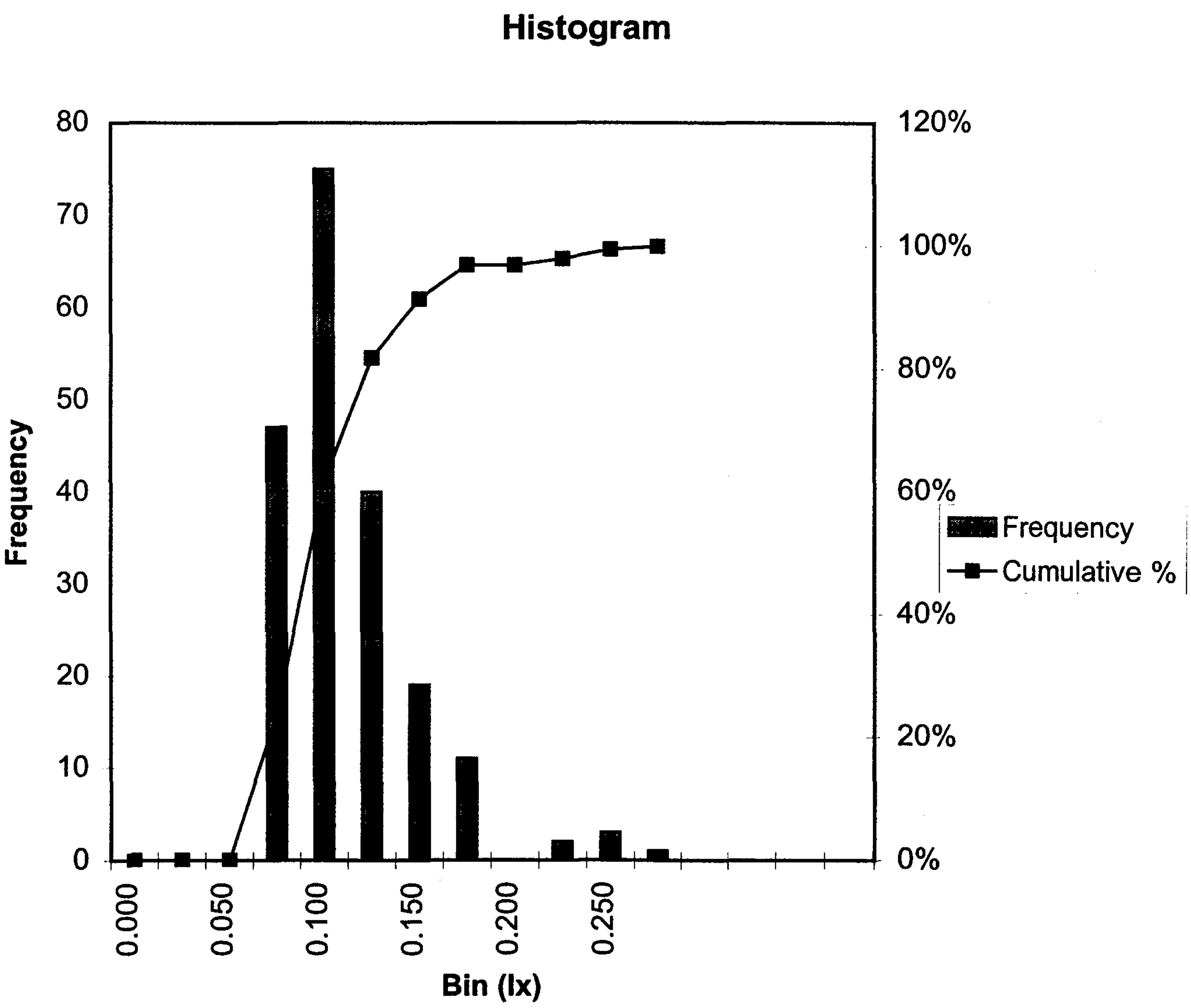


Minolta Green (left shoulder 2.12 m high) at 152 m

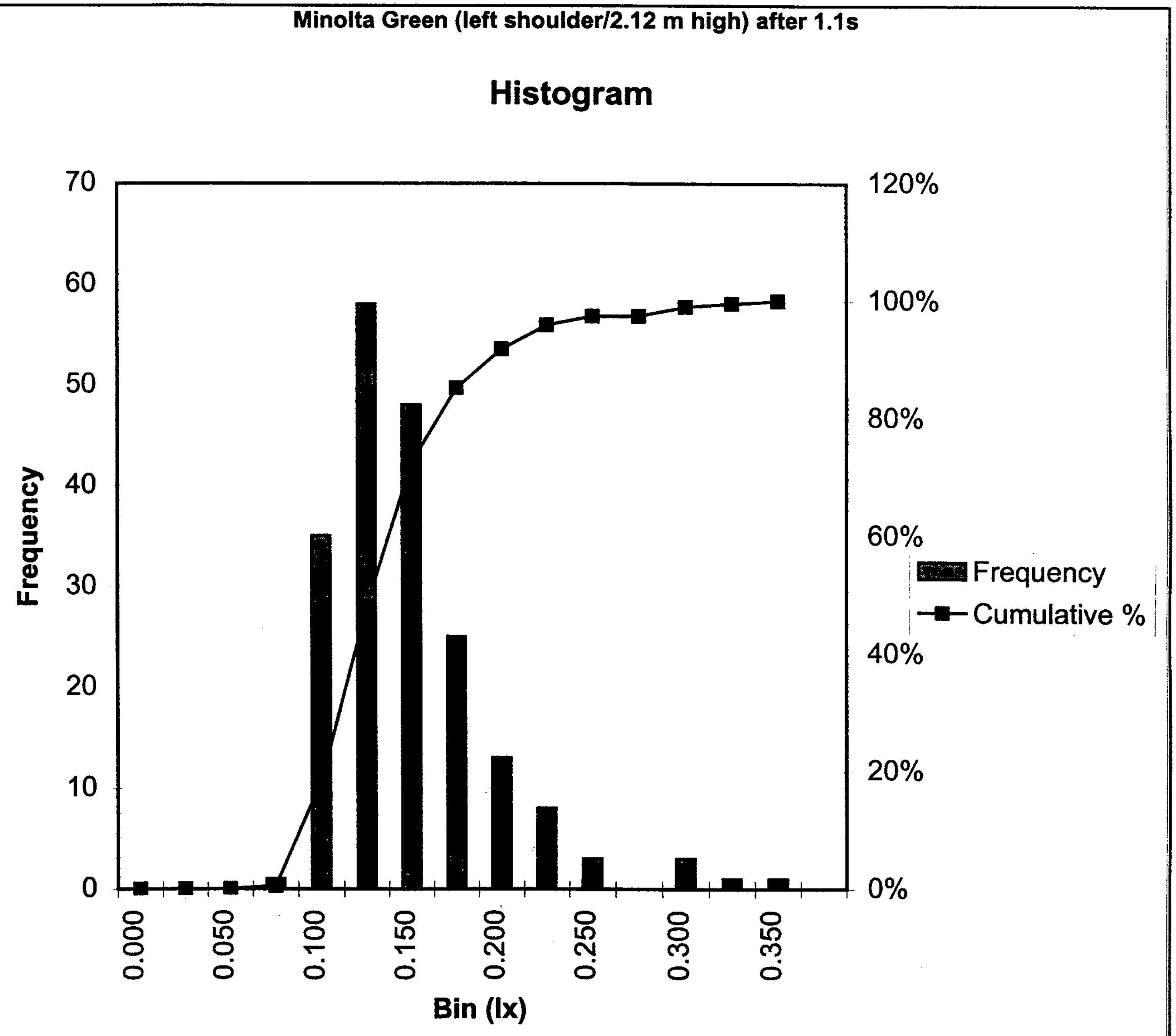
Histogram

Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	0	.00%
0.050	0	.00%
0.075	47	23.74%
0.100	75	61.62%
0.125	40	81.82%
0.150	19	91.41%
0.175	11	96.97%
0.200	0	96.97%
0.225	2	97.98%
0.250	3	99.49%
0.275	1	100.00%

Minolta Green (left shoulder/2.12 m high) at 114 m

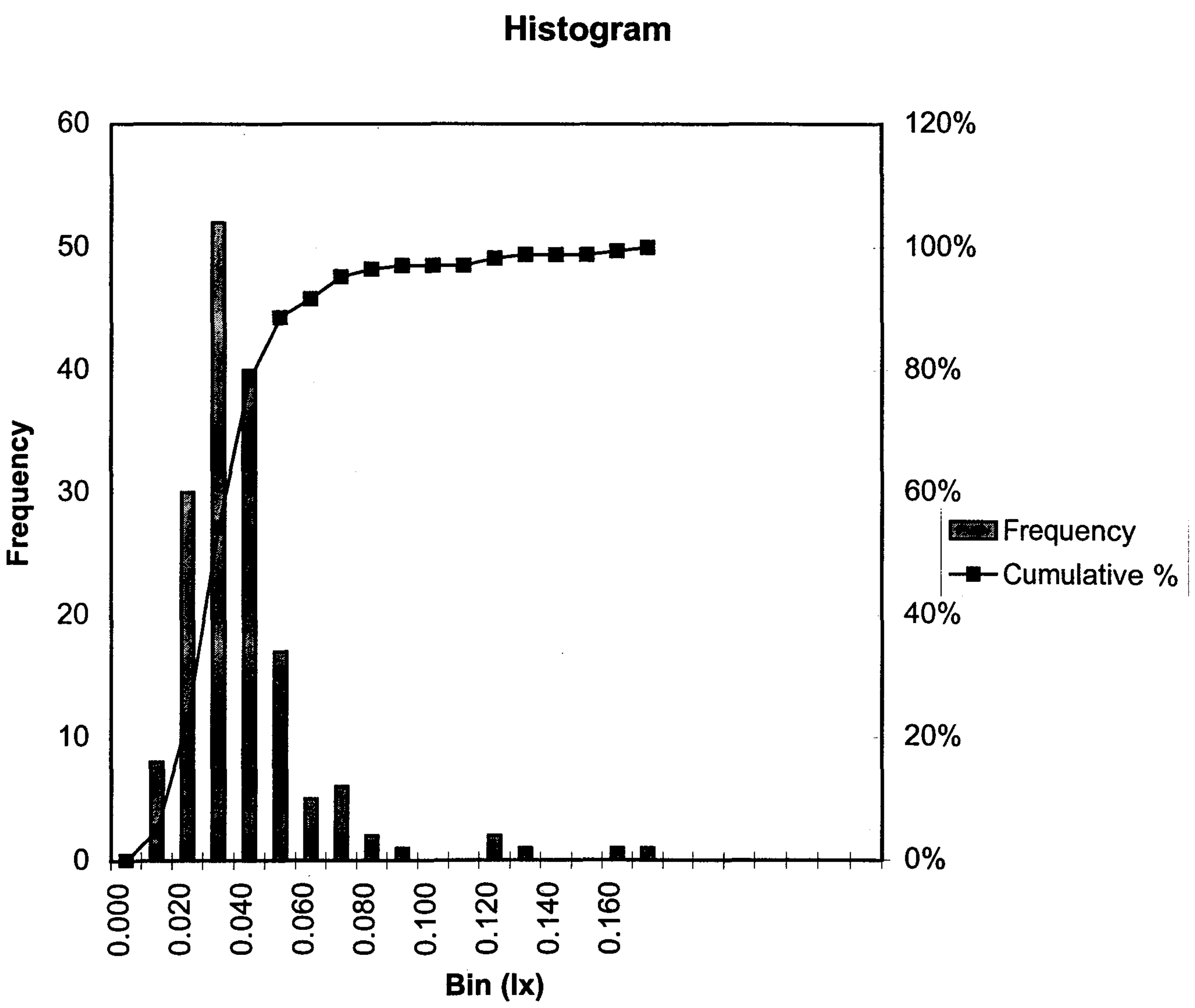


Bin (lx)	*Frequency*	*Cumulative %*
0.000	0	.00%
0.025	0	.00%
0.050	0	.00%
0.075	1	.51%
0.100	35	18.37%
0.125	58	47.96%
0.150	48	72.45%
0.175	25	85.20%
0.200	13	91.84%
0.225	8	95.92%
0.250	3	97.45%
0.275	0	97.45%
0.300	3	98.98%
0.325	1	99.49%
0.350	1	100.00%



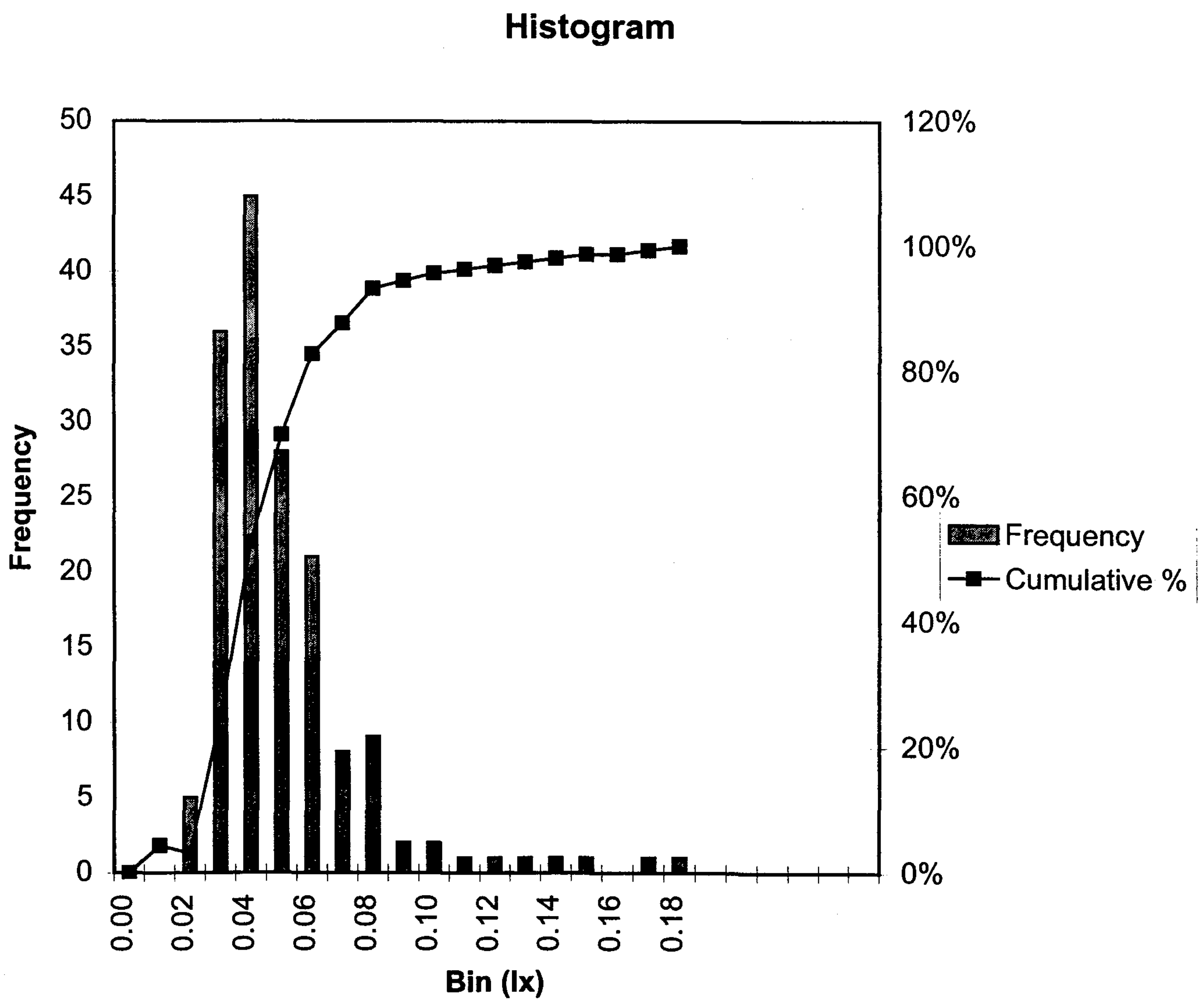
Bin (lx)	*Frequency*	*Cumulative %*
0.00	0	.00%
0.01	8	4.82%
0.02	30	22.89%
0.03	52	54.22%
0.04	40	78.31%
0.05	17	88.55%
0.06	5	91.57%
0.07	6	95.18%
0.08	2	96.39%
0.09	1	96.99%
0.10	0	96.99%
0.11	0	96.99%
0.12	2	98.19%
0.13	1	98.80%
0.14	0	98.80%
0.15	0	98.80%
0.16	1	99.40%
0.17	1	100.00%

IL 1700 #1 (above the right lane/7.62 m high) at 152 m



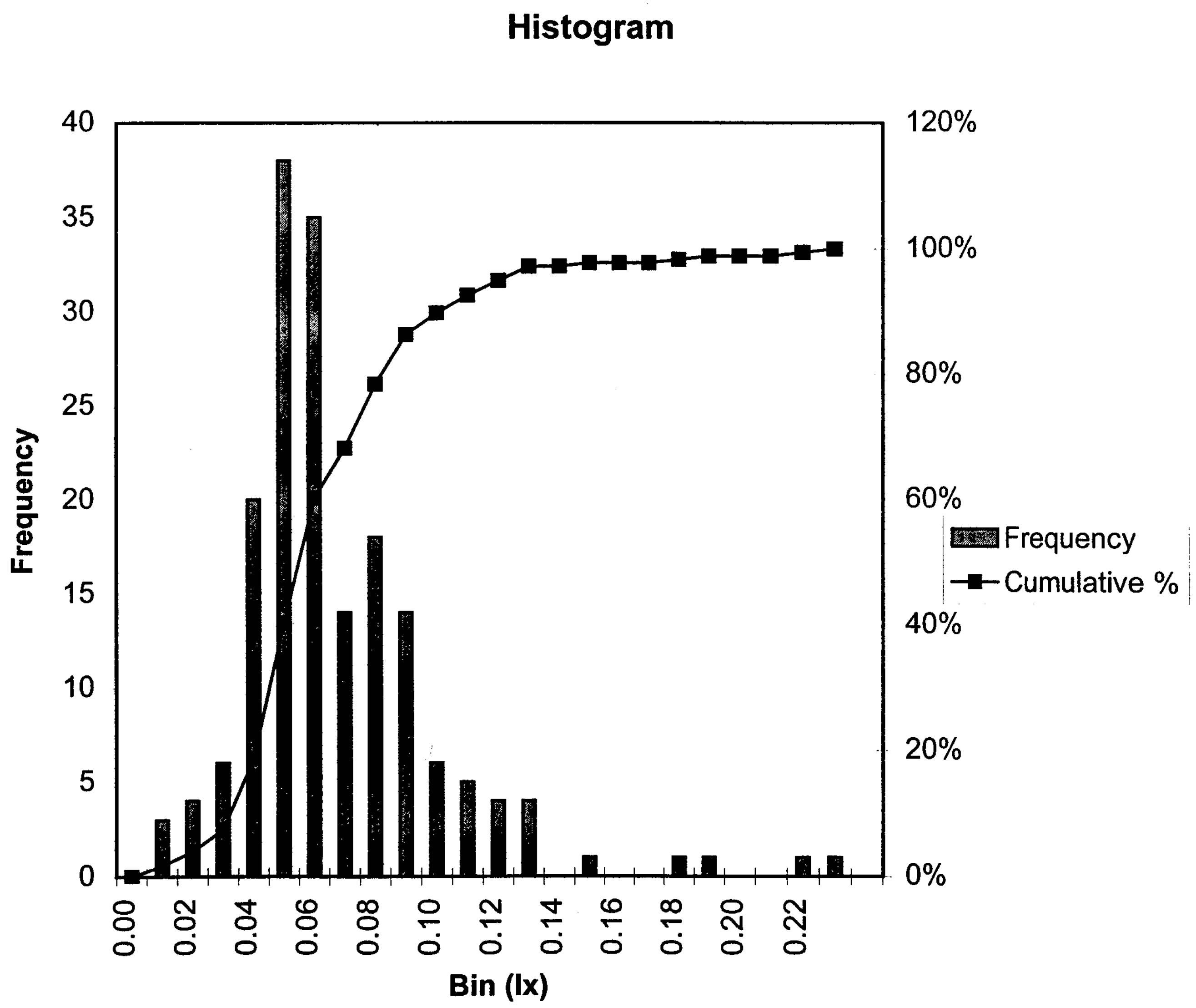
Bin (lx)	*Frequency*	*Cumulative %*
0.00	0	.00%
0.01	0	4.35%
0.02	5	3.07%
0.03	36	25.15%
0.04	45	52.76%
0.05	28	69.94%
0.06	21	82.82%
0.07	8	87.73%
0.08	9	93.25%
0.09	2	94.48%
0.10	2	95.71%
0.11	1	96.32%
0.12	1	96.93%
0.13	1	97.55%
0.14	1	98.16%
0.15	1	98.77%
0.16	0	98.77%
0.17	1	99.39%
0.18	1	100.00%

IL 1700 #1 (above the right lane/7.62 m high) at 114 m



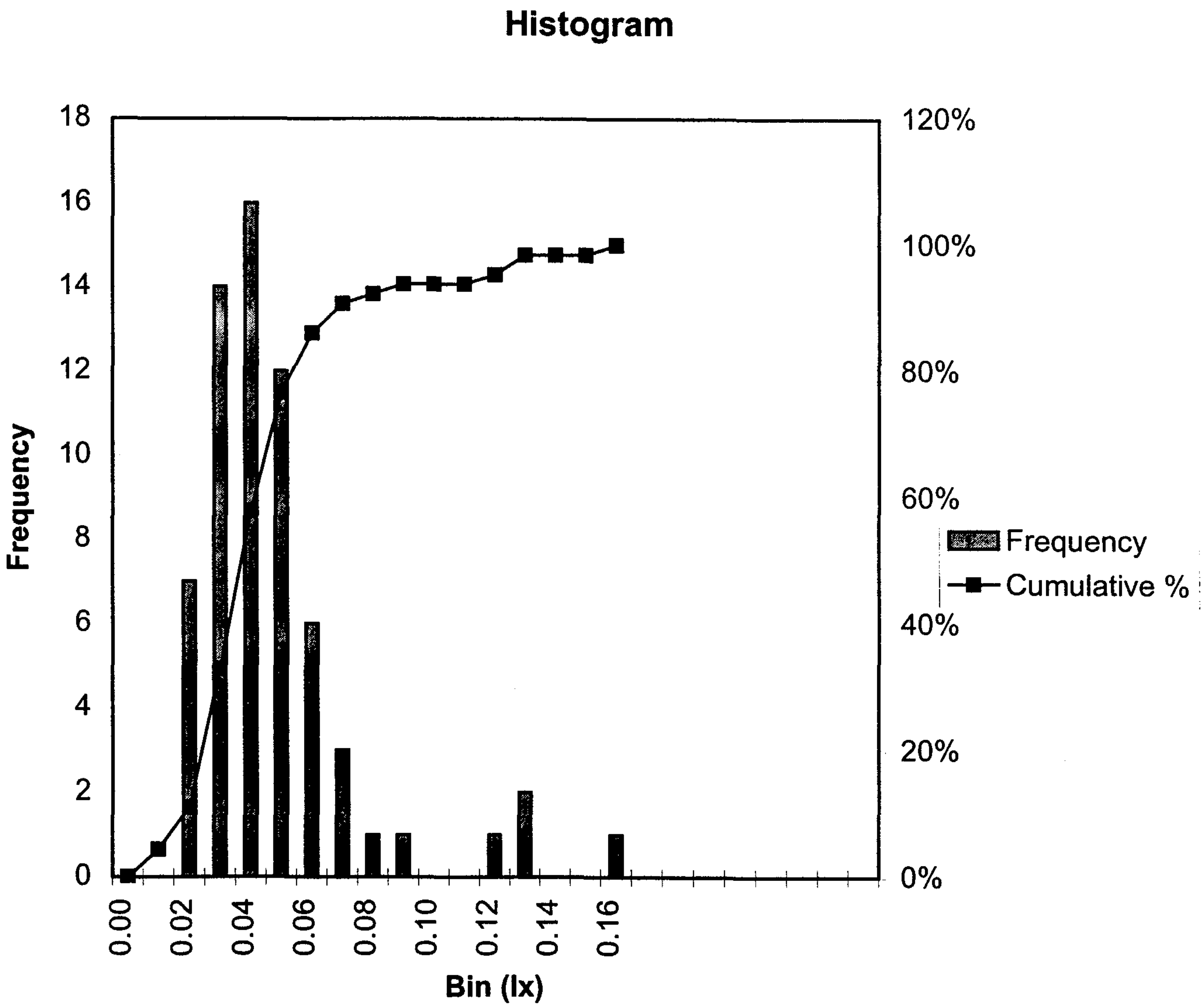
Bin (lx)	*Frequency*	*Cumulative %*
0.00	0	.00%
0.01	3	1.70%
0.02	4	3.98%
0.03	6	7.39%
0.04	20	18.75%
0.05	38	40.34%
0.06	35	60.23%
0.07	14	68.18%
0.08	18	78.41%
0.09	14	86.36%
0.10	6	89.77%
0.11	5	92.61%
0.12	4	94.89%
0.13	4	97.16%
0.14	0	97.16%
0.15	1	97.73%
0.16	0	97.73%
0.17	0	97.73%
0.18	1	98.30%
0.19	1	98.86%
0.20	0	98.86%
0.21	0	98.86%
0.22	1	99.43%
0.23	1	100.00%

IL 1700 #1 (above the right lane/7.62 m high) after 1.1s



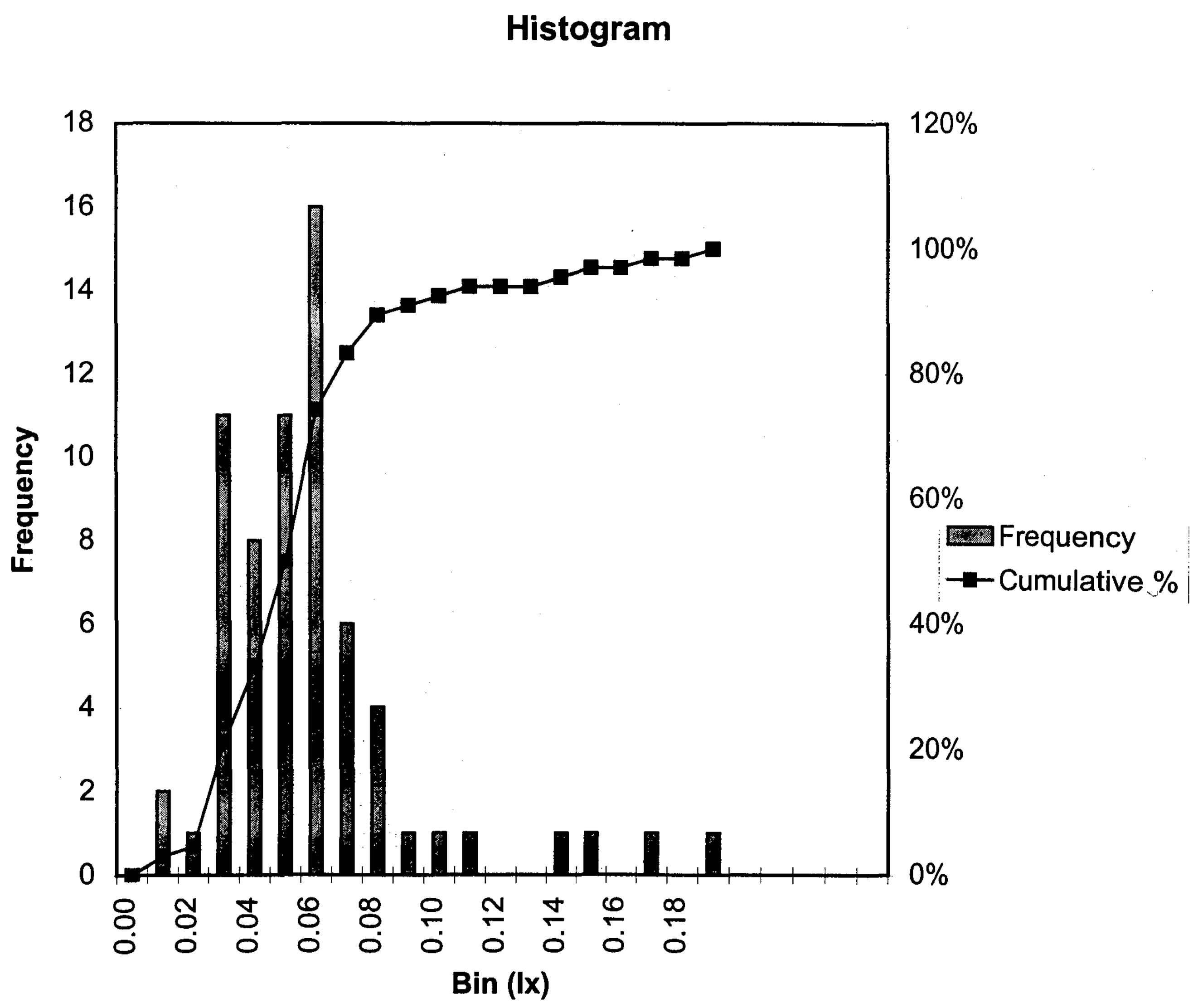
Bin (lx)	*Frequency*	*Cumulative %*
0.00	0	.00%
0.01	0	4.35%
0.02	7	10.94%
0.03	14	32.81%
0.04	16	57.81%
0.05	12	76.56%
0.06	6	85.94%
0.07	3	90.63%
0.08	1	92.19%
0.09	1	93.75%
0.10	0	93.75%
0.11	0	93.75%
0.12	1	95.31%
0.13	2	98.44%
0.14	0	98.44%
0.15	0	98.44%
0.16	1	100.00%

IL 1700 #2 (above the right lane/7.62 m high) at 152 m

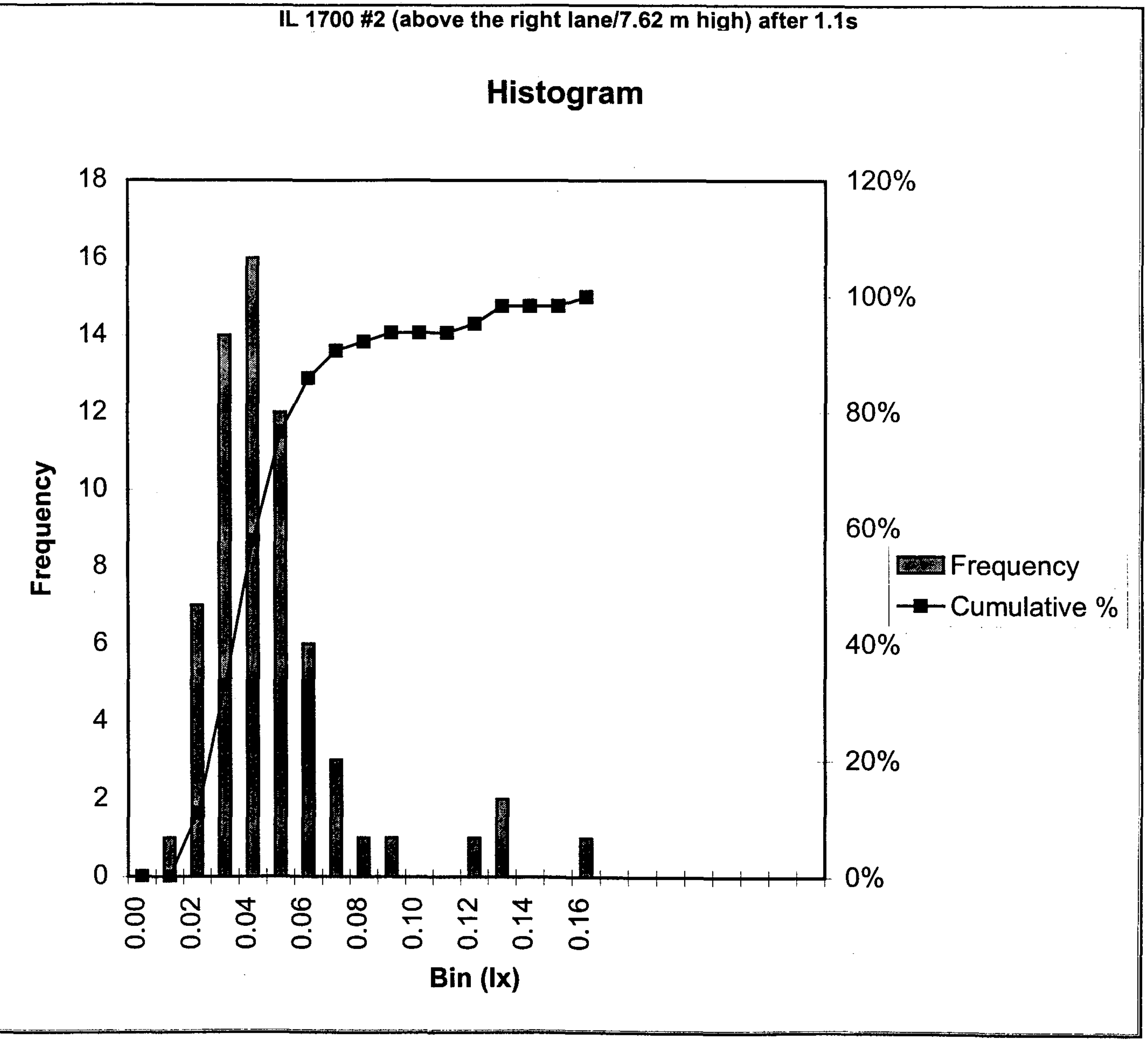


Bin (lx)	*Frequency*	*Cumulative %*
0.00	0	.00%
0.01	2	3.03%
0.02	1	4.55%
0.03	11	21.21%
0.04	8	33.33%
0.05	11	50.00%
0.06	16	74.24%
0.07	6	83.33%
0.08	4	89.39%
0.09	1	90.91%
0.10	1	92.42%
0.11	1	93.94%
0.12	0	93.94%
0.13	0	93.94%
0.14	1	95.45%
0.15	1	96.97%
0.16	0	96.97%
0.17	1	98.48%
0.18	0	98.48%
0.19	1	100.00%

IL 1700 #2 (above the right lane/7.62 m high) at 114 m



Bin (lx)	*Frequency*	*Cumulative %*
0.00	0	.00%
0.01	1	.00%
0.02	7	10.94%
0.03	14	32.81%
0.04	16	57.81%
0.05	12	76.56%
0.06	6	85.94%
0.07	3	90.63%
0.08	1	92.19%
0.09	1	93.75%
0.10	0	93.75%
0.11	0	93.75%
0.12	1	95.31%
0.13	2	98.44%
0.14	0	98.44%
0.15	0	98.44%
0.16	1	100.00%

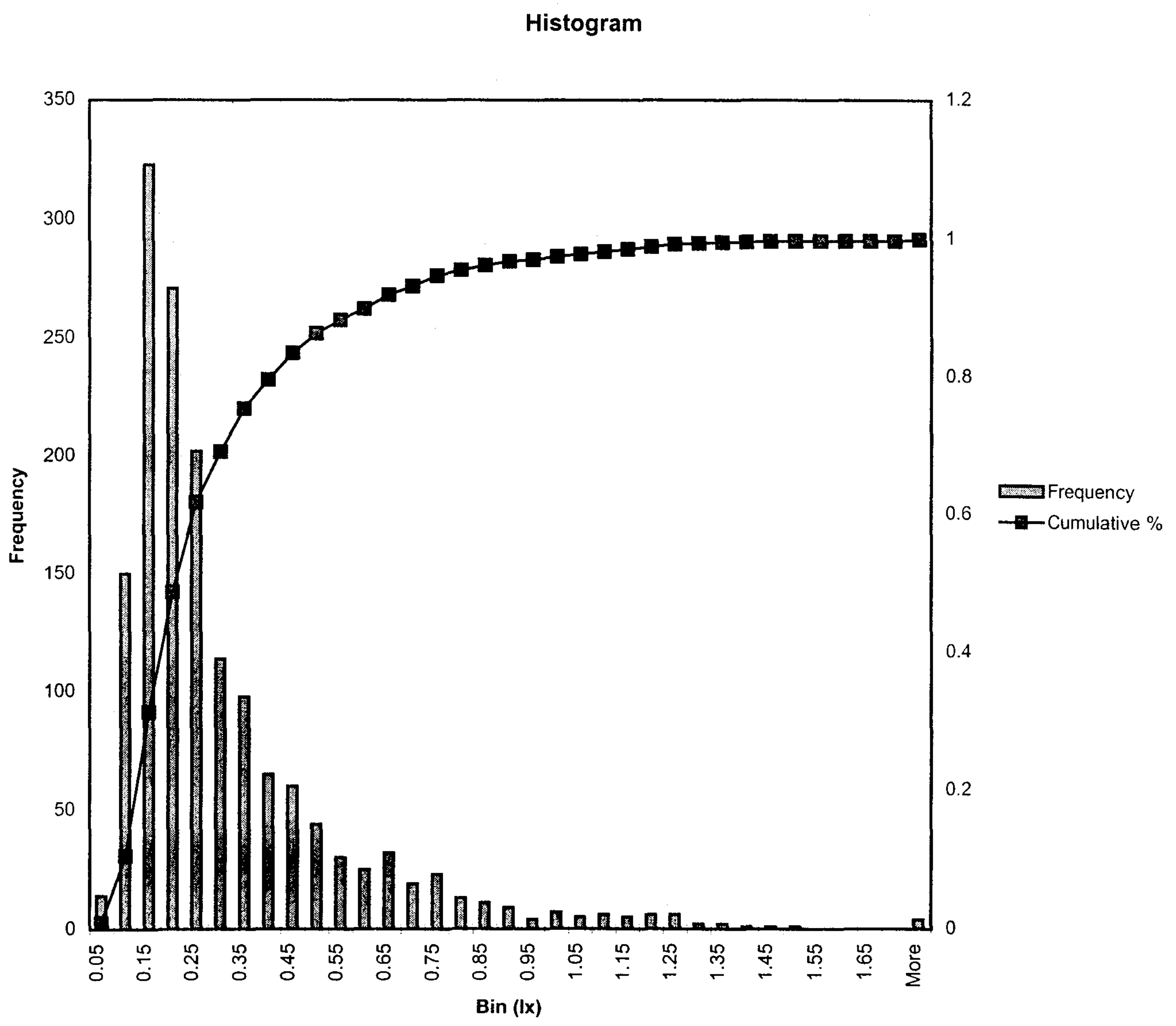


APPENDIX E

HISTOGRAMS
FOR 1,500 UNKNOWN CARS

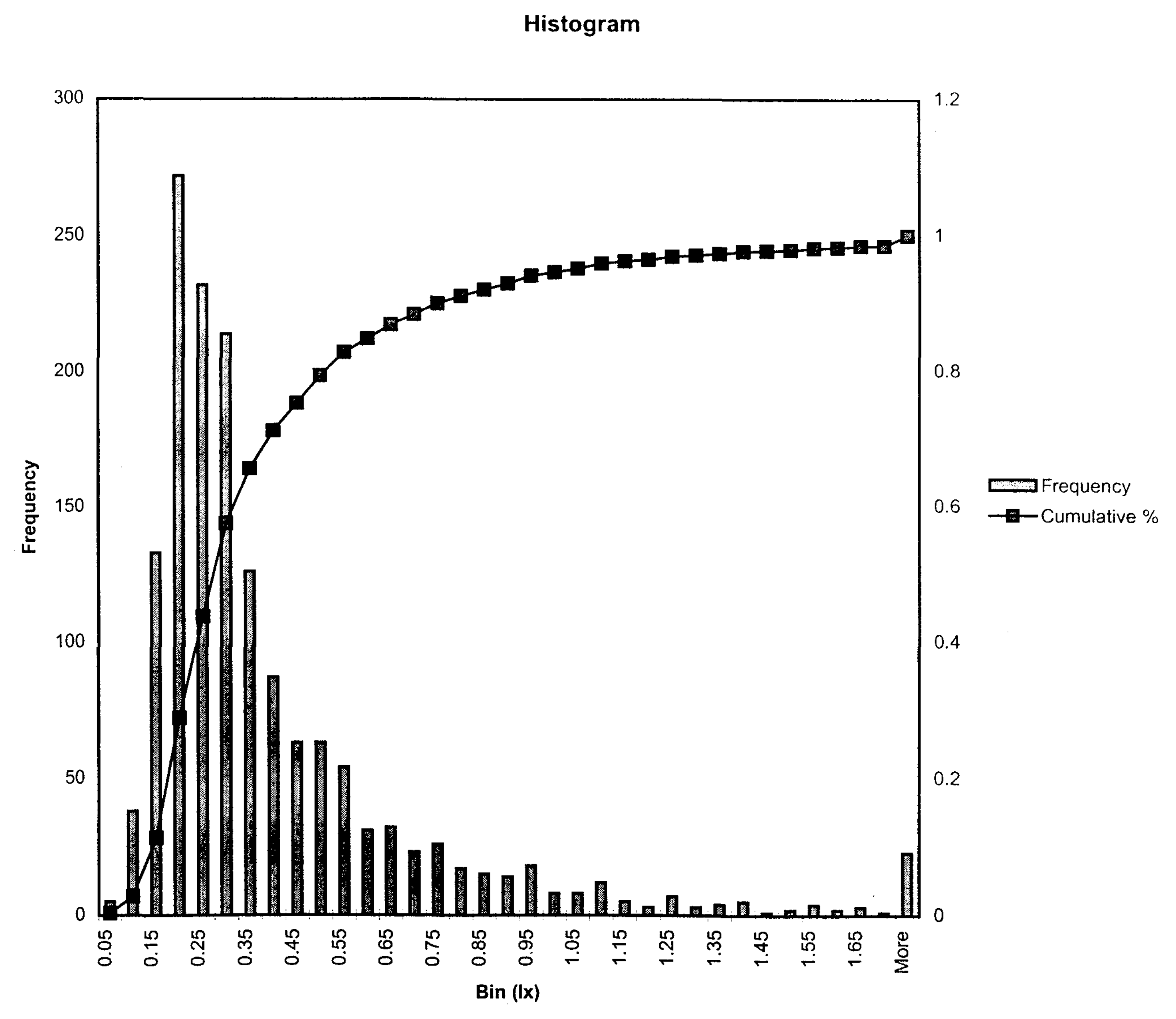
Bin (lx)	*Frequency*	*Cumulative %*
0.05	14	.90%
0.1	150	10.56%
0.15	323	31.36%
0.2	271	48.81%
0.25	202	61.82%
0.3	114	69.16%
0.35	98	75.47%
0.4	65	79.65%
0.45	60	83.52%
0.5	44	86.35%
0.55	30	88.28%
0.6	25	89.89%
0.65	32	91.95%
0.7	19	93.17%
0.75	23	94.66%
0.8	13	95.49%
0.85	11	96.20%
0.9	9	96.78%
0.95	4	97.04%
1	7	97.49%
1.05	5	97.81%
1.1	6	98.20%
1.15	5	98.52%
1.2	6	98.91%
1.25	6	99.29%
1.3	2	99.42%
1.35	2	99.55%
1.4	1	99.61%
1.45	1	99.68%
1.5	1	99.74%
1.55	0	99.74%
1.6	0	99.74%
1.65	0	99.74%
1.7	0	99.74%
More	4	100.00%

Minolta Blue (right shoulder/2.12 m high) at 152 m



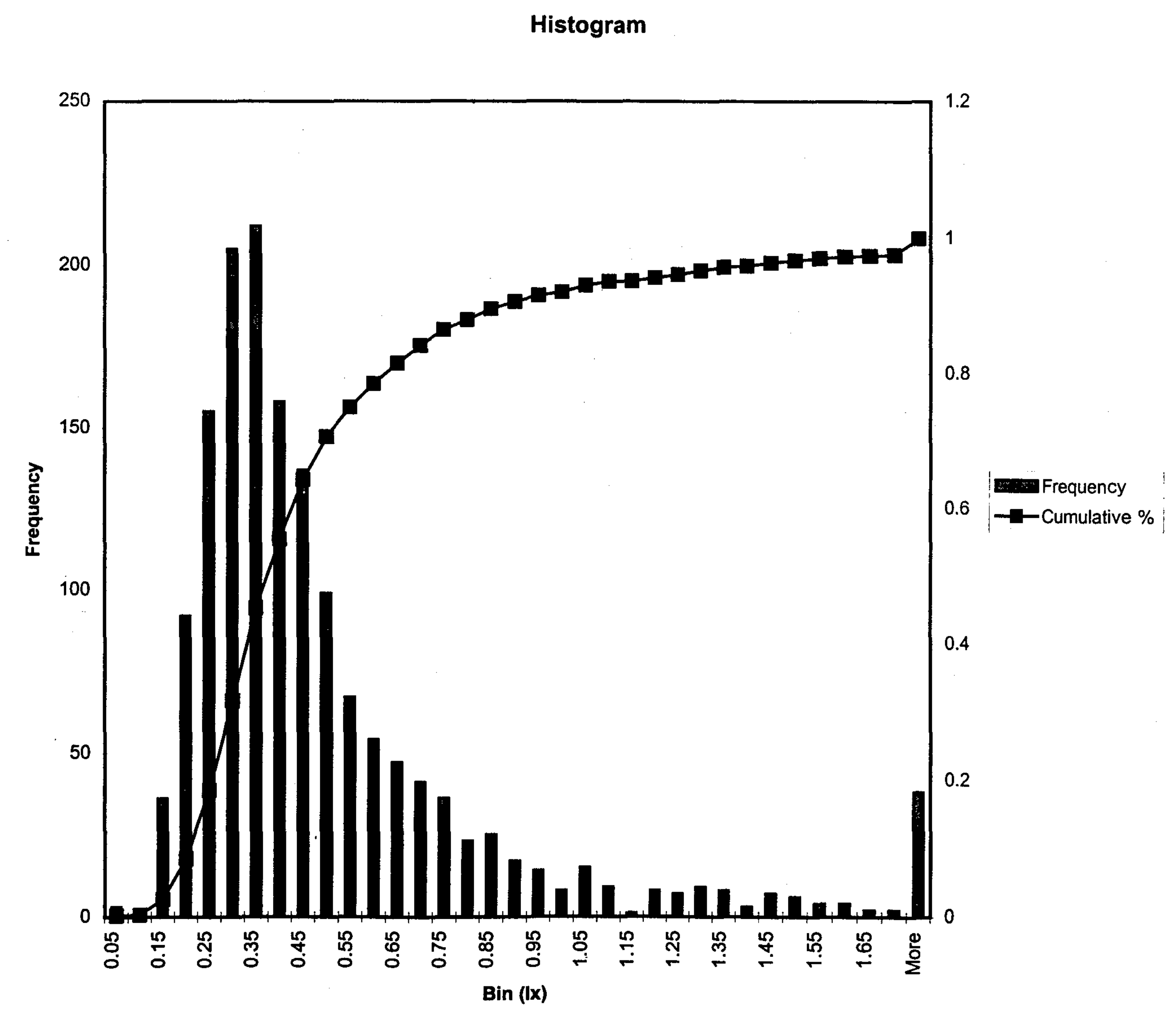
Minolta Blue (right shoulder/2.12 m high) at 114 m

Bin (lx)	*Frequency*	*Cumulative %*
0.05	5	.32%
0.1	38	2.77%
0.15	133	11.33%
0.2	272	28.83%
0.25	232	43.76%
0.3	214	57.53%
0.35	126	65.64%
0.4	87	71.24%
0.45	63	75.29%
0.5	63	79.34%
0.55	54	82.82%
0.6	31	84.81%
0.65	32	86.87%
0.7	23	88.35%
0.75	26	90.03%
0.8	17	91.12%
0.85	15	92.08%
0.9	14	92.99%
0.95	18	94.14%
1	8	94.66%
1.05	8	95.17%
1.1	12	95.95%
1.15	5	96.27%
1.2	3	96.46%
1.25	7	96.91%
1.3	3	97.10%
1.35	4	97.36%
1.4	5	97.68%
1.45	1	97.75%
1.5	2	97.88%
1.55	4	98.13%
1.6	2	98.26%
1.65	3	98.46%
1.7	1	98.52%
More	23	100.00%



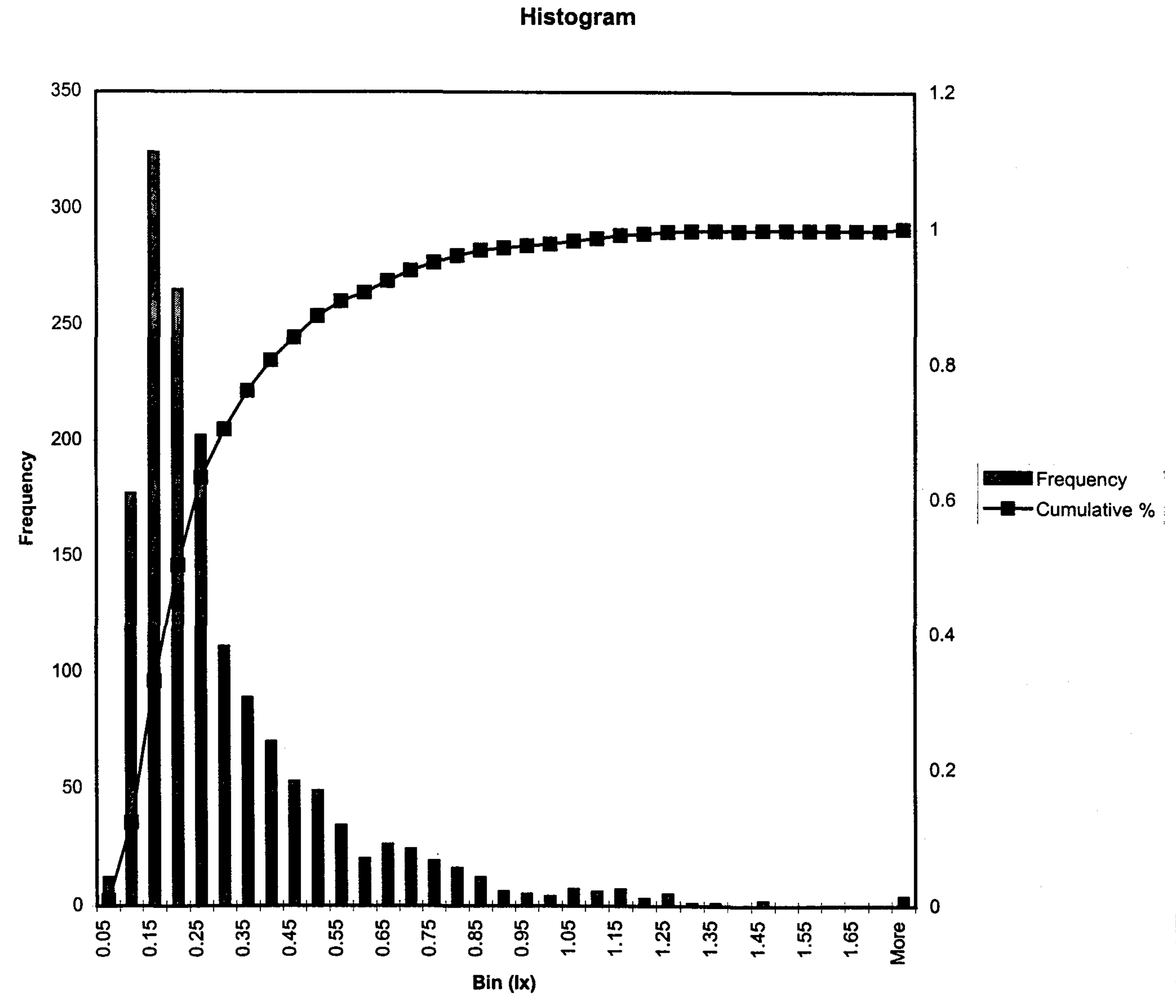
Bin (lx)	*Frequency*	*Cumulative %*
0.05	3	.19%
0.1	2	.32%
0.15	36	2.64%
0.2	92	8.56%
0.25	155	18.53%
0.3	205	31.72%
0.35	212	45.37%
0.4	158	55.53%
0.45	137	64.35%
0.5	99	70.72%
0.55	67	75.03%
0.6	54	78.51%
0.65	47	81.53%
0.7	41	84.17%
0.75	36	86.49%
0.8	23	87.97%
0.85	25	89.58%
0.9	17	90.67%
0.95	14	91.57%
1	8	92.08%
1.05	15	93.05%
1.1	9	93.63%
1.15	1	93.69%
1.2	8	94.21%
1.25	7	94.66%
1.3	9	95.24%
1.35	8	95.75%
1.4	3	95.95%
1.45	7	96.40%
1.5	6	96.78%
1.55	4	97.04%
1.6	4	97.30%
1.65	2	97.43%
1.7	2	97.55%
More	38	100.00%

Minolta Blue (right shoulder/2.12 m high) after 1.1s



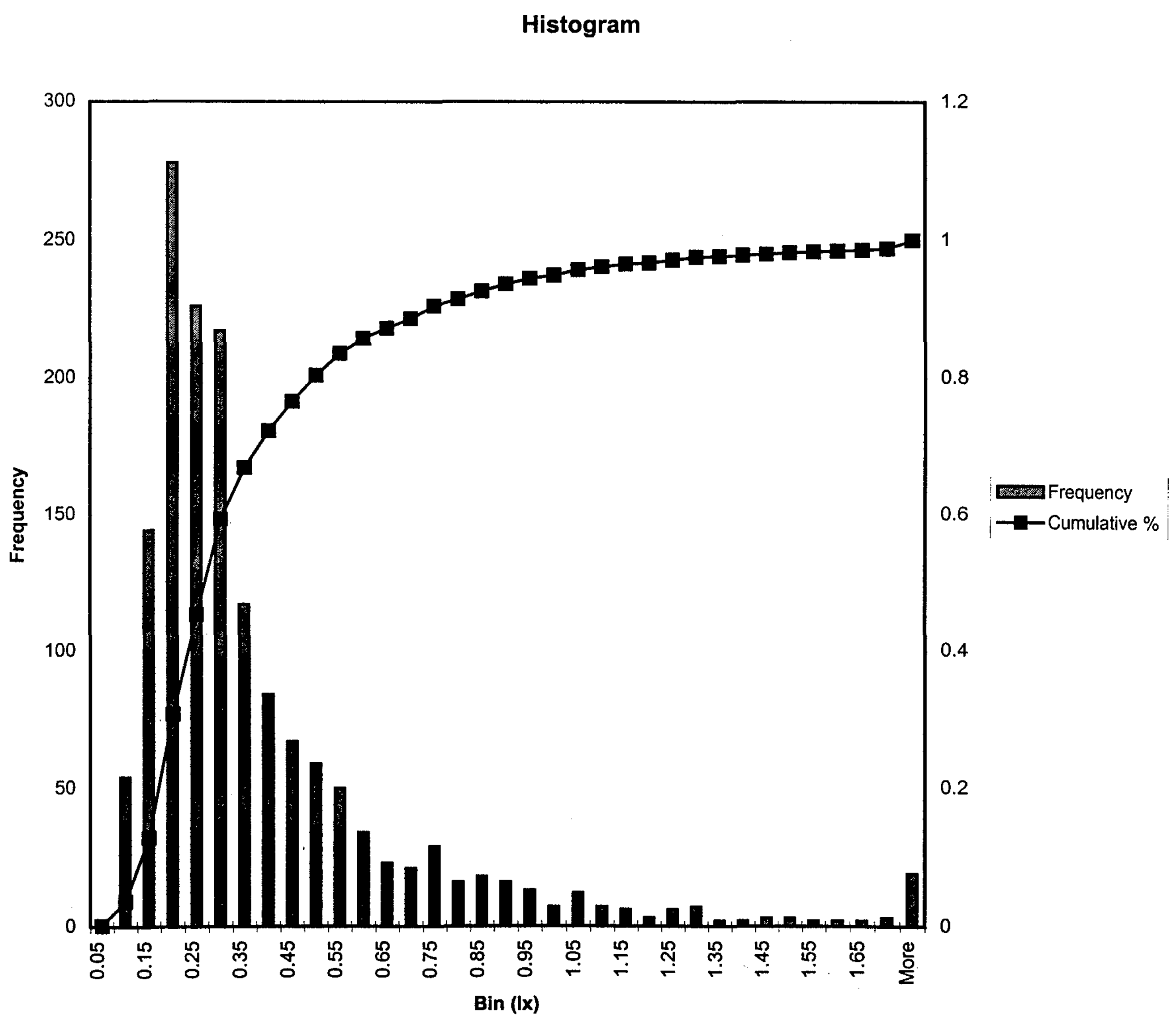
Minolta Clear (right shoulder/2.12 m high) at 152 m

Bin (lx)	*Frequency*	*Cumulative %*
0.05	12	.77%
0.1	177	12.16%
0.15	324	33.01%
0.2	265	50.06%
0.25	202	63.06%
0.3	111	70.21%
0.35	89	75.93%
0.4	70	80.44%
0.45	53	83.85%
0.5	49	87.00%
0.55	34	89.19%
0.6	20	90.48%
0.65	26	92.15%
0.7	24	93.69%
0.75	19	94.92%
0.8	16	95.95%
0.85	12	96.72%
0.9	6	97.10%
0.95	5	97.43%
1	4	97.68%
1.05	7	98.13%
1.1	6	98.52%
1.15	7	98.97%
1.2	3	99.16%
1.25	5	99.49%
1.3	1	99.55%
1.35	1	99.61%
1.4	0	99.61%
1.45	2	99.74%
1.5	0	99.74%
1.55	0	99.74%
1.6	0	99.74%
1.65	0	99.74%
1.7	0	99.74%
More	4	100.00%



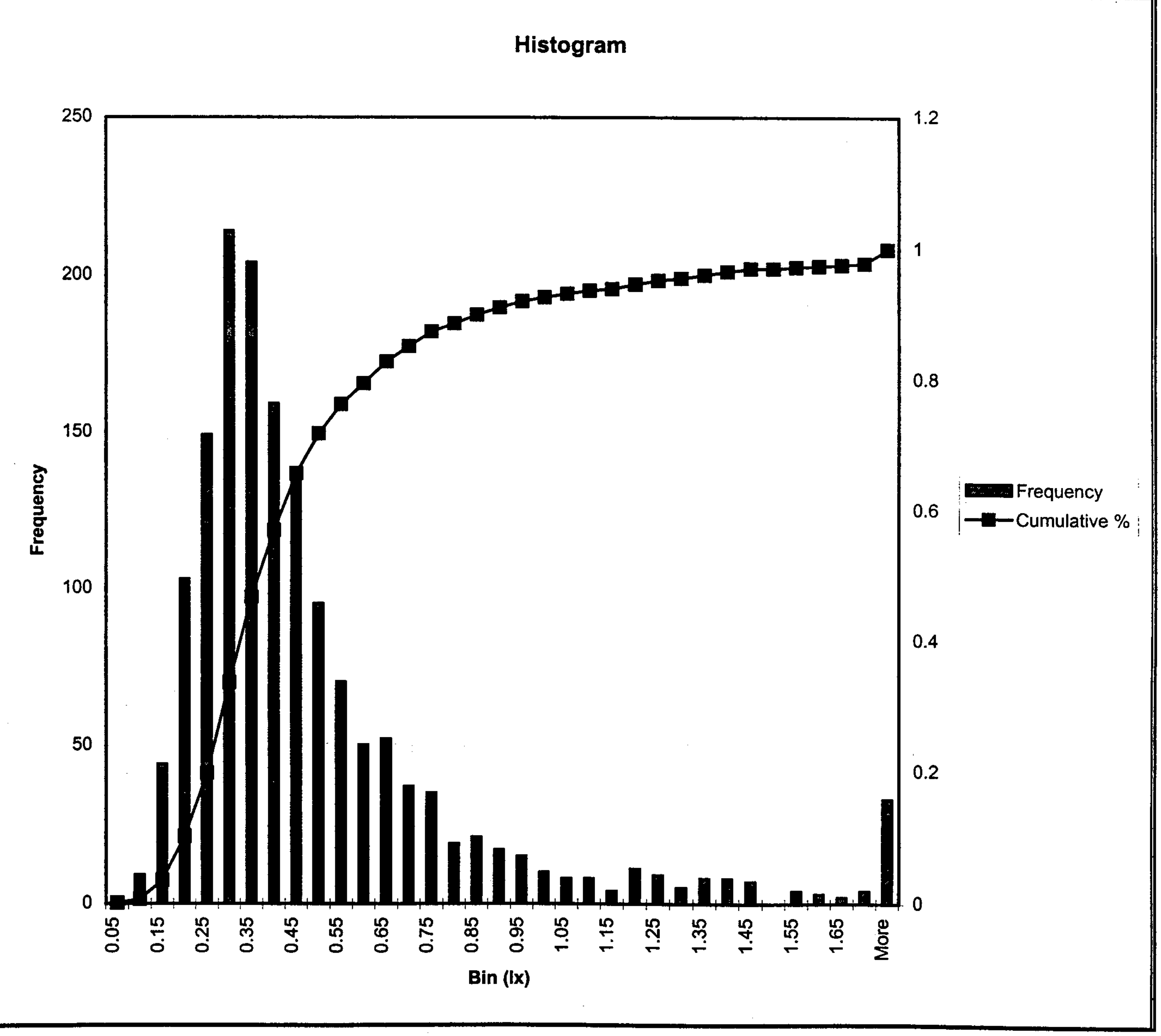
Minolta Clear (right shoulder/2.12 m high) at 114 m

Bin (lx)	*Frequency*	*Cumulative %*
0.05	2	.13%
0.1	54	3.60%
0.15	144	12.87%
0.2	278	30.76%
0.25	226	45.30%
0.3	217	59.27%
0.35	117	66.80%
0.4	84	72.20%
0.45	67	76.51%
0.5	59	80.31%
0.55	50	83.53%
0.6	34	85.71%
0.65	23	87.19%
0.7	21	88.55%
0.75	29	90.41%
0.8	16	91.44%
0.85	18	92.60%
0.9	16	93.63%
0.95	13	94.47%
1	7	94.92%
1.05	12	95.69%
1.1	7	96.14%
1.15	6	96.53%
1.2	3	96.72%
1.25	6	97.10%
1.3	7	97.55%
1.35	2	97.68%
1.4	2	97.81%
1.45	3	98.01%
1.5	3	98.20%
1.55	2	98.33%
1.6	2	98.46%
1.65	2	98.58%
1.7	3	98.78%
More	19	100.00%



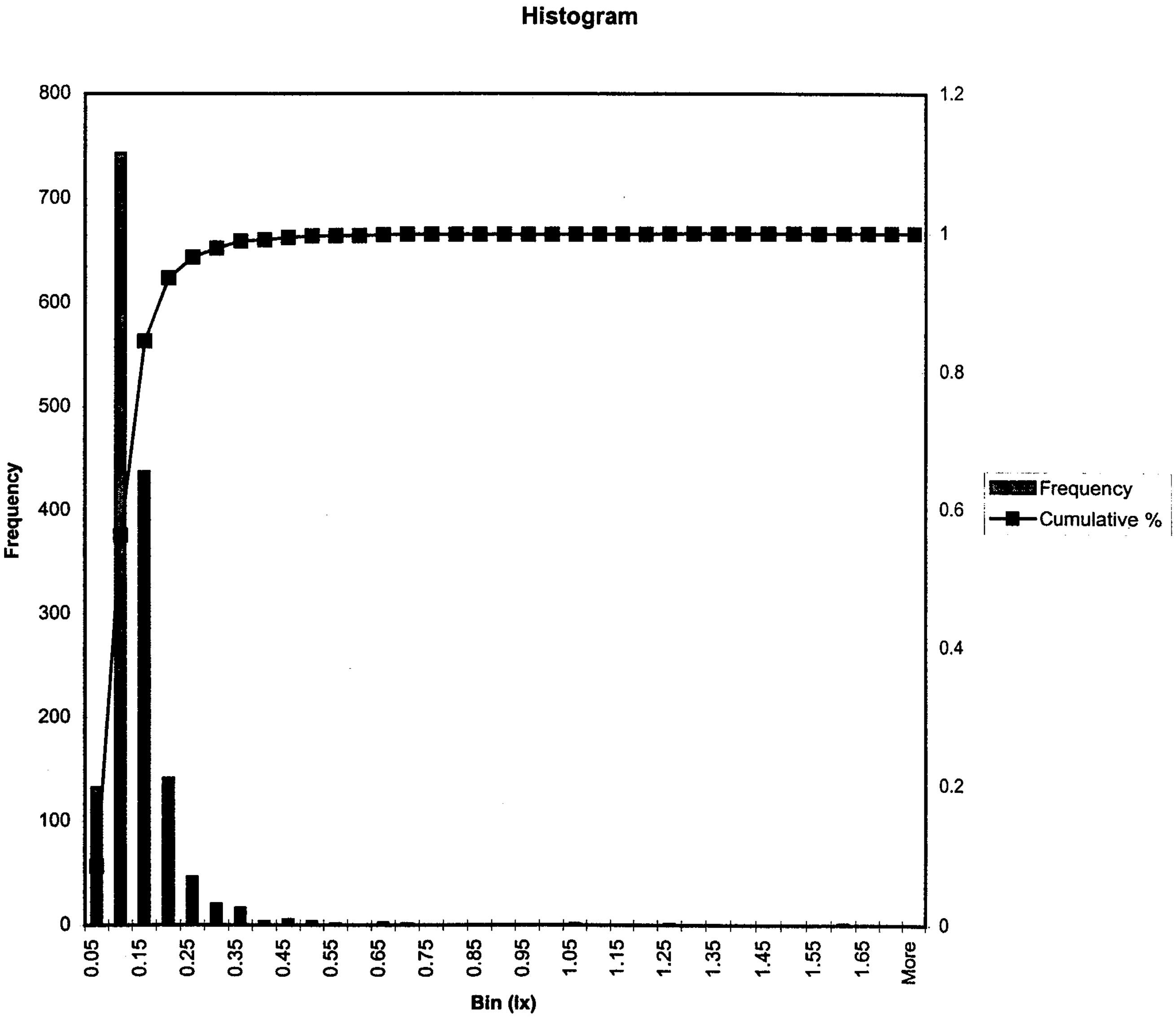
Minolta Clear (right shoulder/2.12 m high) after 1.1s

Bin (lx)	*Frequency*	*Cumulative %*
0.05	2	.13%
0.1	9	.71%
0.15	44	3.54%
0.2	103	10.17%
0.25	149	19.76%
0.3	214	33.53%
0.35	204	46.65%
0.4	159	56.89%
0.45	135	65.57%
0.5	95	71.69%
0.55	70	76.19%
0.6	50	79.41%
0.65	52	82.75%
0.7	37	85.14%
0.75	35	87.39%
0.8	19	88.61%
0.85	21	89.96%
0.9	17	91.06%
0.95	15	92.02%
1	10	92.66%
1.05	8	93.18%
1.1	8	93.69%
1.15	4	93.95%
1.2	11	94.66%
1.25	9	95.24%
1.3	5	95.56%
1.35	8	96.07%
1.4	8	96.59%
1.45	7	97.04%
1.5	0	97.04%
1.55	4	97.30%
1.6	3	97.49%
1.65	2	97.62%
1.7	4	97.88%
More	33	100.00%



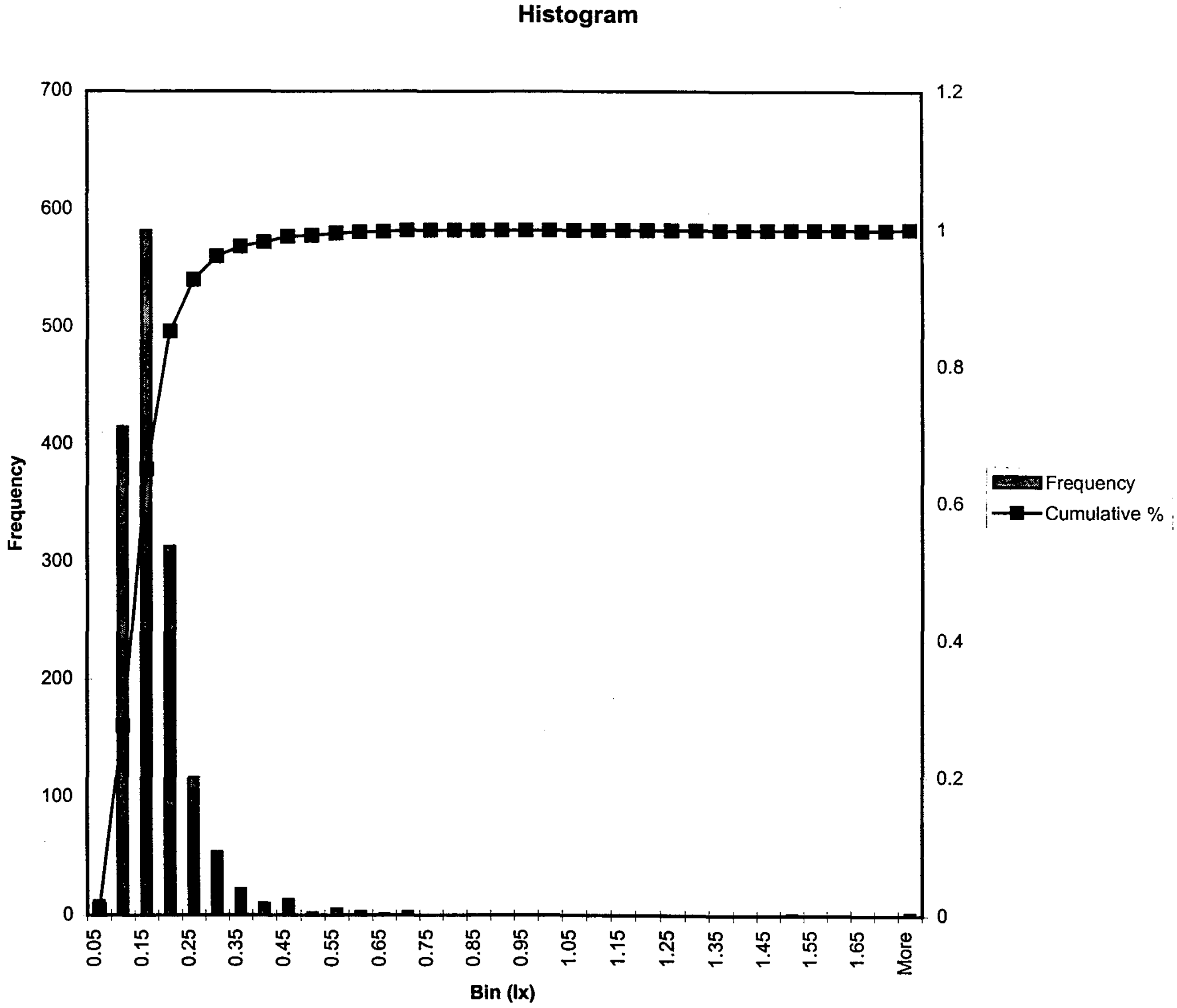
Minolta Yellow (left shoulder/2.12 m high) at 152 m

Bin (lx)	*Frequency*	*Cumulative %*
0.05	132	8.50%
0.1	743	56.34%
0.15	437	84.48%
0.2	141	93.56%
0.25	46	96.52%
0.3	20	97.81%
0.35	16	98.84%
0.4	3	99.03%
0.45	5	99.36%
0.5	3	99.55%
0.55	1	99.61%
0.6	0	99.61%
0.65	2	99.74%
0.7	1	99.81%
0.75	0	99.81%
0.8	0	99.81%
0.85	0	99.81%
0.9	0	99.81%
0.95	0	99.81%
1	0	99.81%
1.05	1	99.87%
1.1	0	99.87%
1.15	0	99.87%
1.2	0	99.87%
1.25	1	99.94%
1.3	0	99.94%
1.35	0	99.94%
1.4	0	99.94%
1.45	0	99.94%
1.5	0	99.94%
1.55	0	99.94%
1.6	1	100.00%
1.65	0	100.00%
1.7	0	100.00%
More	0	100.00%



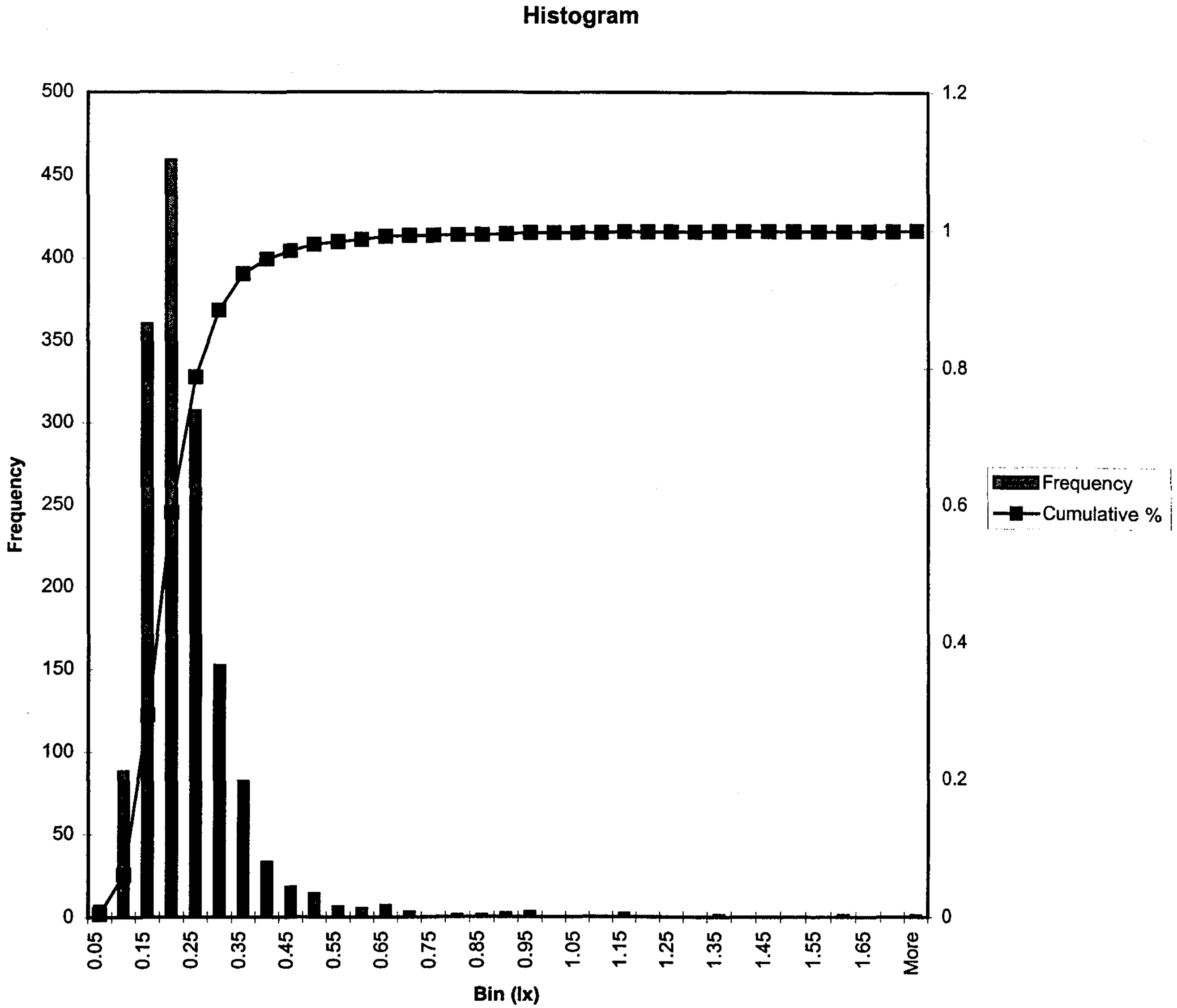
Minolta Yellow (left shoulder/2.12 m high) at 114 m

Bin (lx)	*Frequency*	*Cumulative %*
0.05	12	.77%
0.1	415	27.50%
0.15	582	64.97%
0.2	313	85.13%
0.25	116	92.59%
0.3	53	96.01%
0.35	22	97.42%
0.4	10	98.07%
0.45	13	98.91%
0.5	2	99.03%
0.55	5	99.36%
0.6	3	99.55%
0.65	1	99.61%
0.7	3	99.81%
0.75	0	99.81%
0.8	0	99.81%
0.85	0	99.81%
0.9	0	99.81%
0.95	0	99.81%
1	0	99.81%
1.05	0	99.81%
1.1	0	99.81%
1.15	0	99.81%
1.2	0	99.81%
1.25	0	99.81%
1.3	0	99.81%
1.35	0	99.81%
1.4	0	99.81%
1.45	0	99.81%
1.5	1	99.87%
1.55	0	99.87%
1.6	0	99.87%
1.65	0	99.87%
1.7	0	99.87%
More	2	100.00%



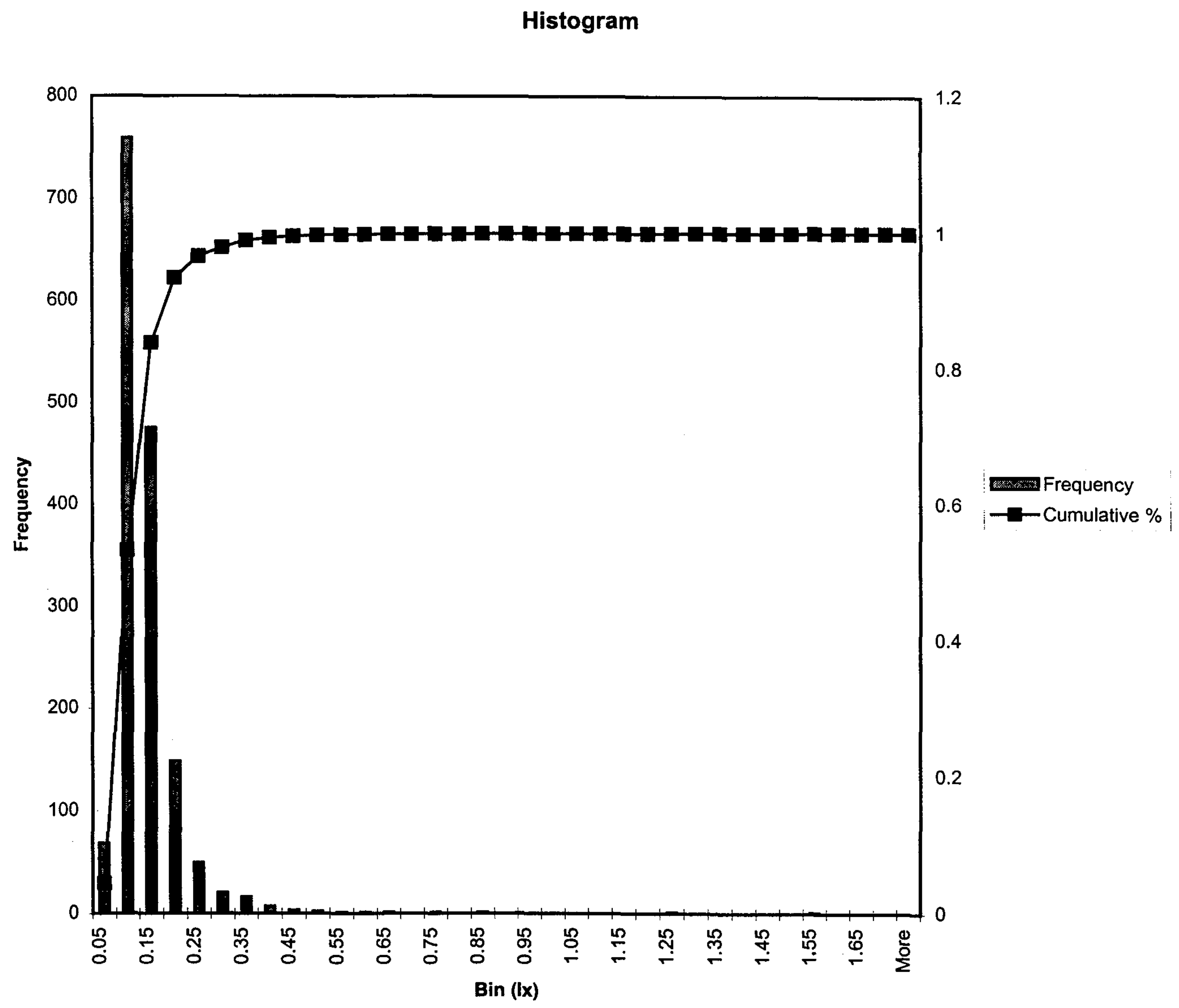
Bin (lx)	*Frequency*	*Cumulative %*
0.05	7	.45%
0.1	88	6.12%
0.15	360	29.30%
0.2	459	58.85%
0.25	307	78.62%
0.3	152	88.41%
0.35	82	93.69%
0.4	33	95.81%
0.45	18	96.97%
0.5	14	97.88%
0.55	6	98.26%
0.6	5	98.58%
0.65	7	99.03%
0.7	3	99.23%
0.75	0	99.23%
0.8	1	99.29%
0.85	1	99.36%
0.9	2	99.48%
0.95	3	99.68%
1	0	99.68%
1.05	0	99.68%
1.1	0	99.68%
1.15	2	99.81%
1.2	0	99.81%
1.25	0	99.81%
1.3	0	99.81%
1.35	1	99.87%
1.4	0	99.87%
1.45	0	99.87%
1.5	0	99.87%
1.55	0	99.87%
1.6	1	99.94%
1.65	0	99.94%
1.7	0	99.94%
More	1	100.00%

Minolta Yellow (left shoulder/2.12 m high) after 1.1s



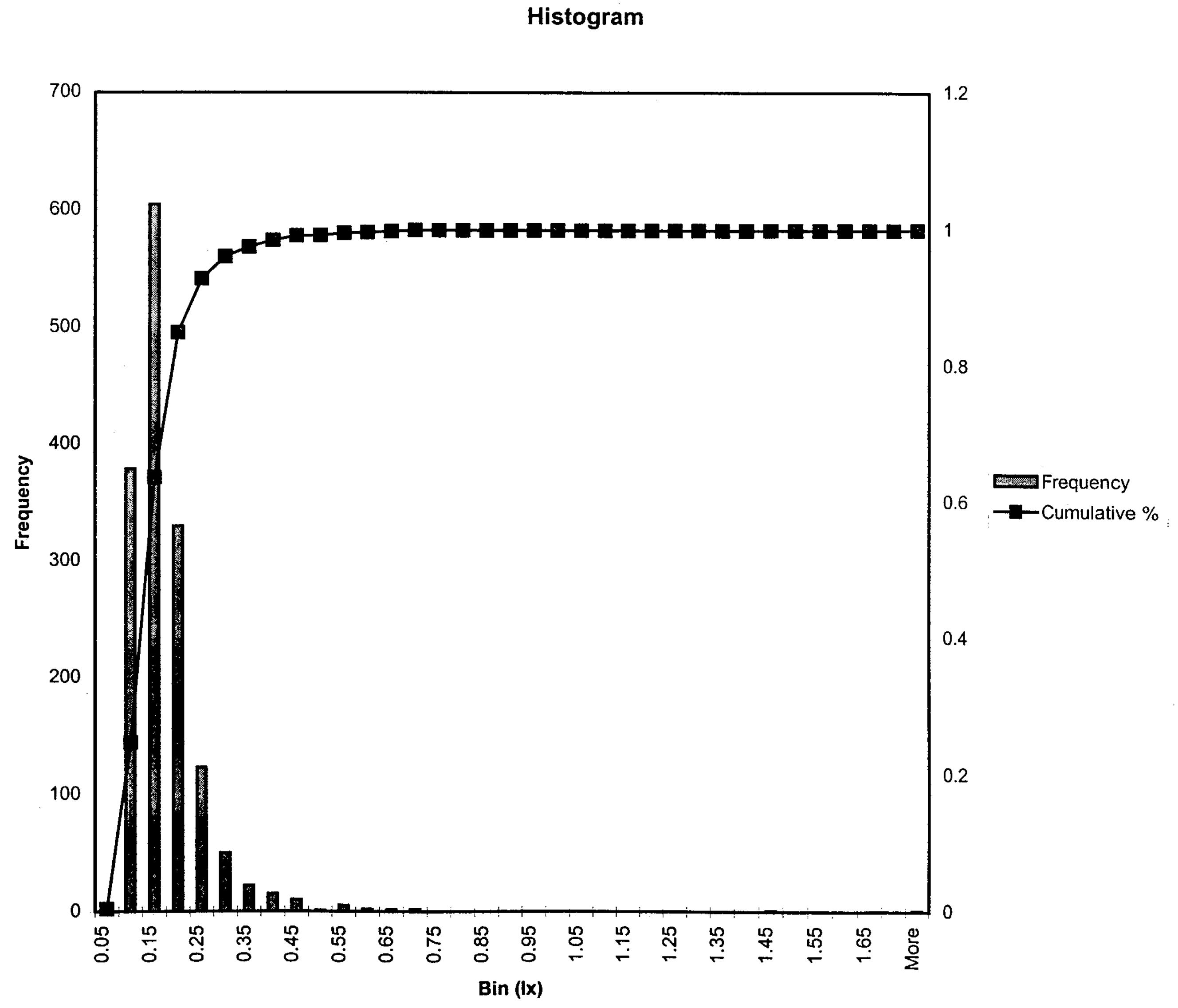
Minolta Green (left shoulder/2.12 m high) at 152 m

Bin (lx)	*Frequency*	*Cumulative %*
0.05	68	4.38%
0.1	759	53.22%
0.15	475	83.78%
0.2	148	93.31%
0.25	49	96.46%
0.3	20	97.75%
0.35	16	98.78%
0.4	7	99.23%
0.45	3	99.42%
0.5	2	99.55%
0.55	1	99.61%
0.6	1	99.68%
0.65	1	99.74%
0.7	0	99.74%
0.75	1	99.81%
0.8	0	99.81%
0.85	1	99.87%
0.9	0	99.87%
0.95	0	99.87%
1	0	99.87%
1.05	0	99.87%
1.1	0	99.87%
1.15	0	99.87%
1.2	0	99.87%
1.25	1	99.94%
1.3	0	99.94%
1.35	0	99.94%
1.4	0	99.94%
1.45	0	99.94%
1.5	0	99.94%
1.55	1	100.00%
1.6	0	100.00%
1.65	0	100.00%
1.7	0	100.00%
More	0	100.00%



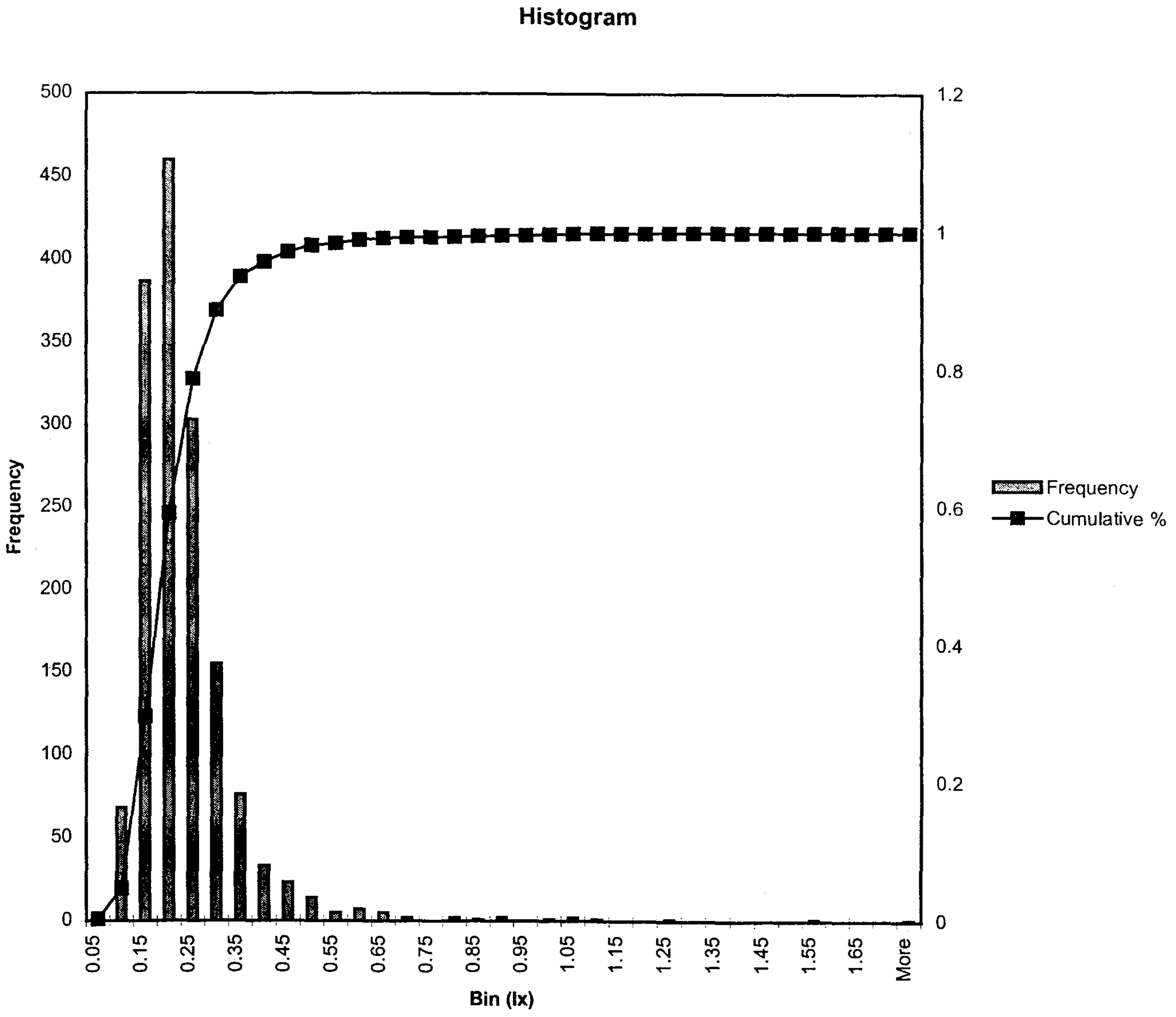
Minolta Green (left shoulder/2.12 m high) at 114 m

Bin (lx)	*Frequency*	*Cumulative %*
0.05	6	.39%
0.1	379	24.77%
0.15	605	63.71%
0.2	330	84.94%
0.25	123	92.86%
0.3	50	96.07%
0.35	22	97.49%
0.4	15	98.46%
0.45	10	99.10%
0.5	1	99.16%
0.55	5	99.49%
0.6	2	99.61%
0.65	2	99.74%
0.7	2	99.87%
0.75	0	99.87%
0.8	0	99.87%
0.85	0	99.87%
0.9	0	99.87%
0.95	0	99.87%
1	0	99.87%
1.05	0	99.87%
1.1	0	99.87%
1.15	0	99.87%
1.2	0	99.87%
1.25	0	99.87%
1.3	0	99.87%
1.35	0	99.87%
1.4	0	99.87%
1.45	1	99.94%
1.5	0	99.94%
1.55	0	99.94%
1.6	0	99.94%
1.65	0	99.94%
1.7	0	99.94%
More	1	100.00%



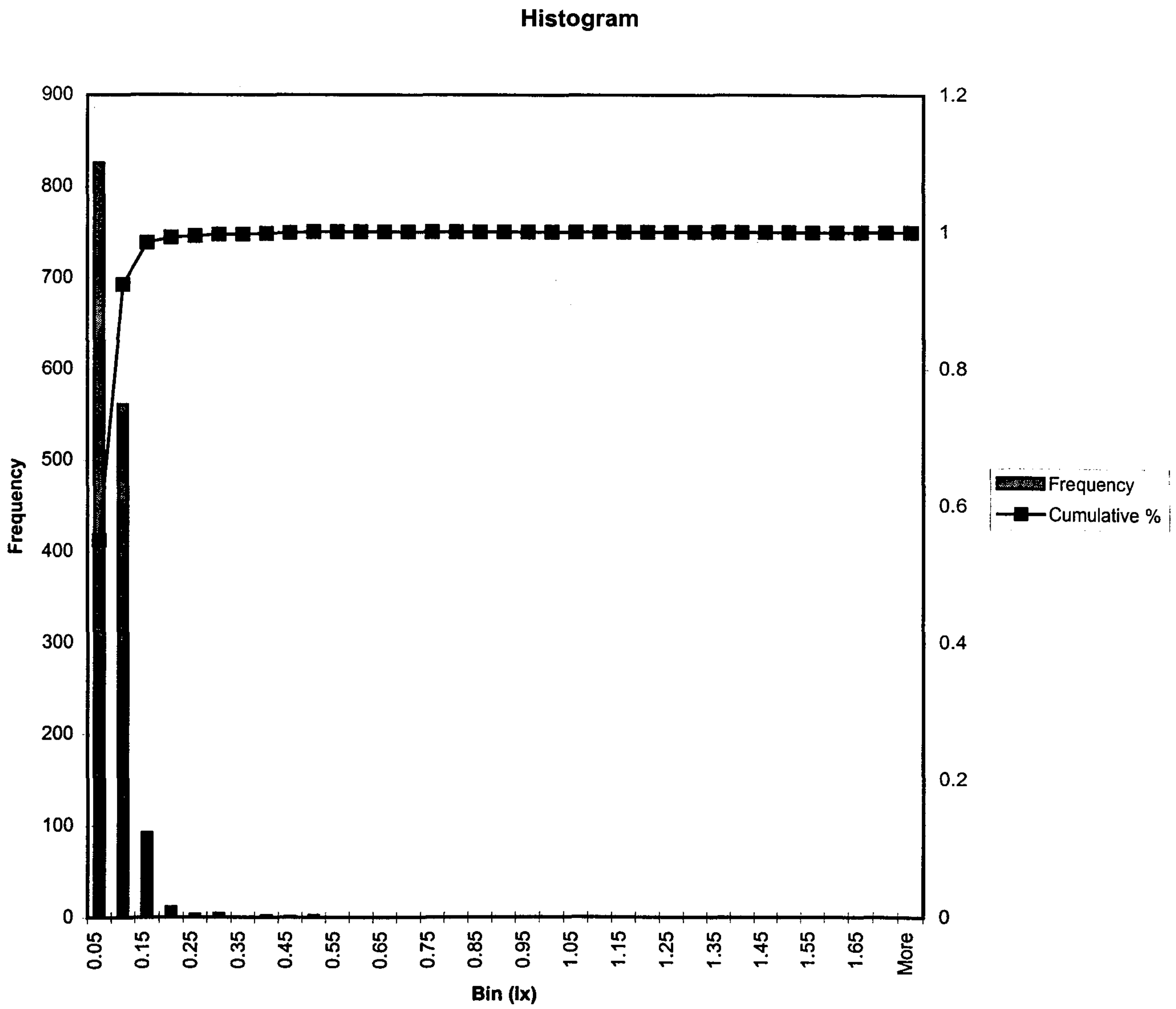
Bin (lx)	*Frequency*	*Cumulative %*
0.05	4	.26%
0.1	68	4.63%
0.15	387	29.54%
0.2	460	59.14%
0.25	303	78.64%
0.3	155	88.61%
0.35	76	93.50%
0.4	33	95.62%
0.45	23	97.10%
0.5	14	98.01%
0.55	5	98.33%
0.6	7	98.78%
0.65	5	99.10%
0.7	2	99.23%
0.75	0	99.23%
0.8	2	99.36%
0.85	1	99.42%
0.9	2	99.55%
0.95	0	99.55%
1	1	99.61%
1.05	2	99.74%
1.1	1	99.81%
1.15	0	99.81%
1.2	0	99.81%
1.25	1	99.87%
1.3	0	99.87%
1.35	0	99.87%
1.4	0	99.87%
1.45	0	99.87%
1.5	0	99.87%
1.55	1	99.94%
1.6	0	99.94%
1.65	0	99.94%
1.7	0	99.94%
More	1	100.00%

Minolta Green (left shoulder/2.12 m high) after 1.1s



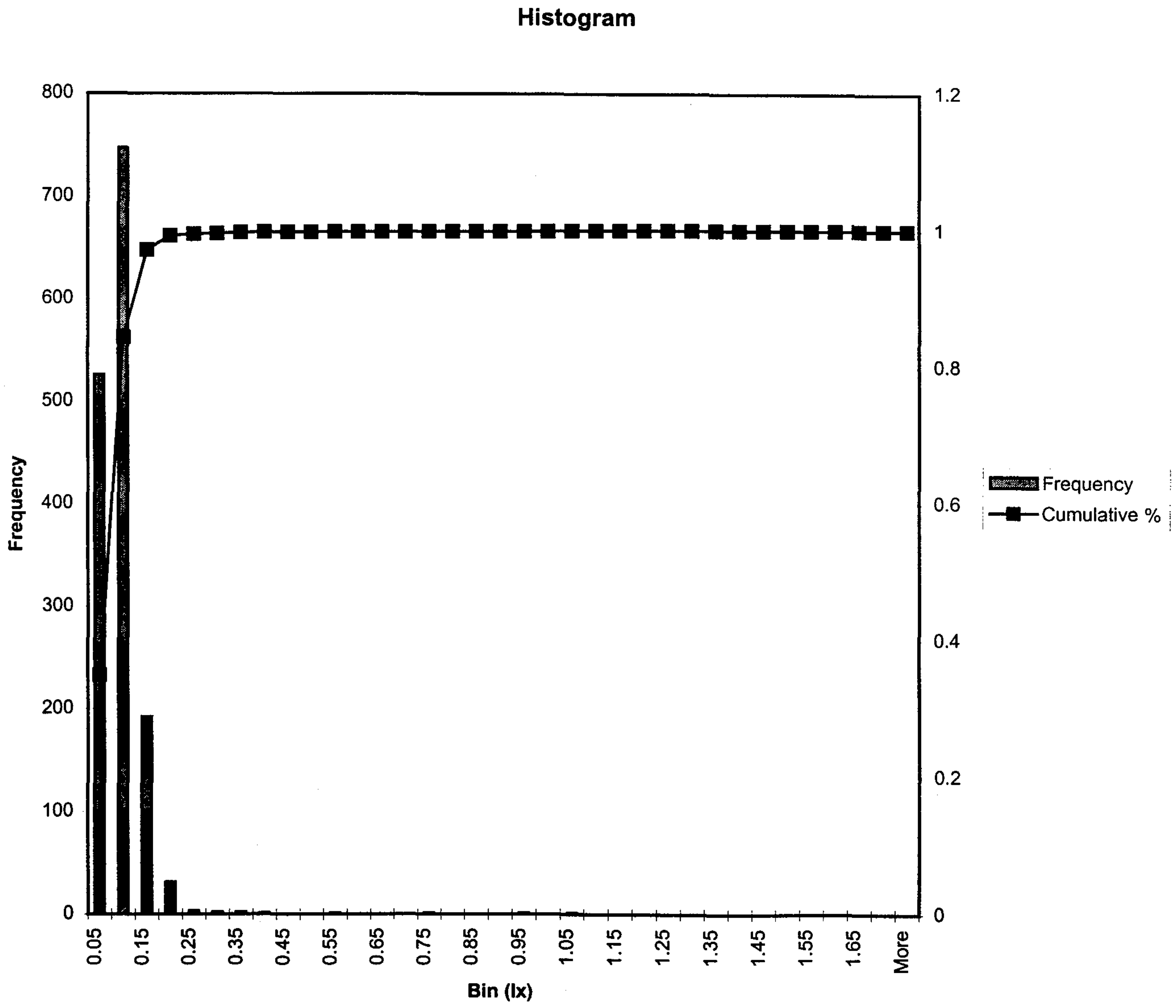
IL 1700 #1 (above the right lane/7.62 m high) at 152 m

Bin (lx)	*Frequency*	*Cumulative %*
0.05	826	54.99%
0.1	561	92.34%
0.15	92	98.47%
0.2	11	99.20%
0.25	3	99.40%
0.3	4	99.67%
0.35	0	99.67%
0.4	2	99.80%
0.45	1	99.87%
0.5	2	100.00%
0.55	0	100.00%
0.6	0	100.00%
0.65	0	100.00%
0.7	0	100.00%
0.75	0	100.00%
0.8	0	100.00%
0.85	0	100.00%
0.9	0	100.00%
0.95	0	100.00%
1	0	100.00%
1.05	0	100.00%
1.1	0	100.00%
1.15	0	100.00%
1.2	0	100.00%
1.25	0	100.00%
1.3	0	100.00%
1.35	0	100.00%
1.4	0	100.00%
1.45	0	100.00%
1.5	0	100.00%
1.55	0	100.00%
1.6	0	100.00%
1.65	0	100.00%
1.7	0	100.00%
More	0	100.00%



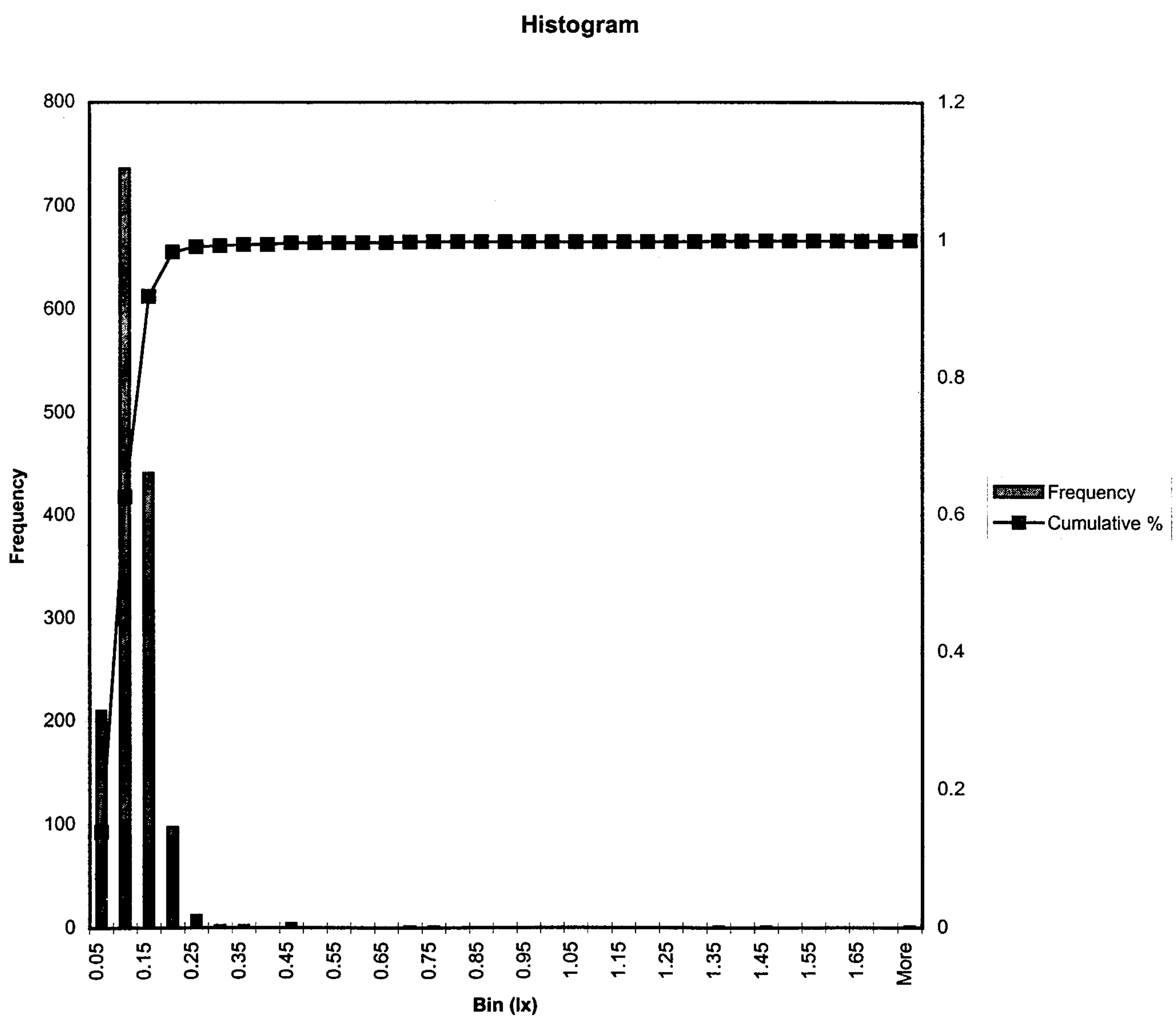
IL 1700 #1 (above the right lane/7.62 m high) at 114 m

Bin (lx)	*Frequency*	*Cumulative %*
0.05	526	34.88%
0.1	747	84.42%
0.15	192	97.15%
0.2	31	99.20%
0.25	3	99.40%
0.3	2	99.54%
0.35	2	99.67%
0.4	1	99.73%
0.45	0	99.73%
0.5	0	99.73%
0.55	1	99.80%
0.6	0	99.80%
0.65	0	99.80%
0.7	0	99.80%
0.75	1	99.87%
0.8	0	99.87%
0.85	0	99.87%
0.9	0	99.87%
0.95	1	99.93%
1	0	99.93%
1.05	1	100.00%
1.1	0	100.00%
1.15	0	100.00%
1.2	0	100.00%
1.25	0	100.00%
1.3	0	100.00%
1.35	0	100.00%
1.4	0	100.00%
1.45	0	100.00%
1.5	0	100.00%
1.55	0	100.00%
1.6	0	100.00%
1.65	0	100.00%
1.7	0	100.00%
More	0	100.00%



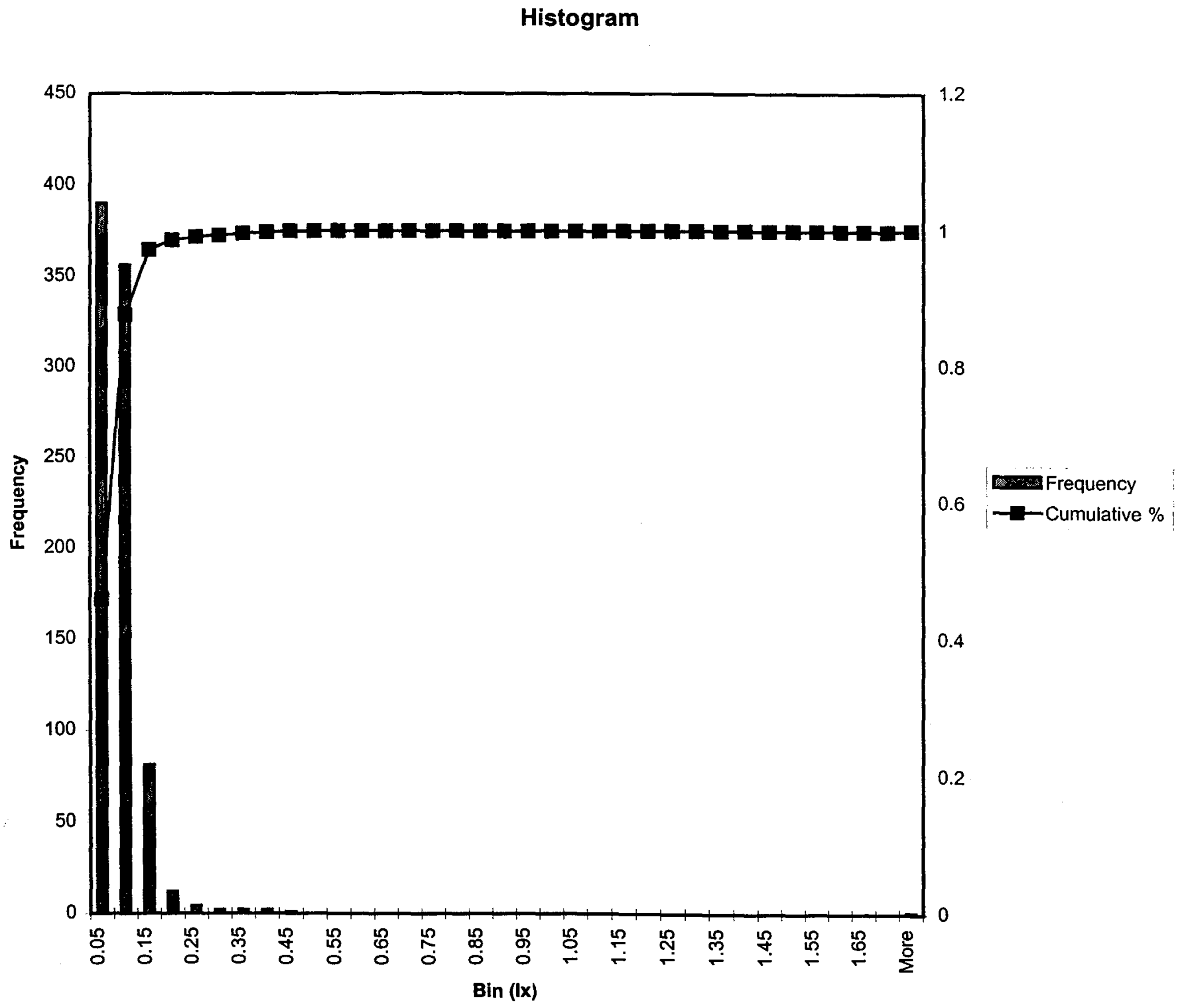
Bin (lx)	*Frequency*	*Cumulative %*
0.05	210	13.92%
0.1	736	62.69%
0.15	441	91.92%
0.2	97	98.34%
0.25	12	99.14%
0.3	2	99.27%
0.35	2	99.40%
0.4	0	99.40%
0.45	4	99.67%
0.5	0	99.67%
0.55	0	99.67%
0.6	0	99.67%
0.65	0	99.67%
0.7	1	99.73%
0.75	1	99.80%
0.8	0	99.80%
0.85	0	99.80%
0.9	0	99.80%
0.95	0	99.80%
1	0	99.80%
1.05	0	99.80%
1.1	0	99.80%
1.15	0	99.80%
1.2	0	99.80%
1.25	0	99.80%
1.3	0	99.80%
1.35	1	99.87%
1.4	0	99.87%
1.45	1	99.93%
1.5	0	99.93%
1.55	0	99.93%
1.6	0	99.93%
1.65	0	99.93%
1.7	0	99.93%
More	1	100.00%

IL 1700 #1 (above the right lane/7.62 m high) after 1.1s



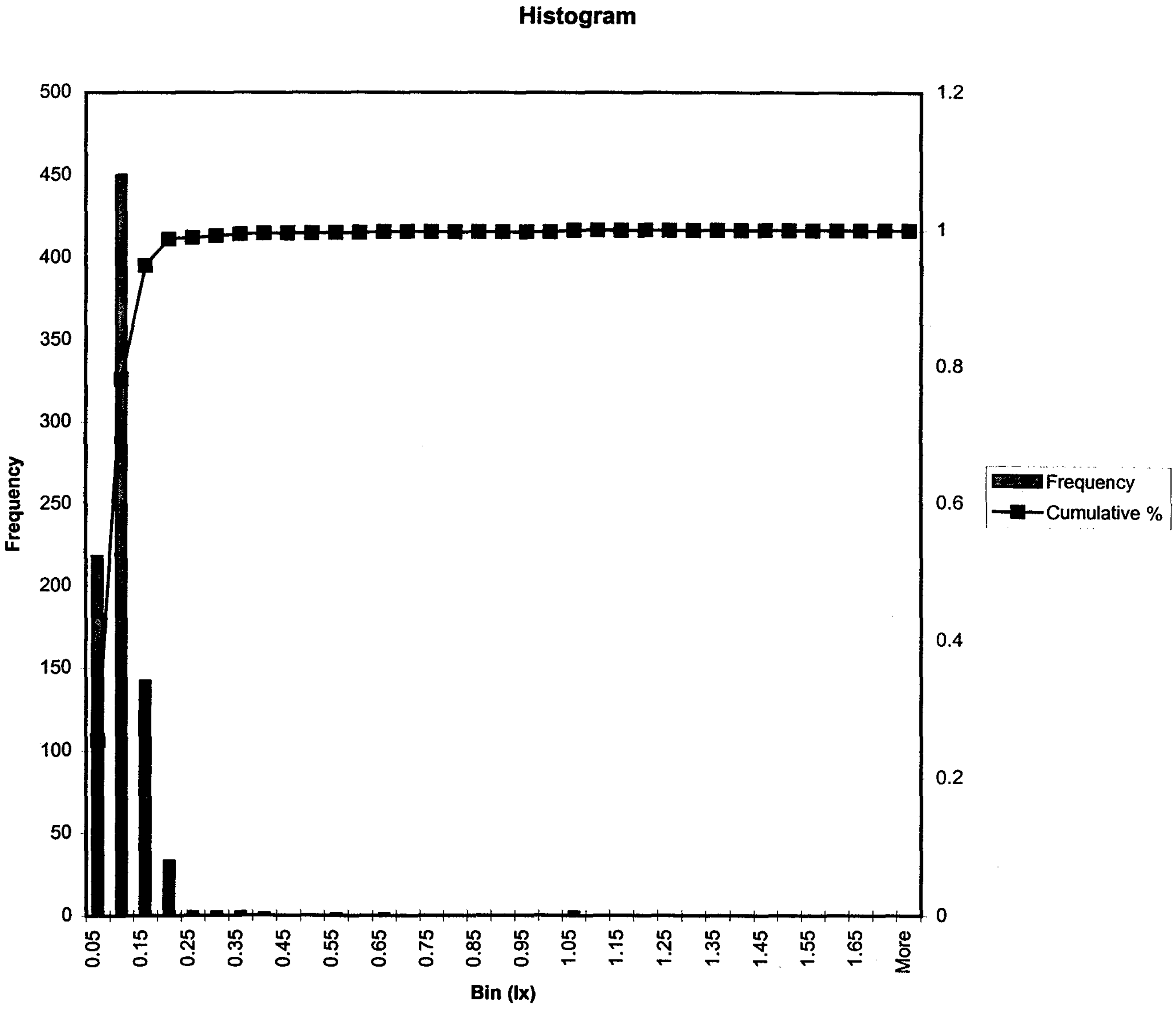
Bin (lx)	*Frequency*	*Cumulative %*
0.05	390	45.83%
0.1	356	87.66%
0.15	81	97.18%
0.2	12	98.59%
0.25	4	99.06%
0.3	2	99.29%
0.35	2	99.53%
0.4	2	99.76%
0.45	1	99.88%
0.5	0	99.88%
0.55	0	99.88%
0.6	0	99.88%
0.65	0	99.88%
0.7	0	99.88%
0.75	0	99.88%
0.8	0	99.88%
0.85	0	99.88%
0.9	0	99.88%
0.95	0	99.88%
1	0	99.88%
1.05	0	99.88%
1.1	0	99.88%
1.15	0	99.88%
1.2	0	99.88%
1.25	0	99.88%
1.3	0	99.88%
1.35	0	99.88%
1.4	0	99.88%
1.45	0	99.88%
1.5	0	99.88%
1.55	0	99.88%
1.6	0	99.88%
1.65	0	99.88%
1.7	0	99.88%
More	1	100.00%

IL 1700 #2 (above the right lane/7.62 m high) at 152 m



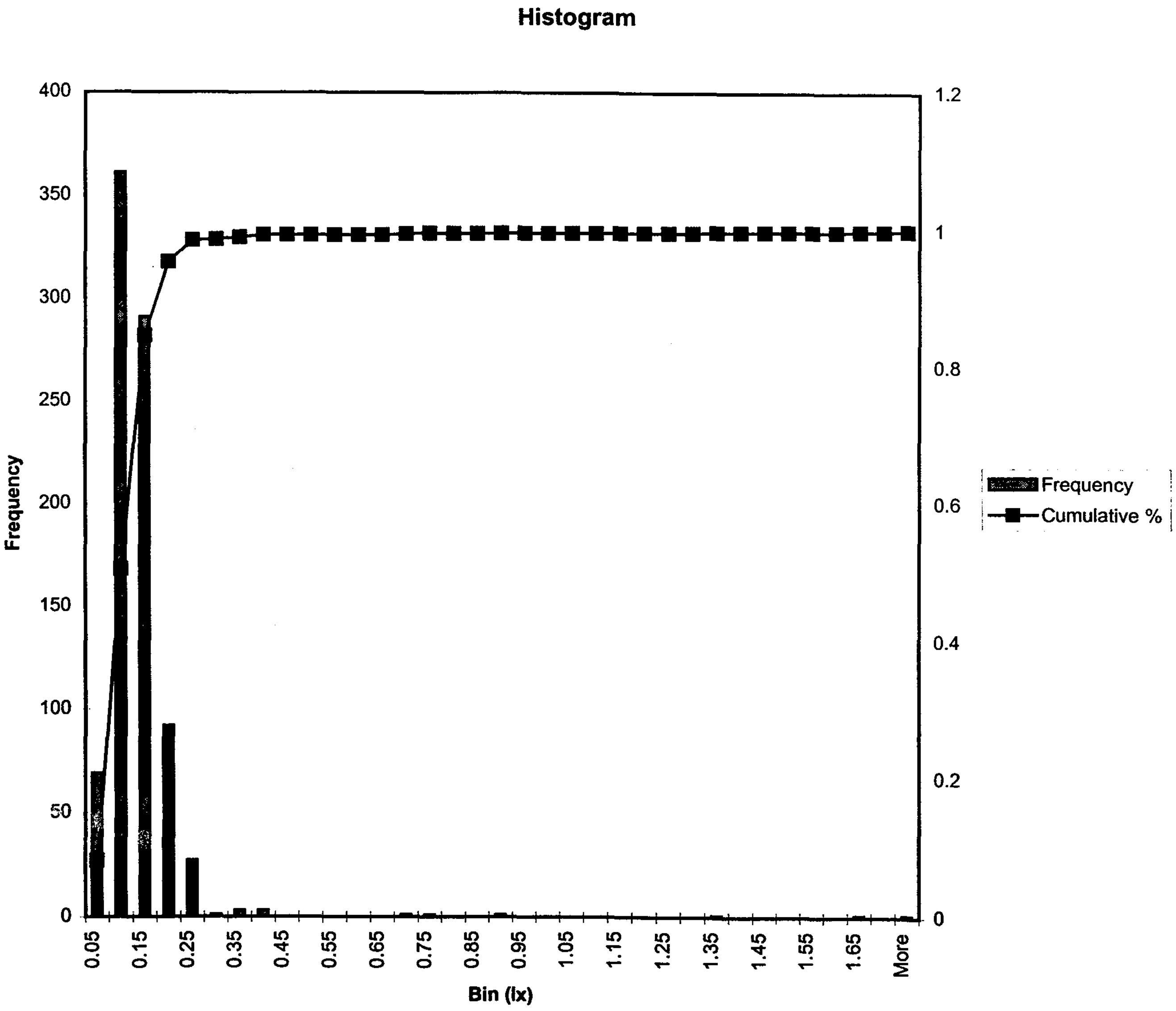
IL 1700 #2 (above the right lane/7.62 m high) at 114 m

Bin (lx)	*Frequency*	*Cumulative %*
0.05	218	25.53%
0.1	450	78.22%
0.15	142	94.85%
0.2	33	98.71%
0.25	2	98.95%
0.3	2	99.18%
0.35	2	99.41%
0.4	1	99.53%
0.45	0	99.53%
0.5	0	99.53%
0.55	1	99.65%
0.6	0	99.65%
0.65	1	99.77%
0.7	0	99.77%
0.75	0	99.77%
0.8	0	99.77%
0.85	0	99.77%
0.9	0	99.77%
0.95	0	99.77%
1	0	99.77%
1.05	2	100.00%
1.1	0	100.00%
1.15	0	100.00%
1.2	0	100.00%
1.25	0	100.00%
1.3	0	100.00%
1.35	0	100.00%
1.4	0	100.00%
1.45	0	100.00%
1.5	0	100.00%
1.55	0	100.00%
1.6	0	100.00%
1.65	0	100.00%
1.7	0	100.00%
More	0	100.00%



IL 1700 #2 (above the right lane/7.62 m high) after 1.1s

Bin (lx)	*Frequency*	*Cumulative %*
0.05	69	8.09%
0.1	361	50.41%
0.15	291	84.53%
0.2	92	95.31%
0.25	27	98.48%
0.3	1	98.59%
0.35	3	98.94%
0.4	3	99.30%
0.45	0	99.30%
0.5	0	99.30%
0.55	0	99.30%
0.6	0	99.30%
0.65	0	99.30%
0.7	1	99.41%
0.75	1	99.53%
0.8	0	99.53%
0.85	0	99.53%
0.9	1	99.65%
0.95	0	99.65%
1	0	99.65%
1.05	0	99.65%
1.1	0	99.65%
1.15	0	99.65%
1.2	0	99.65%
1.25	0	99.65%
1.3	0	99.65%
1.35	1	99.77%
1.4	0	99.77%
1.45	0	99.77%
1.5	0	99.77%
1.55	0	99.77%
1.6	0	99.77%
1.65	1	99.88%
1.7	0	99.88%
More	1	100.00%



REFERENCES

Colomb, M., and Michaut, G., *Retroreflective Road Signs; Visibility at Night.* Transportation Research Record 1093, Transportation Research Board, Washington, D.C. (1989).

Erickson, R. L. and Woltman, H. L., *Sign Luminance as a Methodology for Matching Driver Needs, Roadway Variables and Traffic Signing Materials.* Proceedings, International Symposium on Traffic Safety Theory and Research Methods, Institute for Road Safety Research SWOV, Leidschendam, The Netherlands. (1988).

Improved Highway Travel Considerations for an Aging Population, Professional Development Seminar Institute of Transportation Engineers (September 1991).

Jenkins, S. E., and Gennaoui, F. R., *Terminal Values of Road Traffic Signs*, Special Report No. 49, Australian Road Research Board Ltd., Vermont South, Victoria. (1992).

Lerner, N. D., and Huey, Jr., R. W., *Older Driver Perception-Reaction Time for Intersection Sight Distance and Object Detection*, Draft, FHA, Contract DTFH 61-90-C-0038.

Mace, D.J., Garvery, P.M., and Heckard, *Relative Visibility of Increased Legend Size vs. Brighter Materials for Traffic Signs*, FHWA-RD-94-035, U.S. Department of Transportation, Federal Highway Administration (1994).

Older Driver Pilot Program, Report of the Secretary of Transportation, Federal Highway Administration, Office of Highway Safety, Washington, D.C. (April.1990).

Paniati, J. F., and Mace, D. J., *Minimum Retroreflectivity Requirements for Traffic Signs*, FHWA-RD-93-077, Federal Highway Administration (October 1993).

Patryka, S.C., *Traffic Victim Age and Gender Distribution*, NHTSA 1979-81 FARS Data, U.S. Department of Transportation (July 1984).

Professional Development Seminar, National Highway Institute, Course #13353, *Improved Highway Travel Considerations for an Aging Population*, FHWA, Office of Traffic Operations and IVHS Traffic Performance Branch (HTV-32 1991).

Retroreflective Road Traffic Signs: Minimum and Optimal Luminance Requirements, International Road Federation, Geneva, Switzerland. (1991).

Russell, E.R., Harwood, D., Rys, M., Rys, A., and Keck, M., *Development of the Headlight Safety Data Base*, National Highway Transportation Safety Administration, DOT HS 807 736 (January 1991).

Sivak, M., and Olson, P. L., *Optimal and Minimal Luminance Characteristics for Retroreflective Highway Signs*, Transportation Research Record 1027: Driver Information Needs and Visibility of Traffic Control Devices, National Research Council, Washington, D.C. (1985).

Sivak, M., and Olson, P. O., *Optimal and Replacement Luminances of Traffic Signs: A Review of Applied Legibility Research,* University of Michigan Transportation Research Institute, Ann Arbor, Michigan. (1983).

Sommons, Y., Information from General Motors and the American Medical Association on the Aging Process and Driving Safety, GM Corporate Relations, Detroit, Michigan.

Staplin, L., Lococo, K., and Sim, J., *Traffic Maneuver Problems of Older Drivers Final Technical Report,* U. S. Department of Transportation, FHWA, Publication No. FHWA-RD-92-092 (August 1993).

Stein, A. C., Paraseghian, Z., Allen, R. W., and Wolf, C. E., *Overhead Guide Sign Visibility Factors, Volume I: Final Report*, U. S. Department of Transportation, FHWA, Publication No. FHWA-RD-88-196 (May 1989).

Tignor, S. C., and Paniati, J. F., *Defining Retroreflectivity Needs for Highway Signs and Markings*, Proceedings of the 59th Annual Meeting of the Institute of Transportation Engineers, San Diego, California, USA, September 17-20 (1989).

Transportation Research Board, Special Report 218: *Transportation in an Aging Society: Improving Mobility of Safety for Older Persons*, Vol. 1, Committee Report and Recommendations, National Research Council, Washington, D.C. (1988).

Woltman, M.L., *Nighttime Visibility of Retroreflective Signs*, CIE Technical Report (October 1993).

Woltman, H., *Retroreflection: Definitions and Measurements*," CIE Technical Report #54 (May 1998).