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Trade-Off Between Delineation and Lighting on Freeway Interchanges

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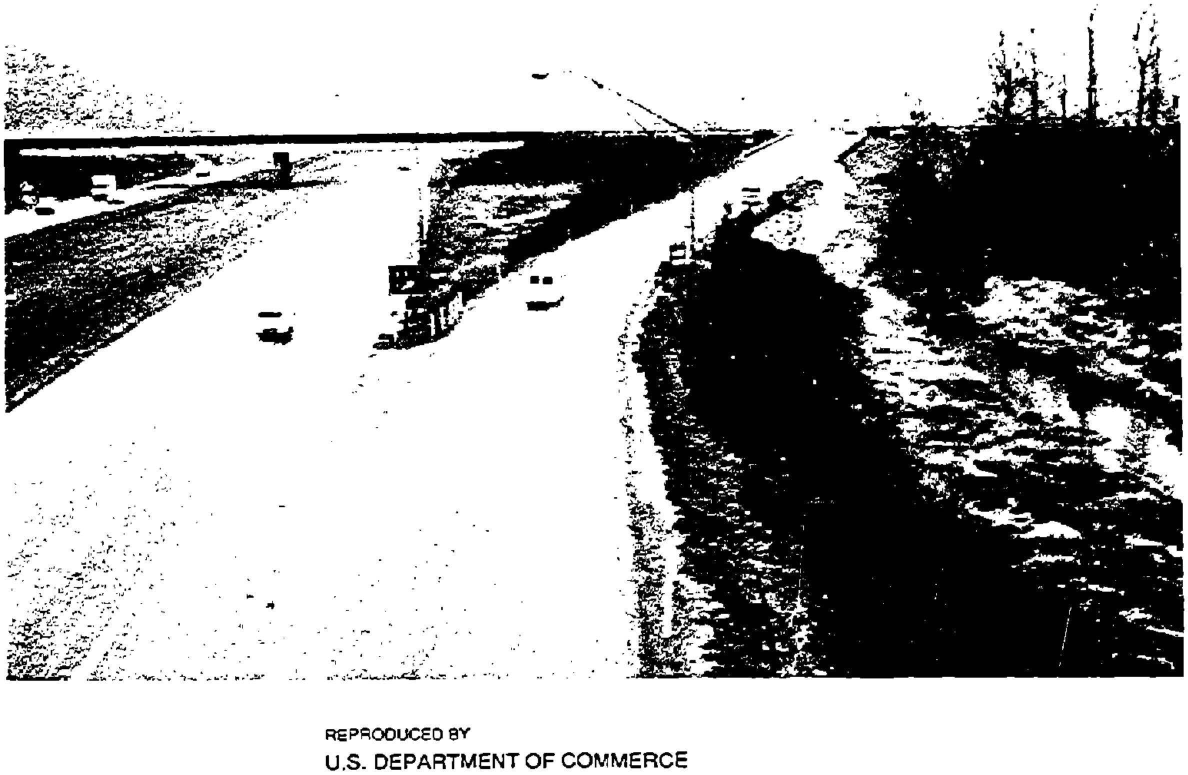

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
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FOREWORD

This report documents the methodology and the results of a study to determine whether driver performance at partially lighted interchanges could be improved by upgrading the delineation system to equal performance at fully illuminated interchanges. The study was carried out under dry as well as under rainy weather conditions. The investigation evaluated drivers' ramp speeds, lateral placement, edgeline and gore encroachments, brake activation, and use of high beams. As part of the study, the effects of transient visual adaptation (TVA) were investigated. TVA is a temporary reduction in the sensitivity of the eye when a person moves from a bright area into a darker area, i.e., that experienced in entering a movie theater or driving into a tunnel in daytime. Driver ramp speed performance downstream of the partial lighting showed such an effect was occurring. The study results also show that even with a substantial upgrade of delineation, driver performance under partial lighting will not equal that of full lighting.

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R. J. Betsold
Director, Office of Safety and Traffic
Operations Research and Development

NOTICE

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16. Abstract

The objective was to determine whether, with improved delineation, performance at partially lighted interchanges can approach performance under full lighting, particularly in rain. Two field studies were conducted. The first was to determine whether transient visual adaptation (TVA) influences detection on partially lighted interchanges and could interact with lighting. It was shown that TVA occurs under partial lighting and influences detection up to 600 feet from the last luminaire. The second field study was to determine the effect of lighting, weather, and improved delineation on driver performance. Data were obtained on two exits in dry and wet weather under full lighting with baseline delineation. Data were then obtained under partial lighting, with baseline and three improved delineation systems. Partial lighting at one exit was with one luminaire, at the other with three luminaires. Findings support the contention that full lighting is superior to partial lighting in ramp speed-related measures. Analysis of delineation effects on ramp and spot speeds and on speed distributions showed few differences under dry conditions. In rain, effects were stronger but were neither large enough nor consistent enough to recommend improved delineation over the baseline system. Nonstatistical comparison of the results from the two sites provided evidence that three-luminaire partial lighting was superior to single-luminaire. Performance on ramp segments downstream of the last luminaire suggested TVA influenced results.

17. Key Words
Delineation, full lighting, partial lighting, illumination, exits, raised pavement markers, post-mounted delineation, gore striping, transient visual adaptation

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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	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C
		Illumination		
fc	foot-candles	10.76	lux	lx
fL	foot-Lamberts	3.426	candela/m^2	cd/m^2

NOTE: Volumes greater than 1000 L shall be shown in m^3.

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	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

* SI is the symbol for the International System of Measurement

(Revised July 1989)

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INTRODUCTION

1. Purpose

The research objectives were:

- o To determine whether, with improved delineation, levels of safety and traffic operations at partially lighted interchanges can approach those of fully lighted ones, particularly in rain.
- o To determine whether transient visual adaptation influenced driver visual performance and could therefore interact with delineation and lighting.

With regard to the first objective, three upgraded delineation systems plus a baseline system were subjected to field testing at each of two sites. One site used single-luminaire partial lighting, but had luminaires in place for full lighting. The other site used three-luminaire partial lighting, but had luminaires in place for full lighting. It was therefore possible to compare driver performance produced by the three upgraded delineation systems with that produced by a baseline delineation system under both full and partial lighting. Data were obtained under clear, dry conditions and under rain conditions.

The upgraded delineation systems employed more raised pavement markers and post delineators than is customary, and experimented with greater areas of retroreflectivity on both. Thicker gore striping was used in one upgrade to provide greater retroreflectivity under rain conditions.

If the transient visual adaptation (TVA) phenomenon were to operate on drivers downstream of the lighted segment on a partially lighted ramp, that area would be a particular candidate for improved delineation. While TVA has been demonstrated in the laboratory, no attempt had been made to establish its existence in the field. Therefore, to satisfy the second objective, a preliminary field test was performed to determine whether the TVA phenomenon operates on partially lighted interchanges.

The preliminary test sought the extent to which TVA, if existent, degrades detection performance as drivers travel from the lighted to unlighted segment of a partially lighted ramp. The test was conducted on a partially lighted exit and entrance ramp (four and five luminaires, respectively) using detection distance to roadside targets as the measure of effectiveness.

2. Background

Prior to a study by Janoff et al. (NCHRP 256), there was no empirical information on the relative effects of partial versus full interchange lighting on driver performance.[1] While partial lighting was thought, by some, to provide many of the benefits of full lighting, there were others who felt that partial lighting was less safe.

NCHRP 256 evaluated the effects of partial lighting, complete lighting, and no lighting on traffic operations at a freeway interchange. Following a pilot study conducted on a direct connection ramp on a three-leg interchange, the main field study was conducted on a loop ramp; a design for which partial lighting is seldom used. The two data collection efforts were conducted on fully lighted facilities for which all or some of the lights were turned off to obtain data under the partial lighting and no lighting conditions. Both the pilot site and the main site were of a design which produces more difficult driving situations than the diamond interchanges studied during the current research.

The findings of the study provided a primary impetus for the current effort. The general conclusion of the study was that complete interchange lighting is superior to partial lighting in providing smoother and safer nighttime operations at the interchange. The major conclusions of the study were:

- Complete lighting performs better than partial lighting consisting of one, two, or four luminaires.
- Either complete or partial lighting normally performs better than no lighting.
- Partial lighting systems with fewer luminaires (one or two) frequently perform better than partial lighting systems with a greater number of luminaires (four).
- There is a trade-off between cost and traffic operations and safety factors in the design of interchange lighting systems.
- Existing complete lighting systems should not be reduced to partial lighting systems if traffic operations and safety (defined in terms of driver behavior measures) are important considerations.

The finding that the partial lighting system with fewer luminaires frequently resulted in performance better than that with a greater number of luminaires suggested that TVA may have produced such a result. This observation resulted in the decision to determine whether the phenomenon occurs in the field, and the extent to which it influences detection performance. Conclusions in the NCHRP study regarding the enhanced safety and operations were based on measures such as headlight usage and erratic maneuvers. Table 1 shows the results reported in NCHRP 256.[1] Note that the different levels of lighting had no significant influence on speed or acceleration measures.

Table 1. Results of the NCHRP study.[1] (PIL is partial interchange lighting; CIL is complete—full—interchange lighting.)

MEASURE	RESULT	IMPLICATIONS
Brake activations	Frequencies higher under PIL than under CIL	CIL performs better than PIL
Mean braking distance	Improved under CIL for cloverleaf interchange	CIL performs better than PIL
High beam use	Frequencies higher under PIL than under CIL	CIL performs better than PIL
Diverge/merge patterns	Improved under CIL	CIL performs better than PIL
Gore and shoulder encroachments	Frequencies higher under PIL than under CIL for three-leg interchange	CIL performs better than PIL
Velocity and acceleration	Not affected by lighting	None

FIELD STUDY OF TRANSIENT VISUAL ADAPTATION

1. Introduction

On the exit of a partially lighted interchange, luminaires are usually not placed downstream of the physical gore. Thus the driver proceeds from a lighted area to a nonlighted area on the ramp. The effect of going from higher to lower levels of luminance has been shown to be a reduction in visual sensitivity. (See references 2 to 7.) That this effect may have operational significance for driver performance was suggested by the results of the NCHRP study.[1] This study showed that drivers frequently perform better in partial lighting systems with fewer luminaires than in those with a greater number of luminaires.

Based on the evidence cited, it was judged necessary to determine, under more controlled conditions, the extent to which TVA occurs under partial lighting conditions. Further, it was decided to use a visual task more closely associated with the lighting and visibility literature; namely the detection of roadside targets having known reflectance values.

It was hypothesized that if TVA occurs, target detection distances would be shorter under partial lighting conditions than under nonlighted conditions. The field test also would seek the duration of any TVA effect. The relevance of this field test to the delineation portions of the study was based on the assumption that a TVA effect shown to influence target detection may also influence detection of delineation devices on partially lighted interchanges.

If the TVA effect were found to operate but be of short duration, it could be advisable to improve delineation on only a short portion of a ramp downstream of luminaires. If, on the other hand, the effect were shown to operate longer, it could be advisable to improve delineation to the end of the ramp. Thus the existence and extent of the TVA effect could influence the cost and cost effectiveness of improved delineation systems.

2. Test Procedure

Fifteen subjects drove an instrumented vehicle through an interchange under both partially illuminated and nonilluminated conditions. A target detection task was used to determine the existence (and extent) of TVA. Subjects pressed a button when they detected a target, placed downstream of the luminaires along the ramp. The switch button was small enough to hold along with the steering wheel. They were also asked to verbally indicate the target configuration (single or double) and to identify whether the target was on the left or right side of the ramp. A switch activation entered the on-board computer and activated the computer clock. The instrumentation also included a distance measuring instrument (DMI) which was sampled every half second by the computer.

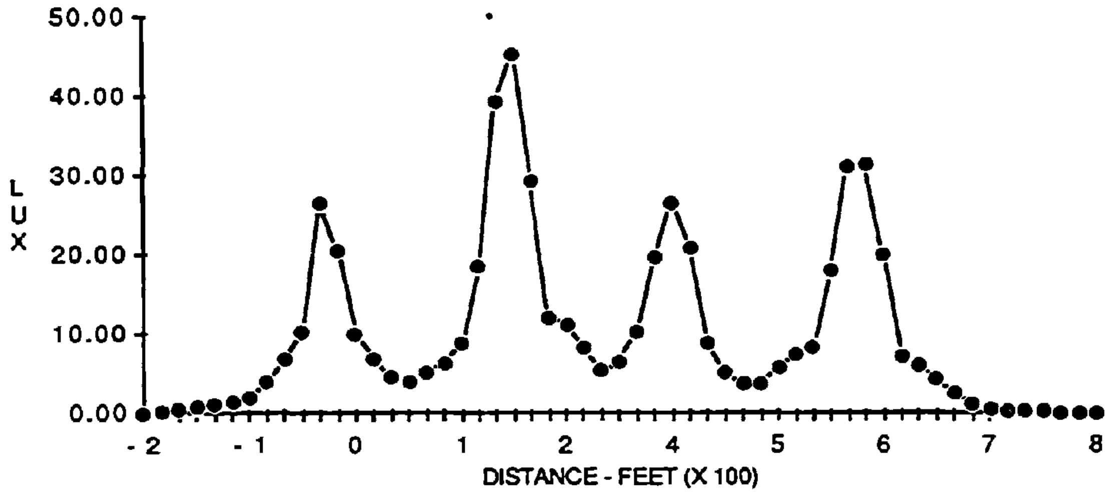
Thus for each trial, the target detection time and distance were available along with the detection accuracy data. Subject drivers were asked to maintain the 45 mi/h (72 km/h) ramp speed and were reminded of that speed limit as they approached the illuminated section of the interchange. On the approach subjects were also instructed to maintain enough distance from lead vehicles to preclude the lead vehicle's headlights from illuminating targets for the subjects.

3. Test Interchange

The interchange used for the TVA test was partially lighted with four luminaires at the northbound exit ramp. The exit contained a fifth "pull through" luminaire on the mainline. The driving circuit used for the study required that the opposite (southbound) entrance of the same interchange be used to return to the test exit. Since the lighting configuration was also partial for the entrance, it was decided to obtain additional detection data on the entrance. The only restriction was that the entrance ramp permitted targets on the right side only, because of the two-lane mainline following the entrance luminaires.

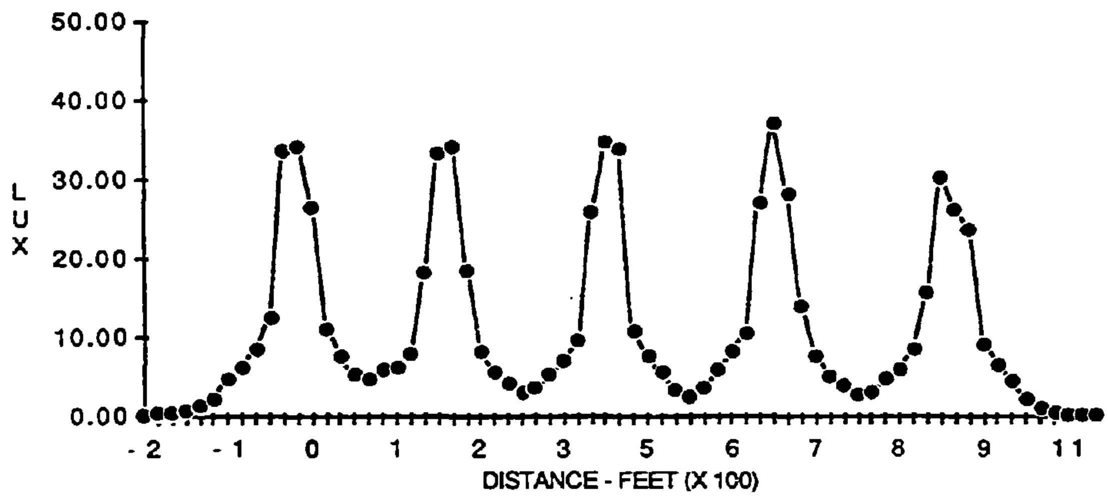
The four luminaires at the northbound exit ramp were spaced over an area of approximately 600 ft (183 m), with each luminaire support being separated by approximately 200 ft (61 m). The exit ramp included a long tangent section of approximately 2,200 ft (671 m) (as measured from the support post of the last luminaire), followed by a sharp curve. The long tangent section prior to the curve was desirable in that it permitted determination of the longevity of TVA without any confounding from the effects of curvature. The southbound entrance ramp contained five luminaires spaced at 200 ft (61 m) and was a tangent from a location well upstream of the luminaires to well past any target location.

The illuminance measures taken on the northbound exit and southbound entrance are shown in figures 1 and 2. The average illuminance was 1.7 fc (18 lx), with a minimum of 0.2 fc (2.4 lx) and a maximum of 4.2 fc (45 lx). The average luminance was 0.47 fL (1.6 cd/m^2) with a minimum of 0.12 fL (0.4 cd/m^2) and a maximum of 0.99 fL (3.4 cd/m^2). The veiling luminance was calculated at 0.20 fL (0.7 cd/m^2).



(1 ft = .305 m; 1 lx = 0.0929 fc)

Figure 1. Illuminance measures on northbound exit ramp, TVA study site.



(1 ft = .305 m; 1 lx = 0.0929 fc)

Figure 2. Illuminance measures on southbound entrance ramp, TVA study site.

4. Targets and Target Placement

The detection targets were 7-in by 7-in (17.8 cm by 17.8 cm) flat panels with a reflectance value of approximately 20 percent; the target characteristics being those adopted by the Roadway Lighting Committee of the Illuminating Engineering Society (IES) for visibility measurements. The targets were sometimes placed singly and sometimes in a pair to create some target configuration uncertainty. Also, targets were sometimes placed on the left side of the exit ramp and sometimes on the right. While this created additional uncertainty and task variation, the primary purpose of the lateral variation was to induce scanning behavior on the part of the subject drivers. This was desired because it has been shown that if the eye is not fixed on an object but is scanning a large field, TVA will have the maximum effect on contrast sensitivity in a nonuniform luminance field.[7] The different target placements created the need for drivers to scan the maximally relevant field rather than searching and fixating on one side of the ramp.

For some trials the targets were located relatively close to the area where the illumination ended, and for others the placement was much farther downstream, but prior to the exit ramp curve. Targets were always placed such that no meaningful target luminance was provided by the fixed lighting.

The measurable light from the luminaires terminated at 200 ft (61 m) downstream from the base of the last luminaire. The "near" target placement for both entrance and exit ramps was 350 ft (106.75 m) downstream of the last luminaire. This distance was chosen because on many sharply curved ramps visited during site selection, the point of curvature was approximately 150 ft (45.75 m) downstream from the influence of the luminaires. The point of curvature may be where delineation is needed most. The "far" target location for the northbound exit ramp was at 600 ft (183 m) from the last luminaire. Again, the distance was based upon observations made during site selection. At many of the partially lighted diamond interchanges, the ramp was initially tangent and then curved. The "far" placements were used to assess the longevity of the transient effect. The "far" placement of the targets on the entrance ramp was selected to be halfway between the "near" and "far" placements of the exit. As such the "far" targets were located 475 ft (144.88 m) downstream from the last luminaire of the entrance ramp. The locations of the targets relative to the luminaries are shown on figure 3. However, only one target location was used on each trial in each direction.

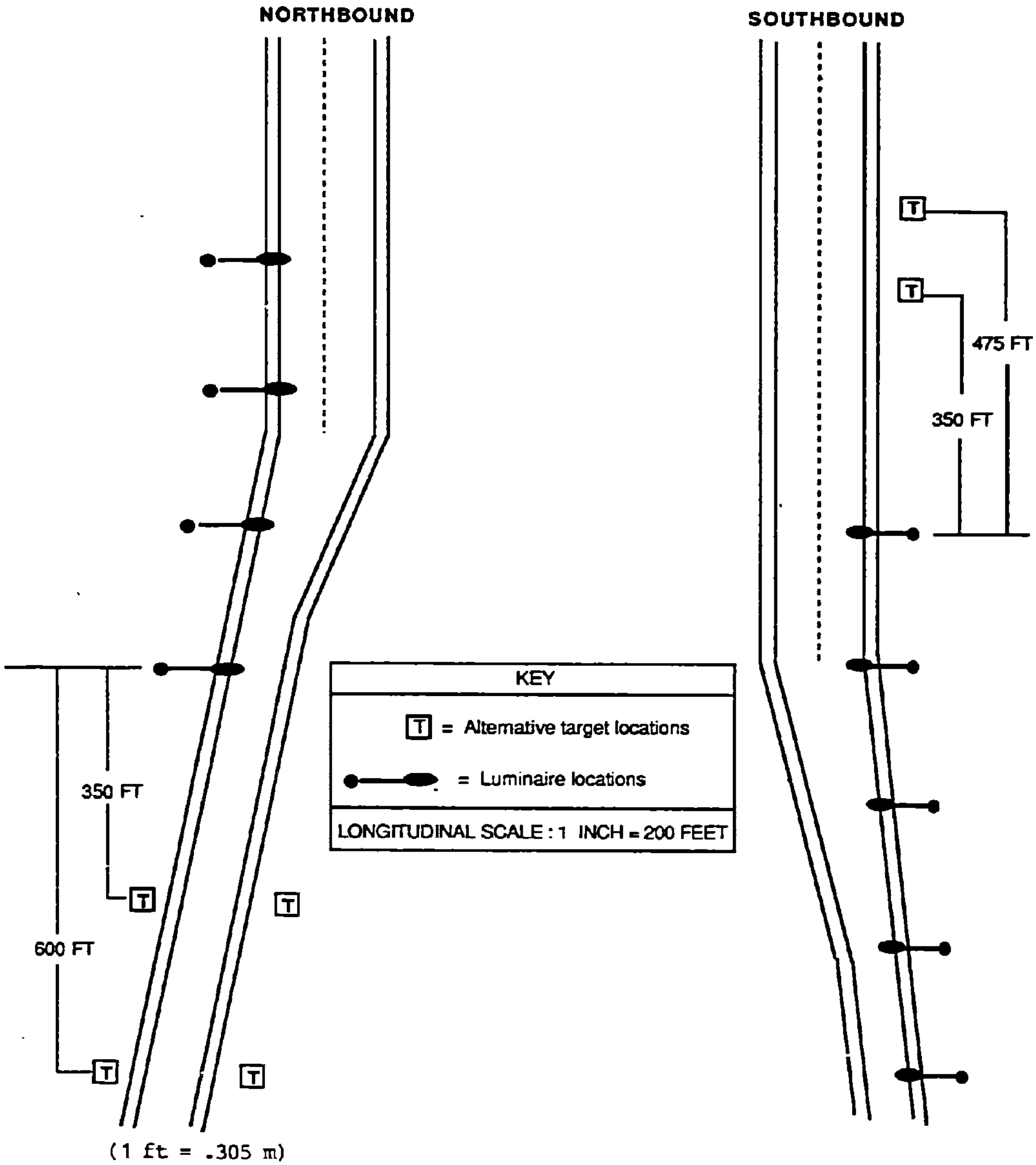


Figure 3. Target locations for TVA study.

Single targets were placed on the shoulders, 2 ft (.61 m) from the outside edge of the ramp stripes. If two targets were used at a location, the second was placed outside the first by 1.5 ft (.46 m). That is, the gap between them was 1.5 ft (.46 m).

5. Subjects

All subjects were tested for contrast sensitivity using the Vistech VCTS 6000 system (Vistech Consultants, Inc., Dayton, OH). All subjects had normal contrast sensitivity. Subjects wore corrective lenses for their driving trials if their licenses so indicated. Subject age and sex breakdown are in table 2:

Table 2. Subjects by age and sex.

Age Group	SEX	
	MALE	FEMALE
18 - 39	4	3
40 - 59	3	3
> 60	2	0

6. Results

To determine whether data from the exit and extrance ramps and from single and paired targets could be grouped to provide larger sample sizes, an analysis of variance was first conducted. The analysis used all data for which the targets were located on the right side at 350 ft (106.75 m). The analysis of variance indicated that there was no significant difference between exit and entrance trials, nor between single and paired targets. Only illumination condition produced a significant F-value; thus data from the exit and entrance trials and single and paired targets were collapsed.

The comparisons of illumination conditions produced differential results depending on the placement of the targets. Better detection performance occurred under nonilluminated conditions for targets located on the right side of the roadway at distances of 350 ft (106.75 m) and 475 ft (144.88 m) from the last luminaire. Targets placed on the right side at a distance of 600 ft (183 m) from the last luminaire and targets placed on the left side of the roadway at both 350 ft (106.75 m) and 600 ft (183 m) produced no significant difference in detection performance between illumination conditions.

Table 3 summarizes the mean detection distances and standard deviations for all targets under both illumination conditions. The t-values associated with the statistical analysis are also provided.

Table 3. Summary of mean distances from point of detection to target, in illuminated and nonilluminated conditions, with targets at various positions downstream of final ramp luminaire.

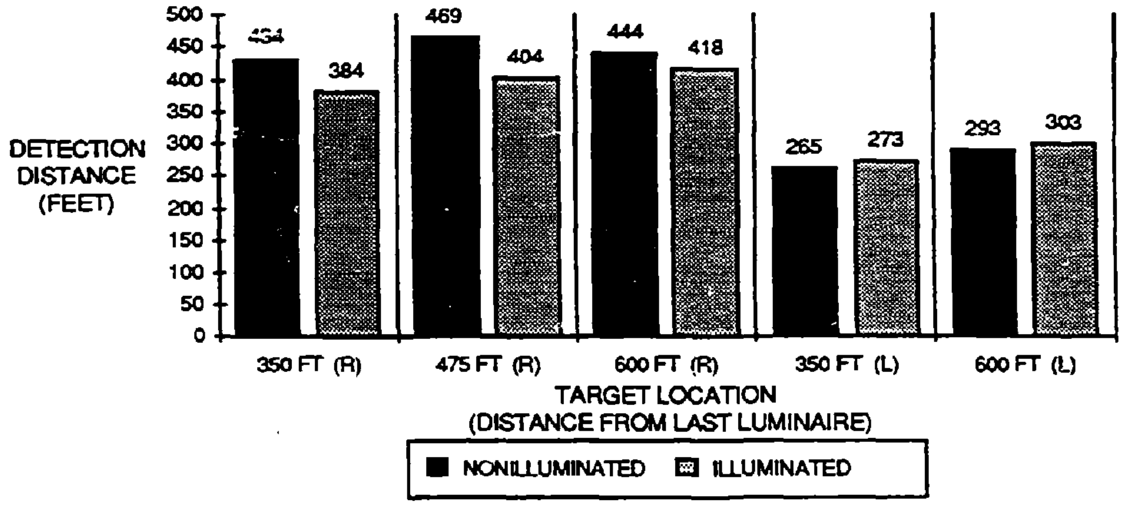
	Illuminated		Nonilluminated		
Target Location (ft)	Mean Detect. Dist. (ft)	Std. Dev.	Mean Detect. Dist. (ft)	Std. Dev.	t-value
Right Side					
350	384	70	434	97	3.91 *
475	404	64	469	80	4.57 *
600	418	103	444	82	0.55 †
Left Side					
350	273	46	265	64	0.02 †
600	303	100	293	54	0.65 †

* is statistically significant.

† is nonsignificant.

(1 ft = .305 m)

The detection distances are shown graphically in figure 4. The detection distances for both lighting conditions and for each target location are shown in appendix A. The confidence intervals for the conditions that were statistically significant are also shown in the appendix.



(1 ft = .305 m)

Figure 4. Distances at which subjects detected targets placed at the five ramp locations (R is right side of ramp; L is left side of ramp).

The t-test for correlated samples was used to assess the significance of the detection differences with targets on the right side at 350 ft (106.75 m). The t-value of 3.91 obtained for the right side targets at 350 ft (106.75 m) is significant at well beyond the .01 level. The mean detection distance for the trials conducted under partial illumination was 384 ft (117.12 m) as compared with a mean detection distance of 434 ft (132.37 m) for the nonilluminated condition. The mean difference in detection distance was 53 ft (16.17 m). Thus it would appear that there is a TVA effect operating when drivers are at a 350-ft (106.75 m) distance from the last luminaire.

As shown in table 3, the targets located on the right side at 475 ft (144.88 m) from the last luminaire also produced a statistically significant difference (t=4.57) in favor of the nonilluminated condition. The mean detection distances were 404 ft (123.22 m) and 469 ft (143.05 m) for illuminated and nonilluminated conditions respectively. The mean difference was 66 ft (20.13 m).

As shown in table 3, the trials with the target located on the right side at 600 ft (183 m) from the last luminaire produced a slight difference in detection distance, with longer detection values under the nonilluminated condition. However, the difference was not statistically significant.

As shown in table 3, with the targets located on the left side, neither the 350-ft (106.75 m) nor the 600-ft (183 m) locations produced a statistically significant difference between the illumination conditions. The shorter detection distances and the lack of a TVA effect for left side targets is most likely due to a combination of the normal right bias of the headlight pattern and the tendency of drivers to drive closer to the right edgeline. All targets were placed on tangent sections and subjects were told that targets would be on the left or right side. Thus neither roadway geometry nor visual scan pattern bias is likely to have produced the left side results.

7. Conclusions

While the conclusions of the TVA study must be tempered because of the relatively small sample, it would appear from the results that TVA occurs under operational conditions. It also appears that the effect is essentially eliminated by the time a driver reaches a point approximately 600 ft (183 m) from the last luminaire (or 400 ft [122 m] from the point at which the influence of the illumination terminates). This suggests that for ramps over 500 ft (152.5 m) in length, an improved delineation system could be terminated at that point, and remaining portions of the ramp could be transitioned to normal delineation. This guideline, of course, takes into consideration only the effects of reduced visual sensitivity produced by the illumination. Other factors such as geometrics and inclement weather must be considered in determining whether or not to improve delineation along the entire ramp.

FIELD STUDY OF LIGHTING AND DELINEATION

1. Method of Selection of Delineation Systems

The delineation systems tested were selected by a panel of eight individuals who had expertise in the areas of delineation, illumination, and visibility. The expert panel included representation from State agencies, a university, and consultants and research organizations. The recommendations from the panel were obtained in two stages. The first stage requested the recommendation of surface (e.g., raised pavement markers, paint, etc.) and vertical (e.g., posts) delineation devices having various characteristics for the different segments of a freeway interchange exit. For purpose of this specification the interchange was divided into the advance area, taper and deceleration lane area, gore area, and the ramp. The panel was asked to choose the delineation devices or combination of devices recommended for use on the left and right side of the driving lane in each of the segments. The results of this first submission were compiled and the delineation systems that represented the greatest degree of agreement were identified. The second phase consisted of submitting these system specifications to the panel members for comment and approval.

2. Delineation Systems Tested

The Baseline delineation system, shown along with the upgraded systems in table 4, was similar to the delineation used at many of the partially lighted interchanges cataloged during site selection. With regard to the opinions of the expert panel, the Baseline condition constituted a minimum system for partially lighted interchanges. Figure 5 shows the Baseline delineation system in illustrative fashion. It should be noted that because of the range in sizes of delineation elements, it was not possible to develop scale drawings that would fit on a page. Therefore, all of the site drawings are illustrative only and are not shown to scale with regard to size or spacing. The actual spacing between delineation elements is given in appendix B.

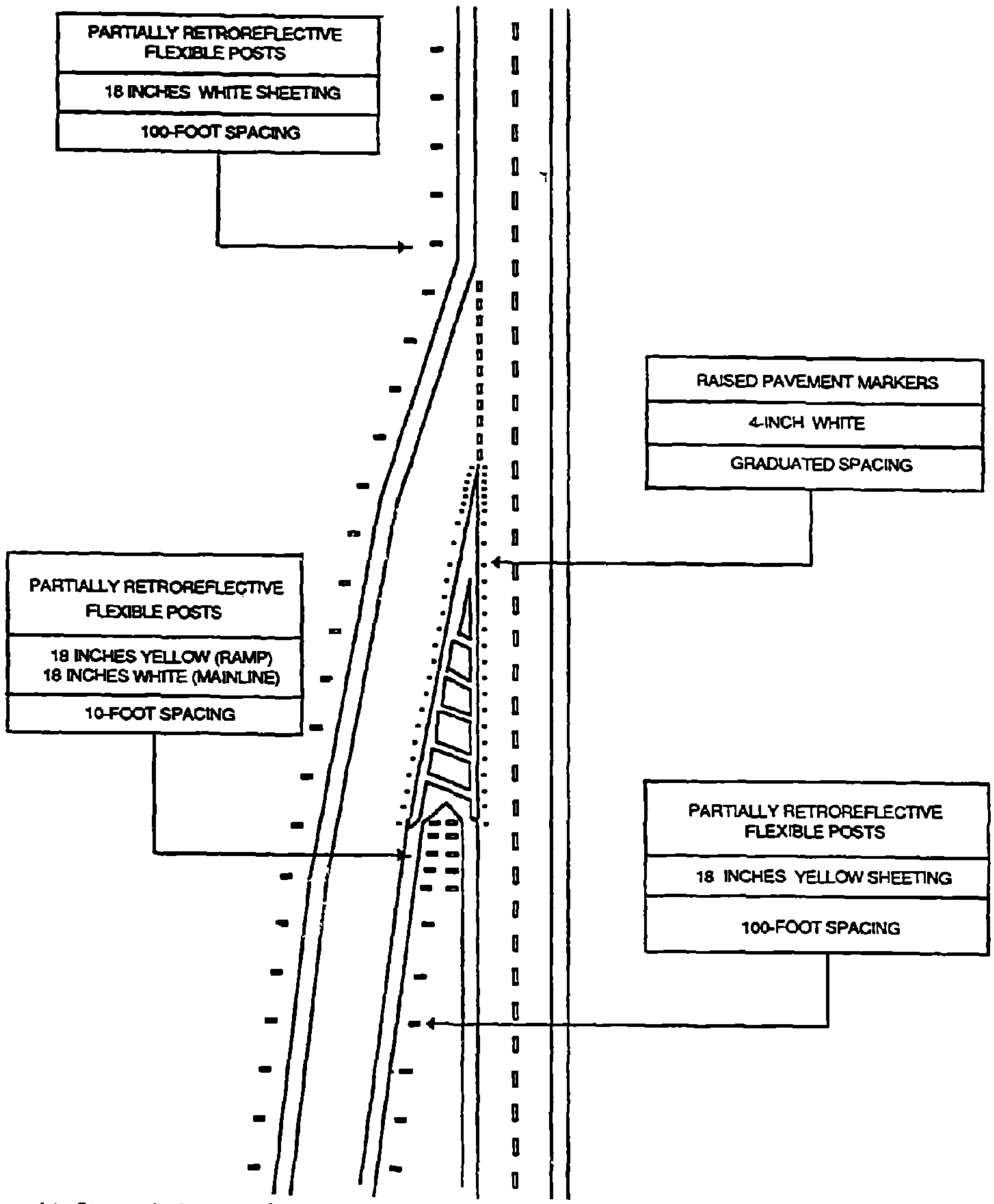
Table 4. Delineation systems tested.

Location	System	Stripes/ raised pavement markers	Flexible posts fully (46 in) or partially (18 in) retroreflective	Spacing (ft)	
				RPM's	posts
Left side of ramp	Baseline	Paint[1]	Partial		100
	Upgrade 1	Paint, RPM's	Partial	20 - 40	100
	Upgrade 2	Paint	Partial		50
	Upgrade 3	Paint, RPM's	Full	20 - 40	100
Right side of taper, ramp	Baseline	Paint	Partial		100
	Upgrade 1	Paint	Partial		100
	Upgrade 2	Paint	Partial		100
	Upgrade 3	Paint	Full		100
Gore stripes	Baseline	Thermoplastic[1], RPM's		Graduated[2]	
	Upgrade 1	Thermoplastic, RPM's		Graduated	
	Upgrade 2	Thermopl., wide RPM's		Graduated	
	Upgrade 3	Beaded, profiled tape			
Gore	Baseline		Partial		10
	Upgrade 1		Full		10
	Upgrade 2		Partial		10
	Upgrade 3		Partial		10

1 All paint and thermoplastic was glass beaded.

2 RPM spacing along gore stripes was 5 to 40 ft (1.5 to 12.2 m), tip to base.

(1 ft = .305 m)



(1 ft = .305 m; 1 in = 2.54 cm)

Figure 5. Baseline delineation.

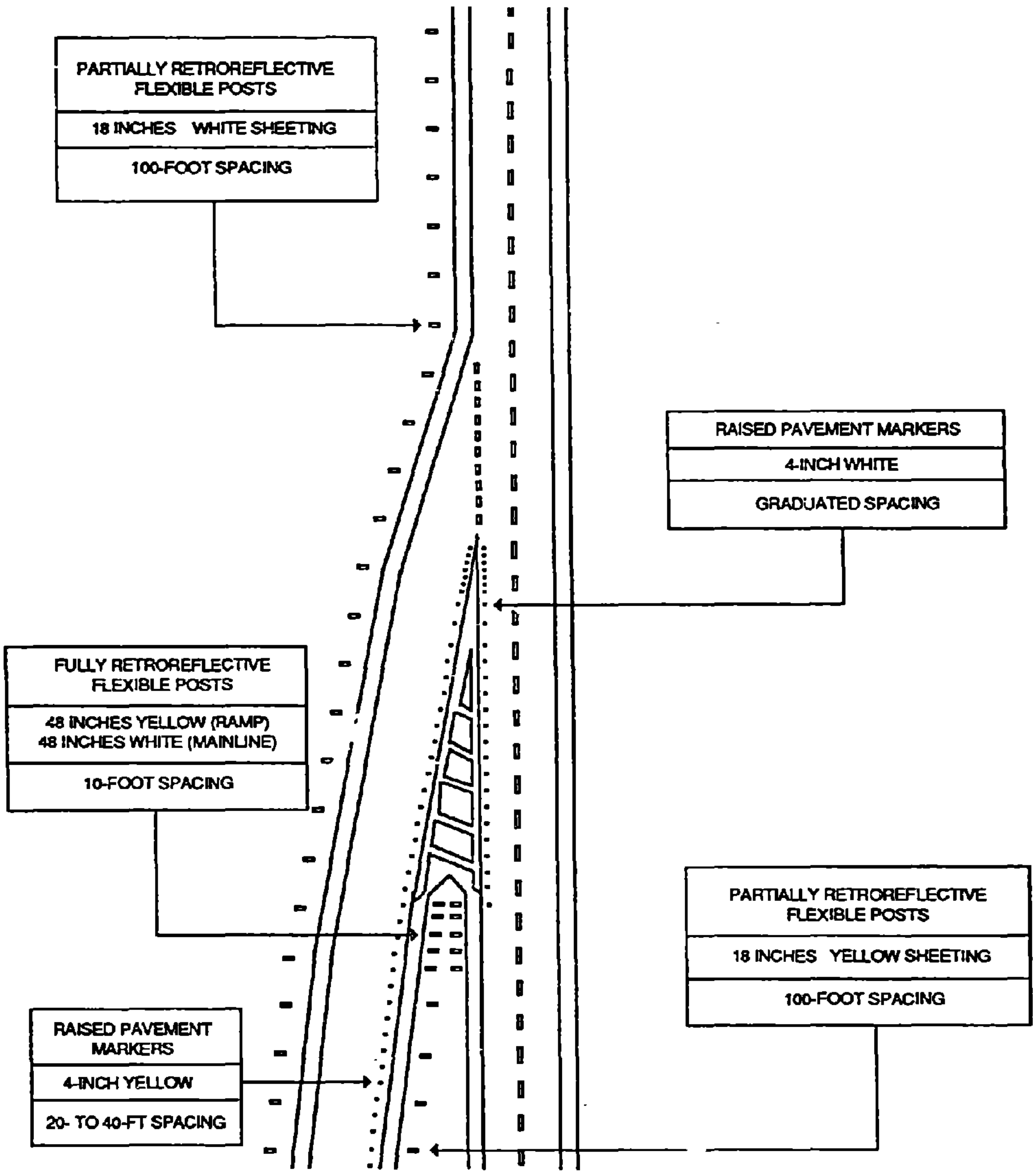
Upgrade 1 differed from the Baseline in the use of raised pavement markers (RPM's) along the left ramp stripe, and the substitution of fully retroreflective posts for partially retroreflective posts in the physical gore. Fully retroreflective posts contained a 46-in (116.8 cm) strip of 3-in (7.62 cm)-wide sheeting. Partially retroreflective posts contained an 18-in (45.7 cm) strip of 3-in (7.62 cm)-wide sheeting. Upgrade 1 is shown in figure 6.

Upgrade 2 differed from the Baseline in the deployment of additional posts along the left ramp shoulder to create a spacing of 50 ft (15.25 m) rather than 100 ft (30.5 m), and in the installation of wide RPM's (called traffic diverters) on the gore stripes to replace the 4-in (10.16 cm) RPM's placed adjacent to the gore stripes in the Baseline system. This upgrade is illustrated in figure 7.

Upgrade 3 replaced all Baseline system partially retroreflective posts with fully retroreflective posts except in the gore; used RPM's along the left ramp stripe; and used beaded, profiled tape containing a raised-diamond pattern for gore striping. The tape, applied without primer for quick installation and removal after data collection, was used because it would project above a film of water during rain like a heavy epoxy stripe containing glass beads. Figure 8 illustrates the Upgrade 3 configuration. As noted, details regarding the configuration of each delineation system tested are given in appendix B.

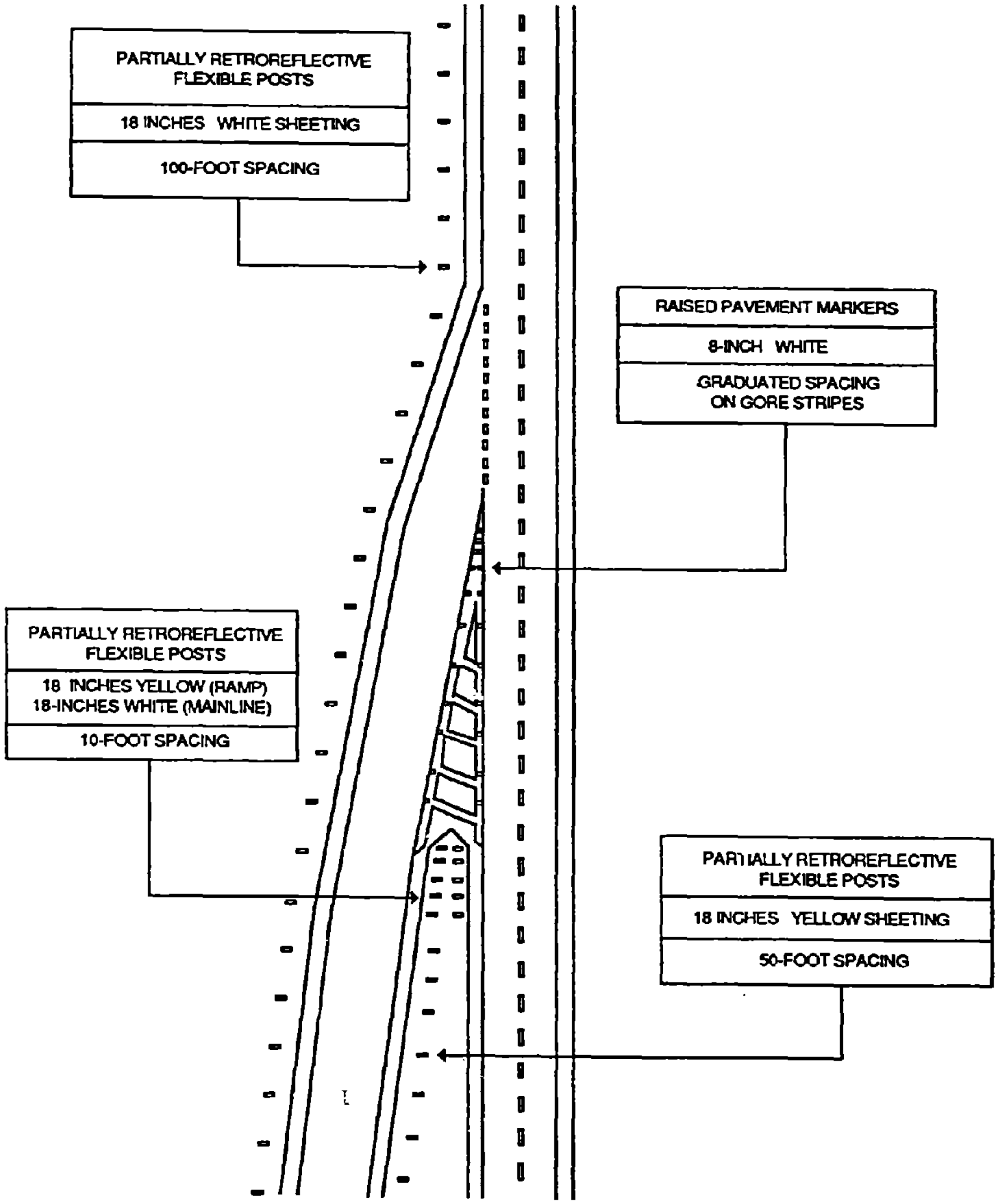
3. Site Selection

The original contract called for the field tests to be done on a cloverleaf interchange. However, in the process of site selection, 450 sites with partial lighting were cataloged and none of the sites was of cloverleaf design. Lighted cloverleafs contained full or high-mast lighting. States would be reluctant to reduce full lighting to partial for a field test, fearing tort liability if an accident ensued. Site selection and cataloging took place on the West Coast (California, Oregon, Washington) and the East Coast (Pennsylvania, Maryland, Virginia). Virtually all of the sites which



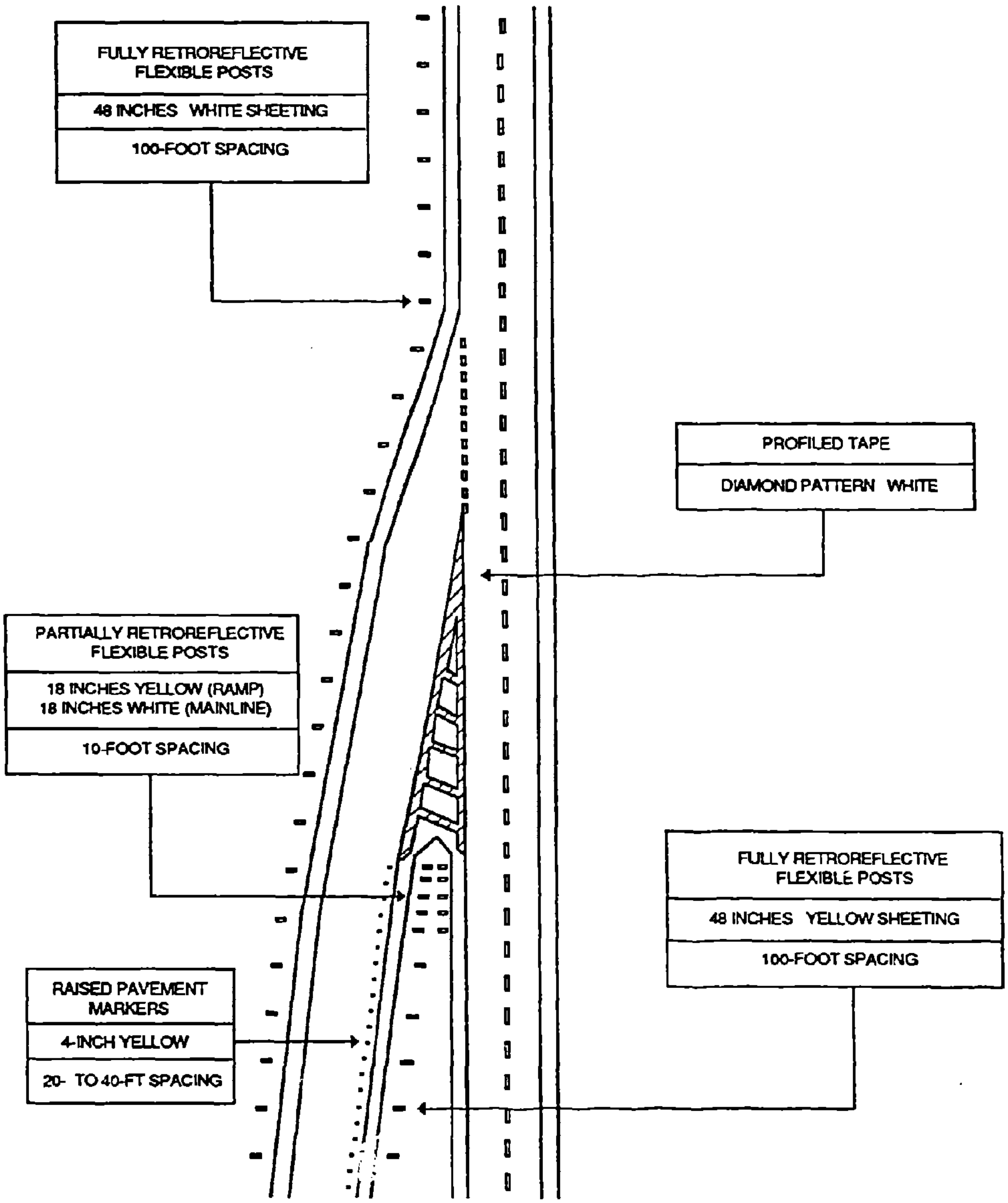
(1 ft = .305 m; 1 in = 2.54 cm)

Figure 6. Delineation Upgrade 1.



(1 ft = .305 m; 1 in = 2.54 cm)

Figure 7. Delineation Upgrade 2.



(1 ft = .305 m; 1 in = 2.54 cm)

Figure 8. Delineation Upgrade 3.

operated with partial lighting were diamond interchanges which exhibited very little ramp curvature. Based on this sample it was determined that the sites selected for the field tests are representative of those for which partial lighting is most likely to be used. One important factor in selection of sites was that the location be in an area in which the probability of obtaining rain data would be maximized. Therefore, following the cataloging of partial lighting to determine the predominant design, site selection was concentrated in the Northwest.

4. Site Characteristics

Both sites selected for the field tests were diamond interchanges representative of the type of geometrics on which partial lighting is most frequently used. A primary advantage of the sites for the purposes of the research was that both were designed and built as fully lighted interchanges but were being operated in a partially lighted mode. Thus there were no problems in obtaining permission to operate under both full and partial lighting conditions during field testing. This made it possible to obtain comparisons of full lighting with nominal delineation and partial lighting with the same delineation and additional upgraded delineation systems. Further, the two sites were reasonably similar in geometric characteristics but differed with respect to the level of partial lighting used, i.e., one of the sites operated as a one-luminaire partial and the other as a three-luminaire partial. While the sites were not "matched" to the extent that direct statistical comparisons could be made, the general similarities provide some insights as to the potential effects of the two levels of partial lighting. For the site descriptions below, and for reference in describing the results, the one-luminaire site will be referred to as Site #1 and the three-luminaire site will be referred to as Site #2. Figures 9 and 10 show photographs of each site to depict the geometrics of the sites.

Figure 9. Site #1 photo.

Figure 10. Site #2 photo.

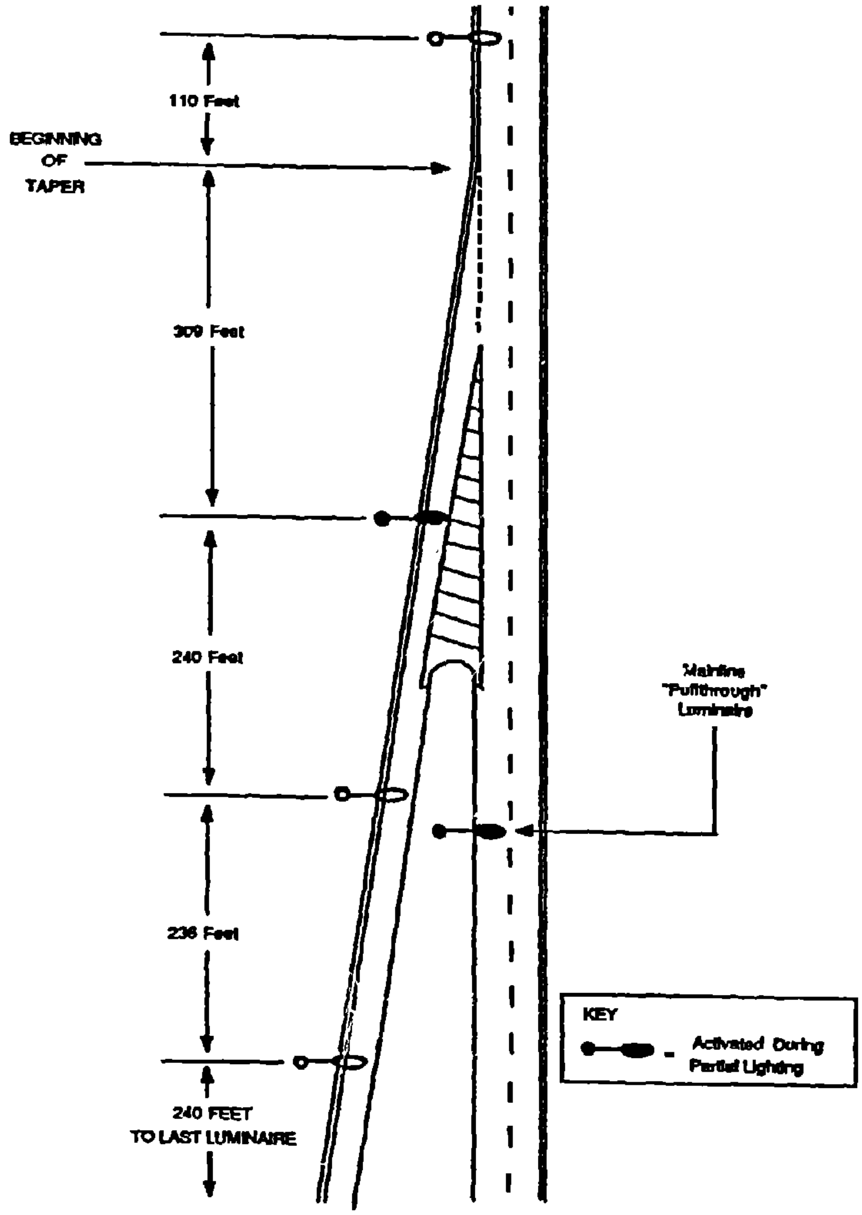
a. Site #1

The interchange design was a half diamond. The exit site was a direct taper from the mainline onto a tangent ramp. The exit taper left the mainline at the end of a very slight horizontal curve and, in effect, continued the curve. The exit itself was straight and level to a stop-sign controlled intersection with the crossroad. While designed and built for full lighting, the site was operated with a single luminaire along the ramp near the gore, and a single luminaire on the mainline side of the gore. The locations of the luminaires relative to the exit and the gore stripes are shown in figure 11. Mainline and ramp were of asphaltic concrete in good condition.

The approach to Site #1 was near the crest of a long incline. The incline was steep enough to drop mainline speeds of commercial vehicles and underpowered cars below the 55 mi/h (88.6 km/h) limit. But most vehicles traveled at or slightly above the speed limit because the incline was leveling to its crest where the exit taper began. The horizontal and vertical curvature of the approach hid the exit, and the driver's primary cues, aside from the advance guide sign upstream of the exit taper, were the white retroreflective, flat, flexible guide posts that lined the right shoulder every 100 ft (30.5 m), beginning 300 ft (91.5 m) in advance of the exit taper and continuing down the ramp. The exit signing was adequate in all respects.

b. Site #2

The interchange was a full diamond. The exit site was a direct taper from the mainline onto a slightly curved ramp. While built for full lighting, the site was operated with three luminaires (the most downstream one adjacent to the gore), and with a "pull-through" luminaire on the mainline side of the gore. Mainline and ramp were of asphaltic concrete in good condition. The ramp exhibited a very slight grade to its intersection with the crossroad. At the terminus was a stop bar and traffic signal. The traffic signal, being demand actuated, was red for all lead vehicles. The detector coils for signal actuation began 55 ft (16.78 m) upstream of the stop bar.



(1 ft = .305 m)

Figure 11. Site #1 lighting configuration.

The signal normally cycled from red to green 6 seconds after the detector was triggered. The cycle was aborted and the light remained red if the vehicle immediately made a right turn on red. In cases where traffic on the crossroad was heavy, the cycle from red to green could take as long as 60 seconds. The light remained green for 3 seconds, then cycled to yellow and, 2 seconds later, back to red. About 75 percent of traffic turned right at the ramp terminus during hours of data collection. Much of it made a right turn on red before the signal cycled to green. The signal was fully visible once the exiting driver reached the physical gore area.

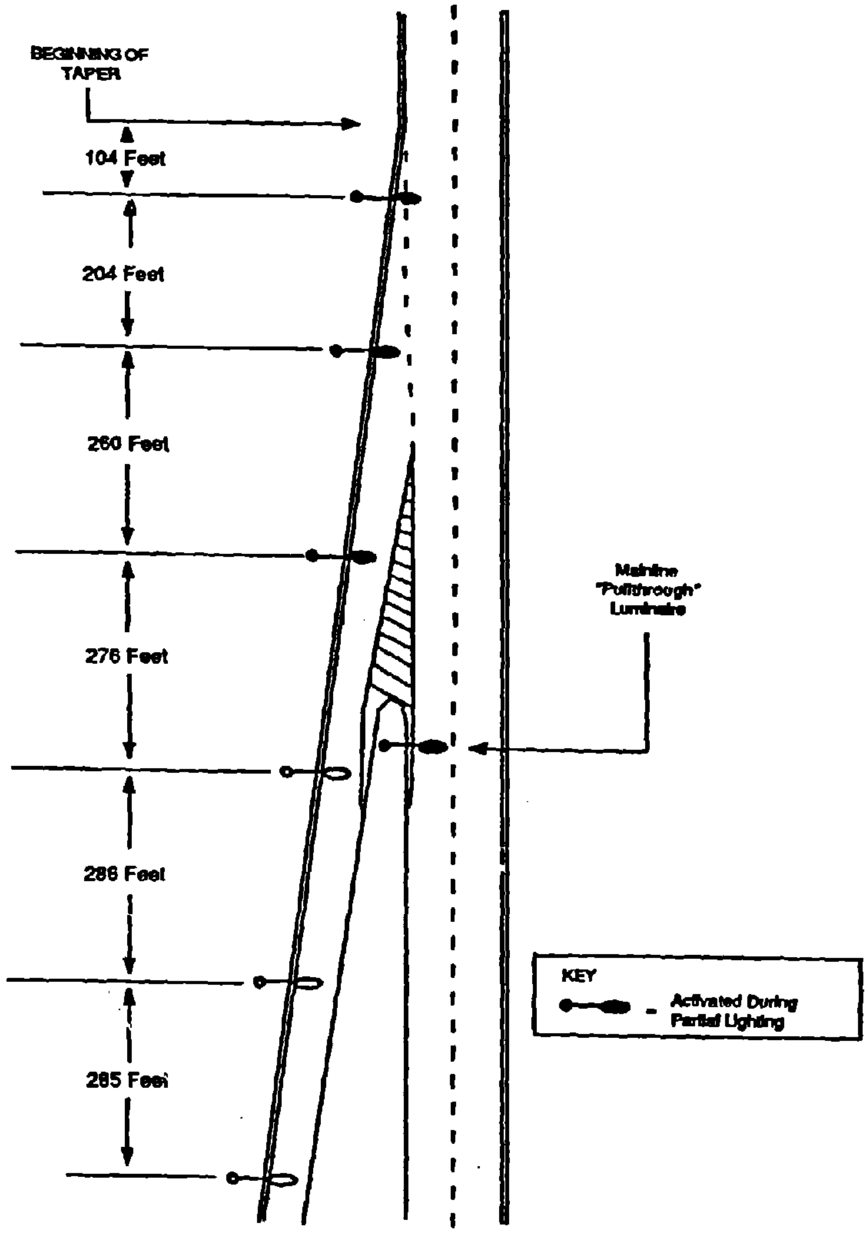
The approach to Site #2 exit was level and straight for about 600 ft (183 m). The approach followed a very gentle curve that required no decrease from freeway speeds. The speed limit was 55 mi/h (88.6 km/h), with most vehicles traveling between 55 and 65 mi/h (104.7 km/h). A driver could detect the Site #2 exit about .75 mi (1.21 km) upstream of the exit taper, because the interchange illumination could be seen. The exit signing was adequate in all respects. The locations of the luminaires are shown in figure 12.

5. <u>Illumination Characteristics</u>

The lighting systems were installed about 15 years ago to provide full lighting for the interchanges. The installations were designed to provide an average level of horizontal illumination in the order of 0.5 to 0.8 fc (6 to 9 lx) maintained in service in accordance with the American Association of State Highway and Transportation Officials (AASHTO) "Informational Guide for Roadway Lighting" applicable at the time they were designed.[8]

The Site #2 ramp utilized clear 700-watt mercury lamps mounted at 41.5 ft (12.7 m). The last luminaire on the exit ramp (location 13.2 in figures 13 and 14) was replaced with a 310-watt high pressure sodium (HPS) lamp as part of a relighting project of the interchange overpass.

The Site #1 ramp utilized 400-watt color improved mercury lamps mounted at 30.75 ft (9.4 m). One pole, 105 ft (32. m) downstream of the beginning of the exit taper, had been knocked down and was never replaced.



(1 ft = .305 m)

Figure 12. Site #2 lighting configuration.

The exit ramps are a nominal 14 ft (4.3 m) in width, single lane, asphaltic concrete, widening to two lanes near the intersection with the crossing roadways. No attempt was made to clean, relamp or otherwise revitalize the lighting systems prior to collection of the primary study data. However, following the primary data collection, the units at Site #2 were cleaned and relamped, and a second set of measurements was taken at the original locations. In addition, a small supplementary set of driver performance measures was taken following the cleaning and relamping of the luminaires to determine whether the enhanced illumination had any effect on performance.

6. Techniques Used to Determine Lighting Levels

The lighting equipment was identified as to manufacturer and catalog number, and manufacturers' photometric data (candela tables) were obtained. Illuminance values along the entire length of the ramps, as well as layout and luminaire locations, were measured and recorded. A comparison of the published data and the "inservice" illuminance measurements at each pole was used to arrive at a maintenance factor (MF) for calculation purposes evaluating the lighting conditions as found during the field measurements. The actual MF for the six luminaires at Site #2 ranged from 0.16 to 0.70, with an average of 0.58. A computer program was used to calculate the initial design (new equipment) and the theoretical "inservice" levels, using MFs of 1.0 and 0.6 respectively. A second set of "inservice" conditions was calculated using the actual MFs found for each luminaire. These calculations provided measures of average illuminance in lux (lx), average pavement luminance in candelas per square meter (cd/m^2), and an experimental measure of small target visibility in VL (visibility level).

VL is being considered as a possible future criterion for roadway lighting. In the initial design level calculations, all luminaires at the Site #2 interchange were considered to be alike, and the knocked down luminaire at the Site #1 interchange was considered to be in place. A MF of 0.60 was used in the initial design level calculations.

This technique was validated at the Site #2 interchange. Horizontal illuminance readings were taken along the right edge of the pavement in 20-ft (6.1 m) intervals over the entire 1,500-ft (457.5 m) length of the ramp with the lighting system in the "inservice" condition. The luminaires were then cleaned and relamped and a second set of illuminance readings was taken at the same locations. The computer program was then used to provide illuminance levels for the 1,500 ft along the right side of the ramp of Site #2 (see figures 13 and 14). A comparison between readings was analyzed. The technique permits calculations of many types to be made, such as levels of illuminance, luminance, or small target visibility at any point under the partial lighting, and eliminates the necessity to close the ramp for several hours while readings are taken over a complete grid pattern on the roadway.

7. Lighting System Performance

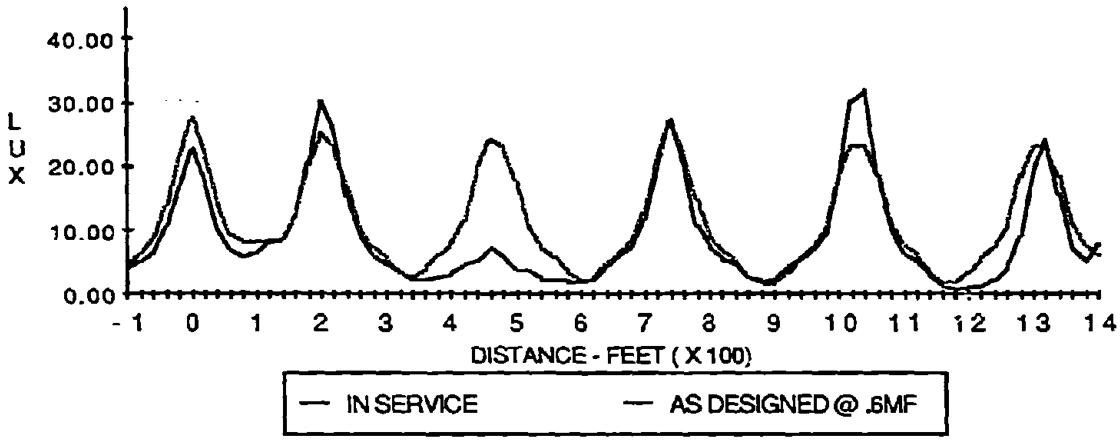
The results of the computer runs to calculate the light levels, pavement luminance levels, and small target visibility are shown in table 5.

Table 5. Computer-calculated road illuminance, pavement luminance, and small target visibility at each exit.

Interchange	Calc. basis	Avg. lux	Avg. cd/m^2	80% of Grid with VL greater than
Site #2	Maintained Design	9.6	.91	4.8
Site #2	Inservice	9.3	.52	3.6
Site #1	Maintained Design	7.8	.66	3.7
Site #1	Inservice	4.5	.22	2.8

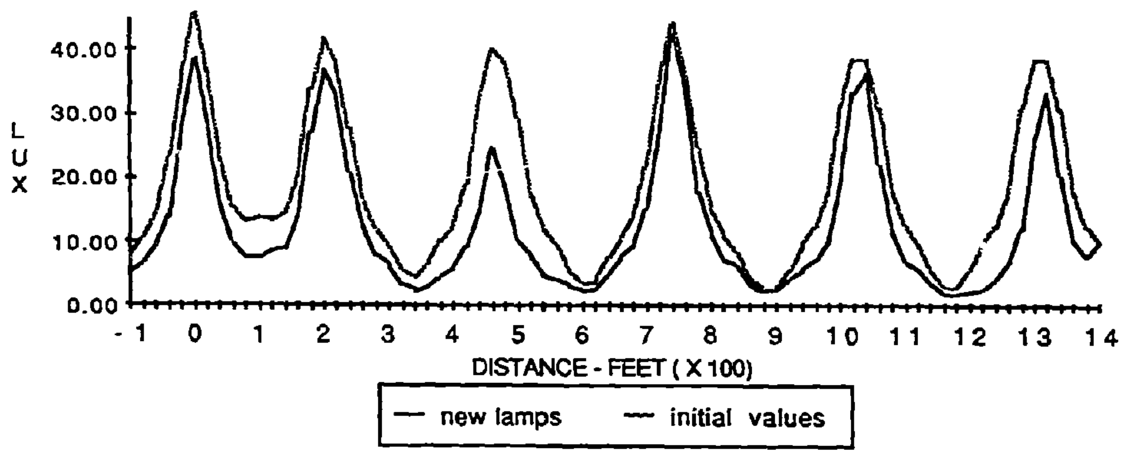
(1 lx = 0.093 fc; 1 cd/m^2 = 0.292 fL)

The Site #2 interchange "inservice" values of average illumination are very close to the calculated values based on a 0.6 MF when all luminaires are considered. Individual luminaire performance, however, varied widely, with the individual MF values ranging from 0.16 to 0.7, which resulted in very poor uniformity and a decline in the VL of the small target. Even after the luminaires were cleaned and relamped the individual MF values ranged from 0.54 to 0.95, indicating that severe permanent deterioration had occurred in one of the luminaires. The standard deviation obtained for the cleaned and relamped data was smaller (.16) than for the "inservice" data (.26). This indicates that dirt does not act as a simple filter reducing all candela



(1 ft = .305 m; 1 lx = 0.0929 fc)

Figure 13. Site #2 illuminance levels under full lighting, as designed and as measured inservice, at intervals along exit.



(1 ft = .305 m; 1 lx = 0.0929 fc)

Figure 14. Site #2 illuminance levels under full lighting, as designed (initial values) and as measured (new lamps), at intervals along exit.

values proportionally, but rather in a selective manner. While this observation is beyond the scope of the present study, this finding should be further investigated by the lighting community.

The Site #1 interchange "inservice" values of average illumination are well below the design assumption of a 0.6 MF and are only one-third of the calculated initial values. A part of this is due to the fact that one of the six luminaires had been knocked down and taken out of service. The actual range of MF for the luminaires still operating was from 0.36 to 0.47, which is well below the 0.6 that could be expected.

Small target visibility is calculated by means of a "visibility model" in which the primary variables are target contrast, adaptation level of the visual system, and disability glare. The calculation purports to predict the amount that the visibility of a small target (7-in, flat square of 20 percent reflectance, perpendicular to the road surface) is above threshold for a young observer viewing it for 0.2 seconds. A VL of 1.0 is threshold (visible 50 percent of the time) for the observer. Since VL is most sensitive to contrast, it is not affected by a reduced light level to the same proportion as is illuminance or pavement luminance. The relationship of VL, illuminance and pavement luminance to night accident rates has been the subject of research.(9) No computer evaluations were made for the partial lighting setups as there are no standard methods of evaluating the effectiveness of a single (or a few) luminaire. Roadway lighting is normally evaluated for a system sufficiently long so that adding or deleting one luminaire at the end does not affect the values on a typical grid near the middle of the system.

In comparing the data relative to vehicle speeds and placements under the full and partial lighting systems, it should be remembered that the fixed lighting systems in their "inservice" condition fail to meet the AASHTO recommendations for illuminance. The Site #2 interchange fails in terms of uniformity, and the Site #1 interchange fails in terms of both average level and uniformity.

8. Field Study Design

Table 6 shows the lighting, weather and delineation conditions under which data were obtained. The intended design of the study called for collection of rain data for delineation Upgrade 1; however, an extended period of dry weather during the time this upgrade was installed prevented this data cell from being filled. Otherwise the data collection was accomplished as planned. Following the completion of the data collection under the conditions specified in table 6, new lamps were installed at Site #2, and several nights of data were obtained under the upgraded lighting condition.

Data were collected on 79 nights and over four seasons. A total sample of nearly 17,000 vehicles was obtained. Because data were collected in each season, start of data collection varied from about 6:15 p.m. to 9:45 p.m., with termination from about 11:00 p.m. to 2:00 a.m., depending on traffic volume. Data collection was not begun until peak-hour traffic had dissipated, usually by 6 p.m., so that mainline speeds and exit speeds would be unimpeded.

Table 6. Lighting and weather conditions under which delineation systems were tested.

		DELINEATION TREATMENT			
LIGHTING	WEATHER	BASELINE	UPGRADE #1	UPGRADE #2	UPGRADE #3
FULL	WET	A	——	——	——
	DRY	B	——	——	——
PARTIAL	WET	C	——	D	E
	DRY	F	G	H	I

—— = empty cell

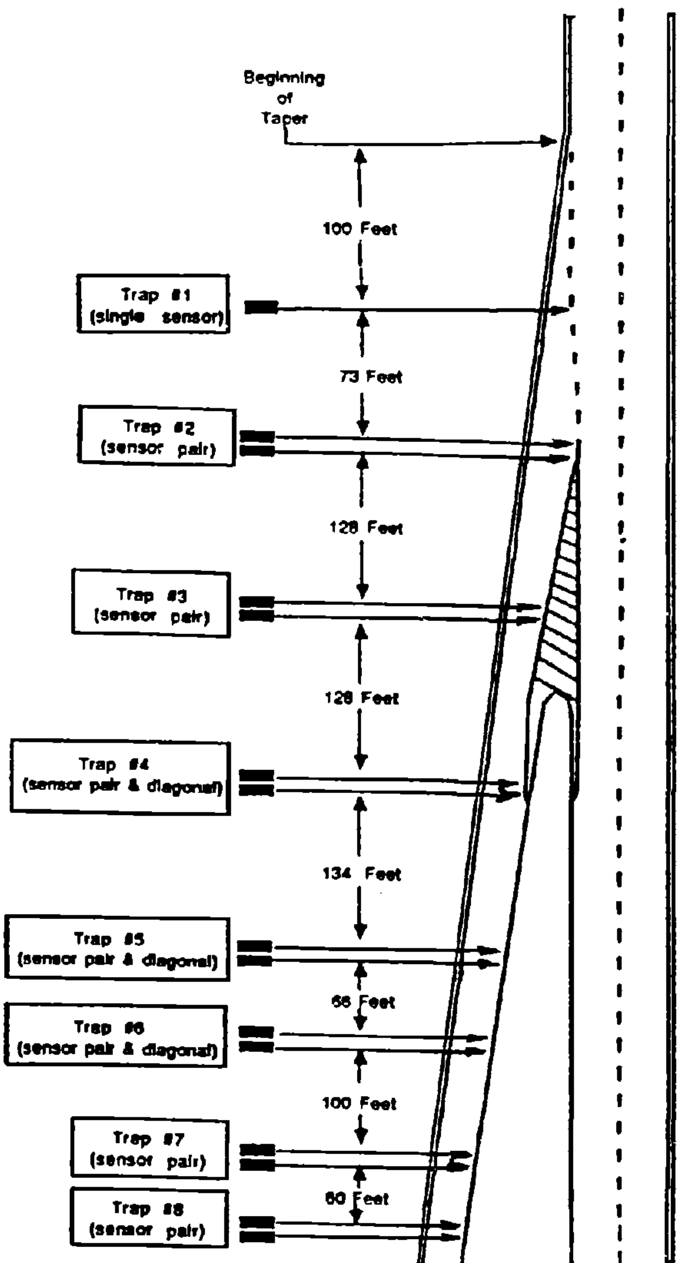
Virtually all data collection took place on Sunday through Thursday nights. However, because of the below normal rainfall that prevailed during much of the overall data collection period, it was necessary to obtain some of the rain data on Friday or Saturday nights (Site #2: two of three nights in Upgrade 3; Site #1: two of four nights in Baseline).

A minimum 2-day adaptation period followed any change in lighting and/or delineation. Because speed is the primary dependent measure used to assess the effects of the independent variables, only single or lead vehicles are represented in the data reported.

9. Evaluation Measures and Instrumentation

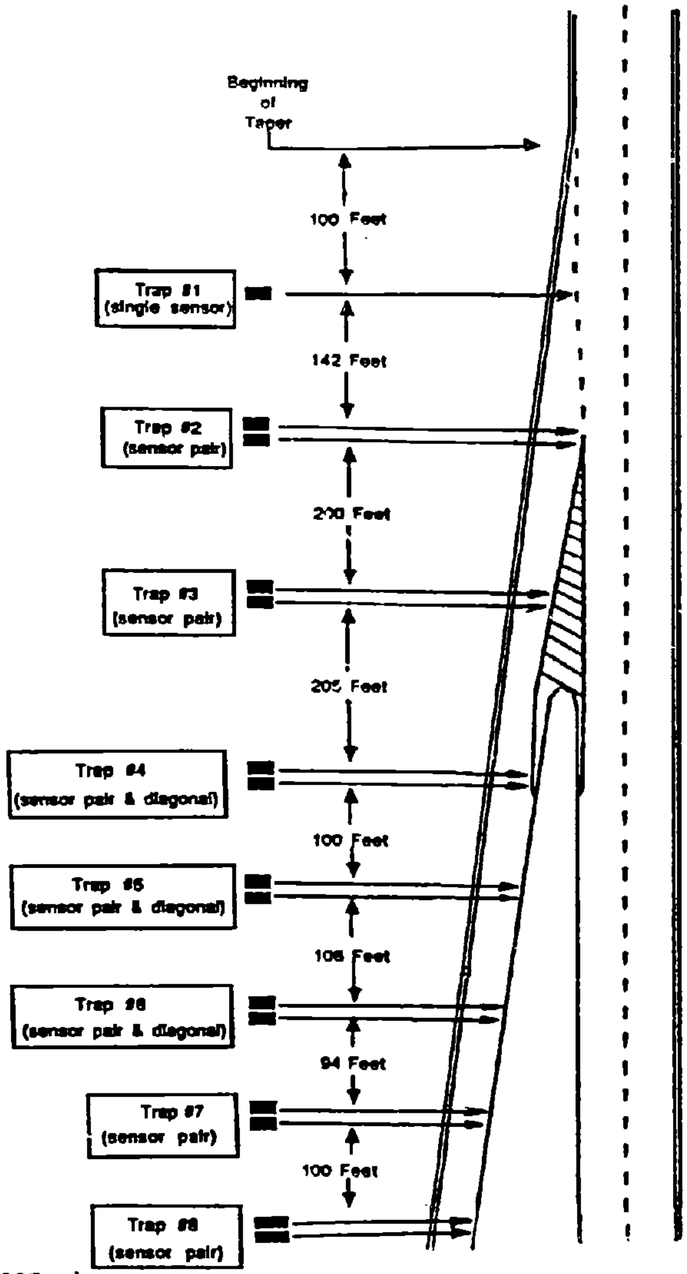
Data collection was achieved through a deployment of infrared (I/R) photo-relay detectors and the FHWA Traffic Evaluator System (TES). The I/R detectors were those commonly used as doorway announcers or home burglar alarms, which were modified to increase their range. The range increase was achieved by replacing the standard I/R light-emitting diode with a high-output one. In operation, an infrared beam is transmitted toward a reflector and then back to the detector; breaking the beam by interposing an object between the detector and the reflector causes a relay in the detector to close momentarily. Relay contacts from the array of detectors were wired into the TES through the standard junction boxes. The TES event recorder automatically records all detector actuations to a precision of 1/16 ms, which allows determination of speeds to well under 1/100 mi/h (.016 km/h), using a "trap" composed of two "switches" (I/R detectors and reflectors) spaced 6 ft (1.83 m) apart and perpendicular to traffic flow. Diagonally arranged switches were used to determine vehicle lane placement. Figures 15 and 16 show the trap layouts for Sites #1 and #2. Detailed information on the deployment of the measurement system is given in appendix C.

Measures available through data analysis include individual vehicle speeds, overall travel time through the trap deployment (or any portion thereof), deceleration estimates, lane placement, and statistics on all the vehicles, such as mean and standard deviation of spot and space mean speeds, lane placement and any other individual measures.



(1 ft = .305 m)

Figure 15. Site #1 speed trap configuration.



(1 ft = .305 m)

Figure 16. Site #2 speed trap configuration.

Observations of selected types of erratic maneuvers, along with brake light and headlight measures, were entered into the TES event recorder via button boxes. Only the activity of single and lead vehicles was recorded. Observers also recorded events which could be expected to influence exit speeds, e.g., vehicles temporarily stopped on the shoulder or between the gore stripes. The latter observations were used in data reduction to edit the data set and exclude vehicles likely to have been influenced by any unusual event.

An observer stationed in advance of the exit coded brake light activations of exiting drivers in advance of the exit taper, i.e., in the freeway mainline. Erratic maneuvers observed and coded from this position were exclusively encroachments by exiting drivers on the right edgeline at the beginning of the exit taper (i.e., cutting the corner).

An observer stationed adjacent to the gore stripes recorded high-beam and low-beam activations. In practice, the buttons for high beam activation or dipping were almost never used. Virtually all drivers entered and traversed the exit with low beams activated. Erratic maneuvers observed from this position included encroachments on the tip of the gore stripes and the ramp-side gore stripe, and cutting across the gore stripes to make a late entry into the exit taper.

Observations from both button box positions were easier to make at Site #1 than Site #2 because at Site #1, observers were on a hillside. As a result, more erratic maneuvers were observed at Site #1. In particular, encroachment on the shoulder at the beginning of the exit taper was much easier to detect at Site #1. At Site #2, such encroachments were difficult to detect, especially on wet pavement when water and spray obscured the right edge stripe.

A third button box was located at the TES event recorder. There were buttons to indicate: the beginning or resumption of data collection after the event recorder was started and tested; interruption or end of good data collection (e.g., used when a State patrolman stopped a vehicle in the exit for a traffic citation); beginning of data collection in rain; end of data collection in rain; and end of wet pavement condition. These codes were subsequently used in data reduction to exclude vehicles that might have been influenced by unusual events and to identify the vehicles that were to be included in the wet weather sample.

10. Data Analysis

Before describing the results of the field study several notes on the analyses and the data to be reported are in order. Recall that the primary objective of the research was to determine the extent to which upgraded delineation under partial lighting can produce performance that is the equivalent of the performance observed under full lighting, i.e., can compensate for the reduced visibility of partial lighting. The treatment conditions can, potentially, influence several aspects of driver performance: the mean speeds; the distribution of speeds; and other aspects of driver behavior such as incidence of erratic maneuvers or the manner in which headlights are used.

Further, the effects may be manifested only at individual traps or, if the effects are stronger, over a longer segment of the ramp. With regard to the analyses then, there are four types of treatment effects to be considered: the effects on space mean speed over a segment of the ramp (hereafter referred to as "ramp" performance); the effects on spot speed at individual traps (hereafter referred to as "trap" performance); the effects on the speed distributions related to both ramp and trap data; and the effects on other aspects of driver behavior such as braking behavior, erratic maneuvers, etc.

The "ramp" space mean speed data reported below represent the speed from Trap 2 (located at the tip of the gore stripes) to Trap 5 (located approximately 100 ft (30.5 m) downstream of the physical gore). A review of the data from the seven full traps showed that speeds for the traps downstream of Trap 5 exhibited a constant decrease that was most likely a response to the traffic control device at the ramp terminal. Consequently, it was decided, in conjunction with the FHWA technical staff, that space mean speed over Traps 2 through 5 would provide the most representative effects of lighting and delineation on overall exiting speed behavior. At Site #1, the distance between Traps 2 and 5 was approximately 390 ft (119 m); at Site #2, approximately 505 ft (154 m).

The effects of weather and delineation on ramp space mean speed were assessed via a two-way Analysis of Variance to determine the singular and interactive effects of the treatment conditions.

Following this analysis the speed distributions for both ramp and individual trap data were determined, and relevant comparisons between delineation conditions were made. The ramp data (performance over Traps 2 through 5) were expected to reveal any general effects. The individual trap data were expected to reveal effects that may have been "hidden" by the aggregation of data over several traps, such as those that may be attributable to TVA. That is, based on the results of the TVA study, effects of TVA would be expected to influence performance in the vicinity of Traps 4 and 5, but not at Traps 2 and 3. The statistical significance of speed distribution differences was determined using the Kolmogorov-Smirnov (K-S) test.

A further analysis of the speed distribution data involved a search for effects represented in the "tails" of the speed distributions. The rationale for this analysis was that a delineation system may produce no statistically significant overall effect on the speed distributions, but may produce significantly different percentages of drivers in the low (15th percentile) or high (85th percentile) end of the distributions. Such effects were postulated to have safety implications.

For example, a delineation system that produces a greater percentage of drivers at lower speeds (particularly on the earlier portion of the exit ramp) is also likely to have produced a greater percentage of drivers who decelerate in the freeway "mainstream." By the same token, a system that produces a higher percentage of speeds at the upper "tail" of the distribution may be linked to a safety problem associated with high speed exiting.

In other words, the analysis of the "tails" of the speed distributions was expected to provide an additional basis for differentiating between delineation conditions. In line with the objective of determining how the various systems under partial lighting compared with full lighting, the analysis of the "tails" of the distributions used full lighting performance as a basis for comparison. That is, the 15th and 85th percentile speeds for wet and dry data under full lighting were determined. These were called the 15th or 85th percentile criterion speeds. The percentage of drivers above and below these 15th or 85th percentile criterion speeds were then calculated for each of the delineation systems in partial lighting. The percentage differences between delineation systems were then compared using a test for the significance between percentages (a variant of the z-test).

In generating some of the graphics and tables used to illustrate the results presented, it was necessary to use abbreviations to identify the experimental conditions. Table 7 below provides the key to the abbreviations used. Heavy vertical lines within speed distribution figures represent 15th and 85th percentile speeds.

Table 7. Key to abbreviations used in graphics and tables.

ABBREVIATION	LIGHTING	WEATHER	DELINEATION
FDB	FULL	DRY	BASELINE
FWB	FULL	WET	BASELINE
PDB	PARTIAL	DRY	BASELINE
PWB	PARTIAL	WET	BASELINE
PD1	PARTIAL	DRY	UPGRADE 1
PW1	PARTIAL	WET	UPGRADE 1
PD2	PARTIAL	DRY	UPGRADE 2
PW2	PARTIAL	WET	UPGRADE 2
PD3	PARTIAL	DRY	UPGRADE 3
PW3	PARTIAL	WET	UPGRADE 3

11. Speed-Related Results—Lighting and Weather with Baseline Delineation

Because of the small amount of driver behavior data relating to the relative effectiveness of full versus partial lighting and to the interaction of lighting and weather, an analysis of these variables was done using only the data collected under the Baseline delineation system. Since this delineation system is similar to the treatments used on many existing interchanges, the results can be generalized to many diamond-type interchanges. Data from the Baseline delineation system taken under full and partial lighting in wet and dry weather (cells A, B, C, and F as designated in table 6, page 30) were used for this analysis.

a. Ramp Space Mean Speed (Trap 2 to 5)

As shown in table 8 both lighting and weather produced statistically significant effects ($p > .05$) on space mean speeds. The difference between the sites from a statistical standpoint is that the interaction between lighting and weather was significant for Site #1 (single-luminaire partial lighting) but not for Site #2 (three-luminaire partial lighting). Recall that space mean speed is the speed between Traps 2 and 5. At Site #1, this distance was approximately 390 ft; at Site #2, approximately 505 ft.

Table 8. Statistical effects of lighting and weather—ANOVA.[1]

	SITE #1		SITE #2	
	F-VALUE	PR > F	F-VALUE	PR > F
WEATHER (W)	72.38	0.0001	47.88	0.0001
LIGHTING (L)	8.97	0.0028	4.95	0.0262
(W) by (L)	16.05	0.0001	1.06	0.3004

In terms of the ramp space mean speed measure (Traps 2-5), there is relatively little difference between full and partial lighting under dry conditions; both the space mean speed and the variances being similar (see table 9). However, the results suggest that, under wet conditions, full lighting produces an improvement in visibility over partial lighting with a one-luminaire configuration. At Site #1 a comparison of full and partial lighting under wet conditions shows that there is a statistically reliable

[1]The full analysis of variance tables for both sites are shown as tables 36 and 37 in appendix A.

difference of nearly 3 mi/h (4.8 km/h) in space mean speed with no increase in speed variance. Whereas at Site #2, there is no difference in speed between full and partial lighting under wet conditions. Also, at Site #1 there is a larger difference between wet and dry conditions under partial lighting than that observed at Site #2.

Table 9. Effects of lighting and weather on space mean speed.

Experimental Condition		SITE #1			SITE #2		
LIGHTING	WEATHER	NUMBER	MEAN	STANDARD DEVIATION	NUMBER	MEAN	STANDARD DEVIATION
FULL	DRY	253	46.0	5.8	834	53.1	5.4
PARTIAL	DRY	1430	46.0	5.8	1661	52.5	5.3
FULL	WET	134	45.6	5.6	315	50.7	8.5
PARTIAL	WET	373	42.7	5.7	194	50.7	7.8

(1 mi/h = 1.6 km/h)

b. Ramp Speed Distributions (Trap 2 to 5)

The speed distribution comparisons of full versus partial lighting for both wet and dry conditions produced a statistically significant (p=>.001) K-S value only for Site #1 under wet conditions. Figure 17 shows the speed distribution obtained on Site #1 in wet conditions. As might be expected from a visibility standpoint, full illumination results in a general upward shift in the distribution at this site. Note that there were no significant values in the analysis of the "tails" of the distributions.

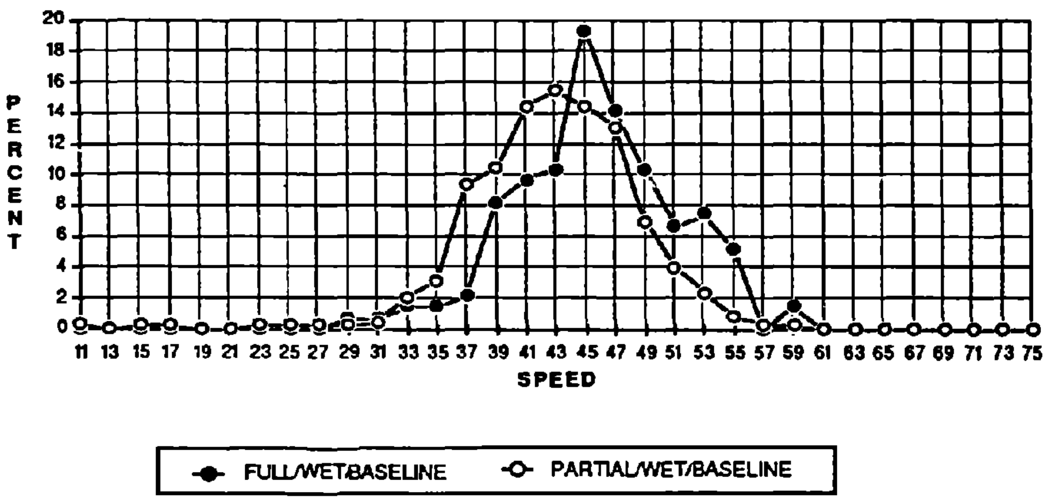


Figure 17. Site #1 ramp speed distributions
(full vs. partial lighting, Baseline, wet).

c. Trap Speed Distributions

The analysis of trap speed distributions at Site #1 showed that there were no significant differences between the lighting conditions for the dry weather data. For the dry data at Site #2 there were significantly different distributions at Traps 4 and 5. These distributions are shown in figures 18 and 19. As illustrated under full lighting, there is a slight upward shift of the distributions as compared with partial lighting, but the differences are not remarkable.

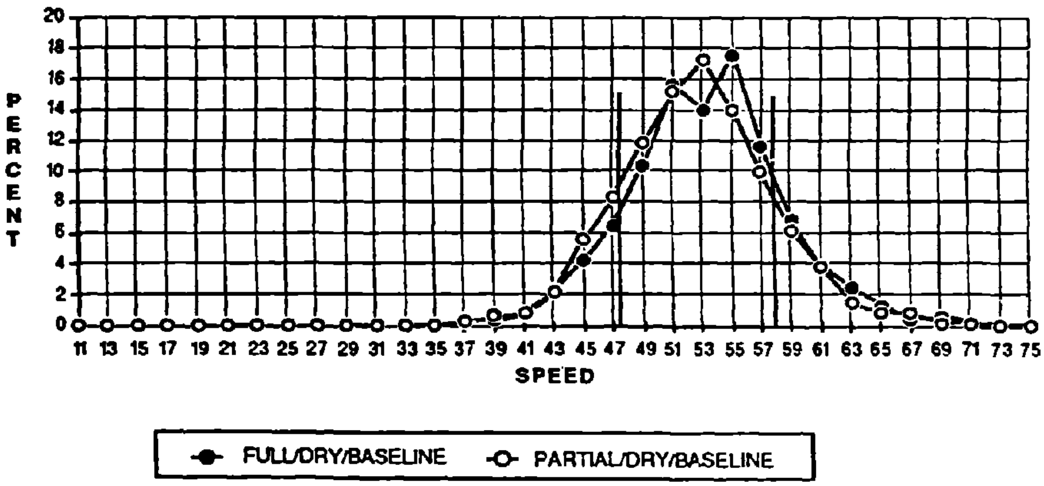


Figure 18. Site #2 Trap 4 speed distributions (full vs. partial lighting, Baseline, dry).

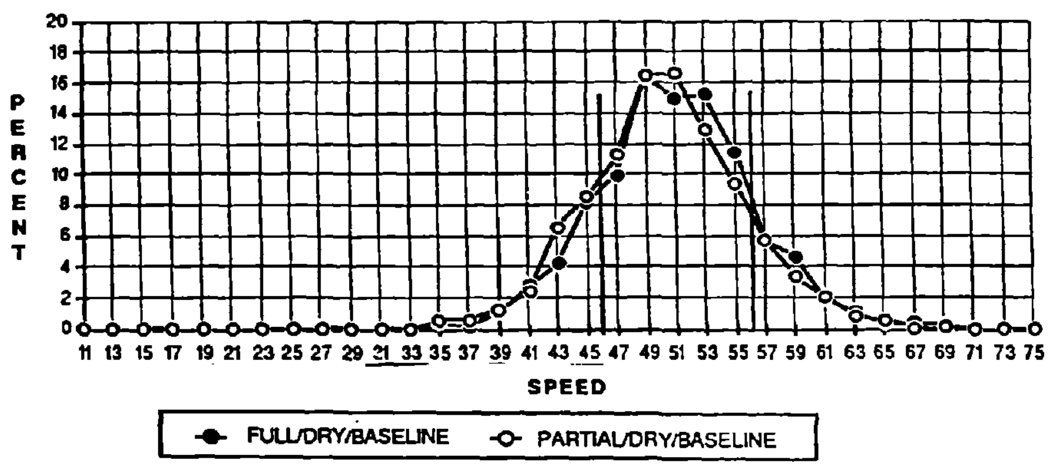


Figure 19. Site #2 Trap 5 speed distributions (full vs. partial lighting, Baseline, dry).

However, the significant differences were observed on Site #2 and not at Site #1. Further, the differences at Site #2 were at Traps 4 and 5; the area of the ramp where TVA would be influencing visual performance. Considering only the improved visibility associated with a greater amount of light, one would assume that differences were more likely at Site #1, since it operated with a single luminare. Because the differences were obtained at the site using three luminaires (Site #2), and at Traps 4 and 5, they suggest the influence of TVA. If so, the effect may be to reduce visual sensitivity of drivers to the point where, from an operational standpoint, the greater amount of light near the ramp entrance has no positive effects on ramp performance.

From an operational standpoint, the trap distribution comparisons indicated that there is little practical difference between lighting conditions in dry weather.

The trap speed distribution comparisons for wet weather, unlike those for dry weather, resulted in no significant differences at Site #2 but significant differences at several traps at Site #1. While this "reversal" seems to contradict the existence of an influential TVA effect, it may indicate that we do not adequately understand the TVA phenomenon. For example, lighting in wet conditions, e.g., with additional specular reflection from the pavement, etc. could affect visual adaptation differently from lighting in dry conditions.

The Site #1 wet weather trap distributions indicated that there were statistically significant differences between lighting conditions at Traps 2, 3, and 4. The comparative distributions for these traps are shown in figures 20, 21, and 22. At all three traps there is a fairly substantial difference in the distributions as compared with the differences under dry conditions. Again, under full lighting, there is an upward shift of the speed distribution curve. The practical importance of the differences in all of the above distribution comparisons lies in whether there were significant differences at the "tails" of the distributions.

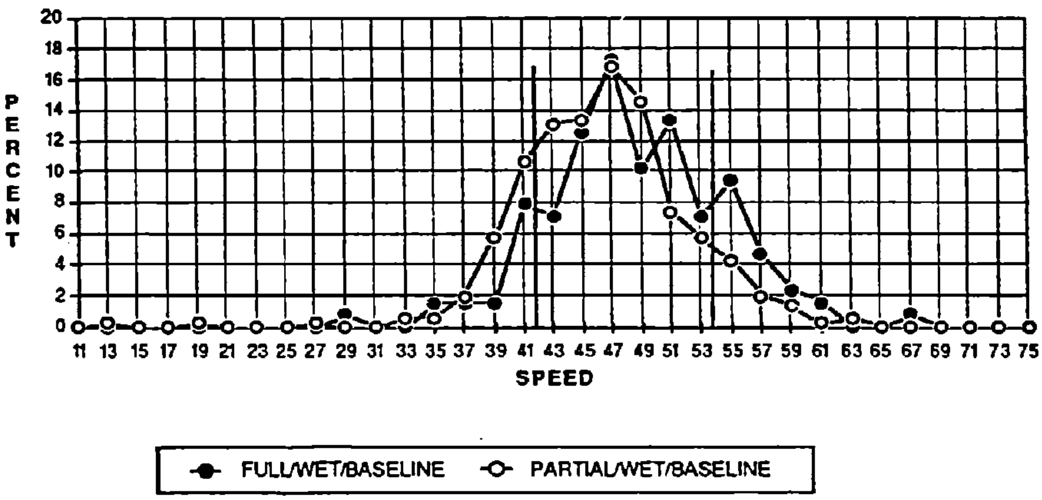


Figure 20. Site #1 Trap 2 speed distributions (full vs. partial lighting, Baseline, wet).

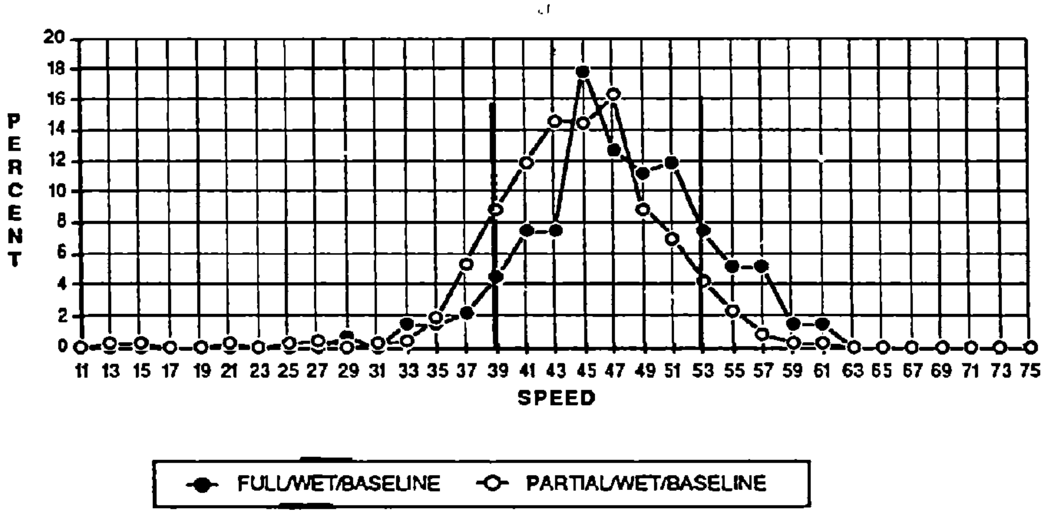


Figure 21. Site #1 Trap 3 speed distributions (full vs. partial lighting, Baseline, wet).

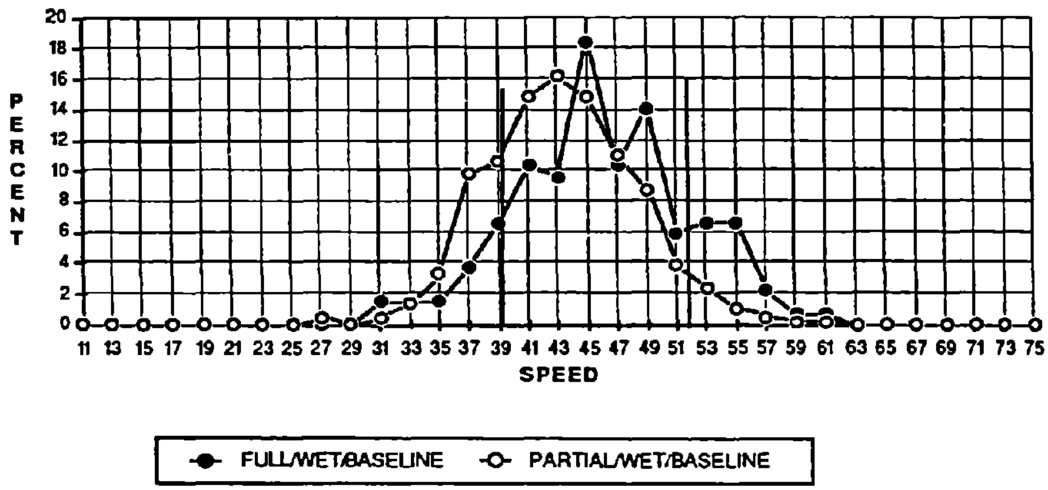


Figure 22. Site #1 Trap 4 speed distributions (full vs. partial lighting, Baseline, wet).

d. "Tails" of the Trap Speed Distributions

Recall that under dry conditions the only significant differences in trap speed distributions were at Site #2 at Traps 4 and 5. An analysis of the "tails" of these distributions revealed that, with one exception, there were no significant differences in the percentage of drivers operating below the 15th percentile or above the 85th percentile criterion speeds (i.e., those associated with full lighting). Table 10 shows the 15th and 85th percentile speeds established at each trap under full lighting with Baseline delineation. The percentage of drivers below or above these criterion speeds under the various conditions are given in tables 11 through 14.

Table 10. 15th and 85th percentile speeds established under full lighting with Baseline delineation, by trap.

	DRY		WET	
Site #1	15th (mi/h)	85th (mi/h)	15th (mi/h)	85th (mi/h)
Trap 2	42.8	55.0	42.2	54.7
Trap 3	42.1	53.4	40.4	53.5
Trap 4	40.6	51.7	39.6	52.6
Trap 5	38.3	50.1	38.4	50.3
Site #2				
Trap 2	51.3	61.0	49.7	60.0
Trap 3	49.2	59.0	47.9	58.0
Trap 4	48.0	58.2	46.7	57.2
Trap 5	45.4	55.8	43.9	54.0

(1 mi/h = 1.6 km/h)

Table 11. Site #1, percentage of drivers who operated at speeds slower than the 15th percentile criterion.

	PARTIAL LIGHTING	PARTIAL LIGHTING
	DRY	WET
	%	%
TRAP 2	12.5	23.1*
TRAP 3	15.5	21.4
TRAP 4	14.7	23.9*
TRAP 5	13.9	28.2*

* is statistically significant.

Table 12. Site #2, percentage of drivers who operated at speeds slower than the 15th percentile criterion.

	PARTIAL LIGHTING	PARTIAL LIGHTING
	DRY	WET
	%	%
TRAP 2	17.3	16.8
TRAP 3	17.7	15.4
TRAP 4	18.4*	18.6
TRAP 5	15.9	13.5

* is statistically significant.

Table 13. Site #1, percentage of drivers who operated at speeds faster than the 85th percentile criterion.

	PARTIAL LIGHTING	PARTIAL LIGHTING
	DRY	WET
	%	%
TRAP 2	15.0	6.9*
TRAP 3	14.0	4.6*
TRAP 4	15.6	3.6*
TRAP 5	14.3	4.3*

* is statistically significant.

Table 14. Site #2, percentage of drivers who operated at speeds faster than the 85th percentile criterion.

	PARTIAL LIGHTING	PARTIAL LIGHTING
	DRY	WET
	%	%
TRAP 2	11.8	21.8
TRAP 3	13.1	18.6
TRAP 4	12.6	15.9
TRAP 5	13.3	26.4*

* is statistically significant.

The one significant difference at Site #2 in dry conditions was at Trap 4. Here, 3.4 percent more drivers operated at speeds under the 15th percentile criterion. Because of the small percentage difference, one can conclude that under dry conditions there is no practical difference between full and partial lighting. However, because the significant difference was in the lower "tail" of the distribution and there was no significant difference at the upper "tail" (85th percentile), the result supports existence of a TVA effect. That is, the greater percentage of slower drivers in this area of the ramp at the three-luminaire site suggests a TVA effect on visibility.

An analysis of the "tails" of the wet-weather trap distributions at Site #2 revealed a significant difference only at Trap 5 at the 85th percentile. It is difficult to interpret the large percentage difference. It is the only significant value for either "tail." Furthermore, the pattern of differences between Traps 2 and 5 (see table 14) shows decreasing percentages from Traps 2 through 4, then a large increase at Trap 5.

The analysis of the "tails" of the wet weather trap distributions at Site #1 resulted in statistically significant differences for 15th and 85th percentile comparisons at nearly all traps. The only exception was for the Trap 3, 15th percentile comparison, and this difference was very close to the .05 level of significance. As a review of tables 11 and 13 will show, partial lighting resulted in a significantly higher percentage of drivers operating below the 15th and 85th percentile criteria as compared with full lighting. This reflects the general upward shift in the speed distribution under full lighting.

The results of analysis of the distribution "tails" further suggest that full lighting is superior to partial lighting in wet weather in that it produces higher and more consistent ramp speed behavior than partial lighting. In addition, the differences between the one-luminaire site (Site #1) and the three-luminaire site (Site #2) suggest that a three-luminaire installation provides better visibility.

Finally, no result in dry conditions leads to a different conclusion. In dry conditions, the differences between full and partial lighting were smaller and generally nonsignificant. However, some results suggest a TVA effect at the three-luminaire site. A TVA effect should be investigated further before recommendations are made about the proper number of luminairies for partially lighted interchanges.

12. Speed-Related Results—Improved Delineation and Weather

The analysis of weather and delineation effects on space mean speed (Traps 2 through 5) included only the data obtained under partial lighting conditions. However, because of the absence of rain during the time period that delineation Upgrade 1 was installed, it was not possible to obtain wet weather data on this treatment.

a. Ramp Space Mean Speed (Trap 2 to 5)

The analysis of variance (ANOVA) showed that weather produced a statistically significant effect on space mean speed at both sites. However, neither delineation nor the interaction of weather and delineation was significant on either site. Table 15 shows the F-values and associated probabilities obtained from the ANOVA. The full ANOVA is shown as table 38 and 39 in appendix A.

Table 15. Statistical effects of weather and delineation.

	SITE #1		SITE #2	
	F-VALUE	PR > F	F-VALUE	PR > F
WEATHER (W)	212.47	0.0001	87.97	0.0001
DELINEATION (D)	1.83	0.1602	1.51	0.2202
(W) by (D)	0.56	0.5719	2.15	0.1166

The comparison of space mean speeds under wet and dry conditions showed that there was a statistically reliable difference of 2 to 3 mi/h (3.2 to 4.8 km/h); the wet conditions producing the lower speeds. Table 16 shows the mean speeds associated with the various conditions under which delineation systems were tested. A review of the data obtained under partial lighting shows that the differences are greater for Site #1 (the single-luminaire partial) than for Site #2 (the three-luminaire partial). This supports the suggestion that the higher level of partial lighting at Site #2 provides better visibility in wet weather conditions. That is, speed performance more nearly duplicates that observed in dry conditions.

Table 16. Effects of lighting, weather, and delineation on space mean speed.

Experimental Condition			SITE #1			SITE #2		
LIGHTING	WEATHER	DELINEATION	NUMBER	MEAN	STANDARD DEVIATION	NUMBER	MEAN	STANDARD DEVIATION
FULL	DRY	BASELINE	253	46.0	5.8	834	53.1	5.4
PARTIAL	DRY	BASELINE	1430	45.9	5.8	1661	52.5	5.3
PARTIAL	DRY	UPGRADE #1	275	46.1	5.6	253	52.7	5.3
PARTIAL	DRY	UPGRADE #2	585	45.9	5.8	527	53.1	5.8
PARTIAL	DRY	UPGRADE #3	193	46.7	5.8	793	53.5	5.5
FULL	WET	BASELINE	134	45.6	5.7	315	50.7	8.5
PARTIAL	WET	BASELINE	373	42.7	5.7	194	50.7	7.8
PARTIAL	WET	UPGRADE #2	653	43.0	5.8	88	50.8	8.5
PARTIAL	WET	UPGRADE #3	183	43.3	5.8	511	50.5	10.5

(1 mi/h = 1.6 km/h)

b. Ramp Speed Distributions (Trap 2 to 5)

With regard to the ramp speed distributions, the upgraded delineation systems were compared with the Baseline system, in dry and in wet conditions under partial lighting. The comparisons for wet conditions showed that the distributions were not significantly different for either site; all comparisons resulting in nonsignificant K-S tests. The K-S values and associated probabilities are given in table 17.

Table 17. Values and probabilities from K-S tests for significant differences in ramp speed distributions, wet and dry weather.

SITE #1			SITE #2		
COMPARISON	K-S VALUE	PROB.	COMPARISON	K-S VALUE	PROB.
PDB-PD1[1]	0.516	0.953	PDB-PD1	0.654	0.786
PDB-PD2	0.853	0.460	PDB-PD2	1.700	0.006
PDB-PD3	1.027	0.242	PDB-PD3	2.511	0.000
PWB-PW2	0.663	0.771	PWB-PW2	1.138	0.15
PWB-PW3	0.725	0.669	PWB-PW3	0.828	0.499

[1] Key to abbreviations in table 7, page 37.

The comparisons for dry conditions indicated no significant differences for Site #1. However, at Site #2 delineation Upgrades 2 and 3 resulted in significantly different distributions when compared to the Baseline treatment. As shown in figures 23 and 24, both of the delineation upgrades produced a greater percentage of drivers in the higher speed ranges. While the upward trend in speeds was not enough to result in a statistically significant difference in means, the curves imply that delineation Upgrades 2 and 3 improve the visibility of the exit under dry conditions. However, based on the failure to find similar significant differences in wet conditions, the improvements are apparently not enough to overcome the visibility problems associated with rain.

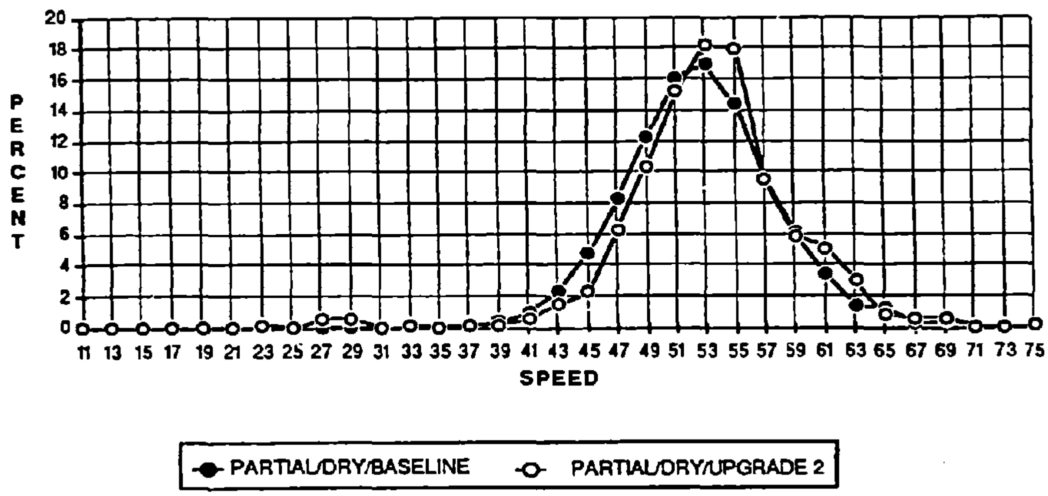


Figure 23. Site #2 ramp speed distributions (Baseline vs. Upgrade 2, dry, partial lighting).

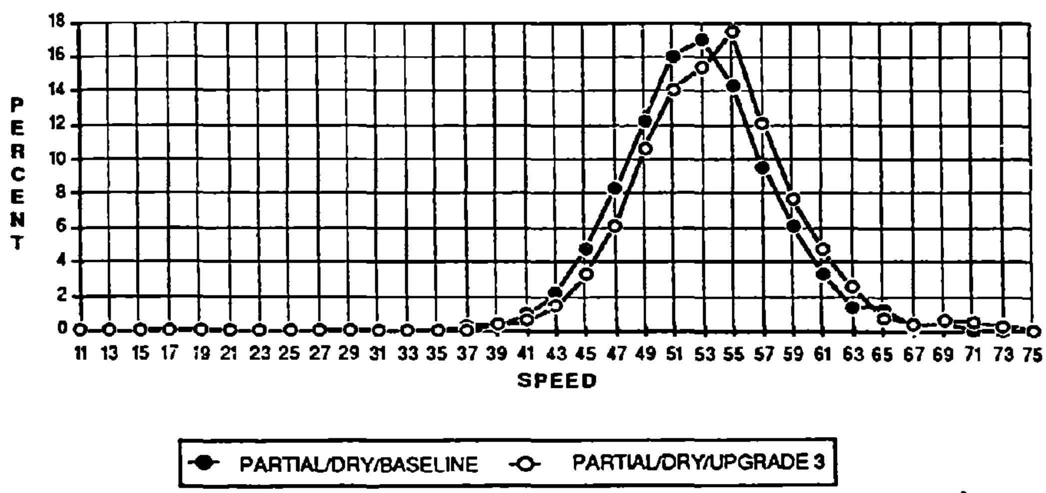


Figure 24. Site #2 ramp speed distributions (Baseline vs. Upgrade 3, dry, partial lighting).

c. "Tails" of the Ramp Speed Distributions (Trap 2 to 5)

The analysis of the "tails" of the ramp speed distributions indicated that there were no significant differences between delineation systems at Site #1 in either dry or wet conditions. At Site #2, the only statistically significant difference was between the Baseline delineation and Upgrade 3 under dry conditions. This comparison was significant (p >.01) for both the 15th and 85th percentile, producing t-values of 3.3 and 2.8 respectively. The t-values obtained for all comparisons are shown in table 18. The speed distributions were shown in figure 24. Upgrade 3 resulted in 5.2 percent fewer drivers below the 15th percentile speed established in full lighting, and 4.3 percent more drivers above the 85th percentile speed. The Upgrade 3 result of significantly fewer drivers under the criterion 15th percentile suggests that it provides improved visibility as compared with the other delineation systems. While this could be interpreted as a safety benefit, the effect at the 85th percentile criterion must also be considered.

Table 18. T-test values for delineation system comparisons.

	SITE #1		SITE #2	
	PERCENTILE 15TH	PERCENTILE 85TH	PERCENTILE 15TH	PERCENTILE 85TH
PDB-PD1[1]	0.665	0.914	0.689	0.651
PDB-PD2	0.127	0.736	0.990	1.707
PDB-PD3	1.218	0.466	3.297	2.761
PWB-PW2	0.351	0.673	0.962	0.262
PWB-PW3	0.209	1.711	0.902	0.469

(1.96 = p .05; 2.48 = p .01)

[1] Key to abbreviations in table 7, page 37.

The 85th percentile ramp speed under full illumination in dry conditions, the basis for comparison, was 58.1 mi/h (93 km/h). One could argue that a delineation system that resulted in a greater percentage of drivers being over this speed was counter to increased safety and that the delineation was "too good," giving drivers a false sense of security. On the other hand, consideration of the relatively simple geometrics of the ramp and the dry conditions can lead to an equally logical conclusion that the slightly greater percentge of drivers above the 85th percentile does not constitute a safety problem.

If similar 85th percentile effects had been observed in wet conditions, safety considerations would have to be weighed. While none of the comparisons in wet conditions resulted in statistically significant differences, the distributions indicated that the delineation upgrades at both sites tended to move drivers in the direction of the number of drivers at the 85th percentile speed associated with full illumination and Baseline delineation. However, the upgrades appeared to have little consistent effect at the 15th percentile levels.

In summary, there is little evidence from the analysis of the "tails" of the ramp speed distributions to indicate that the delineation upgrades had any major effect. With the exception of the significant differences associated with delineation Upgrade 3, all other differences were nonsignificant.

d. Trap Speed Distributions

The analysis of trap speed distributions obtained under wet conditions at Site #1 showed that there were no statistically significant differences at any of the traps. At Site #2 the only significant difference in wet conditions was at Trap 5, where Upgrades 2 and 3 differed from Baseline delineation. As shown in figures 25 and 26, the Baseline delineation results in a slight upward shift in the distribution as compared with the upgrades.

The analysis of trap speed distributions obtained under dry conditions at Site #1 showed few differences. Here the only statistically significant differences occurred between Baseline delineation and Upgrade 2, for

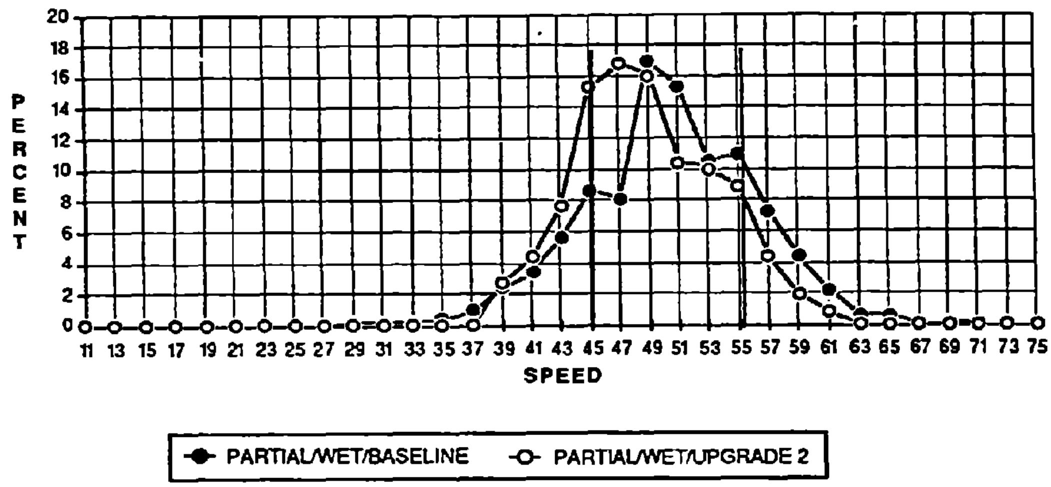


Figure 25. Site #2 Trap 5 speed distributions (Baseline vs. Upgrade 2, wet, partial lighting).

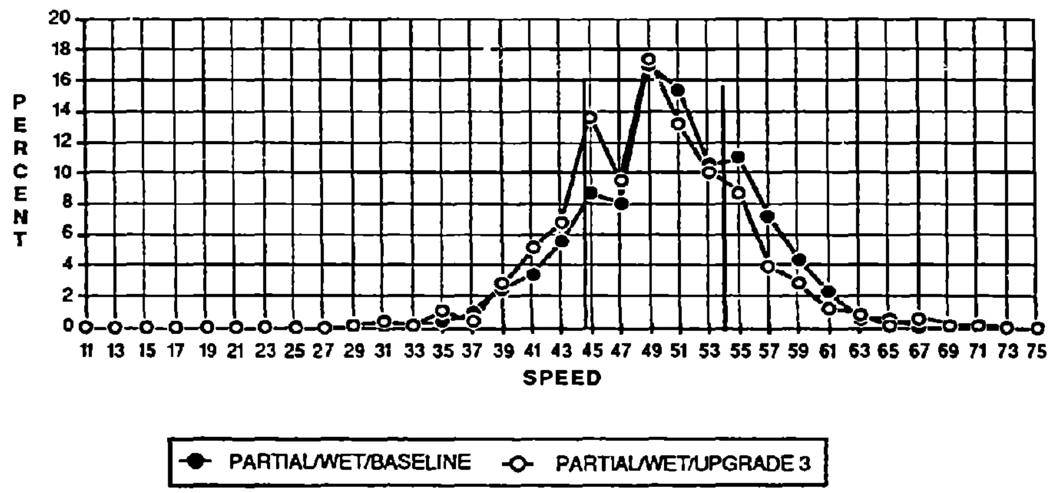


Figure 26. Site #2 Trap 5 speed distributions (Baseline vs. Upgrade 3, wet, partial lighting).

which significant K-S values were obtained at Traps 2 and 4. As shown in figures 27 and 28, the differences in the distributions are not substantial. K-S values and associated probabilities are given in table 19.

Table 19. Values and probabilities from K-S tests for significant differences in trap speed distributions.

SITE #1

	TRAP 2		TRAP 3		TRAP 4		TRAP 5	
Comparison	K-S Value	Prob.	K-S Value	Prob.	K-S Value	Prob.	K-S Value	Prob.
PDB-PD1[1]	1.043	0.227	0.782	0.573	0.881	0.420	0.559	0.914
PDB-PD2	1.588	0.013	0.930	0.353	1.508	0.021	0.658	0.779
PDB-PD3	0.544	0.929	1.276	0.077	0.923	0.362	0.959	0.316
PWB-PW2	0.544	0.929	0.430	0.993	0.901	0.392	0.970	0.304
PWB-PW3	0.653	0.787	0.813	0.532	1.258	0.084	0.880	0.420

SITE #2

	TRAP 2		TRAP 3		TRAP 4		TRAP 5	
Comparison	K-S Value	Prob.	K-S Value	Prob.	K-S Value	Prob.	K-S Value	Prob.
PDB-PD1[1]	0.958	0.318	0.489	0.970	0.601	0.863	0.620	0.837
PDB-PD2	0.707	0.700	1.574	0.014	1.939	0.001	1.698	0.006
PDB-PD3	1.134	0.153	2.306	0.000	2.789	0.000	1.801	0.003
PWB-PW2	0.606	0.856	0.800	0.545	1.188	0.119	2.220	0.000
PWB-PW3	0.756	0.617	0.825	0.504	0.959	0.317	1.683	0.007

[1] Key to abbreviations in table 7, page 37.

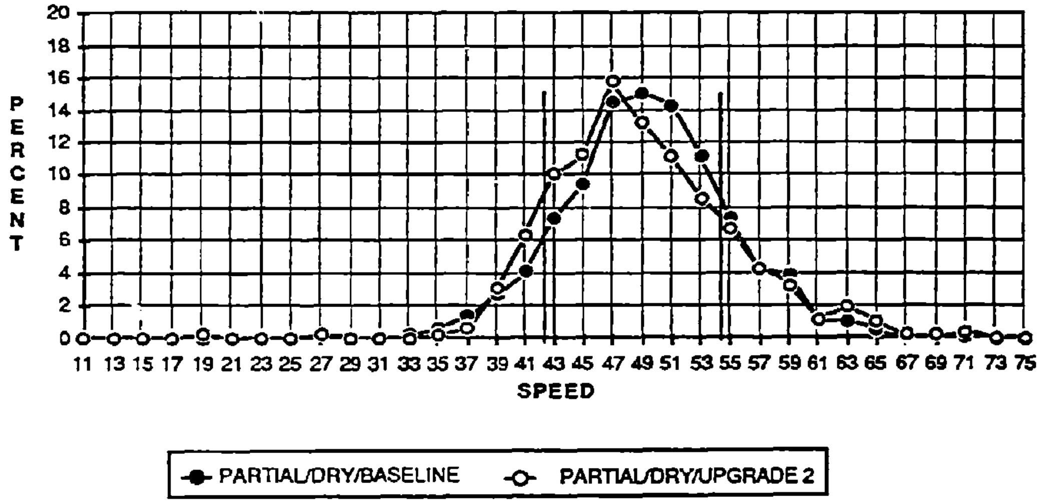


Figure 27. Site #1 Trap 2 speed distributions
(Baseline vs. Upgrade 2, dry, partial lighting).

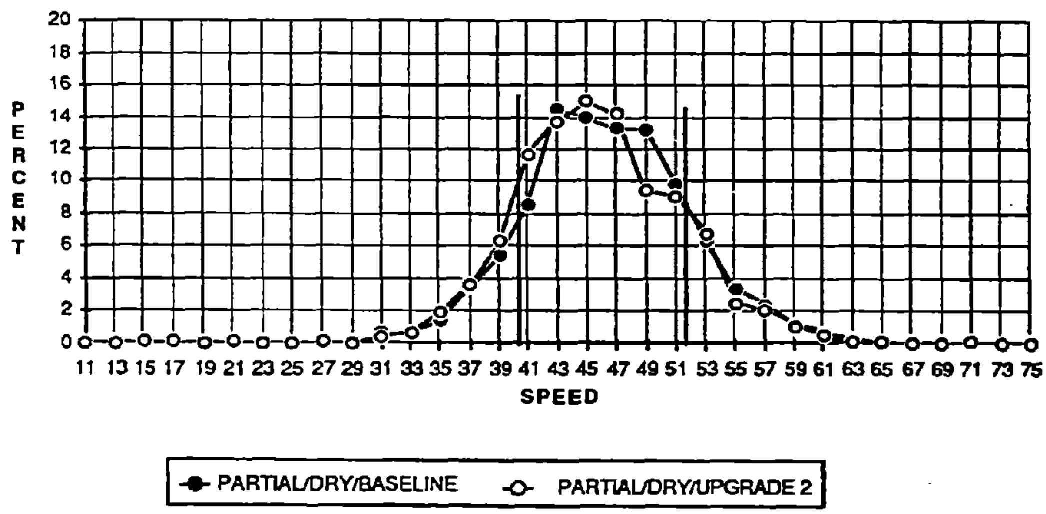


Figure 28. Site #1 Trap 4 speed distributions
(Baseline vs. Upgrade 2, dry, partial lighting).

Under dry conditions at Site #2, the comparison of Baseline delineation with both Upgrade 2 and Upgrade 3 resulted in statistically significant differences; in this case at Traps 3, 4, and 5. The speed distributions for the significant comparisons are shown in figures 29 through 34. Greater differences were produced at the low end of the distributions, generally, than at the high end.

In summary, the analysis of trap speed distributions provided no strong support for any of the upgraded delineation over the Baseline system. While some of the comparisons resulted in statistically significant differences, the magnitude of the differences was not large enough to provide a basis for choosing between delineation systems.

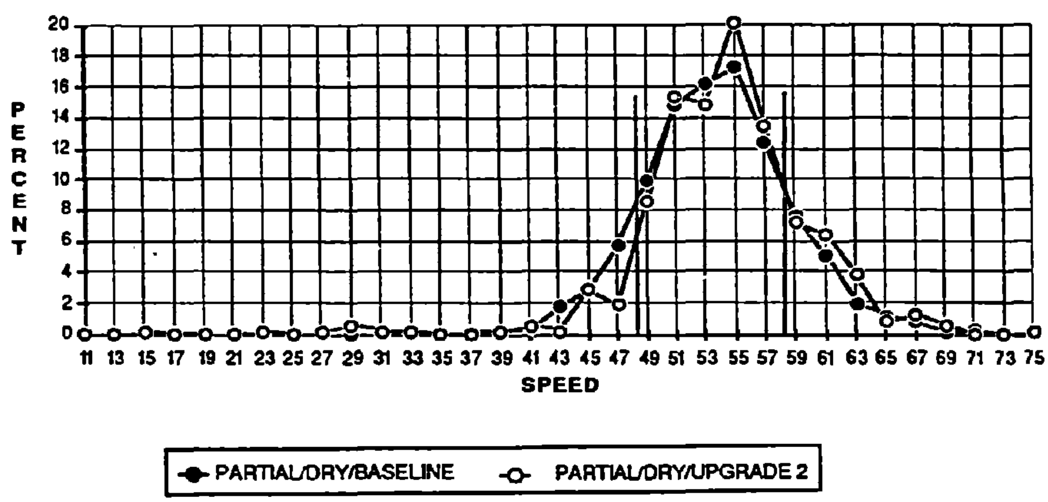


Figure 29. Site #2 Trap 3 speed distributions (Baseline vs. Upgrade 2, dry, partial lighting).

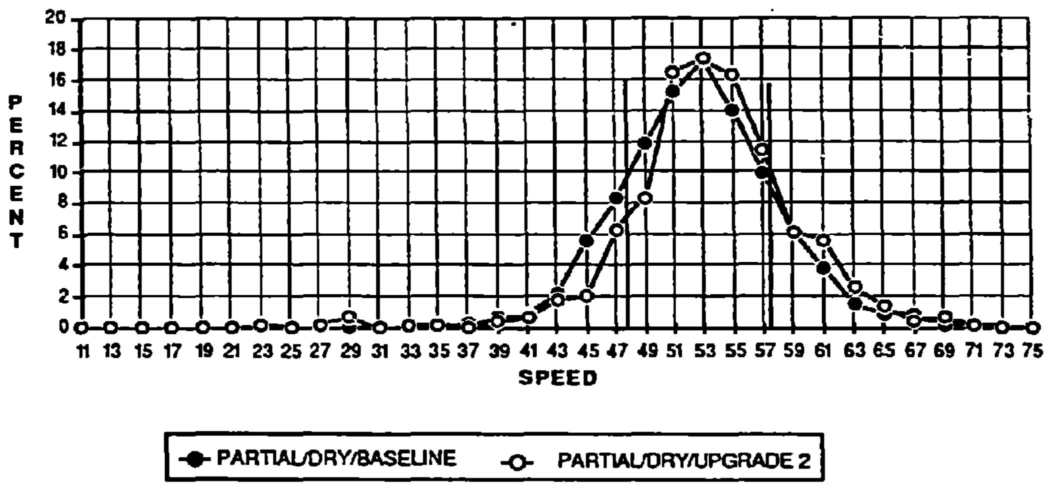


Figure 30. Site #2, Trap 4 speed distributions (Baseline vs. Upgrade 2, dry, partial lighting).

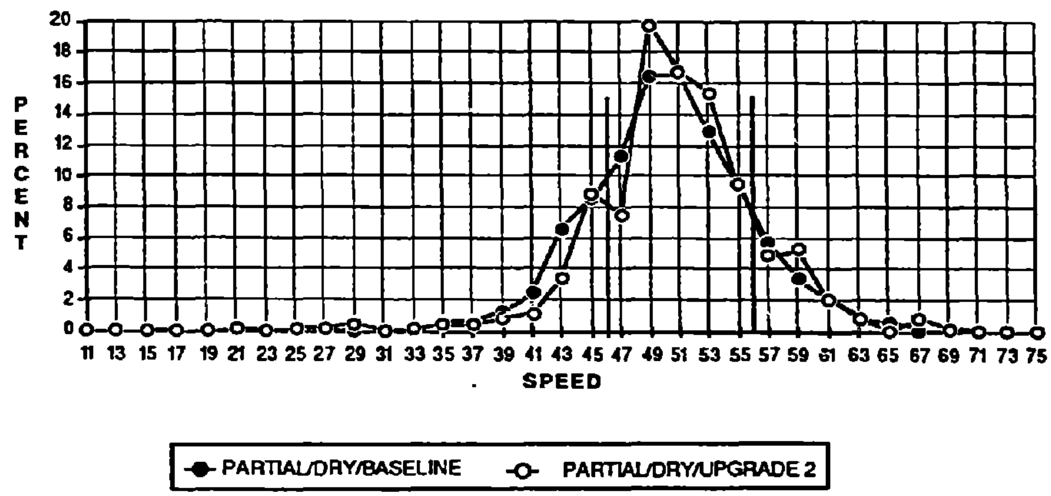


Figure 31. Site #2 Trap 5 speed distributions (Baseline vs. Upgrade 2, dry, partial lighting).

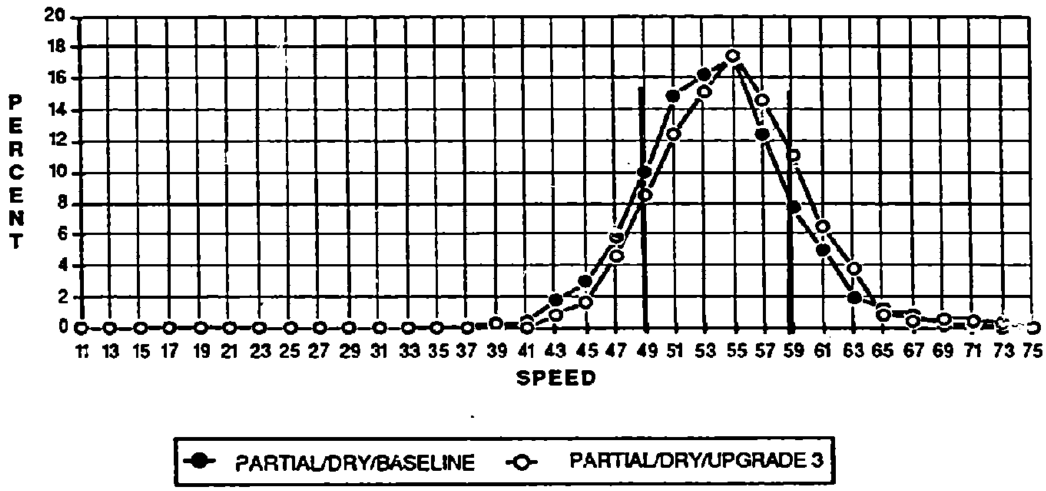


Figure 32. Site #2, Trap 3 speed distributions (Baseline vs. Upgrade 3, dry, partial lighting).

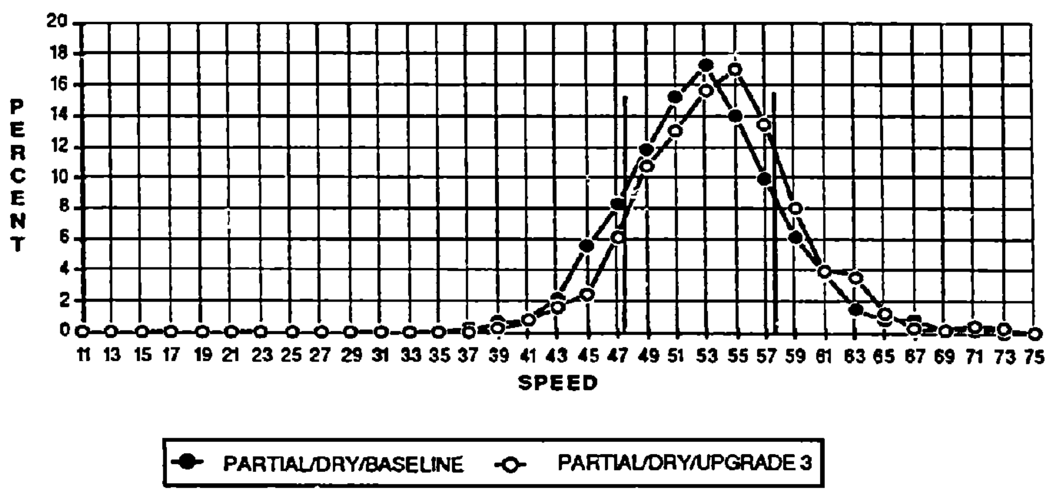


Figure 33. Site #2 Trap 4 speed distributions (Baseline vs. Upgrade 3, dry, partial lighting).

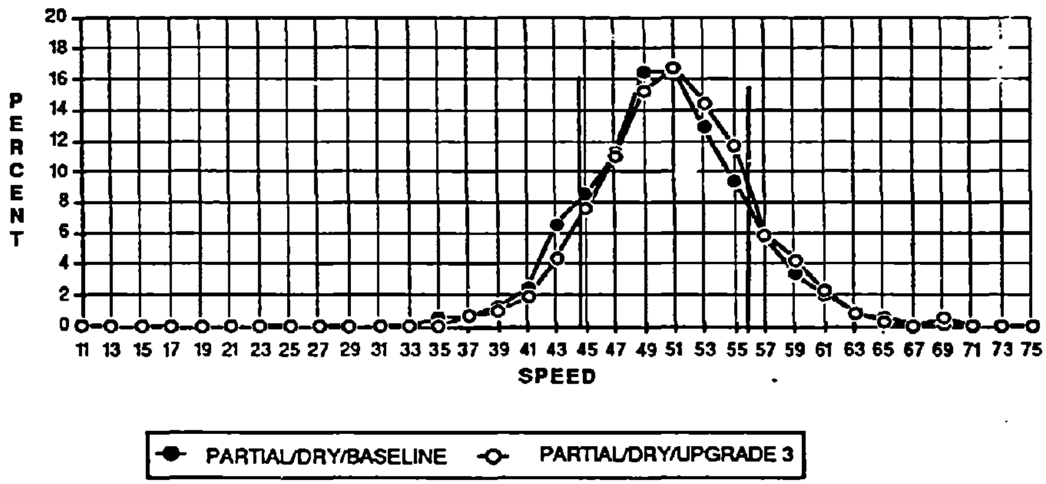


Figure 34. Site #2 Trap 5 speed distributions (Baseline vs. Upgrade 3, dry, partial lighting).

e. "Tails" of the Trap Speed Distributions

For reference in discussion of the "tails" of the trap speed distributions, table 20 shows the percentage of drivers operating below the 15th percentile criterion speed and the percentage above the 85th percentile for each delineation system and trap. Recall that the 15th and 85th percentile speeds used for the statistical analysis were those obtained under full illumination with Baseline delineation. The t-score values from the analysis are given in table 40 in appendix A.

As discussed in the previous section (d.), Upgrades 2 and 3 at Site #2 produced significantly different speed distributions versus the Baseline under wet conditions at Trap 5; these being the only significant differences resulting from the analysis of the "wet" data set. Comparisons of the

Table 20. Percentage of drivers below the 15th percentile speed and above the 85th percentile speed for each delineation system (15th and 85th percentile were established under full lighting with Baseline delineation).

PERCENT DRIVERS < 15TH PERCENTILE							
	PDB[1]	PD1	PD2	PD3	PWB	PW2	PW3
SITE #1	%	%	%	%	%	%	%
TRAP 2	12.5	9.3	15.0	15.1	23.1	24.1	20.6
TRAP 3	15.5	11.3	16.6	14.0	21.4	21.3	15.3
TRAP 4	14.7	14.1	17.0	12.4	23.9	27.5	21.6
TRAP 5	13.9	11.3	12.5	10.0	28.2	30.5	33.0
SITE #2							
TRAP 2	17.3	25.0	15.1	15.0	16.8	18.8	19.9
TRAP 3	17.7	18.7	12.4	12.7	15.4	12.6	19.9
TRAP 4	18.4	18.9	12.8	12.0	16.3	16.3	19.8
TRAP 5	15.9	19.9	14.2	13.9	13.5	14.5	17.2

PERCENT DRIVERS > 85TH PERCENTILE							
	PDB	PD1	PD2	PD3	PWB	PW2	PW3
SITE #1	%	%	%	%	%	%	%
TRAP 2	15.0	16.1	15.9	17.0	6.9	6.3	8.1
TRAP 3	14.0	15.3	15.7	17.6	4.6	5.1	5.7
TRAP 4	15.6	14.9	14.3	19.4	3.6	5.6	9.1
TRAP 5	14.3	15.1	13.6	17.4	4.3	4.9	7.1
SITE #2							
TRAP 2	11.8	15.3	13.9	14.4	21.8	7.6	15.2
TRAP 3	13.1	13.5	16.3	17.9	18.6	18.4	15.8
TRAP 4	12.6	14.3	16.3	17.0	15.9	13.0	15.8
TRAP 5	13.3	14.6	14.6	15.1	26.4	16.1	18.9

[1] Key to abbreviations in table 7, page 37.

"tails" of the Trap 5 distributions showed that both upgrades differed significantly from Baseline delineation at the 85th percentile but not at the 15th percentile. As shown on table 20, with Baseline delineation (PWB), 26.4 percent of the drivers operated above the criterion 85th percentile speed at Trap 5, whereas with the delineation upgrades (PW2 and PW3), 16.1 percent and 18.9 percent did so, respectively.

Both delineation upgrades could be chosen over Baseline delineation for producing speed distributions closer to distributions obtained under the full lighting that served as the model. However, because the significant differences occurred only at Trap 5, they are not sufficient for choosing either upgraded system in place of the Baseline under wet conditions.

Recall that under dry conditions at Site #1, the only significantly different trap distributions occurred between the Baseline and Upgrade 2 at Traps 2, 3, and 4. Further analysis of these distributions failed to reveal statistically significant differences at either the 15th or 85th percentile "tail." In summary, data from Site #1 does not recommend any of the delineation upgrades over the Baseline system.

Under dry conditions at Site #2, significantly different trap speed distributions were obtained at Traps 3, 4, and 5 for both Upgrade 2 and Upgrade 3 versus Baseline delineation. Analysis of the "tails" of these distributions showed significant differences at the 15th percentile "tail" at Traps 3 and 4 only. As can be seen in table 20, the differences between the Baseline delineation and each upgrade are similar at each trap. At Trap 3 with Baseline delineation, 17.7 percent of the drivers operated below the 15th percentile speed, compared with 12.4 percent and 12.7 percent during Upgrades 2 and 3 respectively. At Trap 4 with Baseline delineation 18.4 percent of the drivers operated below the 15th percentile speed, compared with 12.8 percent and 12.0 percent during Upgrades 2 and 3 respectively.

The 5 to 6 percent fewer drivers operating below the 15th percentile speed during upgraded delineation would have been important at Trap 2.

There, it could be argued that the upgrades increased the number of drivers who entered the ramp at an appropriate speed and did not reduce speed on the freeway mainline. However, since the differences were observed at Traps 3 and 4, the delineation upgrades cannot be credited with such safety benefits.

At the 85th percentile "tail," differences between the Baseline and Upgrade 3 distributions were also statistically significant at Traps 3 and 4, but between the Baseline and Upgrade 2, only Trap 4 distributions were statistically significant. As can be seen in table 20, 4 to 5 percent more drivers operated above the 85th percentile speed during upgraded delineation than during Baseline delineation. While there are statistically significant differences, they are not strong enough to conclude that any of the delineation upgrades is superior to the Baseline delineation.

13. Driver Behavior Effects

The driver behavior measures consisted of lateral placement, brake applications, edgeline encroachments, gore encroachments, and headlight changes. The lateral placement data were obtained from the diagonal IR detectors at Traps 4, 5, and 6. The other measures were obtained from observer input to the TES recording unit via button boxes.

a. Lateral Placement Measure

The purpose of the lateral placement measure was to determine whether any of the delineation systems would result in better lane placement, particularly under wet conditions when visibility was degraded. Some of the delineation upgrades, with RPM's or fully retroreflective posts on the ramp, could be expected to provide a better path definition than the Baseline delineation system. Table 21 shows the sample sizes, means (displacement from the right edgeline), and standard deviations at each trap for both sites. The mean lateral placement for each trap is shown graphically in figures 35, 36, and 37 for Site #1, and figures 38, 39, and 40 for Site #2. The darker bars in the figures represent wet road conditions and the lighter represent

Table 21. Mean distance (ft) of vehicles from right edgeline at Traps 4, 5, and 6.

Site #1 Lateral Placement

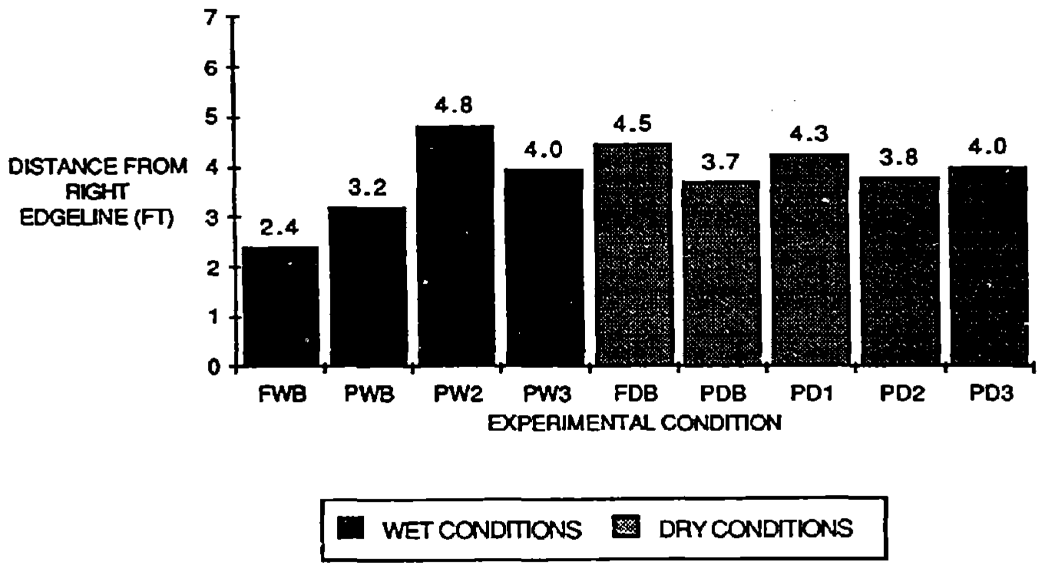
	Trap 4			Trap 5			Trap 6		
Condition	No.	Mean	Std.Dev.	No.	Mean	Std.Dev.	No.	Mean	Std.Dev.
FWB[1]	112	2.4	2.5	151	5.2	2.2	149	3.8	2.5
PWB	355	3.2	2.1	218	6.3	2.8	381	4.9	3.0
PW2	516	4.8	3.1	820	4.9	2.0	744	6.3	2.4
PW3	117	4.0	1.9	220	4.0	2.1	198	6.4	2.4
FDB	266	4.5	2.1	266	5.0	2.5	266	2.8	2.4
PDB	1431	3.7	2.4	1509	5.2	2.3	1311	4.4	2.7
PD1	283	4.3	2.3	292	5.4	2.1	292	5.4	2.8
PD2	798	3.8	2.2	801	5.1	2.1	796	6.9	2.6
PD3	203	4.0	2.4	204	3.9	1.9	186	4.8	2.0

Site #2 Lateral Placement

	Trap 4			Trap 5			Trap 6		
Condition	No.	Mean	Std.Dev.	No.	Mean	Std.Dev.	No.	Mean	Std.Dev.
FWB	360	4.3	2.7	371	2.8	2.0	397	1.6	1.6
PWB	331	4.6	2.5	467	2.7	1.8	461	3.0	1.8
PW2	242	3.9	2.6	245	4.0	1.9	253	1.9	1.7
PW3	524	3.9	2.0	503	2.5	1.6	493	1.8	1.6
FDB	1020	3.8	2.2	1069	2.0	1.9	1015	2.5	2.1
PDB	1728	4.3	2.4	1849	2.9	1.9	1851	2.8	1.8
PD1	265	3.4	2.1	266	2.0	1.7	268	2.9	1.9
PD2	536	3.8	2.5	559	3.0	1.8	567	2.9	2.3
PD3	875	3.7	2.0	868	3.4	2.1	880	2.5	2.0

[1] Key to abbreviations in table 7, page 37.
(1 ft = .305 m)

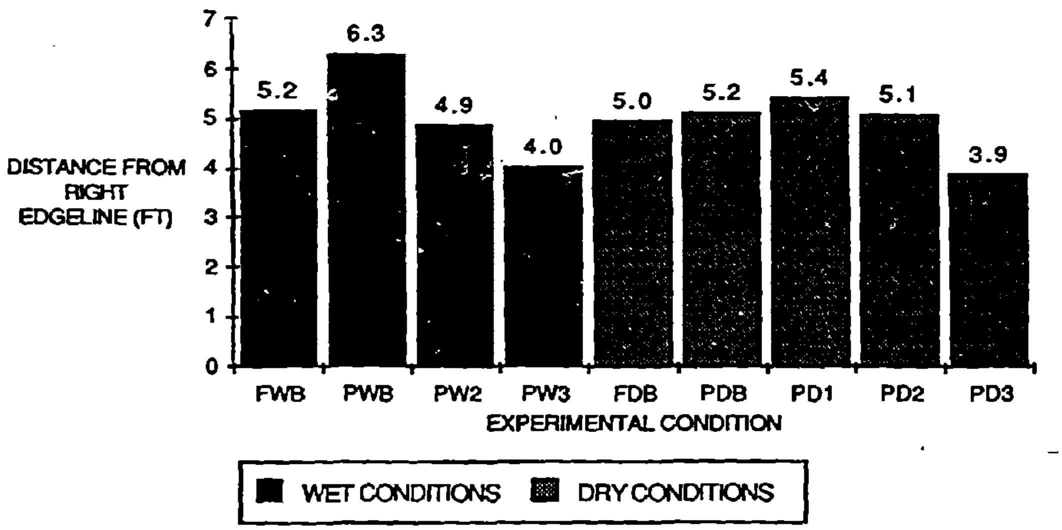
dry conditions. Trap 4 was located near the physical gore and Traps 5 and 6 were located downstream at approximately 100-ft (30.5 m) intervals. The means shown in the figures represent the distance from the right edgeline at which the vehicle broke the diagonal I/R beam. For both sites the lane width between the edgelines was approximately 14 ft (4.27 m). Thus a lateral position of 3.5 ft (1.07 m) would indicate a vehicle near the center of the lane.



Key to abbreviations in table 7, page 37.

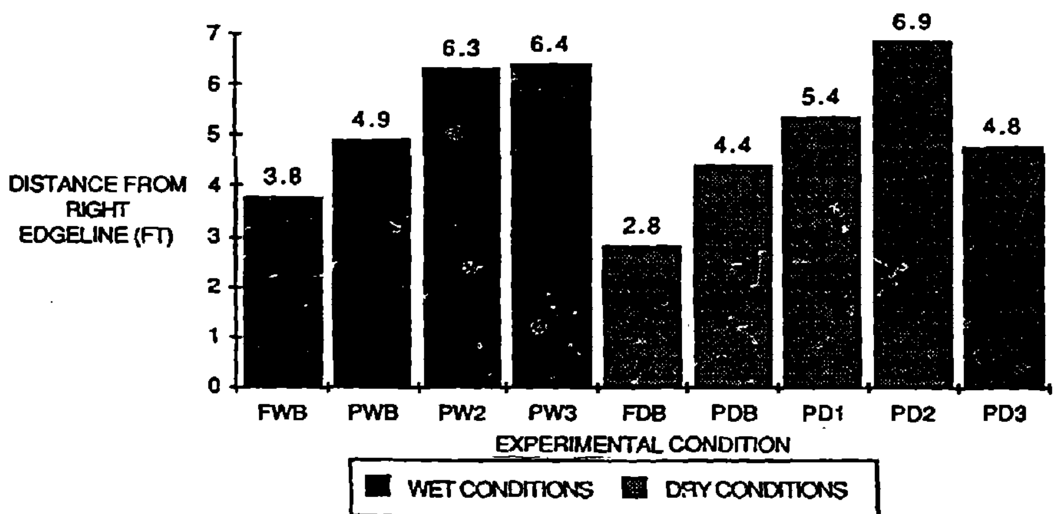
(1 ft = .305 m)

Figure 35. Lateral placement - Trap 4 - Site #1.



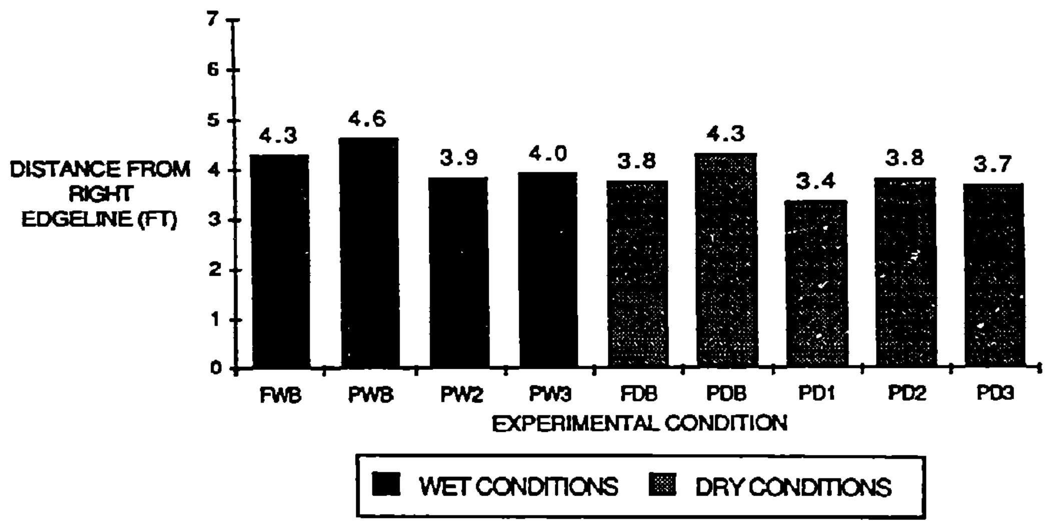
Key to abbreviations in table 7, page 37.
(1 ft = .305 m)

Figure 36. Lateral placement - Trap 5 - Site #1.



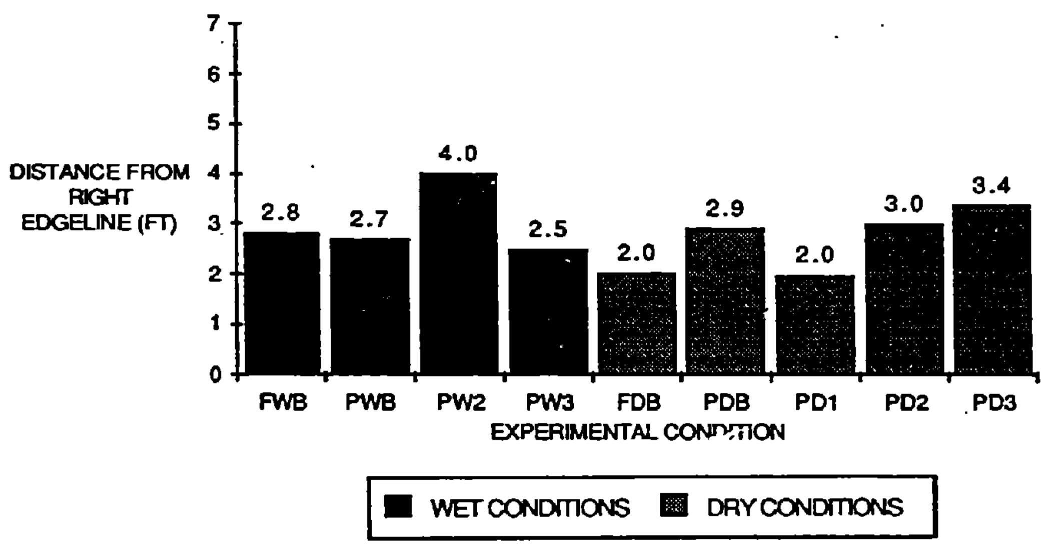
Key to abbreviations in table 7, page 37.
(1 ft = .305 m)

Figure 37. Lateral placement - Trap 6 - Site #1.



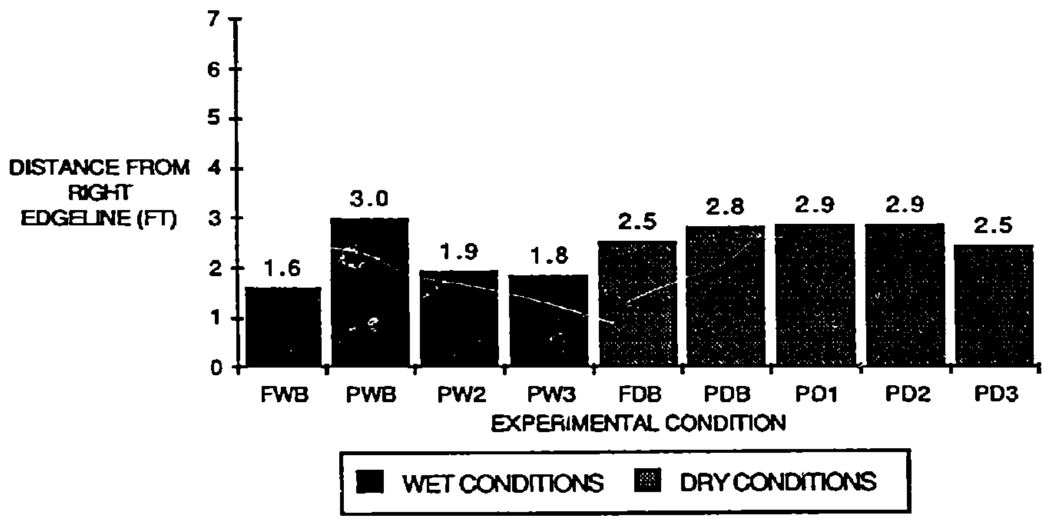
Key to abbreviations in table 7, page 37.
(1 ft = .305 m)

Figure 38. Lateral placement - Trap 4 - Site #2.



Key to abbreviations in table 7, page 37.
(1 ft = .305 m)

Figure 39. Lateral placement - Trap 5 - Site #2.



Key to abbreviations in table 7, page 37.
(1 ft = .305 m)

Figure 40. Lateral placement - Trap 6 - Site #2.

It was assumed that the delineation system that produced lateral placements similar to those observed under full lighting would be the best. A series of t-tests was used to determine the statistical reliability of the observed differences.

Table 22 shows the lateral placement differences between full lighting with Baseline delineation and the delineation systems under partial lighting, along with the statistical significance of the differences. With few exceptions, the magnitude of the differences is small. However, with the large sample sizes, a difference of more than 0.3 ft (0.1 m) is usually statistically significant.

To determine whether any delineation system produced a pattern of results across sites or traps, the lateral placement values were used to create system rankings for each weather condition at each site. That is, the system that produced a lateral placement value closest to the value observed under full lighting was ranked first, the next closest value second, etc. Where rankings did not differ significantly, they were given the same rank. The rankings of each system are given in table 41 in appendix A. The ranking failed to reveal a pattern of superiority for any of the delineation systems.

Table 22. Lateral placement differences between full lighting with Baseline delineation and delineation systems under partial lighting.

SITE #1					
SYSTEM			DIFF. FROM FULL LIGHTING PLACEMENT (in feet)		
LIGHTING	WEATHER	DELINEATION	TRAP 4	TRAP 5	TRAP 6
PARTIAL	DRY	BASELINE	0.8*	0.2	1.6*
PARTIAL	DRY	UPGRADE 1	0.2	0.4*	2.6*
PARTIAL	DRY	UPGRADE 2	0.7*	0.1	4.1*
PARTIAL	DRY	UPGRADE 3	0.5*	1.1*	2.0*
PARTIAL	WET	BASELINE	0.8*	1.1*	1.1*
PARTIAL	WET	UPGRADE 2	2.4*	0.3	2.5*
PARTIAL	WET	UPGRADE 3	1.6*	1.2*	2.6*

SITE #2					
SYSTEM			DIFF. FROM FULL LIGHTING PLACEMENT (in feet)		
LIGHTING	WEATHER	DELINEATION	TRAP 4	TRAP 5	TRAP 6
PARTIAL	DRY	BASELINE	0.5*	0.9*	0.3*
PARTIAL	DRY	UPGRADE 1	0.4*	0.0	0.4*
PARTIAL	DRY	UPGRADE 2	0.0	1.0	0.4*
PARTIAL	DRY	UPGRADE 3	0.1	1.4*	0.0
PARTIAL	WET	BASELINE	0.3	0.1	1.4*
PARTIAL	WET	UPGRADE 2	0.4*	1.2*	0.3*
PARTIAL	WET	UPGRADE 3	0.4*	0.3*	0.2*

* indicates statistically significant ($p > .05$) differences.

(1 ft = .305 m)

In addition to the ranking of systems against the full lighting criterion, an additional ranking compared lateral placements relative to the center of the lane. Recall that a lateral position of 3.5 ft (1.07 m) would put a vehicle near the center of the lane. A placement closest to the center of the lane was ranked 1. As with the full lighting criterion, the significance of the differences was taken into account in assignment of rank. The rankings are shown under criterion 2 on table 41 in appendix A. Again, the variation in rankings across sites and conditions was such that no delineation system emerged as superior.

In summary, the lateral placement data do not aid in discriminating between any of the independent variables of concern.

b. Brake Application Measure

The observer input to the TES data tape via hand-held button boxes included brake light applications in advance of the exit taper (i.e., on the freeway mainline).

The design of both exits permitted a driver to safely leave the mainline and enter the taper at 55 mi/h (88 km/h). Further, the signing was adequate and not likely to produce confusion. Given this situation, it was assumed that braking in mainline would be associated with the visibility of the exit. That is, it was assumed that better visibility, whether produced by lighting or upgraded delineation, would lead to fewer occurrences of brake light applications in mainline in advance of the exit.

Table 23 shows the percentages of drivers braking in mainline under wet and dry conditions at Site #1. Table 24 shows the same for Site #2. Also shown on the tables are the multiway Chi Square values associated with the statistical tests for independence. Given the uniformly low percentage of drivers braking in mainline, a strong case cannot be made for any of the delineation systems.

Table 23. Site #1 - mainline braking.

	DRY			WET		
CONDITION	TOTAL VEHICLES	NO. BRAKING	PERCENT BRAKING	TOTAL VEHICLES	NO. BRAKING	PERCENT BRAKING
BASELINE	1397	7	0.50%	No	Data	
UPGRADE 1	260	6	2.30%			
UPGRADE 2	684	17	2.50%	640	9	1.40%
UPGRADE 3	185	2	1.10%	192	0	0.00%
(ChiSq = 16.97, $p \geq .01$)				(ChiSq = 7.186, $p \geq .05$)		

Table 24. Site #2 - mainline braking.

	DRY			WET		
CONDITION	TOTAL VEHICLES	NO. BRAKING	PERCENT BRAKING	TOTAL VEHICLES	NO. BRAKING	PERCENT BRAKING
BASELINE	1540	12	0.80%	406	6	1.50%
UPGRADE 1	237	3	1.30%			
UPGRADE 2	540	1	.20%	180	5	2.80%
UPGRADE 3	No	Data		No	Data	
(ChiSq = 6.18, NS)				(ChiSq = 9.087, $p \geq .05$)		

c. Edgeline Encroachment Measure

All of the erratic maneuvers observed from the brake-light position were encroachments on the right edgeline at the beginning of the exit taper. Because Site #2 did not provide a good vantage point from which to observe edgeline encroachments and still remain hidden, it was virtually impossible to see encroachments under rain conditions. Even under dry conditions the percentage of drivers observed encroaching on the right edgeline was very small. Because it is felt that the low percentages are due to the inability of the observer to accurately detect the encroachments, this data is not reported for Site #2. The data from Site #1 are shown in table 25.

Table 25. Site #1 - edgeline encroachments.

	DRY			WET		
CONDITION	TOTAL VEHICLES	NO. ENCROACH.	PERCENT ENCROACH.	TOTAL VEHICLES	NO. ENCROACH.	PERCENT ENCROACH.
BASELINE	1397	470	33.60%	315	164	52.10%
UPGRADE 1	260	92	35.40%			
UPGRADE 2	684	270	39.50%	640	272	42.50%
UPGRADE 3	185	19	10.30%	192	52	27.10%
(ChiSq = 55.99, p $\geq$.01)				(ChiSq = 30.45, p $\geq$.01)		

Both of the delineation upgrades produced lower percentages of encroachments than Baseline delineation under wet conditions. Upgrade 3 resulted in significantly lower percentages of encroachments under both dry and wet conditions. Further, performance under delineation Upgrade 3 was approximately the same as that observed under wet conditions with full lighting and Baseline delineation. It appears that Upgrade 3, with the fully retroreflectorized posts along the exit, acts to better align drivers in the exit.

d. Gore Encrochment Measure

The percentage of encroachments on the gore stripes was low on both sites and under all conditions as shown on tables 26 and 27. On both sites there was a lower percentage under full lighting than under any of the partial lighting conditions. As the Chi-Square values associated with each data set indicate, there are no statistically reliable differences between the delineation systems.

Table 26. Site #1 - gore encroachments.

CONDITION	DRY			WET		
	TOTAL VEHICLES	NO. ENCROACH.	PERCENT ENCROACH.	TOTAL VEHICLES	NO. ENCROACH.	PERCENT ENCROACH.
BASELINE	978	24	2.50%	223	7	3.10%
UPGRADE 1	261	10	3.80%			
UPGRADE 2	457	16	3.50%	649	0	0.00%
UPGRADE 3	158	2	1.30%	38	3	7.90%
(ChiSq = 3.64,NS)				(ChiSq = low cell freq. = unreliable)		

Table 27. Site #2 - gore encroachments.

CONDITION	DRY			WET		
	TOTAL VEHICLES	NO. ENCROACH.	PERCENT ENCROACH.	TOTAL VEHICLES	NO. ENCROACH.	PERCENT ENCROACH.
BASELINE	822	12	1.50%		No Data	
UPGRADE 1	209	5	2.40%			
UPGRADE 2	291	6	2.10%		No Data	
UPGRADE 3	311	2	0.60%		No Data	
(ChiSq = 3.277, NS)						

14. Effects of New Lamps on Driver Performance

Upon completion of data collection associated with the main purpose of the study, the luminaires on Site #2 were cleaned and new lamps were installed. While the average illuminance under existing conditions was above AASHTO specifications, the lamps had not been changed for some time. Thus it was deemed desirable to refurbish the lights and collect a small amount of data to determine whether the additional light output would result in any difference in traffic performance.

Statistically comparable data under existing and refurbished lighting were in delineation Upgrades 1 and 3 under dry conditions. The analysis showed that the differences in space mean speed were significant ($p>.05$) for the Upgrade 3 comparisons and nonsignificant for Upgrade 1. The differences in mean speed, however, were not practically significant: a difference of 0.9 mi/h (1.44 km/h) between lighting conditions under delineation Upgrade 1, and a difference of 1.1 mi/h (1.76 km/h) under Upgrade 3. Also, the change in lighting had virtually no differential effect on the speed distributions for either upgrade.

15. Comparative Costs of Lighting and Delineation

The purpose of this section is to provide information on the cost comparisons between full lighting with Baseline delineation and partial lighting with upgraded delineation systems. Clearly, it is not possible to provide a single cost comparison that will be directly applicable in all States. Luminaire maintenance and power costs will vary from State to State, as will costs associated with delineation system installation and maintenance. The cost comparisons presented in this section are based on actual State of Washington delineation installation and maintenance costs and costs for luminaire installation, maintenance, and power.

Luminaire installation and operating costs are for a 250-watt, high pressure sodium lamp mounted on a 40-ft (12.2 m) pole. The cost to install a complete luminaire, including foundation, pole, and wiring is approximately $3500. Assuming a 20-year service life, an interest rate of 6 percent, and no salvage value, the equivalent uniform annual cost of a luminaire would be $305. The annual operating cost for each luminaire is $100, $46 of which goes for maintenance and $54 for power. Thus the total cost per luminaire would be $405 per year; the value used in the comparisons below. One further assumption made in calculating the cost comparisons is that luminaires are spaced at approximately 180 ft (54.9 m); a spacing which provides the most effective light distribution on a relatively straight section of roadway.

Two different levels of maintenance were assumed in developing the annual maintenance cost of the delineation system upgrades. Case 1 assumed that the delineation systems would have to be totally refurbished each year to maintain maximum effectiveness. That is, rather than cleaning delineator posts, replacing reflector elements in RPM's, etc., the entire system would be replaced. This represents States which experience significant weather-related delineator and marking wear and tear, such as is likely in areas with heavy snowplow activity. For the purpose of developing equivalent uniform annual costs for this case, delineation system costs were based on a 1-year service life, an interest rate of 6 percent, and no salvage value. Case 2 assumes that the delineator systems would have to be totally refurbished every 2 years and that there would be no other annual maintenance costs. This represents States which have a much more benign climate where weather-related effects are far less pronounced. In this case, delineation system annual costs are based on a 2-year service life, an interest rate of 6 percent, and no salvage value.

For the cost comparison presented in table 28, actual delineation costs for Site #2 were used (see table 29). However, rather than using the actual spacing of luminaires on Site #2, the more desirable 180-ft (54.9 m) spacing was assumed for the calculation of lighting cost. Given the length of the ramp at this site, such spacing would result in the requirement for nine luminaires. At an annualized cost of $405 per luminaire, the lighting cost for full lighting of the ramp would then be $3,645. Table 28 shows the cost comparison of full lighting with Baseline delineation and two partial lighting configurations with each of the delineation systems tested, for cases 1 and 2.

The dollar values listed represent the combined annualized cost of lighting and delineation. It will be recalled that the profiled tape used on the gore stripes for delineation Upgrade 3 was chosen to represent a treatment such as a thick application of thermoplastic which would be raised far enough off the surface of the roadway to reduce the negative effects of water film. Thus for the cost comparisons shown in table 28, Upgrade 3A reflects the cost of a thick application of epoxy, whereas Upgrade 3B reflects the cost of the profiled tape actually used in the field study. Finally it will be noted that, because the Baseline delineation used on the test sites included the use of RPM's, the Baseline treatment actually constituted an upgrade over the delineation systems used in many other States.

A review of table 28 shows that even with the most conservative assumption of a 1-year service life for delineation systems, from a cost standpoint, combinations of partial illumination and a delineation system upgrade are almost always preferable to the nine-luminaire implementation.

Table 28. Comparative delineation and lighting costs.

Case 1 - One-year service life for delineation systems					
	DELINEATION				
LIGHTING	BASE-LINE	UPGRADE 1	UPGRADE 2	UPGRADE 3A	UPGRADE 3B
FULL (9 LUMINAIRES)	$4,737	---	---	---	---
PARTIAL (3 LUMINAIRES)	$2,307	$2,450	$2,588	$3,664	$5,190
PARTIAL (1 LUMINAIRE)	$1,497	$1,640	$1,778	$2,854	$4,380

Case 2 - Two-year service life for delineation systems					
	DELINEATION				
LIGHTING	BASE-LINE	UPGRADE 1	UPGRADE 2	UPGRADE 3A	UPGRADE 3B
FULL (9 LUMINAIRES)	$4,737	---	---	---	---
PARTIAL (3 LUMINAIRES)	$1,777	$1,868	$1,921	$2,475	$3,260
PARTIAL (1 LUMINAIRE)	$ 967	$1,058	$1,111	$1,665	$2,450

Table 29. Costs to delineate Site #2.

	Right side 1,800 ft	Left side 867 ft, curved	Gore stripes 400 ft each; avg. spacing RPM's and diverters 25 ft	Gore 10 posts	Totals
Baseline	$463.50	$221.97	$88	$257	$1,030.47
Upgrade 1	$463.50	$221.97 plus $114.38	$88	$277	$1,164.85
Upgrade 2	$463.50	$436.97	$137.68	$257	$1,295.15
Upgrade 3	$499.50	$239.17 plus $114.38	$1,200 thermo-plastic or $2,640 profiled tape	$257	$2,310.05 or $3,750.05

(1 ft = .305 m)

SUMMARY OF RESULTS

1. Transient Visual Adaptation

Field tests, using a small sample (N = 15) of subject drivers, indicated that TVA occurs in drivers traversing a partially lighted ramp. Comparisons of detection performance to roadside targets under lighted versus unlighted conditions showed that detection performance is better under unlighted conditions. However the improved detection performance was observed only for targets placed at 350 ft (106.75 m) and 475 ft (144.88 m) downstream of the last luminaire. For targets placed at 600 ft (183 m) from the last luminaire, there was no significant performance difference between lighting conditions.

2. Effects of Lighting and Weather on Ramp Speed

At both sites, weather (dry versus wet) and lighting (full versus partial) were shown to have statistically significant effects on ramp space mean speeds. However the absolute differences were not large. At Site #1 the maximum difference between lighting conditions was approximately 3 mi/h (4.8 km/h); this being obtained under wet conditions. At Site #2 the maximum difference was less than 1 mi/h (1.6 km/h); this being obtained under dry conditions.

At both sites the results are consistent with what would be expected from the standpoint of visibility. That is, the highest mean speeds were observed under full lighting and dry conditions and the lowest under partial lighting and wet conditions. The significant effect on speed in wet weather at Site #1 (a single-luminaire installation) and the lack of the same at Site #2 (a three-luminaire installation) suggest that the greater number of luminaires results in improved visibility.

3. Effects of Lighting and Weather on Ramp Speed Distributions

Analysis of the ramp speed distributions and additional analysis of the "tails" of the distributions did not provide any information that would contradict the above results. For ramp speed distributions, the only significant differences between full and partial lighting were at Site #1 under wet conditions. There were no significant differences at either "tail" of the distributions.

4. Effects of Lighting and Weather on Trap Speed Distributions

The trap distribution comparisons indicated that there is little practical difference between lighting conditions in dry weather. While statistically significant differences were obtained at Traps 4 and 5 on Site #2, the differences in the distributions were small at both traps. No significant differences were observed at Site #1.

In wet weather, no significant differences were observed at Site #2. At Site #1, there were significant differences at Traps 2, 3, and 4, with full lighting resulting in distributions having a higher speed range. The differences in the distributions were larger than those observed under dry conditions. The larger differences at Site #1 as compared with Site #2 suggest that the three-luminaire installation (Site #2) provides better visibility than the single-luminaire installation. That is, performance is more like that obtained under full lighting.

The analyses of the trap distribution "tails" produced results consistent with the above findings but did not provide additional insights.

In summary, the various analyses of the weather and illumination variables consistently suggest that, under dry conditions, lighting has little effect on the speed behavior of drivers. In wet weather, however, full lighting is superior to partial lighting. Finally, it was found that a partial lighting configuration using three luminaires is superior to one using a single luminaire in that it produces results that are more consistent with those obtained under full lighting.

5. Effects of Weather and Delineation on Ramp Speeds

The analysis of variance of weather and delineation data showed that only weather produced statistically significant effects on ramp space mean speeds. Neither delineation nor the weather and delineation interaction was significant. The effects of weather were discussed above. The largest difference between any of the delineation systems was 1 mi/h (1.6 km/h).

6. Effects of Weather and Delineation on Ramp Speed Distributions

The comparisons of ramp speed distributions for wet conditions resulted in nonsignificant K-S values at both sites. The comparisons under dry conditions, however, indicated significantly different distributions for delineation Upgrades 2 and 3 when compared with Baseline delineation. An examination of the speed distributions showed that the delineation upgrades produce a general upward shift of the distributions. While the shift is not enough to produce a statistically significant difference in means, the curves imply that both delineation upgrades produce an improvement in the visibility of the exit under dry conditions. However, based on the failure to obtain significant differences under wet conditions, the improvements are not enough to overcome the visibility problems associated with rain.

The analysis of the "tails" of the ramp speed distributions for Site #1 did not show any statistically significant differences for wet or dry conditions. At Site #2 the delineation comparisons in wet conditions produced no significant differences. However, under dry conditions, delineation Upgrade 2 resulted in a speed distribution that was significantly different from the Baseline delineation at the lower "tail." Upgrade 3 was found to be significantly different at both "tails." That is, Upgrade 2 and 3 produced a lower percentage of drivers operating below the 15th percentile speed established in full lighting, and Upgrade 3 also produced a higher percentage operating above the 85th percentile speed.

The lower percentage of drivers below the 15th percentile supports the suggestion that both upgrades produced improved visibility compared with the Baseline delineation. One could argue that because of the higher percentage of drivers over the 85th percentile speed, Upgrade 3 was less desirable than Upgrade 2. However, given that the significant results were obtained under dry conditions, and that the geometrics of the ramp are relatively simple, there is not sufficient evidence to choose one of the upgrades over the other on the basis of the ramp speed distribution comparisons.

7. Effects of Weather and Delineation on Trap Speed Distributions

The analysis of the trap data obtained in wet conditions revealed little additional information with regard to the speed-related behavior. At Site #1 none of the delineation comparisons resulted in statistically different distributions. At Site #2 the only significant distribution differences were at Trap 5, where delineation Upgrades 2 and 3 differed from the Baseline delineation.

The analysis of speed distributions at individual traps in dry conditions indicated some difference in effects between the two sites. At Site #1 the only significantly different distributions were for the comparison of delineation Upgrade 2 and the Baseline delineation. While statistically significant, the differences at Traps 2 and 4 were not large enough to justify a conclusion that either delineation system was better than the other.

The analysis of the "tails" of the distributions showed that at Traps 3 and 4, delineation Upgrade 2 resulted in a significantly ($p \geq .05$) lower percentage of drivers operating below the 15th percentile, compared with Baseline delineation. Upgrade 2 also produced a higher percentage of drivers operating at speeds higher than the criterion 85th percentile. However, the difference in percentage at the upper "tail" is statistically significant only for Trap 4. In other words, while delineation Upgrade 2 appears to shift the speed distribution generally upward compared with the Baseline system, not all of the percentage differences are statistically significant. A very similar pattern of distributional speed shifts and statistical significance was also associated with delineation Upgrade 3.

While the analysis of speed distributions at individual traps did not produce a consistent pattern of results, all of the statistically significant differences between the delineation upgrades and the Baseline delineation system suggest that the delineation upgrades provide better visibility of the site under dry conditions. The comparative analyses of the distribution "tails" showed that the upgrades, where significantly different from the

Baseline, resulted in a lower percentage of drivers operating below the criterion 15th percentile speed and above the 85th percentile speed; performance more closely matching that observed under full illumination. However, under wet weather conditions, where one would hope for the delineation to produce better performance, the upgrades were not found to produce any benefits over the Baseline system.

8. Effects of Weather and Delineation On Driver Behavior Measures

The driver behavior measures consisted of lateral placement, brake applications, edgeline encroachments, and gore encroachments. Of these measures only edgeline encroachments provide basis for choosing between the delineation systems.

With regard to edgeline encroachments, both of the delineation upgrades produced lower percentages of this maneuver under wet conditions, with Upgrade 3 showing the best performance under both dry and wet conditions. Further, performance under delineation Upgrade 3 was approximately the same as that observed under wet conditions with full lighting and Baseline delineation. It appears that Upgrade 3, with the fully reflectorized posts along the exit, acts to better align the drivers in the exit.

CONCLUSIONS AND RECOMMENDATIONS

A comparison of target detection performance under no lighting and partial lighting showed that TVA has a detrimental effect on target detection when measured under four- and five-luminaire partial lighting configurations. A comparison between these two partial lighting conditions, however, showed no significant differences.

A review of the pattern of results from the field study of lighting and delineation suggests that TVA may operate when partial lighting consists of fewer than four luminaires. Since Site #1 had a lower level of lighting (a one-luminaire partial) than Site #2 (a three-luminaire partial), one would expect upgraded delineation to be more beneficial at Site #1. However the pattern of results from comparisons of the trap speed distributions indicated that delineation upgrades tended to be more effective at Site #2. Further, where significant differences were obtained at Site #2, they more frequently occurred at ramp locations where TVA would most likely be manifested. It is possible that the higher lighting level at Site #2 (and the consequent TVA-related reduction in visual sensitivity) produced an "effective" visibility situation that accounts for the increased effectiveness of the delineation upgrades. Consider also the previously cited findings from NCHRP 256 that performance was better under two-luminaire partial lighting than under four-luminaire lighting.(1)

The combination of empirical evidence from the TVA study, the suggestive evidence from the field study of lighting and delineation, and the results of NCHRP 256 provide a basis for recommending that conditions under which TVA influences performance be further studied. Specifically, it is recommended that a study be conducted under partial lighting conditions which include one, two, and three luminaires. The results of such a study would provide a better empirical basis for recommendations on the most appropriate partial lighting configuration.

With regard to lighting, the findings support the contention that full lighting is generally superior to partial lighting in terms of ramp speed measures. Further, a number of supporting results suggest that, for a partially lighted exit, a three-luminaire configuration is superior to a single-luminaire configuration.

With regard to the effects of alternative delineation systems on ramp space mean speed, there were no significant differences between the Baseline delineation and the upgraded delineation systems. The analysis of speed distribution data obtained under dry weather conditions provides evidence that delineation Upgrades 2 and 3 are superior to the Baseline delineation. Both upgrades appear to provide better visibility of the exit because, in comparison with Baseline delineation, they result in performance that is closer to that observed under full lighting. However, the analysis of the speed distributions obtained under wet conditions provided no basis for differentiating between the delineation systems.

Because of the failure of the delineation upgrades to maintain a speed-related advantage over the Baseline system under the more demanding visibility conditions of rain, neither of the delineation upgrades can be strongly recommended over the Baseline system.

The only evidence to support the superiority of any delineation upgrades was in the incidence of edgeline encroachments. With regard to this measure, delineation Upgrade 3 produced the best performance under both dry and wet conditions; performance comparable to that observed under full lighting. However, from the standpoint of operation, safety benefits, or cost effectiveness, none of the delineation upgrades demonstrated enough advantage to merit a recommendation.

The lack of compelling evidence regarding the effectiveness of the upgraded delineation systems should not be generalized to other situations. The sites on which the delineation upgrades were tested were diamond interchanges with little ramp curvature. For the purposes of the project, sites of this design were appropriate because they were representative of the design on which partial lighting is most frequently used. However, slightly curved ramps do not pose a significant path maintenance problem for drivers, and the transition along the exit taper is comparatively easy. Consequently, upgraded delineation may not be as useful as it would be on ramps with a great deal of curvature, e.g., a loop ramp, which entail more difficult guidance problems for drivers. Should the future see more frequent use of partial lighting on ramps with significant curvature, it is recommended that further testing of upgraded delineation be conducted.

APPENDIX A: Supporting Data

Table 30. Detection distance with target location at right side, 350 ft (106.75 m).

TRIAL	ILLUMINATION CONDITION		DIFFERENCE
	ILLUMINATED	NONILLUMINATED	(NI-I)
1	383		
2	290	378	88
3	677	427	-250
4		378	
5	306	475	169
6	308	444	136
7	426	467	41
8		240	
9	349	522	173
10	288	470	182
11	403	116	-287
12	486	420	-66
13		415	
14	303	477	174
15	474	474	0
16	306		
17	284	346	62
18	397	463	66
19	375	411	36
20	401	508	107
21	348	386	38
22	432	534	102
23	323	231	-92
24	418	433	15
25	360	449	89
26	338	428	90
27	350	414	64
28	415	409	-6
29	431	501	70
30	472	556	84
31	330		
32	320	137	-183
33	339	399	60
34	355	345	-10
35	331	511	180
36	373	407	34
37	464	543	79
38	317	366	49
39	361	487	126
40	350	472	122
41	365	456	91
42	384	495	111
43	478	557	79
44	401	513	112
45	460	574	114
46	371		
47	340	387	47
48	347	444	97
49	375	363	-12
50	336	506	170
51	330	499	169
52	416	510	94
53	338	246	-92
54	410	445	35
55	424	421	-3
56	373	453	80
57	425	508	83
58	470		
59	478	459	-19
60	508	582	74
AVERAGE	384	434	53
COUNT	57	55	52
STD. DEV.	70	97	98
T-VALUE			3.90

(1 ft = .305 m)

Table 31. Detection distance with target location at right side, 475 ft (144.88 m).

TRIAL	ILLUMINATION CONDITION		DIFFERENCE (NI-I)
	ILLUMINATED	NONILLUMINATED	
1	336		
2	354	347	-7
3	383	666	283
4	276	416	140
5	333	531	198
6	344	467	123
7	437	540	103
8	322	279	-43
9	301	506	205
10	368	433	65
11	378	506	128
12	405	472	67
13	533		
14	407	404	-3
15	457	448	-9
16			
17			
18	436	421	-15
19	344		
20	373	481	108
21	370	468	98
22	469	523	54
23	324		
24	382	465	83
25	419	375	-44
26	409	615	206
27	420	516	96
28	462		
29	436	411	-25
30	474	512	38
31	406		
32		385	
33	361	499	138
34	408	371	-37
35	435	557	122
36	379	453	74
37	513	526	13
38	332	305	-27
39	400	493	93
40		518	
41	427	377	-50
42	480	526	46
43	486	510	24
44		470	
45	568	551	-17
AVERAGE	404	469	66
COUNT	40	37	34
STD. DEV.	64	80	84
T-VALUE			4.57

(1 ft = .305 m)

Table 32. Detection distance with target location at right side, 600 ft (183 m).

TRIAL	ILLUMINATION CONDITION		DIFFERENCE (NI-I)
	ILLUMINATED	NONILLUMINATED	
1	299		
2	234	341	107
3	414	405	-9
4		397	
5	485	436	-49
6	465	430	-35
7	401	557	156
8	274	384	110
9	390	487	97
10		425	
11	475	360	-115
12	483	357	-126
13	551	515	-36
14		500	
15	543	621	78
AVERAGE	418	444	16
COUNT	12	14	11
STD. DEV.	103	82	97
T-VALUE			0.55

Table 33. Detection distance with target location at left side, 350 ft (106.75 m).

TRIAL	ILLUMINATION CONDITION		DIFFERENCE (NI-I)
	ILLUMINATED	NONILLUMINATED	
1	252		
2	187	255	68
3		219	
4	271	217	-54
5	250	280	30
6	231	252	21
7	342	335	-7
8	251	112	-139
9	278	341	63
10	279	256	-23
11	269	228	-41
12	241	305	64
13	346		
14	275	309	34
15	351	339	-12
AVERAGE	273	265	0
COUNT	14	13	12
STD. DEV.	46	64	60
T-VALUE			0.02

(1 ft = .305 m)

Table 34. Detection distance with target location at left side, 600 ft (183 m).

TRIAL	ILLUMINATION CONDITION		DIFFERENCE (NI-I)
	ILLUMINATED	NONILLUMINATED	
1	221		
2	234	212	-22
3	275	267	-8
4	295	234	-61
5	279	354	75
6	192	275	83
7	340	370	30
8	270	192	-78
9	343	314	-29
10	251	288	37
11	306	298	-8
12	253	292	39
13	459	331	-128
14	242	331	89
15	583	349	-234
AVERAGE	303	[illegible]	-15
COUNT	15	14	14
STD. DEV.	100	54	89
T-VALUE			0.65

(1 ft = .305 m)

Table 35. Confidence intervals for significant TVA target locations.

	350 ft - right side targets		475 ft - right side targets	
CONDITION	95% Confidence Interval ft	99% Confidence Interval ft	95% Confidence Interval ft	99% Confidence Interval ft
ILLUMINATED	336-402	360-408	384-424	378-430
NONILLUMINATED	408-460	400-468	443-495	435-503
DIFFERENCE	37-95	28-104	26-80	17-89

(1 ft = .305 m)

Table 36. Site #1 ANOVA table for statistical effects of lighting and weather (see table 8).

SAS
GENERAL LINEAR MODELS PROCEDURE
CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
W	2	DRY WET
I	2	FULL PARTIAL
C	1	BASELINE

DATA SET = SITE #1
NUMBER OF OBSERVATIONS IN DATA SET = 2190

DEPENDENT VARIABLE: SPEED (SMS 2-5)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	3	3260.64631165	1086.8821039	32.46	0.0001	0.042653	12.7479
ERROR	2186	73184.5128485	33.47873415		ROOT MSE		SPEED MEAN
CORRECTED TOTAL	2189	76445.1591601			5.78608107		45.3886758

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
W	1	2423.14534229	72.38	0.0001	1	915.09335556	27.33	0.0001
I	1	300.24376567	8.97	0.0028	1	609.75257908	18.21	0.0001
W * I	1	537.25720369	16.05	0.0001	1	537.25720369	16.05	0.0001

Table 37. Site #2 ANOVA table for statistical effects of lighting and weather (see table 8).

SAS
GENERAL LINEAR MODELS PROCEDURE
CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
W	2	DRY WET
I	2	FULL PARTIAL
C	1	BASELINE

DATA SET = SITE #2
NUMBER OF OBSERVATIONS IN DATA SET = 3004

DEPENDENT VARIABLE: SPEED (SMS 2-5)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	3	1890.44784649	630.14928216	17.96	0.0001	0.017643	11.3183
ERROR	3000	105257.355177	35.08578506		ROOT MSE		SPEED MEAN
CORRECTED TOTAL	3003	107147.803023			5.92332551		52.3340213

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
W	1	1679.86718054	47.88	0.0001	1	1734.4528257	49.43	0.0001
I	1	173.55294494	4.95	0.0262	1	37.85301394	1.08	0.2990
W * I	1	37.02772101	1.06	0.3044	1	37.02772101	1.06	1.3044

Table 38. Site #1 ANOVA table for statistical effects of weather and delineation (see table 15).

SAS
GENERAL LINEAR MODELS PROCEDURE
CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
W	2	DRY WET
I	1	PARTIAL
C	3	BASELINE UPGRADE 2 UPGRADE 3

DATA SET = SITE #1
NUMBER OF OBSERVATIONS IN DATA SET = 3417

DEPENDENT VARIABLE: SPEED (SMS 2-5)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	5	7299.10676758	1459.8213535	43.45	0.0001	0.059877	12.9
ERROR	3411	114601.619713	33.59766043		ROOT MSE		SPEED MEAN
CORRECTED TOTAL	3416	121900.72648			5.79634889		44.9330992

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
W	1	71383414 15493	212.47	0.0001	1	5243.0792958	156.05	0.0001
C	2	123.13479979	1.83	0.1602	2	132.27766687	1.97	0.1398
W * C	2	37.55781286	0.56	0.5719	2	37.55781286	0.56	0.5719

Table 39. Site #2 ANOVA table for statistical effects of weather and delineation (see table 15).

SAS
GENERAL LINEAR MODELS PROCEDURE
CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
W	2	DRY WET
I	1	PARTIAL
C	3	BASELINE UPGRADE 2 UPGRADE 3

DATA SET = SITE #2
NUMBER OF OBSERVATIONS IN DATA SET = 3774

DEPENDENT VARIABLE: SPEED (SMS 2-5)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	5	3947.31324308	789.46264862	19.06	0.0001	0.24668	12.2865
ERROR	3768	156069.455947	41.41970699		ROOT MSE		SPEED MEAN
CORRECTED TOTAL	3773	160016.76919			6.4358144		52.3810811

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
C	2	125.40383889	1.51	0.2202	2	87.61017735	1.06	0.3474
W	1	3643.75227966	87.97	0.0001	1	2288.5344907	55.25	0.0001
W * C	2	178.15712453	2.15	0.1166	2	178.15712453	2.15	0.1166

Table 40. T-score values for Baseline and upgraded delineation at the 15th and 85th percentile "tails" of the trap speed distributions.

SITE #1	15th PERCENTILE				85th PERCENTILE			
	TRAP 2	TRAP 3	TRAP 4	TRAP 5	TRAP 2	TRAP 3	TRAP 4	TRAP 5
PDB-PD1[1]	1.513	1.969*	0.079	1.250	0.426	0.543	0.311	0.347
PDB-PD2	1.364	0.594	1.429	0.914	0.504	0.968	0.842	0.416
PDB-PD3	0.870	0.556	0.908	1.711	0.632	1.252	1.294	1.111
PWB-PW2	0.344	0.032	1.396	0.821	0.314	0.391	1.643	0.509
PWB-PW3	0.643	1.756	0.632	1.235	0.498	0.522	2.532*	1.393

SITE #2	15th PERCENTILE				85th PERCENTILE			
	TRAP 2	TRAP 3	TRAP 4	TRAP 5	TRAP 2	TRAP 3	TRAP 4	TRAP 5
PDB-PD1[1]	1.449	0.369	0.155	1.538	0.783	0.198	0.750	0.575
PDB-PD2	0.813	3.107*	3.339*	0.887	0.802	1.829	2.176*	0.763
PDB-PD3	1.133	3.290*	4.489*	0.985	1.369	3.055*	2.938*	1.269
PWB-PW2	1.580	0.628	0.772	0.368	0.669	0.045	1.068	3.334*
PWB-PW3	0.650	1.261	0.489	1.628	1.358	0.807	0.061	2.830*

[1] Key to abbreviations in table 7, page 37.

* indicates statistical significance.

Table 41. Delineation systems ranked for lateral placement against Baseline delineation with full lighting, and against center-of-lane position.

SITE #1								
TREATMENT			CRITERION 1*			CRITERION 2†		
LIGHTING	WEATHER	DELINEATION	TRAP 4	TRAP 5	TRAP 6	TRAP 4	TRAP 5	TRAP 6
PARTIAL	DRY	BASELINE	4	1	1	1	2	1
PARTIAL	DRY	UPGRADE 1	1	1	2	2	2	2
PARTIAL	DRY	UPGRADE 2	2	1	3	2	2	3
PARTIAL	DRY	UPGRADE 3	3	2	1	2	1	1
PARTIAL	WET	BASELINE	1	2	1	1	3	1
PARTIAL	WET	UPGRADE 2	3	1	2	3	2	2
PARTIAL	WET	UPGRADE 3	2	3	2	2	1	2

SITE #2								
TREATMENT			CRITERION 1*			CRITERION 2†		
LIGHTING	WEATHER	DELINEATION	TRAP 4	TRAP 5	TRAP 6	TRAP 4	TRAP 5	TRAP 6
PARTIAL	DRY	BASELINE	3	2	2	3	2	1
PARTIAL	DRY	UPGRADE 1	2	1	2	1	3	1
PARTIAL	DRY	UPGRADE 2	1	2	2	2	2	1
PARTIAL	DRY	UPGRADE 3	1	3	1	2	1	2
PARTIAL	WET	BASELINE	1	1	2	2	2	1
PARTIAL	WET	UPGRADE 2	2	3	1	1	1	2
PARTIAL	WET	UPGRADE 3	2	2	1	1	3	2

* Criterion 1 concerns difference from full lighting (rank of 1 is closest to lateral placement under full lighting).

† Criterion 2 concerns difference from center-of-lane position (rank of 1 is closest to center of lane).

APPENDIX B: Detailed Description of Delineation Systems

The two test exits lacked a deceleration lane; these exits tapered directly from the mainline. The ramp at Site #1 was straight, and Site #2 was slightly curved. The 4-in (10.16 cm) yellow stripe on the left side of the ramp, and the 4-in (10.16 cm), white, right edge stripe were repainted at each site 12 days before the start of data collection. Repainting of the right edge stripe commenced 300 ft (91.5 m) upstream of each exit taper.

The 8-in (20.32 cm) gore stripes at each site were of old thermoplastic in a thin layer. They were almost indistinguishable from glass-beaded paint. For Upgrade 3, each gore stripe (mainline stripe and ramp stripe) was completely covered with 8-in (20.32 cm) profiled tape. As such, the tape also simulated a thick application of thermoplastic.

Space between each 4-in (10.16 cm), white-retroreflective RPM used to line the vehicle side of each gore stripe increased gradually from the tip. This spacing was maintained in the Baseline, Upgrade 1, and for the 8-in (20.32 cm), white-retroreflective RPM's (called traffic diverters) placed on the gore stripe in Upgrade 2. At Site #2, the spacing was, from the tip: 5 (ft), 5, 7, 10, 15, 20, 30, and 40 repeated eight times (1.5, 1.5, 2.1, 3.1, 4.6, 6.1, 9.2, 12.2 m)—16 pair, one to the mainline side for each one to the ramp side. At Site #1, 12 pairs were spaced at 5 (ft), 5, 7, 10, 15, 20, 30, 40, 40, 40, 47 (1.5, 1.5, 2.1, 3.1, 4.6, 6.1, 9.2, 12.2 m).

The 4-in (10.16 cm) yellow-retroreflective RPM's lining the yellow ramp stripe from the gore to the ramp terminus in Upgrades 1 and 3 were placed adjacent to the vehicle side of the stripe. They were installed every 40 ft (12.2 m) at Site #1, because the ramp was straight, and every 20 ft (6.1 m) at Site #2, because of the curve in the ramp. The retroreflective posts used in all delineation systems to line the exit shoulders were white, flat, flexible road markers, 3.75 in (9.53 cm) wide, placed according to the <u>Manual on Uniform Traffic Control Devices</u> (MUTCD).[10] The top of the retroreflective surface was 4 ft (1.22 m) above the near roadway edge; the posts were installed not less than 2 ft (.61 m) or more than 8 ft (2.44 m) outside the outer edge of the shoulder, or in line with a roadside barrier that is 8 ft (2.44 m) or less outside the outer edge of the shoulder.

All posts were retroreflectorized with a 3-in (7.62 cm)-wide strip of high intensity sheeting that was 18 in (45.72 cm) long on partially retroreflective posts and 46 in (116.84 cm) long on fully retroreflective ones. Posts along the left shoulder of the ramp, and right (ramp) shoulder of the gore, carried yellow sheeting. Posts along the right shoulder of the exit, and left (mainline) shoulder of the gore, had white sheeting.

Posts installed along the right shoulder of the exit commenced 300 ft (91.5 m) upstream of the beginning of the exit taper, and were spaced every 100 ft. (30.5 m) to the ramp terminus.

The posts along the gore shoulders appeared in pairs, spaced downstream at 10-ft (3.05 m) intervals. At Site #2, the first (most upstream) pair was installed where the original first pair was located: on either side of, and in line with, the exit sign support in the gore. Four more pairs were then ranged back from the first pair to present the exiting driver with a formation that resembled two slashes, "\ /".

At the Site #1, the first pair of posts also was installed on either side of the exit sign support, but 10 ft (3.05 m) downstream of the support, on which there were installed strips of yellow (right) and white (left) retroreflective sheeting. Only two more pairs were ranged back from the first pair, because the gore was stubby. The effect of the formation was the same as at Site #2.

The posts lining the left shoulder of the ramp at both sites commenced about 100 ft downstream of the lead gore post, and were installed every 100 ft (30.5 m) to the ramp terminus. When the interval was halved to 50 ft (15.25 m) in Upgrade 2, a post was inserted into each gap.

APPENDIX C: Detailed Description of Measurement System Deployment

The locations of traps for determining vehicle speeds in response to test delineation and lighting were established by measuring along the exits' right shoulders. The tape measure was pulled parallel to the exits' right edgelines.

Parallel infrared beams from paired detectors, 6 ft (1.83 m) apart, aimed perpendicular to exiting traffic, comprised the traps. Detectors were mounted on steel posts.

First a reference was marked perpendicular to the point where the exit diverged from the mainline. The location for the single detector that was to register normal entries into the exit taper was established 100 ft (30.5 m) downstream of the diverge mark. It was called Trap 1 although not paired with another detector.

True traps were established across the exit near the apex of the gore stripes (Trap 2), at the gore (Trap 4), and half way between these places (Trap 3). Four more traps were established every 100 ft (30.5 m) downstream from Trap 4.

Traps 4, 5, and 6 had a third (diagonal) detector, located 6 ft (1.83 m) upstream of the trap. The purpose of the diagonal beam was to indicate vehicles' lateral positions on the ramps at these traps. The diagonal beam was aimed downstream of the parallel beams, at a 45-degree angle to exiting traffic.

Reflectors were used to bounce each detector's infrared beam back to the detector, to complete the beam circuit. Reflectors at Traps 1, 2, and 3 had to withstand being run over, so raised pavement markers were placed just inside the ramp gore stripe (Traps 2 and 3), and on an imaginary extension of the mainline's right edgeline (Trap 1), to serve as reflectors. The reflector at Trap 1 was placed on a perpendicular from the sensor mount through the exit's right edgeline to the imaginary extension of the mainline edgeline. The two upstream reflectors at Traps 2 and 3 were similarly placed, the perpendicular running to the ramp-side gore stripe. The downstream reflectors were placed 6 ft (1.83 m) away.

At Site #1, pavement reflectors also were needed at Trap 4, and for the upstream beam at Trap 5, because gore pavement made it difficult to install the posts used elsewhere for reflector-mounts. Reflectors for remaining traps were mounted on steel posts in the dirt off the left shoulder of the ramps. Marks for the upstream reflector posts at each trap were made on a perpendicular from the detector post through the ramp right edgeline to the left off-shoulder area. The downstream posts were marked 6 ft (1.83 m) away.

To establish the mark for a diagonal beam's reflector, a perpendicular from the location of the detector was measured across the ramp to the opposite shoulder or off-shoulder area. From this location, the same distance was measured downstream parallel to the ramp. This served as the mark for the reflector.

After layout of the traps and installation of detector and reflector mounts at each site, TES was deployed. Cables were run from the location of the TES event recorder, hidden behind vegetation, to the traps to be serviced. Lead wires were strung from each detector mount to junction boxes at the cable ends. They would carry the signal (when an exiting vehicle interrupted a detector beam) to the event recorder. Carrying power to the detectors were extension cords, strung from a battery, hidden in vegetation, upstream to Trap 1 and downstream to Trap 8, with outlets at each trap.

Fine tuning was performed next. Brackets were installed atop each sensor mount for easier attachment of detectors, and reflectors were treated with water repellent and installed on their mounts. Cables, leads, and extension cords were camouflaged in vegetation. Junction boxes and all cable and extension cord connections and outlets were inserted into plastic bags, as were button boxes used for manual input by observers. Detector mounts were painted flat black to reduce their visibility. Plastic bags used to hood the detectors were also sprayed black. Detector lenses were fitted with plastic visors for additional protection.

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