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THE INFLUENCE OF GLARE ON THE DETECTION OF HAZARDOUS OBJECTS IN AUTOMOBILE NIGHT DRIVING

BY

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THE INFLUENCE OF GLARE ON THE DETECTION OF HAZARDOUS OBJECTS IN AUTOMOBILE NIGHT DRIVING

L'INFLUENCE DE L'ÉBLOUISSEMENT SUR LA DÉTECTION D'OBJETS DANGEREUX EN CONDUITE NOCTURNE

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SUMMARY

This study consists of the visibility calculations for a series of automobile headlight experiments employing retractable detection targets under opposing glare. The present work is the natural continuation of the unopposed target experiments published earlier.

With the addition of opposing glare, attention is directed to describing the glare levels, eye movements, and the spatial adaptation levels associated with the visual task. The transient adaptation states consisting of both dark-to-light and light-to-dark transitions are then determined.

It is shown that one-to-one correspondence is possible between field detection trials and predictions based on laboratory visual potential.

RÉSUMÉ

Le présent rapport consiste en des calculs de visibilité entrepris pour analyser une série d'expériences en conduite nocturne sous des conditions d'éblouissement entreprises à l'aide d'un système de cibles escamotables. Ce travail est la suite naturelle de la série d'expériences concernant la visibilité en champ libre déjà publiée.

Dans le cas présent nous avons tourné notre attention à la description des niveaux d'éblouissement, des mouvements des yeux et des niveaux d'adaptation spatiale associés à la tâche visuelle. Conséquemment, les états d'adaptation éphémères consistant en des transitions obscur à brillant et vice versa sont devenus déterminables.

Finalement on démontre qu'une correspondance biunivoque entre les essais de route et les prédictions basées sur des études de potentiel visuel en laboratoire peut être établie.

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THE INFLUENCE OF GLARE ON THE DETECTION OF HAZARDOUS OBJECTS IN AUTOMOBILE NIGHT DRIVING

1.0 INTRODUCTION

Current research in automobile headlighting is focused on the analysis of the visibility conditions that exist during night driving. The present study is concerned with the description and analysis of an obstacle detection experiment under opposed glare light and is part of a comprehensive research study on headlighting (Refs. 1, 2). An unopposed series of headlight tests (Ref. 3) formed the background for subsequent work on the simulation of night driving passing encounters on two-lane roads.

Experiment-controlled targets served as detection elements in a visual driving task that characterized the visibility of small, dark, hazardous objects under opposing glare light.

In the aforementioned work for unopposed headlighting it was shown that one-to-one correspondence could be established between field detection trials and laboratory measurements of observer-driver luminance difference requirements. (To avoid repetition, that study (Ref. 3) will be subsequently referred to as the "unopposed" or "previous" study.) A precise description of the illuminance and luminance levels and distributions occurring during target detection was shown to be necessary in order to obtain good correlation. Several new areas were emphasized in the previous study. These included: 1) the formulation of a luminance difference metric for hazard-like objects, 2) the determination of the enhancement of visibility due to object shadows, 3) study of the time necessary for target search and target fixation, 4) the influence of dynamic vehicle pitch changes on the headlamp system light distribution, and 5) the contribution of foreground luminance to the disability glare effect.

Several new mechanisms are introduced when an opposing headlight source is added to a target detection task. The presence of direct glare adds dynamic elements that are not present in the unopposed tests. Thereby, the factors of interactive lighting, direct glare and transient adaptation are also considered in the analysis and discussion of this phase of the NRCC headlight program. The present description of the visibility conditions existing during passing maneuvers in night driving is a natural continuation of the unopposed series of tests.

A measurement methodology based on threshold values was incorporated in this study. The 50% threshold detection distances were obtained in these opposed lighting experiments. The observer-driver drove the vehicle containing the test beams through the zone containing four retractable targets and the opposing headlamp system. A target in front of the opposing source involved the interaction of the two beams and the target appeared darker than the roadway throughout most of the detection zone. Two other targets were positioned next to the opposing lamp system so as to create detection tasks having varying glare levels. A fourth target was positioned behind the glare vehicle in order to facilitate the study of the phenomenon of transient decay.

2.0 THE GLARE MECHANISMS OF NIGHT DRIVING

2.1 Salient Features

The two occular mechanisms of discomfort and disability glare occur during night driving to decrease driving performance. These deleterious glare phenomena influence the driving age as well as the road conditions under which safe driving is possible. (Both, sensitivity to and recovery from glare are strongly dependent on age.) Discomfort glare operates at the lower light levels and does not directly affect visual performance in the short term. Its effects are manifest in driver discomfort and fatigue if prevalent for long driving periods. Discomfort glare does not interfere with the visual performance involved in the detection of small roadway objects.

The aspect of glare of concern here is known as disability glare. It reduces visual performance and is often accompanied by discomfort. Disability glare is present only at the higher illuminance levels. Visual performance is adversely affected simultaneously upon exposure to the glare source. It will be necessary to focus on the work of past research in order to quantify the disability glare mechanism occurring in a night driving encounter. The areas of concern (Refs. 4, 5, 6) deal with 1) glare illuminance, 2) eye-source direction, 3) age of the observer, 4) observer glare sensitivity and 5) scene-complexity.

Description of the deleterious visual effects consists of calculating the magnitude of the adaptation changes that can occur. Glare light is assumed to be scattered in the eye resulting in the superposition of a uniform luminance over the retinal image. This "veiling" luminance is added to the luminance of the scene and leads to an increased adaptation of the eye.

2.2 Spatial Adaptation

It is customary to describe transient processes as perturbations to steady state phenomena. Adaptation changes caused by rapidly fluctuating light levels are considered to be alterations of quasi-static processes. In the passing encounter under discussion, the static (spatial) nature of the light is perturbed by both vehicle motion and the eye movements inherent in a tracking task.

The consideration of quasi-static processes (the eye is assumed to be fully adapted to the level in question) involves the determination of the glare "veiling" luminance created by all the glare sources in view. The contribution of individual sources is the summation (in fL) of

$$10\,\pi\,\kappa\,\Sigma\,E_g/\theta^{2.3} \tag{2.2.1}$$

where E_g is the illuminance at the eye on a plane that is perpendicular to the foveal axis and θ is the angle (in degrees) between the fixation and source directions. The glare sensitivity parameter κ, is influenced by observer age and individual eye lesions. The quantity $10\,\pi$ relates to the glare produced by complex visual environments. Values as high as 3.0 are not uncommon for the magnitude of κ (Ref. 4). Whereas the index for θ does not change appreciably with age, κ increases approximately threefold with age with reference to the 20-30 age group. The multiplication of the veiling luminance by the constant factor κ results in a nonlinear change in the required luminance difference ΔL_R. The correction to ΔL_R decreases as the adaptation level L decreases since the ΔL_R function is relatively independent of adaptation at the lower luminance values. (The foveal adaptation is the summation of all the corresponding illuminances contributing to foveal luminance, whether direct or like glare, indirect.)

In the analysis of the experimental detection trials it will be necessary to regard the glare sensitivity parameter κ as a degree of freedom. Test data for the glare sensitivity of the participants of the headlighting program were not available and the starting values for subsequent iterative calculations have to be approximated by referring to earlier work.

A question of interest with respect to the formulation given in Equation (2.2.1) concerns the form of the θ dependency. The luminous contributions of most night driving environments to the veiling luminance will be quite small for the case of large angles between the source and viewing directions (i.e. $\theta > 40°$). When the glare source is imaged near the edge of the foveal region ($\theta \simeq 3/4°$), another formulation may be more appropriate. Some work (Ref. 7) has suggested a θ dependency given by $\theta^{-1}(1.5 + \theta)^{-1}$. Other work at small angles has resulted in an expression of the form $\theta^{-3.44}$ (Ref. 8).

In this program, θ was greater than 0.7 degrees in the target regions of the field experiments and Equation (2.2.1) is used throughout.

2.3 Transient Adaptation

The retina of the eye adjusts to the quantity and quality of light during adaptation. The process of adaptation is different for different parts of the retina when the visual scene is of non-uniform luminance. Adaptation is a function of time, being both temporal as well as spatial.

It can be assumed that the instantaneous state of adaptation for any given area of the retina at any specific time can be described by an equivalent luminance of a uniform source that fills the visual field until equilibrium is reached. It is clear that the same state of adaptation can be produced by infinitely many visual configurations.

Attention is confined to the adaptation of the fovea since it is of primary importance in the study of the detectability of foveal-imaged hazardous objects.

If the luminance of a scene is suddenly changed from one level to another there may be a temporary loss of visibility in reference to a task seen against that scene. Likewise, experience has shown that exposure to very bright regions can subsequently degrade visual processes in regions of lower luminance. Thus visibility is reduced in a change from one adapting level to another with the visibility loss increasing with the ratio of the change.

For downward luminance changes from the 4000 fL level considerable photopigment bleaching occurs. For upward changes, loss of fixation, blinking and bleaching cause substantial losses.

For the lower luminance levels (below about 400 fL) the degree of visibility loss is influenced mainly by the ratio of the scene luminance shift and essentially independent of the actual values of the field luminances.

At the engineering levels of luminance of interest here, there is almost no photopigment bleaching and secondary neural processes are responsible for changes in adaptation. Also, there are two different adaptation rates since a state of equilibrium is reached faster going from a low level to a higher one than in the opposite direction. Both of these mechanisms, light and dark adaptation, will be considered in the derivation of the state of adaptation in a night driving encounter.

The spatial adaptation of the observer can be described in terms of the scene luminance, foreground glare, and the direct glare from the opposing headlamps. The dynamic nature of the passing maneuver is simulated by introducing observer motion through the target zone at the test velocity. The eye saccades necessary to fixate the targets are superimposed on this motion.

Spencer and Peek (Ref. 9) described the adaptation changes that occur during night driving by means of an analytical expression. A similar formulation, proposed in Reference 10 is given by

$$L_t(t) = k \int_{-\infty}^{t} w(\tau)\, L_s(\tau)\, d\tau \tag{2.3.1}$$

where

$$w(\tau) = e^{-k(t-\tau)\ell(t)} \tag{2.3.2}$$

and $\ell(t) = L_t(t) - L_s(t)$, k being a decay constant. $L_t(t)$ and $L_s(t)$ are the transient and spatial (static) adaptation luminances. They are functions of time (position) as a result of movement through the glare test zone. Equation (2.3.1) applies to downward changes, i.e. dark adaptation.

For a step change in luminance from L_1 to L_2 at t = 0, Equation (2.3.1) reduces to the transcendental equation

$$x = e^{-xt'} \tag{2.3.3}$$

where $x = \ell(t)/(L_1 - L_2)$ and $t' = k(L_1 - L_2)t$ is the modified time.

The work of Boynton and Miller (Ref. 11) is used to relate adaptation changes in time following light changes. Although they used letter recognition thresholds these have the same general behaviour as do the functions describing detection. Equation (2.3.1) shows surprisingly good agreement for the decay aspect of adaptation as exemplified by the experimental results of Boynton and Miller (Ref. 11). Figure 1 shows this agreement for a step change from 40 milli lamberts (mL) to 0.04 mL at t = 0. The values of Equation (2.3.3) are denoted by a dashed line for a glare decay value of k = 3.

The above formulations describe downward changes in luminance and do not predict an overshoot at the moment of transition for upward changes. This is a severe limitation in the case of large sudden increases in luminance, i.e. for $L_2 \gg L_1$. Transient overshoots occur as a result of the assumed instantaneous eye movements from one target to the succeeding one.

An empirical expression was derived from the Boynton-Miller data (Ref. 11) using their tau = 0.3 sec. values to describe visibility losses caused by sudden increases in luminance. Transient overshoot will be slightly underestimated by employing these later tau values. However, peak values are difficult to define and the overall discrepancies should be small because the effects of the overshoot are localized by the decay aspect of transient adaptation.

The equation used to obtain the adapting luminance at the moment of transition is

$$L_t = L_2 \left\{1.0 + 0.75 \log(L_2/L_1)\right\} \qquad (2.3.4)$$

valid for the approximate range

$$1 < (L_2/L_1) < 500$$

When this result is combined with Equation (2.3.1) representing the decay part (light-to-dark transition) it is possible to specify the complete course of adaptation if the spatial adaptation, the occurrence of saccades and the velocity of the test vehicle are known.

3.0 THE METHODOLOGY OF THE NRCC DETECTION EXPERIMENT

The test methodology described here was developed for the series of unopposed headlighting experiments (Ref. 3). The basic feature of the NRCC detection experiment is the retractable target that can quickly rotate to the down position presenting an acceptably small angle in the process. This action can occur at a predetermined distance from the test vehicle, thereby establishing the visibility levels for the observer-driver. The target was triggered by the test vehicle to provide a luminance difference signal at or near the threshold of detection. Interrogation of the participant beyond the test zone resulted in the detection ogives illustrated in Figure 2.

The test layout is shown in Figure 3. A stationary cart serving as the glare vehicle and containing the opposing lamp system was positioned in the opposing lane. The structure housing the glare lamps is illustrated in Figure 4. This cart was equipped with a regulated power supply, a levelling system and a telescope to align the unit accurately with respect to the roadway. The various glare headlamp units could be quickly and accurately interchanged to provide reproducible light sources in opposition.

The target faces were square and of light metal construction. These were covered with grey, achromatic non-specular paints, the characteristics of which are given in Reference 3. The target actuator mechanism rotated the target face to a down position in less than 100 millisec. (The luminous flux decreased to e^{-1} of its original value in about 50 millisec.) Targets of two sizes and two retro-reflectances were employed in the program.

Four targets were positioned in the test zone with their locations fixed in relation to the glare source. This target pattern is illustrated in Figure 3. The shoulder target T_2, was detected at a greater distance than target T_3 because of the difference in magnitude of the direct glare present at the eye. The location of each target was marked by a small (two inch square) off-set target to provide a well defined fixation pattern for the observer-driver. This was found to be necessary so as to maintain an eye path devoid of extraneous eye movements which tend to obscure results in the presence of high levels of direct glare. With repeated trials the participant became thoroughly familiar with the target locations and the eye movements associated with tracking the targets. An element of randomness was introduced into the procedure by leaving some targets un-activated, constituting response in a forced-choice mode.

Several processes or phenomena were investigated with the target arrangement shown. The forward target location served as a means of studying the interaction of the driving and opposing beams by creating various roadway luminance distributions in this area. It will be seen that the luminance difference signal of this target was strongly influenced by the roadway luminance surrounding it. The shadows associated with target T_1 and created by the opposing lamp system may significantly increase target detectability.

The two targets, T_2 and T_3 were displaced laterally with respect to the glare source and constituted two levels of glare governed primarily by the angular distance between the targets and the lamp cart.

The final target, T_4 was situated in a zone of little or no direct glare. It was included in order to study the manner in which the eye can adapt to the dark region beyond the glare vehicle.

4.0 THE GLARE EXPERIMENT CONFIGURATIONS AND RESULTS

The series of target detection trials with an opposing lamp system acting as a glare source was conducted on one site, an unopened section of a recently completed thoroughfare. One observer-driver was involved with the expectation that the use of more participants would obscure the results unless a comprehensive laboratory program was set up to measure individual sensitivity to glare. (Other work has shown that individual variability in both static and dynamic sensitivities to glare can be pronounced.)

Measurements of roadway and target reflectance factors were carried out as previously described (Ref. 3). These values were obtained in situ by means of a target substitution technique in order to compensate for the effects of atmospheric scattering. Figure 5(a) illustrates the set-up used to measure the roadway retro-reflectance ρ_P which is assumed to be a function of distance. A similar arrangement can be employed to measure the target retro-reflectance ρ_T. The forward reflectance of the roadway ρ_P' was measured with the set-up shown in Figure 5(b). Good quality control procedures must be employed since ρ_P' is extremely sensitive to roadway position as far as the source and viewing locations are concerned. The luminance of the atmosphere caused by scattering is usually of little significance in this case because the roadway luminances under consideration are several orders of magnitude greater.

Intensities of both driving and opposing lamp systems were measured in situ in accordance with accepted photometric procedures to ensure repeatability and accuracy. A systems engineering approach was undertaken so as to maintain repeatability of lamp characteristics. Lamp voltage was regulated on the test car as well as on the glare vehicle. Lamp alignment was carefully maintained.

A detection trial was carried out in the manner described in Section 3. The observer-driver was interrogated after passing through the test zone with each maneuver consisting of the display of four targets as illustrated in Figure 3. Targets T_1, T_3 and T_4 were located in the center of the driving lane whereas target T_2 was located on the crushed stone shoulder, three feet from the edge of the driving lane. A detection ogive, an example of which is shown in Figure 2 was derived for each sub-configuration. (A configuration consists of each of the combinations of driving lamps, opposing lamps, target sizes and reflectances employed. A sub-configuration consists of one of the targets; T_1, T_2, T_3 or T_4.)

A configuration list is given in Table 1. Included in this list is the target size, target reflectance, driving beam type, opposing beam type, number of trials and the experimental detection distance designated as s_e.

Table 2 lists some typical photometric values of the three lamp systems in order to indicate the relative intensities of their outputs.

LB_1 is an extensively used lamp system that was aimed excessively downward with the peak intensity at the roadway occurring close to the vehicle. LB_2 is a different system of comparable peak intensity but aimed higher. It has a reduced output in the sector in which an opposing driver's eyes would appear and is considered to have a sharp cut-off. The experimental MID beam system has increased intensities in both the driving and opposing sectors as compared to the other two systems.

An attempt was made to conduct the tests in block format. However, operational difficulties such as equipment malfunction, driver fatigue, and unfavourable weather conditions often precluded the completion of all of the configurations in a block. Detection trials were terminated whenever the effects of either atmospheric scattering or moonlight became noticeable. Data was edited and consolidated on this basis.

There appeared to be no other systematic trends or anomalies caused by weather conditions apart from the possible effect of shoulder dampness. As a test session progressed there was a tendency for the onset of shoulder dampness with a consequent increase in the experimental detection distance s_e for target T_2 resulting from the decrease in background reflectivity.

5.0 DERIVATION OF THE VISIBILITY CONDITIONS AT DETECTION

Recently there has been an increase in emphasis placed on the formulation of detection models to replace extensive field testing in automobile headlight research. A significant portion of the present work has been directed to the computation of the visibility conditions present during a passing maneuver.

The computational scheme now developed is an outgrowth of the analysis employed in the description of the unopposed series of target detection trials. A luminance difference metric was formulated in terms of the target mid-point luminance and the luminance of a point on the roadway corresponding to the target mid-point as viewed by the driver. Prior analysis of visibility conditions based on this metric showed strong correlation between uniform target and background observer data and the roadway target experiments.

Multiple-beam systems create shadows in conjunction with vertical objects. These shadows augment the visibility of the target if the target and roadway reflectance are not too dissimilar. It was shown that shadow enhancement should be included in the visibility calculations if the reflectance ratio approximately satisfies the inequality given by

$$\rho_T / \rho_P < 3$$

Thus, shadows are not included in the analysis of targets T_2, T_3 or T_4 with an expected inaccuracy in the luminance difference formulation of less than 5%. (The influence of shadows on the detectability of target T_1 is omitted for reasons to be discussed later.) The pitch changes of the moving test vehicles are included in order to correct the static in situ illumination values. Most automobiles pitch up with speed resulting in changes in light intensities of up to 100%.

Also included in a manner similar to that of the previous study are the factors of atmospheric attenuation and foreground glare.

Other elements are introduced in order to compute the visibility of targets under opposing glare light. These relate to:

a) Roadway luminance values include light from opposing glare lamps (illuminance E') in conjunction with the forward reflectance factor of the roadway (ρ_P').

b) The assumed pattern of eye movements is based on target position and the experimental detection distances. This fixation history is necessary in order to compute the source-eye direction angle θ of Equation (3.2.1).

c) The opposing lamp illuminance is computed at the eye position as part of the direct glare calculation.

d) Glare illuminance from the foreground luminance produced by the opposing system is calculated and included in the disability glare effect.

e) The spatial adaptation luminance is computed as a function of position.

f) Transient adaptation values include both the over-shoot and decay phenomenon once vehicle speed is established.

Calculation of the available luminance difference ΔL_A proceeds as follows:

Let ρ_P be the retro-reflectance and ρ_P' be the forward reflectance of the roadway (see Figs. 5(a), (b)). Let E and E' be the illumination from the driving and opposing lamp systems at the distance s^*. This distance corresponds to the mid-point of the target. The roadway luminance corresponding to the target mid-point is

$$L_P^* = \rho_P E + \rho_P' E' \tag{5.0.1}$$

If ρ_T is the target reflectance and $E_{(mid)}$ is the illumination at the target mid-point, then the mid-point luminance of the target is

$$L_{T(mid)} = \rho_T E_{(mid)} \tag{5.0.2}$$

and the available luminance difference of target T_1 becomes

$$\Delta L_A = \rho_T E_{(mid)} - \left[\rho_P E + \rho_P' E'\right] \tag{5.0.3}$$

This luminance difference quantity is dominated by the ρ_P' term because on most roadways $\rho_P' >> \rho_P$, even though in general $E' < E$. Over most of the T_1 target region $\Delta L_A < 0$ and the target appears darker than the roadway. At certain positions of the test vehicle only a section of this forward target is back-lit by the opposing lights. In this case, the target size α is corrected to include only that part.

There is no back-lighting in the case of the final three targets and Equation (5.0.3) becomes

$$\Delta L_A = \rho_T E_{(mid)} - \rho_P E \tag{5.0.4}$$

The obstacle size and the adaptation level of the eye define the luminance difference ΔL_R necessary for detection. The expression employed here was previously empirically derived (Ref. 12) and applied to the work on the unopposed series of headlight experiments. The form for the required luminance difference is

$$\Delta L_R = \lambda f(\alpha, L_t) \tag{5.0.5}$$

where α is the angle (radians) of the object that is subtended at the eye, L_t (fL) is the adaptation luminance of the eye, and λ is the participant sensitivity factor accounting for individual variations in luminance difference requirements. Generally, λ increases with age, with the increase becoming pronounced after the age of 40.

Since we are concerned with vehicle movement against an opposing glare source, the transient adaptation L_t must be defined before the formulation in Equation (5.0.5) can be employed.

6.0 A VISIBILITY ANALYSIS OF THE TEST RESULTS

The calculations presented here are based on a model of detection that was outlined in the previous section. Attention will be directed to the validity, completeness and consistency of these visibility calculations. Comparisons are made between the predictions of the detection model and those obtained from experimental target detection trials. The field work provided some important data for the visibility calculations. Judicious comparisons are to be made between the predicted and actual field results by an iterative procedure in which the values of some free parameters are allowed to vary through a suitable range. Some assumptions and conclusions of the earlier unopposed study are then tested.

This work separates naturally into two areas, the first of which is the specification of the illumination and luminance conditions existing during an opposed encounter. The other relates to the visual potential of the observer in a controlled task. When the observer is introduced into the defined visual environment it becomes possible to quantify the visibility of the presented targets. The visual scene defines the available luminance difference ΔL_A and in large measure determines the adaptation level. The observer requirements are specified by the luminance difference quantity, ΔL_R given by Equation (5.0.5).

It is known (Ref. 13) that atmospheric scattering can influence a target detection model in two ways. First, the luminance of the air must be compensated for in the determination of roadway retro-reflectance by use of target substitution techniques. Second, in field detection trials, the atmospheric luminance increases the adaptation level to which the eye is exposed. (The luminance difference ΔL_A as defined here is essentially unchanged in the presence of atmospheric attenuation.) The increase in L_s is not expected to be of concern in the case of detection at the relatively short distances of the opposed targets T_2, T_3 and T_4. The presence of the glare light raises the adaptation level a hundredfold and the luminance of the air becomes of secondary importance.

Previous calculations concerning the unopposed series indicated that the average increase in the pitch of the test vehicles was of the order of 0.0065 radians. This is in agreement with approximate calculations and some measurements of illuminance output from moving test vehicles. The vehicle pitch term is initially set to the above value and the illuminance data was corrected accordingly.

Some free parameters exist in the formulation of the direct glare expression of Equation (3.2.1) and the decay phase of adaptation in Equation (3.3.1). Values are necessary to start the calculation which will be of an iterative nature. Work on complex glare fields has shown (Ref. 4) that the glare sensitivity parameter κ can have a value ranging from about 0.5 to 3.0. A representative value of 1.0 is chosen initially. Previous work on transient decay has shown (Fig. 1) that k = 3.0 satisfies the data of Boynton and Miller (Ref. 11). The two free parameters κ and k will be finally determined when the visibility calculations of the field detection trials are carried out and the variances of discrepancies in ΔL ascertained.

The spatial luminance L_s is the static or positional luminance level to which the eye would be exposed to in the absence of any transients. It is the sum of the two glare quantities; direct glare and foreground glare as well as the luminance of the roadway corresponding to the mid-target point at the distance s* (see Fig. 5(a)). With the adoption of eye movements and motion with respect to the glare system, the effective adaptation level of the eye becomes the transient quantity denoted by L_t.

The quantity

$$\delta = \Delta L_R / \Delta L_A - 1 \qquad (6.0.1)$$

is the discrepancy in the available and required luminance differences at the detection distance s_e. The quantity $(s_e - s_c)/s_e$ is the discrepancy in distance and of the same sign as δ.

The quantity Δt_{av} in Table 1 is the average test time in seconds that was available between target T_2 and T_3 events, i.e. the average time between the retractions of targets T_2 and T_3. The significance of Δt_{av} will be discussed when considerations regarding the time available for the detection of target T_3 are made.

Field work experience dictated that possible systematic discrepancies in the target detection trials should be investigated first. For example, it was noted that the visibility of target T_2 increased with roadway shoulder dampness. This was in all likelihood due to a decrease in ρ_P and a consequent increase in ΔL_A. Average values of the shoulder retro-reflectance ρ_P are used to account for the dampness. (Later, the variance of target T_2 results will be seen to be about twice as great as those of targets T_3 and T_4.)

It appears that there may have been insufficient time for the detection of several of the T_3 sub-configurations. The last column of Table 1 lists the average experimental elapsed time between the retractions of targets T_2 and T_3. Work on the unopposed target series indicated that an elapsed time of 0.5 sec. or more was required for detection. The addition of glare and the introduction of a more complex task as far as eye movements are concerned would have a tendency to increase the required time. (The overall average time as listed in Table 1 is 0.96 sec. with a standard deviation of 0.25 sec.)

Some correlations are calculated to test the premise that there was insufficient time for the detection of target T_3. These correlations are designated by C_i where the subscript indicates the number of configurations included. For the quantities δ and $s_{e2} - s_{e3}$, $C_{10} = -0.4222$ and C_7 (BCDEFGJ) $= -0.9362$. This confirms the above premise since an increase in $s_{e2} - s_{e3}$ (due to a decrease in s_{e3} for example) results in a statistical decrease in δ (in the negative sense). Other linear correlation coefficients were calculated to test this hypothesis. These are:

δ; s_{e2}	$C_{10} = 0.1756$	
	$C_8 = 0.6992$	(ABCDEFHI)
$s_{c2} - s_{c3}$; $s_{e2} - s_{e3}$	$C_{10} = -0.0724$	
	$C_7 = 0.8005$	(ADEGHIJ)
Δt_{av}; $s_{e2} - s_{e3}$	$C_{10} = 0.8385$	
	$C_8 = 0.9885$	(ABCDEHIJ)

The above results are iterated quantities since values of k and κ were required in order to proceed with this analysis. It can be concluded from the entirety of these correlations that some of the s_{e3} experimental distances were underestimated due to a lack of time necessary for the process of detection consisting of eye movement, search and fixation.

Earlier, it was noted that the luminance difference sensitivity of the participant λ, was determined in a comprehensive laboratory program. However, the reaction to glare was not determined in a like manner and is not directly available. The glare indices κ and k can be selected.by minimizing the standard deviation and the mean values of the luminance difference discrepancy δ for the 20 sub-configurations consisting of targets T_2 and T_4. (Target T_1 results are omitted because of the difficulties inherent in determing the corresponding ΔL_A values and T_3 results are omitted because the associated detection distances have been shown to be statistically underestimated.

There appears to be no unique way of selecting the parameters κ and k with the aid of the field detection data. Considerations relating to target position appear to favour the use of target T_2 data in the process of selecting κ and the use of target T_4 data to choose k. Certainly, direct glare is the predominant influence in the case of the earlier targets. The final target was detected during the transient decay phase of adaptation. But the relatively great variance in the target T_2 data was largely a result of the variability in shoulder reflectivity.

Figure 6 shows the average value of the luminance difference discrepancy for target T_4 ($\bar{\delta}_4$) as a function of the glare decay k with the glare sensitivity κ being the parameter. Inspection of the data field (all possible combinations of k and κ values) for targets T_2 and T_4 shows a self-consistency in the relationships presented in Figures 7 and 8. The standard deviation for target T_4 ($\tilde{\delta}_4$) is at a minimum when k = 12 and κ = 2.8. As seen in Figures 6 and 7, $\bar{\delta}_4$ is approximately zero for these values of the glare parameters. It should be noted that both k and κ fall within the estimated probable range for these quantities.

The resulting values for k and κ are dependent on the moment of the macro eye movement from one target to the next as well as the numerical procedure employed to solve Equation (3.3.1).

Once the selections of k and κ have been made, the influence of ξ variations (ξ is the pitch of the test vehicle in radians) can be illustrated. The previous study on unopposed detection had shown that a pitch condition of ξ = 0.0065 radians resulted in a minimum in the standard deviation of δ. The functional relationship between $\tilde{\delta}$ (for targets T_2 and T_4) and ξ is shown in Figure 9 for glare parameters k = 12 and κ = 2.8. The minimum in $\tilde{\delta}$ is again seen to occur near ξ = 0.0065 radians. The variation in $\tilde{\delta}$ is similar if all 30 sub-configurations featuring targets T_2, T_3 and T_4 are included. This behaviour is also illustrated in the figure.

Most considerations of the visibility conditions at detection involve knowledge of the required and available luminance differences ΔL_R and ΔL_A. The values of ΔL_R and ΔL_A are shown in Figures 10(a) to 10(j) as a function of distance for the 10 configurations of Table 1. The experimental detection distances are indicated by vertical lines. The ΔL_R, ΔL_A crossings denote the occurrence of detection and the associated distances are designated by s_c. In the case of the forward target T_1, ΔL_A is negative because the target background that is illuminated by the opposing lamp system is of greater luminance than that of the target. In the field trials, detection was seen to occur over large distances in the case of target T_1 for configurations A, B and C as indicated by the underlined values of Table 1. The $\Delta L_R - \Delta L_A$ relationship shows this possibility by exhibiting near coincidence in some of the T_1 target regions.

There was an insufficient number of trials to identify the detection of target T_1 for the configurations H, I and J (the targets were smaller and darker in these three configurations). As seen in Figures 10(h), 10(i) and 10(j).

$$|\Delta L_A| < \Delta L_R$$

over an appreciable range and there would appear to be no coincidence or intersection of the ΔL_R and ΔL_A functions for the negative ΔL_A (silhouette) zone.

The predominant feature of the forward target T_1 is the high intensity of the roadway luminance created by the opposing lamp system. The large values of the forward reflectance factor ρ_P' dominate both the available and required luminance differences. (The direct glare also raises the adaptation level as a result of the small object to eye-direction angle involved. Transient over-shoot also has an influence on ΔL_R.) Some difficulty was experienced in completing the site measurements for ρ_P' and consequently some of the values used are those obtained at another location. Therefore the results obtained for T_1 should be considered as being only indicative of the mechanisms involved.

The computation of ΔL_A for the last three targets; T_2, T_3 and T_4 is less cumbersome than that of target T_1. The validity of the luminance difference metric for targets having no back-lighting has been established. Computation of the visibility conditions of the final three targets resulted in the quantities listed in Tables 3, 4 and 5. Except for s_c, all evaluations were performed at the experimental detection distance, s_e.

The phenomena of transient overshoot and decay are illustrated in Figure 11 for a sample configuration. The spatial or static adaptation and the resulting transient adaptation L_t are shown for the four target zones. The macro eye movements are assumed to have taken place at the transitions in L_s.

The transient adaptation L_t is governed primarily by the glare quantities — direct glare, and foreground glare, and by the transient overshoot phenomenon as well as by the decay parameter k. The magnitudes of the glare quantities are determined in part by the glare sensitivity parameter κ. However, little correlation exists between δ and L_t evaluated at s_e over the dynamic range

$$0.1 < L_t < 1.3 \ \text{(fL)} \tag{6.0.2}$$

The correlation coefficient for the T_2, T_3 and T_4 sub-configurations is 0.0270. It can thus be concluded that the assumed occurrences of eye movements as well as the selection procedure for κ and k are representative of the field detection trials.

Other work had shown that there was no discernible difference in the phenomenon of detection between the large and small targets. Because the beam specifications are identical for the paired configurations AH, DI and GJ, any existing systematic discrepancies can be investigated. Selecting δ as the index parameter, and considering only T_2 and T_4 targets, the correlation coefficient for $\delta_{(ADG)}$ and $\delta_{(HIJ)}$ is 0.6249 and for $\delta_{(AG)}$ and $\delta_{(HJ)}$ it is 0.7156. Here is an indication of a systematic discrepancy which is likely due to some imprecision in the beam description.

A summary of the average and standard deviation values ($\bar{\delta}$ and $\tilde{\delta}$ respectively) for targets T_2, T_3, and T_4 is given in Table 6. It is seen that target T_2 results show the largest variance due primarily to the decrease in ρ_P which was caused by shoulder dampness. Targets T_3 and T_4 show approximately equal variance but the large (negative) value of $\bar{\delta}$ for target T_3 indicates that there was in all likelihood insufficient time for the detection of this target.

7.0 DISCUSSION

A more detailed description of the available luminance difference existing in the T_1 target zone may be necessary in order to better understand the visibility conditions concerning forward targets. Rather complex interactions can occur in this zone with these interactions being governed largely by the opposing lamp system and the forward reflectance characteristics of the roadway. It may be necessary to include the forward-cast as well as the rear-cast shadows as detectable elements for certain combinations of target and roadway. Most targets and shadows will be detected at a negative luminance difference. This is in contradistinction to solely front-lit targets on relatively dark asphaltic roadways. Objects of relatively large retro-reflectance can be hidden (apart from the effect of shadows) when they are at the null condition, i.e. when the luminance of the roadway approaches the object luminance as a result of the large values of ρ_P' possible in combination with the light from the opposing lamp system.

Previous work had shown that 0.5 seconds was required for target search and fixation during unopposed detection. An opposed visual task is more complex because of the greater magnitude and frequency of eye movements required. It is not unreasonable to expect the addition of opposing glare to cause more extraneous eye movements and eye blinking and hence increase the time required for the detection of multiple targets. In Section 6 it was shown that sufficient time was not available for some of the sub-configurations of target T_3. Also, when the previous target, T_2 was not detected during a maneuver there may have been some latency and subsequently a decrease in the time available to fixate target T_3.

The moment of transition or eye movement from one target to the next was assumed to take place at or near the optimum time as far as detection is concerned. This is not a limiting assumption in the case of targets T_2 and T_4 since the light-to-dark transition or decay has a tendency to quickly smooth out peaks and depressions in the adaptation levels. It is more difficult to accurately describe the visibility conditions in the T_3 target zone because of the limited time available. Consequently the results of the T_3 target sub-configuration should not be included in any subsequent statistical analysis.

The target detection trials were carried out at a velocity of 60 mph. Dynamically, this corresponds to two vehicles approaching and passing at 30 mph. At higher rates of closure, more typical of roadway speeds, the influence of transient overshoot would increase in importance in relation to the decay mechanism. Light-to-dark and dark-to-light transitions can then be seen to be of nearly equal importance.

Atmospheric scattering is not expected to have much direct influence during opposing glare experiments. The detection distances for the T_2, T_3 and T_4 targets were not of sufficiently large magnitude to require the inclusion of air luminance in the visibility calculations. The luminance of the atmosphere must however be included in the ρ_P determinations, but this term is expected to be quite small in comparison to the glare related quantities comprising the spatial adaptation level, L_s.

Inspection of the correlation analysis does show some systematic discrepancies. However, it is not readily apparent to what factor or factors some of these discrepancies can be ascribed. Two areas are under investigation here; the calculation of the visibility conditions at detection and the determination of the experimental detection distances. It is emphasized that the input data for the calculation of visibility conditions was obtained largely on the test site but not necessarily coincident with the detection trials. Although it is apparent that the detection experiment closely represents the detection potential for that instant, the exact description of the conditions existing during any particular trial is usually not possible.

Therefore it may be inappropriate to call quantities such as $s_c - s_e$ and $\Delta L_R - \Delta L_A$ discrepancies. Rather it is reasonable to call them simple differences with the realization that s_c and s_e may refer to slightly different conditions.

It is generally agreed that a definite sequence be followed in target detection trials, i.e. a block format be used. Several factors can interfere with proper scheduling of events, the most important of which are: 1) driver fatigue, 2) equipment malfunction and 3) weather conditions. The lack of uniformity in the number of trials carried out on each configuration listed in Table 1 can be attributed to the aforementioned factors. These variations in the number of trials prevented any analysis of the detection ogives. (The slope of the detection ogive was shown to correlate with discrepancies in detection distance (Ref. 3).)

The unopposed automobile headlighting detection trials were carried out for the adaptation luminance range (fL) given by

$$0.001 < L < 0.03$$

Combining this with the transient adaptation range specified by Equation (6.0.2) results in the approximate luminance range given by

$$0.001 < L < 1 \text{ (fL)}$$

One-to-one correspondence between laboratory detection threshold measurements and roadway detection experiments has been found to exist for this luminance range. (The same laboratory observer data and λ values were used in the analysis of both the unopposed and this, the opposed experiment.)

Glare light is considered to be scattered by the eye media and is thereby included as a veiling luminance in the adaptation calculations. Some research has shown that a correction can be applied directly to the required luminance difference ΔL_R (Ref. 14). It is informative to see what the glare sensitivity factor of k = 2.8 as derived in Section 6 is equivalent to when expressed in terms of corrections to ΔL_R. The quantity ΔL_R is a nonlinear function of L and α. Choosing one of the sub-configurations as an example (assuming α is constant) a change in glare sensitivity by a factor of 2.8 translates into an increase in ΔL_R by a factor of 1.59. The participant of this program had a greater potential for detection, his average requirement in luminance difference being about 0.72 times that of the young normal adult taken as the reference observer (λ = 0.72). When these two factors are combined it is seen that the result is an overall factor of 1.14 applied to ΔL_R for this observer.

8.0 CONCLUSIONS

The study of a well-defined visual task in conjunction with automobile driving under opposed glare has resulted in the following conclusions:

1. In order to specify the luminance distribution in the opposed glare encounter it is necessary to quantify:

   i) foreground luminance distribution from the driving and opposing lamp sets,

   ii) direct glare from the opposing lamps,

   iii) target luminance,

   iv) roadway luminance in the vicinity of the target as caused by the driving and opposing lamp sets.

2. An accurate assessment of the detection potential under dynamic glare conditions is possible if:

   i) the participant luminance difference and glare sensitivity are known,

   ii) the spatial and transient adaptation levels are established.

3. This work has shown that one-to-one correspondence between field and laboratory visibility data is possible if sufficient precision can be applied to the description of existing field conditions in the presence of glare light.

9.0 REFERENCES

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TABLE 1

DESCRIPTION OF THE TEST CONFIGURATIONS

Test	Target Size (Ft.)	Target Reflectance	Driving Beam	Opposing Beam	Trials	Detection Distances (Ft.)				Δt_{av} (sec.)
						s_{e1}	s_{e2}	s_{e3}	s_{e4}	
A	1.333	0.090	LB_1	LB_1	19	480.0	243.8	155.4	223.6	1.09
B	1.333	0.090	LB_2	LB_2	22	459.1	437.9	322.9	381.2	1.32
C	1.333	0.090	LB_2	LB_1	30	408.8	453.0	349.6	399.3	1.23
D	1.333	0.090	MID	MID	20	346.7	466.4	406.7	429.3	0.70
E	1.333	0.090	LB_1	LB_2	23	890.7	279.8	173.6	235.3	1.30
F	1.333	0.090	LB_2	MID	12	249.3	356.1	240.6	342.6	0.95
G	1.333	0.090	LB_1	MID	20	321.8	220.4	143.0	207.8	0.68
H	0.656	0.072	LB_1	LB_1	9	—	208.1	141.3	192.5	0.77
I	0.656	0.072	MID	MID	11	—	312.9	249.9	326.2	0.78
J	0.656	0.072	LB_1	MID	14	—	204.1	136.5	191.4	0.73

Lane Width = 12 Feet
Lamp Height = 2.17 Feet
Observer Eye Height = 3.83 Feet

TABLE 2

THE PHOTOMETRIC OUTPUT OF THE TEST HEADLAMP SYSTEMS

System	Illuminance		
	E_1	E_2	E_g
LB_1	0.0077	0.0116	0.0039
LB_2	0.0511	0.0658	0.0041
MID	0.216	0.2852	0.0205

NOTES:

a) E_1 is the illuminance (ft. cd.) at the roadway corresponding to targets T_1, T_3, T_4 (s = 500 ft.).

b) E_2 is the illuminance (ft. cd.) at the roadway corresponding to target T_2 (s = 500 ft.).

c) E_g is the glare illuminance (ft. cd.) at the eye (s = 500 ft.).

TABLE 3

SUMMARY OF THE VISIBILITY CALCULATIONS: TARGET T_2

Test	Direct Glare	Foreground Glare	Dynamic Adaptation	ΔL_R	δ_2	$(s_e - s_c)/s_e$
A	0.0393	0.0211	0.1218	0.004421	-0.6948	-0.3392
B	0.0545	0.0085	0.1149	0.007076	0.2284	0.0651
C	0.0557	0.0085	0.1224	0.007547	0.3815	0.0982
D	0.2917	0.0216	0.5377	0.018435	-0.0357	-0.0058
E	0.0386	0.0196	0.1326	0.010455	-0.5095	-0.1751
F	0.1659	0.0091	0.3229	0.010475	0.3240	0.0696
G	0.0948	0.0223	0.2085	0.005624	-0.6920	-0.3131
H	0.0364	0.0246	0.1271	0.007185	-0.3291	-0.1264
I	0.1303	0.0244	0.2619	0.016381	-0.1080	-0.0387
J	0.0885	0.0271	0.2054	0.009131	-0.1792	-0.0603

All luminance values are in fL.

TABLE 4

SUMMARY OF THE VISIBILITY CALCULATIONS: TARGET T_3

Test	Direct Glare	Foreground Glare	Dynamic Adaptation	ΔL_R	δ_3	$(s_e - s_c)/s_e$
A	0.1283	0.2482	0.3816	0.007082	-0.4978	-0.2793
B	0.1655	0.0384	0.2636	0.008528	-0.3195	-0.1242
C	0.1969	0.0148	0.2590	0.008998	-0.1518	-0.0535
D	0.9443	0.1256	1.3014	0.029513	0.1219	0.0270
E	0.1015	0.1459	0.2639	0.005722	-0.3696	-0.1187
F	0.4353	0.1475	0.6580	0.012937	-0.4453	-0.2107
G	0.2825	0.9273	1.2171	0.017432	-0.1255	-0.0797
H	0.1209	0.3037	0.4366	0.010826	-0.3481	-0.1444
I	0.4487	0.1581	0.7573	0.025005	-0.4778	-0.1773
J	0.2724	0.8469	1.1331	0.020675	0.0866	-0.0227

All luminance values are in fL.

TABLE 5

SUMMARY OF THE VISIBILITY CALCULATIONS: TARGET T_4

Test	Direct Glare	Foreground Glare	Dynamic Adaptation	ΔL_R	δ_4	$(s_e - s_c)/s_e$
A	—	0.0180	0.0899	0.003568	-0.1183	-0.0322
B	0.1052	0.0086	0.1904	0.008096	-0.0867	-0.0239
C	0.1430	0.0085	0.2058	0.008826	0.0957	0.0263
D	0.4175	0.0391	0.5748	0.017850	-0.2441	-0.0757
E	—	0.0172	0.1112	0.004109	0.1473	0.0323
F	0.2819	0.00890	0.4462	0.012516	0.1310	0.0277
G	—	0.0193	0.1097	0.003743	-0.2404	-0.0611
H	—	0.0230	0.0921	0.005713	0.1991	0.0338
I	0.2558	0.0465	0.4339	0.023262	-0.1635	-0.0445
J	—	0.0232	0.1013	0.005938	0.2196	0.0361

All luminance values are in fL.

TABLE 6

A STATISTICAL SUMMARY OF THE LUMINANCE DIFFERENCE DISCREPANCY FOR INDIVIDUAL TARGETS

Target	$\bar{\delta}$	$\tilde{\delta}$
T_2	-0.1614	0.3764
T_3	-0.2527	0.2137
T_4	-0.0060	0.1735

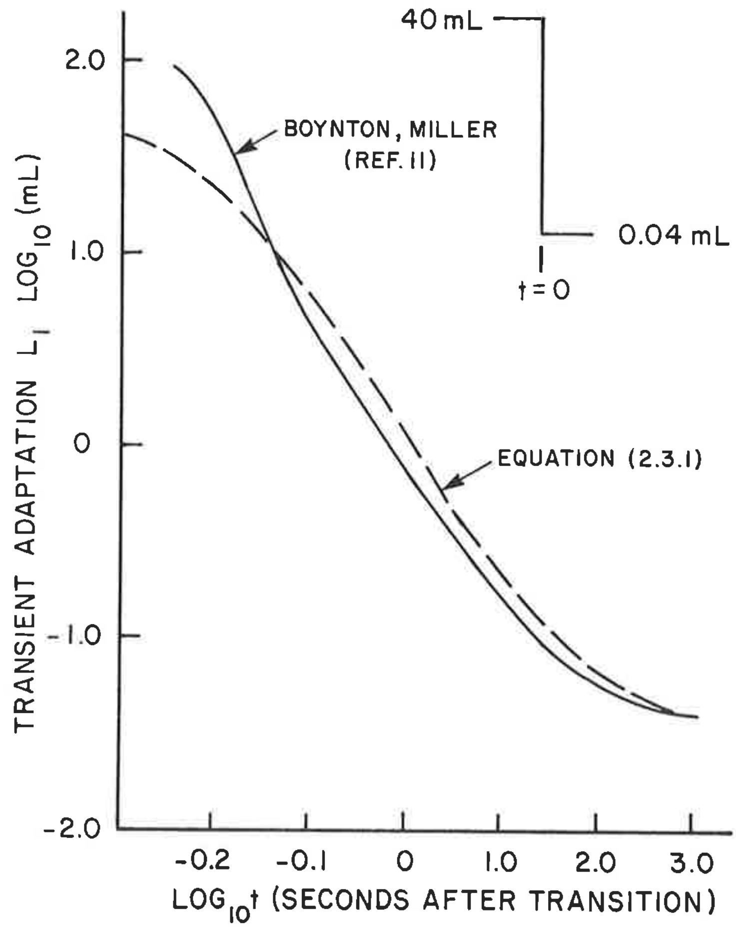

FIG. 1: ANALYTICAL REPRESENTATION OF LIGHT-TO-DARK TRANSIENT ADAPTATION

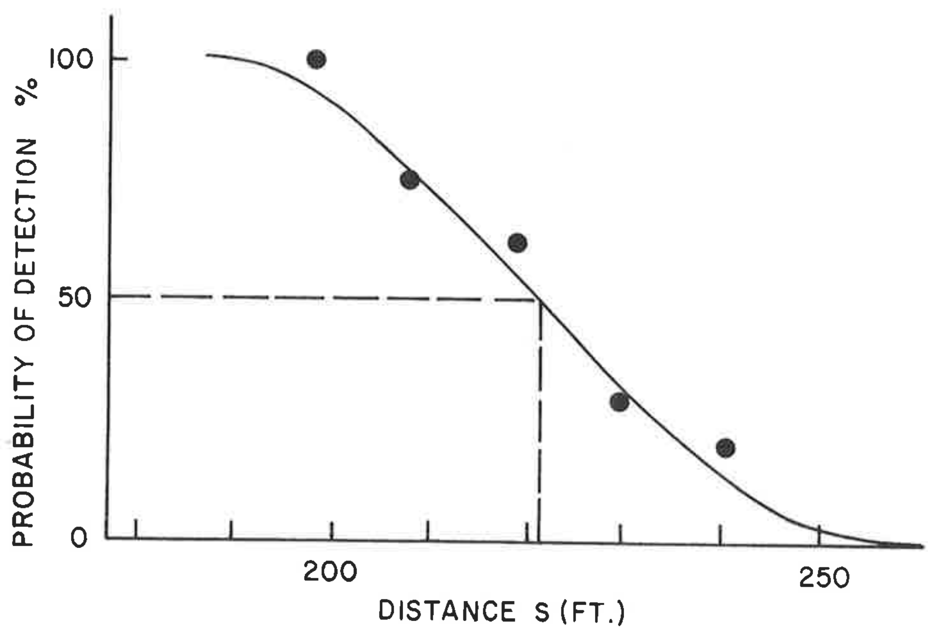

FIG. 2: DETERMINATION OF THE 50% PROBABILITY DETECTION DISTANCE: AN EXAMPLE

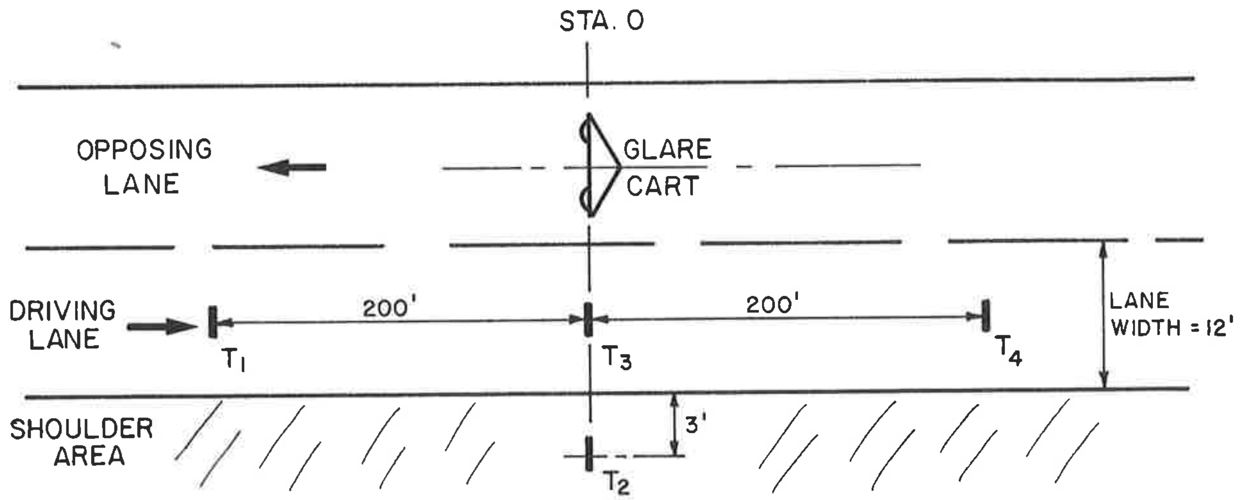

FIG. 3: TEST ARRANGEMENT OF FOUR TARGETS AND THE OPPOSING GLARE VEHICLE

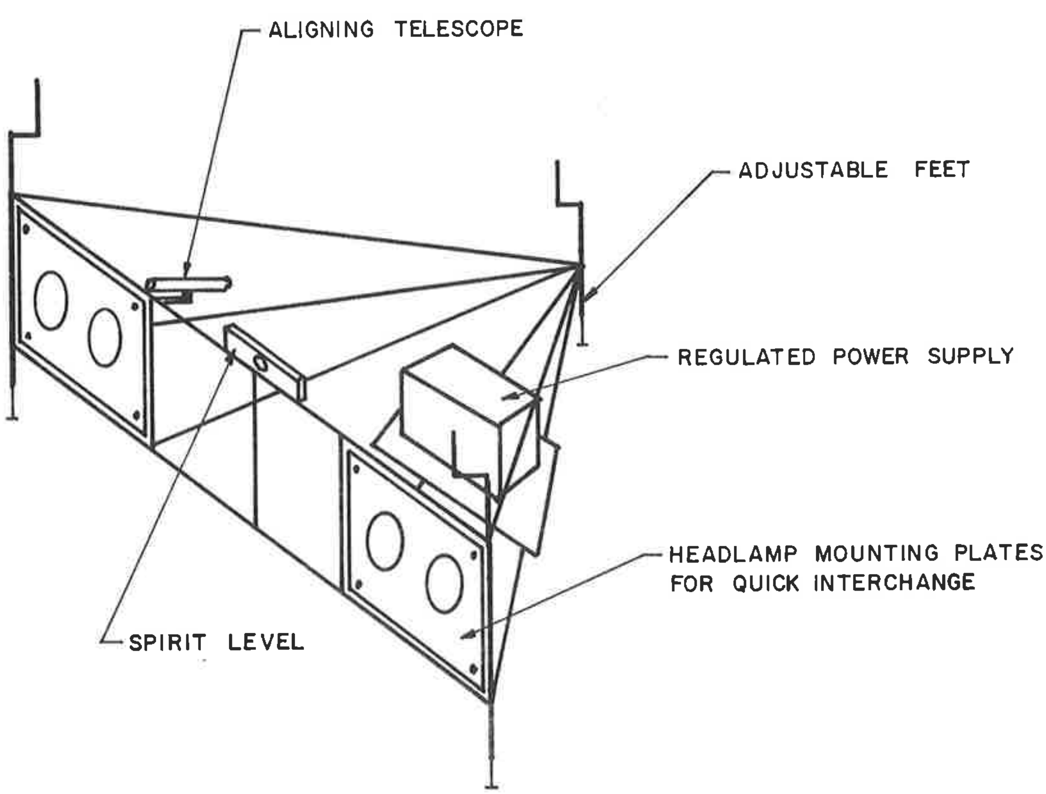

FIG. 4: AN EXPERIMENTAL CART TO HOUSE THE GLARE LAMP SYSTEM

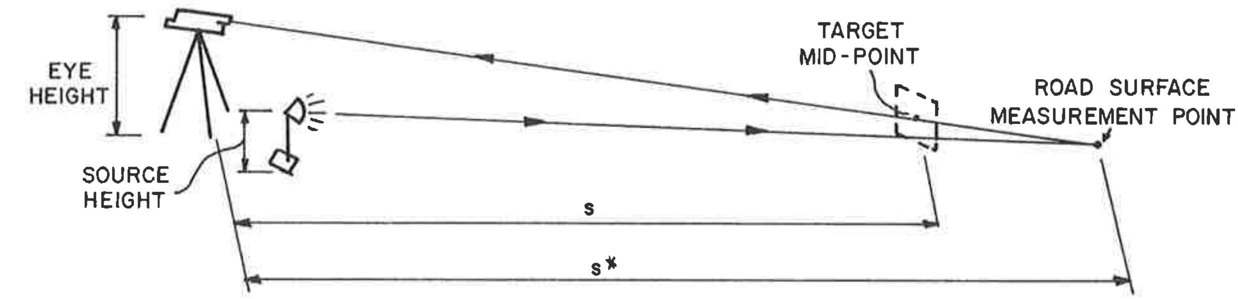

FIG. 5(a): TEST SET-UP TO MEASURE THE RETRO-REFLECTANCE OF THE ROADWAY

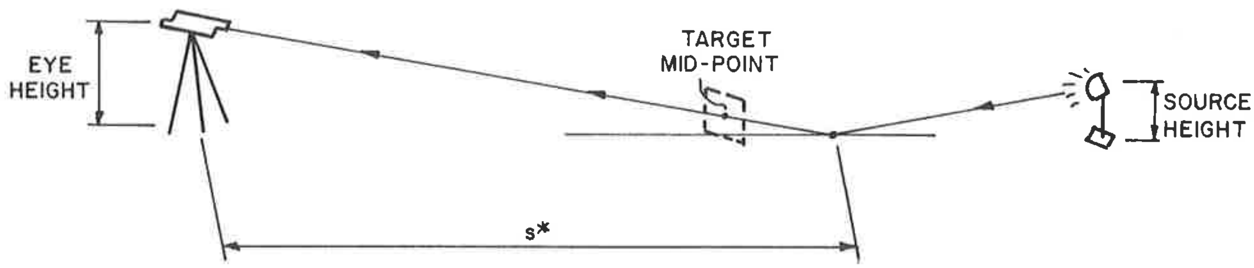

FIG. 5(b): TEST SET-UP TO MEASURE THE FORWARD REFLECTANCE OF THE ROADWAY

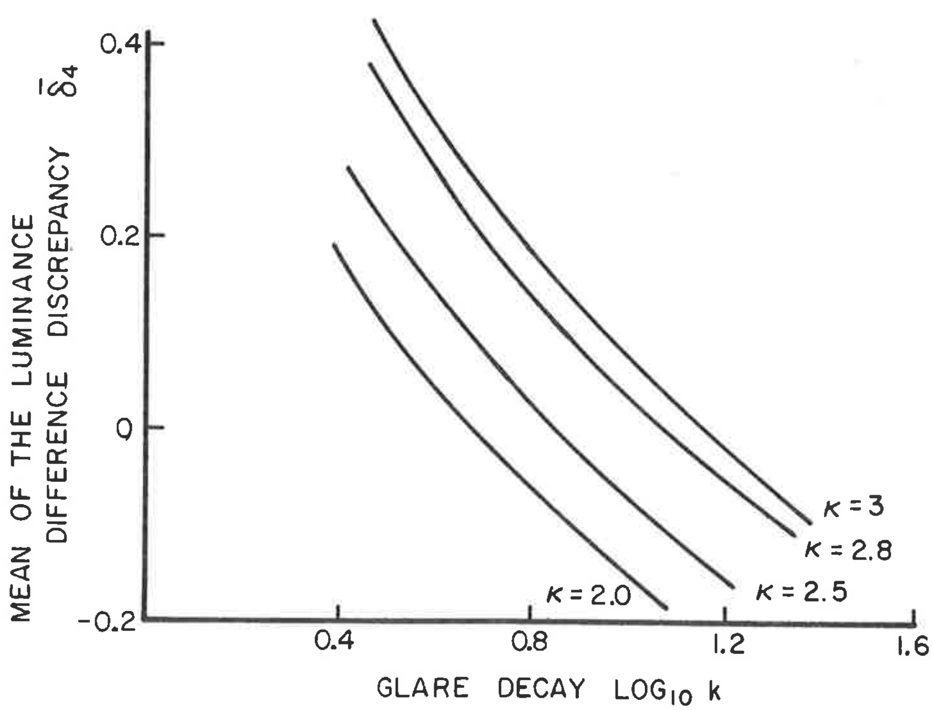

FIG. 6: DETERMINATION OF THE GLARE PARAMETERS: $\bar{\delta}_4$ VERSUS $\log_{10}$ k

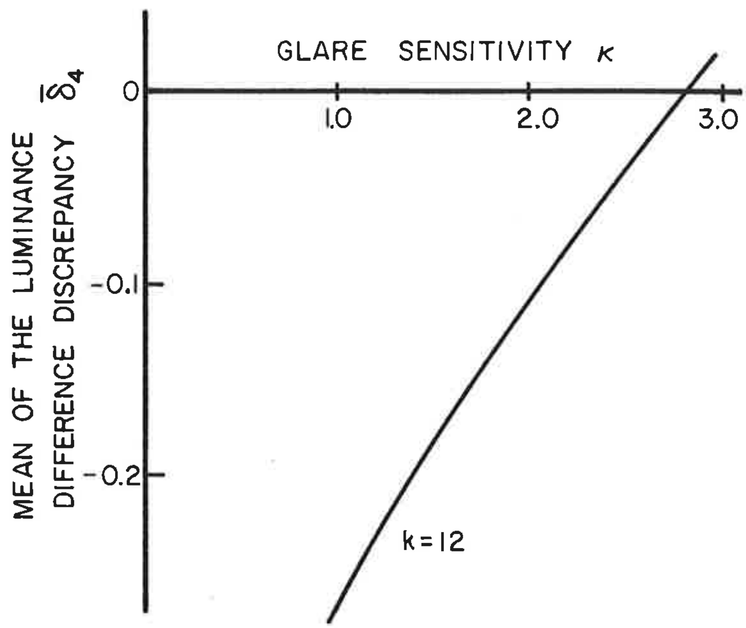

FIG. 7: DETERMINATION OF THE GLARE PARAMETERS: $\bar{\delta}_4$ VERSUS κ

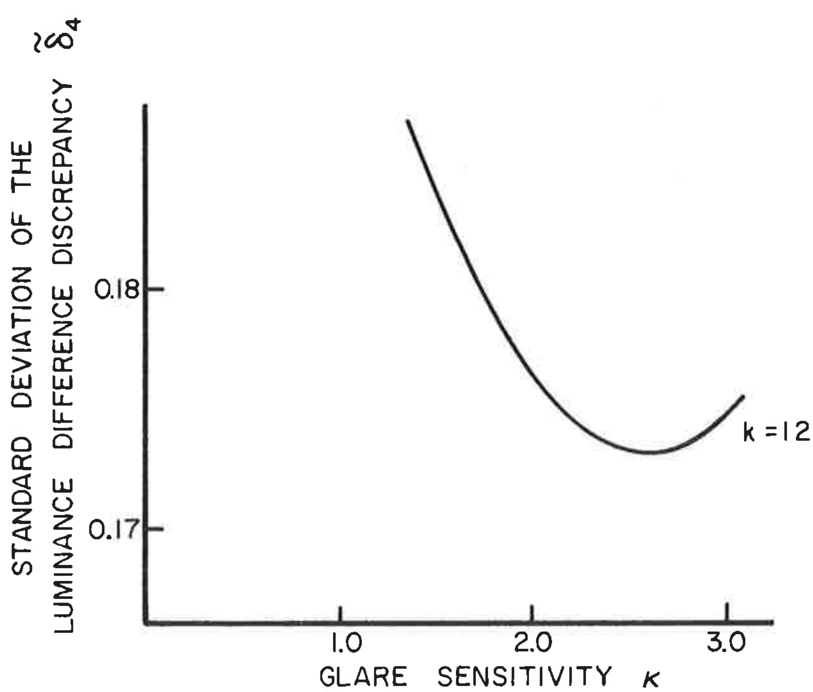

FIG. 8: DETERMINATION OF THE GLARE PARAMETERS: $\tilde{\delta}_4$ VERSUS κ

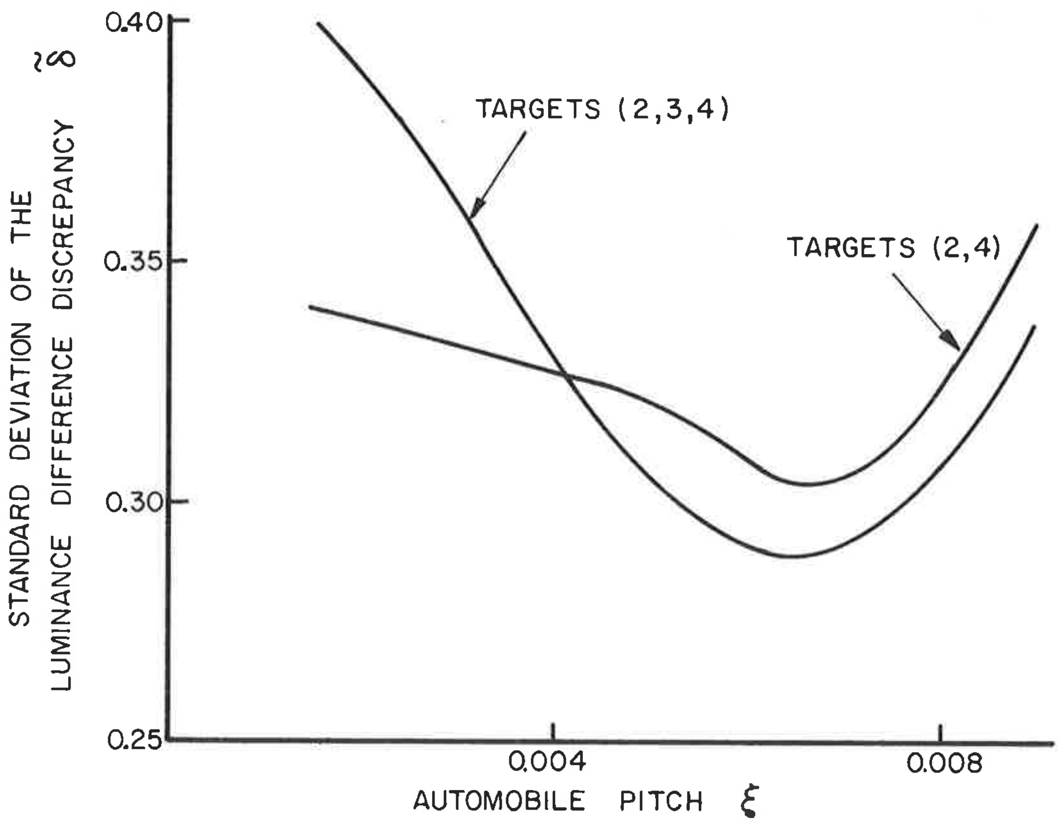

FIG. 9: INFLUENCE OF AUTOMOBILE PITCH ξ ON THE LUMINANCE DIFFERENCE DISCREPANCY

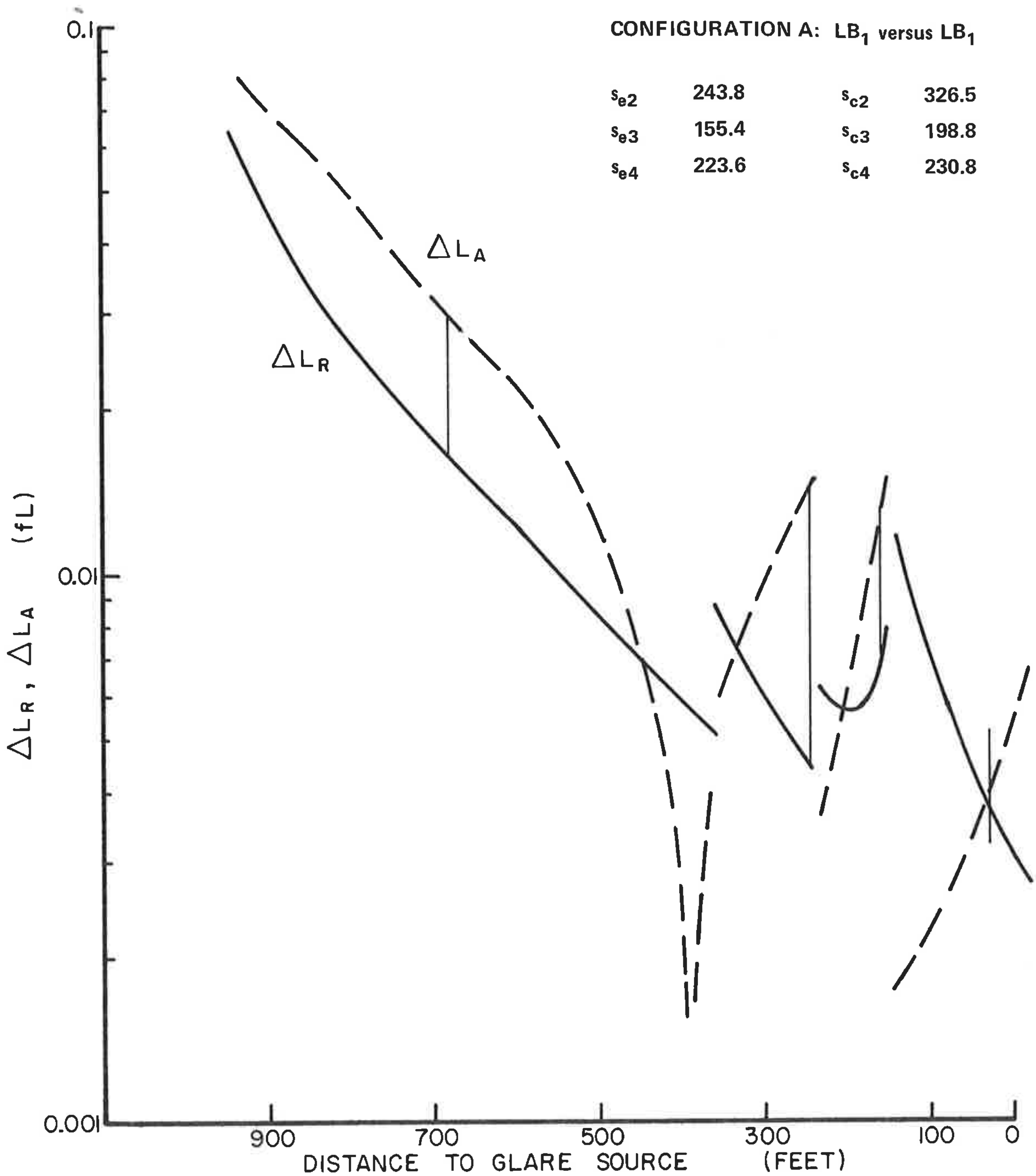

FIG. 10(a): REQUIRED AND AVAILABLE LUMINANCE DIFFERENCE HISTORY: CONFIGURATION A

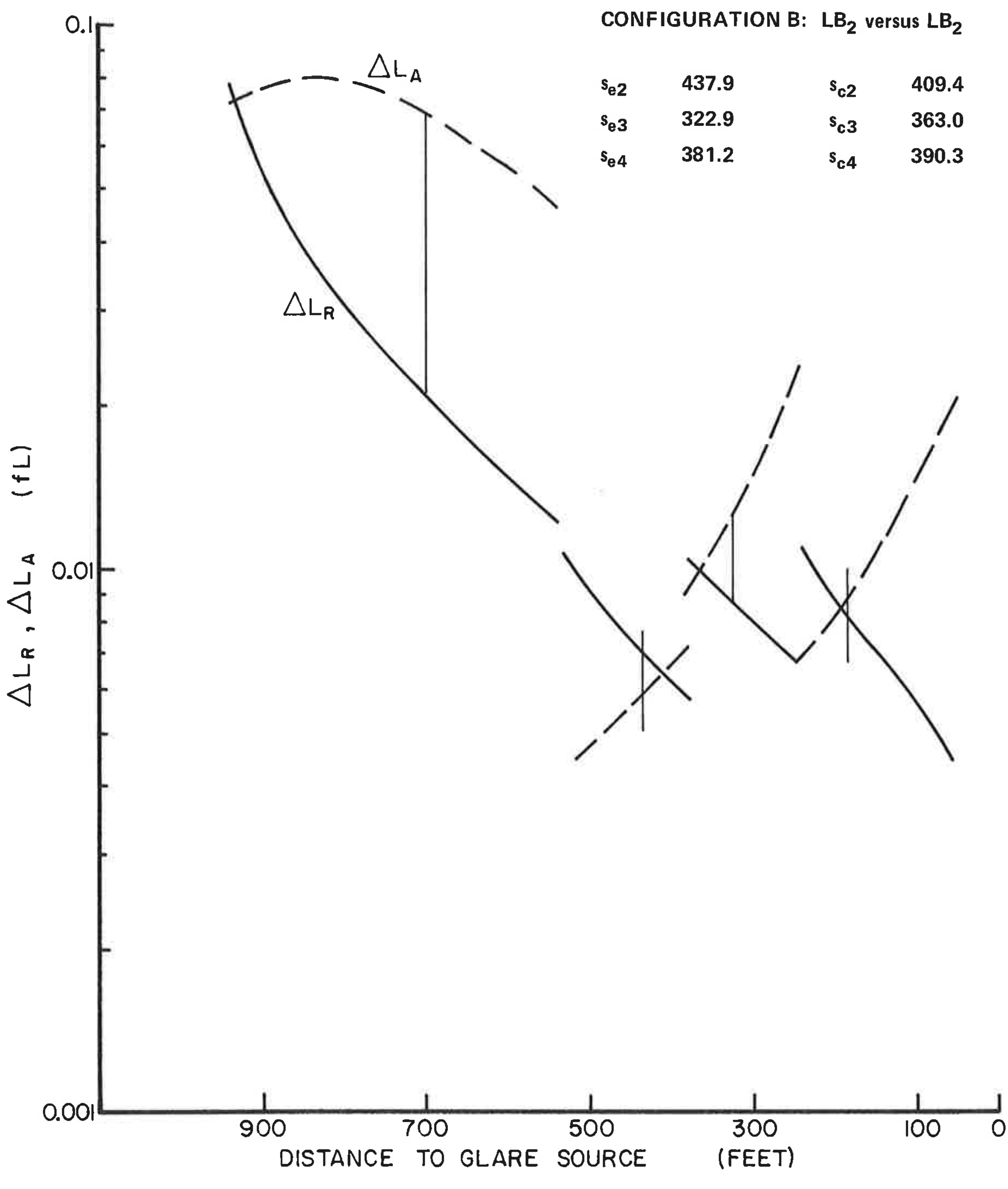

FIG. 10(b): REQUIRED AND AVAILABLE LUMINANCE DIFFERENCE HISTORY: CONFIGURATION B

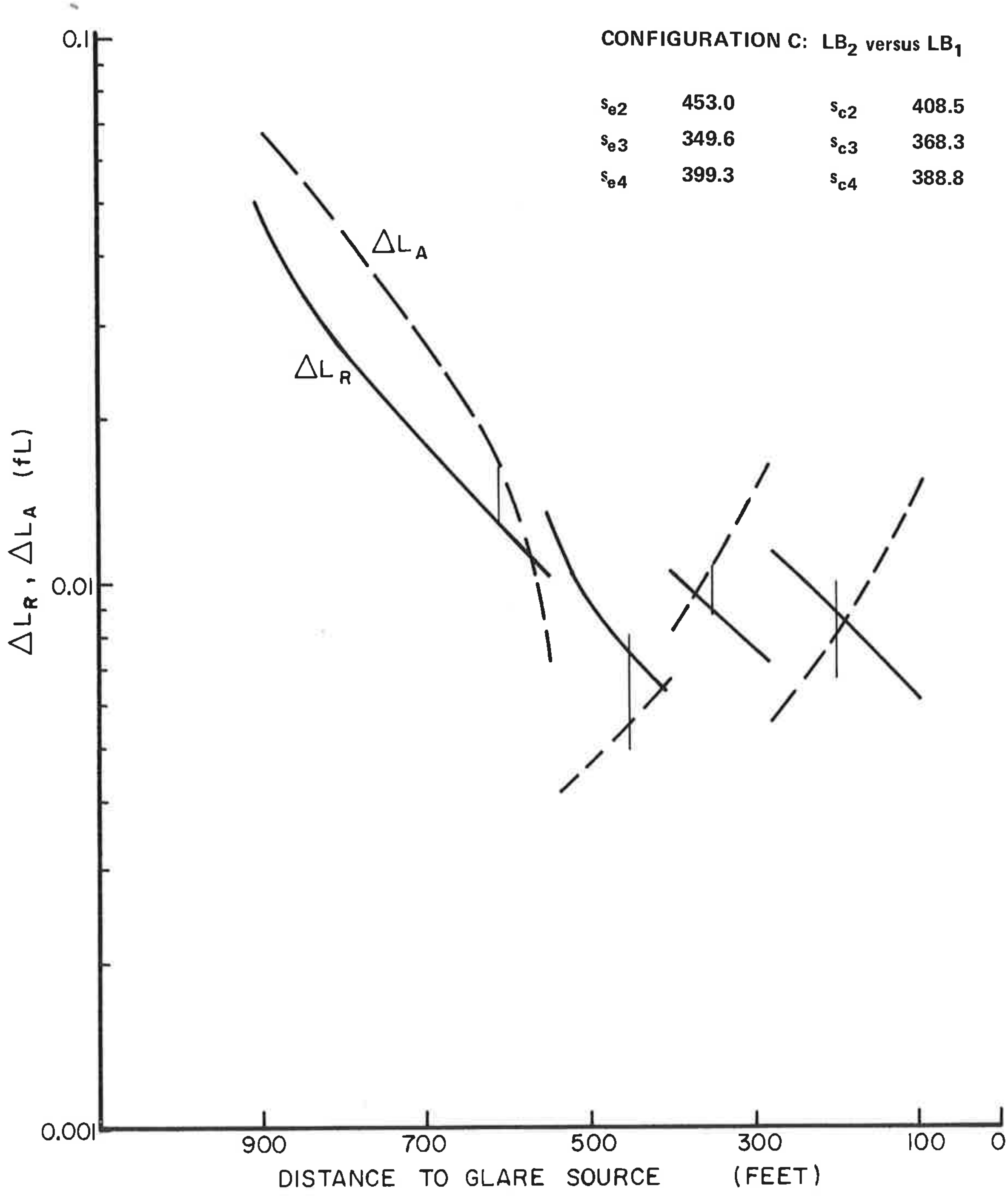

FIG. 10(c): REQUIRED AND AVAILABLE LUMINANCE DIFFERENCE HISTORY: CONFIGURATION C

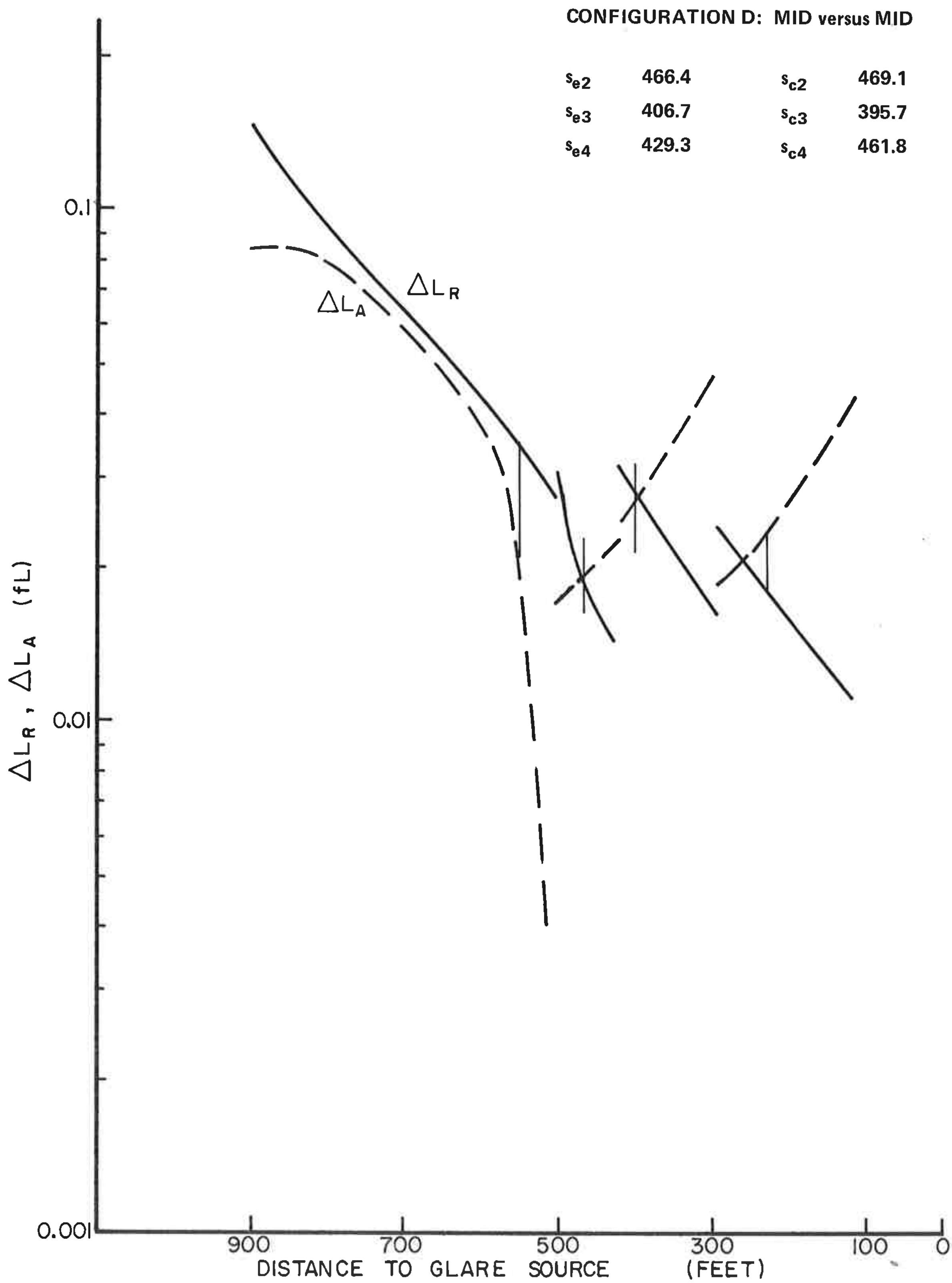

FIG. 10(d): REQUIRED AND AVAILABLE LUMINANCE DIFFERENCE HISTORY: CONFIGURATION D

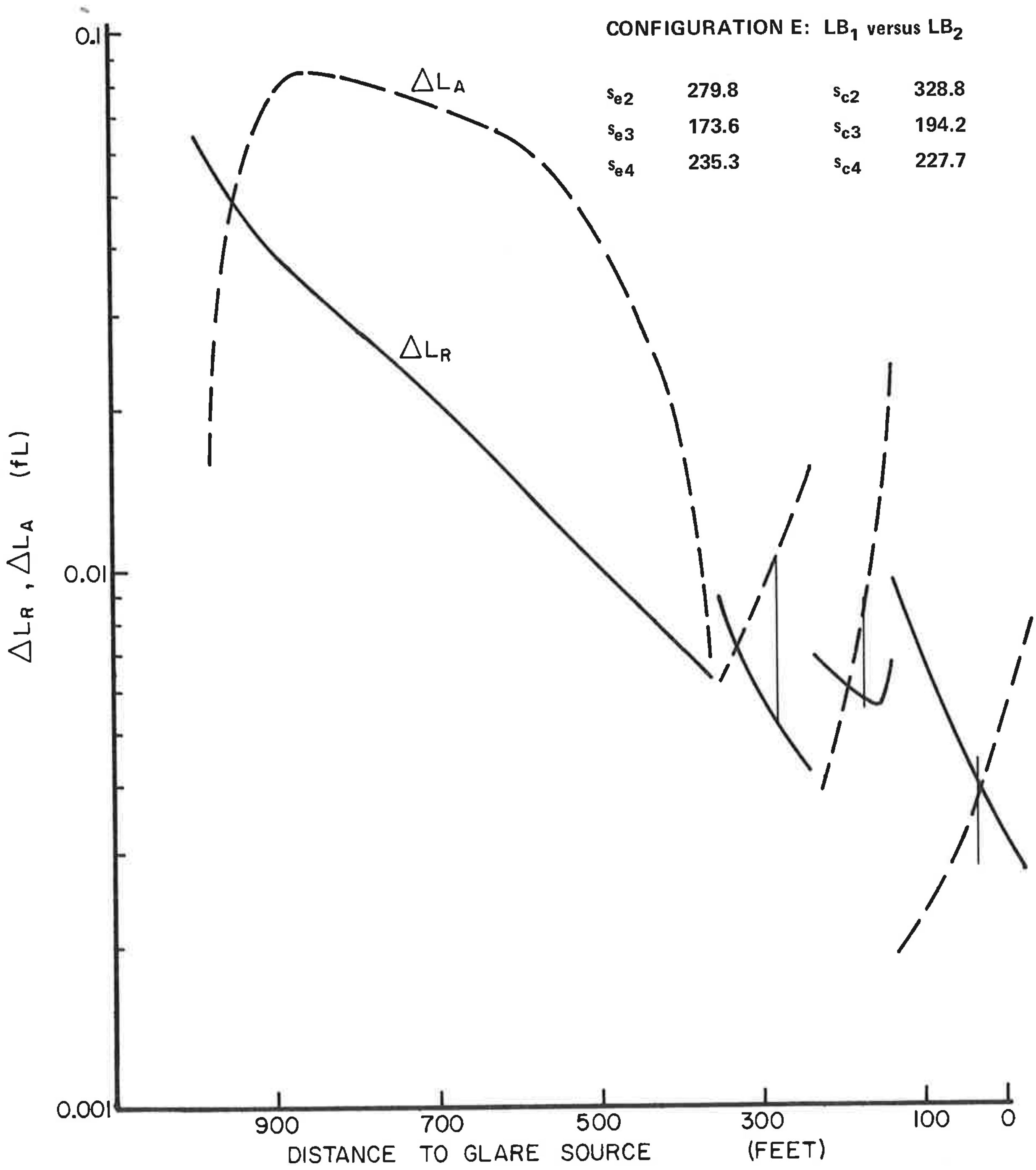

FIG. 10(e): REQUIRED AND AVAILABLE LUMINANCE DIFFERENCE HISTORY: CONFIGURATION E

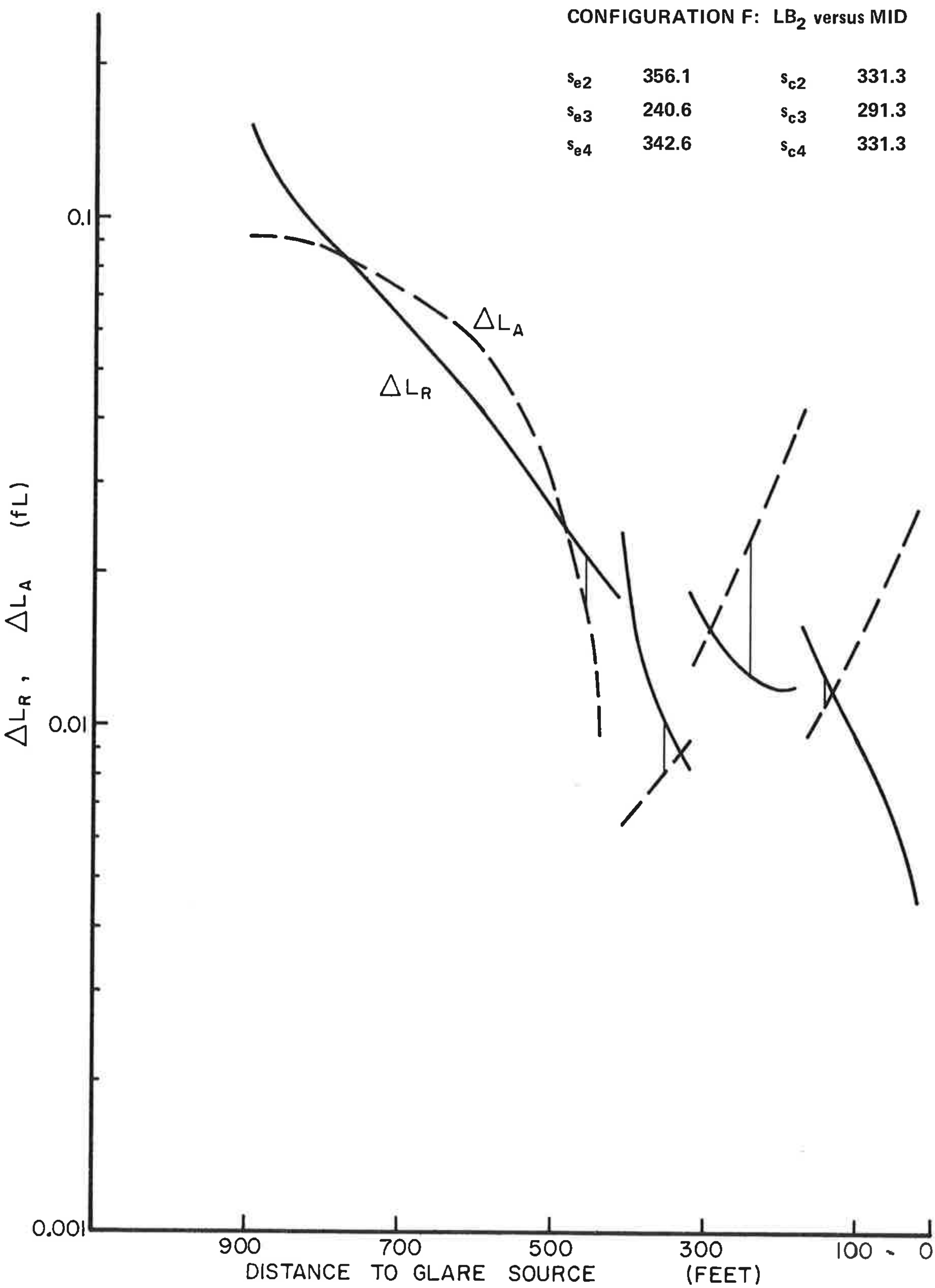

FIG. 10(f): REQUIRED AND AVAILABLE LUMINANCE DIFFERENCE HISTORY: CONFIGURATION F

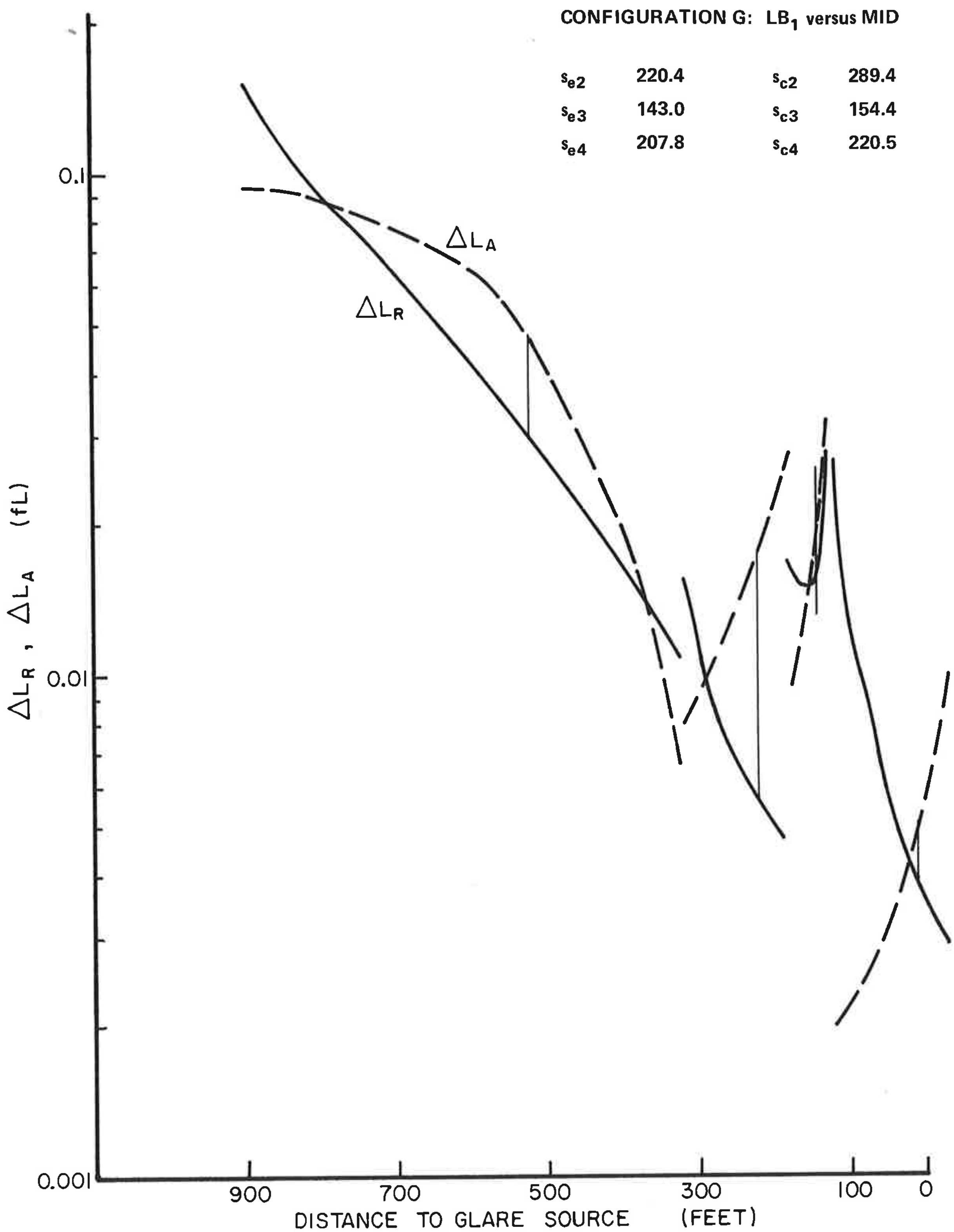

FIG. 10(g): REQUIRED AND AVAILABLE LUMINANCE DIFFERENCE HISTORY: CONFIGURATION G

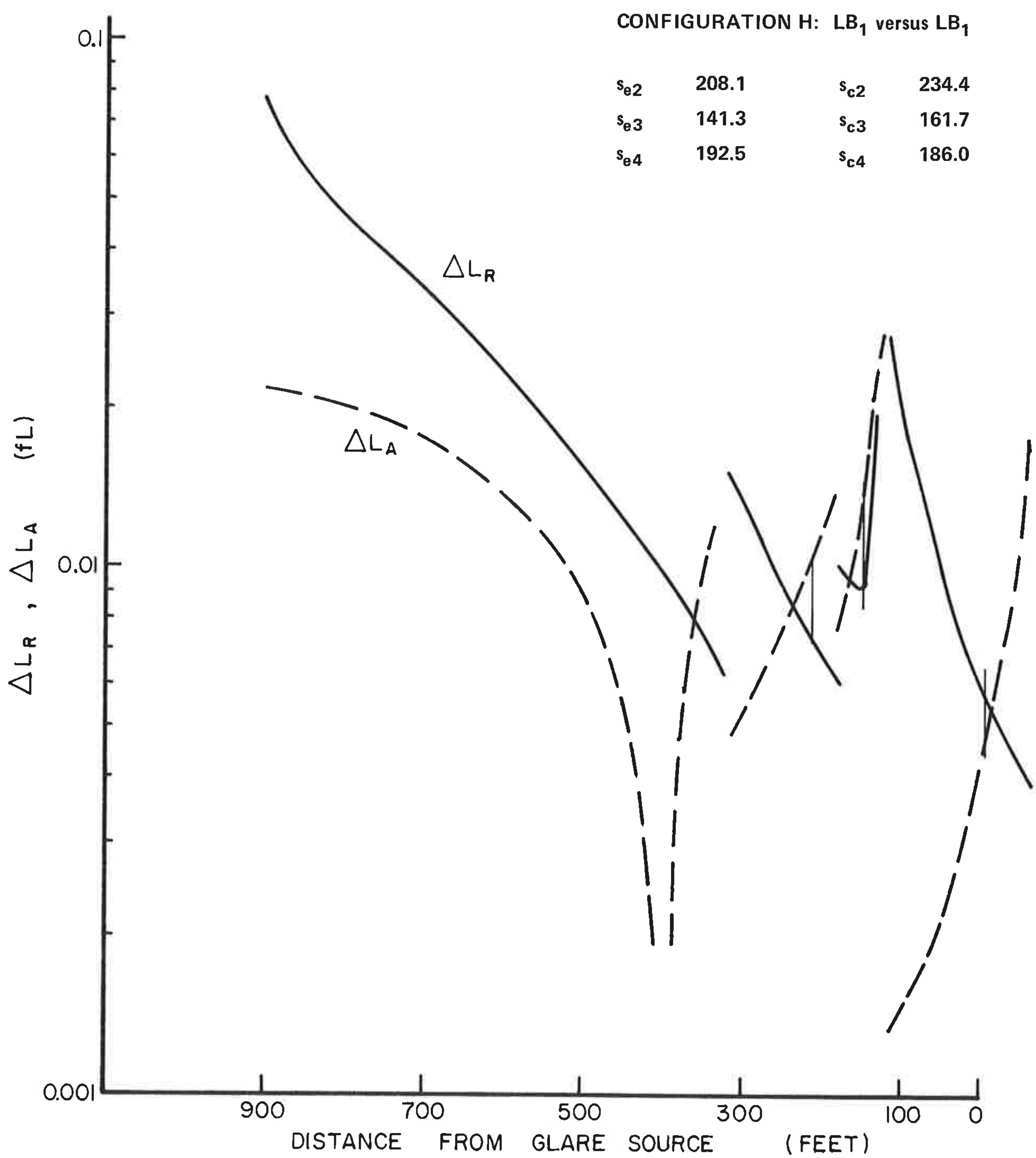

FIG. 10(h): REQUIRED AND AVAILABLE LUMINANCE DIFFERENCE HISTORY: CONFIGURATION H

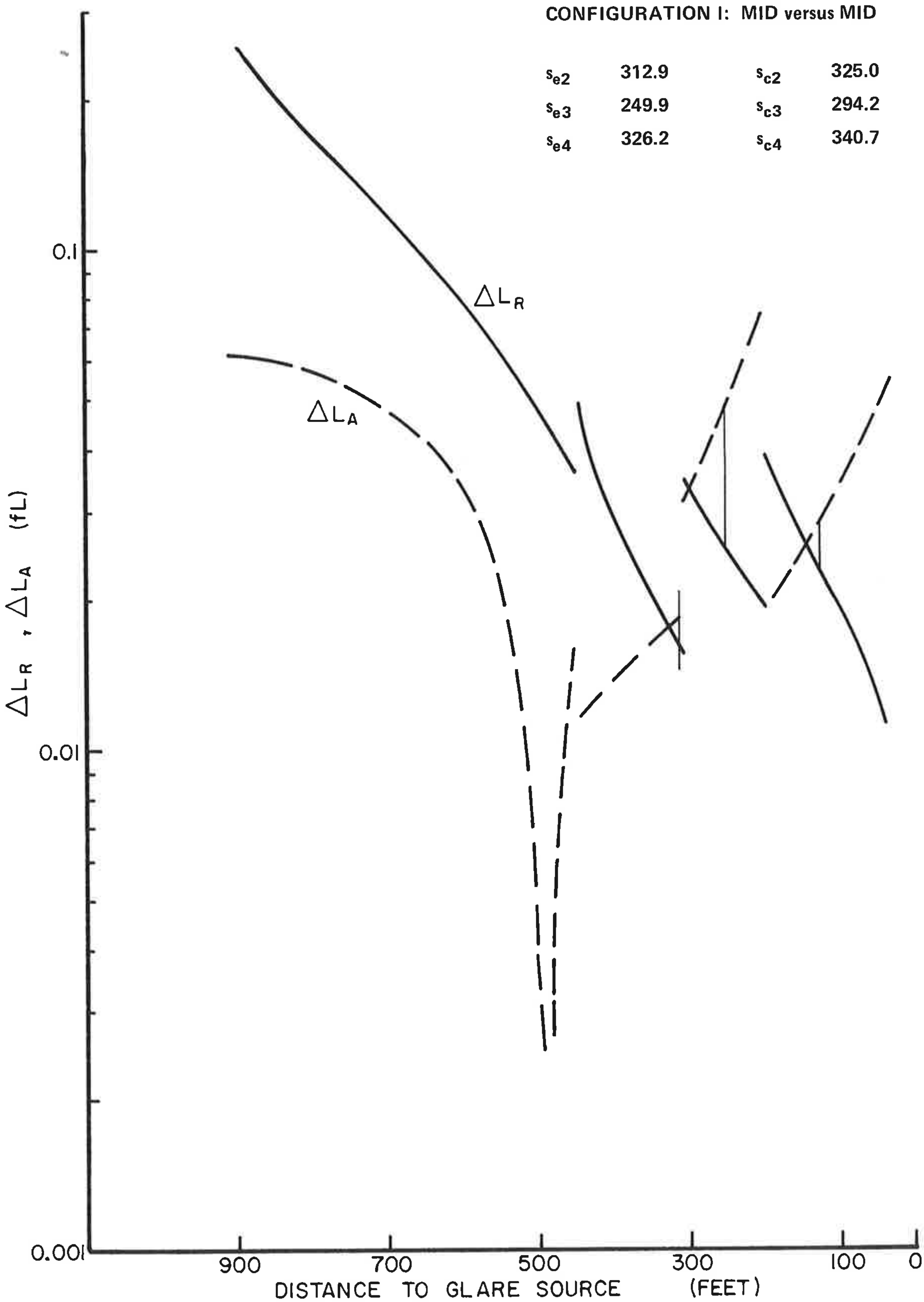

FIG. 10(i): REQUIRED AND AVAILABLE LUMINANCE DIFFERENCE HISTORY: CONFIGURATION I

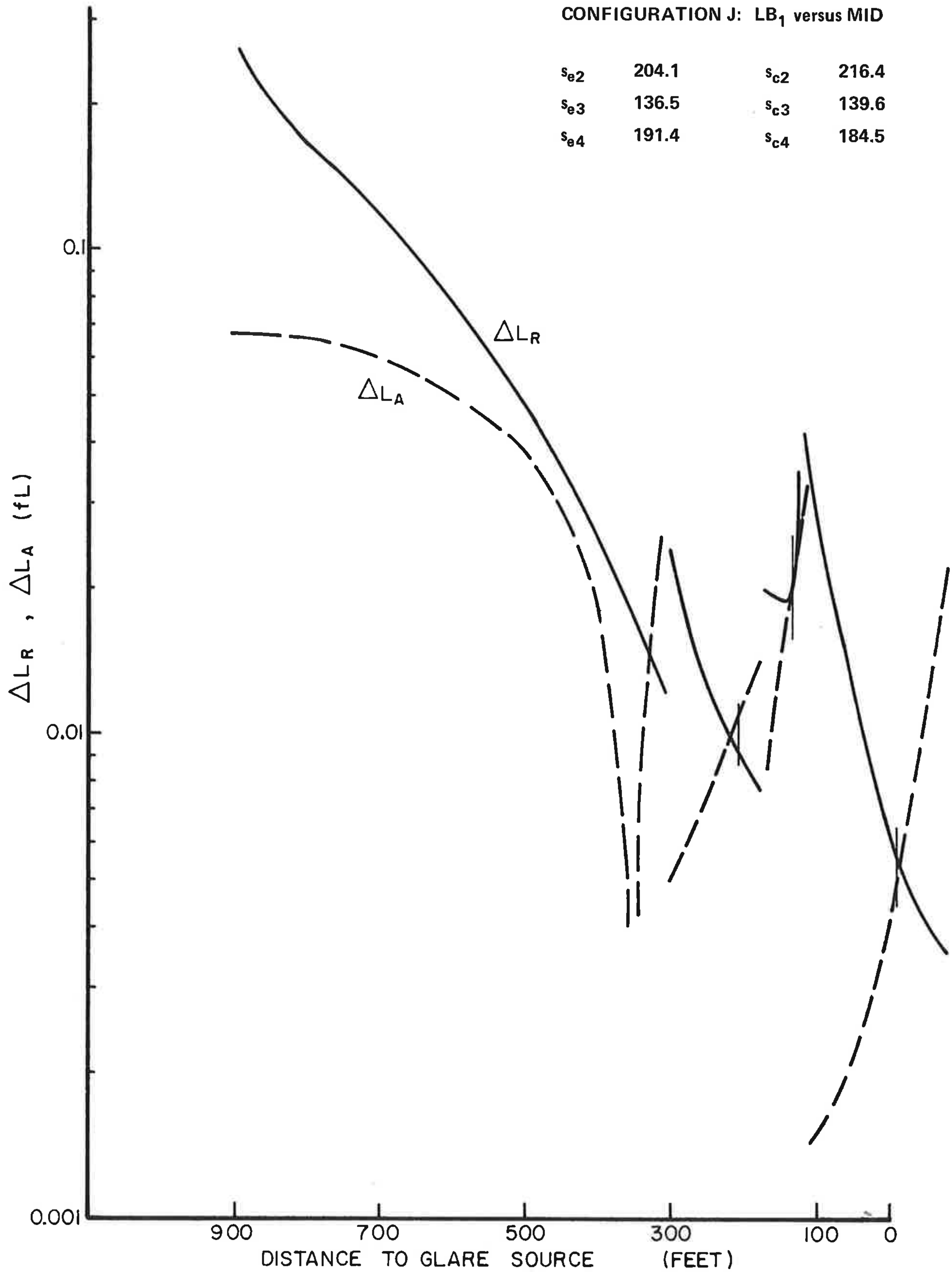

FIG. 10(j): REQUIRED AND AVAILABLE LUMINANCE DIFFERENCE HISTORY: CONFIGURATION J

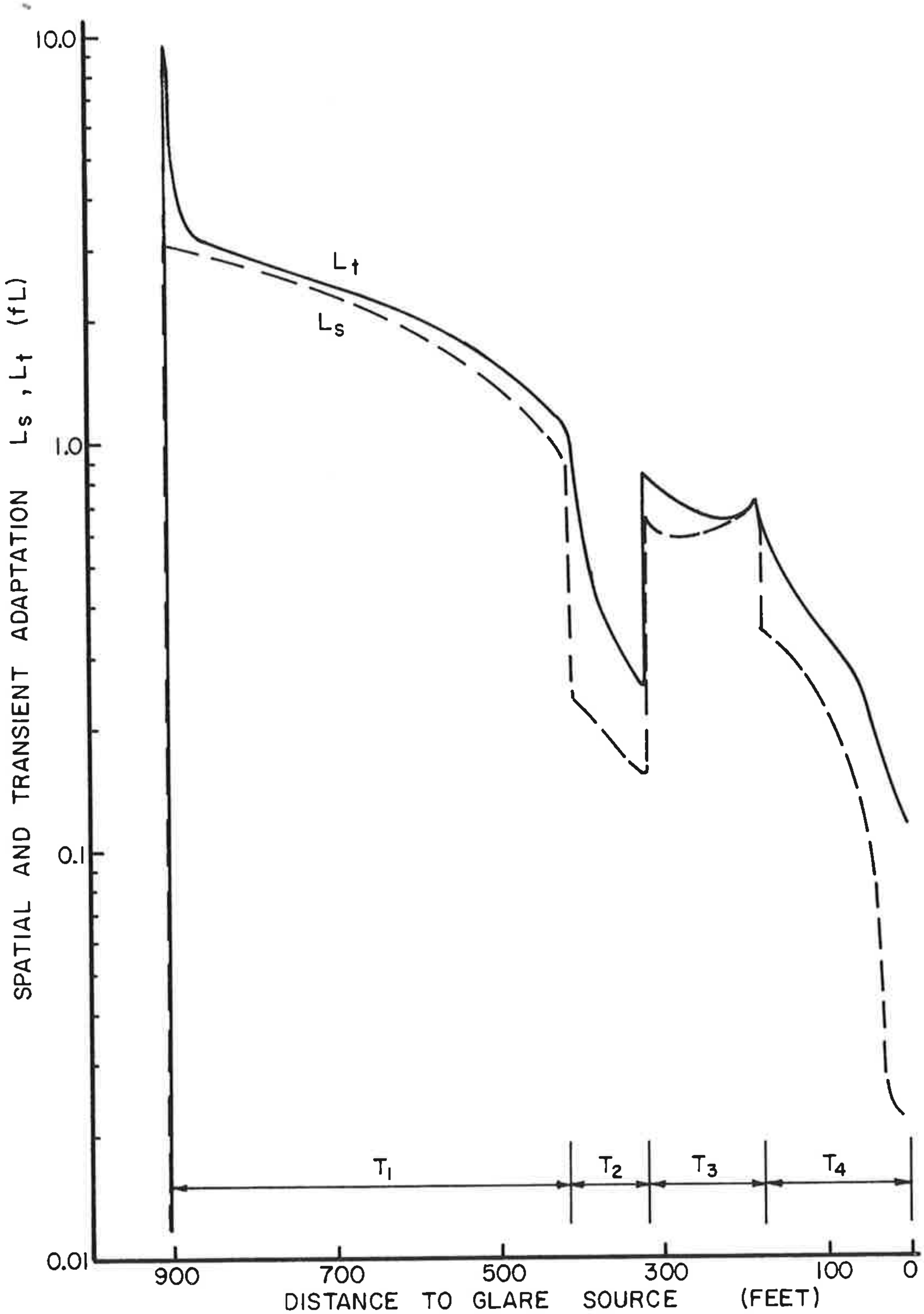

FIG. 11: SPATIAL AND TRANSIENT ADAPTATION HISTORIES OF A SAMPLE CONFIGURATION