FRY'S DYNAMIC DISK ROADWAY LIGHTING SIMULATOR

by

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TABLE OF CONTENTS

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LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

With the advent of high speed road vehicles, the necessity for improving visibility on the roads increased. A unique characteristic of the visual task imposed on a motorist is that it is imposed on him as long as he remains at the wheel of his vehicle. In practically all other kinds of activities, a break in visual performance is not only permissible but common. In addition to the task of receiving and processing visual information, the motorist must give part of his attention to the actual driving of his vehicle.

The task of driving gets more difficult during the night time. The principal purpose of roadway lighting is to ease the complexity of this driving task and to create a night-time environment conducive to quick, accurate and comfortable seeing for the user of this facility. These objectives, if attained, combine to improve traffic safety, achieve efficient traffic movement and promote the general use of the roadway during darkness and under a wide variety of weather conditions. Adequate visibility at night results from lighing (both fixed and vehicular) which provides adequate luminance contrast with good uniformity together with reasonable freedom from glare. The discussions in this report are confined to one aspect of visibility from fixed roadway lighting, namely glare.

Glare in roadway lighting

When the field of vision of an observer contains a light source whose luminance in the direction of the observer is appreciably greater than that of the other part of his field of vision, this light source will give rise to glare. The glare produced increases with increased glare source luminance, apparent size and number and with decreasing luminance of the background and with decreasing angle between the direction of observation and the direction to the light source.

There are two types of glare effect. They are

1. Disability glare

2. Discomfort glare

Disability glare

Glare which results in a reduction of visual performance is known as "disability glare". It is sometimes also referred to as "blinding glare" or "veiling glare". In the German literature the term "physiologische Blendung" (physiological glare) is used on the grounds that this is a purely physiological (that is, peripheral) reaction, which can be measured by purely physiological methods.

Discomfort glare

Discomfort glare is the negative subjective reaction to too-bright lights, as contrasted with disability glare which is a visual performance loss. Discomfort glare can definitely be observed in cases where disability glare can hardly be measured. Thus, in an artificially lighted street where a measurable effect of glare on the visual performance is practically absent, discomfort glare can still be inadmissibly high. Discomfort glare is referred to in the German literature as "psychologische Blendung" (psychological glare), on the grounds that the sensations involved are largely or wholly of a psychological (that is, in the central nervous system) nature.

Discomfort glare as a design criterion

While both forms of glare reactions are caused by the same light, the many factors involved in roadway lighting such as source size, displacement angle of the source, illuminance at the eye, adaptation level, surrounding luminance, exposure time and motion do not affect both forms of glare in the same manner, nor to the same degree. The only two factors common to both forms of glare are illuminance at the eye and the angle of entrance into the eye. Even these factors have varying effects on the two forms of glare.

It is generally true that even though the disability glare is negligible, the discomfort glare can be appreciable. Conversely, if the discomfort glare is acceptable, hardly any effect on visual performance may be expected. Thus, discomfort glare frequently serves the protective function of preventing disability glare, or worse, because it generally occurs at lower luminances and because people avoid situations which produce discomfort and thus, avoid disability. Clearly, such a conclusion is of extreme importance for the proper design of street-lighting installations: it means that one might be able to restrict one's attention to discomfort glare. Hence, further discussions in this report will be confined to the discomfort glare aspect of roadway lighting.

Purpose of this report

The general objective of engineering research on discomfort glare is to define and if possible specify mathematically permissible limits of glare for any particular conditions of interest. In addition, basic research is needed to determine the mechanisms underlying the discomfort reaction.

The principal purpose of this report is to analyze and describe mathematically a particular means of simulating roadway lighting, which will henceforth be referred to as the "Fry Simulator", and to indicate how such a Fry Simulator has been developed and used for research on dynamic discomfort glare to motorist from roadway lighting.

Before this, this report will outline prevalent roadway lighting practices and give a summary of other studies on discomfort glare and discomfort glare simulators.

PREVALENT ROADWAY LIGHTING PRACTICES

Prevailing roadway lighting practices will be summarized in the following sections.

1. Light sources
2. Luminaires
3. Luminaire mounting height
4. Luminaire spacing
5. Transverse location of luminaires

Light sources

Light sources (lamps) used today in artificial lighting can be divided into two main categoris.

1. Incandescent lamps
2. Gaseous discharge lamps

The gaseous discharge type of lamps is either low or high pressure. Low-pressure gaseous discharge sources are the fluorescent and low-pressure sodium lamps. High-pressure gaseous discharge sources are mercury vapor, metal halide and high-pressure sodium lamps.

The energy distributions of these lamps are shown in Figures 1, 2 3, 4, 5, and 6. These figures show how the input power is distributed and how much of the input power is obtained as visible radiation (Helms, 1980).

Light sources for road lights. A summary of light sources as they apply to exterior lighting is given below (Helms, 1980).

1. Incandescent lamps should be avoided for exterior applications because of their low efficiency and short life. Incandescent lamps create high operating and maintenance costs.
2. Fluorescent lamps should be avoided for exterior applications because of their sensitivity to temperature and the poor quality of optical

control. Enclosed and gasketed luminaires may maintain sufficiently high ambient temperature to allow for operation under low temperatures; however, the enclosure that holds the heat in the unit during cold weather also holds the heat in during warm weather, which causes a drop in the lumen output of the lamps. Because of the physical size of the light source, optical control will be poor, resulting in lower utilization characteristics.

3. Low-pressure sodium lamps produce monochromatic yellow light which turns all colors gray, brown, or black, except yellow. The lamp alone has a very high efficiency. However, when the source is combined with a ballast and luminaire, the overall efficiency of the system is low. Because of the physical size of the source, optical control is poor, resulting in low utilization characteristics.

4. Mercury vapor lamps require a phosphor coating if color rendition is to be acceptable. The phosphor-coated lamp is a large source, which means that optical control is poor and utilization decreases. The mercury vapor lamp also has a relatively low efficacy, which makes it the third choice for exterior applications.

5. Metal-halide and high-pressure sodium lamps have relatively small light-emitting elements (arc tubes), which allow for good optical control. Each of the two sources has high lamp efficacy and good system efficiency. Thus these two sources are the top choices for exterior applications. The metal halide lamp has better overall color balance and is preferred where color is important. The high-pressure sodium lamp has a higher lamp efficacy but a dominant orange appearance that may be objectionable for some applications.

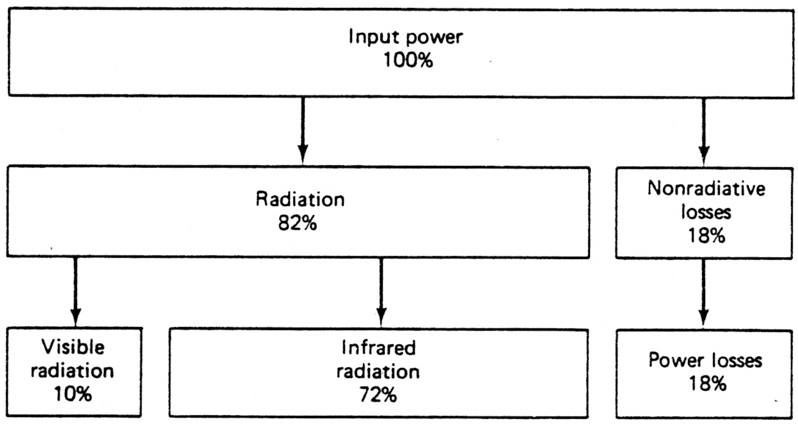


Figure 1. Energy Distribution of an Incandescent Lamp. 17.5 lm/watt (100") @ 10% visible radiation (Helms, 1980).

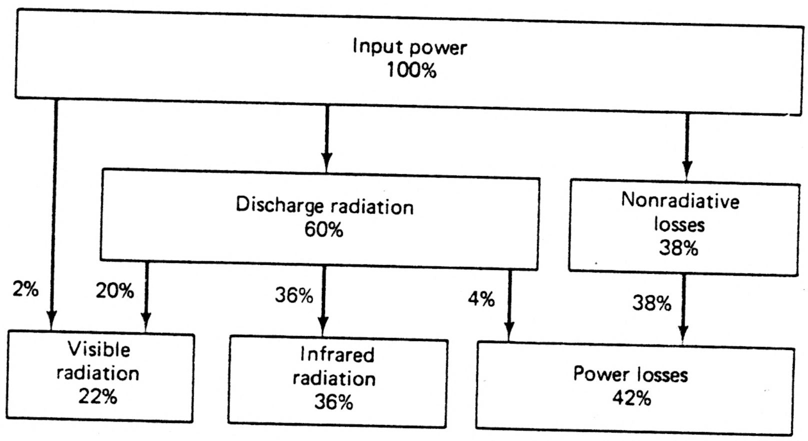


Figure 2. Energy Distribution for a Fluorescent Lamp. 78.8 lm/watt (40W) @ 22% visible radiation (Helms, 1980).

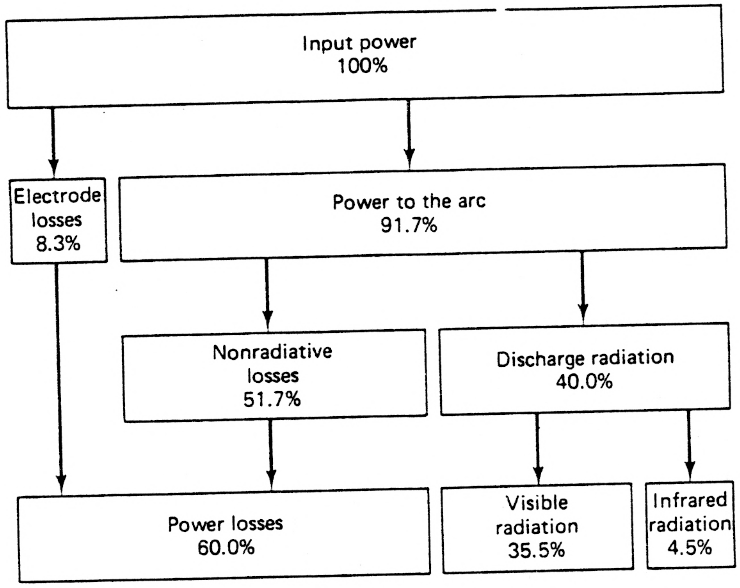


Figure 3. Energy Distribution of a Low-Pressure Sodium Lamp 183 lm/watt (180W) @ 35.5% visible radiation (Helms, 1980).

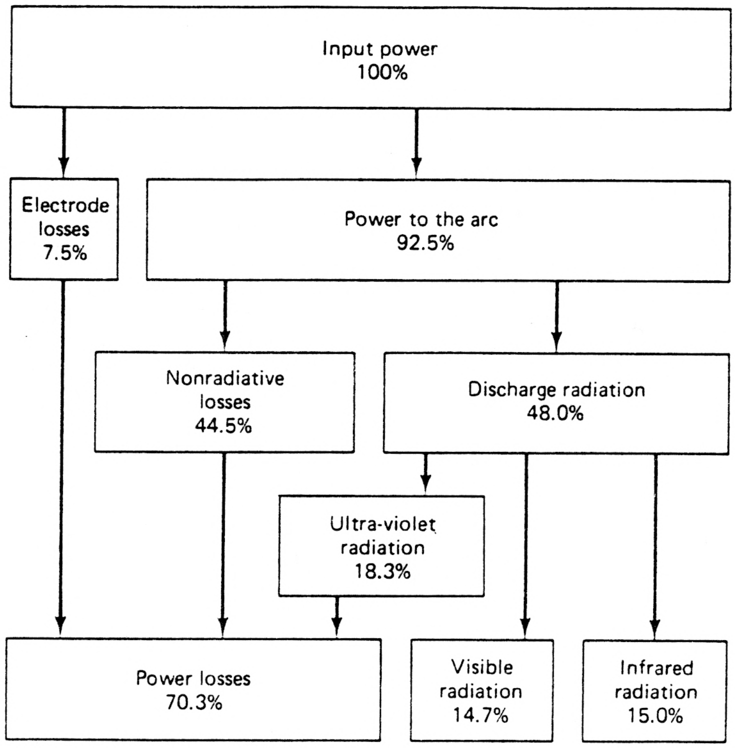


Figure 4. Energy Distribution for Mercury Vapor Lamps 56.3 lm/watt (400W) @ visible radiation (Helms, 1980).

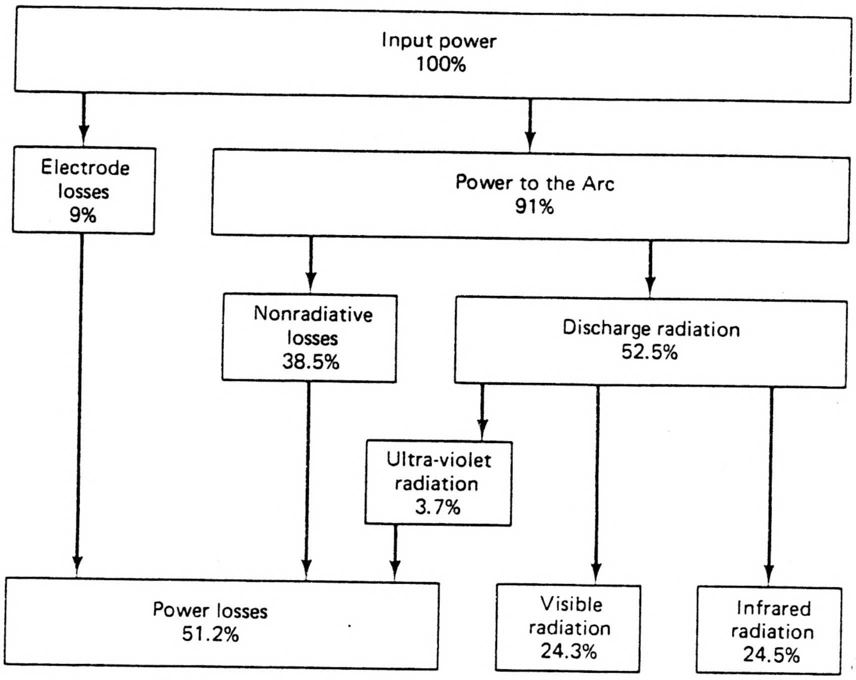


Figure 5. Energy Distribution for Metal Halide Lamp 100 lm/watt (40W) @ 24.3% visible radiation (Helms, 1980).

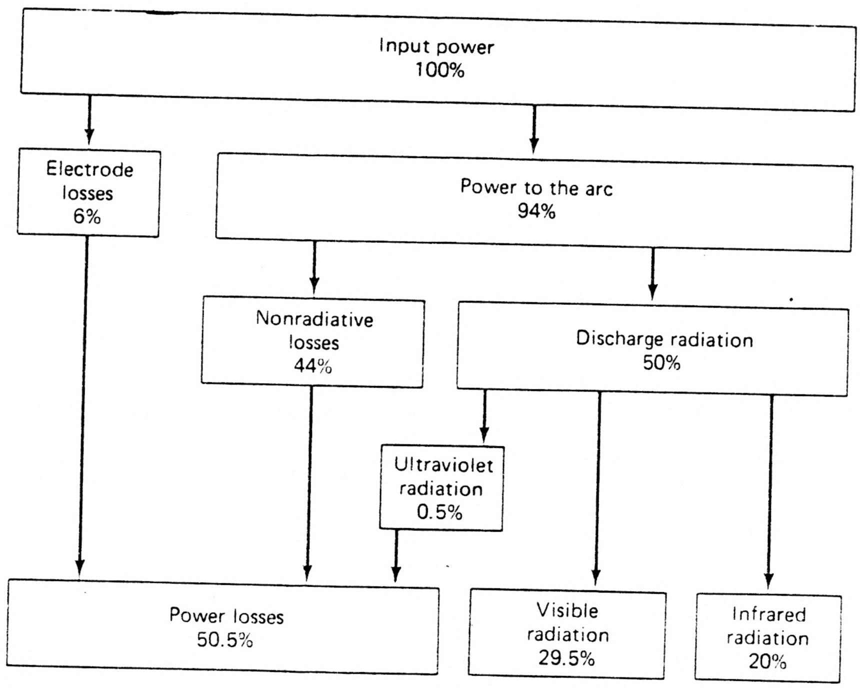


Figure 6. Energy Distribution for the High-Pressure Sodium Lamp 125 lm/watt @ 29.5% visible radiation (Helms, 1980).

Light source comparisons. (Helms, 1980). Tables 1 through 3 are provided to allow comparison of the light sources described so far. Tables 1 and 2 compare light sources in terms of the lamp only (no ballast losses), using constant wattage (400 W) and constant lumens (approximately 30,000 lm), respectively. Table 3 compares the light sources with the combined effect of lamp plus ballast loss. (Ballasts are required on all gaseous discharge lamps in order to provide the starting voltage, power-factor correction and current limitation.) This gives a more meaningful picture of lamp performance.

Luminaires

A luminaire is the lighting equipment that houses the light source, electrical components, and light-control method. It provides a luminous intensity distribution for the light source.

Luminaire classification. The light distribution from roadway luminaires is classified in terms of the following.

1. Spread (short, medium, long), which describes the vertical light distribution.
2. Type (I, II, III, IV, V), which defines the lateral light distribution.
3. Control, which is divided into three categories (cutoff, semicutoff, noncutoff)

The terminology used in this classification is indicated in Figure 7.

Spread. The classification according to spread is determined by measurements in a longitudinal direction (Figure 8). The spread is assigned on the basis of the location of the intersection of the maximum candlepower (luminous intensity) with the roadway surface. Thus, it indicates the vertical light distribution of the luminaire. Spread classification is shown in Figure 8. According to this classification, a luminaire is classi-

TABLE 1. Source Comparison Based on Equal Watts (400 W).

Lamp	Design	Quantity	Watts (total)	Lumens (each)	Source efficacy[c] (each)	BTU per hour (total)	Life in hours (each)	Total cost (each)[b],$
Incadescent	100A19	4	400	1,740	17.4	1364	750	(0.50)[a] 2.00
Fluorescent	F40CW	10	400	3,150	78.9	1364	20,000	16.70
Low-pressure sodium	SOX135	3	405	21,500	159.3	1381	18,000	(40.00) 120.00
Mercury vapor	H33GL-400/DX	1	400	22,500	56.3	1364	24,000[a]	15.50
Metal halide	M400/BU-HOR	1	400	34,000	85.0	1364	15,000	34.50
High-pressure sodium	LU400/BU	1	400	50,000	125.0	1364	20,000	60.00

[a]Rated life is 24,000 h; usable life is 16,000 to 18,000 h.

[b]Values in parenthesis are costs per individual lamp.

[c]Unit for efficacy in lumens/watt.

TABLE 2. Source Comparison Based on Equal Lumens (30,000 lm)

Lamp	Design	Quantity	Total Lumens (each)[b]	Watts (each)	Source efficacy (each)	BTU per hour (total)	Life in hours (each)	Total cost (each)[b] $
Incandescent	100A19	17	29,580 (1,740)	100	17.4	5797	750	(0.50) 8.50
Fluorescent	F40CW	10	31,500 (3,150)	40	78.9	1364	20,000	(1.67) 16.70
Low-pressure sodium	SOX180	1	33,000	180	183.9	614	18,000	60.00
Mercury vapor	H37KC-250/DX	2	26,000 (13,000)	250	52.0	1705	24,000[a]	(18.75) 37.50
Metal Halide	M400/BU-HOR	1	34,000	400	85.0	1344	15,000	34.50
High-pressure sodium	LU250/BU/S	1	30,000	250	120.0	853	15,000	64.00

[a]Rated life is 24,000 h; usable life is 16,000 to 18,000 h.

[b]Values in parenthesis are for individual lamps.

TABLE 3. Light Source Summary

	Designation	Watts	Lumens	Source efficacy	System efficacy	Life in hours
Incandescent						
Standard	100A19	100	1,750	17.5	17.5	750
Gaseous Discharge						
Low pressure						
Fluorescent	F40CW	40	3,150	78.8	68.5[a]	20,000
Low-pressure sodium	SOX180	180	33,000	183.3	150.0 119.3[b]	18,000
High-pressure						
Mercury vapor	H33GL-400/DX	400	22,500	56.3	49.2[c]	24,000
Metal halide	MS400/HOR	400	40,000	100.0	85.0[d]	15,000
High-pressure sodium	LU400/BU	400	50,000	125.0	100.2[e]	24,000

[a]HPF-RS two-lamp ballast, 92 W.

[b]HPF, high reactance, 220 W at 33000 lm (100 h) to 285 W at 34000 lm (18,000 h).

[c]Regulating, 457 W.

[d]Autostabilized, 471 W.

[e]Stabilized, 499 W.

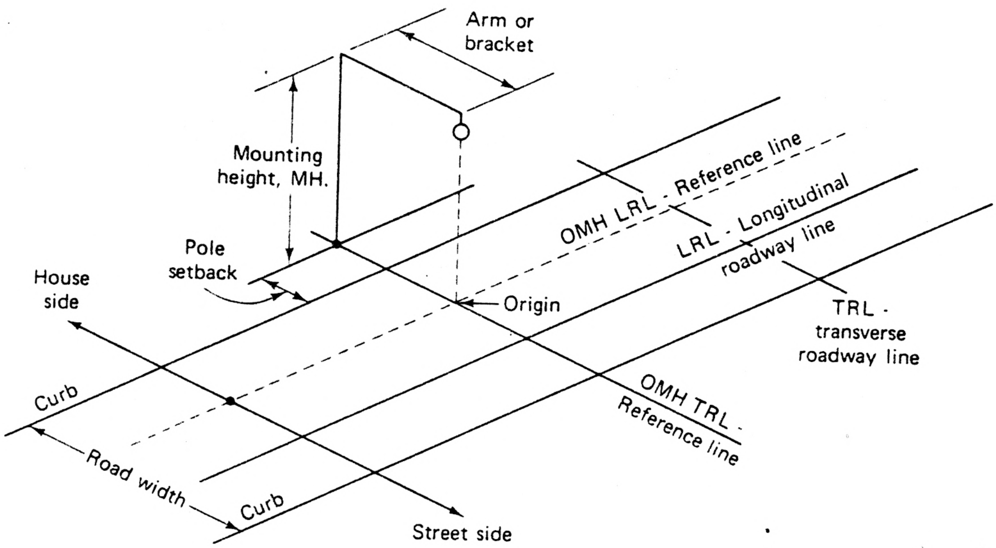


Figure 7. Terminology for Roadway Lighting (Helms, 1980).

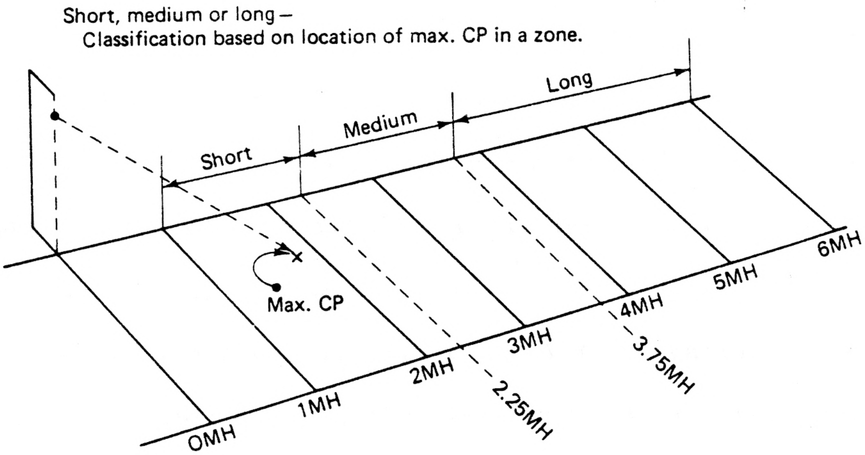


Figure 8. Spread Classification (Helms, 1980).

fied as having a short light distribution when its maximum candlepower point lies between the 1.0-MH TRL and the 2.25-MH TRL. A luminaire is classified as having a medium light distribution when its maximum candlepower point lies between the 2.25-MH TRL and the 3.75-MH TRL. A luminaire is classified as having a long distribution when its maximum candlepower point lies between the 3.75-MH TRL and the 6.0-MH TRL.

Type. The type classification indicates the lateral light distribution of the luminaire. The type is assigned on the basis of the location of the segment of the half maximum candlepower trace (Figure 10) which falls within the longitudinal distribution range, as determined by the point of maximum candlepower (short, medium or long). Lateral light distributions of type I, II, III and IV are shown in Figure 9. A distribution is defined as Type V when the distribution has a circular symmetry of candlepower distribution, which is essentially the same at all lateral angles around the luminaire. Figure 10 shows an example of a luminaire having a Type III - Medium distribution.

Control. The classification according to control is determined by the candlepower distribution at vertical angles above maximum candlepower distribution. Increasing the vertical angle of light flux emission normally increases the uniformity of pavement luminance as well as glare. However, the respective rates of increase are not the same. Hence, design compromises become necessary in order to achieve balanced performance. Therefore, varying degrees of candlepower in the upper portion of the beam above maximum candlepower are required. This control of the candlepower distribution is divided into thre categories. A luminaire light distribution is designated as cutoff, when the candlepower per 1000 lamp lumens does not numerically exceed 25 (2 1/2 per cent) at an angle of 90 degrees above nadir

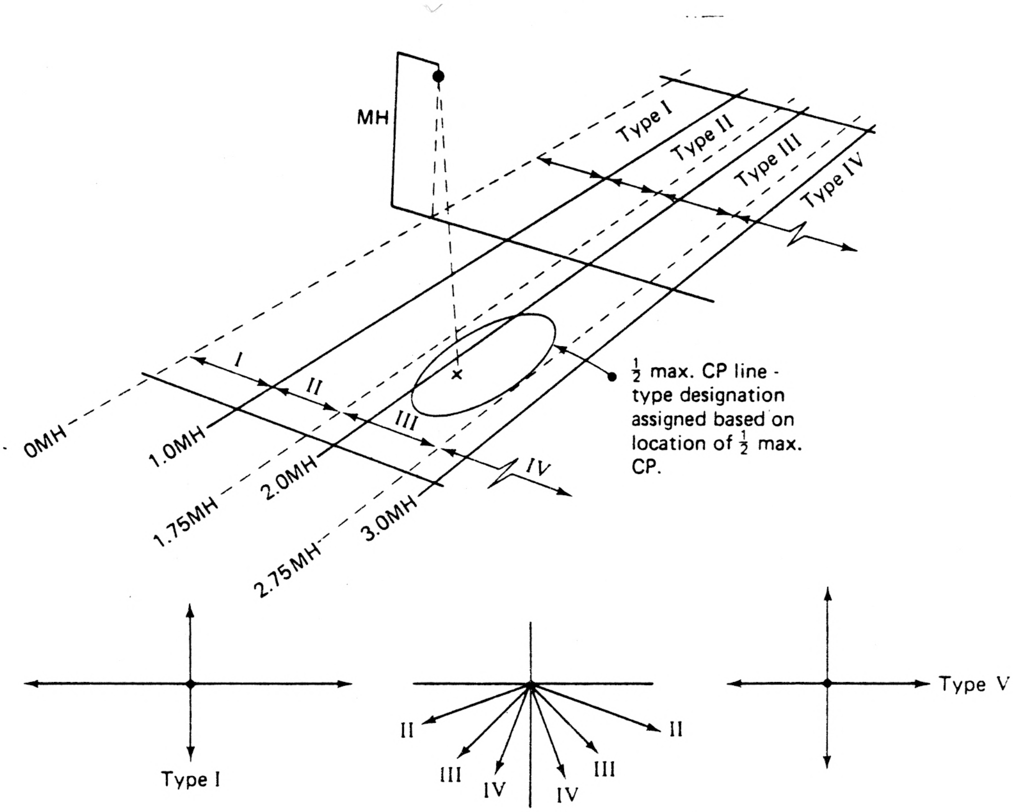


Figure 9. Type Classification (Helms, 1980).

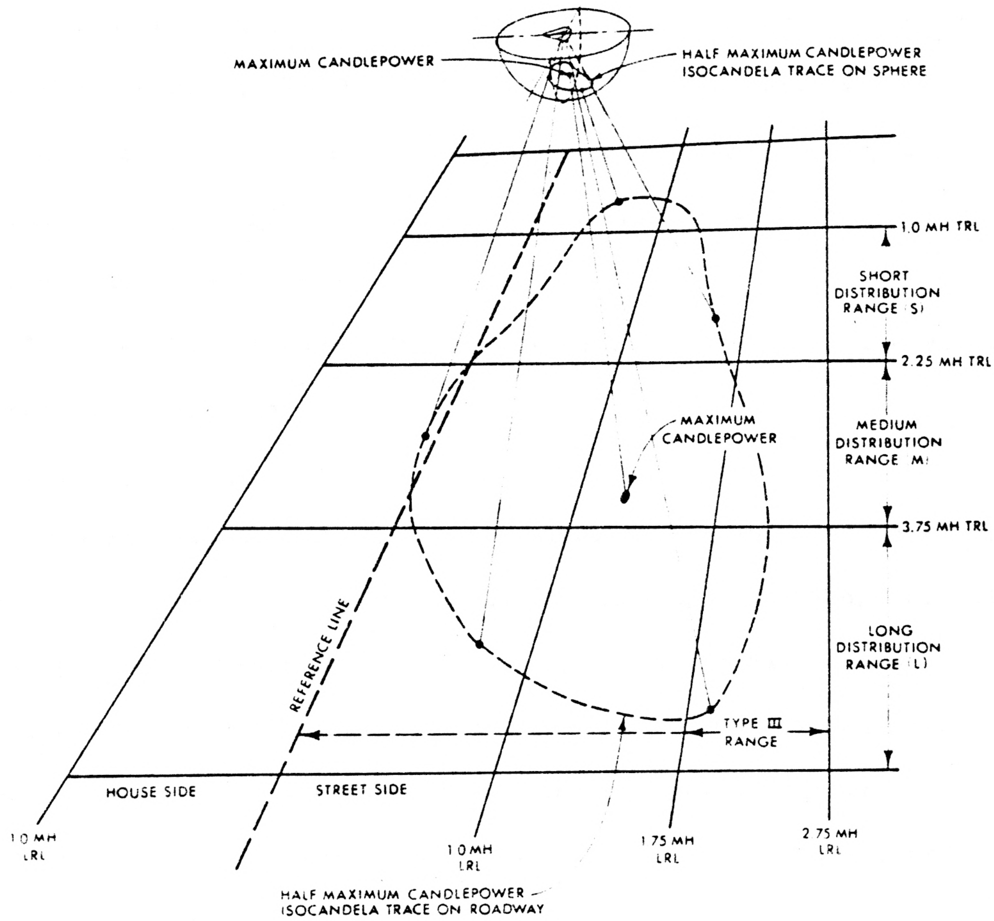


Figure 10. Diagram showing projection of maximum candlepower and half maximum candlepower isocandela trace from a luminaire having a Type III - Medium distribution on the imaginary sphere and the roadway (IES Lighting Handbook, 1981).

(horizontal), and 100 (10 per cent) at a vertical angle of 80 degees above nadir. This applies to any lateral angle around the luminaire. A luminaire light distribution is designated as semicutoff when the candlepower per 1000 lamps lumens does not numericaly exceed 50 (5 per cent) at an angle of 90 degrees above nadir (horizontal), and 200 (20 per cent) at a vertical angle of 80 degrees above nadir. This applies to any lateral angle around the luminaire. Noncutoff luminaires have no candlepower limitations in the zone above maximum candlepower.

Table 4 shows recommended luminaires, on the basis of control, for various types of roads.

Luminaire Mounting Height (IES Lighting Handbook, 1981)

Mounting heights of luminaires have, in general, increased substantially during the past several decades. The advent of modern, more efficient and larger size (lumen output) lamps has been the basic reason. Engineers have increased mounting heights in order to obtain economic and esthetic gains in addition to increased illuminance uniformity when utilizing the newer large lamps. Mounting heights of 40 feet (12 meters) and higher are used along roadways.

When designing a system, mounting height should be considered in conjunction with spacing and lateral positioning of the luminaires as well as the luminaire type and distribution. Uniformity and illuminance levels should be maintained as recommened regardless of the mounting height selected. (From uniformity considerations, the ratio of average-level-to minimum illuminance on the roadway should not exceed 3 to 1 for any roadway, excepting local residential streets.)

Increased mounting height may, but will not necessarily, reduce glare. It increases the angle between the luminaires and the line of sight to the roadway; however, luminaire light distributions and candlepower also are

TABLE 4. Recommended Luminaires for Street Lighting (de Boer, 1967).

Average luminance $\bar{L}$ cd/m^2	Types of road		cut-off	semi cut-off	non cut-off
4	Rural roads	Motorways with very heavy traffic, complex junctions	3	3*	0
	Urban roads	Main streets, through ways, boulevards etc. with mixed traffic	2	3	0
2	Rural roads	Motorways with heavy traffic, trunk roads	3	2	0
	Urban roads	Through ways with mixed traffic	2	3	0
1	Rural roads	Secondary roads with considerable traffic	3	2	0
	Urban roads	Principal local traffic routes with mixed traffic	2	3	0
0.5	Rural roads	Secondary roads with light traffic	3	3	0
	Urban roads	Secondary local traffic routes	1	3	1
	Squares, etc.		3	3	1
	Tunnels		3	3	0

0: to be avoided
1: permissible
2: satisfactory
3: recommended

* Semi-cut-off luminaires are convenient particularly at high levels of luminance in view of economy of the installation. The proviso must be made however, that glare is sufficiently limited.

significant factors. Glare is dependent on the flux reaching the observer's eyes from all luminaires in the scene.

Luminaire Spacing (IES Lighting Handbook, 1981)

It is generally a more economical practice to use larger lamps at reasonable spacings and mounting heights than to use smaller lamps at more frequent intervals with lower mounting heights. This is usually in the interest of good lighting provided the spacing-to-mounting height ratio is within the range of light distribution for which the luminaire is designed. The desired ratio of lowest illuminance at any point on the pavement to the average illuminance should be maintained. The disregarding of luminaire light distribution characteristics and the exceeding of maximum spacing-to-mounting height ratios can cause loss of visibility of objects between luminaires.

Transverse Location of Luminaires (IES Lighting Handbook, 1981)

Type II, III and IV luminaires are intended (unless designated as offset luminaires) to be mounted over or near the edge of the roadway. Type I and V are generally designed to be mounted over or near the center of the area to be lighted. Usually, luminaire overhang exceeding 0.25 mounting height does not contribute to visibility and often increases system glare and cost.

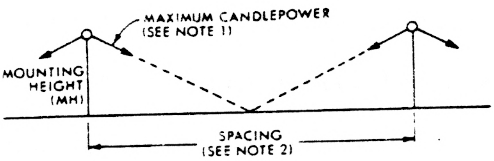
Optimum luminaire location is best determined by reference to the photometric data showing illumination distribution and utilization. Other factors that must be considered are:

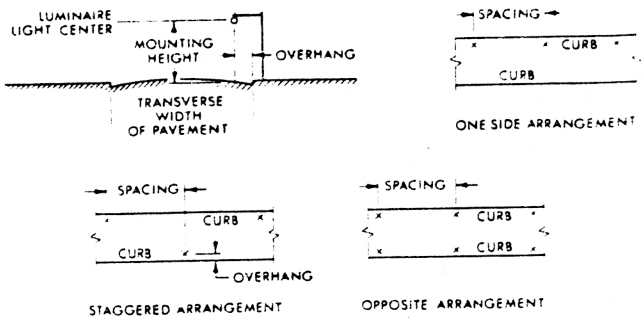
1. Access to luminaires for servicing.
2. Vehicle-pole collision probabilities.
3. System glare aspects.
4. The visibility (both day and night) of traffic signs and signals.

5. Esthetic appearance.

6. Trees.

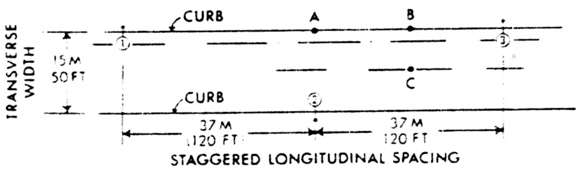
Typical lighting layouts and terminology with respect to luminaire arrangements and spacing are shown in Figure 11.

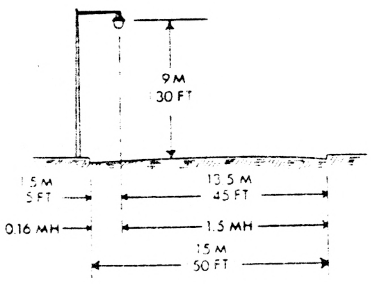




Note 1: Maximum candlepower beams from adjacent luminaires should at least meet on the road surface.
Note 2. Maximum luminaire spacing generally is less than:
A —Short Distribution—4.5 MH;
B —Medium Distribution—7.5 MH; and
C —Long Distribution—12.0 MH

Typical lighting layouts showing spacing-to-mounting height relationships and terminology with respect to luminaire arrangement and spacing.





Layout of luminaire and roadway assumed for typical computation

Figure 11. Typical lighting layouts (IES Lighting Handbook, 1981).

RESEARCH ON DISCOMFORT GLARE IN ROAD LIGHTING

Roadway lighting design practices in North America and Europe have been based on elimination of disability glare. In Europe, a procedure called "Glare Mark" is in use to prevent discomfort glare in the design of lighting for streets and highways. The IESNA Roadway Lighting Committee wishes to add procedures for dealing with discomfort glare to its currently-being-revised and future revisions of the Standard Roadway Lighting Practice. Unfortunately, field tests of Glare Mark in this country have not shown it to have much predictive power (Keck and Odle, 1975). A North American approach called "CBE" (Cumulative Brightness Evaluation) is being developed based upon Kansas State research and will require validation.

In a typical North American glare experiment, the observer sits with his face in a face-rest (to maintain distance and angular size and position values) with the glare source(s) either on or above his line-of-sight. He adjusts a transformer which controls glare source luminance. He adjusts to a given criterion, such as "Borderline between Comfort and Discomfort (BCD)''.

This BCD value, when the visual sensation experienced by the observer changes from comfortable to uncomfortable, varies widely from observer to observer. This variation seems to be related to the observers' age, eye color and other undiscovered factors (Bennett, 1977). Considerable variation exists even within the same observer over a period of time (Bennett, et. al., 1982).

A series of researches relative to the application of the BCD concept to roadway lighting has been underway at Kansas State University. At this point, the research efforts have progressed to the point where the brightness of a single source necessary to produce BCD for an average observer can be predicted. Further investigations using the BCD concept have resulted in a Visual Comfort Probability (VCP) system to predict the percentage of a population who can be expected to find an installation comfortable.

A multiple regression model has been developed for predicting glare sensitivity as a function of glare source size, position and background luminance for a single glare source (Bennett, 1977). Further analysis has extended this model to a multiple probit model which not only enables prediction of the average person's response to glare, but also any arbitrary percentage response within wide limits (Bennett and Rubison, 1979). Further research extended this to a linear array of multiple sources for a particular simulated set of lights (Bennett, 1979). This research has also showed the declining influence of lights as one looks down the roadway and led to a "Cumulative brightness" model where summation of effects over successive lights are substituted for size, position and background in the previous multiple regression model. This, currently, is the CBE procedure. The calculation of CBE is tedious but not complex. The equation as found by Dr. Glenn Fry is as follows:

$$CBE = \frac{(B_1^{1.67})\, S_1}{e^{0.08 A_1}} + \frac{(B_2^{1.67})\, S_2}{e^{0.08 A_2}} + \ldots$$

where B (in fL) is the brightness of the glare source.

S (in steradians) is the source size.

A (in degrees) is the source angle off the line of sight.

The research effort has not reached the point that VCP calculations can be made for multiple light sources. It is however possible to predict, from mathematical combination of all luminances in the field of view, which of several installations will be found most comfortable if viewed by the same observers within a reasonable span of time.

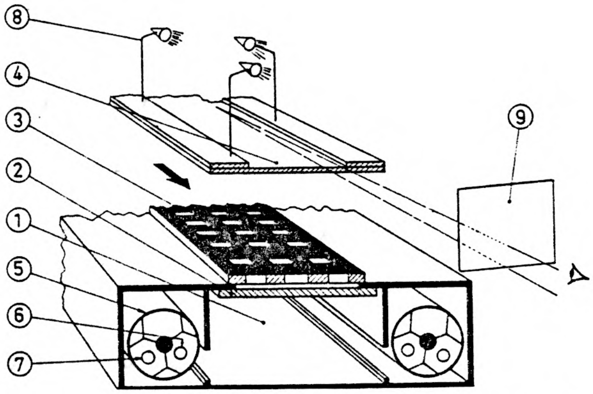
Dynamic Glare Research

With each step of the research program, further fidelity has been created in the simulation. The next major step is from static viewing to a dynamic, driving situation. Research efforts in this direction fall into two major categories.

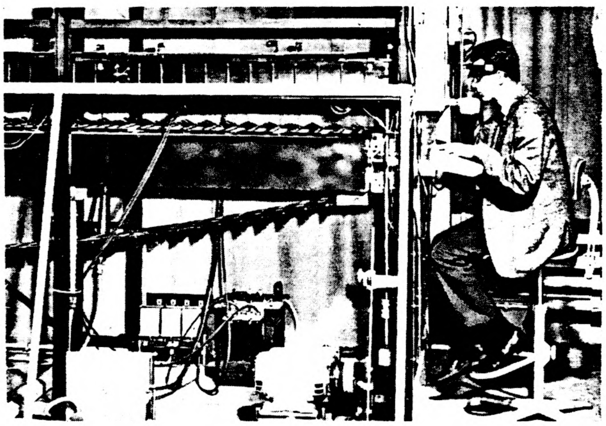
1) Those studies which are carried out either on real roads or in outdoor laboratories.

2) Those studies which are done with scale models in laboratories, simulating the real world conditions.

The first type of study is expensive, limited in flexibility and calls for elaborate coordination. An example of the second type of study, carried out in Philips Lighting Laboratory, Eindhoven, Netherlands is shown in Figure 12 (de Boer, 1967). Even though this is a good simulation, it can be seen that the experimental setup calls for extensive changes, when different conditions and configurations of road-lighting installations have to be studied. A simpler and less expensive scale model, dynamic simulation is needed. Such an approach has been suggested by Dr. Glenn Fry of Ohio State. The analysis and development of such a simulator for dynamic glare research in roadway lighting is the principal purpose of this report.



Sketch of street-lighting simulator for observations on discomfort glare under semi-dynamic conditions. The light box (1) serves as light source. Its light comes through the glass plate (2) and the openings in a conveyor belt (3) to the underside of a plate of frosted glass (4) which represents the road surface. The luminance pattern on the "road surface" can be varied by opening or closing certain groups of openings in the belt (3). The light box (1) is illuminated by the light sources (6) and (7) (sodium and mercury respectively). These light sources can be interchanged by revolving their housing (5). Small incandescent lamps (8) move synchronously with the belt (3) and simulate the luminaires of the street-lighting installation. The intensity and light distribution of these luminaires can be adjusted by changing the voltage of bars from which they obtain their voltage by means of sliding contacts. In some experiments a neutral filter (9) was used to vary the simulated road-surface luminance. The observer's position is shown to the right.



The observer's seat and part of the simulator. Part of the endless belt and the light box can be seen.

Figure 12. Street Lighting Simulator Used in Philips Lighting Laboratory (de Boer, 1967).

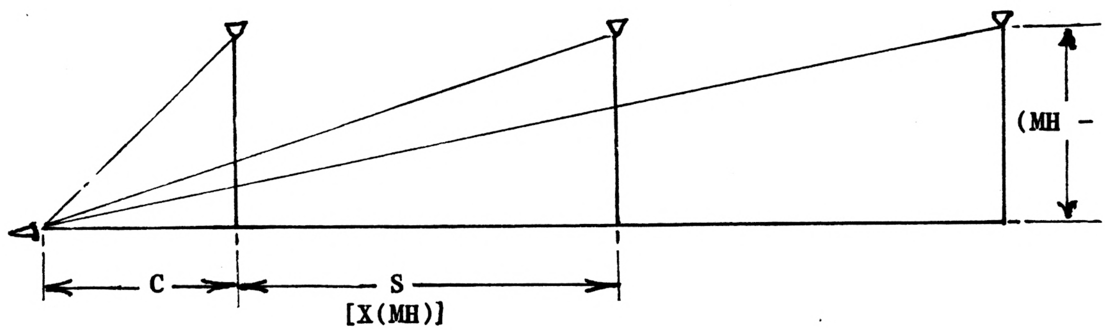
THE FRY SIMULATOR

A disk is rotated in front of a light(s). The disk has a clear spiral track which increases in width as it spirals outward. An opaque mask with a narrow open sector occludes most of the disk. As the disk cycles behind the mask, the observer sees a series of roadway lights ranging from the large first light above him down to the ever more closely-spaced, small lights near the horizon. Such a simulator will hereafter be referred to as the "Fry Simulator". The major objective of this report is the development of this dynamic simulation capability. The principal purpose is to create a document which will enable a given set of roadway lighting conditions to be translated to the Fry Simulator parameters.

Real World Conditions vs Simulation Parameters

The first step is to establish the relationships between the road-lighting conditions and the simulation parameters. Table 5 establishes such relationships.

Design Calculations for Fry Simulator



Let (MH) be the mounting height of the luminaire

(EL) be the eye level of the motorist from the road

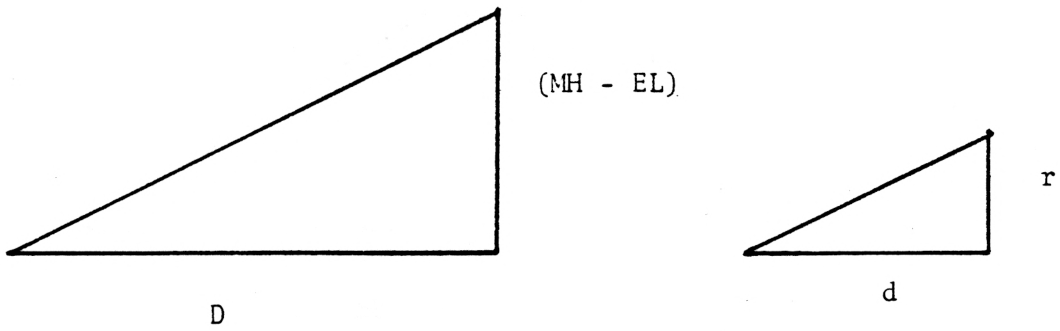
α be the windshield cut-off angle

and C be the corresponding distance of the closest pole to the motorist.

TABLE 5. Relationship Between Real World Conditions and Simulation Parameter.

REAL WORLD CONDITION	SIMULATION PARAMETER
1) Speed of the car, M mph	1) Rotatational speed of the disk, m rpm
2) Angular distance from the observer's line of sight to the road light (varying between α and β)	2) Angular distance from the observer's line of sight to the spiral segment (varying between α and β)
3) Distance from the motorist to the light pole, D	3) Spiral segment radius, r
4) Horizontal dimension of luminaire, W	4) Width of the narrow open sector in the opaque mask, w
5) Vertical dimension of luminaire, H	5) Width of the spiral (in the radial direction), h
6) Lateral displacement of the light pole from the line of sight, L	6) Angular position of open sector on mask from the vertical, λ

The spacing (S) between two adjacent light poles can be expressed as a multiple of mounting height (MH). Let this spacing be X(MH). Let d be the viewing distance of the simulation spiral. The instantaneous radius r of this spiral can be calculated from the similar triangles shown below, where D is the instantaneous distance (in the real world) of the light pole from the motorist.



$$\frac{(MH - EL)}{D} = r/d$$

$$r = \frac{(MH - EL)\ d}{D} \qquad (1)$$

Now, a distance of S or X(MH) corresponds to one revolution (i.e., 2π radians) of the spiral. Therefore, a distance of D corresponding to an angular rotation of θ radians is given by

$$\frac{X\ (MH)}{2\pi} = D/\theta$$

$$D = X(MH)\ .\ \theta/2\pi \qquad (2)$$

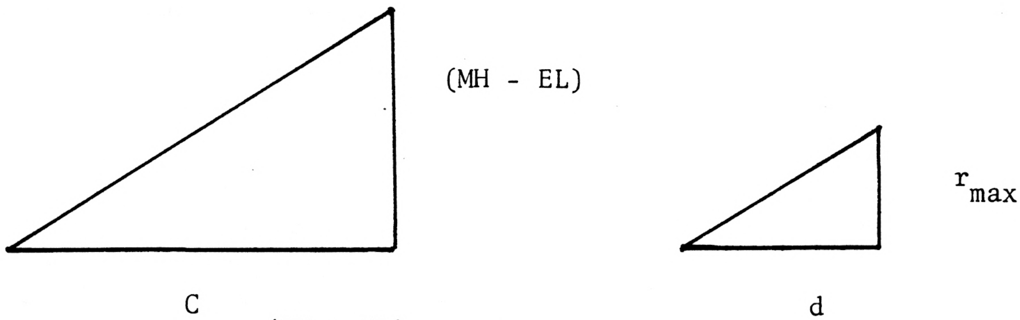
Substituting for D in equation (1),

$$r = \frac{(MH - EL)\ d}{X(MH)}\ .\ 2\pi/\theta \qquad (3)$$

From equation (2),

$$\theta = \frac{2\pi}{X(MH)} \cdot D \tag{4}$$

The limits for the value of θ have to be fixed. Considering the one extreme condition, when the closest luminaire is just about to be cutoff from view by the windshield, the following limiting condition is obtained.



Now $\tan \alpha = \frac{(MH - EL)}{C} = \frac{r_{max}}{d}$

$$r_{max} = d \tan \alpha \tag{5}$$

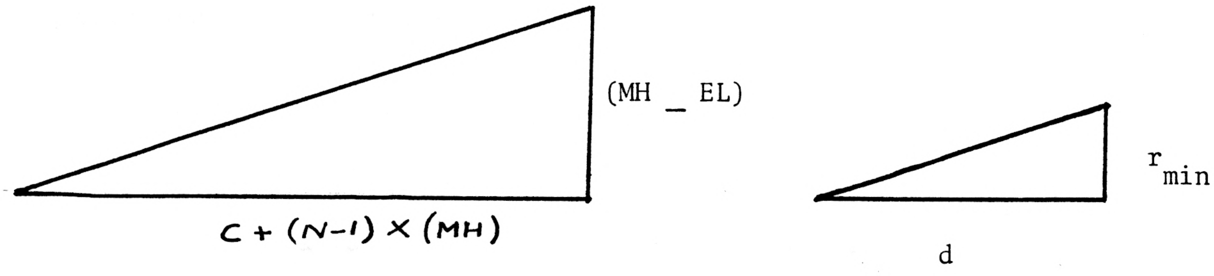
$$C = \frac{(MH - EL)}{\tan \alpha} \tag{6}$$

From equation (4)

$$\theta_{max} = \frac{2\pi}{X(MH)} \cdot C$$

$$= \frac{2\pi}{X(MH)} \cdot \frac{(MH - EL)}{\tan \alpha} \tag{7}$$

The other limiting value θ_{min} is obtained, considering the luminaire farthest away from the motorist. If the motorist is able to see a total of N luminaires, then the distance of the luminaire farthest away from the motorist is C + (N−1) S i.e., C + (N−1) X(MH).



From these similar triangles,

$$\frac{r_{min}}{d} = \frac{(MH - EL)}{C + (N-1)\ X(MH)}$$

$$r_{min} = \frac{d.(MH - EL)}{C + (N-1)\ X(MH)} \qquad (8)$$

From equation (4),

$$\theta_{min} = \frac{2\ \pi}{X(MH)} \cdot [C + (N-1)\ X(MH)] \qquad (9)$$

Thus, equation (3) establishes the radius of the spiral and equations (7) and (9) establish the limits for the rotational angle θ through which the spiral has to be plotted. This spiral may be taken to correspond to the lowest point on the luminaire. The vertical dimensions of the luminaire has to be simulated by plotting another concentric spiral, corresponding to the highest point on the luminaire. This will give rise to a spiral track, the width (in the radial direction) of which will correspond to the vertical dimension of the luminaire. The radius of this outer spiral is given by

$$R = \frac{(MH - EL + H)\ d}{X\ (MH)} \ .\ 2\pi/\theta \qquad (10)$$

where H is the vertical dimension of the luminaire. The difference between

R and r (the instantaneous radii of the outer and inner spirals) gives the width of the spiral in the radial direction, which corresponds to the vertical dimension of the luminaire.

The instantaneous width h of the spiral = R − r

$$= \frac{(MH - EL + H)\ d}{X(MH)} \cdot 2\pi/\theta - \frac{(MH - EL)\ d}{X(MH)} \cdot 2\pi/\theta$$

$$h = \frac{H \cdot d}{X(MH)} \cdot 2\pi/\theta \qquad (11)$$

The horizontal dimension W of the luminaire is simulated by the narrow opening in the mask, by maintaining the angle subtended by the width w of the opening at any point the same as that subtended by the corresponding luminaire on the road. This is done by considering the two sets of similar triangles shown in Figure 13. From the lower set of similar triangles,

$$\frac{PQ}{OQ} = \frac{XY}{OY}$$

$$\frac{OQ}{OY} = \frac{PQ}{XY} = \frac{r}{(MH - EL)} = d/D \quad \text{from equation (1)}$$

From the upper set of similar triangles,

$$\frac{RQ}{OQ} = \frac{ZY}{OY}$$

$$w = RQ = ZY \cdot \frac{OQ}{OY} = W \cdot d/D$$

$$w = \frac{(W.d)}{D}$$

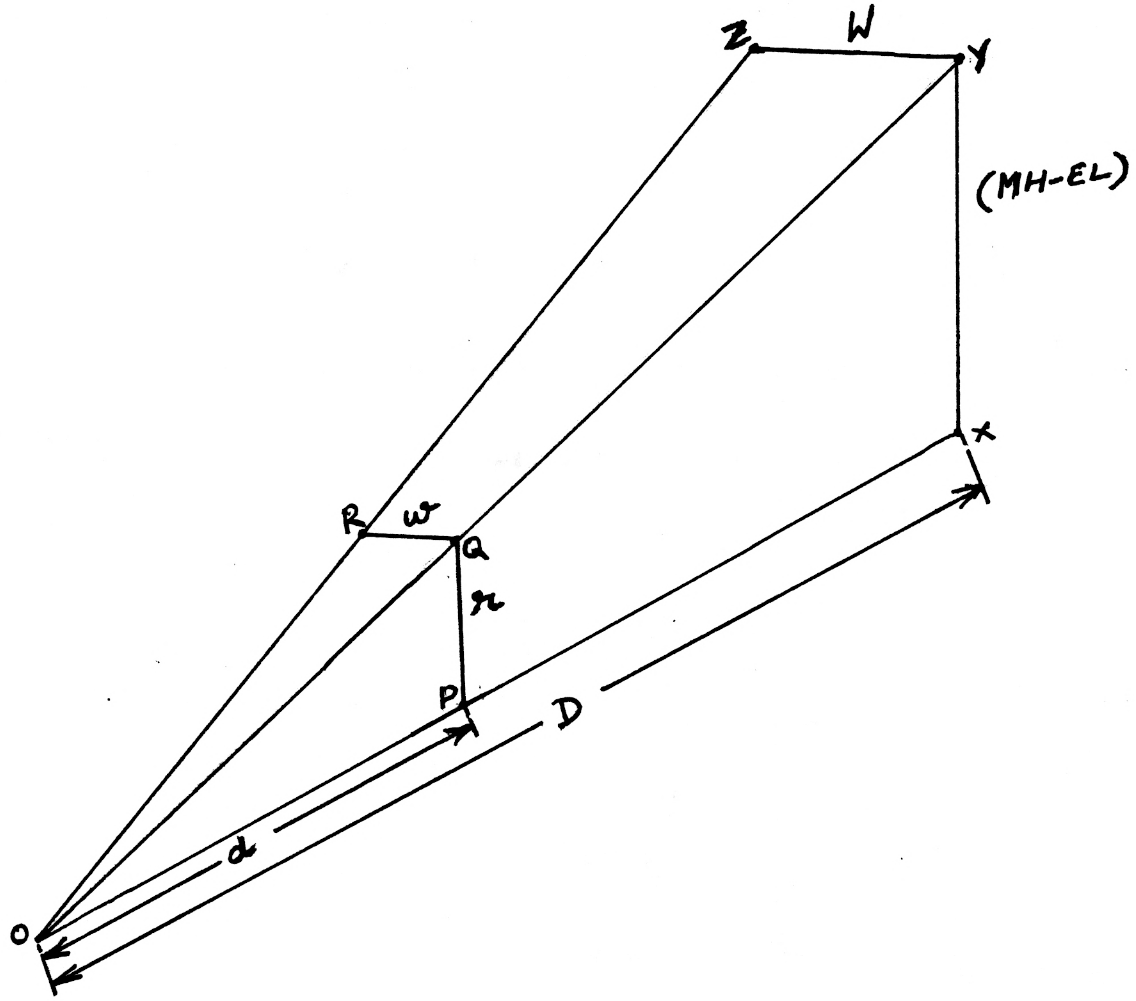
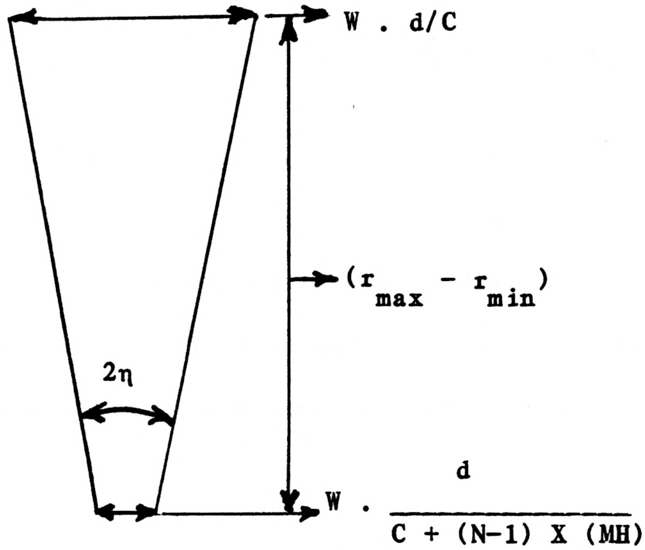


Figure 13. Geometry for Luminaire Width Simulation.

Thus, the width of the narrow opening in the mask is linearly related and inversely proportional to the distance D of the motorist from the light pole. At the windshield cut-off angle point, this width $w_c = W \cdot d/C$. At the other end, corresponding to the farthest luminaire, it will be

$$W \cdot \frac{d}{C + (N-1) X (MH)} .$$

Thus the slit diverges from the center of the disk to the outer radius, as shown below



If the angular width of this opening is 2η,

$$\text{then } \tan\eta = \frac{1/2\left[W \cdot d/C - W \cdot \frac{\alpha}{C + (N-1) X (MH)}\right]}{r_{max} - r_{min}}$$

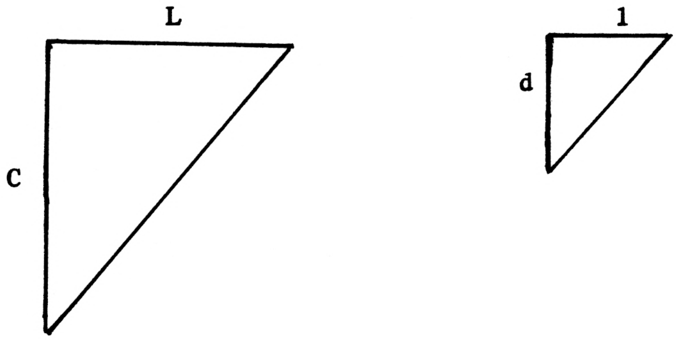
$$= \frac{1/2\, W \cdot d\left[1/C - \frac{1}{C + (N-1) X (MH)}\right]}{d\left[\tan\alpha - \frac{(MH - EL)}{C + (N-1) X (MH)}\right]}$$

$$= \frac{1/2\ W \left[\dfrac{C + (N-1) \times (MH) - C}{C[C + (N-1) \times (MH)]}\right]}{\dfrac{\tan\alpha \,.\, [C + (N-1) \times (MH)] - (MH - EL)}{[C + (N-1) \times (MH)]}}$$

$$= \frac{W\ [(N-1) \times (MH)]}{2C\ \{\tan\alpha .\ [C + (N-1) \times (MH)] - (MH - EL)\}}$$

$$\text{Angular width, } 2\eta = 2 \tan^{-1} \frac{W[(N-1) \times (MH)\}}{2C\{\tan\alpha \,.\, [C + (N-1) \times (MH)] - (MH-EL)\}}$$

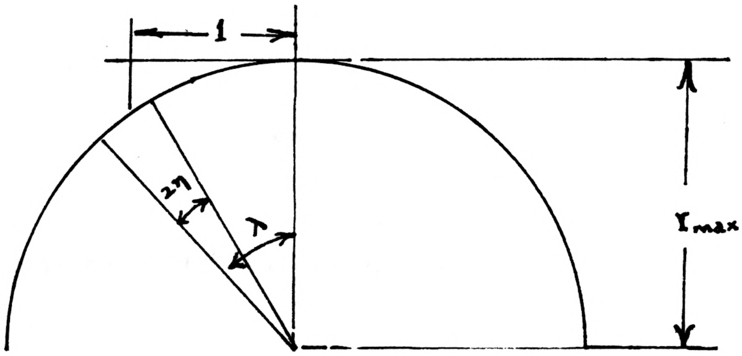
This slit in the mask will be vertically positioned, only when the row of lights are along the line of sight. However, this is not generally the case. If the lights are on one side of the road and laterally displaced from the line of sight by a distance L and if it is assumed that the light which is farthest away from the motorist is on the line of sight, then the following consideration is valid.



$$L/C = 1/d$$

$$1 = L/C \,.\, d$$

Thus, the slit in the mask must be laterally off-set by the amount 1 at the maximum radius, corresponding to the windshield cut-off point.



If λ is the angle by which this slit must be tilted from the vertical position, then

$$\tan\lambda = \frac{1}{r_{max}} = \frac{L \, . \, d/C}{d \, . \, \tan\alpha}$$

$$= \frac{L}{C \tan\alpha}$$

$$= \frac{L}{\dfrac{(MH - \ell L)}{\tan\alpha} \, . \, \tan\alpha}$$

$$= \frac{L}{(MH - \ell L)}$$

The angle λ by which the narrow opening in the mask must be tilted from the vertical is given by

$$\lambda = \tan^{-1} \frac{L}{(MH - \ell L)}$$

Finally, the rotational speed of the disk, simulating the speed of the car is calculated, considering the fact that one revolution of the spiral corresponds to a distance travelled of one spacing between the poles. In other words, X(MH)'/min corresponds to 1 rpm of the spiral. Therefore, the rotational speed of the spiral, to simulate a driving speed of M mph (i.e.

88 M'/min) is $\frac{88\ M}{X(MH)}$ rpm.

$$\text{RPM of the disk, } m = \frac{88\ M}{X\ (MH)}$$

where M is the speed of the car in mph and MH is the mounting height of the luminaire in feet.

Summary of Dynamic Glare Simulation

The development of the Fry Simulator for roadway lighting can be summarized as follows.

Knowing the mounting height (MH) of the luminaire, eye level (EL) of the motorist, the ratio X of the spacing between light poles and the mounting height, the windshield cut-off angle α, the number N of the road-lights in view of the motorist, and the lateral displacement L of the light pole from the line of sight of the motorist, a disk having a transparent spiral track can be made and rotated at m rpm in front of a row of lights and behind an opaque mask with a narrow open sector, tilted at an angle λ to the vertical. The observer will be positioned at a distance d from the disk. The lighted spiral track segments seen by the observer will simulate the road lights as seen by a motorist driving on an artificially lighted roadway.

THE CURRENT STUDY

A Fry Simulator was designed and built at Kansas State University in Spring, 1982. Seventy four subjects were run in Summer, 1982.

Figure 14 is a line diagram of the simulator set-up. Figure 15 shows one of the disks used in the simulator. Two such disks were mounted on a shaft, as shown in Figure 16, at 180^{o} out of phase, so that a staggered lighting arrangement was obtained. One of the disks was rotated by a motor with speed control. The lighting fixture and the cooling arrangement were as shown in Figure 17. Two mirrors, perpendicular to each other, were positioned in between the two disks and in front of the observer's position. The reflected images of the spiral segments, from the two disks simulated the road lights on both sides of the road. To simulate one side lighting condition, one set of lights was turned off. A separate masking arrangement (Figure 18) was used to obtain a required number of road lights seen by the observer. The observer's position was as shown in Figure 19. The speed and source luminance were varied by the control panel shown in Figure 20.

On account of the requirement of a hub on the disk for the purpose of mounting, the spiral radii, as calculated from the formulae, were increased by the hub radius.

The conditions simulated included

1) Car speeds of 30 mph and 60 mph.

2) Spacing of 4 MH and 8 MH. (Choice of spacing was obtained by personal communication with Dr. Merle Keck.)

3) One side lighting and two side staggered lighting.

4) Number of lights of 26, 10, 2, and 1.

5) A dynamic condition and a static condition.

Details of the experimental condition and the various levels of source luminances are given in Appendix. At each luminance level, the subject was asked to judge the lighting glare condition on the following scale.

1. Pleasant.
2. Borderline between pleasant and comfortable.
3. Comfortable.
4. Borderline between comfort and discomfort.
5. Uncomfortable but still tolerable.
6. Borderline between tolerable and intolerable.
7. Intolerable.

At the end of the experiment, the subject was asked the following questions.

1) Which of the experimental conditions was most preferable?

2) Which of the conditions was most annoying?

3) Did the simulation give the same sensation as experienced in night time driving?

Subjects' responses to these questions are summarized in Table 6. Eighty-five per cent of the subjects rated the simulation as very good, 7.5 per cent as fairly good and 7.5 per cent as bad.

Further improvements/developments planned for the Fry Simulator are

1) Observer's position being made more realistic by providing a car seat, steering wheel, etc.

2) Simulation of varying light intensities of actual roadway lights as a function of viewing angle. (This will throw more light on whether peak or average intensity determines glare sensitivity).

3) Automation of data collection.

4) Introducing non-uniform background luminances representative of roadways.

5) Field validation of newer roadway light types.

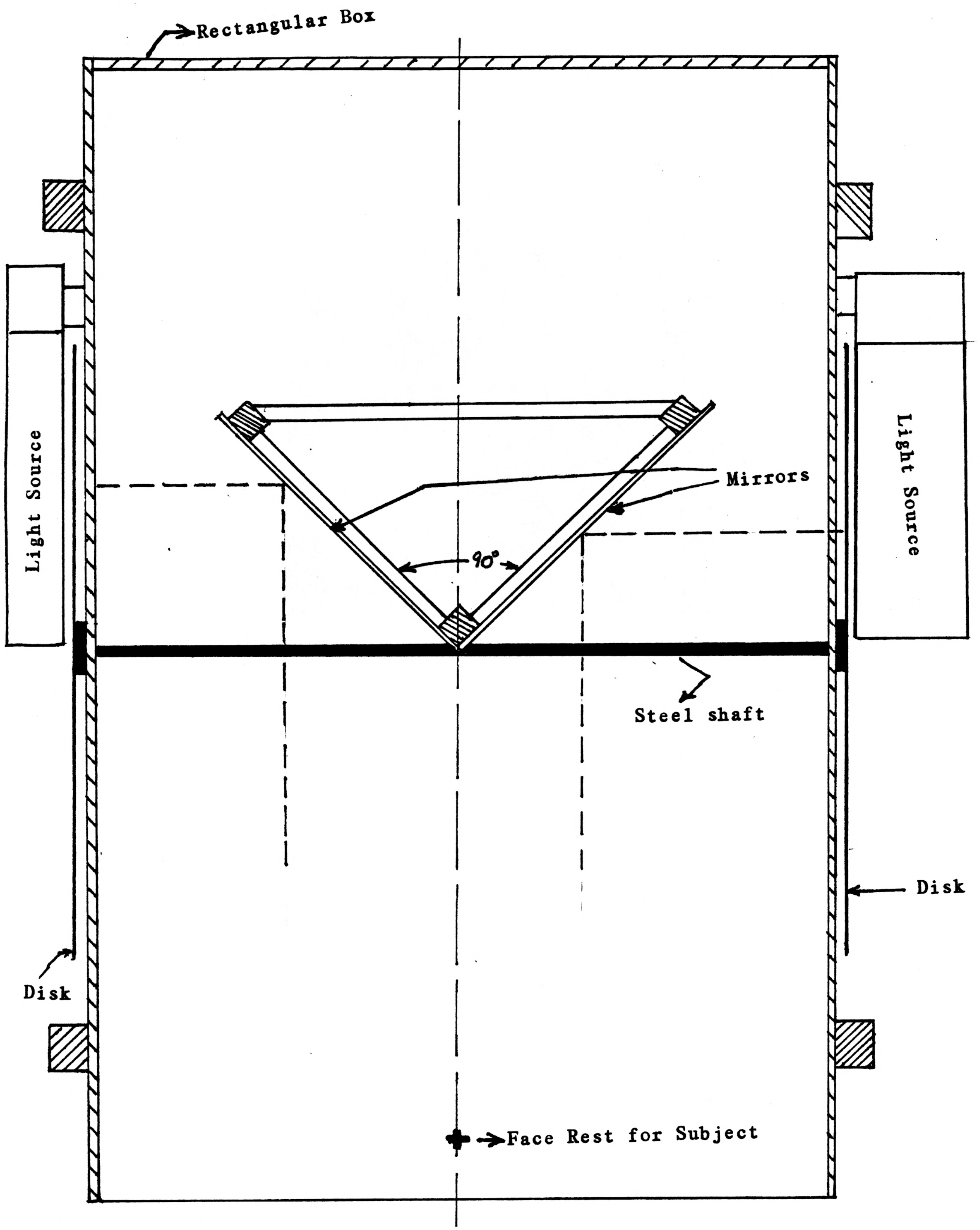


Figure 14. Line Diagram for the Fry Simulator Set-Up Used in the Current Study.

Figure 15. Fry's Dynamic Disk.

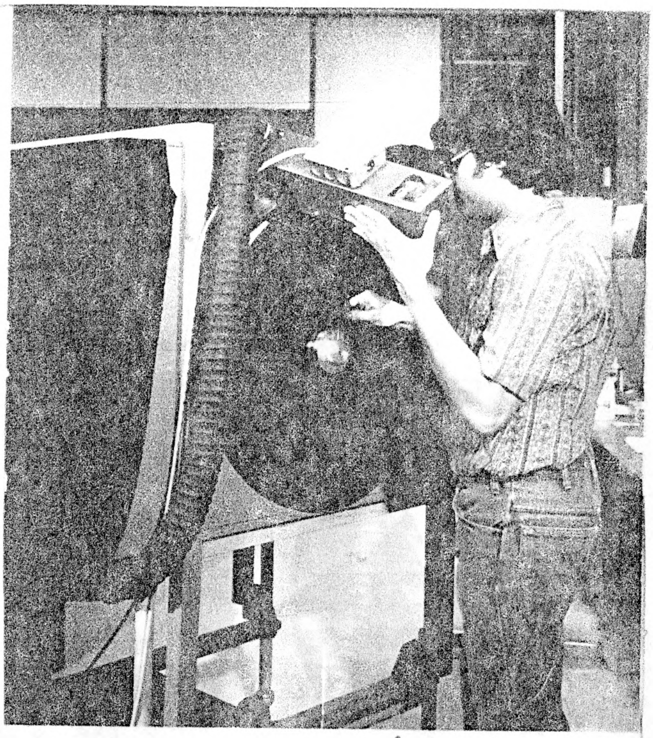


Figure 16. Disk Mounting.

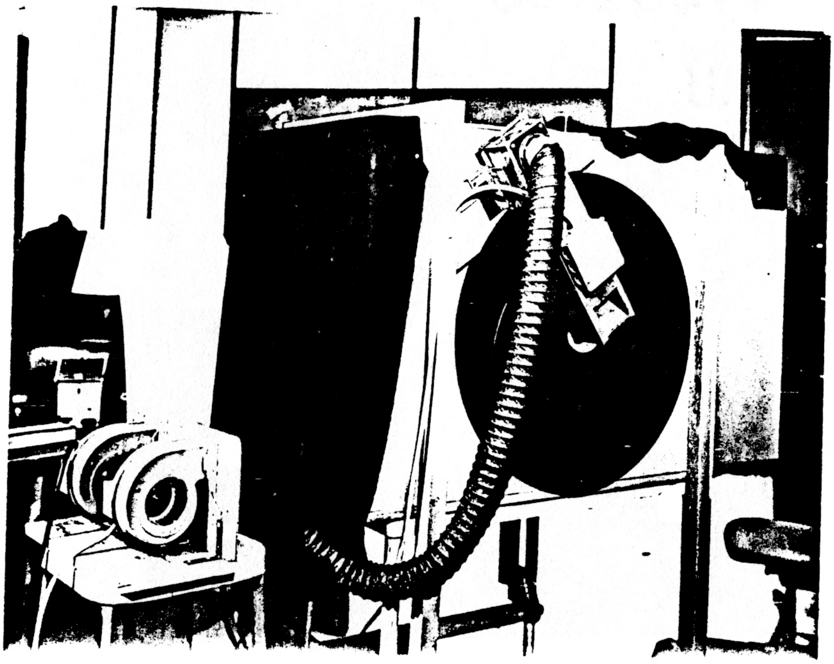


Figure 17. Lighting Fixture and Cooling Arrangement.

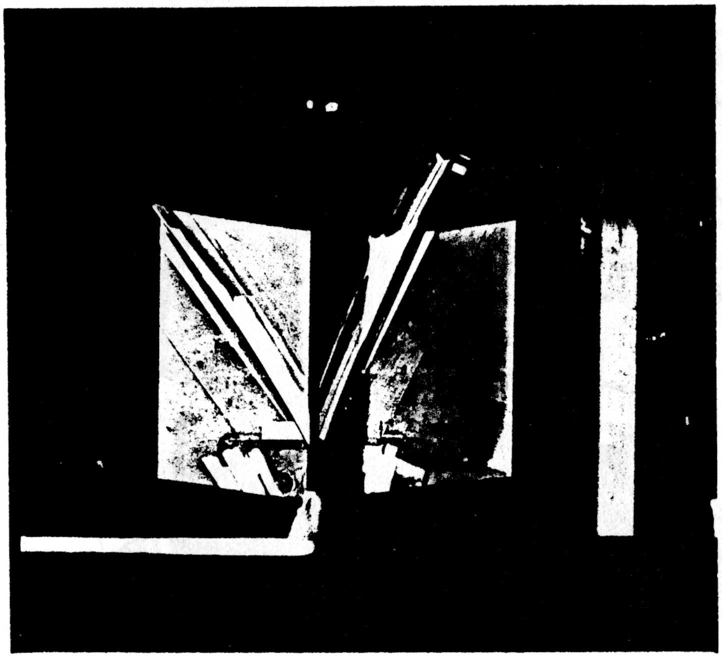


Figure 18. Masking Arrangement for Varying the Number of Lights.

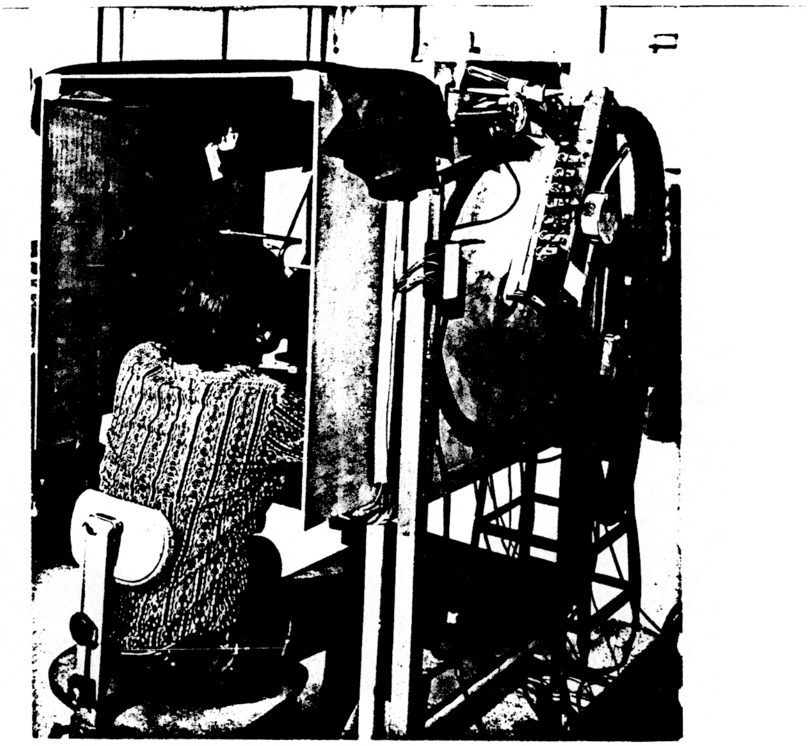


Figure 19. Observer´s Position.

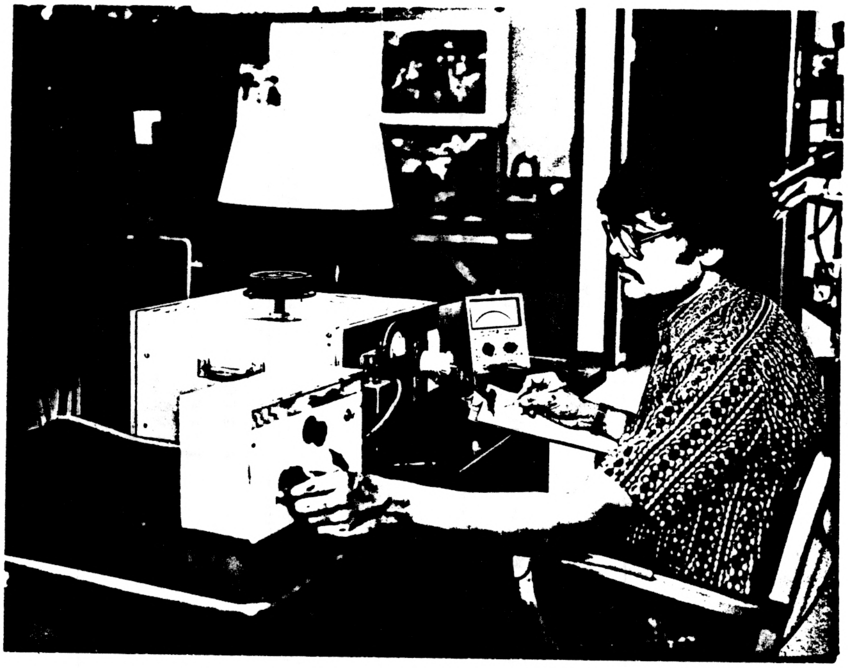


Figure 20. Control Panel.

TABLE 6. Preference and Annoyance Reporting by Subjects.

	SPACING			SPEED		CONFIGURATION		NUMBER OF LIGHTS			
	Static	4MH	8MH	60 mph	30 mph	One side	Two side (stag- erred)	26	10	2	1
# Pre- ferred	2/60	40/60	19/60	5/61	55/61	14/67	54/67	13/39	29/60	12/60	8/60
% Pre- ferred	3	66	33	10	90	19	81	33	48	20	13
# Annoyed	1/55	0/55	3/55	36/55	3/55	4/55	0/55	6/39	0/55	6/55	8/55
% Annoyed	2	0	5	65	5	7	0	11	0	11	15

CONCLUSION

The development of the Fry Simulator has created further fidelity in the research program on discomfort glare from roadway lighting. From the simulation viewpoint, this is a major step from static viewing to a dynamic driving situation.

The uniqueness of the Fry Simulator is its simplicity of approach and flexibility in application. Different sets of roadway lighting conditions can be studied by changing the disks alone. Scope exists for the dynamic validation of the research done with static viewing. Further development possibilities for the Fry Simulator will go a long way in including discomfort glare as one of the design parameters in road lighting design.

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APPENDIX

Details of Summer, 1982 study using Fry Simulator

Source luminances:
100 cd/m^2
200 cd/m^2
500 cd/m^2
1000 cd/m^2
2000 cd/m^2
5000 cd/m^2
10000 cd/m^2
20000 cd/m^2
25000 cd/m^2

Background luminance : 1 cd/m^2

Viewing distance : 28 inches

Mounting height (MH) : 33 feet

Eye level (EL) : 4 feet

Overhang : 0.2 (MH)

Lateral displacement of lights

Right : 13 feet

Left : 24 feet

Experimental condition	Disk RPM
4 MH spacing, 30 mph,	22
4 MH spacing, 60 mph,	44
8 MH spacing, 30 mph,	11

FRY'S DYNAMIC DISK ROADWAY LIGHTING SIMULATOR

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AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

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Department of Industrial Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1982

Discomfort glare in roadway lighting serves the protective function of preventing disability glare, which results in reduction of visual performance. Research efforts are on for including discomfort glare as a design parameter in roadway lighting. The majority of the research in this area is based on simulation employing static viewing conditions. A simple and flexible dynamic glare simulator, which will henceforth be termed as "Fry Simulator", is analyzed and described mathematically in this report. This report will serve as a document enabling a given set of road lighting condition to be translated into the Fry simulator parameters. Research work carried out using such a simulator is also reported. Future possibilities and applications for this simulator are indicated.

This report also outlines the prevalent road lighting practices and the state-of-the-art in discomfort glare research and discomfort glare simulators.