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EVALUATION OF HIGH-MAST INTERCHANGE AREA LIGHTING AT TWO SOUTH DAKOTA LOCATIONS

a report from the Texas A&M RESEARCH FOUNDATION

College Station, Texas

TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY
COLLEGE STATION, TEXAS

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FINAL REPORT

EVALUATION OF HIGH-MAST INTERCHANGE AREA LIGHTING AT TWO SOUTH DAKOTA LOCATIONS

By

Ned E. Walton

and

Neilon J. Rowan

Sponsored by

The South Dakota Department of Highways

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It is not possible to thank each individual who has contributed to this research; the writers therefore acknowledge all of the help given.

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The research staff has attempted to be responsive to the objectives of the research and particularly to the need for improving out night driving environments. The staff accepts all responsibility for shortcomings in this regard but share credit for that which is worthwhile with all those who have contributed.

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INTRODUCTION

The Need for New Lighting Concepts

Early in the history of freeway lighting, illumination designers adopted the continuous or strip lighting principles of city street lighting because of the similarities in the function and design of the facilities. This "carry over" has been used indiscriminately on major highway-freeway facilities, in the interchanges as well as on the major roadway. Although similarities exist, the design and function of the freeway, especially the interchange, is sufficiently different and consideration should be given to the possible adverse effects of transposed lighting designs.

Continuous lighting systems only illuminate the roadway and the immediately adjacent areas. This is normally sufficient for traffic operation on the main lanes of the freeway because driver visual cues are generally limited to this area. Major maneuver decisions are few or non-existent and the lighting system outlines the geometric features of the roadway. However, care must be taken in the design of the system so that undue driver fatigue is not induced and that maximum utilization of the lighting system is obtained from the standpoint of visibility. The two main criteria are uniformity of illumination and reduced glare. Both can be achieved by mounting the light sources at sufficient heights above the pavement to reduce glare and at optimum longitudinal spacings to provide uniform light coverage.

Acceptable designs developed in applied research utilize the 400-watt and 1000-watt mercury vapor light sources in Type III medium distribution semi-cutoff luminaires. The 400-watt units mounted at heights of 40 feet and spaced approximately 200 feet apart can be used to illuminate roadways of two traffic lanes; for three or more lanes 1000-watt units mounted at 50 feet and spaced 275 to 325 feet can be used. The 1000-watt units provide the most desirable system although the 400-watt units are considered acceptable by current standards.

These designs do not always provide the desired environment for interchange areas. There are many decisions that the driver must make in negotiating an interchange and these decisions quite often require the driver to be able to judge other roadway elements, particularly their relation to the roadway on which he is operating. Generally, this is not possible with continuous lighting because only the roadway or an inclusive tunnel is lighted leaving dark areas between roadways that prohibit immediate association. Thus it is desirable that the driver be able to see the entire interchange area similar to the view provided during daylight hours. This permits the driver to plan his maneuvers in advance and execute them in a systematic and orderly fashion.

In many interchanges there are appreciable differences in elevation of the various roadways, especially in the three and four level interchanges. Difficulties frequently arise in using continuous lighting in these interchanges because luminaires placed properly to illuminate one roadway quiet often result in extreme glare and discomfort to drivers on other roadways. For example, luminaires placed on the lower level of a three level interchange may be directly in the line of vision of a driver on the top level.

In continuous lighting systems it is necessary that luminaire supports be placed in reasonable proximity with the roadway. This constitutes a hazard of magnitude related to the lateral placement of supports with respect to the roadway, and the longitudinal spacing of the supports. The probability of a vehicle striking a luminaire support appears to be higher in interchange areas because of the greater number of decisions to be made and thus the greater chance for error. Although the problem can be alleviated greatly with the use of break away supports, there is always economic loss even in minor accidents. Therefore, one major consideration in the selection of illumination systems should be the consequental hazard introduced by the physical nature of the system.

One solution to the many problems outlined in lighting interchanges seems to be high-mast area lighting.

History of High-Mast Lighting

In the early days of public lighting (about 1875) with electric arc lamps, people had already begun to think of lights on very tall masts, but for technical and economic reasons the idea was not successful at that time.(1)* However, in the late 1890's the city of Austin, Texas obtained numerous 150' lighting masts to provide nightly "moonlight" in areas such as parks.(2) So successful were these towers that rigid maintenance has preserved several of them and they are still in operation today providing low levels of illumination over large areas.

In the late 1950's the Europeans carried the area lighting

*Numbers in parentheses refer to references in Bibliography.

concept to highway application. (1) The first installation was that at the Heerdter Triangle near Dusseldorf. Steel towers 25 to 35 meters apart were equipped with 24 lights, each with a sodium lamp of 200 watts rated at 23,000 lumens. The overall impression presented by the interchange at night is rather like that presented on a cloudy day, even though the illumination level is much lower for reasons of economy.

Interest in the European lighting application moved the Texas Highway Department to request that similar concepts of lighting be investigated. These investigations on high-mast lighting were begun in early 1964.

The Concept of High-Mast Lighting

The complexity of modern interchanges and the presence of roads of greatly varying character entering at different levels require more than conventional lighting can afford. The primary requirements for a satisfactory driving environment are: (1) good seeing conditions to guide motorists through the interchange area; (2) adequate illumination and brightness on the roads enabling motorists to see each other clearly and well in time, especially at points of conflict; and (3) a feeling of security on the part of the motorists. These requirements are normally met during daylight hours, but present many problems for night driving operation.

The goal of high-mast lighting is the duplication, as closely as is technically and economically feasible, of the view provided by daylight. During periods of daylight, a panoramic view, that is, an unobstructed or complete view of the area in every direction, is provided the motorist. The visual cues that the motorist depends on while driving during hours of daylight are a combination or horizontal and vertical relief features; i.e., roadway, curbs, median, merging vehicles, signs, etc. Therefore, the high-mast concept is an attempt to provide adequate illumination to light these features. This requires a blend of horizontal and vertical components of light at intensities great enough to bring out these features with as much uniformity as possible.

The high-mast concept then consists of mounting light sources at sufficient heights and adjusted to produce light in both the horizontal and vertical planes to bring out the features of the area. Careful consideration must be given in producing the horizontal component of light to assure that extreme glare will not result.

OBJECTIVES OF RESEARCH

OBJECTIVES OF RESEARCH

At the completion of the preliminary investigations of high-mast area lighting conducted by the Texas Transportation Institute and Texas Highway Department, several highway departments initiated experimental installations. Included are two installations in South Dakota; one in Rapid City and one in Sioux Falls. These two installations are the subject of the research contained in this report.

The objectives of this research are to investigate and report the characteristics of traffic operations, photometrics, and visibility relating to high-mast interchange area lighting at the installations in Rapid City and Sioux Falls. These objectives have the purpose of evaluating the functional efficiency of the high-mast installations and to assist in the development of performance criteria for future installations.

The installation in Rapid City is at a directional "T" in very rugged topography (Figure 1). The interchange covers an area of approximately 100 acres in an isolated area. Prior to the installation, the interchange was in complete darkness and it was extremely difficult to follow and plan maneuvers in advance.

Five arealight assemblies were used in the design for this interchange. One tower has a height of 120 feet while the remaining towers are at heights of 100 feet. The 120-foot height is necessary because of the rugged topography of the interchange. The design is illustrated in Figure 2. The design criteria were:

Initial Average Intensity of Individual Roadways

Horizontal Footcandles	Vertical Footcandles
.25	.25

Initial Average to Minimum Ratio on Individual Roadways

Horizontal	Vertical
3.0 to 1	3.0 to 1

The installation in Sioux Falls is at a large typical cloverleaf applied to very flat topography (Figure 3). The interchange covers an area of approximately 150 acres and all quadrants of the cloverleaf are basically identical. There is no development or extraneous light in the immediate area. Eight arealight assemblies were used in the design of lighting for this interchange. Four of the assemblies are located on each main leg of the interchange and the other four are located within the loops of the cloverleaf. This design is illustrated in Figure 4. The design criteria were the same as in Rapid City.

FIGURE 1
RAPID CITY LOCATION

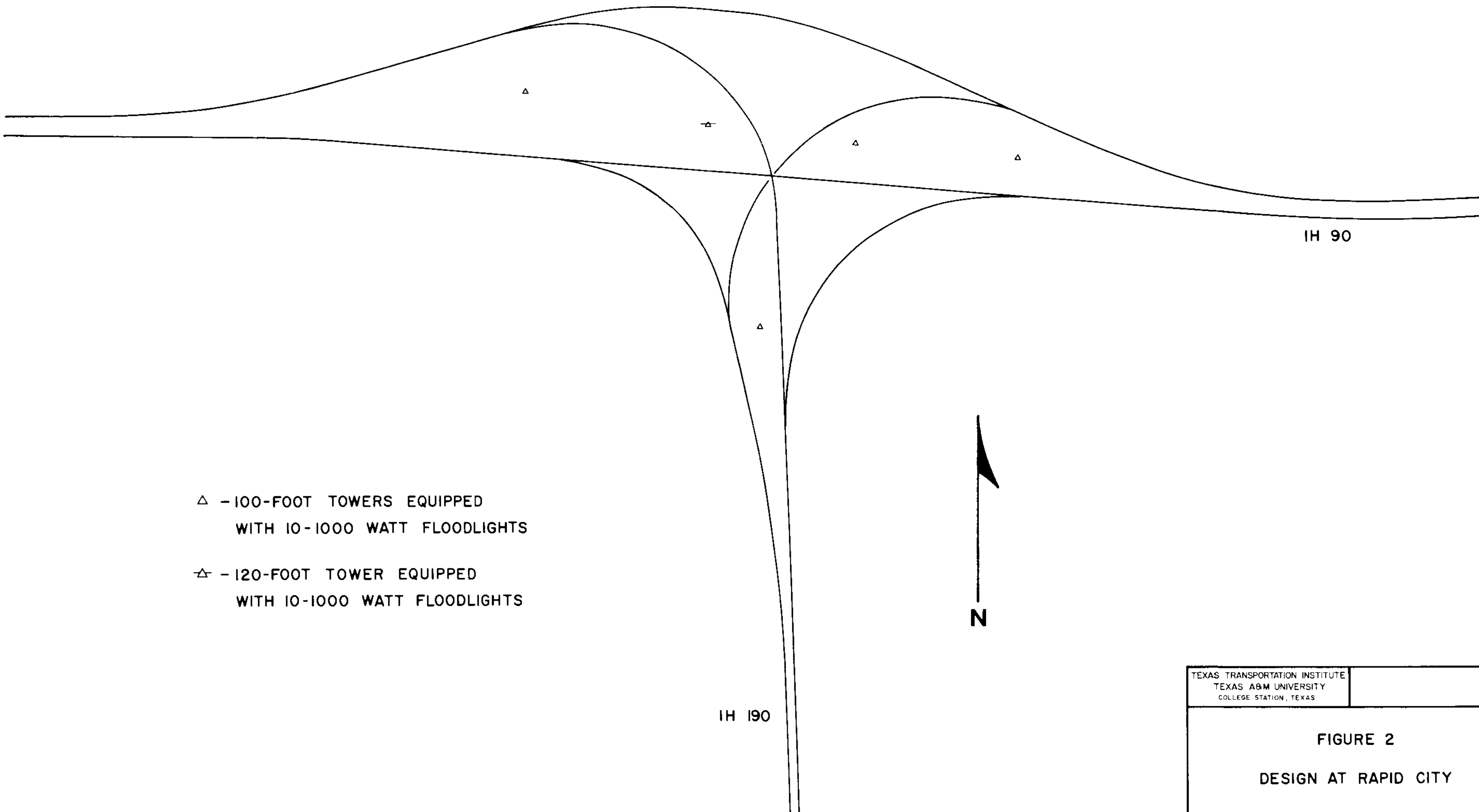

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FIGURE 2

DESIGN AT RAPID CITY

FIGURE 3
SIOUX FALLS LOCATION

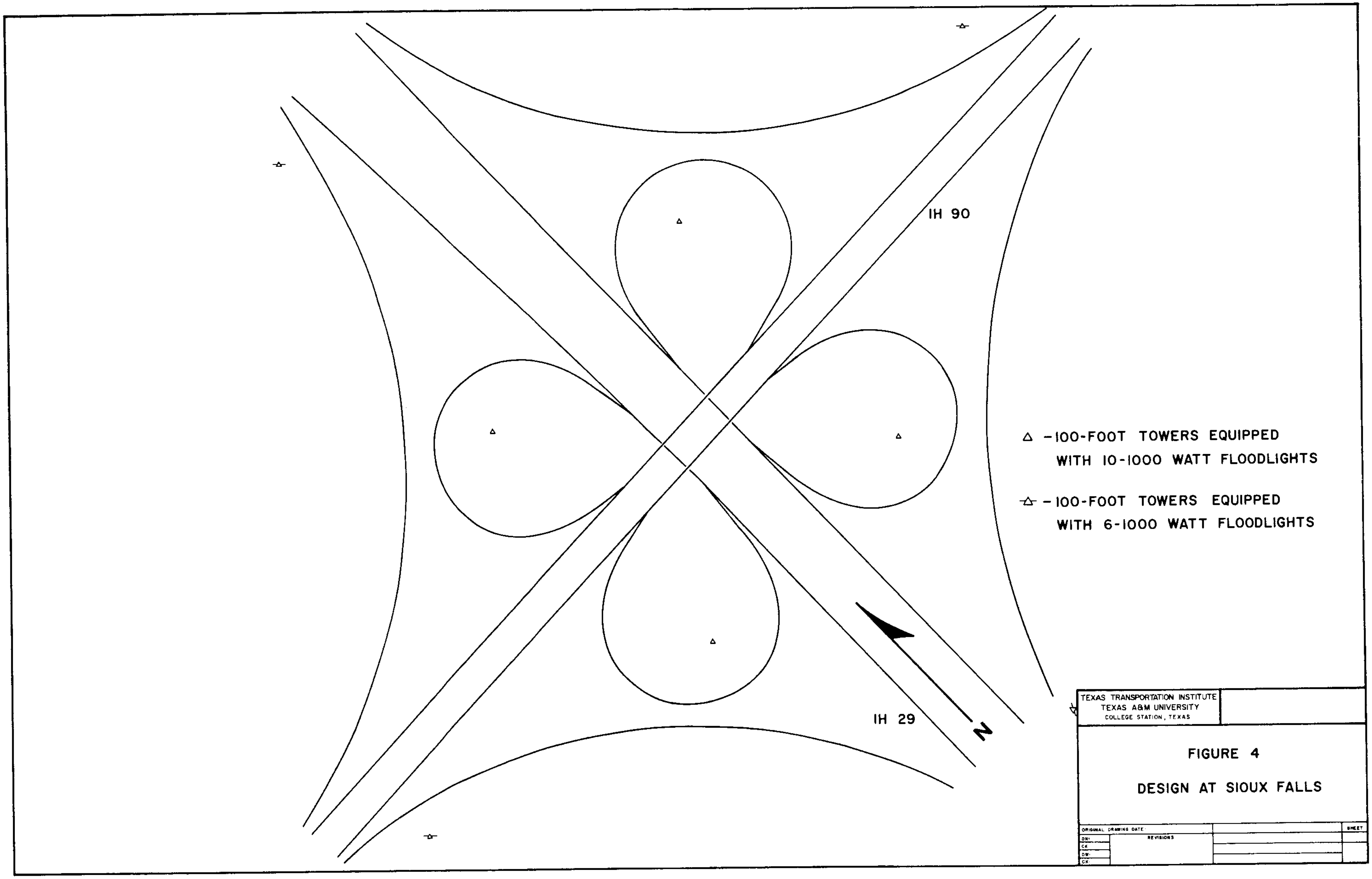

FIGURE 4

DESIGN AT SIOUX FALLS

THE STUDY

THE STUDY

All investigations of this study were conducted at the two interchange locations in South Dakota through cooperation with the South Dakota Department of Highways. The department contributed to the research by furnishing technical personnel and a principal investigator to assist in the planning and conduct of the field investigations.

From past experience it was apparent that the evaluation of night driving environments could not be handled using only the conventional research procedures. Therefore, the methodology utilized in the research involved engineering and professional judgement in conjunction with conventional research procedures which were applicable in arriving at realistic and useful evaluations.

Diagnostic Studies

Diagnostic studies were conducted at both installations in an effort to subjectively evaluate the environments produced by the high-mast lighting. Previous studies using this technique have produced excellent results which otherwise could not have been obtained due to the complexity of the problem and all of the interrelated variables.

This approach to research utilizes practicing professionals as team members and provides an excellent avenue for the implementation of the results. Such a team approach has proven effective in the past because the professional man has the unique ability to use the transportation system as a driver and then evaluate it as a professional.

This appears to be the most positive means of identifying relationships of the human element--driver performance, comfort, and convenience--with the visual environment.

To explain this research procedure further, the diagnostic team is composed of experts from the disciplines related to the problem. Under the supervision of research personnel, this team is required to perform driving tasks in selected study situations. Also, they have an opportunity to observe their fellow team members performing these same or similar tasks.

An on the spot informal interview is conducted by a research staff member. The team member performing the driving task is asked to comment freely on any reactions, observations, or other information pertinent to the driving task as related to the subject of study. This interview fills in the minute details that are often forgotten in completing a questionnaire.

After the team members have completed the assigned driving task, they are asked to complete a questionnaire form pertaining to their experiences in the driving task. In this research the questionnaire was designed in three parts. Part A pertained to the evaluation of the study areas as they existed with the high-mast illumination systems off. Part B pertained to an evaluation of the study area with the high-mast lighting in use. Part C of the questionnaire was designed to evaluate the specific designs of the installation and to present ideas for future installations. These questionnaires are included in Appendix A of this report.

Traffic Operation and Driver Behavior Studies

An instrumented test vehicle was used to conduct studies of traffic operations and driver behavior at the two installations for the "before and after" conditions. The vehicle was equipped with a recording speedometer to give a continuous recording of the test vehicle speed and distances within the interchange. The vehicle was also equipped with a dermograph to measure and record driver responses over the test route.* In addition, the vehicle was equipped with photometric instruments to measure and record pavement brightness and glare intensities which are discussed in the following section.

Five persons were selected to drive the instrumented vehicle through the two interchange test areas. These drivers were instrumented with the dermograph to record their responses to the driving task. These studies were conducted during the day and night, with and without the lighting system in operation. During these test runs over the selected study site, both dermograph and speed data were recorded. Figures 5 and 6 show the selected study route for the Sioux Falls and Rapid City installations.

Photometric Studies

The research staff of Texas Transportation Institute, with assistance from the South Dakota Department of Highways, collected photometric data at the two installations for the "after" condition. This consisted of measuring light intensity in terms of horizontal footcandles in a grid pattern superimposed on the interchange areas.

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* Appendix B of this report contains a discourse on the various measures of driver responses.

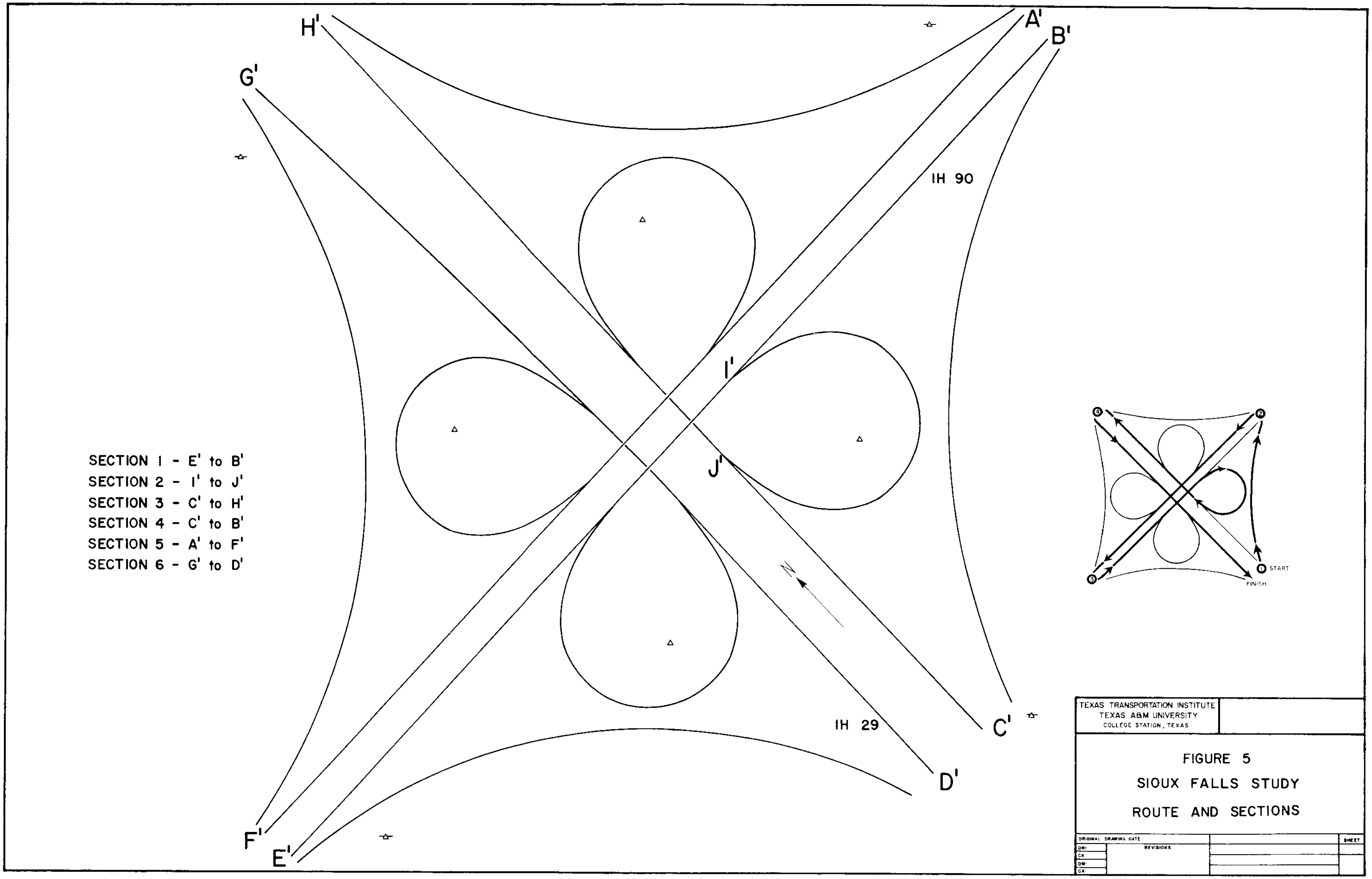

FIGURE 5
SIOUX FALLS STUDY
ROUTE AND SECTIONS

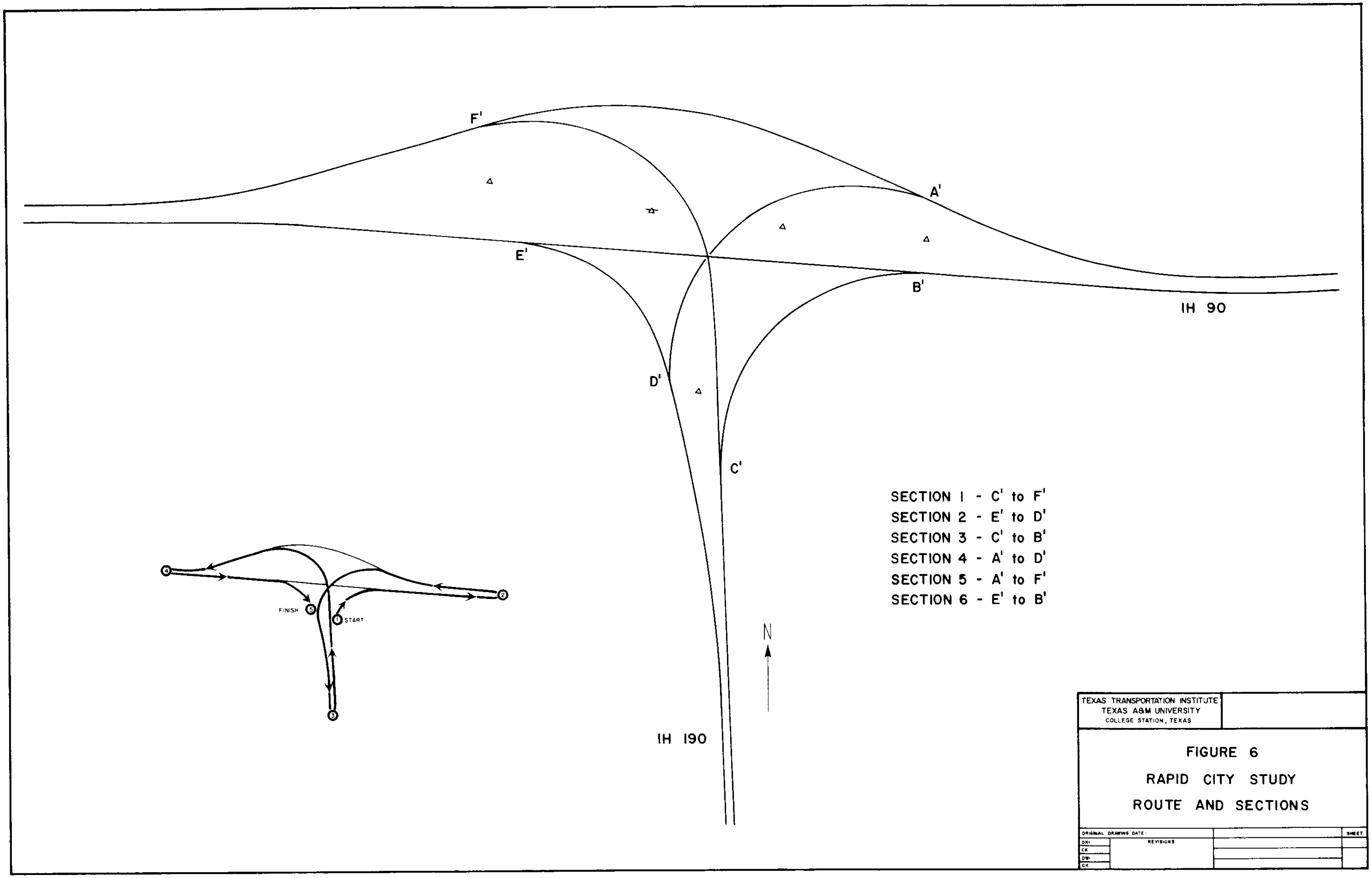

FIGURE 6
RAPID CITY STUDY
ROUTE AND SECTIONS

In addition, both horizontal and vertical footcandles were recorded on all pavements within the interchange areas at 100 foot increments. The instrumented vehicle, which was equipped with a Pritchard Spectra Photometer, was used to record continuously pavement brightness and glare within the two interchange areas.

DISCUSSION OF STUDY

DIAGNOSTIC STUDIES

Sioux Falls

The diagnostic questionnaires have been summarized to indicate team feelings with regard to the interchange study situation. The following sections describe the questions asked in the study and response from the participants.

1. Did you feel that roadway markings were adequate under the conditions tonight?

With lighting system off. Seventeen (17) participants indicated yes; sixteen (16) participants indicated no. Qualifying comments were: gore striping was not adequate, not visible; bead application would be beneficial; emphasis should be given to gore stripe and delineation where gore sign is lacking; I-90 bridge delineation is inadequate; lighting of overhead signs would be beneficial; ramp markings were not definitive; condensation reduced reflective qualities of signs; markings better on high beam than on low beam.

With lighting system on. Twenty (20) participants indicated yes, thirteen (13) participants indicated no. Qualifying comments were: they were better, but better markings still needed; traveling west to east, approaching crest of hill, tower lights distracted from the roadway; overhead signs still need illumination; condensation still a problem on signs.

2. Which of the answers below best describe your evaluation of the visibility of geometric features of the roadway such as curves, structures, etc.?

With lighting system off. Sixteen (16) participants replied that visibility is below minimum acceptable level for this type facility; twelve (12) participants indicated minimum visibility requirements of normally alert drivers satisfied; five (5) members replied that visibility is adequate for most drivers. Comments were: visibility not adequate for prevailing speeds; location of exits indefinite beyond 150 feet; right hand delineation confuses gore locations.

With lighting system on. Five (5) participants replied that minimum visibility requirements of normally alert drivers satisfied; ten (10) members indicated visibility is adequate for most drivers; eighteen (18) members said visibility was totally adequate for them. Comments were: geometrics show up well; visibility is totally adequate except when first entering the interchange when glare is noticable; visibility of gores and ramps very good; glare is significant coming over hill from the west; outer ramps could use more light.

3. Which of the following best describe the visibility of roadside signs?

With lighting system off. Nine (9) participants replied visibility always adequate; nineteen (19) replied visibility usually adequate with high beams; five (5) replied visibility never adequate. Qualifying comments included: poor sign reflectance; use of lighting would be helpful; visibility affected by condensation; markers have low reflectivity, need replacing; designation sign on west leg too bright.

With lighting system on. Nineteen (19) replied that visibility always adequate; ten (10) replied visibility usually adequate with high beams; four (4) participants replied visibility never adequate. Comments were: high beams necessary to clearly read signs just beyond lights on extremity of interchange.

4. *Which of the following best describes the visibility of overhead signs with external lighting?* (Since there were no signs with external lighting, most participants did not answer this question. However, some indicated that external lighting was required under both conditions for adequate visibility.)

5. *Which of the following best describes your evaluation of seeing a major obstacle (such as a stalled unlighted vehicle) in the roadway in time to allow drivers to come to a safe stop?*

With lighting system off. Twelve (12) replied that visibility would never be adequate; fifteen (15) indicated that visibility would sometimes be adequate; six (6) indicated that visibility would usually be adequate. Comments were: would depend on approach speed, but nighttime speed limit is unsafe; non-reflective obstacles would not be seen.

With lighting system on. One (1) participant replied that visibility would sometimes be adequate; twenty (20) participants indicated that visibility would usually be adequate; twelve (12) members replied that visibility would always be adequate. These answers were qualified by: for a normally alert driver, visibility would always be adequate; some areas seem to be darker than other; lighting may need more adjustment; visibility always adequate except in glare areas on entering system and one dark spot; inclement weather may pose restrictions on visibility.

6. *Do you feel the existing roadway delineation systems are effective under tonights' conditions?*

With lighting system off. Nineteen (19) replied yes; fourteen (14) replied no. Comments were: gore areas need improvement; more delineation needed on bridges; delineators lead to confusion on loops and exit ramps; edge striping needed; round buttons better than wood posts; need more markers.

With lighting system on. Thirty (30) participants replied yes; six (6) replied no. In comparing with the previous study with lighting system off, twenty (20) participants indicated they were better with lighting system on, six (6) indicated they were worse, and ten (10) indicated there was negligible change. Qualifying comments were: you don't rely on them as much; their effect is diminished because of lighting; they seem to be less pronounced but still effective; lighting improved locations where delineation would normally be needed.

7. *In the interchange area, how accurate are you able to judge speeds and distances of other vehicles?*

With lighting system off. One (1) replied as well as in daylight for all distances, seven (7) replied as well as in daylight for short distances only, twenty (20) replied not as well as in daylight at any distance, and six (6) replied that speed and distance judgement of other vehicles is severely restricted at night with no illumination. Comments were: no geometric association; headlight glare a problem in curves.

With lighting system on. Three (3) replied as well as in daylight for all distances, one (1) replied as well as in daylight for short distances only, ten (10) replied not as well as in daylight at any distance, and twenty-one (21) replied as well as in daylight for most distances. None replied that judgement is restricted. Comments were: headlight glare is not as distracting; no real challenge in seeing; noticeable improvement in this area.

8. *In driving through the interchange, were you able to detect all the information you desired about the roadway, shoulder, and elsewhere in the right-of-way?*

With lighting system off. Thirteen (13) replied in most instances this was possible, seventeen (17) indicated some of the time, and three (3) indicated never. Comments were: hard to determine location of gores where overhead standards are outside the headlights; lights on car ineffective going around loops; sharp loops leave the inside shoulder dark.

With lighting system on. Thirty-one (31) indicated in most instances this was possible, three (3) indicated some of the time and none (0) indicated never. Comments were: some difficulty in locating gore areas; shape and size of everything within right-of-way is visible; more lighting needed in gore area of outside ramps; very good visibility of off pavement areas and gore area; improvements most noticeable in exit ramps or points which were hard to define without the lighting.

9. *Was headlight glare from opposing traffic a problem to you?*

With lighting system off. Thirteen (13) replied yes, twenty (20) replied no. Comments were: medians were wide enough to cut down normal glare; glare was very significant; too many drivers are driving with the high beams on in an interchange area; glare made signs difficult to read.

With lighting system on. Seven (7) replied yes, twenty-five (25) replied no. Comments were: even less of a problem than before.

10. Were gore areas a problem to you in locating?

With lighting system off. Twenty-four (24) replied yes, twelve (12) replied no. Comments were: where overhead signs were in place with no gore sign; hard to locate; some problem for locating beginning of inside loops; could not locate at comfortable distance; difficult; gore painted lines not reflectorized; too much right-hand delineation; poor delineation and pavement markings; very difficult to find; bad markings and geometry.

With lighting system on. Nine (9) replied yes, twenty-four (24) replied no. Comments were: a few dark spots but not objectionable; greatly improved over no illumination; easier in loop areas than outer ramps; still a problem; better gore delineation and reflectorized marking would help; not enough light in gore.

11. Did you feel secure in driving through the interchange area?

With lighting system off. Twenty-two (22) replied yes, nine (9) replied no. Comments were: no problems because of light traffic; only at moderate speeds and straight through runs; higher speeds and exit maneuvers led to insecurity; yes, but a driver tends to slow down to feel secure.

With lighting system on. Thirty-one (31) replied yes, one (1) replied no. Comments were: a stranger would no doubt find it much better; much more secure at higher speeds; except in glare areas.

The following question and comments apply to the interchange with the lighting system off only.

1. How would you describe the conditions that existed tonight with no illumination? Consider signs, marking, delineation, geometry, etc.

Some improvements could be made in gore striping and delineation in the same areas. Signing I would consider adequate. I do believe that lighting overhead signs would be beneficial. Conditions not adequate for speed limit. Need additional delineation of bridges and tangents. Need edge striping. Signing was not visible a great enough distance; off ramps were hard to locate. Right-hand delineation should be removed. Pavement markings should be reflectorized. Rather inadequate for the stranger in the area. I believe that some advance indication of interchange type (cloverleaf, directioned, etc.) would be helpful to a stranger at night. Can be described as "follow your nose." Could not find exits. I did not feel safe. Needs a general upgrading of signs, markings on delineation. Geometrics at gore areas were confusing. Delineation at gores confusing. Nerve wracking for a stranger. Signing not adequate for 65-70 mph. Headlight glare from opposing traffic caused difficulty.

The following questions and comments apply only to the interchange with the lighting system on.

1. Was glare from the towers a problem to you? Twenty (20) indicated yes, twelve (12) replied no. Of those replying yes, the majority said this was occuring at a distance of 1500 feet away or more. Comments were: glare a problem for only an instant, give impression of approaching car with headlights on high beam.

2. *Of the following factors generally conceded to be important in illumination systems, how would you rate their importance? (No. 1 is most important).*

	No. replies for each rating				
	1st	2nd	3rd	4th	5th
Level of illumination	2	4	11	11	4
Uniformity of illumination	20	5	4	3	
Area of coverage	5	8	7	2	8
Glare characteristics	5	10	7	6	4
Pavement brightness	3	3	2	10	15

This would give an overall rating of:

1st - Uniformity of illumination

2nd - Tie between glare and area of coverage

3rd - Level of illumination

4th - Pavement brightness

3. *Do you feel there is any advantage to illuminating areas other than roadway surfaces in interchange areas?* Thirty (30) replied yes, three (3) replied no. Comments were: the illumination of the entire interchange area removes some of the unknowns, such as slopes, hazards off the roadway, obstructions, etc.; lighting of entire area outlines geometrics and eases driving; lighting entire area enables one to observe configuration and greatly improves driving ease and safety; it helps somewhat to get an overall picture of the interchange; gives the driver a somewhat closer approximation of daylight driving; reduces headlight glare, reduces driver indecision; geometrics of interchange are beneficial in direction through area. Areas off the roadway add to the overall picture and make driving a more relaxed experience; reduces uncertainty.

4. Do you feel the high-mast lighting closely duplicates daytime visibility as regarding driving tasks? Seventeen (17) participants replied yes, fourteen (14) replied no. Comments were: It seems better than conventional lighting but there is still room for improvement; not closely but better than what we have been using; yes and no, yes for larger objects, no for smaller objects; increases general visibility; it worsens non-lighted advance signs.

5. Is there any transitional problem when entering the interchange lighting area? Twelve (12) replied yes, twenty-one (21) replied no. Comments were: there is some problem but generally not objectionable; on entering there is a tendency toward insecurity and speed adjustment; transition better than with conventional lighting; at sudden changes in grade line on approaches, high intensity is without transition.

6. Is there any transitional problem when leaving the area? Three (3) replied yes, thirty-one (31) replied no. Comments were: could extend further on acceleration lane; better than conventional lighting; the level is low enough to prevent night blindness when leaving area; light from behind gradually looses intensity, retaining necessary visibility of object outline.

7. How would you best describe the conditions that existed tonight with the lighting system on? Consider signing, marking, delineation, geometrics, etc. Comments were: The lighting provides a more relaxed driving atmosphere; driving conditions are very satisfactory with all features well defined; although light intensity is on low side, I would consider it entirely adequate for rural conditions; reflectorized signs appear to lose some of their effectiveness with the lighting; the glare is a problem on the west approach; within the interchange the lights are distracting but this is due to the novelty of them; illumination is excellent except for the overhead signs; signs are difficult to read with lights as background; glare was slightly uncomfortable; lighting should be mandatory on overhead signs.

The final part of the diagnostic questionnaire was designed to obtain information from the participants regarding the design of the lighting. Eighteen (18) participants, all professionals, completed this part. The following questions and comments summarize the groups input to the questionnaire.

1. If you had the opportunity to redesign this system, using eight light towers and 6-10 lights per tower, what changes would you make? The comments were: the far extreme light on the off ramp towers is obviously out of position which could be a construction error. Ramp tower should probably be further in advance of gore area. Increase intensity, direct bright spots to diverging and converging areas. On outer ramps more light should be directed to the roadway. Also, more should be directed to opposite ramp. Move the towers on the approach further away from interchange and begin illumination at one preceding gore at ramp. Use 150' towers on the approaches. Keep angle of lights to a maximum of 45° and use 150' towers.

2. Assuming the lights can be re-aimed, what changes would you make? Comments were: Put more light on outer ramps. Increase brightness on merge areas. Spread illumination on approach legs.

3. Assuming you had unlimited towers to use, where would you place them? Comments were: add four towers, one each in advance of outer loops. Add four in remaining ramp quadrants. I would not add more towers but would shift tower locations on approaches. I would increase tower height to 150 feet.

4. *Do we need to make changes in signing, marking, and delineation practices when using high-mast lighting?* Ten (10) participants replied yes, eight (8) replied no. Comments were: Overhead signs definitely need to be illuminated under any conditions. Pavement marking practices should be reviewed. Be sure light strikes sign face and not back. It was not adequate to start with.

5. *The eight towers support sixty-four (64) 1000-watt lights. If you had 64 standard luminaires to use, do you think that you could achieve a lighting design as good or superior to this design?* One (1) participant said yes, seventeen (17) said no. Comments were: I doubt that glare could be controlled as well as it is in this project. Ramps would have bad uniformity. I could produce a higher level of intensity but it would not improve the lighting.

Rapid City

The questionnaires from the Rapid City diagnostic study have been summarized similarly to those at Sioux Falls. The following questions and comments, in general, highlight the team inputs to the study.

1. *Did you feel that roadway markings were adequate under the conditions tonight?*

With lighting system off. Thirteen (13) participants replied yes, one (1) replied no. Comments were: adequate except from entrance ramp from West Blvd. going east; not enough markings; good on high beams.

With lighting system on. Twelve (12) participants replied yes, two (2) replied no. Comments were: quality of marking did not seem quite so critical; tower lights distracted from markings when traveling west to east.

2. *Which of the answers below best describe your evaluation of the visibility of geometric features of the roadway such as curves, structures, etc.?*

With lighting system off. Three (3) replied that visibility is below minimum acceptable level for this type facility, seven (7) replied minimum visibility requirements of normally alert drivers satisfied, and four (4) replied visibility is adequate for most drivers. Comments were: you have to rely on the signs; ramps are hard to find; signs do not instill confidence; exit from east bound lane to West Blvd. is below acceptable level; lighting from the service roads creates dark feeling on main lanes; movement from westbound to southbound is not definitely defined.

With lighting system on. Eight (8) participants replied that visibility was totally adequate, two (2) replied visibility was adequate for most drivers, and four (4) replied minimum visibility requirements of normally alert drivers satisfied. None replied that visibility was below minimum acceptable levels. Comments were: visibility is totally adequate except in glare area entering from the west; ramps are not completely visible; lighting tends to relax me.

3. *Which of the following best describes the visibility of roadside signs?*

With lighting system off. Seven (7) replied visibility always adequate, seven (7) replied visibility usually adequate with high beams. There were no replies that visibility never adequate. Comments were: visibility not good on some signs; some markers have lost reflectivity; considerable over flow on Rushmore sign.

With lighting system on. Thirteen (13) replied visibility always adequate and one (1) replied visibility usually adequate with high beams. Comments were: reflection from headlights on high beam was reduced; signs were visible without headlights being reflected.

4. *Which of the following best describes your evaluation of seeing a major obstacle in the roadway in time to allow drivers to come to a safe stop?*

With lighting system off. Four (4) replied visibility would never be adequate, seven (7) replied visibility would sometimes be adequate, and three (3) replied visibility would usually be adequate. Comments were: visibility would be good on straight sections but very poor on turning roadway; pavement seems unusually dull; high beams would have to be on to see stalled vehicle in time.

With lighting system on. Five (5) participants replied that visibility would always be adequate, eight (8) replied visibility would usually be adequate, and one (1) replied that visibility would sometimes be adequate. Comments were: visibility was always adequate except in glare area approaching from west and in one dark spot; shape of object could be determined before entering area of headlights.

5. *Do you feel the existing roadway delineation systems are effective under tonights conditions?*

With lighting system off. Eleven (11) participants replied yes, three (3) replied no. Comments were: must be alert when approaching ramps; new type delineators would help; need more markers; some have lost quality.

With lighting system on. Twelve (12) participants replied yes, two (2) replied no. Six (6) indicated they were better with system on than with system off, four (4) said worse and four (4) said there was a negligible change. Comments were: their effect is diminished and because of lighting less necessary; seem to be less pronounced but still effective.

6. *In the interchange area, how accurate are you able to judge speeds and distances of other vehicles:*

With lighting system off. One (1) replied as well as in daylight for all distances, four (4) indicated as well as in daylight at any distance, and one (1) replied that judgement is severely restricted. Comments were: headlight glare is a problem.

With lighting system on. Three (3) replied as well as in daylight for all distances, eight (8) replied as well as in daylight for most distances, one (1) replied as well as in daylight for short distances and two (2) replied not as well as in daylight at any distance. Comments were: except in glare area from the west.

7. *In driving in the area, were you able to detect all the information you desired about the roadway, the shoulder, and elsewhere in the right-of-way?*

With lighting system off. Eight (8) replied in most instances this was possible, five (5) replied some of the time, and one (1) replied never. Comments were: objects ahead were not visible particularly bridge piers and ramp entrances; the exact turn off location is difficult to see at high speeds; there is a concern for possible hazards approaching from the side of roadway.

With lighting system on. Thirteen (13) replied in most instances this was possible, and one (1) replied some of the time. Comments were: except in glare area.

8. Was headlight glare from opposing traffic a problem to you?

With lighting system off. Seven (7) replied yes and seven (7) replied no. Comments were: lane separation kept glare at a minimum; very much so when meeting bright lights on curves.

With lighting system on. Four (4) replied yes, nine (9) replied no. Comments were: yes, but much less with lights and only in fringe areas; high beam glare is worse than towers.

9. Were gore areas a problem to you in locating?

With lighting system off. Seven (7) participants indicated yes and seven (7) indicated no. Comments were: bad markings and bad geometry; new type delineators would help; at high speeds hard to find; seeing down main line at gore was difficult; it would be very difficult for strangers.

With lighting system on. Two (2) replied yes, twelve (12) replied no. Comments were: it is a problem from east to south and from west to south; a few dark spots but not objectionable, better than in dark.

10. Did you feel secure in driving through the interchange area?

With lighting system off. Twelve (12) indicated yes, two (2) indicated no. Comments were: only at reduced speeds; familiar with interchange.

With lighting system on. Fourteen (14) said yes, none (0) said no. Comments were: I felt as secure with lights at 65 mph as I did without lights at 50 mph; some problem in glare area.

11. While riding as a passenger through the interchange, did other drivers in your vehicle seem to make sudden or sharp maneuvers at decision points?

With lighting system off. Four (4) indicated yes, ten (10) indicated no. Comments were: at left exits.

With lighting system on. One (1) replied yes, thirteen (13) replied no. There were no comments.

The following question and comments apply only to the interchange with the lighting system off.

1. How would you best describe the conditions that existed tonight with no illumination? Consider signing, marking, delineation, geometrics, etc. Comments were: signs were acceptable except under high speeds; delineation and geometrics were okay. Markings were poor, additional light would help; headlight glare was a problem; overall opinion is "fair".

The next questions and comments apply only to the interchange with the lighting system on.

1. Was glare from the tower a problem to you? Thirteen (13) said yes, one (1) said no. All indicated this was true at a distance of 1000-2500 feet. Comments were: only when tower is in direct line of sight; just west of crest on west leg; not after initial adjustment; only from the west.

2. Do you feel that the lighting closely duplicates daytime visibility as regarding driving tasks? Eight (8) indicated yes, six

(6) indicated no. Comments were: Not closely but certainly a long step in this direction; it simplifies the driving tasks but does not duplicate.

3. *Is there any transitional problem when entering the high-mast area?* Nine (9) indicated yes, five (5) indicated no. Comments were: at sudden grade changes; from west approach due to hilly terrain where towers are in direct line of sight; from east and west; dark area in middle on east approach; gradual illumination makes transition easy; going from west to east; eastbound into interchange; entering, there is a tendency to slow down; very slight; only from the west.

4. *Is there any transitional problem when leaving the high-mast area?* Fourteen (14) replied no. There were no (0) yes replies. Comments were: light gradually loses intensity; gradual change makes transition easy; very gentle transition when leaving lighted area; it was excellent.

5. *Do you feel there is any advantage to illuminating areas other than the roadway surfaces in interchange areas?* Thirteen (13) replied yes, one (1) replied no. Comments were: complete illumination of area gives visibility close to that of daytime; ramps and main lanes much better; much more decision making time; it reduces headlight glare and driver indecision; all possible hazards are visible; feel more secure and relaxed; high speed highway driving does not require that the driver know where traffic in other roadways is going.

6. *Of the following factors generally conceded to be important in illumination systems, how would you rate their importance? (No. 1 is most important).*

	No. replies for each rating				
	1st	2nd	3rd	4th	5th
Level of illumination	2	3	7	1	1
Uniformity of illumination	6	4	2	2	0
Area of coverage	2	2	4	3	3
Glare characteristics	5	2	1	6	0
Pavement brightness	0	2	0	2	10

This would give an overall rating of:

1st - Uniformity of illumination

2nd - Glare characteristics

3rd - Level of illumination

4th - Area of coverage

5th - Pavement brightness

7. How would you best describe the conditions that existed tonight with the high-mast lighting? Consider signing, marking, delineation, geometrics, etc. Comments were: the lighting provides a more relaxed driving atmosphere; driving conditions were very satisfactory with all features well defined; the glare is a problem when entering from the west; signing good, marking poor; delineation and geometrics good; wonder what it would do in bad weather; conditions desirable; all information readily available; good; generally good; much improved; good improvement; glare is bad from west; it really surprised me; better conception of all conditions within interchange area; shows the depths and dimensions of the area. (This study was conducted when weather conditions included 30 degree temperatures, and very strong wind. A very predominant comment in answer to No. 7 above was "cold".)

The final part of the questionnaire was again designed to obtain information from the participants about the designs of tower lighting.

The following discussion presents this phase of the questionnaire which was completed by five (5) participants, all professionals.

1. *If you had the opportunity to redesign this system, using five towers and ten lights per tower, what changes would you make?* Comments were: none; eliminate the cluster appearance present when approaching from the east; darken the area at the on ramps and lighten at the off ramps.

2. *Assuming the floodlights can be re-aimed, what changes would you make?* Comments were: reduce brightness on merging points, increase at diverging points; put more light on eastbound lane exit gore to West Blvd.

3. *Assuming you had unlimited towers to use, where would you place them?* Comments were: add one tower on the east end; add one tower on west end; use conventional lighting from interchange to the city.

4. *Do we need to make changes in signing, marking, and delineation practices with high-mast lighting?* Four (4) replied no, one (1) replied yes. Comments were: get the new type delineators; concrete structures should be painted with reflectorized paint.

5. *The five towers support fifty (50) 1000-watt lights. If you had 50 standard 1000-watt luminaires to use, do you feel that you could achieve a lighting design as good or superior to the high-mast design?* Four (4) replied no, one (1) replied yes. Comments were: yes, put the 50 luminaires at the gores, the sharper turns and the concrete structures. A continuous light pattern is not necessary in my opinion.

The data from the diagnostic studies were further used to arrive at levels of effectiveness for various features of the interchange situation. Levels of effectiveness were assigned to the various possible responses to each question in the questionnaire. For example, question No. 5 in part A of the Rapid City questionnaire would have the following levels of effectiveness:

Level of Effectiveness 4 (Optimum) - visibility would always be adequate.

Level of Effectiveness 3 - visibility would usually be adequate.

Level of Effectiveness 2 - visibility would sometimes be adequate.

Level of Effectiveness 1 - visibility would never be adequate.

To arrive at the level of effectiveness achieved by the particular feature of the interchange situation (in this case ability to see a major obstacle), the following procedure is used:

$$\text{Level of Effectiveness} = \frac{\Sigma \text{ ni Li}}{\text{NL}_0}$$

where ni = Number of responses at level Li

Li = Level of effectiveness

N = Total number of responses

L_0 = Optimum level of effectiveness.

Therefore, if all responses had been at Level 4 in the above example, the level of effectiveness achieved would be 100%. For this particular question the actual level is:

$$\frac{\Sigma \text{ ni Li}}{\text{NL}_0}$$

$$= \frac{(0)\ (4) + (3)\ (3) + (7)\ (2) + (4)\ (1)}{(14)\ (4)}$$

= 27/56 = 48%

Where questions are answered by either yes or no, only two levels of effectiveness are assigned, levels 1 and 2.

Levels of effectiveness achieved have been computed for the two interchanges and are listed in Tables 1 and 2.

In addition to these diagnostic studies, the South Dakota Highway Patrol was requested to observe the installations, especially during inclement weather, and report their observations. Four members of the Patrol submitted their observations on the following points posed by the principal investigator from the South Dakota Department of Highways:

A. Does a general ground cover of snow have any effect on the interchange lighting? The patrolmen reported:

No. 1 - No.

No. 2 - It appears to give a high reflective value.

No. 3 - On a clear night it doesn't have too much effect. On a night that is dark the snow cover has a definite aid.

No. 4 - The lights do a much better job with snow cover, doesn't have the glare.

B. What effect does snow fall or fog have on visibility? Reported observations were:

No. 1 - I have not seen fog in this area. During snow fall (fairly heavy) visibility is good.

No. 2 - It appears to have little effect on it.

No. 3 - Visibility of lights from any distance is greatly reduced. The area around the lights does have a greater amount of visibility. A definite advantage.

No. 4 - With snow fall and rain, the lights create a glare coming from the north. With fog I haven't noticed.

C. Does snow fall or fog significantly diffuse and reduce the amount of light on the road surface? Observations were:

No. 1 - Snow fall on the one occasion that I have seen it made very little difference. (It has been reported to me that these lights coming over the hill in east-bound traffic have a blinding effect as a plane with landing lights coming toward you.)

No. 2 - Somewhat but it still does a good job of lighting the roadway.

No. 3 - There is a reduction, but not enough to create any problem.

No. 4 - Not known or noticed.

D. What general statement would you make on the operation of this lighting under adverse weather conditions? Statements were:

No. 1 - None.

No. 2 - It is my opinion that when all towers are lighted adverse conditions have little effect on the performance.

No. 3 - I believe there is a definite advantage to the driving public. Greater visibility under adverse conditions is something we can certainly use.

No. 4 - I believe it should be a continuous operation in all kinds of weather.

Table 1

SUMMARY EVALUATION - DIAGNOSTIC STUDY - SIOUX FALLS

Particular Feature of the System	Percent Effectiveness Achieved	
	Without Lights	With Lights
Roadway Markings (lane lines, striping at gores, etc.)	52%	80%
Visibility of Geometric Features (curves, structures etc.)	56%	85%
Visibility of Roadside Signs	71%	89%
Visibility of Major Obstacles	61%	83%
Roadway Delineation	79%	92%
Speed and Distance Judgement of Other Vehicles	52%	70%
Information Desired About Interchange	77%	97%
Reduction of Headlight Glare	80%	89%
Location of Gore Areas	67%	86%
Security	85%	95%
Transitional Lighting Into System	N.A.*	82%
Transitional Lighting Out of System	N.A.	95%
Average Effectiveness of the System	68%	87%

* Not Applicable

Table 2

SUMMARY EVALUATION - DIAGNOSTIC STUDY - RAPID CITY

Particular Feature of the System	Percent Effectiveness Achieved	
	Without Lights	With Lights
Roadway Markings (lane lines, striping at gores, etc.)	96%	93%
Visibility of Geometric Features (curves, structures, etc.)	69%	82%
Visibility of Roadside Signs	83%	98%
Visibility of Major Obstacles	48%	82%
Roadway Delineation	89%	93%
Speed and Distance Judgement of Other Vehicles	59%	77%
Information Desired About Interchange	83%	98%
Location of Gore Areas	75%	85%
Security	93%	100%
Transitional Lighting Into System	N.A.*	68%
Transitional Lighting Out of System	N.A.	100%
Average Effectiveness of the System	77%	89%

* Not Applicable

TRAFFIC OPERATION STUDIES

Sioux Falls

The data collected by the continuous speed recorder were reduced to yield average speed and acceleration noise.* Five drivers were selected from the diagnostic team to make the study runs over the assigned sections indicated in Figure 5. An equipment failure during one run for one driver prevented complete data collection for him. Therefore, only four drivers' records have been included in the analysis.

Average Speed - Day. Average speeds for all sections combined varied during the daylight runs, from 37 mph for Driver No. 3 to 44 mph for Driver No. 4. The overall average speed, for all sections and drivers, was 40.3 mph. When broken down into sections, average speeds for all drivers combined varied from 30.5 mph on Section 2 (inner loop) to 51 mph on Section 5 (through movement on main lane).

Average Speed - Night - Without Lighting System. Average speeds for all sections combined varied during the night runs with the illumination system off, from 37 mph for Driver No. 4 to 47 mph for Driver No. 1. The overall average speed, for all sections and drivers was 43 mph, an increase of approximately 2 mph over the daylight condition. When broken into sections, average speeds, for all drivers combined varied from 33.3 mph on Section 2 to 54 mph on Section 5.

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* Acceleration noise is a measure of speed changes used to indicate smoothness of vehicle operation. It is discussed in Appendix C.

Average Speed - Night - With Lighting System. Average speeds for all sections combined, varied from 38 mph for Driver No. 2 to 44 mph for Driver No. 4. The overall average speed for all drivers and sections combined was 40 mph, almost the same for the daylight condition and both of which are lower than the night without lights condition. Average speeds for all drivers combined over the various sections, varied from 33 mph on Section 2 to 48.8 mph on Section 5.

Acceleration Noise - Day. Average acceleration noise for all sections combined varied from 1.12 for Driver No. 1 to 2.00 for Driver No. 4. The overall average value for all combinations was 1.57. Taken over sections, the values ranged from 0.49 on Section 4 to 2.59 on Section 6.

Acceleration Noise - Night - Without Lighting System. Average acceleration noise for all sections combined varied from 1.12 for Driver 4 to 1.95 for Driver 2. The overall value was 1.54, very close to the daytime condition. Taken over sections, the values varied from 1.17 on Section 2 to 2.13 on Section 6.

Acceleration Noise - Night - With Lighting System. Average acceleration noise for all sections combined varied from 1.03 for Driver 3 to 1.92 for Driver 1. The overall value was 1.40, lower than for the other conditions. Taken over sections, the values varied from 0.41 on Section 4 to 1.94 on Section 6.

Comparison of the Conditions. Table 3 has been prepared summarizing average speeds and acceleration noise for all drivers, sections, and lighting conditions. Appropriate statistical analysis (analysis of variance) were used to determine the significance in the difference

Table 3

SUMMARY OF SPEED DATA

SIOUX FALLS LOCATION

AVERAGE SPEED/ACCELERATION NOISE

DAY

DRIVER	SECT 1 EB I 90	SECT 2 INNER LOOP	SECT 3 NB I 29	SECT 4 OUTER LOOP-SE	SECT 5 WB I 90-THR.	SECT 6 SB I 29-THR.	AVERAGE
No. 1	38/1.45	33/.23	48/1.48	43/1.23	52/.29	42/2.68	40/1.12
2	40/1.28	33/1.02	48/1.47	47/.31	50/.30	40/2.57	40/1.24
3	41/1.76	23/2.18	46/1.62	50/.10	49/1.29	40/2.40	37/1.91
4	47/2.67	33/1.34	52/1.67	51/.30	53/1.72	39/2.71	44/2.00
AVERAGE	41.5/1.79	30.5/1.19	48.5/1.56	47.8/.49	51/.90	40.3/2.59	40.3/1.57
				LIGHTS ON			
No. 1	44/2.12	33/1.52	40/2.14	50/.55	54/1.51	44/1.58	39/1.92
2	38/1.37	31/.98	46/1.15	45/.84	46/1.12	36/1.89	38/1.16
3	37/1.3	34/.27	46/.26	42/.12	43/.25	35/1.65	39/1.03
4	38/1.62	34/1.40	52/1.49	50/.12	52/1.67	39/2.62	44/1.49
AVERAGE	39.3/1.60	33/1.04	46/1.26	46.8/.41	48.8/1.14	38.5/1.94	40/1.40
				LIGHTS OFF			
No. 1	46/2.26	34/1.26	56/2.00	39/2.31	57/1.55	48/2.29	47/1.87
2	49/2.74	34/1.25	52/1.55	39/2.02	61/2.73	43/1.07	45/1.95
3	41/1.93	35/1.15	54/.29	37/.29	50/1.86	38/2.68	43/1.22
4	39/1.25	30/1.02	45/1.12	51/.47	48/1.22	36/2.49	37/1.12
AVERAGE	43.8/2.05	33.3/1.17	51.8/1.49	41.5/1.27	54/1.84	41.3/2.13	43.0/1.54

for the various conditions.

Using speed as the criterion, the statistical analysis (Table 1, Appendix D) reflected that there was no significant difference in the average speeds, for the three lighting conditions. The analysis did indicate a highly significant difference between sections of roadway. In referring to Table 3 these differences can be readily explained. For example, Section 2 with a low average speed represents a tight inner loop of the cloverleaf where section 5 with a higher average speed represents a straight through maneuver on a main lane with few restrictions on speed. The analysis further indicated that there was no significant interaction between lighting conditions and the six sections. These results seem to indicate, using average speed as a level of service measure, that there is no change due to lighting conditions. The results do point out a relative level of service for the six sections of roadway.

Using acceleration nosie as the criterion, (Table 2, Appendix D) the statistical analysis reflected no difference due to lighting conditions. The analysis did indicate differences due to the sections, similar to the average speed results. Again, there was no significance in the lighting conditions-section interactions.

Rapid City

The data collected at the Rapid City location (Figure 6) was treated similarly to that collected at Sioux Falls. Four drivers' data were used in the final analysis.

Average Speed - Day. Average speeds for all sections combined varied during the daylight runs, from 47.25 mph for Driver No. 1 to

57.5 mph for Driver No. 3. The overall average speed, for all sections and drivers was 51.38 mph. When broken down into sections, average speeds for all drivers combined, varied from 48.75 mph on Section 1 to 52.75 mph on Section 4.

Average Speed - Night - Without Lighting System. Average speeds for all sections combined varied from 45.25 mph for Driver Numbers 2 and 4 to 49.75 mph for Driver No. 3. The overall average speed for all sections and drivers was 46.6 mph, a reduction of approximately 5 mph from the daytime condition. When broken into sections, average speeds, for all drivers combined varied from 42.3 mph on Section 1 to 48.3 mph on Section 3.

Average Speed - Night - With Lighting System. Average speeds for all section combined, varied from 47 mph for Driver No. 1 to 53.5 mph for Driver No. 3. The overall average speed was 50.1 mph, a reduction of approximately 1 mph from the daytime condition. For the various sections the average speed varied from 49 mph on Section 3 to 51.8 mph on Section 2.

Acceleration Noise - Day. Average acceleration noise for all sections combined varied from 0.49 for Driver No. 1 to 1.06 for Driver No. 3. The overall average value for all combinations was 0.73. Taken over sections, the values ranged from 0.51 on Section 3 to 0.99 on Section 2.

Acceleration Noise - Night - Without Lighting System. The average value for all sections combined varied from 0.45 for Driver No. 1 to 0.94 for Driver No. 4. The overall value was 0.68. Over sections, the values varied from 0.50 on Section 1 to 0.78 on Section 2.

Acceleration Noise - Night - With Lighting System. The average value for all sections combined varied from 0.80 for Driver No. 1 to 1.57 for Driver No. 4. The overall average was 1.13, higher than for both of the other two conditions. Taken over sections, the average value varied from 0.87 on Section 4 to 1.36 on Section 2.

Comparison of the Conditions. Table 4 has been prepared summarizing average speeds and acceleration noise for all conditions. Again, analysis of variance techniques were used to determine the significance in the differences for the various conditions.

Using speed as the criterion, the analysis (Table 3, Appendix D) reflected a significant difference in speeds, especially between the without lights and with lights conditions. There is no indication of significance between the sections or for lighting conditions - sections interaction. These results indicate a significant improvement in level of service when average speed is used as the criterion.

Using acceleration noise as the criterion, the only significance shown was that between lighting conditions (Table 4, Appendix D).

Table 4

SUMMARY OF SPEED DATA

RAPID CITY LOCATION

AVERAGE SPEED/ACCELERATION NOISE

DAY

DRIVER	SECT 1 NB 190 to WB 90	SECT 2 EB 90 to SB 190	SECT 3 NB 190 to EB 90	SECT 4 WB 90 to SB 190	AVERAGE
No. 1	41/.37	50/.66	48/.47	50/.45	47.3/.49
2	49/.49	51/.62	50/.52	52/.47	50.5/.53
3	57/.96	57/1.67	58/.49	58/1.13	57.5/1.06
4	48/.94	50/.99	52/.54	51/.94	50.3/85
AVERAGE	48.8/.69	52.0/.99	52.0/51	52.8/.75	51.4/.73
			LIGHTS ON		
No. 1	43/.74	50/.94	46/.96	49/.57	47.0/.80
2	46/.69	49/1.00	45/1.20	50/.69	47.5/.90
3	52/.75	55/1.46	55/1.61	52/1.21	53.5/1.26
4	55/1.68	53/2.04	50/1.52	52/1.02	52.5/1.57
AVERAGE	49.0/.97	51.8/1.36	49.0/1.32	50.8/.87	50.1/1.13
			LIGHTS OFF		
No. 1	44/.10	47/.54	47/.65	47/.51	46.3/.45
2	45/.61	39/.78	48/.50	49/.58	45.3/.62
3	46/.24	54/.90	51/.82	48/.86	49.8/.71
4	46/1.05	43/.89	47/1.03	45/.77	45.3/.94
AVERAGE	45.3/.50	45.8/.78	48.3/.75	47.3/.68	4.66/.68

DRIVER BEHAVIOR STUDIES

(GALVANIC SKIN RESPONSE)

At the initiation of this research, the South Dakota Department of Highways and the Bureau of Public Roads requested that the proposal to use galvanic skin response, as a measure of driver behavior, be examined very closely. There was some question as to the suitability of this measure for driver studies. Therefore, the research staff conducted an exhaustive review of literature on psychophysiological measurements as related to the operation of a motor vehicle. (See Appendix B). Briefly, the review indicated that a satisfactory psychophysiological measure of driver responses in the complex driving environment has not as yet been developed. Of the various measures available for use, the galvanic skin response appeared to be the most nearly suited to the driving task. Therefore, the measure was used in the research, not expecting spectacular results, but hoping that some indications of driver reactions would be given.

Attempts made in analyzing the data proved to be fruitless. Therefore, the data has not been included in this report.

PHOTOMETRIC STUDIES

Sioux Falls

Measurements of horizontal footcandles were made over the entire interchange area and have been superimposed over a layout of the interchange. Points of equal intensity have been connected with smooth lines to form an isofootcandle diagram of the interchange area. This diagram is shown in Figure 7. By following each individual leg of the interchange, the relative lighting intensities and changes in intensities can be visualized. It can be noted that changes are rather minor and adequate uniformity has been achieved.

In addition to these measurements, recordings of horizontal and vertical footcandles were made along the roadways of the interchange at 100-foot increments of distance. Table 5 is a summary of the data giving average intensity and average to minimum ratios for the various sections. In most cases the average values and the ratios compare favorably with the design values.

The pavement brightness and glare data collected with the recording photometer is presented in Figures 8-12. In most cases the graphs reveal high degrees of uniformity. The only serious exception to this is shown in Figure 9. (Southbound I-29, Section 6) The floodlights involved in the lighting of this section should be reaimed to better distribute the brightness.

Rapid City

The intensity data from the Rapid City location has been treated similarly to that of Sioux Falls. Figure 13 presents the isofootcandle diagram for the interchange area. Again, by following the individual legs of the interchange, the relative intensity and uniformity can be visualized.

Table 6 is a summary of horizontal and vertical footcandle data collected on the individual roadways of the interchange. On four of the six sections, average values equaled or exceeded those values anticipated from the design criteria. The values can probably be raised slightly through careful readjustment of the floodlights, although there was no apparent deficiency as reported by the study team.

The pavement brightness and glare data from the Rapid City location are presented in Figures 14a-15d. As in the Sioux Falls installation, the graphs reveal adequate intensity and uniformity of pavement brightness with no excessive glare.

It should be pointed out here that the glare levels do not appear to be high enough to cause alarm. The glare reported by the team apparently is discomfort glare and is caused primarily by the novelty of the installations. This does not mean however, that reaiming could not eliminate or reduce the apparent problem.

TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY
COLLEGE STATION, TEXAS

FIGURE 7
ISOFOOTCANDLE DIAGRAM
SIOUX FALLS INSTALLATION

ORIGINAL DRAWING DATE:
DN:
CK:
DW:
CK:
REVISIONS
SHEET

Table 5

SIOUX FALLS PHOTOMETRICS*

SECTION	AVERAGE INTENSITIES		RATIO AVG./MIN. INTENSITIES	
(Direction of Travel)	Horizontal Footcandles	Vertical Footcandles	Horizontal	Vertical
East Bound I90	.28	.29	2.8/1.0	2.9/1.0
West Bound I90	.23	.34	2.3/1.0	3.4/1.0
North Bound I29	.29	.27	3.6/1.0	2.3/1.0
South Bound I29	.31	.31	2.8/1.0	2.6/1.0
I29S - I90E	.45	.26	2.4/1.0	1.7/1.0
I90W - I29S	.47	.28	2.5/1.0	2.8/1.0
I29N - I90W	.50	.27	2.5/1.0	1.8/1.0
I90E - I29N	.38	.21	2.9/1.0	2.1/1.0
I90E - I29S	.28	.27	3.5/1.0	3.4/1.0
I90W - I29N	.32	.26	4.0/1.0	4.3/1.0
I29N - I90E	.43	.26	4.7/1.0	3.7/1.0
I29S - I90W	.26	.29	3.7/1.0	3.6/1.0
Average	.35	.28	3.1/1.0	2.9/1.0

*These values were computed by dropping the highest and lowest reading on each section.

SIOUX FALLS INSTALLATION

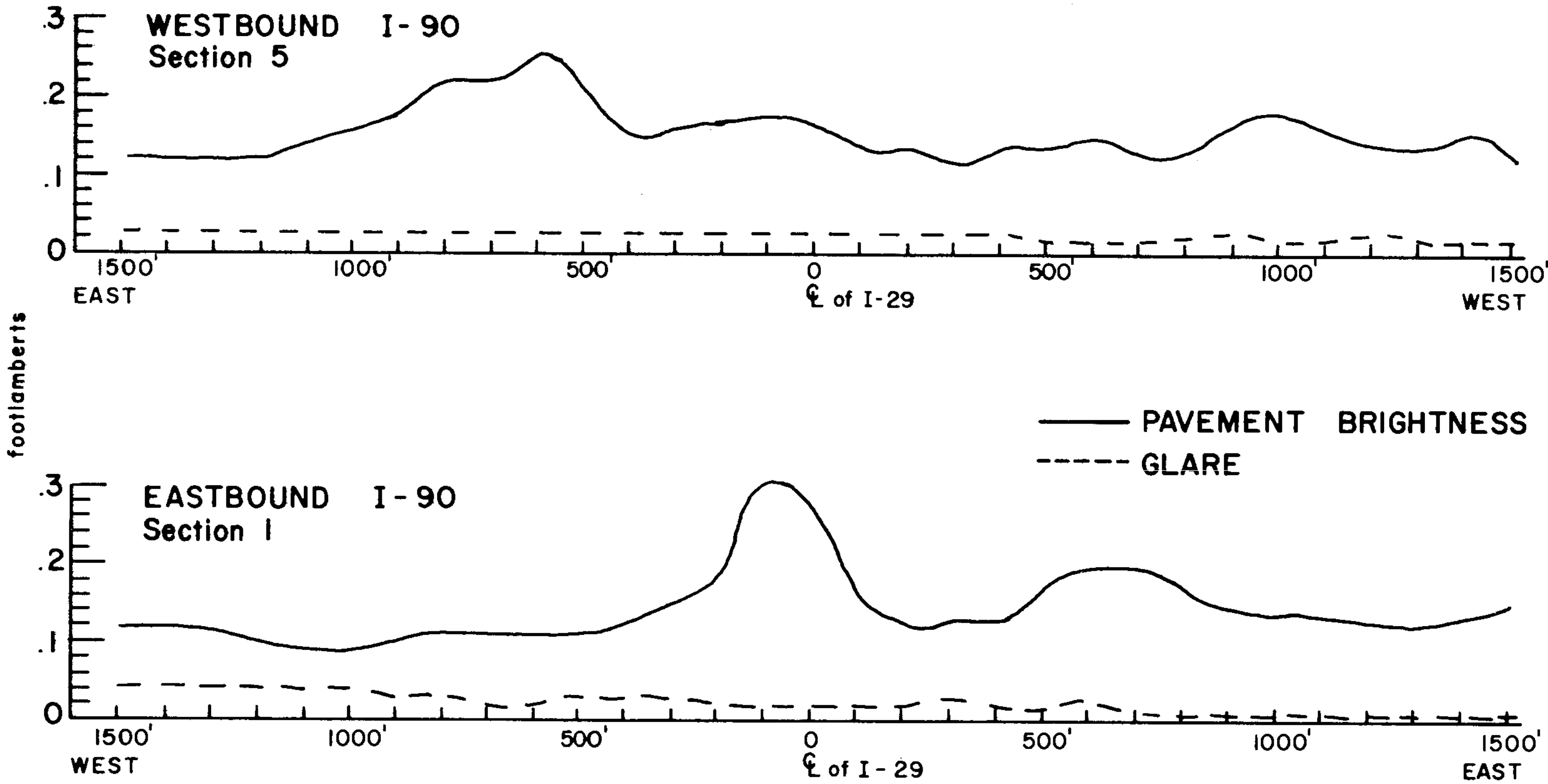


FIGURE 8 BRIGHTNESS & GLARE

SIOUX FALLS INSTALLATION

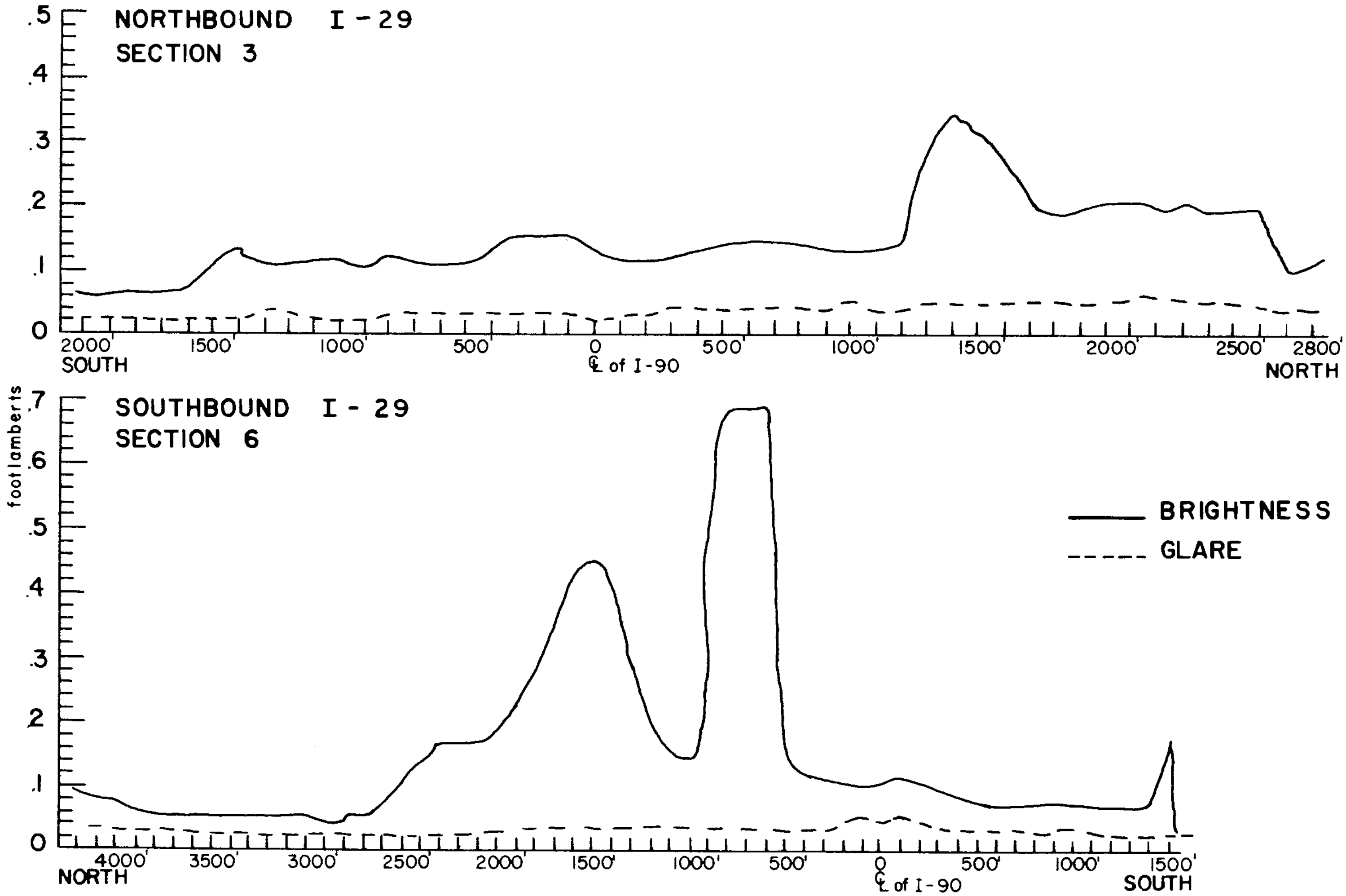


FIGURE 9 BRIGHTNESS & GLARE

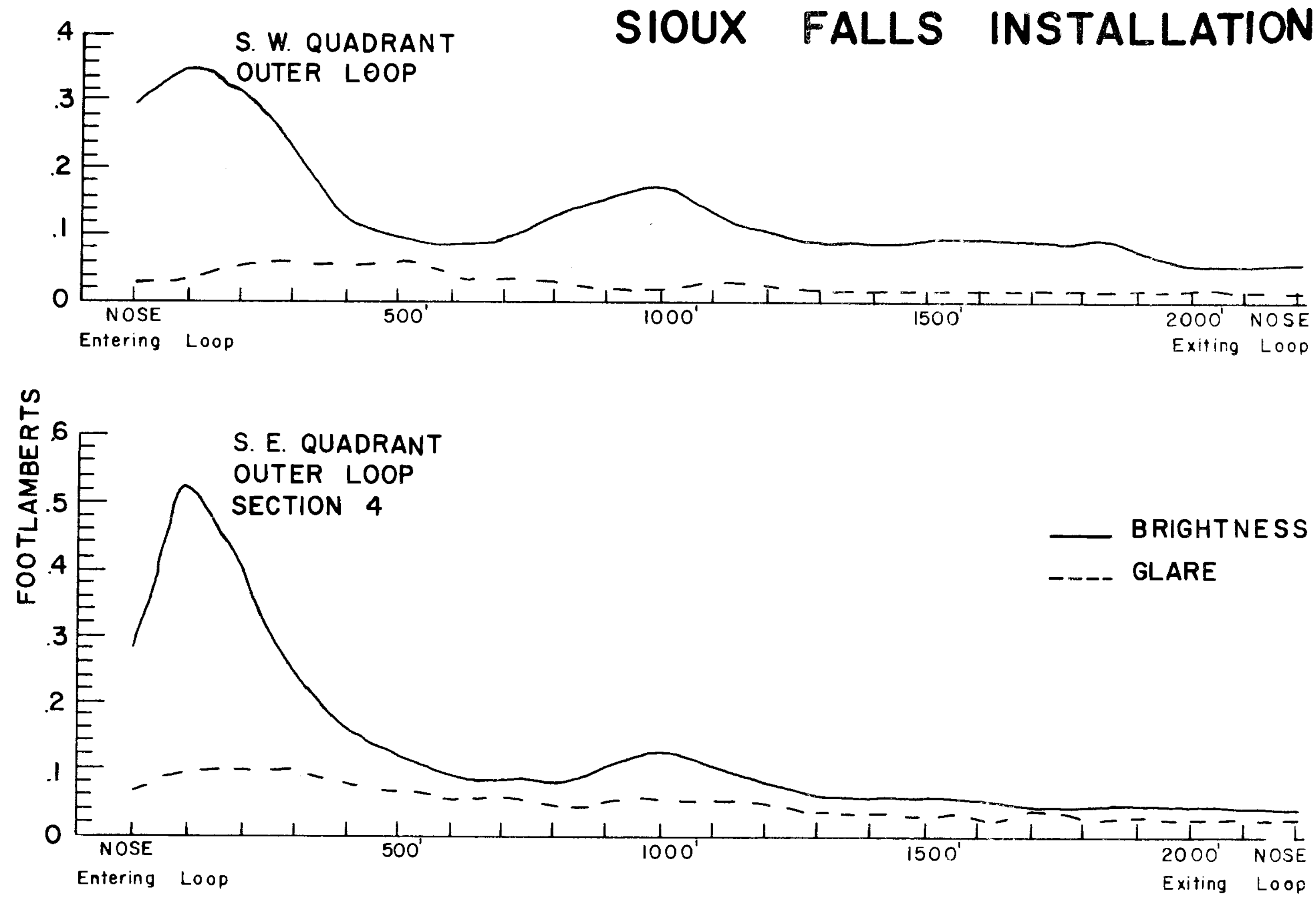


FIGURE 10

BRIGHTNESS & GLARE

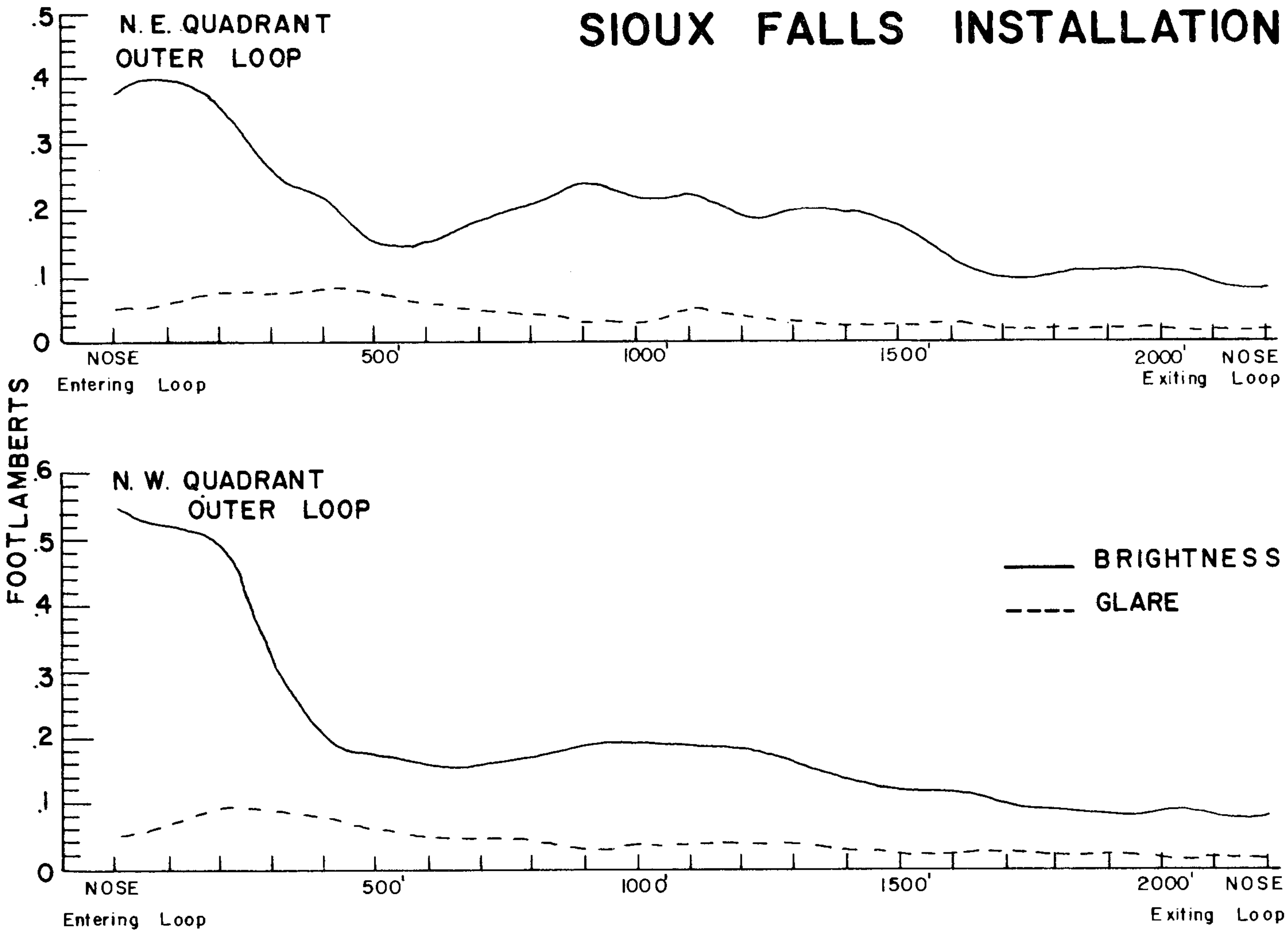


FIGURE II BRIGHTNESS & GLARE

SIOUX FALLS INSTALLATION

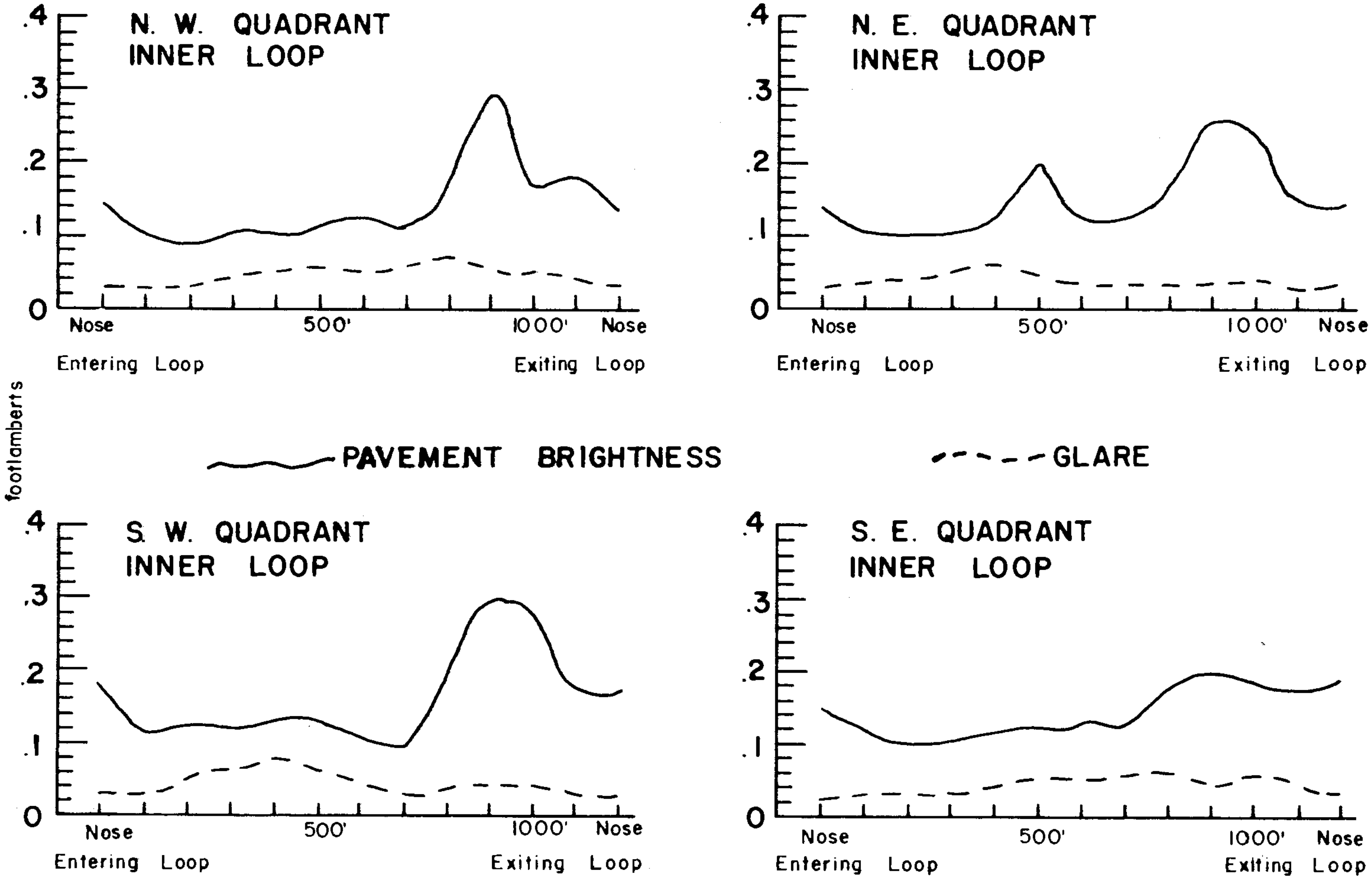
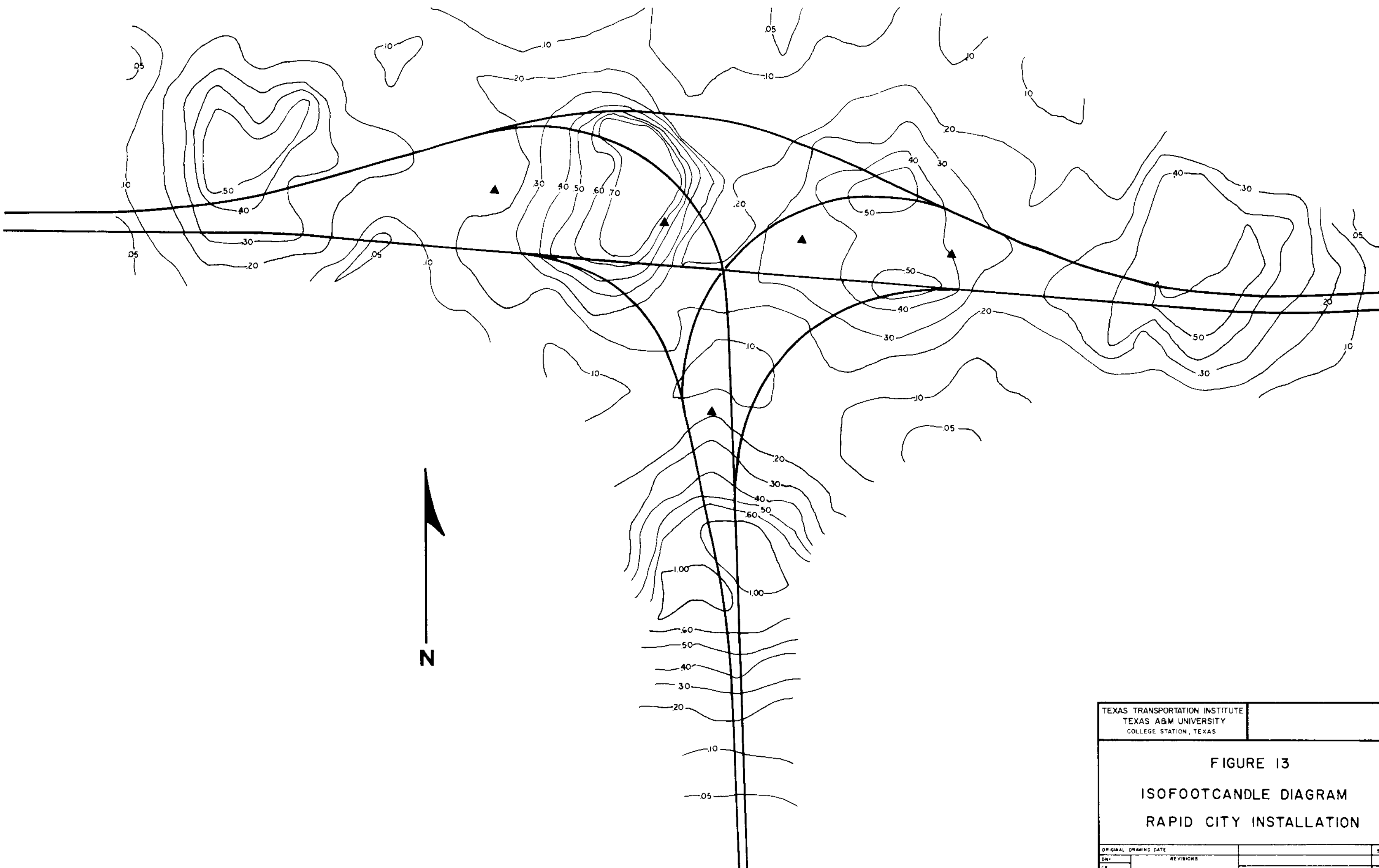


FIGURE 12 BRIGHTNESS & GLARE



TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY
COLLEGE STATION, TEXAS

FIGURE 13

ISOFOOTCANDLE DIAGRAM

RAPID CITY INSTALLATION

Table 6

RAPID CITY PHOTOMETRICS*

SECTION	AVERAGE INTENSITIES		RATIO AVG./MIN. ILLUMINATION	
(DIRECTION OF TRAVEL)	HORIZONTAL FOOTCANDLES	VERTICAL FOOTCANDLES	HORIZONTAL	VERTICAL
East Bound I90	.32	.33	3.2/1.0	4.0/1.0
West Bound I90	.17	.19	2.1/1.0	2.7/1.0
I90E - I190S	.17	.18	1.7/1.0	1.8/1.0
I190N - I90E	.28	.30	2.0/1.0	3.0/1.0
I90W - I190S	.30	.25	2.0/1.0	1.8/1.0
I190N - I90W	.35	.37	3.5/1.0	2.8/1.0
Average	.27	.27	2.4/1.0	2.7/1.0

* These values were computed by dropping the highest and lowest reading on each section.

WEST 90 THROUGH (SECTION 5)

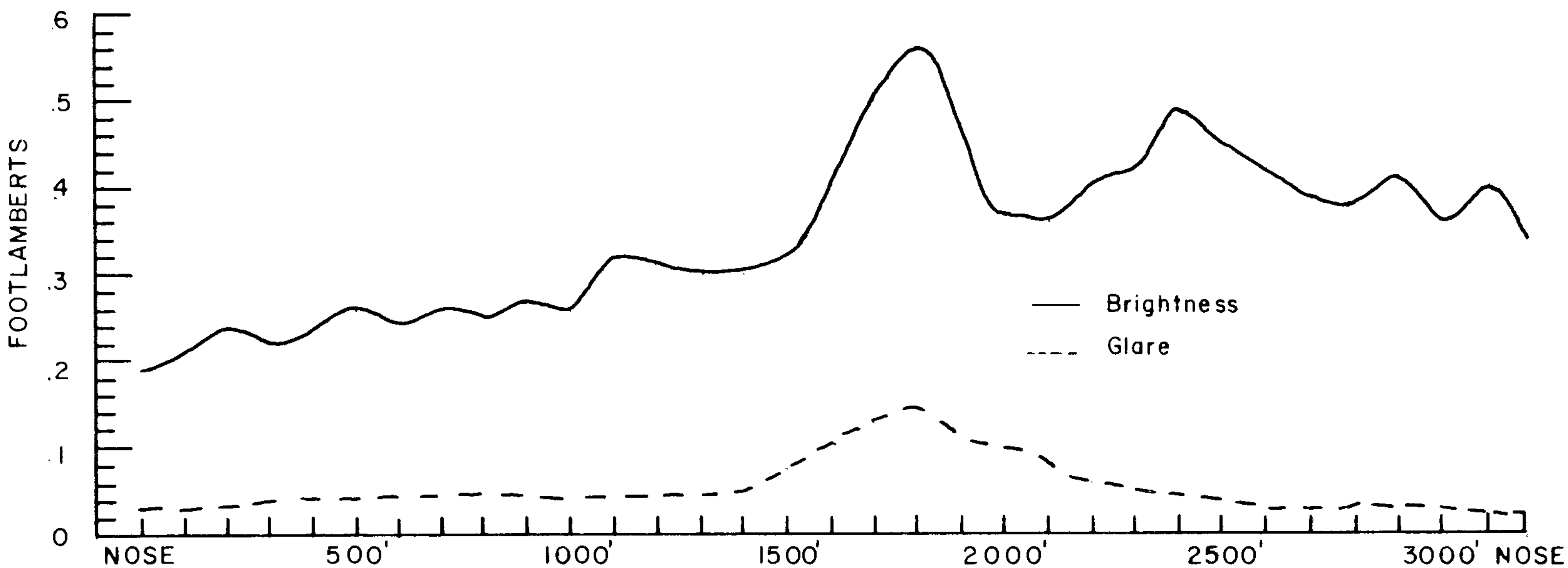


FIGURE 14a BRIGHTNESS & GLARE

EAST 90 THROUGH (SECTION 6)

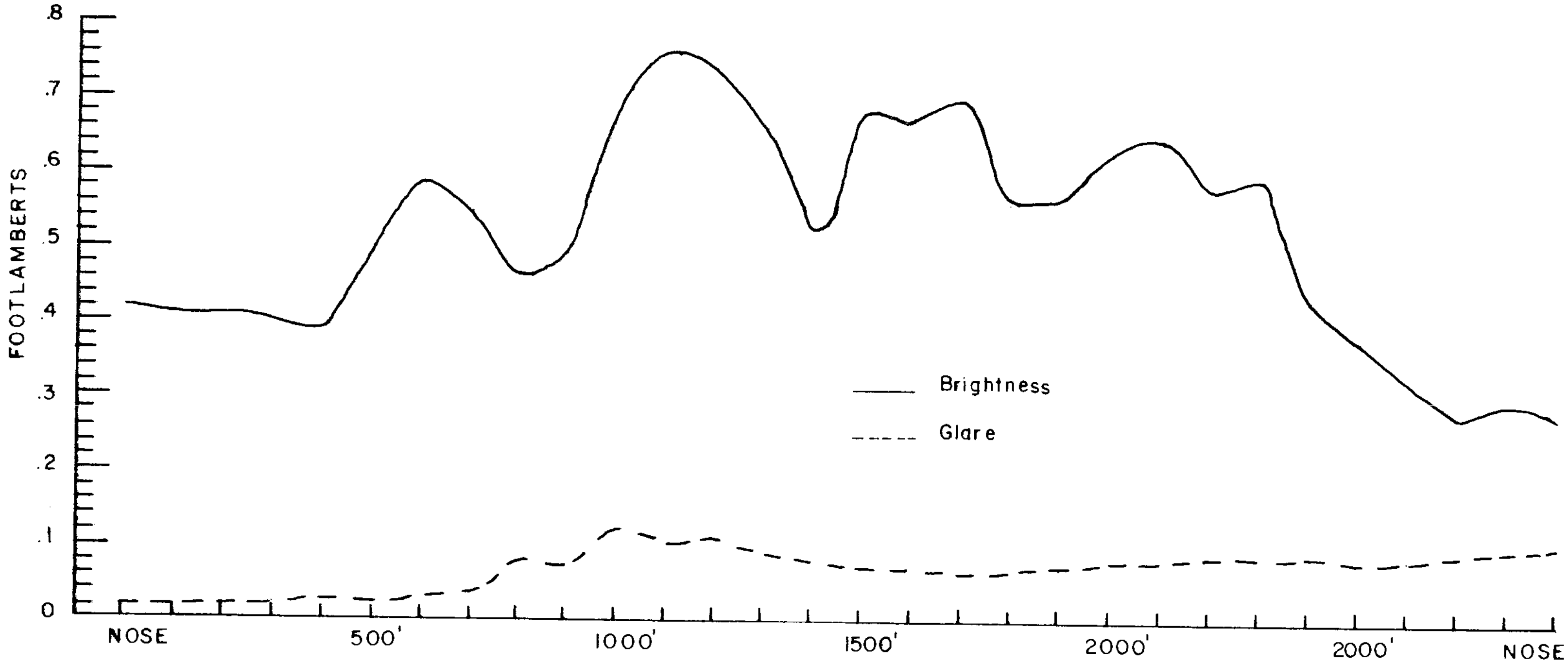


FIGURE 14b BRIGHTNESS & GLARE

EAST 90 to SOUTH 190 (SECTION 4)

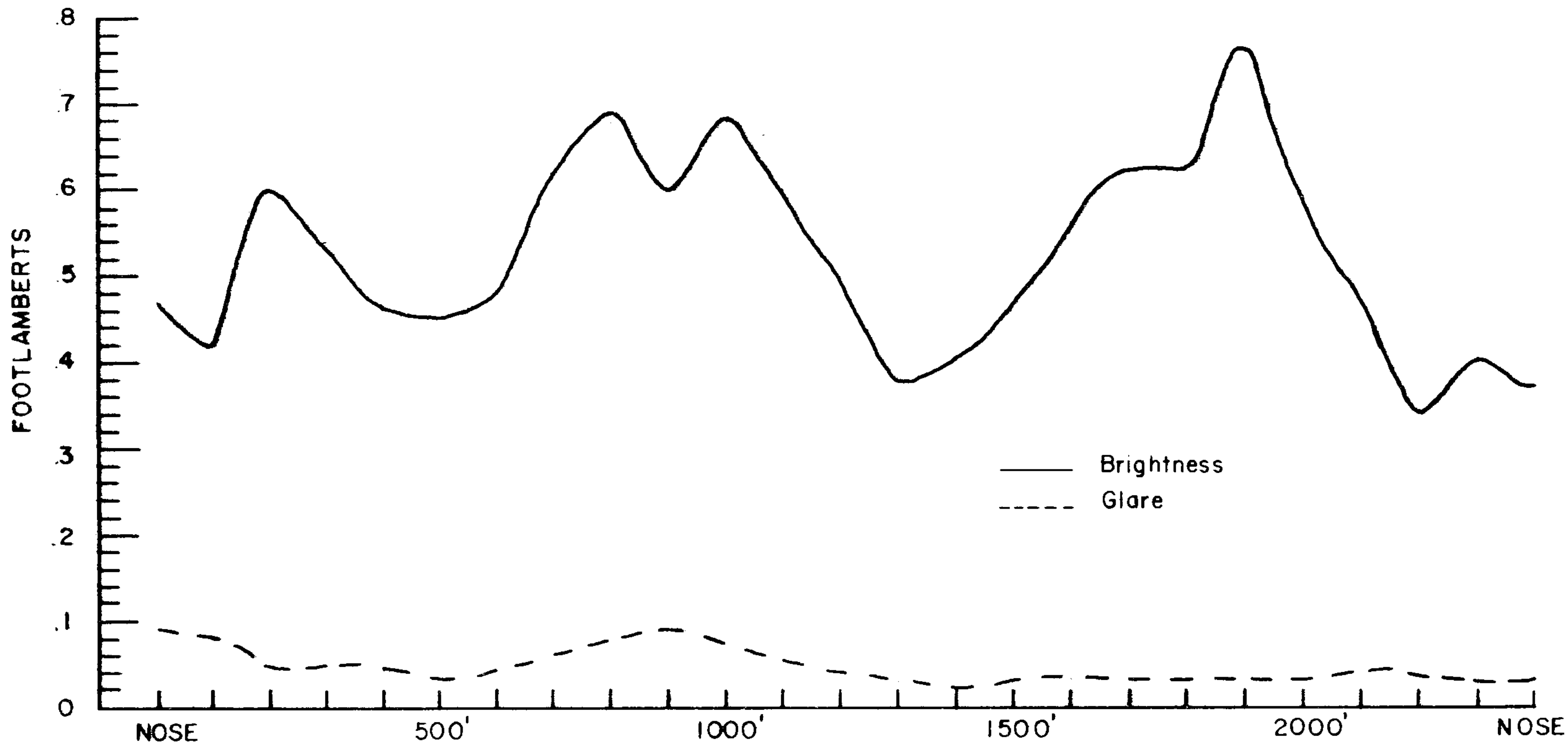


FIGURE 15a BRIGHTNESS & GLARE

SOUTH 190 to EAST 90 (SECTION 3)

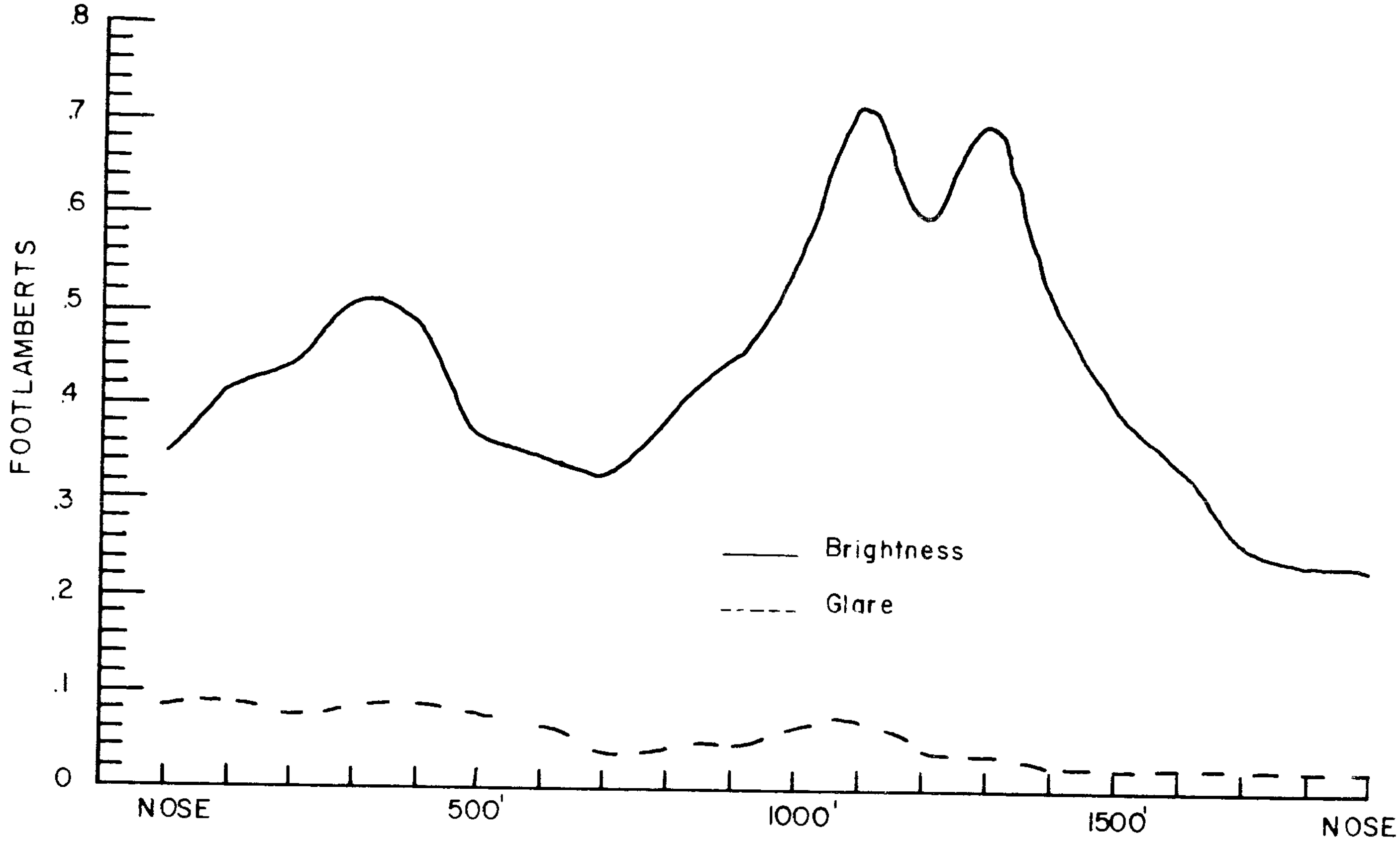


FIGURE 15b BRIGHTNESS & GLARE

WEST 90 to SOUTH 190 (SECTION 2)

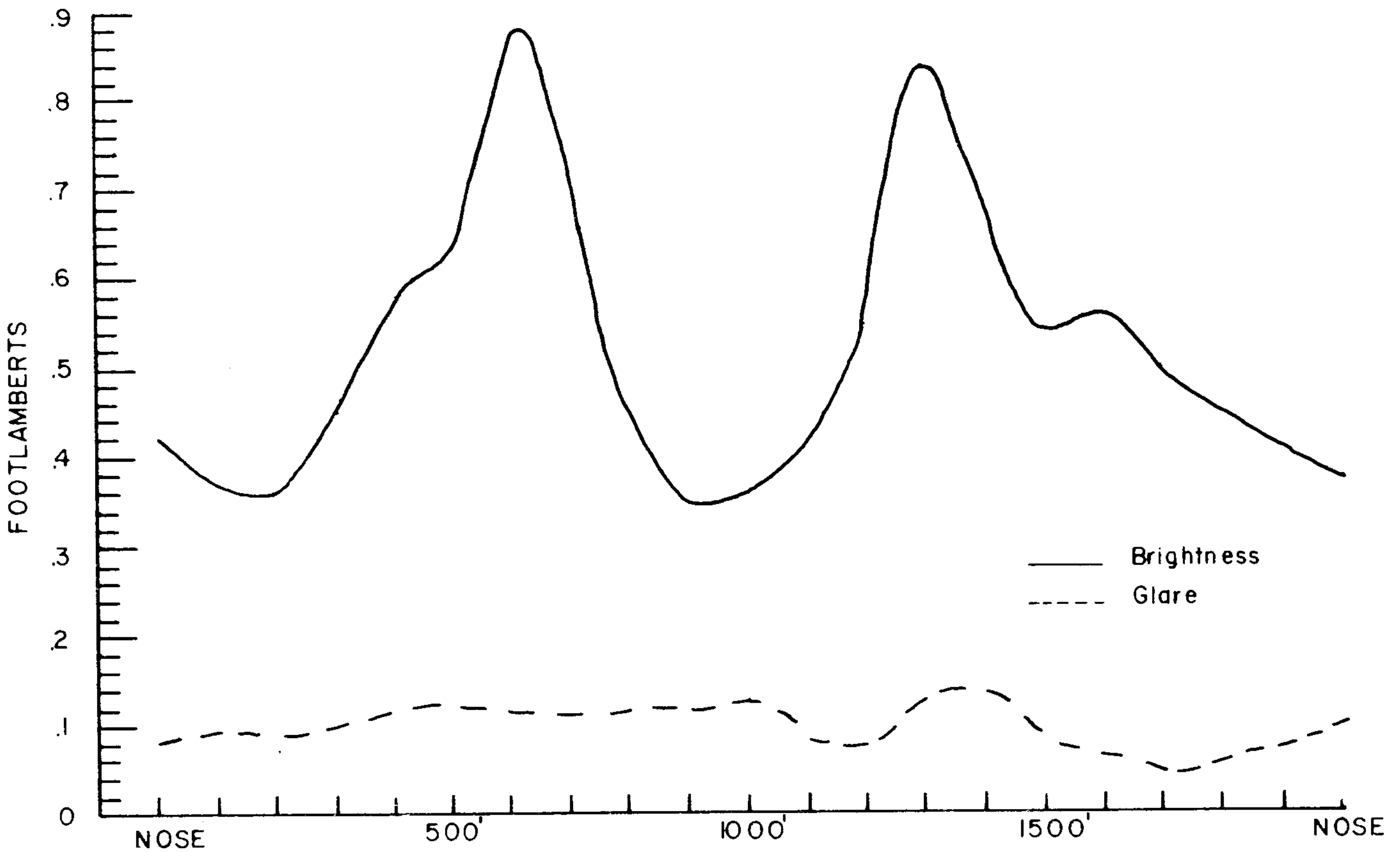


FIGURE 15c BRIGHTNESS & GLARE

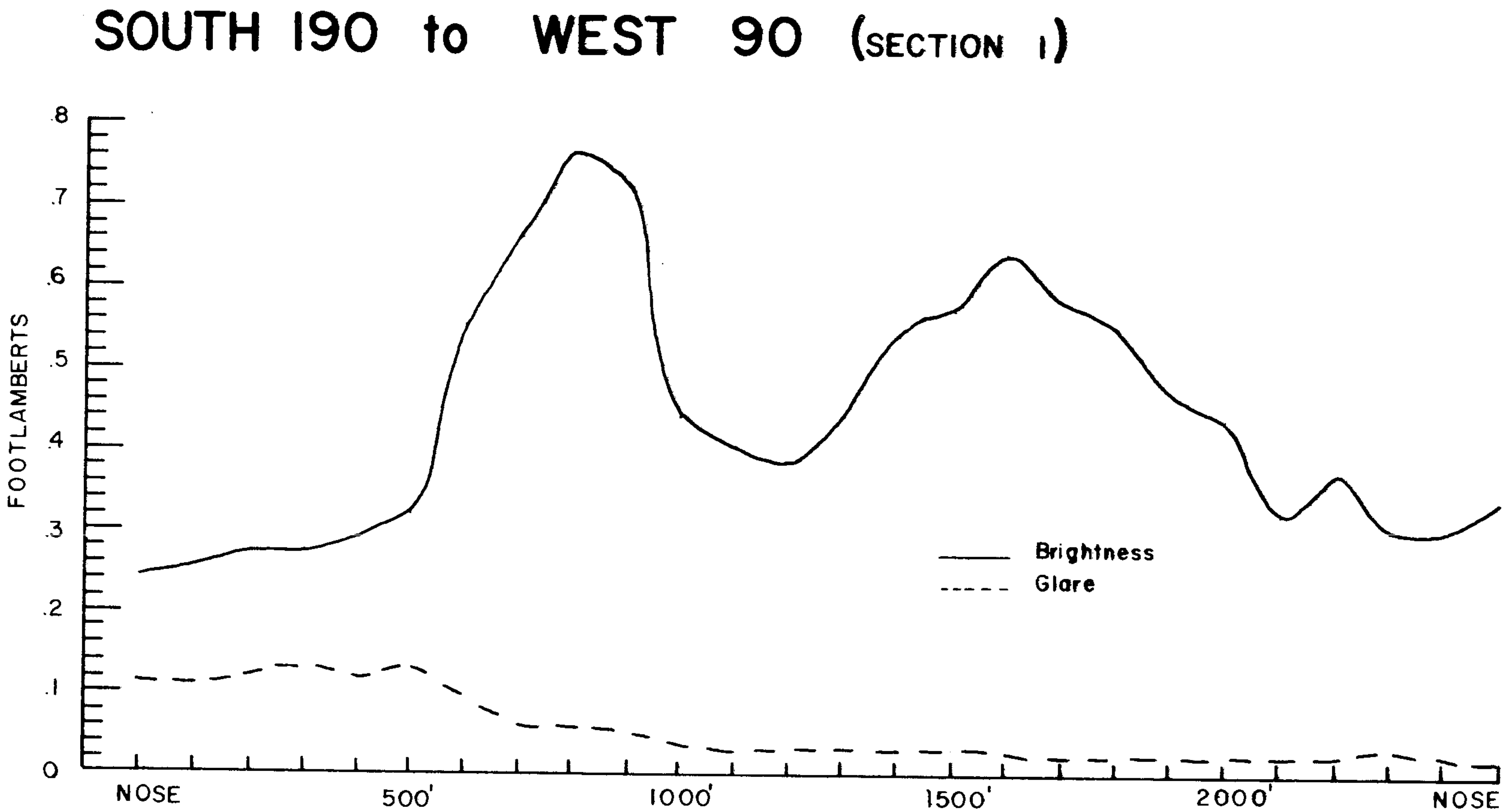


FIGURE 15d BRIGHTNESS & GLARE

SUMMARY OF RESULTS

HIGH-MAST ILLUMINATION DIAGNOSTIC STUDY QUESTIONNAIRE SUMMARY

The questionnaires for both the Sioux Falls, South Dakota; and Rapid City, South Dakota, diagnostic studies are based on the individual perception of different conditions by persons trained in some phase of highway design and/or construction. Perception is a psychological phenomenon having the consideration of individual differences as one of its factors. Therefore, to the extent which different individuals report the same or similar perceptions is the validation that certain conditions exist. The training of persons in a specific area does not affect this validity; they are trained to be aware of many conditions but perception of certain conditions is still an individual matter. For these reasons, the diagnostic study questionnaires cited must be considered as valid indications of what conditions actually exist on the highways studied.

Without high-mast illumination, there is general agreement that visibility is barely adequate for formal information transmission, depending on speed, climatological factors, and geometric features of the roadway. However, information needed for warning, such as distant observation of a major obstacle (stalled unlighted vehicle), was never adequate in non-illuminated conditions.

With high-mast lighting in use, the adequacy of visibility of formal means of information transmission is greatly enhanced, with one exception: overhead signs. Other information needs, such as the warning described above, are visually satisfied easily with high-mast illumination. The most apparent problem with this lighting technique is glare, but most comments indicated it was a short-lived factor.

There is an overwhelming agreement that complete illumination of an area would increase the possible visual perception of a driver close to that of daylight driving.

Recommendations for improvement of the high-mast illumination projects studied center primarily on the need for complete illumination of the entire area rather than spots on the interchange and on the need for external illumination of overhead signs. Most of the subjects felt high-mast illumination is a promising tool by which the driver's visual perception at night may be increased, thereby enhancing his safe, convenient, efficient, and comfortable performance in driving.

TRAFFIC OPERATION STUDIES

Statistical analysis of speed and acceleration noise data from the Sioux Falls location failed to indicate any significant differences for the three lighting conditions: day (40.3 mph/1.57 AN), no lights (43.0 mph/1.54 AN), lights (40.0 mph/1.40 AN). The analysis did reflect significant differences over the various sections and this would be expected, since some sections were straight through maneuvers and others tight turning maneuvers on inner loops of the cloverleaf.

Analysis of the speed and acceleration noise data from the Rapid City location showed significant differences between lighting conditions. Using the higher average speed as the criteria, the conditions would be rated in the following order: day, lights, no lights. Using the lower acceleration noise as the criteria they would be rated no lights, day, lights.

PHOTOMETRIC STUDIES

Measurements of horizontal and vertical footcandles at both installations revealed that the values were fairly close to the design values. Average values for the various sections ranged from 0.23 to 0.47 horizontal footcandles at Sioux Falls and 0.17 to 0.35 horizontal footcandles at Rapid City. Average to minimum ratios varied from 2.3/1.0 to 3.7/1.0 and 1.7/1.0 to 3.5/1.0 respectively at the two locations.

Pavement brightness and glare, very important factors in visibility, showed very surprising uniformity at both locations. Some "hot spots" were noted and should be reduced through re-adjustment of the floodlights. This will be covered further in the section on CONCLUSIONS AND RECOMMENDATIONS.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

The procedures and techniques used in this research have produced results worthy of being used for drawing conclusions and making recommendations. The following summary listing presents these conclusions and recommendations.

DIAGNOSTIC STUDIES

1. Without high-mast illumination, there is agreement that visibility is barely adequate and in some cases never adequate for safe vehicle operation.

2. With high-mast lighting in use, the adequacy of visibility is enhanced and in almost all cases satisfactory for vehicle operation.

3. There is overwhelming agreement that complete illumination of an interchange area would increase the possible visual perception of a driver close to that of daylight driving.

4. An apparent problem of glare has been brought out and it is recommended, that in those specific areas where glare appeared to be a problem re-adjustment of the floodlights be made.

5. Visibility of overhead signs was below acceptable levels with and without the lighting system. Therefore, it is recommended that consideration be given to externally illuminating these signs.

6. Security and comfort, as expressed by the study team was greatly enhanced by the use of high-mast lighting.

7. Based on ranking given by the study team the following ratings were given to illumination design variables:

SIOUX FALLS	RAPID CITY
1st Uniformity of illumination	1st Uniformity of illumination
2nd & 3rd Glare and area of coverage	2nd Glare
	3rd Level of illumination
4th Level of illumination	4th Area of coverage
5th Pavement brightness	5th Pavement brightness

8. Using level of effectiveness derived from the questionnaires, significant improvements were realized through the use of high-mast lighting (68% vs 87% at Sioux Falls and 77% vs 89% at Rapid City, without lights and with lights respectively).

9. Factors contributing to lowering levels of effectiveness with the lighting system on are primarily speed and distance judgement of other vehicles (both locations) and transitional lighting into the system (Rapid City only).

TRAFFIC OPERATION STUDIES

1. Using speed as the criterion, there is no significant differences due to lighting conditions at Sioux Falls. At Rapid City the differences are significant and can be rated as day, with lights and without lights.

2. Using acceleration noise as the criterion, there is no significant differences due to lighting at Sioux Falls. There was a significant difference at Rapid City with the rating being without lights, day, light.

3. Both speed and acceleration noise indicated different levels of effectiveness on the various roadway sections for the Sioux Falls location but not the Rapid City location.

DRIVER BEHAVIOR STUDIES

No worthwhile conclusions can be drawn from the galvanic skin response studies. However, it can be recommended that very serious consideration be given before using the measure in the complex driving environment. Similar recommendations have been made in previous research.

PHOTOMETRIC STUDIES

1. Levels and uniformity of illumination at both locations are well within the design values and were judged sufficient by the diagnostic study team. Some "hot-spots" as reflected by the isofoot-candle curve should be eliminated through re-adjustment of the flood-lights.

2. Pavement brightness and glare appear to be within acceptable limits. There is a need to re-adjust some of the floodlights at Rapid City to reduce glare on some entering roadways, which at the same time will improve transition into the system.

SIGNIFICANCE OF RESEARCH

SIGNIFICANCE OF RESEARCH

Some very significant factors have been "high-lighted" by the completion of the research discussed in this report. These factors should contribute substantially to the "state-of-the art" in interchange lighting and provide guidelines for the establishment of specific design criteria.

Those factors that appear to be most significant are outlined below and include both good and bad features.

1. When using the floodlighting concept, careful attention must be given to the aiming to assure that excessive glare and hot-spots do not result. For the particular locations of this study, no floodlights on the edge of the system (i.e. facing roadways entering the interchange) should be aimed at a greater angle than 45 degrees measured from the down vertical axis of the support.

2. Lighting assemblies should never be placed directly in the line of sight for motorists entering the interchange area. They should be offset sufficient distances so as not to attract the motorists' attention.

3. Mounting heights of 100 feet appear to be lower than desirable. Heights of 150 feet should be considered in the future. This will provide for better uniformity, less glare, larger area of coverage, and superior transitions into the systems.

4. Lighting levels of 0.25 footcandles and less from high-mast lighting are adequate and feasible for use in large complex interchanges where there is a minimum of extraneous light from the surrounding area.

5. Consideration should be given to the possible use of conventional lighting for transitional purposes into the interchange area.

6. There appears to be no significant changes in the effectiveness of supporting systems, such as delineation, to warrant any consideration in design concept changes.

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APPENDICES

APPENDIX A

HIGH-LEVEL ILLUMINATION

DIAGNOSTIC STUDY QUESTIONNAIRE

PART A

PROJECT RF 593

IH 90 - IH 190 RAPID CITY, S. D.

NAME ____________________

AFFILIATION ____________________

____

____

PART A

Questions in this part apply to an evaluation of the study area as it existed prior to the high-level illumination construction project.

Please answer all questions to the best of your judgement by checking the appropriate box. Space is provided for any comment you may have on any question. Please use this space as the comments will be most helpful to us in our evaluations.

1. Did you feel that roadway markings were adequate under the conditions tonight?

   /_/ YES   /_/ NO

   Comments: ____

   ____

   ____

2. Which of the answers below best describe your evaluation of the visibility of geometric features of the roadway such as curves, structures, etc.?

   /_/ Visibility Is Below Minimum Acceptable Level For This Type Facility

   /_/ Minimum Visibility Requirements Of Normally Alert Drivers Satisfied

   /_/ Visibility Is Adequate For Most Drivers

   Comments: ____

   ____

   ____

3. Which of the following best describe the visibility of roadside signs?

   /_/ Visibility Always Adequate

   /_/ Visibility Usually Adequate With High Beams

   /_/ Visibility Never Adequate

   Comments: ____

   ____

4. Which of the following best describes the visibility of overhead signs with external lighting?

/_/ Always Adequate

/_/ Usually Adequate

/_/ Adequate Sometimes

/_/ Never Adequate

Comments:

5. Which of the following best describes your evaluation of seeing a major obstacle (such as a stalled unlighted vehicle) in the roadway in time to allow drivers to come to a safe stop?

/_/ Visibility Would Never Be Adequate

/_/ Visibility Would Sometimes Be Adequate

/_/ Visibility Would Usually Be Adequate

/_/ Visibility Would Always Be Adequate

Comments:

6. Do you feel the existing roadway delineation systems are effective under tonight's conditions?

/_/ YES /_/ NO

Comments:

7. In the interchange area, how accurate are you able to judge speeds and distances of other vehicles?

/_/ As Well As In Daylight For All Distances

/_/ As Well As In Daylight For Short Distances Only

/_/ Not As Well As In Daylight At Any Distance

/_/ Speed And Distance Judgement Of Other Vehicles Is Severely Restricted At Night With No Illumination

Comments:____

8. In driving in the area with no illumination, were you able to detect all the information you desired about the roadway, the shoulder area and elsewhere in the right-of-way?

/_/ In Most Instances This Was Possible

/_/ Some Of The Time

/_/ Never

Comments:____

9. Was headlight glare from opposing traffic a problem to you?

/_/ YES /_/ NO

Comments:____

10. Were gore areas a problem to you in locating?

/_/ YES /_/ NO

Comments:____

11. Did you feel secure in driving through the interchange area?

/ / YES / / NO

Commemts: ____

____

____

12. While riding as a passenger through the interchange, did other drivers in your vehicle seem to make sudden or sharp maneuvers at decision points?

/ / YES / / NO

Comments: ____

____

____

13. How would you describe the conditions that existed tonight with no illumination? Consider signing, marking, delineation, geometrics, etc.

____

____

____

____

____

HIGH-LEVEL ILLUMINATION

DIAGNOSTIC STUDY QUESTIONNAIRE

PART B

PROJECT RF 593

IH 90 - IH 190 RAPID CITY, S. D.

NAME ______________________

AFFILIATION ______________________

____

____

PART B

The questions in this part apply to an evaluation of the study area with the high-level lighting in use.

Please answer all questions to the best of your judgement by checking the appropriate box. Space is provided for any comment you may have on any question. Please use this space, as the comments will be most helpful to us in our evaluations.

1. Were the roadway markings adequate under the conditions with the lights on?

   /_/ YES /_/ NO

   Comments: ____

   ____

   ____

2. Which of the answers below best describe your evaluation of the visibility of geometric features of the roadway such as curves, structures, etc.?

   /_/ Visibility Is Below Minimum Acceptable Level For This Type Facility.

   /_/ Minimum Visibility Requirements Of Normally Alert Drivers Satisfied

   /_/ Visibility Is Adequate For Most Drivers

   /_/ Visibility Was Totally Adequate For Me

   Comments: ____

   ____

   ____

3. Which of the following best describes the visibility of roadside signs?

   /_/ Visibility Never Adequate

   /_/ Visibility Always Adequate

   /_/ Visibility Usually Adequate With High Beams

   Comments: ____

4. Which of the following best describes the visibility of overhead signs with external lighting?

/ / Always Adequate

/ / Usually Adequate

/ / Adequate Sometimes

/ / Never Adequate

How does the visibility of these signs compare with the before study with no illumination?

/ / Better   / / Worse   / / Negligible Change

Comments:

5. Which of the following best describes your evaluation of seeing obstacles in the roadway in time to allow drivers to come to a safe stop?

/ / Visibility Would Never Be Adequate

/ / Visibility Would Sometimes Be Adequate

/ / Visibility Would Usually Be Adequate

/ / Visibility Would Always Be Adequate

Comments:

6. Do you feel the existing roadway delineation systems are effective under the lighting conditions?

/ / YES   / / NO

How do they compare to the before study with no illumination?

/ / Better   / / Worse   / / Negligible Change

Comments: ____

____

____

7. In the interchange area, how accurate are you able to judge speeds and distances of other vehicles?

/ / As Well As In Daylight For All Distances

/ / As Well As In Daylight For Short Distances Only

/ / Not As Well As In Daylight At Any Distance

/ / As Well As In Daylight For Most Instances

/ / Speed And Distance Judgement Of Other Vehicles Is Severely Restricted At Night With The High-Level Lighting

Comments: ____

____

____

8. In driving through the interchange, were you able to detect all the information you desired about the roadway, shoulder, and elsewhere in the right-of-way?

/ / In Most Instances This Was Possible

/ / Some Of The Time

/ / Never

Comments: ____

____

____

9. Was headlight glare from opposing traffic a problem to you?

/ / YES   / / NO

Comments: ____

____

____

10. Was glare from the towers a problem to you?

/_/ YES /_/ NO

At what distance? ____________ feet

Comments: ____

____

____

11. Was locating gore areas a problem to you?

/_/ YES /_/ NO

Comments: ____

____

____

12. Did you feel secure in driving through the interchange area?

/_/ YES /_/ NO

Comments: ____

____

____

13. While riding as a passenger through the interchange, did other drivers in your vehicle seem to make sudden or sharp maneuvers at decision points?

/_/ YES /_/ NO

Comments: ____

____

____

14. Of the following factors generally conceded to be important in illumination systems, how would you rate their importance? (No. 1 is most important).

/_/ Level Of Illumination

/_/ Uniformity Of Illumination

/_/ Area Of Coverage

/_/ Glare Characteristics

/_/ Pavement Brightness

/_/ Others ______________________________

Comments: ______________________________

____

____

15. Do you feel there is any advantage to illumination areas other than the roadway surfaces in interchange areas?

/_/ YES /_/ NO

Give a brief explanation: ______________________________

____

____

____

____

16. Do you feel the high-level lighting closely duplicates daytime visibility as regarding driving tasks?

/_/ YES /_/ NO

Comments: ______________________________

____

____

17. Is there any transitional problem when entering the high-level area?

/_/ YES /_/ NO

Explain briefly: ____

____

____

18. Is there any transitional problem when leaving the high-level area?

/_/ YES /_/ NO

Explain briefly: ____

____

____

19. How would you best describe the conditions that existed tonight with the high-level lighting? Consider signing, marking, delineation, geometrics, etc.?

____

____

____

____

____

HIGH-LEVEL ILLUMINATION

DIAGNOSTIC STUDY QUESTIONNAIRE

PART C

PROJECT RF 593

IH 90 - IH 190 RAPID CITY, S. D.

NAME ______________________

AFFILIATION ______________________

____

____

PART C

This part of the questionnaire is to get your ideas on design of high-level lighting installations. Please do not hesitate to discuss this openly.

1. If you had the opportunity to redesign this system, using five towers and ten lights per tower, what changes would you make?

2. Assuming the floodlights can be re-aimed, what changes would you make on the existing installation?

3. Assuming you had unlimited towers to use, where would you place them? Draw a sketch below if you desire.

(DRAW SKETCH BELOW)

4. Do we need to make changes in signing, marking, and delineation practices when using high-level lighting?

/_/ YES /_/ NO

If so, describe:____

5. The five towers support fifty (50) 1000 watt floodlights. If you had 50 standard 1000 watt luminaires to use, do you feel that you could achieve a lighting design as good or superior to the high-level design?

/_/ YES /_/ NO

Comments:____

APPENDIX B

PSYCHOPHYSIOLOGICAL MEASUREMENTS AS RELATED TO THE OPERATION OF A MOTOR VEHICLE

At the initiation of this research, the South Dakota Department of Highways and the Bureau of Public Roads requested that the proposal to use galvanic skin response, as a measure of driver response, be examined very closely. There was some question as to the suitability of this measure for driver response studies. Therefore, the research staff conducted an exhaustive review of literature on psychophysiological measurements as related to the operation of a motor vehicle.

The discourse that follows is a summary of this review and of private communication with professionals well versed in this area. Briefly, the review indicated that a satisfactory psychophysiological measure of driver responses in the complex driving environment has not as yet been developed. Of the various measures available for use, the galvanic skin response appears to be the most nearly suited to the measurement of driver responses. Therefore, this measure was used in the research, not expecting spectacular results, but hoping that some indications of driver reactions would be given.

Introduction

The operation on any complex piece of equipment produces physical and mental changes which are generally grouped into one gross descriptive term "operator fatigue". This term carries the conotations of reduced effectiveness and increased hazard in the operation of the equipment. The rather simple approach however, does not describe all or even a sizeable percentage of the behavior of the operator. Such gross over-simplifications of the problem have led to attempts to correlate time behind the wheel with accident experience, age with accident experience, etc. with little or no success. This is particularly true when the driving environment becomes one of the variables being correlated.

The question then resolves itself into one of measuring the physical and mental states of the operator. Two fundamental characteristics are of importance[1]:

a. Arousal or Alarm experienced by the operator.

b. The State of Consciousness of the operator.

"Operator Fatigue" is a complex relationship of physical and mental behavior. Complex because the response to a given situation is dependent upon the nature of the stimulus and the condition of the operator. Physical fatigue can be completely overcome, for short periods of time, when the operator is alarmed by an external stimulus[2]. The degree to which a given stimulus creates alarm is dependent upon the level of physical fatigue. When one is alert, the defensive mechanism is more relaxed and thus a given stimulus will produce a lower level of alarm than would occur when the operator is fatigued. This already complex picture is further distorted by the fact that the operator apparently adjusts his level of vigilance in accordance with the amount of time he expects to have to operate the equipment[3].

The following sections will report a few facts on some of the psychophysical measures that can be used in an attempt to measure arousal or alarm.

Physiological Measures of Arousal or Alarm

E. E. G. (ELECTROENCEPHALOGRAM)

G. S. R. (GALVANIC SKIN RESPONSE)

E. K. G. (ELECTROCARDIOGRAM)

Respiration

Skin Temperature

E. M. G. (ELECTROMYOGRAM)

Blood Pressure

Eye Movement

Electroencephalogram (EEG)

The most fundamental method of measuring state of consciousness is the electroencephalogram (EEG) or "brain wave". EEG also responds to arousal but in a negative direction (i.e., reduced activity with increased arousal). Therefore, it is not particularly well adapted to the measure of arousal. The same statement can be made regarding EKG (electro-cardiogram). EKG is considered to be less reliable than EEG[1].

Galvanic Skin Response (GSR)

There are two theories of why there is a change in skin resistance with mental and/or physical activity[4]:

Theory 1 - The resistance of the skin is believed to be due to the polarization-capacity effect that varies as a function of the sweat gland activity. This is supported by measures of skin potential in the absence of an external electrical source.

Theory 2 - The change in skin resistance is simply a measure of the contraction of the smooth muscles in the sweat glands. This is supported by the fact that the time and form characteristics of the potential waves are very similar to those of smooth muscle potentials recorded elsewhere in the body.

The neural and effector mechanisms of the sweat glands underlying the GSR apparently differ to marked degree from the other body responses. The neural response is almost exclusively sympathetic but the effector is acetylcholinic rather than adrenergic as are most sympathetic response agents. Thus, skin response is a complex measure of sympathetic nerve discharge (arousal) and other elements of the autonomic nervous system.

"GSR measures both the state of consciousness and arousal. It reflects the state of consciousness over a more restricted portion of the spectrum and is particularly insensitive to the fractional depressions which are important" in driving. "GSR is not suited to the resolution of drowsiness versus moderate sleep, versus coma, etc."[1] Thus it is well suited for the measure of arousal or alarm but poorly suited to the measure of the state of consciousness (i.e., degree of fatigue in the case of driving).

There are several rather serious limitations to the use of GSR as a measure of alarm. These are:

1. The latency problem
2. The anticipation problem
3. The chance response
4. The response magnitude problem
5. The change in basal resistance
6. The electrode polarization problem

GSR Latency - The time between the beginning of the stimulus and the beginning of a measurable response is defined as the latency of the response. Grim and White[5] indicate that the GSR latency is typically one to one and one-half seconds after the stimulus is applied. Van Twyver and Kimmel[6] state that a measurable GSR can occur up to five seconds after the stimulus is applied. A considerable variation in latency has been found between individuals, however, the latency for a given individual seems to be rather constant for a given day and physical condition of the subject.

Anticipation Response - When a subject is expecting something to occur, a response occurs even though no physical stimulus has been applied. This response is referred to as an anticipatory response and is commonly of greater magnitude than the response associated with the stimulus[7]. The anticipatory response and the response to a stimulus are combined if there is not sufficient time between the anticipation of the stimulus and the application of the stimulus producing a GSR of greater magnitude that would occur if the stimulus is unexpected. Zimmy et al.[8] and Cofer and Appley[10] indicate that this in fact does occur as the GSR response is more pronounced when the subject is expecting a stimuli in the very near future.

Chance Response - Lockhart[9] states that as many as 1/5 of all GSR's are randon (i.e., chance) responses and bear no relationship to an external stimulus. Geer[11] suggests that any response of less than 500 MOHMS greater than the basal value should be considered as chance responses and not included in the analysis. Van Twyver and Kimmel[6] suggest 1% greater than the basal value as the cutoff point. This approach assumes that the chance response amplitude will be considerably less than the response due to a stimulus. The chance response will combine with a stimulus response to produce a response of greater magnitude than would occur with the stimulus alone if the two should occur simultaneously or within a very short time span.

GSR Magnitude - The magnitude of the electrodermal response is affected by many factors. A few of these are:

1. Latency - The shorter the latency the greater the GSR amplitude[12].
2. Body Movement - Any significant body movement will produce a measurable GSR and when combined with a stimulus, response, should be expected to increase the response amplitude[5, 6].
3. Conditioning Effect - The GSR amplitude is greater if the subject is expecting a stimulus[10].
4. Temporal Effect - Some individuals have the capability of controlling their responses and may not respond at all to a given stimulus. In such cases however, a sizeable response may then occur at some later time to a stimulus of rather minor magnitude[9, 10].
5. Alarm or Arousal - The amplitude of the GSR is greater if the

driver is alarmed by the stimulus. This degree of alarm created by a particular stimulus is a function of the degree of vigilance which the driver is exerting at the time the stimulus occurs. The greater the vigilance the lower the degree of alarm. The degree of vigilance appears to vary with the length of time the driver expects to operate his vehicle[3].

6. Operator Fatigue - Physical fatigue has a mixed effect on GSR amplitude. It will increase the latency and thus tend to reduce the amplitude. At the same time, the probability of the driver being alarmed due to the startle effect is higher and the amplitude of the GSR may be greater with increasing fatigue[3].
7. Individual Response - Every individual responds differently and electrodermal response is no exception. Some individuals respond very easily and thus produce a substantial magnitude of response while others respond only very slightly. Comparison between two test subjects is difficult and great care should be taken to match the subjects prior to the test runs if direct comparison of their responses is desired.

Change of Basal Resistance - One of the most difficult problems in interpretation of GSR data is the change in basal skin resistance (drift) which occurs for all subjects. Some have less change than others but very few demonstrate stable base skin resistances. This means that the evaluation of GSR on the basis of amplitude is very difficult as a new base value exists for each response. Good technique and equipment can reduce this problem but it can't be completely eliminated[4, 7, 10].

Electrode Polarization - Grim and White[5] state "Electrode polarization, always a factor to be considered in GSR work, probably had little influence on the results of this study". The implication is that electrode polarization is a serious problem which must be carefully considered any time that GSR is used. A brief review of the problem indicates that only two situations truly produce a problem of this type:

1. When poor contact exists between the electrode and the skin.
2. When the GSR recording time exceeds 15 minutes.

The contact problem can be greatly reduced by using a high quality electrode paste and the recording time problem must be included in the experimental design.

To test for excessive electrode polarization, the two contacts should be shorted out. If a measurable deflection of the galvanometer occurs, excessive polarization probably exists[9].

GSR Parameters

Four basic parameters have been suggested for use in GSR analysis:

1. Frequency range of responses
2. Number of significant responses
3. Peak amplitude time
4. Amplitude
5. Time of Significant GSR

There is some indication that the frequency of GSR's is related to the state of arousal of the individual[1]. The greater the frequency of response the higher the level of alarm in the individual.

The normal range is 0.02 to 2 responses per second. This type of analysis includes the chance of random responses as well as responses to the various stimuli presented to the subject. Correlation of frequency of response with state of arousal is weak and thus this measure has not been widely used.

The number of significant responses per unit of time has been rather widely used. The primary reason appears to be the fact that the change in basal resistance problem is completely eliminated using this procedure. The correlation of the number of significant responses with arousal seem to be high in the single stimulus, single response situations. When continuous recordings of GSR are made, the correlation is much less significant due to the washing out of secondary responses by one primary response and the movement GSR responses which are included[5]. There are indications[6, 9] that the frequency of significant responses does not measure the arousal level as well as might be desired. This has been attributed to equating a response of a magnitude just greater than the level selected as a significant response to a response which goes off the scale.

The use of the number of significant responses as a parameter very often leads to insignificant relationships[6, 8, 9, 11]. It must be considered however, that this conclusion was reached for single stimuli, single response situations and may not be valid for continuous recording situations.

The use of peak amplitude time (i.e., time between response onset and peak response, which is also called GSR recruitment) seems to be more closely associated with the state of arousal than is the frequency of responses[7, 8, 9, 11, 13]. This is a rather simple measure in single stimulus, single response situations but almost impossible to measure in the complex driving environment.

The amplitude of the GSR is directly related to the degree of arousal and is probably the most sensitive index of a change in the external situation of the subject. Geer[11], Zimmy et al.[8] and Lockhart[9] all make very strong cases for the use of amplitude rather than frequency of response in the analysis of GSR data. This requires the use of a basal value just prior to the beginning of the response in order to take into account the change in basal resistance. The use of amplitude in measuring driver alarm is not easy. The stimuli are presented very rapidly and the GSR is a combination of movement and psychological responses to several stimuli at any given time.

The percentage of the recording time during which a significant GSR exists is in reality a combination of the frequency of significant responses and amplitude of the response. The greater the amplitude of the response or the greater the frequency, the greater the amount of time that will have a significant GSR. The effects of secondary responses within a primary response will also be included in this measure. A basal GSR value must be established in order to define a significant response using this procedure. The primary advantage of using this measure is that responses which exceed the range of the recorder and would have to be discarded in the amplitude analysis can be measured with the same degree of success as those which remain within the recorder range.

<u>Analysis of GSR Data</u>

Geer[11] suggests that a change of 500 MOHMS or more from the basal skin resistance should be considered significant. Van Twyver and Kimmel[6] indicate that any response of less than one percent greater than the base value should be disregarded in the analysis. These two basic approaches to the problem of selecting the level of response which is to be considered significant is typical of how the problem of normal variation or chance responses are eliminated from the analysis. The selection of the criteria as a basis for defining significant responses is dependent upon the type of equipment being used and magnitude of the response for the particular test subject involved. It therefore, cannot be specified for every situation and must be determined in accordance with the particular requirements of the study.

The body movement responses which occur with any appreciable movement of the body make the interpretation of GSR data somewhat difficult and tends to obscure the meaningful responses. Van Twyver and Kimmel[6] suggest that an EMG (electromyogram) of a muscle associated with the member to which the GSR electrodes are attached can be used to correct the GSR data for body movement. In their case, they exclude from the data any GSR which occurs within five seconds of a significant EMG. Using this procedure they were able to find a significant correlation when none existed in the original data. This approach would be somewhat difficult to use in a driving situation as the driver's body is almost continually in motion.

The frequency changes of the GSR are commonly transformed using a logarithmic or square root transform prior to evaluation. This is done in an attempt to correct some of the deficiency of the orginal frequency distribution in regard to the statistical model assumed and thus permit statistical tests to be made on the differences between two or more treatments. The transforms usually take the form $\sqrt{x+1}$ or $\ln(x+1)$. The quantity x+1 is used as x is commonly a relatively small number.

The magnitude of the skin resistance change (difference between the basal value and peak value) has also been used as a measure of arousal. The basic considerations are essentially the same as GSR measurements and many authors use skin resistancy and GSR interchangeably. The magnitude of the response is a rather sensitive index of arousal and is recommended by several researchers[8, 9, 11]. In the driving environment, the almost continuous presentation of stimuli make the determination of the base value difficult and, since a significant change of resistance can occur up to five seconds after the application of the stumulus[8], the two or more responses may superimpose and make the magnitude of response meaningless. Discarding these responses from the analysis would tend to bias the results toward the lower amplitude responses as there is a greater probability of superimposition with responses of greater magnitude.

When magnitude is used, it is very often converted to conductance by taking the reciprocal of the skin resistance difference. Conductance is used as a more convenient measure of arousal. As an example, Geer[11] used a conductance measure determined as follows:

> The reciprocal of the initial skin resistance subtracted from the maximum skin resistance value was taken and the result multiplied by 10^9, 1.0 added to produce the conductance index.

<u>Selecting the Test Subjects for GSR</u>

The reporting of GSR research data will very often indicate that one or more test subject's data had been omitted from the analysis. Sometimes a vague reference is made to an abnormal subject or a non responsive subject. As previously reported, all individuals do not respond in the same manner to the various types of stimuli presented to them. Cofer and Appley[10] state:

> "Individuals that tend to lose control during a critical situation usually do not exhibit temporal responses at some later time. Those who do well under stress usually do have some type of temporal response at some later time."

This simply points out the necessity of selecting test subjects which show a response to the desired stimulus which is of sufficient magnitude to record and not so great so that even the very minor stimuli produce a substantial response. Since individuals do not all respond in a similar manner, before and after studies must be conducted with the same subject in as nearly similar conditions as it is possible to attain.

Dardano[13] investigated the feasibility of predicting reaction time from measurements of skin resistance (actually conductance). A relationship was found to exist but it was very weak. Dardano concluded that reaction time could not be predicted with a reasonable degree of accuracy using skin resistance measurements. It is highly probable that the reverse is also true and there is little possibility that the magnitude of the GSR can be predicted from a physical test.

EKG (Electrocardiogram)

EKG is a measure of the electrical potential associated with the action of the heart. It tells a great deal about the cardiovascular state of the individual but doesn't measure emotional change to any marked degree in the single stimulus, single response situations. The use of EKG in a complex environment has been limited as most researchers did not feel that a sufficient measure of arousal would be obtained[4]. EKG measures are usually heart rate or magnitude of the potential. Heart rate is commonly transformed by a log or square root transform in order to permit statistical analysis of the data.

Cardiotachometer

The heart rate can also be measured using a pneumatic device known as a cardiotachometer. This device has had limited use primarily due to the fact that the heart rate is "not particularly well related to emotional change"[4]. A change of heart rate is a complex reaction which results from sympathetic and parasympathetic effects but is also affected by the moderator nerves. The latency on heart rate is rather large and the changes which occur must be considered as complex measures of stimuli presented during a considerable period of time. Typically, cardiovascular latency is 2.5 to 5 seconds and the reaction lasts 15 to 20 seconds[16]. The anticipatory response is also a difficult one to handle.

Several measures of heart action other than rate have been suggested. To establish a base value for any given situation, Zimmy et al[8] used the average of the last four heart beats just prior to the stimulus. The average of four beats was necessary in order to smooth out the normal variation between beats. They then used two measures of heart activity which they believed should best indicate the level of excitation:

1. Heart Rate Acceleration - Maximum rate of change of heart rate after stimulus is applied with a limit of 12 beats.
2. Heart Rate Change - the mean of the fastest and next succeeding heart beat.

The conclusion of this study was: "The experimental conditions did not produce a measurable effect on cardiac activity. The GSR amplitude demonstrated the greatest effect."

Deane[14] conducted a series of experiments relating the heart rate to an inducted shock. The measure used was the difference in heart rate before and after the application of the shock. The results indicate that the heart rate changes with the inducted shock or when the subject is told to expect a shock. The rate did not return to the initial value for a considerable period of time thus a tendency exists for the heart rate to drift upward. This effect is also noted in the discussion of the GSR. It is known as the "Law of Initial Values" and refers to the fact that any physiological function will either show an increase or decrease as the result of certain kinds of stimulating conditions depending upon the initial level of the particular function prior to stimulation.

Blood Pressure

The use of blood pressure changes to indicate the level of excitation has been used for many years. There are two blood pressure measures: The Systolic or high blood pressure and the Diastolic or low blood pressure. Blood pressure can be measured in many ways, however, the system most convenient to use is a pneumatic device attached to one of the body extremities, usually the arm. The primary measure of excitation is the systolic blood pressure where the blood flow is completely stopped. This measure cannot be used on a continuous basis and therefore, is not acceptable for studies of driver tension. Average blood pressures have been used (somewhere between the systolic and diastolic levels) but are poorly correlated with the level of excitation.[4]

Respiration Rate

The use of changes in the respiration rate as a measure of arousal has been rather common. This measure is particular well suited as an indicator of certian emotional situations, especially startle, conscious attempts at deception and conflict. Like heart rate, respiration rate is a complex reaction which includes sympathetic and parasympathetic effects and certain moderator nerve effects. The complex nature of respiration changes in complex situations makes interpretation very difficult for most conditions similar to those associated with driving.

Skin Temperature

The temperature of the body as a whole remains relatively constant but there are variations between the various parts of the body. The skin temperature in particular is subject to a considerable degree of variation depending upon the physical and emotional state of the subject. The skin temperature increases under emotional stress and decreases in a relaxed state or with emotional security. This measure has not been widely used. The most common reason appears to be the latency is rather large and interpretation in single stimulus, single response situations is difficult.

Electromyography (EMG) (Muscle Tension)

Associated with the action of every muscle is an electrical potential which varies as the muscle is contracted or relaxed. The measure can be magnitude of the potential field[15] or frequency of muscle of action[6]. When frequency is used, a log or square root transform is commonly performed in order to permit statistical analysis of the data.

Stevens[4] suggests that since EMG is particularly subject to body movement more than one sensor should be used. The muscle or muscles to be used in any particular situation should be selected after careful study of the movements required in the task involved. In the case of driving, the muscle at the back of neck and in the calf of the leg appears to be the best measure of driving associated tension.*

Van Twyver and Kimmel[6] used the frequency of muscle action (movements per minute) transformed by $\sqrt{X+1}$ (where X is the frequency of muscle action) and expressed the transformed values as a percentage of the transformed frequencies during a five minute rest period. Any transformed frequencies less that 10% greater than the average transformed five minute rest period frequency were discarded in the analysis. This procedure alone did not produce a significant correlation with the other variables being measured but when combined with GSR did produce significant correlations as previously reported.

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*Personal correspondence with Dr. Slade Hulbert of the University of California at Los Angeles.

Eye Movement

Attempts to correlate the various movements of the eye with the emotional level of the subject have been conducted for many years. Three basic measures are used:

1. Pupillary response
2. Eye blink or eyelid movement
3. Eye movement

The pupillary response is extremely complex and attempts to correlate these responses with a particular stimulus have been noteably unsuccessful.

Eye blink or eyelid movement have been correlated with certain emotions but these correlation are usually rather weak. Stevens[4] states that eye blink "may or may not be related to emotion. The rate and degree of response is highly variable between and within individuals. Eye blink measures excitement, embarassment and similar emotions, if anything." Care must be used in selecting the test subjects and "calibration" or initiallization runs must be made prior to each set of observations.

Movement of the eyeball is another measure of the degree of alarm that the individual experiences due to a visual input or a lack of it. When the individual feels uncomfortable and expects a visual input he begins a series of rapid eye movements searching the visual field for the information he desires. The frequency of eye movement is significantly greater in this situation than the frequency under normal conditions. This measure has been successfully used to measure the degree of arousal in the individual.

Summary

The previous discussion indicates that a satisfacrory psychophysiological measure of driver arousal in the complex driving environment has not as yet been developed. GSR appears to be the most reliable measure in the single stimuli, single response situations due to its rather short latency.

Heart rate, muscle movement frequency, skin temperature and eye movement all appear to have some merit in measuring the complex reaction to the driving environment, however, the cause and effect relationship is impossible to determine using these measures. GSR still appears to be the most nearly suited to the measurement of driver arousal. Physical measures (such as steering wheel reversals) may be more strongly correlated with alarm than any of the psychophysical measures mentioned above, however.

Finally, the information included in this evaluation is by no means absolute. It should serve as a basis on which to begin the planning of studies in which psychophysiological measures are expected to be used.

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APPENDIX C

ACCELERATION NOISE

Traffic engineers are becoming more and more cognizant of the fact that judgement and motivation of the driver is an important consideration. Due to the freedom of individual transportation, the driver has considerable influence because he has the latitude to select the manner in which he operates his vehicle. An evaluation of the individual driver, then, could facilitate the development of a quantitative measure of level of service or quality of traffic operations.

One concept of the measurement of level of service or quality of operations is acceleration noise. The term "acceleration noise" was first used by Montroll and Potts[1] in their car-following theory as a measure of human response to external stimuli, or changing relationships between vehicles in a traffic stream. This concept is based on the hypothesis that a driver operating a vehicle on an open road without the influence of traffic or changes in roadway geometry attempts to maintain a uniform velocity, but never succeeds. In actuality, he accelerates and decelerates, even on the ideal roadway, and it has been shown that the distribution of the acceleration is essentially normal. The measurable quantity of acceleration noise on an ideal roadway is generally referred to as natural acceleration noise.

As the driver is exposed to physical, environmental and traffic conditions less than ideal, the velocity of his vehicle becomes less uniform and the accelerations are increased due to these external stimuli. In other words, the smoothness of traffic flow is inversely related to these external stimuli. Therefore, a measure of the smoothness of driving is the dispersion of accelerations, or acceleration noise. This quantity is defined mathematically as follows:

$$\sigma = \left(\frac{1}{T} \int_0^T [a(t)]^2 \, dt \right)^{1/2}$$

where T is total running time and a(t) is the acceleration at time t.

An applicable equation was developed[2, 3] from earlier work by Jones and Potts for approximating acceleration noise. If V(t) and a(t) are velocity and acceleration, respectively, at time t, then the average acceleration of the car for a trip of running time T is:

$$A_{avg} = \frac{1}{T} \int_0^T a(ti) \, dt = \frac{1}{T} [V(t) - V(0)]$$

By analogy with the classic equations of the standard deviation of a set of numbers, acceleration noise can be written as

$$\sigma^2 = \left(\frac{1}{T} \int_0^T [a(t_i) - A_{avg}]^2 dt \right)^{1/2}$$

and the variance as

$$\sigma^2 = \frac{1}{T} \int_0^T [a(ti) - A_{avg}]^2 dt$$

By expanding and combining terms, the variance equation is reduced to

$$\sigma^2 = \frac{1}{T} \int_0^T [a(ti)]^2 \, dt - [A_{avg}]^2$$

An approximation of the value of σ^2 can then be obtained by

$$\sigma^2 = \frac{1}{T} \sum_{i=0}^{T} \left(\frac{\Delta v}{\Delta t} \right)^2 \Delta t - \left(\frac{vt - v_0}{T} \right)^2$$

where Δv = a change in speed in mph

Δt = time duration of speed change in seconds

v_0 = vehicle velocity at time zero in mph

vt = vehicle velocity at time T in mph

For this research Δv was selected as 2 mph. In other words, a speed change of $\pm$ 2 mph was considered a significant change in operation. This value was selected on the basis of previous work by Rowan[4].

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APPENDIX D

TABLE 1

ANALYSIS OF VARIANCE, SIOUX FALLS SPEED DATA

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-RATIO
Treatments	17	3085	181.47	
Observers	3	112		
Lighting (L)	2	59	29.50	.604
Sections (S)	5	2798	559.60	11.46 *
L X S	10	228	22.80	.47
Error	17	830	48.82	

*Highly Significant (99% Level).

TABLE 2

ANALYSIS OF VARIANCE, SIOUX FALLS ACCELERATION NOISE DATA

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-RATIO
Treatments	17	219,384	12,905	
Observers	3	15,253		
Lighting (L)	2	17,866	8,933	.827
Sections (S)	5	165,874	33,175	3.073*
L X S	10	35,644	3,564	.330
Error	17	183,530	10,796	

*Significant (95% Level).

TABLE 3

ANALYSIS OF VARIANCE - RAPID CITY SPEED DATA

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-RATIO
Treatments	11	277	25.18	
Observers	3	322	107.33	
Lighting (L)	2	194	97.00	4.073*
Sections (S)	3	48	16.00	.672
L X S	6	35	5.83	.245
Error	11	262	23.82	

*Significant (95% Level).

TABLE 4

ANALYSIS OF VARIANCE - RAPID CITY ACCELERATION NOISE DATA

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-RATIO
Treatments	11	334.43	3,040.27	
Observers	3	238.04		
Lighting (L)	2	193.96	9,698.00	5.896*
Sections (S)	3	72.53	2,417.67	1.470
L X S	6	67.94	1,132.33	.688
Error	11	180.94	1,644.91	

*Significant (95% Level).