zone diversions proved favorable, low-priced, temporary markers should be developed. In addition, a faster, less labor-intensive method of marker installation is needed.

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The contents of this paper reflect my views, and I am responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the New Jersey Department of Transportation or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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Abridgment

Potential Adverse Impacts of Reflective Solar Spot Glare on Motorists: Seattle's Experience

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A discussion of reflected solar spot glare, based on research in Seattle, is presented. The topics discussed include the causes of reflected spot glare, when and where it is most likely to occur, how it can be predicted, how it can affect the vision of motorists and thereby pose a threat to the safety of the driving public, and how it can be avoided through sensitive environmental design. One factor that makes reflective spot glare a potential traffic problem is that unlike the sun, which we are generally accustomed to in the sense that we know its location in the sky, solar-caused spot glare is often visible where one least expects it, creating a surprise reaction for the unaccustomed viewer. Such impacts are often not easily mitigated and (because an offending structure may have a life expectancy of 50 years or more) should be considered long lasting. Experience in Seattle, Dallas, and other cities indicates a growing problem, with nationwide implications, due to the use of new, highly reflective building materials. By graphically depicting patterns of reflective spot glare during certain periods of the year near potential or suspected trouble spots such as heavily traveled urban arterials, one can predict fairly accurately the potential for adverse glare impacts, their duration, and their intensity before buildings are built. The Seattle study stresses that the solution is not to prohibit the use of highly reflective building materials but rather to ensure that they are installed or applied in such a way as not to create visible glare within the driver's task-oriented cone of vision.

Glare is a problem nearly all of us experience to one degree or another on a daily basis. The problem this paper addresses is solar-caused glare given off by specular surfaces, which can adversely affect the vision of motorists and thereby pose a threat to the safety of the driving public. Examples of such surfaces include bodies of water, shiny surfaces such as chromed car bumpers or window trim, and, lately, reflective coated glass that is used on the exterior of buildings. Although disabling solar-caused spot glare from these surfaces can be reduced for motorists--by using matt rather than glossy surfaces and highway alignments that help direct the motorist's line of sight away from sunlight reflecting off waterways and other highly reflective surfaces--it can never be fully prevented.

REFLECTIVE BUILDING MATERIALS AND SOLAR SPOT GLARE

A new glare source of substantial magnitude not previously anticipated in highway design is that caused by the increasing use of reflective coated glazing in buildings. Recently constructed buildings throughout the country are now using these and other highly reflective materials and, in some cases, even older buildings are being retrofitted with them. Experience in Seattle, Dallas, and other cities indicates a growing potential problem, with nationwide implications, as these buildings (depending on siting, orientation, and time of year) develop visible specular solar spot glare of sufficient magnitude and duration to impair the vision of motorists using nearby major arterials.

The glare caused by the recently opened Park Hilton Hotel in downtown Seattle adversely affects nearby freeway users traveling away from the sun in a northerly direction. A number of near accidents were reported by motorists because of alleged glare effects on their vision resulting from the building, and the speed of travel in the affected northbound freeway lanes dropped from 40-45 to around 25 miles/h when the problem was occurring.

Figure 1 shows the reflective solar spot glare caused by this structure. At 40 miles/h, motorists are exposed for more than 20 s; as traffic slows down, exposure increases (because of less intense background lighting and size of glare patterns, relative glare intensity was found to be greater for northbound traffic driving away from the sun than for southbound traffic driving in the direction of the sun).

The building's owners were directed to seek ways of removing the problem, since both the city and state departments of transportation believed that the building posed a hazard to the traveling public. Informal reports from other cities indicate that they are experiencing similar problems.

If reflected solar spot glare does pose a potential threat to the health and safety of the driving public, what can be done to lessen its impacts in the future? This paper discusses the causes of reflected spot glare, when and where it is most likely to occur, how it can be avoided through sensitive environmental design, and how it can be predicted by using simplified graphic techniques.

With increasingly stringent federal and local standards for energy conservation, we can expect to

Figure 1. Reflective solar spot glare on I-5 in Seattle.

see the continued use of highly reflective materials to lessen cooling requirements for new buildings, even though alternatives such as reduced window size, recessed windows, or solar sun screens may achieve the same end. It is to be hoped that, by understanding the environmental impacts of these and other highly reflective materials, architects and building designers will be able to mitigate adverse impacts before they occur. As a condition for the approval of such materials, highway engineers, after further research, may wish to require their use within a specified distance of major arterials to show that they are not apt to adversely affect the traveling public.

Light and glare are in the environment at almost all times and affect us to different degrees, depending on their intensity, the intensity of the background lighting, the angle at which they are viewed, and our susceptibility to them. The problem of glare resulting from reflected sunlight has been recognized as potentially serious enough to be addressed along with other types of impacts in the preparation of environmental impact statements in many states.

In September 1978, the city of Seattle adopted an ordinance establishing policies for the substantive implementation of the Washington State Environmental Policy Act of 1973. Specifically, in terms of light and glare, this ordinance authorizes the responsible city official or authorizing agency to require mitigation of the adverse impacts of lighting and glare by measures such as

1. Limiting the reflective qualities of surface materials that can be used in development;
2. Limiting the area of intensity of illumination; and
3. Limiting the location or angle of illumination.

One of the difficulties with considering the adverse impacts of glare, and particularly specular glare from reflected sunlight, was that tools for disclosing these impacts did not exist. With sunlight the problem of disclosure was even greater than with other sources, since the sun is not stationary but constantly changing its location throughout the day relative to objects on earth.

Besides impairing a person's ability to see detail clearly, bright light sources such as the sun or its reflected image can actually create visual discomfort or impair one's vision. Glare itself usually refers to the condition of lighting that causes eyestrain or discomfort and reduces visibility. Usually, unexpected, bright, unscreened sources of light are considered to be a visual nuisance; in some cases, they are debilitating enough to be considered a threat to an observer's well-being, especially if the observer is carrying out a task such as driving a motor vehicle at high speed or in crowded conditions that require good visibility of directional signs or nearby traffic conditions. Glare sources that distract drivers or blur their vision should be avoided whenever possible.

The sun is the greatest single source of both visual discomfort and disability due to glare in the environment. Reflected specular glare from the sun is most noticeable during the early or late hours of the day, when the altitude of the sun is still relatively low, or during the winter months at latitudes greater than 40°, where the sun is continuously at an angle of less than 30° with the horizon. Cars, because of their reflective bumpers and windshields (which, because of their slanted angle, often reflect sunlight that normally would not be visible), are often common sources of visible specular glare from the sun.

The major determinants of how adverse the impacts of solar-caused glare will be are (a) the intensity (luminance) of the sun, (b) the intensity of the surroundings in which it is seen, and (c) the reflectivity of the surface giving off the light.

The luminance of the sun and, subsequently, its reflected glare are affected by its altitude. The sun has its lowest luminance at sunrise and sunset, when it approximates a 100-W tungsten bulb. As the sun rises above the horizon, the amount of atmosphere its rays must pass through is reduced, and this results in a significant increase in luminance--e.g., from approximately 3870 cd/in^2 near the horizon to nearly 1 million cd/in^2 above the horizon (1, Figure 8).

In terms of visual impacts on motorists, specular surfaces such as reflective coated glass are worse than opaque porous surfaces, even though the former may reflect a smaller percentage of the sun's rays back toward the observer. This is because the rays from reflective coated glass are reflected back in a near-parallel fashion, maintaining much of the integrity and intensity of the original light source, whereas the opaque porous surface scatters the sun's rays. The reflectivity of a specular surface is also affected by the angle of incidence of the light rays striking it. As this angle increases to more than 70°, even nonreflective glass takes on approximately the same degree of reflectivity (±90 percent) as reflective coated glass that has an average daily reflectance of 35-44 percent.

In evaluating the impacts of glare on people, normal viewing angles should be used. This is defined as an angle 30° above the horizontal and an angle of 65° to the right or left of a forward line of sight. For motorists, a more narrow cone of vision can be defined depending on the speed of travel. The higher the speed, the narrower is the cone of vision and the farther ahead one's eyes focus on the roadway.

Since spot glare reflected off large specular surfaces was known to be a potential problem that could at times impair the vision of motorists and pedestrians alike by forcing them to look away from the glare source, there was a need to develop an easily usable technique for disclosing the geographic extent of glare at a particular time and its probable intensity or brightness. It was found that much of the existing disclosure was superficial and did not adequately convey graphically or verbally the geographic extent of the effects of glare. As a result, a methodology similar to that used for depicting shadows caused by buildings and other objects was developed to allow one to diagram sunlight reflected off mirrored or specular surfaces.

Weather also plays an important role in the frequency of occurrence of reflective glare from sunlight. Although November, December, January, and February have only about half as many clear days (34) as the months of May, June, July, and August (84), in the Seattle area the sun was found to pose a much greater threat at this time of year, because of its low altitude in the sky and subsequent visibility, than during other months, when it shines more but is at a higher altitude in the sky and therefore is less visible.

By graphically depicting reflective spot glare patterns during certain periods of the year, especially when the altitude of the sun is less than 30° above the horizon, and by paying particular attention to potential trouble spots, such as heavily traveled urban arterials and nearby residential areas, the potential for adverse glare impacts, their duration, and their intensity can be predicted with a fair degree of accuracy.

The impacts of unanticipated reflective glare are often not easily mitigated. Since an offending structure may have a life expectancy of 50 years or more, the impacts on the environment should be considered long lasting. Had Seattle's new Park Hilton Hotel across the street from I-5 been diagrammed for the morning rush hours--say, on December 22--it would have been apparent before the building was constructed that the south facade would be reflecting visible spot glare from the sun in and parallel to the northbound lanes of the freeway for a distance of more than 0.5 mile (approximately 1200 linear ft) during the morning rush hour. It would also have been known that the angle of reflectance of the glare was much less than 30° and that the resulting glare would be continuously visible by motorists in the task-oriented line of sight for as long as 30 s. Persons on the freeway who experienced the reflective solar spot glare from this building in January 1979 indicated that their visibility was reduced dramatically, in some cases to about two car lengths.

Had this glare problem been identified earlier, mitigating measures could have been taken. A slight reorientation of the windows on the south facade from their present southeast orientation to a southern orientation would, it was shown, have substantially reduced the geographic extent and time of exposure of the glare experienced by northbound motorists. In addition, the angle of reflectance would have been such that drivers could have blocked much of the glare by using their sunvisors.

Since visible reflected spot glare resulting from direct sunlight is invariably less intense than looking at the sun itself, some people question whether or not we should be concerned about it. Even at low levels of reflectance, reflective spot glare from the sun is enough at nearly all times to create sufficient visual discomfort to cause the observer to either look away from it or block it from view. Even when the sun's image is seen reflected off clear glass that has an average daily reflectance of, say, only 8 percent, its intensity or luminance is nearly 10 000 times greater than the borderline of comfort-discomfort measured for interior light sources (2). In addition, the sun is a natural phenomenon that we have little control over, whereas a lot of visible reflective glare is man-made. Another factor that makes reflective spot glare a potential traffic problem is that unlike the sun, which we are generally accustomed to in the sense that its location in the sky is known, spot glare from the sun is often visible where least expected, creating a surprise reaction for the unaccustomed viewer.

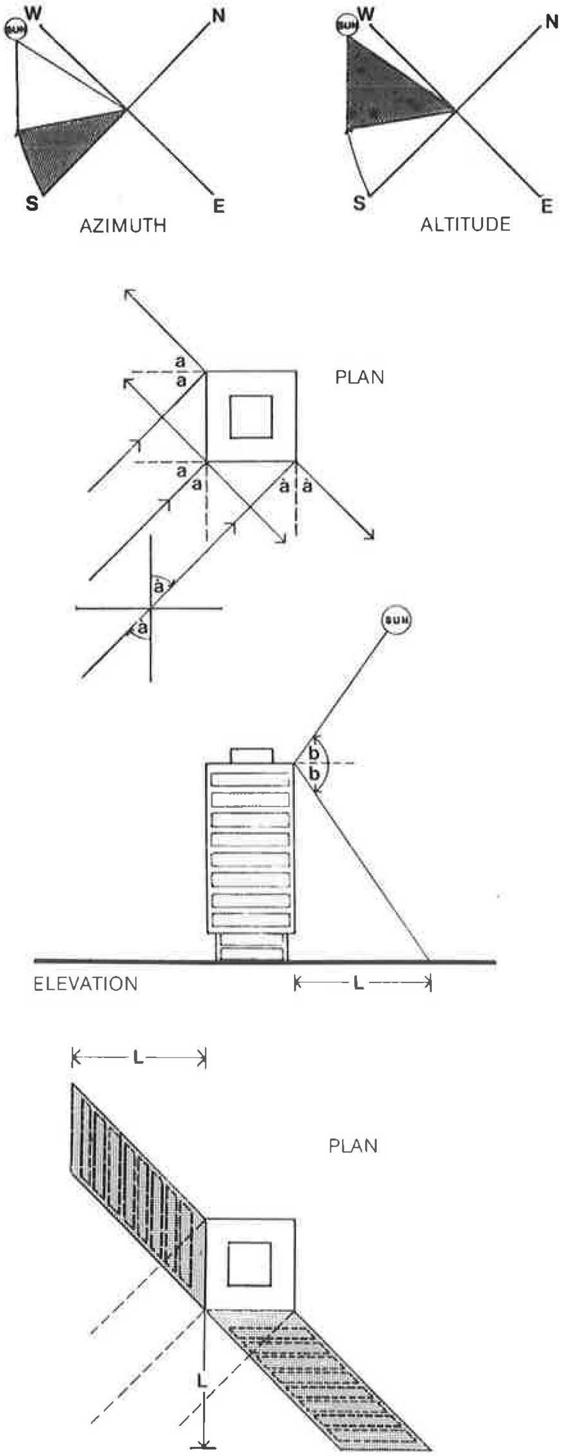
SOLUTIONS TO THE PROBLEM

Many of the problems arising from the use of highly reflective materials on new buildings near major urban arterials can be avoided by the proper design of these structures. The Seattle Light and Glare Study (3) stressed that the solution was not to prohibit the use of these materials but rather to ensure that they were installed or applied in such a manner as not to create visible glare within the driver's task-oriented cone of vision.

By using the simplified solar glare diagramming technique shown in Figure 2, the reflected glare patterns of a building can be projected before it is built to determine their physical extent during different periods of the year. From this, one can tell whether any major arterials and lanes of travel nearby would be affected. Where adverse impacts are indicated, modifications should be made before the structure is erected.

Besides changing the orientation of the building or the reflective surface on it, another way of controlling reflected solar glare off specular surfaces is to shield these surfaces or to intercept the reflected rays before they can affect the observer. Glare off water can often be reduced by landscaping with trees and shrubs or by using screening devices. Glare off smooth, reflective

Figure 2. Simplified methodology for solar glare diagrams.



As in the case of shadow diagramming, in order to cast reflective spot glare it is first necessary to know the azimuth and altitude of the sun at the time of day and time of year we want to show the patterns. (Often June 21 and December 21 are used to show the extremes of variation.) Such information is available in most solar handbooks.

With the azimuth and altitude of the sun known, it is then possible to diagram most spot glare situations caused by direct sunlight using simple orthographic projection. For simplification, it is usually assumed that the whole exterior surface of the building being diagrammed is highly reflective.

Using the principal that the angle of reflectance of parallel light is equal to the angle of incidence, we begin by extending in plan parallel lines to the corners of the building at the same angle as the sun is in plan (azimuth). Since sunlight is reflected off a specular surface at the same angle as that at which it strikes it, we can easily determine its angle of reflectance in plan, since it will be the same as the angle of incidence, i.e. angle A_1 = angle A_2.

In order to determine the horizontal extent of the reflected sunlight off the exterior of the building, we use the sun's angle in elevation (altitude) measured from the building's highest points. Again, using the principle of reflectance, we know that angle B_1 is equal to angle B_2.

By repeating this process for two or three different time periods throughout the day, a Composite Reflected Sunlight can be prepared.

surfaces such as glass can be prevented much or all of the time by the use of screening devices that intercept the sun's rays before they can reflect off the surface.

One of the major recommendations coming from the Seattle study would require the owners of any new or remodeled structure on which reflective coated glass or other highly reflective specular surfaces are to be installed (when the structure is located within 400 ft of a designated urban arterial that has posted speeds of 40 miles/h or greater and carries at least 20 000 vehicles/day) to have such materials applied or installed in a manner that would not adversely affect the vision of motorists. As a means of showing that solar-caused reflective spot glare would not occur within a driver's normal cone of vision, applicants for building or use permits would be required to submit diagrams of reflective solar spot glare for the winter and summer solstices. Where problems are indicated, mitigating measures are required. The type of mitigating measure really is a function of the particular glare problem identified. It is for this reason that full, definitive disclosure should be provided at an early stage in the design process so that solutions are incorporated architecturally in the design of the structure. We are also learning, by looking at examples of structures already built, that certain architectural configurations, like certain materials, pose greater visual hazards than others and should be avoided in environmentally sensitive areas such as along freeways.

Highly luminous light and reflected solar spot glare pollute the visual environment in much the same way that loud noises pollute the auditory environment. The solution is not reflecting it onto one's neighbors but rather trying to control it at the source or intercepting (absorbing) it before it does harm. Where neither of these solutions works, glare should at least be reflected away from those areas where it can do the greatest harm.

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Effects of Turning Off Selected Roadway Lighting as an Energy Conservation Measure

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In early 1973, the continuous roadway lighting on the southbound main lanes of Interstate 35 through Austin, Texas, was turned off as a power-saving measure in response to a critical area energy shortage. Analyses of accident data revealed that this cutback in roadway lighting significantly increased the frequency, rate, and severity of nighttime accidents in the affected freeway sections. The most notable increases were associated with a sharp rise in nighttime rear-end and pedestrian-related accidents. The cutback in roadway lighting saved approximately 450 000 kW·h of electrical power per year, enough to maintain 20 all-electric homes of average size for the same time period. In terms of energy cost savings to the city, this reduction amounted to $25 250/year. In addition, estimated savings of $2500/year in lamp-replacement costs were realized through the cutback. However, increases in accident costs after the lighting cutback were conservatively estimated to be slightly less than $17 000/year. Therefore, although positive energy conservation gains were made through the lighting cutback, these gains were accompanied by a measurable decrease in motorist safety.

On January 3, 1973, the Texas State Department of Highways and Public Transportation (TSDHPT) granted the city of Austin permission to turn off the continuous roadway lighting on the southbound main lanes of Interstate 35 through the city. The city requested the lighting cutback in response to a critical shortage of electrical power in the area. After the department's authorization was received, the lighting cutoff was carried out by city technicians between January 9 and 15, 1973.

The lighting reduction affected only the main lanes in three freeway sections that had a total length of 7.2 miles. Section 1 had median-mounted lighting and all lighting for the southbound lanes was turned off. Sections 2 and 3 had shoulder-mounted lighting on both northbound and southbound lanes and, again, all lighting for the southbound lanes was turned off. Ramp and frontage road lighting in the three sections was not affected by the cutback.

All three sections had four 12-ft travel lanes (two lanes per direction) with inside and outside shoulders. A 30-ft clear ditch median separated opposing traffic in section 1. A 20-ft raised median and semirigid barrier (W-beam section) separated traffic in sections 2 and 3.

Table 1 summarizes the roadway lighting characteristics of each of the three sections and also gives the average daily traffic (ADT) for each section averaged over the four-year study period. There were light to moderate increases in traffic volume on the three sections during the four-year study period, ranging from 6 percent for section 2 to 32 percent for section 1. In the computation of accident rates, 28 percent of the ADT was assumed to be nighttime traffic for all sections.

ACCIDENT STUDY

An extensive analysis of accident data gathered from all three study sections was conducted to determine the effects of the lighting cutback on motorist safety. The data, furnished by the Austin Transportation Department, consisted of computerized coded records of all accidents that occurred in the three sections during the study period. These records included information on accident location, type, and severity as well as lighting conditions during each accident. Two years of before data and two years of after data were evaluated.

The accident study revealed that 296 accidents were reported to have occurred on the main lanes of I-35 during 1971 and 1972 and 254 accidents during 1973 and 1974. It should be noted that, since entrance and exit ramp lighting was not reduced in the after period, accidents that occurred at the ramps were omitted from consideration.

Accident Frequency

Table 2 summarizes the changes in accident frequency that occurred between the before and after periods. The data in the table indicate that there was a significant decrease (-22.1 percent) in accident frequency in the after period except on the unlighted southbound side at night (1,2), where there was a significant increase in accident frequency (+47.1 percent) in the after period. The same trends were observed for all three study sections