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A PRELIMINARY COST-BENEFIT STUDY OF HEADLIGHT GLARE REDUCTION

by

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ABSTRACT

A preliminary cost-benefit analysis is made of means for and results of reducing the deleterious effects of headlight glare from opposing vehicles on the highway. It is shown that polarization of headlights may be a feasible solution in terms of reduced accident costs.

ACKNOWLEDGEMENT

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TABLE OF CONTENTS

LIST OF TABLES

I. INTRODUCTION

Headlight glare is considered to be a serious driving hazard by almost every nighttime vehicle driver. Since the beginning of the automotive industry, literally thousands of designs of headlamps and headlighting systems have been evolved, attempting to provide adequate lighting for the driver to see the road ahead while reducing the glare that he must face from approaching vehicles. The present vehicle headlamp systems represent the latest industry-government accepted compromises of these two factors. The resulting lighting is not satisfactory, however. It does not provide sufficient illumination of the roadway ahead at modern highway speeds and it does not provide protection to the opposing driver from Disability Veiling Brightness (glare) which seriously impairs his vision.

There are solutions to this problem and this study will provide information which can assist in determining which of the several solutions is the most feasible for nationwide application.

A number of means exist for eliminating or greatly reducing glare while permitting increased illumination of the roadway ahead of the driver, and these must be carefully considered before proposing any major change in nighttime driving practices for the entire nation.

On undivided, multilane highways with two or more traffic lanes in each direction, passing is normally not allowed over the roadway centerline. In many cases, a median strip is provided between the opposing traffic lanes, sometimes including barrier fencing. Where such exists, glare screens erected on this fencing, or planting of trees or shrubs in the wider medians, will greatly reduce the glare from opposing vehicles at short intercar distances where it is most objectionable and dangerous. This may not, however, provide acceptable extinction of oncoming vehicle lights under certain topographical conditions, particularly where road sections are separated by a stretch of lower elevation. The beams, under this condition, will be projected above the glare screen and the drivers will be faced with sudden flashes of light which may be even more disturbing and dangerous than a steady, continuous beam. In any case, the glare screen cannot be considered for two-lane highways where passing must be allowed over the roadway centerline. Since two-lane highways constitute the major portion of the rural highway system and the locale of the greatest glare hazard in driving, as borne out by their higher night accident experience rate, the above solution for multilane highways is of questionable importance in the overall issue.

Another solution is to establish one-way traffic on all streets and roads. This might be reasonably accomplished in most urban areas; however, in rural areas, it would seem impractical without the virtual duplication of the existing two-lane major highway network. That is, where surfaced or improved two-lane roads presently exist which could carry traffic in one direction, a parallel, equally improved, two-lane road sufficiently near for user convenience generally is not available to carry the opposing traffic. This would require the improvement of a possibly available unimproved road, the construction of a completely new roadway, or conversion of the two-lane roadway into a multilane section of road (where an adjacent parallel road was not practical).

Work in prior phases of this program, as well as that conducted by many other investigators[1, 2],* has shown that **a practical, feasible and essentially completely developed solution exists which will not merely reduce but will virtually eliminate glare from opposing vehicles, while providing more illumination for the highway scene ahead of the vehicle than is now available. This can be accomplished through the use of polarized lighting systems on all vehicles.**

The proposal to adopt polarized headlighting as the most positive means of eliminating glare from approach vehicles at night is not new. F. Short and L. W. Chubb had pointed out the potentialities of polarization to include vehicle headlighting in 1920. Almost immediately following the development of dichroic polarizer film by E. H. Land in the late 1920's, its use with vehicle headlamps was proposed because this invention provided, for the first time, a practical, relatively low cost, mass producible polarizing material[2]. In 1936, U.S. patent No. 2,301,045 was issued to cover the use of polarization for vehicle headlights. Although it provided the only practical solution to the problem, the proposal was met with a negative attitude[Ref. 2, p. 23]. On numerous occasions during the intervening years, the adoption of polarized headlighting has again been proposed. On each occasion, a few real but minor deficiencies have been emphasized, together with many presumed deficiencies which could have been easily overcome with no great ingenuity. Vehicle evolution has now negated most of the arguments which were brought out to defeat any concerted move toward the adoption of polarization by the automotive industry.

As a result, a good, practical solution to the problem of safe night vision on the highway could have been incorporated in 1941 with the necessary conversion of only 35,000,000 vehicles. It was passed up then and again in 1949 when only 45,000,000 vehicles required conversion. Now, in 1969, with 100,000,000 vehicles on the road, polarization still remains the only really practical solution. During this period, deaths from traffic accidents have risen from some 40,000 per year to over 53,000 in 1967[3, 4]. How many of these might have been avoided by the elimination of headlight glare will be discussed in a later portion of this study.

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*Superscript numbers in parentheses refer to the List of References at the end of this report.

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The application of polarized headlighting to a vehicle can be a relatively minor modification involving, in its simplest configuration, merely placing polarizer screens over the headlamps and providing an analyzer (polarizing viewer) for the driver to look through at oncoming vehicles. Its adoption and acceptance by the driving public, the Automotive Industry, and the Government, both State and Federal, however, presents much more complex problems.

Another possible solution to the glare and visibility problem may be the illumination of all highways with fixed lighting systems to provide a level of illumination which would make vehicle headlamps unnecessary, except perhaps as marker lights. Such levels of illumination are found, at times, in urban areas, at major freeway interchanges, urban center expressways, and other high traffic density locations. Even where other solutions for headlight glare might be considered sufficient in general (polarized headlights, one-way traffic, glare screens, etc.), there will undoubtedly be highway locations and configurations in which overhead fixed highway lighting would still be necessary to provide the safest environment for road users. How far this might or should be extended to the solution of the overall glare/visibility problem is essntially an objective of this study.

A final possible alternative is that of modification of beam patterns. Headlamp aiming, or special spot lamps or fill-in lamps which would provide closer control of beam spread and high level beam intensities, may improve the glare situation somewhat. This has, however, been the principal approach to the problem for at least 60 years of headlamp design by the automobile industry and lamp designers[2], and the problem is still with us.

In its optimum form, which may be represented either by the US/UK or the European standard configurations, glare is still present and visibility is only marginal even when no opposing headlamps are present[5]. The present configurations represent compromises in illumination and glare characteristics which are the result of many years of conferences and coordinating efforts. It is unlikely that major modifications which would greatly improve this situation could be effected in the present agreed upon standards for such vehicle lighting. The subject is still, unquestionably, open to further discussion and modification on the basis of vehicle, lighting and highway evolution and changing requirements.

The study reported here represents an approach to providing an evaluation of the factors above. It presents the relative costs of the provision of adequate lighting for driving safety and the elimination of glare from vehicle headlights balanced against the value of benefits to be obtained by such improved night vision.

In all candor, it must be stated that this study must be considered as only a first-stage, preliminary review of the cost and benefit factors of concern. Much of the data on which its findings and conclusions are based are fragmentary and, in many respects, unreliable. **There is perhaps too much emphasis on accident reduction benefits, particularly in view of the erratic and limited data found available relating headlight glare to accident frequency.** Also, there are other benefits which are touched on in the following discussions which may have real, economic benefits greater than reduction of accident costs but, for which, only gross hypotheses could be formed, owing to lack of factual data. It was considered unwarranted to try to base cost or benefit comparisons on such fragmentary information.

It is suggested that the following analysis is justifiable and desirable, however, in that it will disclose areas of information needed to achieve a proper and detailed evaluation of the problem.

II. ECONOMICS OF IMPROVED NIGHTTIME VISION

The primary objectives of a program to improve the visibility of the highway scene during night driving are considered to be threefold.

(1) Reduce Accidents - Reduce death, injury, and property damage.

(2) Improve Traffic Flow - Increase speed safely and accommodate higher traffic volume during the hours of darkness. Increase nighttime use of highways by persons now reluctant to use them because of sensitivity to glare.

(3) Reduce Stress - Reduce tension and driver stress, improve vehicle control, enhance driver decision making, decrease frequency of "emergency situations" by increasing the visibility of road obstacles at greater distances.

These objectives are completely interrelated. They might even be considered different expressions for a single basic objective of increased nighttime traffic flow with reduced accident rate.

Other factors may be present in nighttime driving such as increased fatigue and greater prevalence of drinking by drivers, but the principal factor which causes the overall nighttime accident rate to be greater than the daytime rate is considered to be the reduced visibility of the highway scene that results from low levels of illumination, increased contrast between lighted and unlighted areas, and glaring headlights on opposing vehicles. Means of achieving improvements in visibility have been investigated in prior studies; this report is concerned solely with establishing the relative costs of these methods or means.

Balanced against the costs of providing alternative solutions to improve visibility is the value of the benefits to be derived. Several major difficulties become apparent immediately in attempting to place monetary values on these benefits. Many investigators have noted the dearth of available data to support causal factors in accident research [6, 7, 8]. This is particularly true when visibility of the highway scene is the principal factor of concern.

To date, about half of the States have been queried and in only a few cases have accident reporting forms and procedures made specific reference to headlight glare as a causative factor in vehicle accidents. Those records which do indicate the presence of glare or "blinded by headlights" as it is more frequently reported, must certainly be considered as highly conservative. Most accident report forms call out much more direct causes, and particularly causes reflecting traffic law violations in which, even though glare may be the underlying factor, it is not so recognized nor reported. Typical of these are accident report statements such as "ran off the road," "crossed road centerline," "lost control of vehicle," "collided with fixed object," or "collided with deer" (or other animals, including pedestrians). In another group of accidents involving fatalities of the driver alone (and even many of those where passengers are also involved it would be virtually impossible to determine that the dead driver had been blinded by oncoming vehicle headlights. Particularly would this be so when the offending vehicle did not become involved in the accident.

The accident frequency data in Table I, collated from the only States among over twenty-five contacted which kept or could readily develop these statistics, must be considered as a highly incomplete and uncoordinated estimate of the involvement of headlight glare in accidents.

TABLE I. REPORTED HEADLIGHT GLARE INVOLVEMENT IN ACCIDENTS

State	All Accidents	All Night Accidents	All Fatal Accidents	Accidents on Rural Roads (Unlighted)*	Accidents on Urban Roads (Lighted)*
Arizona	--	3.8%	1.3%	--	--
Florida	--	0.2%	--	0.4%	0.7%
Maine	0.9%	--	--	--	--
Montana '65	--	0.92%	--	1.08%	--
Montana '66	--	0.35%	--	0.66%	--
New York	--	1.8%	--	4.27%	--
Virginia	--	0.24%	--	0.53%	--

*Presence or absence of lighting assumed, as indicated.

Table I illustrates the problem faced when attempting to develop meaningful data to assess the benefits which might be expected from an improvement in vehicle design, where the influence of the vehicle change cannot be directly related to accident causation. It is to be noted that these data are compiled differently in the several States. They are variously collected, recorded, and reported and are not readily comparable. Although incomplete and almost inadequate for this analysis, they are the best data available and can provide at least a guide .

Assessment of the benefits to be obtained in improving traffic flow and reducing stress in drivers at night is even more tenuous. From the results of the simulated highway operational studies of Phases I and IV of this program, some realistic predictions may be made of improvement in driver performance under conditions of reduced glare and improved visibility. The translation of these improvements in detectability of highway objects into finite increases in traffic flow or hours of additional safe driving capability by vehicle drivers cannot be much more than a subjective interpretation, however, and will not be attempted.

Every vehicle operator recognizes the need for increased attention to the task of driving at night, as compared to driving during the day. Ostensibly, such increased vigilance results in a faster build up of tension and the onset of driver fatigue with greater time required to determine necessary control actions (decision time), and, perhaps, even more time to initiate required action (reaction time). No data currently exist that relate these or comparable effects directly to increased traffic volume or decreased driver fatigue. The effectiveness of any of these alternative means of increasing driver vision at night cannot be fully assessed until the specific alternatives can be evaluated by analysis of performance of a cross section of the driving public in full-scale trials initiated for this purpose.

In the interim, and for the purposes of this study, the data developed in the other phases of this work will be utilized to provide what is believed to be reasonably realistic estimates of levels of achievement.

A cursory review of the factors discussed in the foregoing paragraphs shows that the only solutions which need be considered in this study are polarization of vehicle headlights and lighting of all highways. The reasons for this determination are:

(1) Beam control will not eliminate glare. Changes in beam patterns can provide only modifications of the existing standards controlling the compromise between glare intensity and road illumination. This does not eliminate glare.

(2) Glare screens cannot be used on two-lane roads. These roads constitute the largest portion of the countrywide network. Glare screens could not therefore solve the problem where it is most serious.

(3) One-way to replace all present two-way roads. This would require the construction of a road net very nearly duplicating the existing two-lane road system. Without further analysis, it can be concluded that the time and money required would be completely unacceptable.

Cost comparisons will be developed for fixed lighting of highways and the adaptation of polarized lighting systems to existing vehicles in the hands of the public and those currently being produced. Only costs directly related to these alternative solutions are considered. Costs for developing and administering the selected program are not included and would probably be nearly the same in either case.

A. Polarized Headlighting Costs

The ultimate headlight system to be used with polarization has not been defined and will unquestionably require considerable discussion between the Government, the Automotive Industry and its lamp manufacturers, and the standardization committees of such agencies as the Society of Automotive Engineers and the Illuminating Engineering Society. The Highway Research Board and driver representative agencies such as the American Automobile Association and insurance and police coordinating agencies must also be involved.

One system aspect on which agreement has not been reached is that of the necessity for polarization in urban driving, particularly on lighted city streets and throughways. It is to be noted[9] that little benefit will be derived from use of polarized low-beam lights in cities, where overhead lighting is adequate for vision. Standard low-beam lamps in the presence of adequate overhead lighting are, however, not especially disabling to opposing drivers, unless badly misaligned, hence there would appear to be no particular advantage to putting polarizers on low-beam (No. 2) headlamps of four-lamp systems. Furthermore, glare from street lamps, store displays, and advertizing signs would still be present, since these lights are unpolarized, although they are not normally hazardous from a glare standpoint. In this, and any other discussions of the use of polarization, it is essential to consider that the analyzer will be in the field of view of the driver only when opposing vehicles with polarized headlamps are present. Some 33% of the vehicles on the road have two-lamp dual-beam lighting systems[5] in which both high- and low-beam filaments are in the same lamp unit. Placing a polarizer over the lens will thus affect both beams, with the result that two different configurations of polarization would be in use:

(1) Four-lamp system with polarized high beam and unpolarized low beam;

(2) Two-lamp system with both high and low beams polarized.

There are three alternative solutions to this dilemma: one, polarize both high- and low-beam lamps of the four-lamp system to make both lighting systems fully polarized; two, disconnect the low-beam filaments of the dual-beam, two-lamp system and add two unpolarized, low-beam lamps as auxiliaries to provide unpolarized low-beam lighting; or, three, accept the difference between the two systems on the basis that the polarized low beam configuration of the two-lamp system does no harm, is not detectable to the driver not equipped with or using an analyzer, and, for the driver using an analyzer, is in fact beneficial.

The ultimate solution, when polarization of all vehicles is completed, would seem to allow the use of a single pair of polarized headlamps of, essentially, high-beam configuration and aiming, providing a maximum of beam intensity for maximum visibility. Whether they remained on in the city or whether only "marker" lights were used on vehicles where adequate overhead lighting was present would be of relatively little concern, since no glare would be experienced by an opposing driver as he viewed the driving scene through his analyzer. However, the effectiveness of the illumination provided by fixed source lighting would be reduced for drivers using their analyzers. Hence, if polarized headlights were allowed, the driver would use his analyzer to eliminate glare from opposing vehicles, but, if only marker lights were allowed, he would not use the analyzer.

Until all vehicles have been converted to polarization, however, both high- and low-beam headlamps in one of the above-mentioned configurations must be fitted to vehicles[9, 10] and urban driving would be with low-beams, polarized or unpolarized, as at present.

A further argument which has been advanced for the need of low-beam lighting in cities (rather than allowing high-beam, polarized headlights to be used under all conditions) is that the high-beam lights would be too blinding to pedestrians. This is a specious argument, since concern for pedestrians has never been a major factor in headlamp design. The pedestrian is not constrained to look at approaching vehicle headlights as the motorist is. Further, if this is considered to be a legitimate issue, the pedestrian could also benefit by wearing polarized spectacles to completely eliminate the headlight glare, which he can not now do even with low-beam lights. Certainly, on unlighted rural highways, no consideration is now given nor should be given to the use of low-beam headlights to reduce glare exposure for pedestrians. Maximum visibility of the pedestrian by the driver is essential in this circumstance, and it usually requires use of high beams to provide this whenever opposing traffic is not present.

For these reasons, the headlamp configurations which will be used as a basis for cost comparisons in this study will be fully polarized for both high and low beams. If it is ultimately determined that unpolarized low-beams are desired, the costs indicated may be adjusted accordingly. Although it is recognized that most new automobiles are purchased on borrowed funds, the cost of funding these additional amounts for polarization will not be included here.

New Vehicles

System 1. Four-headlamp system: Assumes two, 100 watt, high beam, PAR 46 type, (No. 1), single-filament, and two, 100-100 watt, (No. 2) two-filament headlamps with integral polarizers, with one polarized visor (analyzer) for the driver.

Additional Cost to Manufacturer

Headlamps at $3.00 each	$12.00
Visor at $3.00	3.00
Windshield processing (*)	3.00
Generator, wiring, and switches (†)	3.00
	$21.00
Additional Cost to Buyer (estimated)	$42.00

System 2. Two-headlamp system: Assumes two, PAR 56 type, 100-100 watt, dual-filament headlamps with integral polarizers, with one polarized visor (analyzer) for the driver.

Additional Cost to Manufacturer

Headlamps and visor at $3.00 each	$ 9.00
Windshield processing (*)	3.00
Generator, wiring, and switches(†)	3.00
	$15.00
Additional Cost to Buyer (estimated)	$30.00

(*) Toughened glass windshields, as used on many foreign automobiles, although illegal in the U. S. A. for reasons of safety in crashes, would also be unacceptable for use with polarized headlights. However, even newly manufactured, laminated windshields will require additional heat treatment to insure elimination of internal stresses and birefringence, when viewed with polarized light. Some striations, spots, or darkened areas may appear in laminated windshields of existing vehicles, although no hazardous conditions have been observed in these studies to date.

(†) Manufacturers have indicated that heavy-duty generators, regulators, light switches, foot dimmer switches, and wiring should be used to provide adequate system reliability at the higher power demand of these lamps.

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Existing Vehicles*

System 3. Four-headlamp system: Replace existing lamps with two, 100 watt, high-beam, PAR 46 type, No. 1 single-filament and two, 100-100 watt, No. 2 two-filament headlamps with integral polarizers and an analyzer for the driver.

Headlamps at $7.00 each	$28.00
Visor at $7.00 each	7.00
Installation labor ($10.00/hr)	10.00
	$45.00

System 4. Four-headlamp system: Retain present headlamps and install polarizing adapters in front of them with an analyzer for the driver.

Adapters with polarizing filter at $6.00 each	$24.00
Visor at $7.00	7.00
Installation labor ($10.00/hr)	5.00
	$36.00

System 5. Two-headlamp system: Replace existing lamps with two, 100-100 watt, PAR 56 type, two-filament headlamps with integral polarizers and one polarized visor (analyzer) for the driver.

Headlamps at $8.00 each	$16.00
Visor at $7.00	7.00
Installation labor ($10.00/hr)	7.50
	$30.50

System 6. Two-headlamp system: Retain present headlamps and install polarizing adapters in front of them with an analyzer for the driver.

Adapters with polarizing filters at $7.00 each	$14.00
Visor at $7.00	7.00
Installation labor ($10.00/hr)	5.00
	$26.00

*Modification of existing vehicles is possible by almost any driver capable of adjusting his headlamps or changing his spark plugs. It will be assumed, however, that the modification is performed by a garage having headlamp aiming facilities and competent mechanics and all prices are retail.

There are still some vehicles being operated which have low-output generators, but since the advent of the alternator, most vehicles have a minimum of 500 watts generating capability. Except for those vehicles with many electrical accessories of high power demand, replacement lamps of 100-watt size could be used in these transitions to polarization with no problems. If a specific vehicle has heavy electrical power requirements (air conditioner, multiple lamp tail and stoplight combinations, etc.) it may be necessary to go to the 750-watt alternator which the automobile industry now regards as heavy-duty but has recommended as standard for production with the adoption of polarized lighting. If such alternators become standard for new vehicle production, they should be available for replacement use at only slightly greater cost than present standard units.

Present production capacity of headlamps is 80, 000, 000 per year for new vehicle installation and for replacement(4). It is estimated that the industry could reach a capacity 130, 000, 000 by going to two-shift operation. A third shift would produce something under 50, 000, 000 additional units. Some question exists as to whether sufficient additional labor could be found to man extra shift operations. It is assumed, for this study, that at least two-shift operation would be feasible.

The 1967 glass and sealed beam headlamp production was 52. 5 million units under 6 in. in diameter and 22. 7 million over 6 inches. Of these, 32 million under 6 in. and 5. 6 million over 6 in. were used in vehicle production(4). If these figures are considered to be applicable in the conversion to polarized lighting, on the basis of the assumed two-shift production capacity, approximately 92 million lamps would be available for conversion of vehicles already on the road. The survey reported in Phase III of this program(5) showed a nationwide average of 66. 7% of the vehicles on the road equipped with four-lamp headlights systems. Assuming that the lamp production capability can be tailored to meet these proportionate types in the replacement lamp demand for conversion of headlamps, some 33. 6 million vehicles can be converted per year. In 1967, there were 97. 5 million vehicles registered in this country and it is estimated that this will increase to 105 million by the end of 1970(4). Thus, at least 3 years of two-shift lamp production would be required to support current vehicle production demands and provide for conversion of vehicles already produced.

The costs shown above for the several headlamp configurations are considered to be quite conservative, particularly with regard to costs of polarizing filters. This is largely because production tooling to support the level of production for this use has not been developed and cost estimates which would adequately project these factors in detail could not be readily obtained. It is reasonable to assume that mass production techniques, particularly in view of the competitive structure of the headlamp industry, would eventually permit major reductions in the costs estimated here.

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Dichroic polarizer patents are now in the public domain and several sources are presently available. Other types of polarizers are likewise under study and development and may result in even greater competition.

Total costs to the public for conversion to polarized headlight systems on all existing vehicles in the country would be:

(a) For 10, 000, 000 new vehicle production/year during 3-year conversion period:

$$\text{(Vehicle production for 3-years)}\ \frac{\text{(less than 6-in. lamps used)(System 1 cost)} + \text{(Over 6-in. lamps used)(System 2 cost)}}{\text{(Total lamps used)}}$$

$$(3 \times 10^7) \left[\frac{(32 \times 10^7)(\$42.00) + (5.6 \times 10^7)(\$30.00)}{(37.6 \times 10^7)}\right] = \$1.20 \times 10^9$$

(b) For 75, 000, 000* existing vehicles:

66.7% four-lamp system (assume 75% convert to System 3, 25% to System 4).
33.3% two-lamp system (assume 75% convert to System 5, 25% to System 6).

$(0.667)(7.5 \times 10^7)(0.75)(\$45.00) = \$16.9 \times 10^8$
$(0.667)(7.5 \times 10^7)(0.25)(\$36.00) = \$\ 4.5 \times 10^8$
$(0.333)(7.5 \times 10^7)(0.75)(\$30.50) = \$\ 5.7 \times 10^8$
$(0.333)(7.5 \times 10^7)(0.25)(\$26.00) = \$\ 1.6 \times 10^8$
$\$28.7 \times 10^8$

Total (a + b) $\$\ 4.07 \times 10^9$

The above $4.07 billion represents the initial 100% conversion costs. To this must be added the requirements for the yearly production input of new vehicles and replacement of lamps on vehicles in the hands of the public for the base period of comparison. As will be developed later in discussion of the fixed lighting concepts, inasmuch as those systems are normally considered to have a useful economic life of 20 years[11], increased headlight costs should also be based on this period in any cost comparison. In this period, it is estimated that the mean vehicle population will be 138 million (extrapolation of current rates from 1957 to 1967)[4].

From the figures previously cited of production capacity in the headlamp industry, approximately 20 million lamps for four-lamp systems (under 6-in. diameter) and 17 million lamps for two-lamp systems (over 6-in. diameter) are presently being produced for the replacement market, or approximately 50% of total production. If we assume a continuing wearout and replacement ratio after polarization, this would mean that half of the

*Over 3-year conversion period, 30, 000, 000 new vehicles incorporating polarization would be entering the population leaving 75,000,000 older vehicles to be modified in a total projected population of 105, 000, 000.

total production for 20 years would be required for replacements, or some 800 million units. This assumes no expansion in replacement requirements which may not be too improbable. Although production of vehicles will increase to meet the requirements of an expanding population, if polarization is adopted, the most probable trend in headlights will be back to two-lamp systems of greater output, greater efficiency, and longer life. Since no glare will be present with complete polarization in effect, no provision for low-beam operation will be necessary and single-filament lamps of broader high-beam configuration together with simplified lamp control circuitry and switch components will be feasible. Halogen type lamps, presently coming into use, have the above mentioned characteristics and could be an acceptable solution.

Because of the uncertainty of these trends, it is considered adequate for purposes of this study to charge only the extra cost of 800 million polarized replacement headlamps over the 20 year period to polarization, along with the extra cost for polarization for all new vehicles produced during this period. Some additional charge might also be made for polarization representing the additional costs for power generation for 100-watt headlamps over that required for present standard 37.5-watt types. However, as discussed in the previous paragraph, if there is a trend toward greater use of two-lamp rather than four-lamp systems, the increase in power generation requirements is relatively undeterminable without data as to the proportion of each system involved. A further complicating factor in this record is the probability of increased nighttime utilization of the highways owing to increased comfort and safety in night driving. This would, of course, bring about an increase in power generation requirements related to increased operating time for the lamps. Vehicle production will increase during this period, unquestionably, but will be assumed at a mean of 10 million units per year. It will also be assumed that after the initial 100% conversion, all vehicles will be produced with only two headlamps of single-filament, high-beam configuration (System 2) with a vehicle cost increase of \$30.00. The added cost of headlamps for vehicle production for the remaining 17 years of the 20-year period (1970 to 1990) would be

$$17 \times 10^7 \times \$30.00 = \$5.1 \times 10^9$$

The added cost of 800 million replacement lamps during this period would be

$$8.0 \times 10^8 \times \$5.00 = \$4.0 \times 10^9$$

which, added to the cost of initial conversion, results in an overall added cost, for the period to 1990, of:

$$\$13.17 \times 10^9$$

B. Highway Lighting

As previously stated, a feasible alternative to polarization of headlights to eliminate glare in opposing motorists' eyes is to make headlights unnecessary by providing sufficient fixed overhead lighting of the highway for all seeing tasks. If this approach is taken, some current practices in fixed illumination for highways will require modification, inasmuch as present illumination levels have been established on the basis of combined vehicle and fixed lighting, except perhaps for high-traffic density areas such as downtown expressway locations. Simulated highway operation of vehicles in the combined fixed lighting/vehicle lighting environment are a part of this study program. Results are not yet available and the determination of proper levels of illumination for highway lighting by fixed luminaires with no contribution by vehicle headlights will be made on the basis of existing standards and guidelines with extrapolations where indicated.

The studies of Cassel and Medville[11], Thompson and Fansler[12], the ASA-IES Standard Practice for Roadway Lighting[13] provide the principal background data which is used in this analysis and others[14, 15, 16, 17, 18, 19, 20].

A primary point of discussion with regard to the economics of this course of action as the optimum solution to the glare/visibility problem is whether fixed lighting should be extended to all two-lane roads or only to those in which it would represent a major advantage in benefits to be obtained.

For purposes of direct comparison, it would seem that complete coverage of the road net with fixed lighting should be considered inasmuch as the competitive system, polarization, does provide a complete solution for all roads. On the other hand, on much of the two-lane road net, particularly the unimproved portion. vehicle meetings are normally so infrequent that glare from present standard headlight systems presents an almost insignificant hazard.

The present (1967) nationwide highway system has the characteristics shown in Table 2, derived from Tables SM-11, M2, and M3 of "Highway Statistics 1967, "[21].

If vehicle headlights as now constituted can be utilized for traversing the unpaved roads, the amount of paved rural and urban highway which would require fixed illumination would be 1, 519, 345 miles. Of this total, 411, 518 miles, indicated as surfaced urban, is considered to be illuminated already, although probably at an insufficient illumination level for vehicle operation without headlights. On this basis, 1, 107, 827 miles are left to be illuminated, of which 35, 909 miles are rural, four-lane or one-way State Primary roads.

TABLE II. SUMMARY OF U.S. HIGHWAYS

Type of Highway	Mileage		
	Rural	Municipal	Total
State Primary, Two-lane, surfaced (Less D and E types)*	382,014	33,660	415,674
State Primary, Three-lane, surfaced	1,969	1,350	3,319
State Primary, Four or more lanes, surfaced	3,201	7,283	10,484
State Primary, Four or more lanes, divided, surface	32,641	11,315	43,956
State Primary, One-way, surfaced	67	369	436
Primitive - nonsurfaced, unimproved (Types A, B, and C)*	847,218	30,333	877,611
Improved - soil, gravel, (Types D and E)*	1,228,606	79,352	1,307,958
Surfaced - bituminous, PCC, (Types F, G, H, I, and J)*	1,107,827	411,518	1,519,345

*See Reference 21.

The large amount of lighting involved makes it imperative that lamps of maximum efficiency be utilized in the system, hence 400 watt, high-efficiency, high-pressure sodium lamps of the General Electric "Lucalox" or Westinghouse "Ceramalux" type are proposed to be used. Faucett(22) has shown in comparative analyses with clear mercury and multivapor lamps that installations utilizing these higher efficiency light sources can be installed for approximately 50% of the cost of clear mercury units and can also be operated with this same saving, even though lamp life is considerably less, in the order of 6000 hr as compared with 24,000 hr for clear mercury lamps.

Certain assumptions are necessary in developing overall characteristics for roadway lighting to be adequate for vehicles to be operated without headlights utilizing marker lamps and tail lamps only. Observation indicates that average horizontal footcandles should be a minimum of 2.0, as specified for major downtown roadways or urban interchange expressways in Table II of the ASA Standard Practice D12.1-1963(13). However, as a basis of comparison, estimated system costs will be carried out, not only for this level of illumination, but also for a lower level of 1.0 footcandle and for 40-ft and 45-ft mounting heights. A measurable saving will be realized if vehicles can be operated without headlights on these lighted highways.

With a reduced electrical power demand of 75 watts (two lamps) and a generation efficiency of 75% (80% for the generator $\times$ 93% for the belt drive), a reduced power demand on the vehicle engine of

$$\frac{75 \text{ watts}}{0.75} \times 0.001341 \text{ HP/watt} = 0.1341 \text{ HP results}$$

Road load fuel consumption of 0.5 pounds per BHP-hr can be considered average for most vehicles, or a saving of

$$0.1341 \times 0.5 = 0.067 \text{ lb of fuel per hr}$$

average vehicle speed for all use is estimated at 40 mph or a decreased fuel consumption of

$$\frac{0.067}{40} = 0.00167 \text{ lb of fuel per mile, or}$$

$$1.67 \times 10^3 \text{ lbs of fuel per million vehicle miles}$$

At 7.0 pounds per gallon, this amounts to 239 gallons or $79.00 saved per million vehicle miles, at a mean fuel cost of $0.33 per gallon. In 1967, vehicle mileage in the U.S. was 965,132 $\times 10^6$ miles(3). Taking the comparative day/night accident involvement rates(5) as a criterion of relative night driving, 32% occur at night.

Operating without lights at night would result in a fuel saving of

$$0.32 \times 965{,}132 \times \$79.00 = \$2.44 \times 10^7 \text{ per year, or}$$

$$\$4.88 \times 10^8 \text{ for the 20-year period}$$

While this is a sizeable amount, it will be noted that it does not affect the comparative costs of providing highway lighting appreciably. Other comparative costs, Table 3, have been calculated using the format of Faucett(23).

C. Benefits

Accident reduction, with consequent reduction in deaths, injuries, and property damage, is the preliminary benefit sought from improved visibility of the road at night. Some data are available that present the current situation with respect to the magnitude of the problem:

Thirty-seven percent of all traffic accidents in 1966 occurred between the hours of 6:00 P.M. and 6:00 A.M.[3]. Deaths in these accidents, however, were 53% of the total. When exposure of the motorist is considered, there is a much greater disparity in death rate between the two periods of the day; 3.7 deaths per 100 million vehicle miles of operation occurred in the daytime and 9.7 deaths at night, or a ratio of 2.82 to 1. Death rates per 100 MVM are much higher in rural areas; 5.2 occurred in daytime and 13.2 at night, but the ratio of 2.54 to 1 is somewhat less.

In the United States in 1967, accident statistics show a total of 53,100 deaths, 1,900,000 injuries, and 12,500,000 incidents of property damage[3]. Although data are not available to relate injuries and property damage on the same basis as deaths for daylight and dark, it is not unreasonable to assume that the figures in the preceding paragraph will provide an adequate guide. Solomon[24] provides some corroboration, showing 54% of the deaths at night on a selected group of main rural highways, 43.5% of the injuries at night, and 41.8% of the property damage. The previously cited reference[3] showed that 53% of the deaths on rural roads occurred at night.

If Solomon's figures for injuries and property damage are used, 825,000 injuries and 5,450,000 property damage accidents would have occurred at night, in addition to 27,200 deaths.

Because of the sparse and uncoordinated character of the data in Table I, and the high probability of omission of many applicable accidents from that compilation, it is considered reasonable to assume that glare may be a causative factor in at least 4.0% of all nighttime accidents. It would appear then, that 1,088 deaths, 33,000 injuries, and 218,000 incidents of property damage could be charged to headlight glare in 1967, a toll that might have been eliminated by the measures under consideration. During the period 1957 to 1967, the average yearly increase in traffic deaths was 3.7% and vehicle mileage increased by 5% per year.

Accident costs have been estimated by a number of investigators[6, 7, 8, 23, 25, 26, 27, 28, 29] in the recent past, but few have used the same basis for evaluation and comparisons are difficult to make. Twombly, et al[23] showed values of $2,180 and $3,500 per urban and rural accident, respectively, for 1967 in England but includes no so-called subjective costs. Reynolds[6], for 1952 in England, showed values of $5,600 per deaths, $950 per injury, and $106 per nonjury property damage accident,

TABLE III. COMPARATIVE LIGHTING COSTS

	Cost Item	Calculation	Two-Lane	Four-Lane	Two-Lane	Four-Lane
			— 2.0 fc Average —		— 1.0 fc Average —	
1.	Initial Investment					
	a. Unif. Ratio	A	3.12	1.38	2.89	2.46
	b. Mounting Height	A	40	45	40	45
	c. Spacing		162	100	324	200
	d. Luminaires per mile	5280/c	32.6	52.8	16.3	26.4
	e. Luminaire at $148	$ × d	4830	7810	2415	3905
	f. Lamp at $25.65	$ × d	835	1352	418	676
	g. Pole & bracket (12 foot) $199.40, $221.45	$ × d	6490	11,660	3245	5830
	h. Foundation & erection $200	$ × d	6520	10,550	3260	5275
	i. Initial investment/mi	e+f+g+h	18,675	31,372	9338	15,686
	j. Total investment	**i × B**	**2.00×10^{10}**	**1.13×10^{9}**	**1.0×10^{10}**	**5.63×10^{8}**
2.	Annual Operating Costs					
	k. Kw/luminaire	C	0.465			
	l. System Kw/mile	d × k	15.13	24.5	7.57	12.3
	m. Annual operation, hours	C	4000			
	n. Kwh/year	l × m	60,500	97,800	30,250	48,900
	o. Energy cost at $0.015/kwh	0.015 × n	907	1465	454	733
	p. Lamp life	C	6000			
	q. Quantity of lamps	d × m/p	21.7	35.2	10.9	17.6
	r. Lamp cost	$ × q	557	903	279	452
	s. Total operating cost	**(o+r) × B**	1.57×10^{9}	8.51×10^{7}	7.85×10^{8}	4.26×10^{7}
3.	Annual Maintenance Costs					
	t. Relamping labor (D)	$1.00 × 9	21.70	35.20	10.90	17.60
	u. Cleaning labor (D)	$2.50 × 9	54.20	88.00	27.60	44.00
	v. Replacement parts	1% × (i-f)	178.40	300.20	89.20	150.10
	w. Total maintenance	**(t+u+v) × B**	2.73×10^{8}	1.52×10^{7}	1.36×10^{8}	7.60×10^{6}
	x. Owning cost (E)	B[0.017 × (i-r)]	2.28×10^{9}	1.24×10^{8}	1.14×10^{9}	6.20×10^{7}
4.	Summary					
	y. Total annual cost	s + w + x	4.1×10^{9}	2.24×10^{8}	2.05×10^{9}	1.12×10^{8}
	z. Life time cost	20 y	8.25×10^{10}	4.49×10^{9}	4.13×10^{10}	2.25×10^{9}

A. Assumed average of 2.0 and 1.0 footcandles with 40-ft MH for two-lane and 45-ft MH for four-lane.

B. Total U.S. mileage of roadway to be lighted

(1) Paved - 1,071,918 miles -- two-lane, rural (assumed 24-ft roadway with 10-ft shoulders).
(2) 35,909 miles -- four-lane and one-way rural State Primary (assumed 12-ft median and 10-ft shoulders).

C. From lamp manufacturer's data and standard practice.

D. Estimated, based on $5.00/hr labor rate, cleaning performed only when relamping.

E. Assumed 10% Capital Recovery Factor (0.11746) for 20-year system life in line with Bureau of the Budget recommendations for the current economic situation.

including loss of potential output in the case of death and injury in addition to direct costs of funeral, medical treatment, and property restitution. Dunman[23] provides an analysis of accident experience in Massachusetts for 1953. These direct costs show values of $3,300 per fatality, $400 per injury, and $203 per property damage only accident. A recent comprehensive study of a limited area[26] has considered total costs including loss of future earnings of killed or injured, legal and court costs of litigations, and medical treatment costs. This showed average costs for fatally injured individuals of $59,178, non-fatally injured of $612 and property damage accidents of $184.

Another relatively current and broad analysis of accident costs appears to be that of Recht[7]. He uses accident cost estimates developed over a number of years by the National Safety Council, compiled on a nation-wide basis, and includes both direct and indirect cost elements. Because it is a comprehensive analysis with allowances for factors other than direct costs and because it has been in use by the National Safety Council for a number of years, the values cited therein will be used in this study.

The estimated motor vehicle accident unit costs shown below, adjusted for the 1970 to 1990 time frame are:

	1967	1970 to 1990
Cost of a death	$37,500	$50,500
Cost of a disabling injury	1,950	2,600
Cost of a property damage accident	320	353

Because of the indeterminate influence of glare as an accident causative factor, the value of accident avoidance will be estimated based on a 1% reduction or 272 deaths, 8,250 injuries, and 54,500 property damage incidents. Adjustments are made for increased exposure and vehicle population during the period 1970 to 1990, assuming the same continuing growth as occurred during the 1957 to 1967 period.

Accident costs = (Mean cost 1970 to 1990) × (Incidents per year) × (Mean increase per year) × (years)

in which:

$$\text{Mean Increase per year} = \frac{1}{n}\int (1+r)^n dn$$

where n = years
r = yearly increase

$$\text{Mean increase per year} = \frac{1}{n}\cdot\frac{(1+r)^n}{\log(1+r)} = \frac{1}{20}\left[\frac{1.037^n}{\log(1.037)}\right]_1^{20}, = 1.476$$

Death costs = (50,500)(272)(20) = $\$4.06 \times 10^8$ *1.476
Injury costs = (2600)(8250)(20) = 6.34×10^8 *1.476
Property Damage = (353)(54500)(20) = 5.68×10^8 *1.476
$\$1.608 \times 10^9$ *1.476 = 2.374x10⁹

The other benefits to be obtained are relatively intangible and no attempt will be made to assign them values. These are real benefits, however, as far as any motorist is concerned. How much they are worth to him is essentially a matter of individual and personal objectives, depending on the need for travel at night, his physical limitations, and the volume and movement of traffic in which he is placed.

Certain hypothetical traffic situations could be considered in which, based on the observations of these studies, improvements in traffic flow or traffic handling capacities of given highways could be shown. Whether (or how) such increased capacity would be utilized raises other questions of primarily subjective character. Older drivers do not use the highways greatly at night, not only because they may be more affected by glare from opposing headlights than younger drivers, but also because they are just less inclined to leave the house at night. Long-established habits of driving in the daytime and resting at night will have to be changed if maximum advantage is to be taken of improved ease of driving at night. In general, tourist travel will not change markedly because, in most instances, such motorists want to see the country as they travel and will therefore probably prefer to drive during the daylight hours anyway. On the other hand, business travel and commercial trucking can be particularly benefited by improved ease of driving at night.

The following somewhat intangible benefits may be expected in greater or lesser measure as a result of reduction in headlight glare and increased visibility of the highway scene:

(1) Increased safe traffic capacity of the highway--greater speed and volume feasible without increase in accident hazard potential;
(2) Increased safe speed limits--no longer overdriving headlights;
(3) Improved driving ease--reduced tension;
(4) Increased time for decision--objects on the highway seen earlier;
(5) Reduced sensation of "tunnel" driving with its pressures for more exact control of lateral positioning;
(6) Increased ability to extend driving periods safely because of reduced tension;
(7) Improved balance of traffic between daylight and night periods; particularly, commerical highway users may switch to nighttime operation to get away from traffic congestion periods during daytime.

The assignment of specific weights and monetary or other rating or comparison values to the above listed benefits is not considered practicable in a preliminary cost-benefit analysis such as this, even though they can be recognized. A number of studies have been conducted relating the effect of highway improvement on accidents and traffic flow[6, 8, 25, 28, 29, 30]. Where data are available which can predict performance with reasonable accuracy in terms of well-established prior performance, such extrapolations are justified. The complexity of such analyses are well and concisely discussed by the Bureau of Public Roads[29], but that discussion clearly demonstrates the need for detailed performance data upon which to base necessary decisions and the futility of attempting such decisions without them.

III. SUMMARY

Table IV is a summation of the benefits to be derived from improved, nonglare lighting and the costs of alternative means of achieving this.

TABLE IV. COST-BENEFIT SUMMARY, 1970 to 1990

		Value	Benefit/ Cost Ratio
1.	Value of 1% accident reduction	$\$2.374 \times 10^9$	
2.	Cost of polarization of all vehicles	$\$ 13.17 \times 10^9$	0.1803
3.	Cost of fixed lighting of all paved streets and highways to:		
	a. 2-footcandle average level	$\$87.1 \times 10^9$	0.0273
	b. 1-footcandle average level	$\$43.6 \times 10^9$	0.0545

It is apparent from these figures that the cost of glare elimination by polarization can be offset by accident reduction if the incidence of glare as a causative influence in accidents is in excess of 5.53%. This is higher than any reported rates (Table I) but, in light of the lack of control and probable omissions from those data which would unquestionably raise the level of glare involvement, may be near the actual case. Further, it must again be noted that no benefit valuation has been assigned in this analysis to other than accident reduction, although other benefits exist and have value, as discussed earlier.

It does not appear that elimination of glare by resorting to complete illumination of the highways is a feasible solution, particularly if its adoption is predicated on accident reduction alone.

In summary, it must be recognized that this attempt to evaluate the costs and benefits to be achieved through the elimination of headlight glare and improvement in night visibility on the highway can only be considered as an essentially gross, preliminary study. The pertinent costs and benefits are not well established and data to support an accurate analysis are almost nonexistent.

Accurate supporting data will be dependent on revised techniques and procedures for collection of data of concern in night visibility and glare from accident experience in the several states coupled with a broader study of driver response in an environment of improved lighting. It is suggested that the most expedient means of developing and supporting data can come through the mechanism of a public trial of such improved lighting in an area where that lighting can be used exclusively. Observation of public response for a test period of approximately 1 full year could provide a highly accurate indicator of the real costs and benefits related to accident reduction and operational improvement (increased traffic flow) and could, in addition, provide answers to many other related questions of public acceptance, maintainability, environmental responses, and other factors which have had only cursory evaluation to date.

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