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HUMAN PERFORMANCE ASPECTS OF REARVIEW MIRRORS: AN APPLIED-LITERATURE REVIEW

Michael Flannagan

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Human Performance Aspects

of Rearview Mirrors:

An Applied-Literature Review

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16. Abstract

This document reviews the literature in the collection of the University of Michigan Transportation Research Institute that is relevant to either of two human performance aspects of rearview mirrors: 1) the tradeoff between visibility and glare due to rearview mirrors, and 2) possible negative perceptual consequences of the use of convex mirrors. Information from relevant items is summarized, and, when possible, presented in tabular form. Original abstracts are presented for the items that include them. A number of areas in which existing work could be extended are identified and discussed.

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1.0 INTRODUCTION

This review covers literature on two issues of current interest in motor vehicle rear vision: the tradeoff between visibility and glare due to rearview mirrors, and possible perceptual problems in the use of convex mirrors. These two issues are currently important for a number of reasons. Technical developments in electronic control of mirror reflectivity levels will soon permit more flexible control of mirror visibility and glare than has been possible. After many years during which convex mirrors were not used on passenger cars in the United States, convex mirrors in the right, outside position are now fairly common. Within the past year, speed limits on Interstate highways in many areas of the United States have been increased from 55 to 65 MPH, thus increasing the risk of certain maneuvers, such as ramp entrances and lane changes, that involve a considerable amount of rearview mirror use.

The purposes of this review are to survey and evaluate existing work on visibility, glare, and convexity of rearview mirrors, and to recommend research that may supplement or extend current work.

The literature search for this review has covered all of the entries in the library of the University of Michigan Transportation Research Institute on the topic of viewing aids for motor vehicles. That broad topic includes various types of rearview mirrors as well as other, less standard viewing aids such as periscopes, video systems, and radar systems. There are currently 187 items under the general topic of viewing aids, of which 150 are concerned with mirrors. Of those 150 entries, 13 are directly relevant to the topic of visibility and glare, and 21 are directly relevant to convex mirrors. Each of the next two sections of this report summarizes and evaluates one of those sets of items.

2.0 VISIBILITY AND GLARE

2.1 Review of existing literature

The 13 items related to mirror visibility and glare are diverse in format and content. The items are summarized in Table 1 in terms of six content classifications. The classifications were chosen after reviewing all the items in detail and are intended to provide a useful, quick summary of the types of information available. It is important to remember that the full diversity of these items is not reflected in this simple table. For example, classifications other than the six chosen here, or finer classifications, could have been used.

The classifications are: 1) empirical studies in which human performance data were collected in laboratories, 2) empirical studies in field settings, 3) studies that provide theoretical analysis and modeling of rearview mirror performance, usually based on prior data concerning human vision, 4) subjective ratings of rearview mirror systems, 5) surveys of technology that are not directly concerned with human performance, and 6) descriptions of specific products. As indicated in Table 1, some items had more than one type of content. In order to provide a somewhat more detailed indication of the information available in these items, section 2.2 of this report includes authors' abstracts from all items that have abstracts. The remainder of the present section is an interpretive review of the main issues dealt with by these items.

The fundamental problem with which these studies are concerned is the need to provide adequate rearward visibility for a driver without causing unacceptably high levels of disability or discomfort glare from following headlights. All of the studies reviewed here are concerned with this problem as it exists for mirror systems. For some alternative rear vision systems (e.g. video or radar) the relationship between visibility and glare is very different, but such relatively exotic and expensive systems are outside the scope of this report.

There is a consensus that glare from rearview mirror systems is a serious problem. The problem is similar in many ways to glare from oncoming headlights, but is worse in that following headlights are often closer and are usually present for many seconds or even minutes (Olson et al., 1974). Theoretical analysis of the glare levels at a driver's eyepoint due to following headlights suggests that they are often unacceptably high even with the "night" setting (about 4% reflectivity) of currently common prism mirrors (Miller et al., 1974). The problems caused by glare from mirrors may be made worse by light from following headlights reflected from non-mirror surfaces in the interior of a car. Theoretical analysis indicates that glare from such surfaces can be important (Rowland et al., 1981).

Within the context of mirror rear vision systems a number of factors can be manipulated in an attempt to achieve an acceptable tradeoff between visibility and glare. The most obvious of these is the reflectivity level or levels of the mirrors. Reflectivity certainly has been the factor most studied, and work on it is reviewed below, but there are a number of other factors that should be noted briefly. Locations of mirrors (and therefore the angle between the normal direction of gaze and the sources of glare) can be manipulated, though the existing work on this issue suggests that, at least within a reasonable range, location will not have a large effect on the severity of glare (Olson & Sivak, 1984). Within one mirror surface it is possible to vary reflectivity so that it is high over most of the surface but low just in the area in which following headlights would normally appear from the driver's eye position (perhaps by means of a horizontal stripe across the face of the mirror). A test of one such design yielded generally favorable results, though people's subjective evaluations of the mirror were negative (Olson et al., 1974). Other factors that might be useful in achieving a satisfactory tradeoff between visibility and glare, but which have received little attention, are the number of mirrors used and their spectral reflectivity (color).

It is difficult to provide a simple summary of what can be learned from the items listed in Table 1 because they address a number of different issues in several different ways. However, on at least one issue—the question of what is (are) the most desirable level(s) of reflectivity—there are a number of recommendations that can be tabulated and compared. Three studies either make explicit recommendations or report results that can be fairly directly translated into recommendations for reflectivity levels. Those recommendations are summarized in Table 2. All three of these studies assumed that it is probably a good idea to provide two levels of reflectivity, one for use during the day and at night when no rear glare source is present, and one for use at night with rear glare. Mansour (1971), however, did note that the range of 30-40% might be a good compromise for a mirror with a single level of reflectivity. There is general agreement among these studies, at least to the point that all of them would suggest that the currently typical reflectivities for interior rearview mirrors, 4% for anti-glare level and 85-90% for normal level, are unnecessarily low and high respectively.

Recent and continuing developments in liquid crystal and electrochromic technologies are permitting more flexible control of mirror reflectivity levels (Kato & Nakaho, 1986; Iversen, 1987; Lynam, 1987; Ohmi et al., 1987; Ueno & Otsuka, 1988). There are several important differences between the capabilities of liquid crystal and electrochromic

Table 1

Summary of items related to rearview mirror glare and visibility

Author(s), date	Human Performance Data		Human Performance Analysis	Subjective Ratings	Survey of Technology	Product Description
	Lab	Field				
Marcus, 1964					x	
Mansour, 1971				x		
Becker & Mortimer, 1974			x			
Miller et al., 1974			x			
Olson et al., 1974	x	x	x	x		
Rowland et al., 1981			x			
Olson & Sivak, 1984	x	x	x	x		
Kato & Nakaho, 1986					x	
Helder, 1987	x			x		
Iversen, 1987						x
Lynam, 1987					x	
Ohmi et al., 1987					x	
Ueno & Otsuka, 1988	x	x				x

Table 2

Recommendations for rearview mirror reflectivity levels

Author(s), date	Recommended Levels (%)			Basis for Recommendation
	Day	Night	Compromise Level	
Mansour, 1971	≥ 55	10–20	30–40	Summary of subjective evaluations of visibility and glare.
Olson et al., 1974	≥ 36	≤ 14		Not explicitly recommended by authors. Based on nonlinearities in reaction time and error data.
Ueno & Otsuka, 1988	>40	8–10		Data on 'glare,' 'visibility,' and 'image brightness' which are presented but not explained in this report.

mirrors, at least at their current stages of development. It is difficult, for example, to achieve high reflectivity levels ($>50\%$) with liquid crystal mirrors. The technologies are fundamentally similar, however, in that they both provide "light valves," that is, they allow flexible electronic control of the transmissivity of various coatings above the reflective surface of a mirror. This allows the effective reflectivity of a mirror to be varied in response to various circumstances, including general ambient light level and illumination from the rear. The human performance issues raised by the new flexibility that these technologies provide include: 1) what are the most desirable reflectivities under various illumination conditions, 2) is the ability to continuously vary reflectivity valuable, 3) how would drivers respond to reflectivity changes that are made automatically and perhaps unexpectedly, and 4) how quickly should reflectivity change in order to adapt to changing illumination but not be disturbing to a driver?

2.2 Visibility and glare abstracts

Becker, J.M. and Mortimer, R.G., 1974

Further Development of a Computer Simulation to Predict the Visibility Distance Provided by Headlamp Beams

This report describes some extensions to a computer simulation program for the evaluation of headlamp beams in terms of visibility and glare of drivers. In particular the effects of glare of headlamps reflected in rearview mirrors, horizontal and vertical road curvature, and a glare discomfort index are incorporated.

Those capabilities are illustrated. A listing of the program and a manual describing its use are included as appendices.

Helder, D.J., 1987

Design Parameters for an Automotive Interior Mirror

This paper presents a review of the work which has been done on determining appropriate automotive mirror reflectivity levels for good vision as well as glare protection. In addition, it presents the results of two recent studies on the effects of glare on driver vision. In the first, the level is determined at which glare from an interior mirror degrades the driver's forward vision. Four different ambient conditions are included. The second study looks at the effect of mirror transition time on discomfort and disability due to glare. Several current mirror systems are compared to the recommended parameters.

Kato, S. and Nakaho, J., 1986

Study of Liquid Crystal Antiglare Mirrors

Antiglare rearview mirrors incorporating liquid crystal (LC) cells which vary the reflectance of the mirrors according to the applied voltage have been developed. Seven different modes of LC mirrors were studied for this purpose. For each mode, the equations of the maximum reflectance and the minimum are derived theoretically and calculated numerically. Based on these results, we obtain a possible variable range of the reflectance which is one of the important requirements. The best modes are selected among the seven modes after evaluations and comparisons on fundamental matters, such as composition for the LC mirror and quality of the image added to the variable range of the reflectance. Brief description on the developed LC mirrors is given finally.

Lynam, N.R., 1987

Electrochromic Automotive Day/Night Mirrors

Over the next several years, electrochromic mirrors will be introduced for use on automobiles, initially as interior mirrors and later for the exterior. Electrochromic mirrors have variable reflectivity and this offers an opportunity to select a reflectance level that avoids glare, but that maintains rear vision. Human factors studies can relate driver discomfort to incident glare and the results can be incorporated into a fully automatic mirror whose reflectivity varies dynamically to suit changing driving conditions. In automatic mode, the electrochromic mirror responds appropriately to all driving situations, and mirror operation is transparent to the driver with smooth response and no unexpected change. This paper explains the scientific basis of electrochromism and traces development of the technology to its present applications. Electrochromic mirrors presently available worldwide are reviewed. The performance desired of an electrochromic mirror is defined and the ability of current electrochromic mirrors to achieve this performance is discussed.

Mansour, T.M., 1971

Driver Evaluation Study of Rear View Mirror Reflectance Levels

There has been a lack of information on image brightness in automotive rear vision systems as related to the driver's needs. This paper presents data on driver evaluation of brightness, in the form of visibility and glare ratings of rear view mirror reflectance levels, based upon actual driving experiences. The effects of roadway types and various ambient lighting conditions are discussed, and ranges of acceptable reflectance levels are recommended. The study was a task group effort, performed for the SAE Rear Vision Subcommittee.

Miller, N.D., Baumgardner, D., and Mortimer, R.G., 1974

An Evaluation of Glare in Nighttime Driving Caused by Headlights Reflected from Rearview Mirrors

This paper presents the results of a study directed toward examining the effects of glare resulting from following headlights reflected in rearview mirrors. In particular, the effects of different driving environments are discussed with regard to their effects on glare. The results of a computer analysis predicting the magnitude of glare reflected from rearview mirrors for several headlight systems are also presented. a These computations cover a range of intercar spacings and both inside and outside mirrors. An important question is also posed concerning the effects of glare in a driver's peripheral field-of-view and its potential effects on the detection of early warning events.

Ohmi, S., Hara, K., Sagiike, M., and Sato, R., 1987

Fail-Safe Type Liquid Crystal Mirror for Automobiles

A new type of liquid crystal anti-glare mirror which satisfies the fail-safe condition, i.e. when electrical power supply of a mirror control is broken, the non-anti-glaring normal mode is always maintained has been developed. While, a conventional liquid crystal anti-glare mirror does not satisfy this fail-safe condition. The development of our new type mirror was supported by our improved surface treatment technique for the perpendicular alignments.

Olson, P.L., Jorgeson, C.M., and Mortimer, R.G., 1974

Effects of Rearview Mirror Reflectivity on Drivers' Comfort and Performance

Three studies were conducted to evaluate the effect of various mirror reflectivities on the opinions and performance of drivers in a variety of situations. One of the mirrors being evaluated employed a dual reflectivity principle, having a narrow band of low reflectivity (about 14%) against a higher reflectivity background (about 45%).

The first study required subjects to detect the presence of a following car, and indicate which lane it was in. This was conducted as a laboratory study using movies of the car and roadway and simulating a twilight condition. Reaction times, error scores, and preferences favored mirrors of 36% reflectance or more. The banded mirror had comparable error performance to the other mirrors but significantly longer reaction times and poorer preference ratings.

In the second study, conducted at night on the road, subjects were asked to rate interior and exterior mirrors for their visibility and glare reduction effectiveness. Only the 85% mirror was rated significantly higher than the banded mirror in visibility. The 4% and 14% reflectivities were rated significantly higher in reducing glare than most other mirrors. The differences were not significant, however, between the 14% and 14% banded mirrors. Thus, the banded mirror was about as effective as the 14% mirror in reducing glare yet gave better visibility to the rear.

The final road study called for subjects to make passing maneuvers in front of an overtaking vehicle at what they considered to be the last safe moment. This study was conducted during the day and at night with the same subjects in each group. Results based on mean glance durations and frequencies and subject evaluations favored the 45% uniform and 14% banded mirror as compared to a 14% uniform mirror. One of the most significant findings of the study was that subjects did not allow enough time to pull out and pass at 15 mph closing speed. Almost half of the trials would have resulted in collisions at this relative speed.

Olson, P.L. and Sivak, M., 1984

Glare From Automobile Rear-Vision Mirrors

Four studies were carried out to measure disability and discomfort glare from automotive rear-view mirrors. The results of the first three studies, which were concerned with disability effects, indicated that there are significant losses in forward visibility even at glare levels associated with low-beam headlamps. the last study measured comfort levels and showed that drivers rated even moderate glare levels uncomfortable, especially if they were exposed to them for a relatively long period of time. The implications of these findings for headlamp design are discussed.

Rowland, G.E., Moretti, E.S., and Patton, M.L., 1981

Evaluation of Glare from Following Vehicle Headlights

A field study compared Standard headlamps of 1978 vintage with an Experimental system which used halogen luminaires. The basic question was the extent to which lights on a following vehicle create illumination which could cause sufficient glare as to degrade the visual performance of the driver of the leading vehicle. Independent variables included headlight type, misaim of headlights, lane occupied by following vehicle, various reflective conditions (mirrors, glazings, etc.), low vs. high beam, headlight height, and distance. Main conclusions were that neither type of headlight regularly produces disabling glare under the varied conditions used in the urban situation and both types quite commonly produce disabling glare in most of the research on the rural situation. Misaim effects are co-dependent on headlight height: low mounted lights are worse if misaimed up, high mounted lights are worse if misaimed down. High beam settings are worse than low beam settings. The worst distance depends somewhat on a combination of aim, height, lane, and other variables but, in general, lies between 59 and 79 feet. Glare remains disabling to some unmeasured distance beyond 300 feet. Even in the absence of mirrors, remaining reflective surfaces alone produce disabling glare out to 200 or 300 feet. The halogen lights are generally brighter under most conditions and appear to be disabling at a greater distance.

Ueno, H. and Otsuka, Y., 1988

Development of Liquid Crystal Day and Night Mirror for Automobiles

The liquid crystal day and night mirror with excellent reflective characteristics has been developed.

The day and night mirror using Guest-Host liquid crystal devices improves the performance of rear view mirrors.

Effects of primary factors on reflective characteristics of the liquid crystal day and night mirror have been investigated. Results are as follows:

(1) The reflective characteristics at wave-length of about 555 nm are important for the selection of liquid crystals and dichroic dyes.

(2) The reflective characteristics are improved by decreasing the reflectivity of glass substrate.

(3) The reflective characteristics are improved by increasing the reflectivity of reflector.

2.3 Issues for future research

1. The disparities between currently available reflectivity levels and the levels that are recommended by a small but consistent set of studies raise the question of how useful people find current day/night mirrors. Presumably the currently available night setting, with a reflectivity of about 4%, is useful for reducing glare. But is it also so dim that people avoid using it in order to maintain clear vision to their rear even when they are experiencing considerable discomfort and disability due to glare? More generally, it might be useful to know how drivers value, and make use of, the manually switchable day/night mirrors that are currently common.

2. There are a number of technical innovations that could provide automatically controlled reflectivity levels responsive to ambient illumination and/or rear illumination. Would drivers accept a mirror whose reflectivity changed at times that, although perhaps appropriate, were beyond their control? How important would it be to provide a manual override control? If people had an override available how many of them would use the automatic mode? How would the answers to these questions be affected by the range of reflectivities that the mirror provided?

3. With multiple mirror systems (such as the two- or three-mirror systems currently common in the United States) there is typically some overlap of the fields of view of the individual mirrors. Considering effects on visibility alone, this redundancy may be beneficial (especially for integrating the information from multiple mirrors) or at least neutral, but at night when following headlights are in regions of overlap their glare effect is multiplied. The issues of how many mirrors should be used and how they should overlap involve many considerations, but evaluation of those issues would be helped by a quantitative sense of the severity of the problem of multiplied glare.

4. Could glare from rearview mirrors be reduced by mirrors with uneven spectral reflectivities (colored mirrors)? Some regions of the visible spectrum may contribute more to discomfort and disability glare than others (e.g. French headlights use yellow filters because of this possibility). Do different regions of the spectrum contribute unequally to target definition in rearview mirrors because of the colors and contrasts of typical targets?

3.0 CONVEXITY

3.1 Review of existing literature

The 21 items related to mirror convexity are also fairly diverse in format. They are summarized in Table 3 using the same format as the summary of visibility-and-glare items in Table 1. Authors' abstracts for all items that have them are included in section 3.2 below. In contrast to the items related to visibility and glare, however, there are a greater number of studies that provide new data about human performance. That fact is evident in the lefthand columns of Table 3.

The main reason for considering the use of convex mirrors is the desirability of providing a larger field of view without using prohibitively large mirrors. There seems to be a fairly strong consensus in the work summarized here that plane mirrors cannot be configured to provide all of the rear field of view that would be useful. Of course, whether convex mirrors are a good alternative also depends on the magnitude of any perceptual problems that might result from the distortions inherent in convex mirrors. Although no study has attempted a quantitative comparison of those factors as a way of evaluating convex mirrors, there has been a fair amount of work on quantifying both the benefits from a wider field of view and the possible costs due to distortions of size, distance, and speed, as well as to changes in accommodation necessary with convex mirrors.

One issue in particular has received enough attention to justify tabulating and comparing the relevant studies. That is the issue of how people perceive distance in convex mirrors. Two general tasks have been used to measure distance perception. One task requires observers to indicate the last possible moment at which they would change lanes in front of an overtaking car, thus indicating when they perceive the distance between them and the overtaking car to be just large enough to avoid a collision. The overtaking car is observed through a rearview mirror that has one of the curvatures to be evaluated. The observer is typically in an automobile, and may be driving in actual traffic, or may be parked in a so-called "semi-dynamic" setup.

The second task involves more direct judgments of distances observed through mirrors of various radii. The simplest version makes use of the psychophysical method of magnitude estimation, requiring an observer to simply estimate a perceived distance in feet, car lengths, or even a dimensionless number. Magnitude estimation is an appealing procedure because it is simple and because it is well established in psychological and human performance studies (e.g. Engen, 1971). However, it is probably not a good idea to assume that subjects' estimates of distance in feet or other units are meaningful in an

Table 3

Summary of items related to convexity

Author(s), date	Human Performance Data		Human Performance Analysis	Subjective Ratings	Survey of Technology	Product Description
	Lab	Field				
Morrow & Salik, 1962	x					
Seashore & Lundquist, 1968						x
Bowles, 1969		x				
Kelley & Prosin, 1969			x	x	x	
Walraven & Michon, 1969		x				
Rowland et al., 1970		x		x		
Mortimer, 1971		x		x		
Hagberg & Bulterman, 1974			x			
Mortimer & Jorgeson, 1974	x	x		x		
Seeser, 1974			x			
Van Eyl, 1974	x					
Kaehn, 1976				x		
Smith et al., 1978	x	x				

Table 3 (continued)

Author(s), date	Human Performance Data		Human Performance Analysis	Subjective Ratings	Survey of Technology	Product Description
	Lab	Field				
Sugiura & Kimura, 1978		x		x		
Mourant & Donohue, 1979		x				
Burger et al., 1980a		x		x		
Burger et al., 1980b		x				
Pilhall, 1981				x		x
Burger & Mulholland, 1982			x			
Fisher & Galer, 1984	x					
Olson & Winkler, 1985					x	

absolute sense, as at least one study has done (Rowland et al., 1970). A second type of psychophysical task requires an observer to make a "null match" between a standard distance and a comparison distance. One way of implementing such a task would be to have a person indicate when a car seen approaching in a mirror appears to be at the same distance as another car seen directly. Both magnitude estimation and null match tasks can provide useful information, but null match to a standard usually yields responses that are more consistent both among and within observers. Also, when all responses are made with respect to a concrete standard the problem of interpreting absolute values of magnitude estimates does not arise.

Studies that have used the lane-change task to indirectly evaluate distance perception are summarized in Table 4. Taken together, these studies suggest that subjects accept smaller gaps when viewing an overtaking car through convex mirrors, presumably because they overestimate distances seen through convex mirrors. There is some evidence that the effect is reduced by learning (Burger et al., 1980), and one study found no substantial effect of convexity (Walraven & Michon, 1969). If subjects have a plane mirror available in addition to a convex mirror (Mortimer, 1971; Mortimer & Jorgeson, 1974) the size of gaps that they accept is independent of the radius of the convex mirror, perhaps because they rely completely on the plane mirror for distance judgments. This later finding supports the suggestion that people may use convex mirrors as "go or no-go" indicators, proceeding with a maneuver if no vehicle is present in the convex mirror, but otherwise supplementing the convex-mirror view with a plane-mirror view or a direct look before making a decision (Mourant & Donohue, 1979).

Studies that more directly measured distance perception are summarized in Table 5. Again there is general agreement that people do overestimate distances seen through convex mirrors. The effect at least can be attenuated by training with feedback (Burger et al., 1980), but it seems to be present even for subjects who have extensive experience with convex mirrors (Sugiura & Kimura, 1978).

The studies summarized in Tables 4 and 5 thus suggest that convexity of mirrors does affect people's perception of distance. There are indications that learning can overcome any resulting misperceptions, and that people might not rely on their perceptions of distance through convex mirrors, perhaps because they are aware of their own tendency to misperceive. Those factors would of course diminish any problems due to perceptual distortions, but it could be argued that drivers would still respond inappropriately if they had to react to visual information from a convex mirror in an emergency situation.

In addition to causing geometric distortions, convex mirrors also change the optical

Table 4

Studies using lane-change maneuver

Author(s), date	Method	Subjects	Radii of mirrors used	Subjects' Convex Experience	Results
Bowles, 1969	dynamic	8	∞, 48 (in)	experienced and inexperienced	Smaller gaps accepted with convex mirror by both experienced and inexperienced subjects.
Walraven & Michon, 1969	dynamic	12	∞, 1200, 600 (mm)	experienced and inexperienced	Little effect of convexity for any subjects.
Mortimer, 1971	dynamic	18	∞, 47, 29 (in)	"majority" no experience	Smaller gaps accepted with smaller radius mirrors but effect disappears if a plane mirror is also available.
Mortimer & Jorgeson, 1974	dynamic	8	∞, 48 (in)	not specified	Consistent with Mortimer, 1971, extends those findings to night conditions.
Burger et al., 1980	semi-dynamic	12	80, 55, 40 (in)	none prior to study, but study includes training	Small increase in "unsafe" gap acceptance for shorter radius mirrors.
Fisher & Galer, 1984	laboratory films	21	∞, 1950, 1400, 600 (mm)	not specified	Smaller margin of safety for shorter radius mirrors.

Table 5

Studies of distance judgments using convex mirrors

Author(s), date	Method	Subjects	Radii of mirrors used	Subjects' Convex Experience	Results
Rowland et al., 1970	magnitude estimation in car lengths, static field setup	18	200, 80, 40, 20 (in)	not specified	Subjects underestimate distance in plane (200 in.) mirror, overestimate in 40 in and 20 in, roughly balanced in 80 in.
Smith et al., 1978	magnitude estimation in feet, laboratory film	47	∞, 50 (in)	some had 3+ years, rest little or none, study includes specific training	Absolute errors decrease with training. Effect of experience on signed errors is not monotonic. Report is cryptic.
Sugiura & Kimura, 1978	null match, semi-dynamic field setup	10	∞, 1500, 1200, 900, 600, 300 (mm)	extensive (all Japanese subjects)	Estimates of distance are greater with shorter radii.
Burger et al., 1980	null match but with standard specified as abstract distance in feet, semi-dynamic field setup	12	80, 55, 40 (in)	not specified, study includes specific training	Small effect, overestimates of distance with shorter radii.

distance to objects seen through them. The image that an observer sees in a convex mirror is an erect, virtual image at a distance slightly further away than the mirror itself. The optical location of the image depends on the distance between the mirror and the actual object, and ranges from the position of the mirror to a position behind the mirror by one half of the mirror's radius. As a practical example, if a convex mirror with a radius of curvature of 40 inches is located 50 inches from a driver's eye position, most important images seen in the mirror will be at an optical distance of $50 + .5(40) = 70$ inches.

If a driver is accommodated at virtual infinity while looking at objects several hundred feet in front of a car, and then glances at a convex rearview mirror, he or she will have to change accommodation to see the mirror image clearly. This aspect of convex mirrors raises at least two potential problems. First, people may have to change accommodation quickly and often while driving. Second, some drivers, particularly older ones, may not be able to focus near enough to see the mirror image clearly. There is no direct evidence about the state of accommodation of a driver's eyes while viewing a roadway directly or while using a convex rearview mirror. Theoretical considerations suggest that loss of near accommodation with age would make it difficult for older drivers to use convex mirrors in near positions, such as the driver's side of the car or perhaps the door on the passenger's side, but not in a far position such as the fender on the passenger's side (Seeser, 1974).

3.2 Convexity abstracts

Bowles, T.S., 1969

Motorway Overtaking with Four Types of Exterior Rear View Mirror

Eight subjects performed an overtaking task on a three-lane motorway, using each of four arrangements for rear viewing. The rear viewing systems compared were plane or convex mirrors, mounted on either the driver's door or in the conventional wing position for exterior mirrors. On each trial the subject, driving the experimental car, followed a lead vehicle down the inside lane of the motorway. On the approach of a third vehicle from behind, travelling in the second lane, the subject had to decide whether there was time to overtake the lead vehicle. The subject was instructed to perform the manoeuvre, on trials when he judged that the offered gap was large enough. The speed of the following vehicle varied over trials in a random order. The sizes of gaps accepted and rejected were recorded for each mirror-mount combination. Decision times were also recorded. The results suggest that distances are considerably over-estimated with convex, as compared with plane mirrors. The effect is more marked when the convex mirror is mounted on the wing. The implications of these findings for road safety are discussed.

Burger, W.J. and Mulholland, M.U., 1982

Plane and Convex Mirror Sizes for Small to Large Trucks; Predictions from Truck Characteristics

An analysis was made of the relationship among Cab dimensions and other characteristics of a sample of 28 U.S. trucks and the sizes of plane and 20 inch convex mirrors needed to view proposed ground and vertical FMVSS 111 indirect field of view targets. The purpose was to determine if 1) mirror size could be predicted form one or at most a few truck dimensions and 2) a few mirror sizes could be identified a providing an adequate FOV for a broad range of trucks classified on that dimension or dimensions.

Truck Eye-Height above ground was found to be the best single predictor of mirror sizes and additional dimensions did not improve predictions. Scatter plots showing the relation between the Eye-Height and mirror sizes are presented. Equations for selecting plane and convex mirror height and width based upon truck Eye-Height were derived. They provide a simple method for selecting necessary mirror sizes and for verification of their adequacy with regard to FMVSS 111 indirect FOV targets.

Burger, W., Mulholland, M., Smith, R., and Sharkey, T., 1980

Passenger Vehicle, Light Truck and Van Convex Mirror Optimization and Evaluation Studies, Vol. 1, Convex Mirror Optimization.

A series of studies were designed and conducted to evaluate passenger car and truck mirror configurations and convex mirror radii of curvature and to identify the most effective mirror systems for actual on-the-road use. The studies were conducted in two phases, during which over 40 combinations of mirror convexities and mirror configurations were evaluated experimentally. Phase 1, which is reported in Volume 1, was directed toward investigating the effect of mirror convexity on driver judgments of adjacent lane following vehicle speed, distance and accepted lane change gap size. The convexity(s) resulting in the best performance were to be used in subsequent on-the-road performance tests. Mirrors of 20, 40, 55 and 80 inch radii of curvature were fabricated in several configurations specifically for a passenger car, light pickup truck and a van. Configurations ranged from viewing the proposed FMVSS 111 passenger vehicle (PV) targets with plane mirrors and convex mirrors of varying radii to mirror systems viewing the truck (TRK) targets with a single mirror of varying convexity or a combination of plane and convex mirrors viewing those targets separately. Male and female drivers under 30 and over 50 years of age provided over 12,000 speed and distance judgments. Results indicated that performance differences between mirror convexities were small and generally not significant because of extensive practice. Since the 80 inch radii mirrors produced large obscurations in the forward field of view (FOV) and since some of the 20 inch radii mirrors yielded significantly poorer performance and all such mirrors were rated low by drivers, convexities selected for further study were those of a 40 and 55 inch radii.

Burger, W.J., Mulholland, M.U., Smith, R.L., Sharkey, T.J., and Bardales, M.C., 1980

Passenger Vehicle, Light Truck and Van Convex Mirror Optimization and Evaluation Studies; Volume 2: Evaluation of Alternative Mirror Configurations

Volume 2 reports on the second phase of a study directed toward investigating performance of different mirror configurations, comprised of 40 or 55 inch convexities, during actual on-the-road lane changing. Passenger car, truck and van original equipment mirrors were compared to 55 inch single mirrors viewing the SR passenger vehicle target and single 40 inch convex and plane/convex mirror combination mirrors viewing the truck X and Y targets. Systems were tested with and without the inside mirror FOV available. Drivers' eye movements were recorded during on-the-road driving involving 22 left and right freeway and city lane changes. Various performance measures were recorded, the primary one being the amount of looking time required to make a safe lane change with a particular mirror system. That measure was based upon looking frequency and time to gather rear information. Results indicated the need to modify FMVSS 111 proposed FOV targets, notably increasing the width of XR, overlapping of X and Y targets, and increasing the vertical height of the SR and SL targets. A final series of tests was conducted to answer specific questions about passenger car right mirror location and convex mirror night performance and to evaluate further refinements of passenger car systems. Results indicated that drivers preferred mirrors with substantially greater vertical height and FOV than proposed FMVSS 111 targets will require and that this preference was supported by on-the-road performance measures.

Fisher, J.A. and Galer, I.A.R., 1984

The Effects of Decreasing the Radius of Curvature of Convex External Rear View Mirrors Upon Drivers' Judgments of Vehicles Approaching in the Rearward Visual Field

Two experimental techniques are explored for laboratory investigation of the effect of reducing the radius of curvature of externally mounted rear-view mirrors, using filmed stimulus material prepared to maintain the ecological validity of the changing information display at the mirror surface. One method is concerned with the effect upon the minimum safety margin which drivers are prepared to leave in committing themselves to an offside lane change manoeuvre in front of a vehicle approaching from the rear. The second method is concerned with providing a continuous record of differences in the change over time in visual sensation caused by viewing the approach of a target vehicle through mirrors of different radii. The importance of distorted time-to-collision processing on the part of the observer is stressed.

Kaehn, C.H., 1976

Evaluation of a New Automotive Plane and Convex Mirror System by Government Drivers

An on-the-road study was made by the National Highway Traffic Safety Administration (NHTSA) with the cooperation of the General Services Administration of new mirror system consisting of larger inside and left side plane mirrors and a convex mirror on the right fender. Approximately 150 Federal drivers evaluated this experimental mirror system on a test fleet of 23 passenger cars located at four sites for a six month period starting in September 1974. An analysis of the questionnaires completed by the drivers shows that in general drivers reacted favorably to this experimental convex mirror system. Comparisons are made with the results of earlier field tests conducted with a periscopic device and with two different experimental convex mirror systems.

Kelley, C.R. and Prosin, D.J., 1969

Motor Vehicle Rear Vision

An in-depth treatment of problems of rear vision of passenger and commercial vehicles. Reviews the state-of-the-art and reports on a questionnaire and interviews of experts in the field. Presents empirical data on the location and duration of eye fixations for obtaining rearward information for various vehicle-mirror combinations. Analyzes and discusses rear field of view, rear view display location, and other factors in motor vehicle rear vision. Concludes that wide-angle (90 − 100°) over-the-top rear view systems are the most effective way of providing adequate passenger car rear vision. Recommends techniques for describing motor vehicle rear view performance, discusses the safety standards problem, and concludes with a proposed motor vehicle rear vision safety standard requiring that blind spots be eliminated for both passenger and commercial vehicles, and that rear view displays be prevented from occluding important areas of the forward scene. Abstracts most prior research in the field. 194 pages, including bibliography, abstracts and two appendices.

Mortimer, R.G., 1971

The Effects of Convex Exterior Mirrors on Lane-Changing and Passing Performance of Drivers

Drivers carried out a lane-changing and passing maneuver using convex and plane exterior mirrors alone or in combination with a plane interior mirror. the data showed that the addition of the plane interior mirror compensated for judgmental errors found when convex mirrors were used alone. When the speed difference was 15 mph between the overtaking car and the subject's car, subjects accepted gaps that were too short irrespective of the exterior mirror type. The data suggested that exterior convex mirrors of radii greater than 30 in. may be used reasonably safely by drivers and would have the advantage of providing a considerably increased field-of-view compared to currently used exterior mirrors.

Mortimer, R.G. and Jorgeson, C.M., 1974

Drivers' Vision and Performance with Convex Exterior Rearview Mirrors

A laboratory simulation of dawn/dusk illumination showed that following vehicles could be detected equally well in plane and convex mirrors, and a night driving test showed that low- and mid-beam headlamps of a following car produced discomfort glare responses that were independent of whether the exterior mirror was plane or convex. Visibility of the following car was rated better with the plane exterior mirror. Measures of performance of drivers relevant to safety in lane changing and passing were not different when they used a plane or convex exterior mirror in conjunction with a plane interior mirror, and did not differ in the day or at night. When the initial speed of the overtaking car was 15 mph (24 km/h) greater than the subjects' car, drivers significantly underestimated the relative speed, indicating a potential cause of collisions with a following vehicle in lane changing and passing maneuvers.

Mourant, R.R. and Donohue, R.J., 1979

Driver Performance with Right-Side Convex Mirrors

The mirror-use behavior of drivers was investigated as they gathered information from rearview mirrors in order to execute freeway lane changes and merges. Nine drivers (three novice, three experienced, and three mature) drove a 1973 Buick LeSabre with and without a right-side fender-mounted convex mirror along a 22.5-km (14-mile) freeway route. The total time to obtain information per maneuver was the same for both cases. In a subsequent study, the mirror-use behavior of five subjects who drove a 1976 Nova without a right-side convex mirror was compared with that of 12 subjects who drove the same vehicle with a right-side door-mounted convex mirror. Again there were no differences in total time to obtain rear-vision information. Experienced drivers (mean age = 24) took less time to obtain information when a right-side convex mirror was available than when it was not; older drivers (mean age = 61) took more time. Also, experienced drivers required about 10 h of driving experience to become efficient users of a right-side convex mirror, while older drivers required considerably more driving experience. Finally, a comparison of right-side door- and fender-mounted convex mirrors indicated that the drivers' total time to obtain information was the same for each mounting location, but drivers who had the fender-mounted mirror made a greater number of direct looks to the rear.

Olson, P.L. and Winkler, C.B., 1985

Measurement of Crash Avoidance Characteristics of Vehicles in Use

The primary purpose of this study was to collect information on the condition of lighting equipment, rearview mirrors, and tires on a nation-wide sample of vehicles in use. In order to more adequately represent cars of the future, the sample was restricted to vehicles built in 1979 and later. As a result, the data may not be completely representative of the current vehicle population.

The results of the study indicate that headlamps are often badly out of aim. About 60% of the vehicles sampled had one or more low-beam units aimed outside of SAE limits. Aim worsens as vehicles age, at least for the first four years. With the exception of side marker lights, all other lights and signals on the vehicles inspected were about 98% operational. Side marker lights were about 90% operational. The condition of all lighting equipment was better in states having motor vehicle inspection programs.

The rearview mirrors in the sample were generally in good physical condition. Their aim was quite variable. However, in general, the mirrors were aimed to provide a reasonably good view of important areas to the rear.

About 90% of the tires in the sample were found to be free of defects. Average tread depth, except for new cars, was about 0.21 inch, with a standard deviation of about 0.07 inch. On average, tires were inflated to within 2–3 psi of the pressure recommended. However, the standard deviation was about 6 psi.

A study was also run of the effects of vehicle loading on vertical headlamp aim. These results suggest that fuel levels will alter aim by about 0.2 degree on average. Full-passenger or full-rated loads have a much greater effect, altering pitch by as much as 1–1.5 degrees.

Literature surveys were also run on aerodynamic effects, and equipment for cleaning headlamps and maintaining their aim under different loading conditions. Summaries of the findings are presented.

Pilhall, S., 1981

Improved Rearward View

Various possibilities to improve the rearward view in passenger cars have been studied, with the aim, among others, to eliminate "dead angle." Tests have been performed with periscopes, vehicle TV, combined mirrors and mirrors with continuously variable curvature. The later ones have been optimized to a well functioning solution.

Rowland, G.E., Silver, C.A., Volinsky, S.C., Behrman, J.S., Nichols, N.F., and Clisham, W.F., Jr., 1970

A Comparison of Plane and Convex Rearview Mirrors for Passenger Automobiles

A systematic comparison was made between certain plane mirrors and convex mirrors for use as a means to provide passenger car rear vision. Experiments were performed on the effects of various convexities in relation to eye/mirror geometry, eye anomalies, time of day, mirror size, learning required to use convex mirrors, and the use of combination mirrors. Data is given for judgments in spatial localization and detection probabilities for a wide range of interior and exterior mirrors. The general conclusion is that convex mirrors provide an improved probability of detection of other automobiles while, at the same time, also providing reasonably accurate spatial localization. In general, convex mirrors of about 40-inch radius appear to be a satisfactory compromise in terms of convexity. It is recommended that 40-inch convex mirrors be installed on left and right front fender areas and in the upper center of the windshield of all passenger automobiles. Brief discussion of further research which is required.

Seashore, C.G. and Lundquist, E.C., 1968

The Scientific Application of Optics and Accident Prevention to Mirror Vision for Commercial Drivers

To the average truck or bus driver the critical problem of the "blind spot" has existed ever since flat mirrors were first applied to vehicles. With large vehicles and the single plane mirror it is entirely possible for a car to be hidden under the driver's lower line of vision. This problem of "blind spot" is compounded, depending on the size of the vehicle, driver's eye level above the ground, and the distance and position of his eyes from the mirrors.

The mathematically designed mirrors discussed in this paper permit the driver to utilize the upper flat mirror for rearward vision; the reflected view of the blind area is in the bottom prepositioned mirror. It is believed that the next area of optics improvement will be with the noncommercial device.

Seeser, J., 1974

Automotive Convex Mirrors—Optical Properties

A series of detailed calculations relating to automotive (including truck) use of left and right outside convex mirrors are presented in an attempt to elicit information about the effect of the purely optical properties of convex mirrors on their use by monocular and binocular human users. A review of the human visual task and a discussion of the methods of calculation are presented. The primary calculations center around a standard large automobile configuration with two targets that simulate the cross section of an automobile in adjacent lanes and at distances behind the driver of thirteen and thirty feet. Quantities defined and calculated are apparent magnifications, gains in field of view, absolute field of view, driver head-turns, binocular and monocular fields of view, accommodation ability redundant as a function of age, near points required for clear vision, eye divergence angles, and mirror quality relative to binocular vision. Calculations were performed for thirty-, forty-, sixty-, and eighty-inch mirrors for a number of positions on both the left and right sides. Truck calculations centered around a standard large truck cab and a trapezoidal ground target. Optimum radii of curvature and mirror shapes to see this target are discussed, along with perspective views of the target. Several recommendations are made regarding types and locations of convex mirrors.

Based on the fact that drivers are binocular creatures, and that older drivers have pronounced near vision problems, it is recommended that, for convex mirrors in the thirty- to eighty-inch radius range, the nearer locations for convex mirrors on both the left and right hand sides should be used with caution. For the right hand side, it is recommended that a convex mirror of fifty-inch radius minimum should be placed at least forty inches forward of the driver's eyes, measured along the longitudinal axis of the automobile. A number of configurations are recommended on the left hand side, with a convex mirror sixty-inches in radius placed fifty inches forward of the driver a representative configuration.

Smith, R.L., Bardales, M.C., and Burger, W.J., 1978

Perceived Importance of Zones Surrounding a Vehicle and Learning to Use a Convex Mirror Effectively

A previous study demonstrated that a group of driver educators, through use of the pair-comparison technique, attached greater importance to zones to the right of a driver than to his left. Numerical weightings were generated for a relatively large number of zones. The present investigation, in part, replicated the earlier study for groups of individuals varying in age and driver experience. The results confirmed the earlier findings, indicating that mere exposure to the driver's situation provides sufficient bases for judging the importance of surrounding zones. Additional experimental work revealed that the higher weightings given to the right-hand zones were primarily, if not entirely, due to the greater difficulty to see those zones.

The present study also investigated the effects of training on judgments of vehicle distances and speeds as viewed through a 50-inch convex mirror. Subjects varying in age and driving experience were given 192 trials over four test sessions. In general, all groups showed substantial learning over test sessions and within-group variability also decreased markedly. The most superior performing group, one having several years of convex mirror usage, produced more accurate judgments than a control group which viewed the vehicle images on plane mirrors.

Sugiura, S. and Kimura, K., 1978

Outside Rearview Mirror Requirements for Passenger Cars—Curvature, Size, and Location

Primary design factors with regard to outside mirrors are curvature, size and spatial localization. Experiments were conducted to find the effects of these factors in relation to visibility and the size of field of view. Investigations to determine visibility requirements were static testing and field testing. The results show that convex mirrors with 47 inch radius of curvature are most preferable for the visibility requirements. Required size of field of view was established taking into account the size of direct field, vehicle size and lateral distance to another car.

Van Eyl, P., 1974

The Effect of Convex Mirror Distortion on Acuity and Size Discrimination Tasks

Six 3 x 5 inch convex mirrors of varying optical quality were tested under simulated twilight conditions for accuracy and reaction time on acuity and size discrimination tasks. Subjects were 12 male and female college students ages 17 – 21 and 12 employed males and females between ages 45 – 62. Sex yielded a minor difference; older subjects worked more slowly and made more errors. the first-surface mirror with good cosmetic appearance was best for the size discrimination task; the first-surface mirror with fair cosmetic quality was best for the acuity task. The results were discussed in regard to rear-view vision with a convex mirror positioned on the right-front fender of a car.

3.3 Issues for future research

1. Discussions of the effect of convexity on perception of distance in rearview mirrors have implicitly assumed that distance perception in plane mirrors is accurate or in some way normative. However, Roscoe (1984) discusses a number of aspects of displays that seem to distort the perceived distances of objects seen through them, including a possible "framing effect" in which distance perception is distorted by a simple frame surrounding a scene. Considering such effects, it does not seem justifiable to assume that distance perception in plane mirrors is accurate. It may be useful to know if and in what way that perception is distorted. People may misperceive distances in convex mirrors, but the significance of that fact would seem less clear if people also misperceive distances in plane mirrors. Perhaps beginning drivers have as much or more trouble in learning to use a plane mirror as experienced drivers would have in switching from a plane to a convex mirror. It may therefore be useful to study the distance perceptions of beginning and experienced drivers using plane mirrors, not only for the information that it might provide about how people adapt to distorted views in general, but also to help design instruction for beginning drivers in the use of plane mirrors.

2. If people can learn to overcome misperceptions of distance in plane or convex mirrors, what type of experience or training is most beneficial in learning to perceive veridically? Presumably some sort of feedback is needed, and it would be undesirable for that feedback to be in the form of collisions with other vehicles or fixed objects.

4. How valuable would it be to locate all information about the rear view in one place (as could be done with a center convex mirror or periscope) rather then in several different mirrors (left and right outside, center inside)?

5. Are there problems associated with having mirrors with different radii of curvature on the same vehicle? Are there problems with having mirrors with different radii of curvature on different vehicles that may be driven by the same people? Both of these situations currently exist in the U.S. because of the mixture of plane and convex mirrors in the right outside position. A survey of recent model cars in the U.S. indicates that about two thirds of them have right outside mirrors, and that plane and convex mirrors are about equally common in that position (Olson & Winkler, 1985).

6. There are now a substantial number of people in the U.S. who have driven cars with convex right outside mirrors. It would be useful to survey the opinions and experiences of those people. It would be interesting to know such things as: how often and in what situations do they use the convex mirrors, how well do they like them, and what

sorts of accidents and near misses have they had more of or less of relative to people using plane mirrors or no right mirrors.

7. As mentioned above, about a third of U.S. cars have convex mirrors in the right outside position, and virtually no U.S. cars have convex mirrors in the left or inside positions (Olson & Winkler, 1985). In other countries, such as England and Japan, convex mirrors are more common. This suggests that it might be useful to compare rates for different types of accidents across countries. If, for example, there is an inherent problem of perceptual distortion in convex mirrors, and if the problem is never fully overcome by learning, there may be a disproportionately high number of rear-end collisions resulting from improper lane changes in countries with more convex mirrors. (There might also be fewer side-swipe collisions resulting from improper lane changes in those countries because of the improved field of view provided by convex mirrors.)

8. If people do learn to compensate for an initial misperception of distance in a convex mirror, does the pressure of an emergency situation, or simply lack of time, degrade that compensation?

9. Direct measurements of where people are actually accommodated while viewing a distant road scene and while viewing the optically nearer image in a convex mirror, especially in conjunction with visual performance measures, would be useful in determining how much of a problem the nearness of a convex mirror image might be. It is not clear, for example, that people would normally be accommodated near infinity while viewing a road scene even if most of the scene was hundreds of feet away. Roscoe (1984) claims that without distant resolvable texture the eye tends to relax to its dark focus distance of about one meter, and that condition may not be infrequent in driving.

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