

Optical Properties of Plane and Convex Mirrors: Investigation of Mirror Use to Enhance Construction Flagger Safety

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Legislation and product development in the USA has prompted an interest in mirror-use by traffic flaggers to improve awareness of vehicles approaching from behind. Helmet- and flagpole-mounted configurations were studied using a graphical approach with field verification studies by comparing fields of view, object magnifications, and human factors considerations. Plane and convex mirrors with different radii of curvature were investigated. Results found image formation on helmet-mounted convex mirrors occurs too close to the mirror. A 0.038 m helmet-mounted plane mirror performed similarly to a 0.076 m diameter, 0.508 m radius of curvature convex mirror. Fields of view and image information between helmet-mounted plane mirrors and flagpole-mounted convex mirrors were compared. Issues of image perception, practical use, and attention were identified; they pose serious issues for use as a primary safety device. Additional investigation is needed to determine the requirements and applicability of mirror-use for flagging in work zones.

flagger work zone safety mirrors vehicle backing intrusion

1. INTRODUCTION

An increased interest in flagger safety has led to a need to investigate the use of mirrors by construction flagging personnel to increase their awareness of objects approaching from behind. The Washington State Legislature passed the Kim Vendl bill, named for a 45-year-old woman who was struck from behind and killed by a dump truck while flagging at a construction project. The bill

lead to the adoption of temporary worker safety rules that took effect on June 1, 2000, and was then followed with permanent rules. Added to the current rules governing the safety of flaggers, the new performance requirements do not specify an approach that must be used but provide example methods. The following is an excerpt from the Washington administrative code [1]:

Adequate warning of approaching vehicles.
Employers must: ... [p]osition work zone

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flaggers so they are not exposed to traffic or equipment approaching them from behind. If this is not possible, then the employer, responsible contractor, and/or project owner must develop and use a method to ensure that flaggers have adequate visual warning of traffic and equipment approaching from behind. ... The following are some optional examples of methods that may be used to adequately warn or protect flaggers:

- Mount a mirror on the flagger's hard hat.
- Use an observer.
- Use "jersey" barriers.

One of the easiest methods to potentially warn flaggers would be to use a mirror, but their effectiveness is unknown. Mirrors have long been used in automobiles to enhance automobile driver's ability to view his or her environment. Their size, optical properties, and placement are all regulated. Because of these regulations, and along with their importance in enhancing visibility, numerous studies evaluating the use of mirrors have been conducted. Although the use of mirrors by automobile drivers and flaggers is different, the main issues are still the same: field of view (FOV), image location, magnification, perception of objects, ease of use, and other human factors considerations. Little, if any, research has been done on the use of mirrors by flagging personnel. There are two basic configurations flaggers may adopt for mirror placement: helmet and flagpole (or wrist) mounting.

Traditionally, plane mirrors have been used for the center-mounted, rear-view mirror and the driver's side, side-view mirror. To increase the drivers' FOV, convex mirrors are currently being used on the passenger-side, side-view mirrors. This increase in FOV caused by the use of convex mirrors comes with a cost, however. Images appear to be farther away than they really are. This phenomenon is called overestimation because drivers will sometimes make lane changes believing that the vehicle in the next lane is farther back than it really is. Flannagan, Sivak and Traube found that the degree of overestimation increased with a decreased radius of curvature (ROC) [2]. This

is an important relationship because as the ROC of a mirror decreases (the mirror becomes more convex), its FOV increases, as does the degree of overestimation. With this inverse relationship, it is critical to find an optimum ROC for convex mirrors that balances the effects of overestimation with an increased FOV.

In another study, Flannagan, Sivak, Schumann, et al. studied the effects of overestimation versus the distance from the mirror to the viewer's eye [3]. Results showed that the driver looking at the passenger-side, convex side-view mirror made mistakes in perceived distances that were twice as great as those made by a driver looking in the driver-side, convex side-view mirror. The importance of this study was that the results suggested that the closer the eye was to the mirror, the smaller the degree of overestimation.

Burger, Mulholland, Smith, et al. conducted a study on the optimization and evaluation of different ROC convex mirrors to find an optimal convex mirror for use in passenger vehicles, light trucks, and vans [4]. Their experiments were semidynamic; the subjects sat in a stationary vehicle and performed several tasks, including making distance and placement judgments on vehicles approaching from behind. After studying 0.508, 1.016, 1.397, and 2.032 m ROC convex mirrors and rating them according to drivers' performance as well as drivers' preference, they chose the 1.016 and 1.397 m ROC mirrors for further study.

Flannagan, Sivak and Traube examined perceptual adaption to convex rear-view mirrors and found that overestimation of object location decreased rapidly after training, but never reached that of plane mirrors [5]. Different types of training were not investigated, but it was found that the learning occurred quickly when the subjects were given feedback on their accuracy.

Rowland, Silver, Volinsky, et al. investigated the use of convex mirrors by farsighted people (hyperopia) [6]. They found that people with hyperopia might not be able to focus on images in convex mirrors. Their study showed that increasing the convexity of mirrors increased this problem. The reason for this was that the image location got closer to the mirror as the

ROC decreased. The researchers also noted that because of their optical qualities, glare was not a problem when convex mirrors were used.

Seeser went further with his study of hyperopia and stated that the changes in the eye that caused hyperopia began to level off around the age of 55, with the near point focus ranging from 0.800 to 1.999 m (average of 1.001 m) [7]. On the basis of his findings, Seeser recommended that convex mirrors of 0.762–2.032 m ROC be used with caution. For the automobile drivers' left side-view mirror placement he recommended a convex mirror with a radius of 1.524 m be placed 1.270 m forward of the driver. This study also highlighted other important issues associated with mirror use. One of these was the quality of mirrors. Mirror imperfections, such as multiple ROCs, dimples on the surface of the mirror, and poor surface finish quality could all affect the perception of images by the viewer.

Sugiura and Kimura studied different side-view mirrors on passenger cars [8]. Their experimental subjects were Japanese drivers who had considerable experience in using convex mirrors. They evaluated mirrors ranging from plane to 0.305 m ROC for judgments of distance, speed, and motion perception. They concluded that mirrors with 0.889–1.194 m ROC were the most preferable side-view fender mirrors in Japan.

Most of the information presently available regarding the use of convex and plane mirrors for increasing one's FOV comes from studies involving their use in automobiles. Although some of this information is useful, the nature of a flagger's job is different from that of an automobile driver. One must be very careful in applying the data taken from automobile studies and applying it to the current study. Standard flagging practices must be taken into account so that the use of mirrors does not distract flaggers from their primary responsibilities, which usually take place in front of them as opposed to behind them.

This report summarizes research done to evaluate potential uses of mirrors to help flaggers increase their awareness of their surroundings.

FOVs, magnifications, and image distances for several mirrors under a variety of scenarios, both using proper and improper flagging technique, are evaluated. Also discussed are some human factors issues that may require additional study. The report concludes with a recommendation of mirror type and placement that may be used by flaggers in conjunction with standard flagging practices.

2. METHOD

One helmet-mounted (HM) and five flagpole-mounted (FPM) mirrors were studied using computer-aided design (CAD) technology (Figure 1). The FPM mirrors were all 0.076 m in diameter and mounted at eye level on the flagpole. The ROC used for the FPM were 0.508, 0.660, 1.016, 2.032 m, and infinite (for a plane mirror). The mirror was always placed at a distance of 0.61 m from the eye(s). The HM mirror used was 0.038 m in diameter and had an infinite ROC. The mirror was located at eye level and was mounted on an arm that extended 0.089 m from the eye. In determining the dimensions of the human body, average values were taken from Woodson, Tillman and Tillman [9].

To find the FOV (Figure 2), image distance, and magnification values (Figure 3), a drawing technique that follows the law of reflection was used. The law states that when dealing with light rays and mirrors, the incident ray, the reflected ray, and the line normal to the surface of a mirror all lie in the same plane, and the angle of reflection equals the angle of incidence [10]. CAD software (AutoCAD 2000, Autodesk, Inc., USA) was used for all the scenarios and provided the numerical values for FOVs, angles of mirrors and arms, and object and image locations and sizes. United States Customary System units¹ were used in the study and the results have been converted to SI units herein.

The mirror equation relating image (i) and object (o) distances to the focal point of a mirror

¹ 1 ft = 0.3048 m = 12 in.

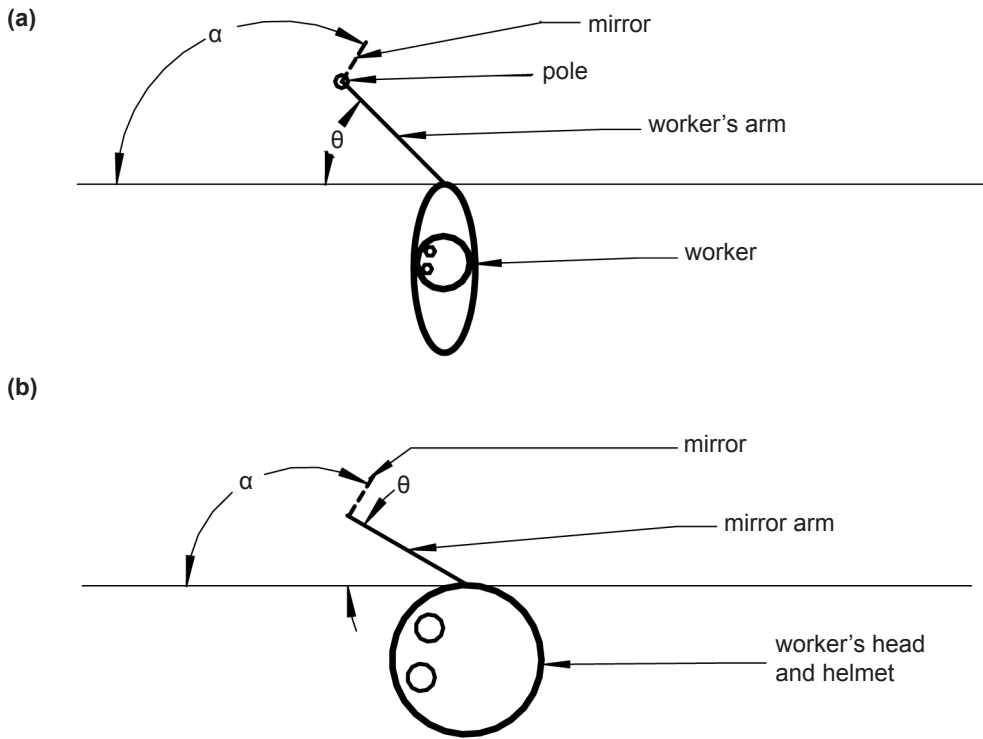


Figure 1. Mounting configurations for (a) the flagpole-mounted (FPM) mirror and (b) the helmet-mounted (HM) mirror. Notes. The distance from the eye to mirror in the FPM is 0.610 m and the distance from the eye to mirror for the HM is 0.089 m; α —angle from forward to mirror, θ —angle from worker’s arm or mirror arm to forward.

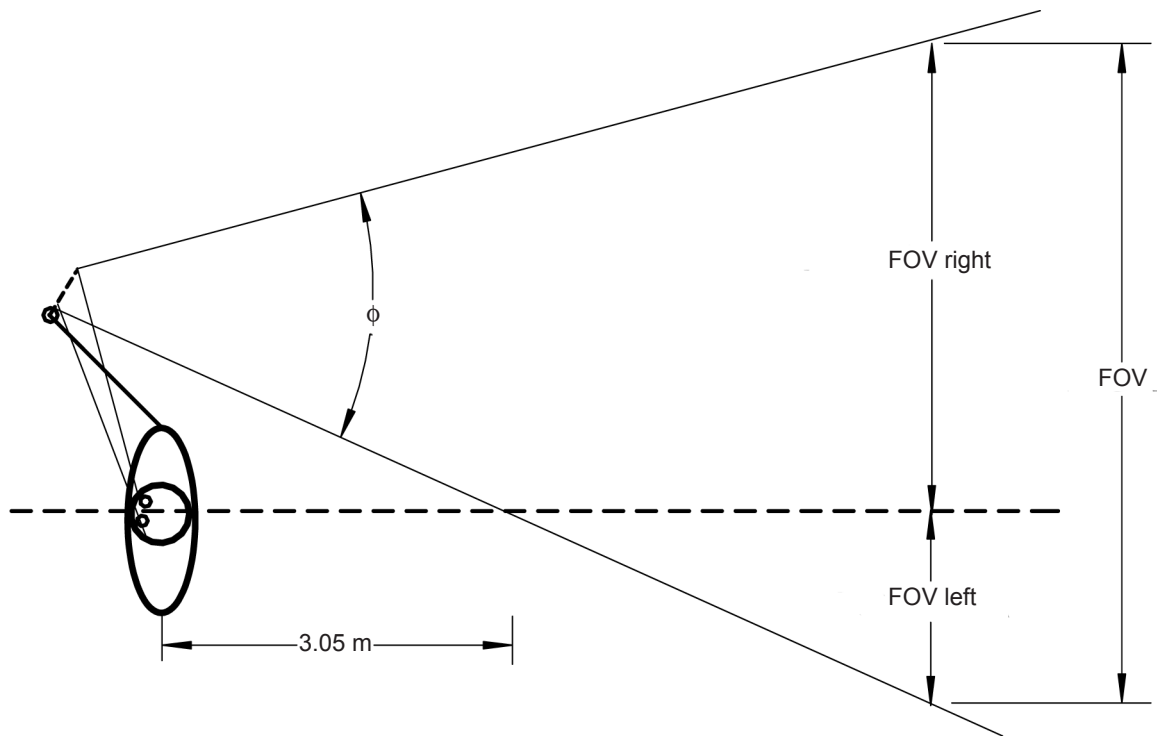


Figure 2. Graphical setup to calculate total field of view (FOV) (scenario 1). Notes. ϕ —angle of FOV; total FOV = FOV left + FOV right.

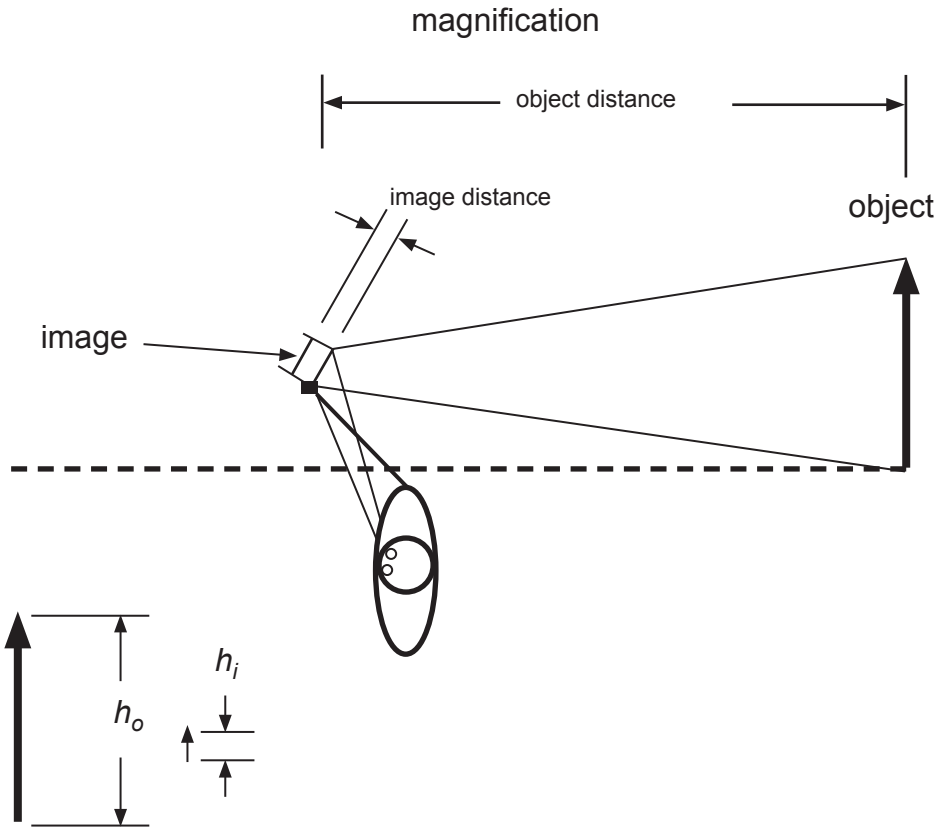


Figure 3. Image formation and magnification conducted to semiquantitatively verify the values obtained using AutoCAD 2000 and to qualitatively judge the image quality and size. Notes. $m = h_i/h_o$, where m —magnification of the object, h_i —height of the image, h_o —height of the object.

(f) (Equation 1) was used as a comparison to the graphic analyses:

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}. \quad (1)$$

This equation provides an estimate of the values because its derivation uses the small-angle approximation, which states that the sine or tangent of an angle is equal to the angle, at small angles. In the present study, this meant that the farther away an object was from the optical axis of the mirror, the larger the error in the mirror equation.

The magnification (m) of the object can be estimated using Equation 2; here h_i is the height of the image and h_o is the height of the object (image and object distances can also be used in this equation):

$$m = \frac{h_i}{h_o}. \quad (2)$$

In determining the magnification, the values used for h_i and h_o were taken directly from the

CAD drawings unless otherwise noted. Of note here is that spherical convex mirrors are not perfect mirrors due to many factors, including spherical aberration; perfectly spherical mirrors do not bring all rays parallel to the axis, to a single image point as expected by theory. Thus the image is somewhat blurred and does not exist at one exact point. Therefore, the image location found using AutoCAD was not exact, but the error in this experimental setup was so small that it was believed to be insignificant for the purposes of this study.

Different arm angles, θ , were tested to show how the FOV changed in relation to the positioning of the mirror around the body. Monovision (viewing with one eye) was used for 0° , 45° , and 90° positions and binocular vision was used for the binocular 45° arm positioning. Zero degrees corresponds to an arm position that is straight forward of the flagger and 90° represents the positioning when the flagger is holding the

flagpole out to the side. In addition, 30° and 60° positions were studied for some mirrors.

Two basic scenarios were utilized in the graphical analyses. The first scenario was set by the ability to see a point 3.05 m directly behind the mirror (Figure 2). This configuration put the same constraints on all mirrors used and allowed for a direct comparison of the FOVs and image information obtained from the graphical analysis. In addition, this scenario was easily applied to real-life situations and allowed for a comparison of data collected from the graphical analysis with those from real life. The angles θ (angle

of flagger's or mirror arm from forward) and α (angle of mirror from forward) were set and ϕ (angle of FOV) (Figure 1) was determined and documented to give the reader an understanding of the relationship between the eye, mirror, and FOV. The second scenario was set by a 15.24 m radius around the flagger bound to the left and right by 45° angles behind the flagger (Figure 4). A vehicle initially 15.24 m away and traveling at 16.1 km/h (10 mph) would give a flagger ~3.4 s to react before they were struck. At these bounds, the FOV was calculated to show the observable views at locations not directly behind the flagger.

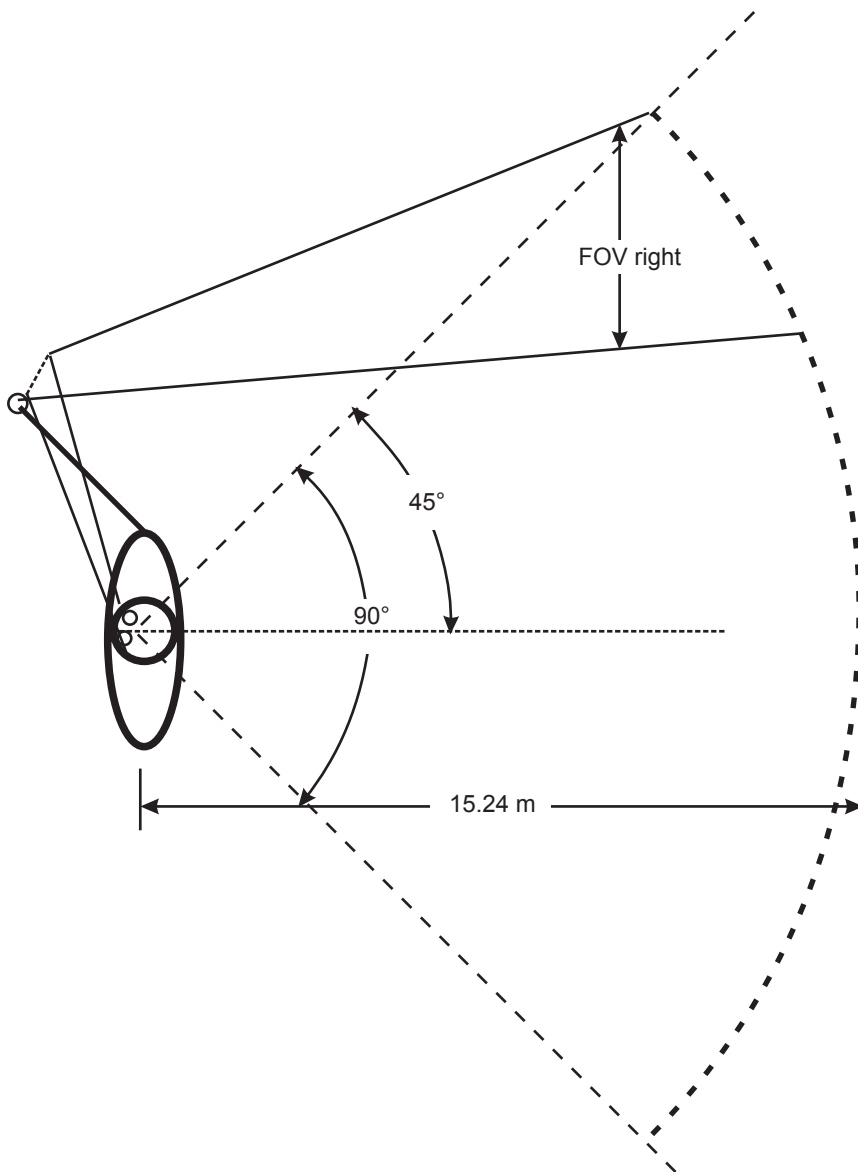


Figure 4. Graphical setup to find field of view (FOV) to the sides at a distance of 15.24 m (scenario 2). Notes. A vehicle traveling at 16.1 km/h would give a flagger ~3.4 s to react before being struck when it was 15.24 m away.

It is important to note that image distances were measured from the mirror to the image. To calculate the distance from the flagger's eye(s) to the image for the FPM, one had to add 0.61 m. For the HM, 0.089 m had to be added.

Field tests were conducted to semiquantitatively verify the values obtained from the graphical analysis and to qualitatively judge the image quality and size. For these experiments, an arm angle of 45° was used with a 0.076 m diameter, 0.66 m ROC FPM mirror. An HM plane mirror with a 0.038 m diameter and a 30° arm angle from forward was also tested.

3. RESULTS

Table 1 shows the FOVs obtained from the first scenario. Here the mirror was always positioned at an angle such that a spot located 3.048 m directly behind the flagpole could just be seen.

With the FPM mirrors in a 90° position (the only accepted flagging stance), the available FOVs at 15.24 m back for the 0.508, 0.660, 1.016, 2.032 m, and infinite ROC mirrors were 6.04, 4.97, 3.78, 2.65, and 1.52 m, respectively. For the HM mirror with an arm angle of 10°, the FOV was 6.80 m at 15.24 m. With the flagger's arm held at 45°, using binocular vision, the FOV increased by 40–100% over monocular vision at 90°. The FOVs were

TABLE 1. Field of View (FOV) With Different Mirrors and Arm Angles

Mirror	θ (°)*	ϕ (°)**	Total FOV at x m					
			x = 3.05	x = 6.10 m	x = 9.14	x = 12.20	x = 15.24	
FPM (m ROC)								
0.508	90	22	1.25	2.44	3.63	4.85	6.04	
	45	24	1.52	2.80	4.08	5.36	6.64	
	0	24	1.74	3.11	4.48	5.85	7.22	
	binocular 45	30	1.95	3.57	5.21	6.86	8.50	
	0.660	90	18	1.04	2.01	3.02	3.99	4.97
0.660	60	19	1.19	2.19	3.23	4.27	5.27	
	45	20	1.28	2.32	3.38	4.42	5.49	
	30	20	1.31	2.38	3.47	4.54	5.61	
	0	20	1.43	2.56	3.69	4.82	5.94	
	binocular 45	26	1.68	3.08	4.48	5.88	7.28	
1.016	90	14	0.79	1.52	2.29	3.02	3.78	
	60	15	0.91	1.71	2.47	3.26	4.02	
	45	15	0.98	1.80	2.59	3.38	4.21	
	30	15	1.04	1.83	2.65	3.47	4.27	
	0	16	1.10	1.95	2.80	3.66	4.42	
1.016	binocular 45	21	1.37	2.50	3.66	4.79	5.94	
	2.032	90	10	0.58	1.10	1.62	2.13	2.65
	45	11	0.73	1.31	1.89	2.44	3.02	
	0	11	0.82	1.43	2.04	2.65	3.26	
	binocular 45	17	1.10	2.01	2.93	3.81	4.72	
Plane								
Plane	90	5	0.34	0.64	0.94	1.22	1.52	
	45	7	0.46	0.82	1.16	1.52	1.86	
	0	7	0.55	0.91	1.31	1.68	2.07	
	binocular 45	13	0.85	1.52	2.19	2.87	3.54	

Notes. Results converted from United States Customary System units; θ —angle of arm from forward, ϕ —angle of FOV, FPM—flagpole-mounted, ROC—radius of curvature. *—These are possible angles flaggers can set the mounting arm at. In all of these cases, the mirror is adjusted so that the flaggers can see the edge of their ear. **—This angle corresponds to flaggers being able to see a spot 3.05 m directly behind them.

TABLE 2. Image Distance (*i*) and Height *h_i* Using a 2.1 m Object at Given Distances Behind the Mirror (*o*)

Mirror	<i>o</i> = 4.57 m		<i>o</i> = 15.24 m		<i>o</i> = 30.48 m	
	<i>i</i> (m)	<i>h_i</i> (m)	<i>i</i> (m)	<i>h_i</i> (m)	<i>i</i> (m)	<i>h_i</i> (m)
0.508 m ROC <i>f</i> = 0.253 m	0.2530	0.1067	0.2499	0.0335	0.2530	0.0183
0.660 m ROC <i>f</i> = 0.329 m	0.3261	0.1372	0.3261	0.0457	0.3261	0.0244
1.016 m ROC <i>f</i> = 0.509 m	0.4816	0.2042	0.4938	0.0701	0.4999	0.0366
2.032 m ROC <i>f</i> = 1.015 m	0.8717	0.3749	0.9571	0.1341	0.9845	0.0671
Plane	4.5720	2.1336	1.5240	2.1336	3.0480	2.1336

Notes. Results converted from United States Customary System units; ROC—radius of curvature, *f*—focal point.

greater for the low ROC mirrors, but the HM plane mirror had a relatively high FOV because it was mounted close to the eye.

Table 2 shows the image distance and height obtained from the graphical analysis of a 2.13 m object located on the optical axis at distances of 4.57, 15.24, and 30.48 m from the mirror. This graphical analysis does not take the potential of the flagger blocking the view into account and is only a function of the mirrors themselves. Note that the objects are directly on the optical axis and the images are located behind the mirror.

A 2.1 m wide object located 30.48 m behind the flagger would have an image size of 1.8, 2.4, 3.7, 6.7, and 2.1 m for the 0.508, 0.660, 1.016, and

2.032 m ROC, and plane mirrors, respectively. These correspond to magnifications of 0.008, 0.011, 0.016, 0.031, and 1, respectively.

For a 0.66 m ROC mirror and a 2.13 m object, the images would be 13.7, 4.6, and 0.024 m for distances of 4.57, 15.24, and 30.48 m, respectively. These correspond to magnifications of 0.06, 0.02, and 0.01, respectively.

Figure 5 shows the relationship between object distance from the mirror and image magnification for mirrors with ROCs of 0.508–2.032 m based on Equations 1 and 2. A plane mirror would have a horizontal line at a magnification of one. These curves show that image magnification drops off

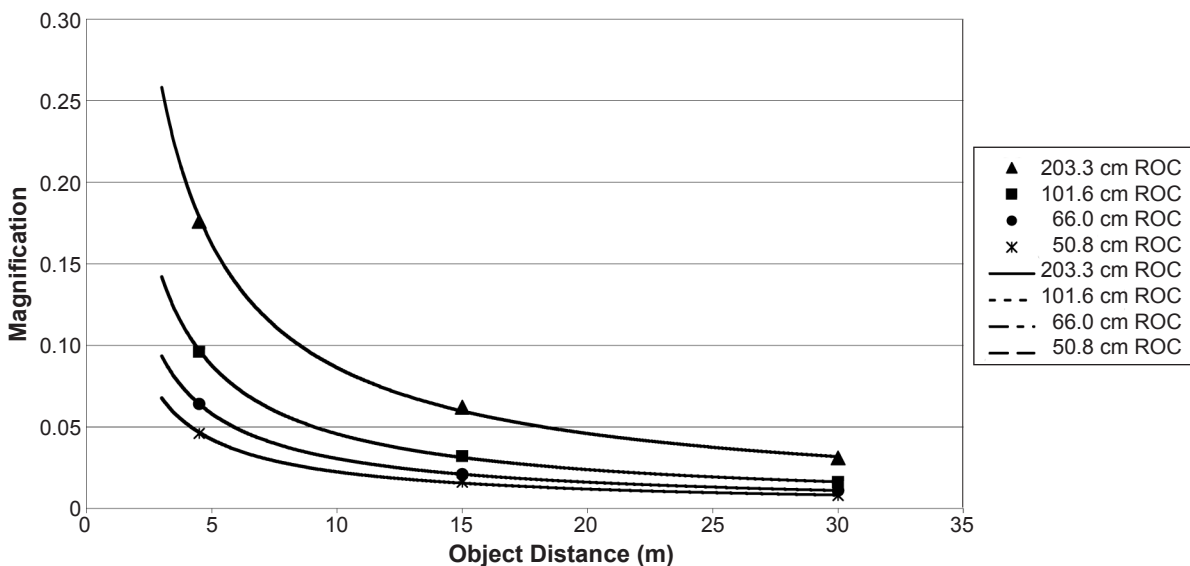


Figure 5. Magnification versus object distance using the mirror equation. Notes. The points on the graph are from the graphical computer-aided design analyses; ROC—radius of curvature.

TABLE 3. Field of View (FOV) 15.24 m Behind Flagger, 45° to the Left and Right Using a Flagpole-Mounted (FPM) Mirror With Arm at 90°

Mirror	FOV Left		FOV Right	
	Total (m)	ϕ (°)	Total (m)	ϕ (°)
FPM				
0.508 m ROC	6.71	23	5.85	21
0.660 m ROC	5.82	19	4.94	17
1.016 m ROC	4.69	14	3.75	12
2.032 m ROC	3.51	10	2.56	8
Plane	2.23	6	1.25	4

Notes. Results converted from United States Customary System units; ϕ —angle of FOV, ROC—radius of curvature.

TABLE 4. Comparison of Field of View (FOV) Calculated Using Graphical and Field Methods

Mirror	θ (°)	ϕ (°)	Total FOV at x m					
			x = 3.04	x = 6.10	x = 9.14	x = 12.19	x = 15.24	
FPM 0.66 m ROC								
Graphical results	binocular 45	26.0	21.68	3.08	4.48	5.88	7.28	
Field testing results	binocular 45	26.7	1.68	2.90	4.27	5.64	7.01	
HM plane								
Graphical results	30	20.0	1.22	2.38	3.51	4.66	5.82	
Field testing results	30	21.4	1.22	2.29	3.20	4.42	5.49	

Notes. Results converted from United States Customary System units; θ —angle of arm from forward, ϕ —angle of FOV, FPM—flagpole-mounted, ROC—radius of curvature, HM—helmet-mounted.

sharply between 3.04 and 9.14 m and then levels off. A 3.05 m wide object, 3.05 m behind the mirror, would appear to be 0.305 m wide (using a 0.66 m ROC mirror). At 30.5 m, the same object would appear to be 0.031 m wide.

The FOVs available when the second scenario is employed and the flagpole is held in the 90° position are shown in Table 3. This scenario simulates flaggers looking for a vehicle coming from behind them at an angle. For the 0.508 m ROC mirror, the FOV to the left is 6.61 m and 5.85 m to the right. For the plane mirror it is 2.23 m to the left and 1.25 m to the right. The HM mirror with an arm angle of 30° has an FOV of 5.79 m to the left and 5.70 m to the right. To achieve this scenario, flaggers must move their head 52° to the right (for left FOV) and 18° to the left (for right FOV). These results are very similar to those found when viewing directly behind the flagger.

Table 4 shows the results of the field testing of the 0.66 m ROC FPM and the HM as compared to the FOVs obtained from the graphical technique.

Results from the field tests were comparable to the results obtained from the graphical method for both the FPM and HM mirrors. Note that the field testing was rudimentary and the data obtained from it are used only to semiquantitatively verify the results obtained from the graphical method.

4. DISCUSSION

The graphical experiments showed that as one decreases the ROC of a mirror three things happen: the FOV increases, the image size decreases, and the distance from the image to the eye decreases. At the same distance from the eye as a convex mirror, a plane mirror has a smaller FOV, but the image is larger and is located farther from the eye, making it easier to focus upon. When the plane mirror is brought up close to the eye, as in the HM mirror, the FOV increases greatly while not altering the image size. When using the FPM, if the flagger's arm is moved from straight ahead to a 90° angle, the FOV decreases by about 20%.

To simplify the analyses, most simulations were conducted with monocular vision. When binocular vision is compared to monocular vision at an arm angle of 45° , the FOV increases by 30–90%, for 0.508 m ROC to infinite ROC, respectively. When viewing an object located off of the optical axis, the FOVs are similar to the left and right, with the left FOV being slightly larger.

To get an understanding of image quality and to validate the graphical calculations of the FOV, the investigators looked at a vehicle ~2.13 m wide and 3.05 m high (the size of a small construction vehicle) 4.57, 15.24, and 30.48 m behind them. The first trial involved a 0.66 m ROC mirror used in the FPM position with the arm angle at 45° and the flagger employing binocular vision. The second trial employed a flagger using the HM position with a 0.038 m plane mirror with the mirror arm located at a $\sim 30^\circ$ angle. In both trials the investigator reported that the objects were clearly visible, easily recognizable, and that he felt comfortable in determining the location of the vehicle. It should be noted that the image quality issues could vary from one person to another depending upon many factors such as eyesight and age. The FOV measurements made in the field were very similar to those calculated graphically.

One practical issue that arose during the field study was that when the HM mirror was used with eyeglasses, the frame partially interfered with the line of sight from the flagger's eye to the mirror. Given that flaggers may wear glasses (sunglasses, bifocals, eye protection, etc) while flagging, more research and testing should be conducted to determine if this interference is significant or if there are better mirror mounting positions available.

Another issue involving the use of convex mirrors is the image distance. If a worker holds a convex mirror at arm's length, the image forms 0.305–0.914 m behind the mirror, depending upon the mirror's ROC. Some workers with farsightedness would not be able to focus on an image located close to them without putting on reading glasses. The average 55-year-old male can focus on an object ~0.991 m from his eye [5]. With a 0.61 m arm length, the minimum

image distance from the mirror would be 0.381 m, which would eliminate both the 0.508 and 0.660 m ROC mirrors for this population of workers.

Convex mirrors also have the disadvantage of making images appear farther away than they really are. This is an undesirable attribute for a mirror in this situation. Another serious issue in using a convex mirror for flagging is the proper flagging method: flaggers should hold the pole out to the side at 90° and have their attention in the forward direction. A mirror in this position requires the flagger to turn their head to look at the mirror, which takes their attention away from the oncoming traffic. To add to this problem, if the flagger were to scan their environment with the mirror by rotating it back and forth, the sign movement may confuse drivers. Having the mirror at the 90° arm position also reduces the flagger's FOV from its optimum location of straight forward. With the mirror at arms' length to their side, it would be difficult for a flagger to perceive moving objects, unless they were looking directly at the mirror.

Further investigation is needed to determine the ability of flaggers to attend to potential visual stimuli from the mirror and from oncoming vehicles or activity. Issues surround selective attention and the ability to attend to two different visual stimuli simultaneously, so this is a serious consideration for application. The ability to separate the visual stimuli may be improved if the two are very different in appearance, which may not be the case with moving vehicles on a work zone [11]. Generally, moving objects toward the edges of the FOV may be perceived while attending to stimuli toward the center of the FOV, though sometimes not consciously [12]. However, these issues need to be further addressed in flagging operations to determine the human performance limitations in the application of flagging mirrors in different work zone configurations.

The HM plane mirror presents the flagger with an image distance equal to the object distance, no distance distortion, and allows a flagger to scan for vehicles coming from behind without as much distraction from the oncoming traffic. The HM

mirror's FOV is better than most of the convex mirrors' using monocular vision, but is similar to or better than the 1.016 m or larger ROC mirrors using binocular vision.

The assumptions for this study include, but are not necessarily limited to, the distance from the flagger's eye to the mirror for the FPM setup is always 0.61 m; no part of the body interferes with the FOV; the eye, mirror, and object are all located on the same plane; the optimum placement for the HM mirror is 0.089 m from the eye (as advised by a bicycle HM mirror manufacturer); and an average construction vehicle is 2.1 m wide. For simplicity, only two-dimensional drawings were made. Since the assumption is made that flaggers and the objects they will be viewing in the mirror all lie on the same plane, it is believed that two-dimensional space is adequate. It is expected that the only assumption to have much impact on the results is that no part of the body interferes with the FOV. It is likely that with the second scenario, when scanning behind and to the left of them, the flagger's body would block part of their view.

5. CONCLUSIONS

We found that although convex mirrors offer larger FOVs, plane mirrors are similar to convex mirrors as they are brought in closer to the eye, as in a HM mirror. Studies show that a 0.038 m HM plane mirror performs very similarly to a 0.076 m diameter, 0.508 m ROC convex mirror when using proper flagging practices. Given that image perception is a problem with small ROC convex mirrors and that it is difficult for a flagger to view the FPM mirror and keep an eye on the traffic in front of them, HM mirrors have been found to be the best option for flaggers. This study also uncovered some human factors considerations, including the interference of eyeglasses with vision, which should be studied regarding flaggers' use of HM mirrors. Also, it should be understood that different flagging situations may require different mirror placements, where one option may be better under one situation but not under another.

Prior to using any type of mirror, it is recommended that flaggers practice aligning, spotting objects, and judging distances and speed with them. The use of mirrors should always be used in conjunction with an appropriate traffic control plan and additional safety controls including physical barriers and others whenever possible.

There are many human factors issues that should be further investigated. Some of these are the detection of motion, attending to two concurrent visual stimuli, the body and head positioning, the required mirror quality, the role of vision deficiencies, day versus night use, the ability to perceive objects, and perception and reaction times. Further evaluations of mirrors should be conducted for flagging to develop more precise recommendations for their applicability in different work conditions before they are implemented in work zones.

REFERENCES

1. Washington State Legislature. Washington administrative code. Signaling and flaggers (296-155-305). Retrieved January 7, 2009, from: <http://apps.leg.wa.gov/WAC/default.aspx?cite=296-155-305>
2. Flannagan MJ, Sivak M, Traube EC. Effects of large-radius convex rearview mirrors on driver perception (SAE Technical Paper Series No. 970910). Warrendale, PA, USA: Society of Automotive Engineers; 1997.
3. Flannagan MJ, Sivak M, Schumann J, Kojima S, Traube EC. Distance perception in driver-side and passenger-side convex rearview mirrors: objects in mirror are more complicated than they appear (Report No. UMTRI-97-32). Ann Arbor, MI, USA: The University of Michigan Transportation Research Institute; 1997.
4. Burger WJ, Mulholland MU, Smith RL, Sharkey TJ. Passenger vehicle, light truck and van convex mirror optimization and evaluation studies. Volume 1: Convex mirror optimization (DOT HS 805 695). Washington, DC, USA: Department of Transportation, National Highway Traffic Safety Administration; 1980.

5. Flannagan MJ, Sivac M, Traube EC. Driver perceptual adaption to nonplaner rearview mirrors (SAE Technical Paper Series No. 960791). Warrendale, PA, USA: Society of Automotive Engineers; 1996.
6. Rowland GE, Silver CA, Volinsky SC, Behrman JS, Nichols NF, Clisham WF Jr. A comparison of plane and convex rearview mirrors for passenger automobiles (Report No. FH-11-7382). Washington, DC, USA: Department of Transportation, National Highway Traffic Safety Administration; 1970.
7. Seeser J. Automotive convex mirrors: optical properties (Technical Report 201). Holland, MI, USA: Donnelly Mirrors; 1974.
8. Sugiura S, Kimura K. Outside rearview mirror requirements for passenger cars: Curvature, Size, and location (SAE Technical Paper Series No. 780339). Warrendale, PA, USA: Society of Automotive Engineers; 1978.
9. Woodson WE, Tillman B, Tillman P. The human factors design handbook. 2nd ed. New York, NY, USA: McGraw-Hill; 1992.
10. Cutnell JD, Johnson KW. Physics. 4th ed. New York, NY, USA: Wiley; 1998.
11. Pashler HE. The psychology of attention. Cambridge, MA: MIT Press; 1998.
12. Corsini RJ, Craighead WE, Nemeroff, CB, editors. Encyclopedia of psychology and behavioral science. 2nd ed. New York, NY, USA: Wiley; 2001.

ABBREVIATIONS AND NOMENCLATURE

FOV	—	field of view
FPM	—	flagpole mounting
HM	—	helmet mounting
ROC	—	radius of curvature of a mirror
f	—	focal point of mirror, $f = \frac{1}{2}r$
h_i	—	height of image
h_o	—	height of the object
i	—	distance from mirror to image
m	—	magnification
o	—	distance from mirror to object
α	—	angle of mirror to the right from forward for FPM; angle from the mirror's arm to the mirror for HM
ϕ	—	angle of field of view ($^{\circ}$)
θ	—	angle of flagger's arm from forward; angle of helmet mounted mirror's arm from forward
binocular-vision	—	vision when using both eyes
convex mirror	—	a spherical type of mirror that has a radius of curvature; a convex mirror has its ROC behind the mirrored side and therefore has a larger field of view than does a plane or concave mirror when viewed under the same circumstances
monovision	—	vision when using only one eye; in this study, the eye closest to the mirror is used
optical axis	—	the axis extending through the center of the mirror to the center of curvature and beyond
plane mirror	—	a flat mirror with an infinite radius of curvature