

**UMTRI-2003-18**

# **GEOMETRIC VISIBILITY OF MIRROR-MOUNTED TURN SIGNALS**

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**September 2003**

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16. Abstract Turn signals mounted on exterior rearview mirrors are increasingly being used as original equipment on passenger cars and light trucks. The potential for mirror-mounted turn signals (MMTS) to improve the geometric visibility of turn signals is examined in this report. A survey of U.S. and European regulations showed that the turn signals of a vehicle that is minimally compliant with U.S. regulations are not visible to a driver of a nearby vehicle in an adjacent lane. Measurements of mirror location and window geometry were made on 74 passenger cars and light trucks, including 38 vehicles with European-style side repeaters. These data were combined with data on driver eye locations from two previous studies to assess the relative visibility of MMTS and conventional signals. Simulations were conducted to examine the potential for signals to be obstructed when a driver looks laterally through the passenger-side window. With a vehicle population that is fifty percent light trucks, MMTS are visible 52 percent more often than European side repeaters in this scenario. Based on the lateral visibility analysis, the optimal height for geometric visibility of a signal in the adjacent-vehicle scenario is 124 cm above the ground, approximately the average height of a light truck mirror. A plan-view eccentricity analysis showed that an MMTS is much closer to the viewing driver's forward-directed line of sight than rear-mounted turn signals when the viewing driver's vehicle is in or near the blind zone between the signaling driver's mirror and direct peripheral fields of view. The report concludes that MMTS can improve the geometric visibility of turn signals in the adjacent-vehicle scenario that is believed to precede many lane-change/merge crashes. Further research will be necessary to determine if improved geometric visibility is accompanied by improved detection of turn signals by viewing drivers, and whether improved detection of turn signals has important safety implications.			
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## INTRODUCTION

Some passenger cars and light trucks are being manufactured with turn signal repeaters in the outside mirror housings. There are two common types of mirror-mounted turn signals (MMTS). One type is only visible from the rear of the mirror and has its light sources mounted behind the mirror surface. Another type is visible from a wider range of positions in front of, behind, and adjacent to the vehicle. Figure 1 shows examples of MMTS on late-model vehicles.



Figure 1. Examples of mirror-mounted turn signals.

Mounting a turn signal repeater in the side mirror housing offers the potential for improved signal visibility in at least three scenarios, depicted in Figure 2:

*Following Vehicle* — Because the mirror housing protrudes from the side of the vehicle and is mounted higher than most rear turn signals, drivers following the signaling vehicle with one or more intervening vehicles may be more likely to see the signal.

*Passing Vehicle* — Drivers overtaking a vehicle in an adjacent lane may be able to see more readily the turn signal of a vehicle about to enter their lane from a position ahead of the vehicle they are overtaking. The advantage becomes apparent if the traffic behind the signaling vehicle obstructs the rear signals.

*Adjacent Vehicle* — A driver whose vehicle is adjacent to the signaling vehicle, perhaps in a blind zone between the direct and indirect fields of view of the signaling driver, may be unable to see the front or rear turn signals but may have a clear view of a mirror-mounted signal.



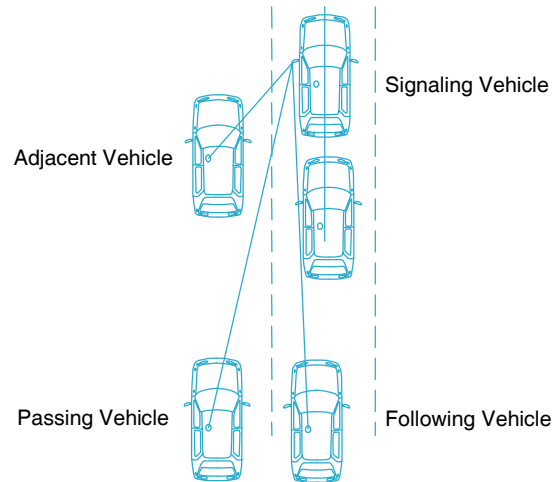


Figure 2. Plan-view schematic of three scenarios in which MMTS might provide enhanced signal visibility.

MMTS may offer the greatest potential safety improvement in the adjacent-vehicle scenario. Due to the proximity of the signaling and viewing vehicles, a lane-change conflict is more likely to lead to a crash than in the other scenarios. Using General Estimates System (GES) data, Chovan et al. (1994) estimated that 92.7 percent of lane-change crashes occurred in “proximity” situations in which there was little or no longitudinal gap or speed difference between the vehicles involved. Lane-change merge (LCM) crashes account for about four percent of crashes and about nine percent of traffic delays, although about 80 percent of these crashes do not result in injury (Wang and Knipling 1994). The most common cause of LCM crashes is the driver of the lane-changing vehicle failing to see the struck vehicle (Wang and Knipling 1994). If the driver of the lane-changing vehicle is using the turn signal, the presence of an MMTS may improve the chances that the driver of an adjacent vehicle will be able to take evasive action to avoid a collision.

This report examines the regulatory requirements for turn signals in the U.S. and Europe to assess the opportunities for MMTS to improve the visibility of turn signals. Data from several sources are combined to compare the geometric visibility of mirror-mounted turn signals with conventional U.S. signals and European side repeaters. Geometric visibility refers only to analyses of lines of sight and does not fully address the perceptual issues relating to the detection of signals. The goal of this analysis is to quantify the relevant geometry of signal and eye locations with respect to vehicle structures in the critical adjacent-vehicle scenario. Subsequent

work will address perceptual issues that may further clarify the safety implications of the geometric findings presented in this report.

## METHOD

### Data Sources

As part of two studies on mirror fields of view, three-dimensional coordinate data were gathered on driver eye locations and mirror locations (Reed et al., 2000, 2001). Participants were measured in the vehicles that they normally drove. Forty-three passenger cars were measured in the first study and 48 light trucks, minivans, and SUVs were measured in the second study. The data included head landmarks used to calculate driver eye locations and points on the perimeters of each of the mirrors. Eye and mirror locations with respect to each other and the ground were analyzed in the current investigation.

Additional data on mirror locations, signal locations, and window geometry were gathered for the current study. Mirror locations and other vehicle dimensions were measured on 44 passenger cars and light trucks in the UMTRI parking lot. Twenty-nine vehicles with side repeaters were measured at local car dealerships.

Figure 3 shows the data sheet used in data collection and illustrates the variables. The goal of the data collection was to quantify the relative location of turn signals, mirrors, and driver window openings. The height and fore-aft location of the exterior mirrors relative to the front and rear turn-signal mounting points were of particular interest.

### Geometric Analyses

#### *Analysis Goals*

MMTS appear to provide three primary geometric advantages over the conventional turn signals used in the U.S. Compared to the typical front and rear signal locations, a signal in the mirror housing is higher, more forward than other signals visible from the rear, and more lateral. Compared with the typical European side repeater, the MMTS is higher and more lateral. The analyses in this report examine the potential importance of the signals being higher than European side repeaters and more forward than the rear turn signals and flashing rear side markers typical on U.S. vehicles.

### *Lateral Analysis*

The goal of the lateral analysis was to estimate what a driver can see when looking at a vehicle in the right adjacent lane to determine if a higher mirror-mounted signal would be less likely to be obstructed by part of the viewing driver's own vehicle than a lower side repeater. This corresponds to the adjacent-vehicle scenario in Figure 2 with a driver viewing a signaling vehicle that is forward and to the right.

### VEHICLE MEASUREMENT DATA COLLECTION FORM

(a1) Window Height: \_\_\_\_\_ (a2) hyp \_\_\_\_\_

(b) Ground to Window: \_\_\_\_\_

(c) Side Repeater Height: \_\_\_\_\_

(d) Mirror Height: \_\_\_\_\_

(e) Mirror Casing Height: \_\_\_\_\_

(f) Rear Bumper to Repeater: \_\_\_\_\_

(g) Rear Bumper to Mirror: \_\_\_\_\_

(h) Mirror to Rear of Window: \_\_\_\_\_

(i) Car Length: \_\_\_\_\_

(j) Mirror to Side of Car: \_\_\_\_\_

(k) Width of Mirror: \_\_\_\_\_

(l) Height of Mirror: \_\_\_\_\_

(m) Upper Mirror Casing Gap

(n) Lower Mirror Casing Gap

l + m + n: \_\_\_\_\_

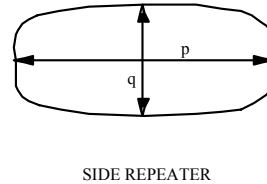
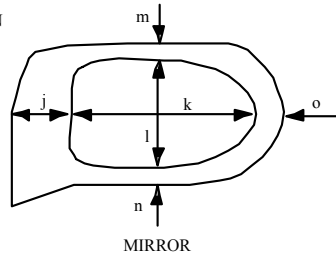
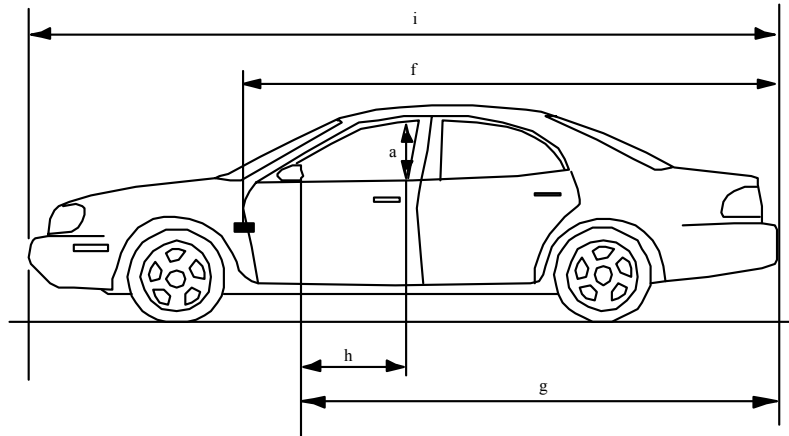
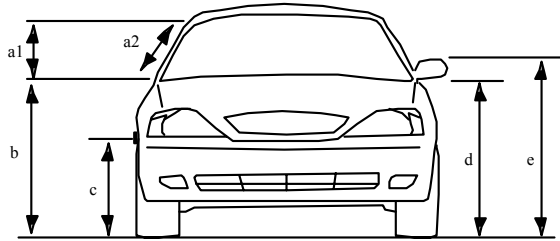
(o) Outer Mirror Casing Gap

k + o: \_\_\_\_\_

(p) Length of Repeater: \_\_\_\_\_

(q) Height of Repeater: \_\_\_\_\_

Signal mirror? Y N



<p>VEHICLE INFORMATION:</p> <p>Body Type: _____</p> <p>Location: _____</p> <p>Investigator: _____</p> <p>VIN#: _____</p> <p>Notes: _____</p> <p>_____</p>	<p>Date: _____</p> <p>POST VEHICLE MEASUREMENT DATA:</p> <p>Vehicle Model: _____</p> <p>Vehicle Make: _____</p> <p>Vehicle Year: _____</p> <p>Length: _____ Width: _____</p> <p>Height: _____</p>
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ALL MEASUREMENTS IN CENTIMETERS.

Figure 3. Data sheet illustrating measurements obtained from vehicles at UMTRI and local dealerships.

A driver's exterior field of view is bounded by the limits of peripheral vision and obstructions due to the vehicle structure (instrument panel, A-pillar, hood, etc.). A comprehensive analysis of direct vision in the adjacent-vehicle scenario would consider the effects of obstruction of the adjacent vehicle by all parts of the viewing vehicle's structure. Unfortunately, the data to perform such an analysis are not readily available and would be expensive to gather. A simpler method was developed to estimate the primary effect of signal height on visibility.

As part of the preliminary work on this project, a front-seat passenger in a vehicle driven on-road recorded a video with a camera pointed out the driver side of the vehicle. The video approximated the view that the driver had to the right side of the vehicle. The video images showed that, for typical vehicle geometry, the driver's view of the right adjacent lane was most restricted when looking through the door window. For a driver, the lower and upper edges of the passenger-side window opening are more restrictive than the combination of the hood edge and upper windshield edge for more-forward viewing angles.

Consequently, a planar rear-view analysis was conducted, considering the vertical range of the side of the right adjacent vehicle that a driver can view through the window. Figure 4 shows the calculation schematically and illustrates the model parameters. Two vehicles are placed in adjacent lanes. Rays are constructed from the eye point in the left vehicle through the upper and lower margins of the passenger window. The points of intersection of these rays with a vertical plane through the left edge of the vehicle in the right lane are recorded. The eye locations and lower window heights were obtained by randomly sampling, with replacement, vehicles from the database of 91 vehicles measured in Reed et al. (2000, 2001). The sampling was weighted so that half of the sampled vehicles were passenger cars and half were light trucks, minivans, or SUVs. The right adjacent vehicle width was obtained from the same database using the same sampling procedure. Lane positions were specified by random sampling from a normal distribution with mean of zero (centered in the lane) and a standard deviation of 0.2 m. The latter value was obtained from data on lane deviations during normal driving in Reed et al. (1999). Lanes were 3.658 m (12 ft) wide. The upper edge of the window restriction was obtained by random sampling from a normal distribution with the mean and standard deviation for window height from the UMTRI parking-lot survey. Separate distributions were used for passenger cars and light trucks.

Analyses were conducted with 10,000 simulated pairs of vehicles. For each pair, the upper and lower boundaries of the viewing driver's vertical field of view on the side of the signaling vehicle were calculated. The simulated mirror and side repeater locations for the signaling vehicle were compared with the visible range to determine if either or both would be visible through the passenger-door window.

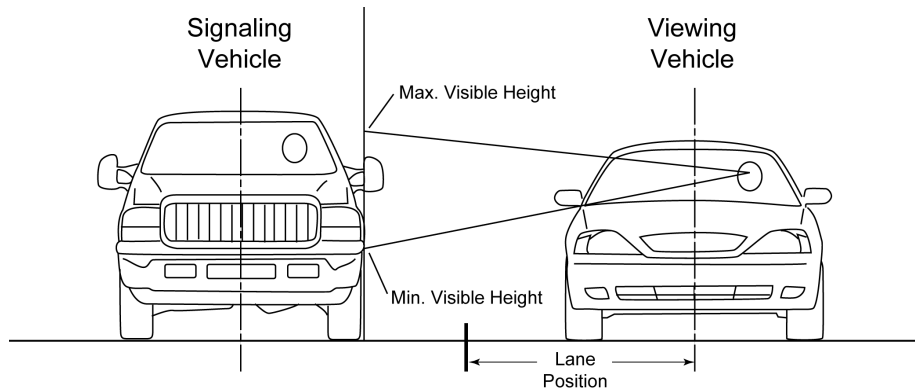


Figure 4. Schematic of lateral view analysis.

### *Eccentricity Analysis*

Signals that are more forward on the signaling vehicle may be more likely to be detected by the viewing driver because they are closer, in angular terms, to the forward-directed line-of-sight of the viewing driver. The viewing angle of the signal with respect to forward is termed the *eccentricity* of the signal. This analysis quantifies the eccentricity of mirror-mounted signals for a particular vehicle positioning relationship.

In the adjacent-vehicle scenario depicted in Figure 2, the eccentricities of locations on the signaling vehicle increase as the viewing vehicle overtakes the signaling vehicle. When the viewing vehicle is far to the rear, all locations on the signaling vehicle have eccentricities within a few degrees. When the vehicles are close together, the difference in eccentricity between points on the front and rear of the signaling vehicle can be large. One threshold of interest occurs when the rear of the signaling vehicle passes behind the viewing driver's eye location. Assuming peripheral vision extending to 90 degrees from forward in a horizontal plane, a signal would no longer be visible once it was rearward of the viewing driver's eyes. In general, the eccentricity of a rear-mounted signal, measured as the plan-view angle of the viewing vector

relative to straight ahead, will be larger than for a mirror-mounted signal in the adjacent-vehicle scenario. (Because of the proximity of the side repeater and the mirror, the eccentricity of the two is approximately the same.)

The eccentricity analysis used data from the mirror-study sample and the UMTRI parking-lot sample to calculate the eccentricity advantage of the MMTS. As in the lateral analysis, the mirror-study data were used to obtain driver eye locations with respect to vehicle widths. The parking-lot sample was used to obtain distributions of mirror distances forward of the rear of the vehicle. For purposes of this analysis, the rear turn signals were assumed to lie at the rear of the vehicle. In reality, the side markers are usually somewhat forward of the rear signals (if the two signals are not integrated in a single housing), but they are also often relatively low, increasing the possibility that they will be obstructed by the viewing driver’s vehicle.

Figure 5 illustrates the eccentricity calculation schematically. The eccentricity  $\varepsilon$  is equal to the arctangent of the lateral distance between the viewing driver’s eyes and the side of the signaling vehicle ( $w$ ) divided by the fore-aft position of the mirror ( $G$ ) plus the fore-aft distance from the viewing driver to the rear of the signaling vehicle ( $x$ ):

$$\varepsilon = \arctan(w/(G+x)) \quad [1]$$

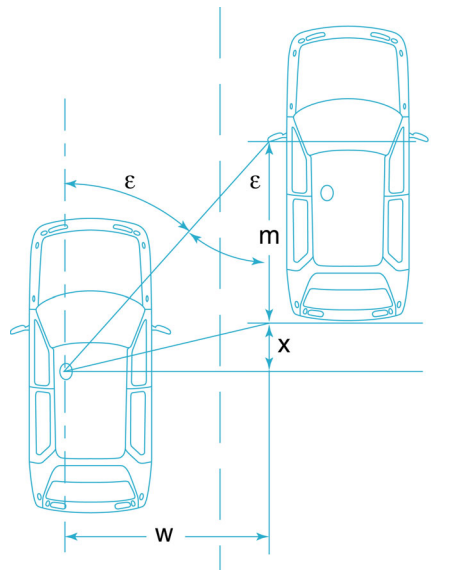


Figure 5. Schematic of eccentricity ( $\varepsilon$ ) calculation.



## RESULTS

### Turn Signal Regulations

The addition of MMTS can increase the size of the area around the vehicle from which turn signals are visible. U.S. and European (ECE) regulations for turn signal visibility differ, as shown in Figure 6. Under the minimum U.S. requirements in FMVSS 108, the turn signals need not be visible from the side of the vehicle, although the standard permits flashing side marker lamps that provide lateral signal visibility. ECE regulations require a side turn signal repeater that is visible to the side and rear (ECE, 2001). The ECE side-repeater is to be mounted as far forward as practicable, which usually means that the repeater is mounted rearward of the front wheel well, forward of the front door opening, and below the external mirrors. On some European vehicles with MMTS, the MMTS functions as the side repeater.

Figure 7 shows that that turn signals of a vehicle that complies with the minimum U.S. requirements are not visible to the drivers of adjacent vehicles. The thick lines in the figure show driver positions from which the turn signals of a minimally compliant vehicle will not be visible. Examination of the figure also shows that MMTS could potentially eliminate the zones in which no signals are visible. The potential benefits of MMTS for situations in which the side markers also flash, or a European-style side repeater is present, are less clear. The subsequent sections of this report examine the potential for MMTS to improve signal visibility in the adjacent-vehicle scenario relative to rear-mounted signals or side markers and side repeaters.

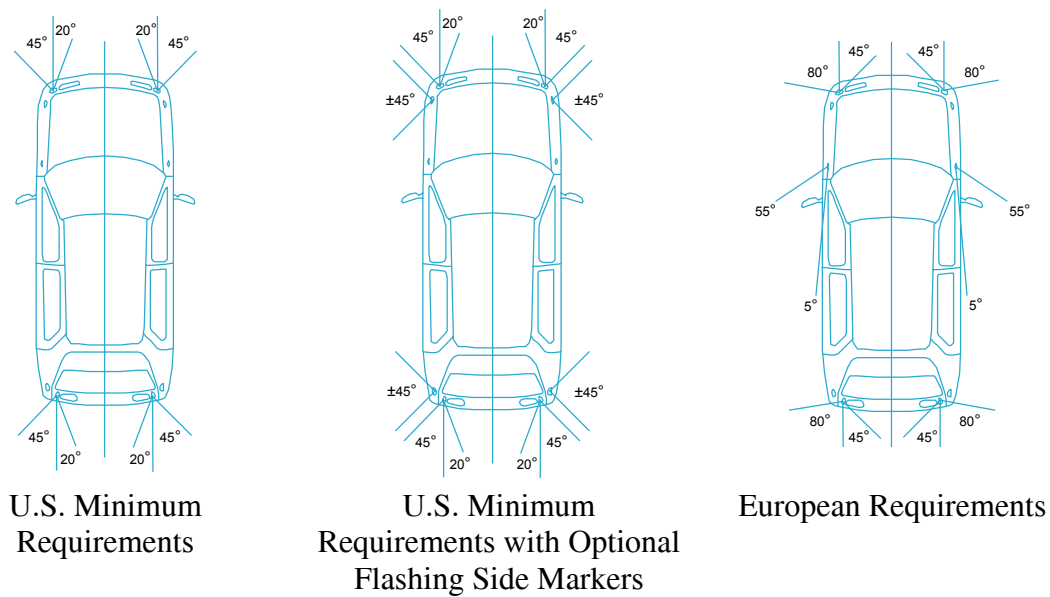


Figure 6. Schematic illustration of turn signal visibility and photometry requirements in U.S. and European regulations.

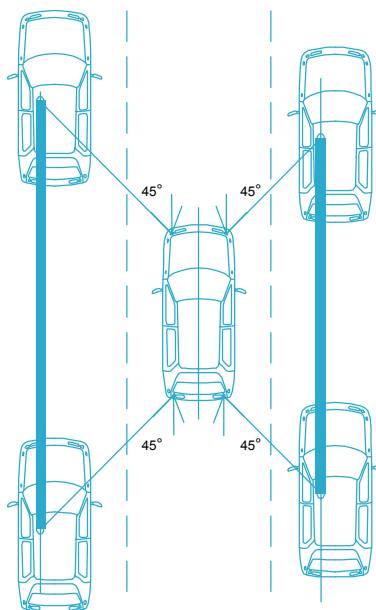


Figure 7. Plan-view illustration of the areas adjacent to a signaling vehicle within which turn signals that meet the minimum U.S. requirements are not visible to drivers of adjacent vehicles.

### **Mirror Locations, Window Heights, and Side-Repeater Locations**

Tables 1 and 2 list summary statistics from the vehicle measurements conducted for this study. Of particular interest, the average passenger car mirror height was 93.1 cm above the ground, 23.9 cm higher than the average side repeater height of 69.2 cm. In the smaller light-truck sample, the average mirror height was 118.6 cm, 38.9 cm higher than the average side repeater height (from only five vehicles) of 79.8 cm. The average distance from the mirror to the rear of the vehicle was 284.2 cm for passenger cars and 332 cm for light trucks. The variance in this dimension was much larger for the light trucks because of greater variance in overall vehicle length and front-end length (e.g., vans vs. pickup trucks). The average vertical height of the front windows was 35.6 cm on passenger cars and 44.3 cm on light trucks. The variability in height and length dimensions is larger for the light-truck sample than for the passenger-car sample. The wide variety of vehicles that could potentially be included in the sample means that the summary statistics for this sample are less representative of the category as a whole than is the case for passenger cars.

Table 1  
Mirror, Window, and Side-Repeater Geometry for PASSENGER CARS

Dimension (see Figure 3)	N	Mean (cm)	S.D. (cm)
A1-Window Height	64	35.6	4.4
A2-Window Surface Height	64	39.5	4.4
B-Ground-Window	64	92.9	3.4
C-Repeater Height	30	69.2	8.7
D-Mirror Height	64	93.1	4.0
Mirror Height Above Repeater	31	24.6	7.0
E-Mirror Housing Height	64	104.0	4.7
F-Repeater re Rear	31	312.8	56.8
G-Mirror re Rear	64	284.2	26.6
H-Window Length	64	74.2	10.3
I-Car Length	64	466.1	30.6
J-Car Side to Inside Edge of Mirror	64	5.2	1.4
K-Mirror Surface Width	64	17.2	1.4
L-Mirror Surface Height	64	10.1	0.7
LMN-Mirror Housing Width	64	12.7	0.9
KO-Mirror Width Plus Outer Housing	64	18.7	1.5
P-Repeater Surface Length	31	7.5	1.9
Q-Repeater Surface Width	31	3.4	1.5

Table 2  
Mirror, Window, and Side-Repeater Geometry for LIGHT TRUCKS\*

Dimension (see Figure 3)	N	Mean (cm)	S.D. (cm)
A1-Window Height	34	44.3	4.5
A2-Window Surface Height	34	46.9	4.6
B-Ground-Window	34	117.9	11.0
C-Repeater Height	5	79.8	11.0
D-Mirror Height	34	118.6	12.1
Mirror Height Above Repeater	5	33.6	1.6
E-Mirror Housing Height	34	133.6	13.3
F-Repeater re Rear	7	323.0	11.8
G-Mirror re Rear	34	332.0	51.8
H-Window Length	34	73.0	6.8
I-Car Length	34	507.5	58.0
J-Car Side to Inside Edge of Mirror	34	8.0	2.5
K-Mirror Surface Width	34	19.5	2.5
L-Mirror Surface Height	34	13.7	2.9
LMN-Mirror Housing Width	34	17.5	3.4
KO-Mirror Width Plus Outer Housing	34	21.0	2.5
P-Repeater Surface Length	7	7.2	3.2
Q-Repeater Surface Width	7	4.2	2.0

\* SUVs, vans, minivans, and pickup trucks.

## **Driver Eye Locations Relative to Mirrors**

Tables 3 and 4 list data for passenger cars extracted from the earlier studies of passenger car (Reed et al., 2000) and light truck (Reed et al., 2001) mirror fields of view. The average mirror heights above the ground are very similar to those obtained in the current study (93.9 vs. 93.1 cm for passenger cars and 118.3 vs. 118.6 cm for light trucks). Driver eye locations relative to the mirrors are also given in the tables. On average, the driver's eyes are 14.9 cm above the center of the external mirrors in passenger cars and 21.2 cm above the mirrors in light trucks. The data from the field study (see Table 1) showed that the height of the lower edge of the mirror surface is usually within 1 cm of the height of the lower edge of the passenger-door window (compare dimensions B and D). Consequently, the height of the lower edge of the mirrors is used as an estimate of the height of the bottom of the window opening for the lateral visibility calculations (the actual window opening heights were not available in this sample).

Tables 3 and 4 also list the downvision angle calculated for the passenger-door window opening (estimated by the height of the bottom of the right external mirror). This dimension is calculated from the vertical and lateral location of the driver's cyclopean eye with respect to the lower edge of the window opening. For light trucks, the average maximum downvision angle is 10.8 degrees, 1.6 degrees greater than the average for passenger cars. However, the window opening height averages 112 cm for light trucks, compared with 89 cm for passenger cars. These values create a threshold distance of 822 cm (or about 2.25 lane widths) from the right side of the vehicle within which passenger car drivers can (on average) see lower targets than light truck drivers. However, the downvision vector for both passenger car and light truck drivers intersects the ground plane before reaching this crossover threshold, meaning that passenger car drivers, on average, can see lower targets adjacent to the vehicle than light truck drivers, even though light truck drivers have larger average downvision angles. The greater downvision angle in light trucks is not sufficient to make up for the higher vehicle height.

Table 3  
 Passenger Car Mirror and Driver Eye Locations (cm)  
 (N=43)

Dimension	Mean	S.D.	Median	10 <sup>th</sup> %ile	90 <sup>th</sup> %ile
<b>Left Mirror</b>					
Fore-aft Position re Eye	-55.3	7.19	-55.1	-63.5	-43.4
Lateral Position re Eye	-52.3	2.96	-52.0	-55.8	-48.8
Vertical Position re Eye	-14.9	3.51	-14.5	-19.8	-10.9
Height (center)	93.9	3.38	93.5	90.3	98.9
Height (lower edge)	89.2	3.36	88.9	85.7	94.5
<b>Right Mirror*</b>					
Lateral Position re Eye	120.9	6.32	119.3	115.8	129.0
<b>Other Dimensions</b>					
Driver Eye Height	108.4	4.9	107.4	103.3	114.2
Lateral Downvision Angle (deg)	9.2	1.8	9.5	7.2	10.9

\* Except for the lateral position, the values for the right mirror are nominally identical to those measured for the left mirror (assuming symmetrical positioning of the left and right mirrors on the vehicle).

Table 4  
Light Truck Mirror Dimensions and Driver Eye Locations (cm)  
(N=48)

Dimension	Mean	S.D.	Median	10 <sup>th</sup> %ile	90 <sup>th</sup> %ile
<b>Left Mirror</b>					
Fore-aft Position re Eye	-59.5	10.5	-61.1	-72.1	-48.0
Lateral Position re Eye	-57.3	3.9	-57.0	-63.5	-52.8
Vertical Position re Eye	-21.2	4.5	-21.6	-26.7	-15.7
Height (center)	118.3	6.9	116.5	110.8	128.3
Height (lower edge)	111.8	6.4	110.1	104.8	122.0
<b>Right Mirror*</b>					
Lateral Position re Eye	135.5	11.2	133.2	123.3	150.5
<b>Other Dimensions</b>					
Driver Eye Height	140.0	6.0	139.8	132.3	147.8
Lateral Downvision Angle (deg)	10.8	1.9	11.1	8.3	12.9

\* Except for the lateral position, the values for the right mirror are nominally identical to those measured for the left mirror (assuming symmetrical positioning of the left and right mirrors on the vehicle).

### Lateral Visibility Analysis

The lateral visibility analysis was performed using 10,000 simulated pairs of vehicles positioned as described above. The primary dependent measure was the minimum height on the side of the signaling vehicle that would be visible to the driver in the viewing vehicle through the passenger-door window. Figure 8 shows a histogram of these minimum viewed heights (MinVH) along with a table of summary statistics.

A sensitivity analysis showed that the variance in lane position was of minimal importance, having the primary effect of smoothing the distribution of MinVH. Lane width (vehicle spacing) has a direct, linear effect, shifting the distribution vertically by the sine of the downvision angle, which averages 10 degrees. On average, the lateral distance between vehicles is 2 m when lanes are 3.658 m wide. With 3-m-wide lanes and the same vehicle mix, the average lateral spacing would be 1.3 m, and the MinVH distribution would shift upward by 0.7



$\sin(10 \text{ degrees}) = 0.12 \text{ m}$  or about 18 percent. Increasing vehicle width has the same effect as decreasing lane width.

Vehicle mix is important, with an increase in the fraction of light trucks increasing the mean MinVH, primarily because of higher windows. For an all-light-truck fleet, the mean MinVH would be 76.8 cm, compared with 57.1 cm for an all-passenger-car fleet. (Note that very large light trucks and SUVs are underrepresented in the data set used for this analysis, so the true difference in MinVH might be larger if all light trucks in the fleet were represented.)

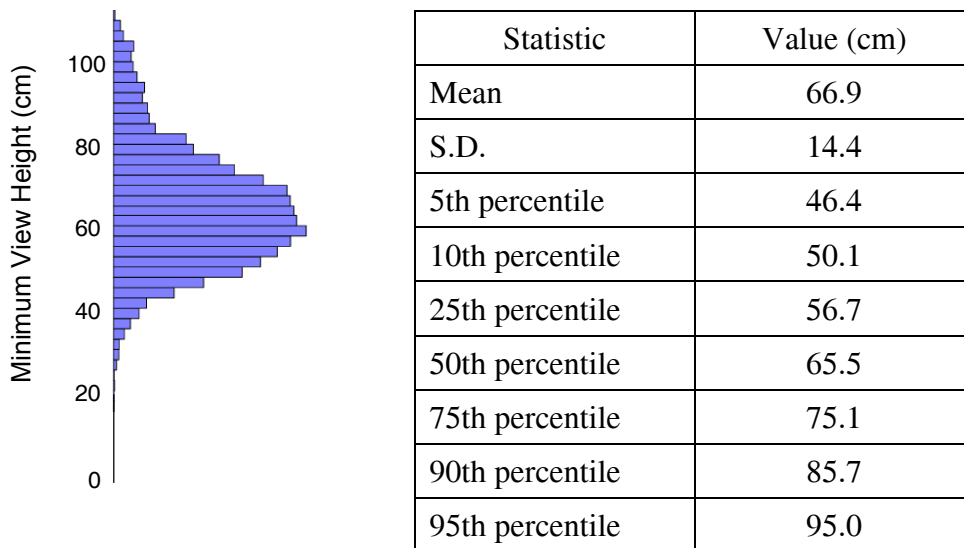


Figure 8. Minimum height visible on signaling vehicle through viewing vehicle’s passenger-door window (minimum viewed height, MinVH) based on a simulation using 50% light trucks. See Methods for more details on simulation methods.

Using the simulation procedure described above, an assessment was made for each pair of simulated vehicles whether the viewing (left-vehicle) driver could see the mirror or side repeater on the signaling (right) vehicle. The mirror or repeater was judged to be obscured (not visible) if the height was less than the minimum view height for the vehicle pair. Side repeater locations were estimated by using the mean and standard deviation of the vertical offset between the mirror and side repeater in the dealership data collected for this study (means of 24.6 and 33.6 cm for passenger cars and light trucks, respectively). For a vehicle population that was 50 percent light trucks, the mirror location on the signaling vehicle was visible 96 percent of the time while the side repeater was visible only 63 percent of the time. Since the mirror was always

visible when the side repeater was visible, the mirror was visible 52% more often than the side repeater alone.

The vehicle mix is an important determinant of these visibility percentages. The worst-case mixture involves 100 percent light trucks as viewing vehicles and 100 percent passenger cars as signaling vehicles. In this case, the signaling-vehicle mirror is visible for 85 percent of vehicle pairs and the side repeater in 25 percent of vehicle pairs. When the viewing vehicle is a light truck and the signaling vehicle is a passenger car, a mirror-mounted signal would be visible 2.4 times more frequently than a European-style side repeater under the simulated lateral-view conditions.

The preceding has been concerned only with downvision, but a mirror-mounted signal on a high vehicle could be obscured by the upper edge of the window of a low viewing vehicle (e.g., a sports car driver passing a large SUV). Upvision angle cannot be calculated directly from the data used in this study, because the upper edges of the windows were not digitized in the mirror field-of-view studies. However, the vehicle measurement data provide summary statistics on window heights by vehicle category. The means and standard deviations of window height (dimension A) from Tables 1 and 2 were included in the simulations to estimate upvision angles. For passenger cars, upvision angles through the passenger window averaged 9.5 degrees (s.d. 2.9 degrees). For light trucks, the mean was 7.2 degrees (s.d. 2.5 degrees). Based on this analysis, average upvision angles through the passenger-door window are similar to average downvision angles for passenger car drivers. Of course, variance in eye height within the vehicles causes these variables to differ inversely across drivers.

Running paired-vehicle simulations several times yielded only three to five cases per 10,000 simulations in which the signaling vehicle mirror was obscured by the roof of the viewing vehicle. The worst-case conditions are a low viewing vehicle with a high driver eye location with the vehicle, a high signaling vehicle mirror, and a small lateral distance between the vehicles.

A separate, more approximate analysis can be conducted with the manually measured vehicle dimension data. Using the average passenger-car upvision angle of 9.5 degrees and the average lateral vehicle spacing of 2 m, the average maximum view height on the signaling vehicle is approximately  $2 \sin(9.5 \text{ degrees}) = 0.33 \text{ m}$  higher than the upper window boundary. This value was added to the measured upper window boundary height (dimension A plus

dimension D) to estimate the maximum view height for each of the passenger cars in the sample (N = 64). These values were then compared to the mirror heights for all vehicles. Of all possible combinations of 98 cars and light trucks, the mirror of the signaling vehicle was above the maximum view height in only seven cases, which involved two light trucks. Four passenger-car maximum view heights were below the mirror height of one light truck and three passenger-car maximum view heights were below the mirror height of another light truck. All other passenger car and light truck mirrors were below the maximum viewing heights for all other vehicles, showing that MMTS are not likely to be too high to be visible to adjacent vehicles.

Returning to the simulations described above, Figure 9 shows the vertical distribution of lateral visibility calculated for a vehicle population with 50% light trucks, including both upper and lower cutoffs. In the figure, the thick line shows the fraction of drivers who can see targets on the side of an adjacent vehicle through the passenger-door window as a function of target height from the ground. This analysis takes into account the window geometry, driver eye locations, and variable lateral spacing of the vehicles. The mounting-height distributions of light-truck mirrors, passenger car mirrors, and passenger-car side repeaters are depicted using normal distributions based on the means and standard deviations from Tables 1 and 2. For this vehicle mix, nearly all drivers can see targets that are about 120 cm from the ground, which is approximately the mean height of light truck mirrors (118.6 cm in Table 2). Most passenger car and light truck mirrors can be seen through the passenger-door window by at least 90 percent of drivers. In contrast, the average side repeater height is visible to only about 60 percent of drivers.

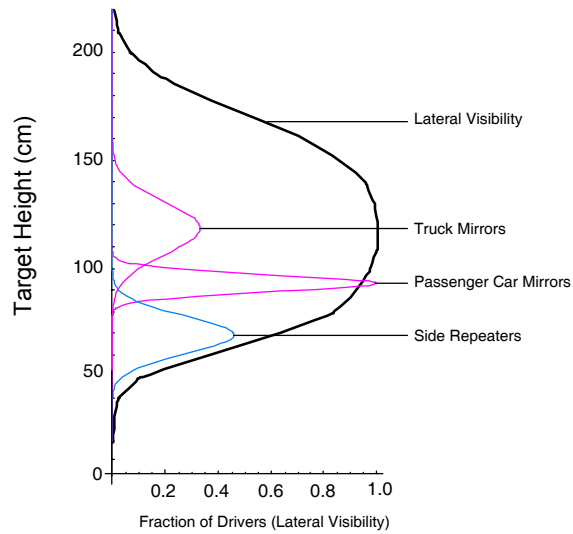


Figure 9. Vertical distribution of lateral visibility for vehicle population with 50 percent light trucks (thick line). Approximate distributions of mirror and side-repeater mounting heights are depicted using normal distributions based on the means and standard deviations from Tables 1 and 2.

This analysis suggests a means of calculating the optimal signal height for lateral (geometric) visibility. Signals will be visible to the maximum number of drivers if they are close to the center of the distribution of vertical fields of view. Since lateral up- and downvision angles are approximately symmetrical (biased slightly downward for light-truck drivers), the optimal lateral signal height to minimize obscuration by the viewing vehicle is approximately equivalent to the average driver eye height. In selecting signal mounting heights on a vehicle, the optimal height depends on the expected distribution of viewing driver eye heights, which is equivalent to consideration of the distribution of viewing vehicle types, since vehicle type affects driver eye height much more than variance in driver eye locations within an individual vehicle. Tables 3 and 4 give average driver eye heights for passenger cars and light trucks. Based on those data, the ideal signal height for a viewing-vehicle population that is 50% light trucks would be 124 cm. This value is considerably higher than the average mirror mounting heights for passenger cars (93 cm in Table 1), but is fairly close to the average truck mirror height (119 cm in Table 2). Figure 9 shows that any target within this height range will be visible to 90 percent or more of viewing drivers in the adjacent-vehicle scenario.

## **Eccentricity Analysis**

As part of the effort to understand signal visibility in the adjacent-vehicle scenario, video was taken with a camera held at a front-seat passenger's eye location with the camera pointed toward the driver's side of the vehicle. When the images are flipped horizontally, they become a reasonable approximation of the view that a driver would have to the right side of the vehicle while passing. (This procedure eliminates the safety issues that would be involved in placing the camera at the driver's eye location.) Figure 10 shows images of two SUVs and one full-size van taken in this manner. The field of view of the camera is considerably smaller than a driver's field of view, but the images illustrate some of the issues. The left image of each pair was taken approximately at the point when the rear signal of the (potentially) signaling vehicle was directly lateral to the viewing driver's eyes. At this point, the rear signal is viewed through the side window of the viewing driver's vehicle and the mirror is viewed through the windshield. The right image of each pair shows the viewing vehicle further rearward relative to the signaling vehicle, at the point where the rear signal is obscured by the A-pillar of the viewing driver's vehicle. (The actual obstruction experienced by a driver with binocular vision would be slightly smaller than that shown by the camera, and any relative movement of the two vehicles would tend to make the signal visible.)

Figure 10 shows that, particularly with long signaling vehicles, the mirror location is much closer to the driver's forward-directed line of sight than the rear-mounted turn signals. In the three scenarios depicted in Figure 10, a lane-change conflict can be anticipated because the viewing vehicle appears to be at least partially in the "blind zone" between the signaling driver's left-mirror field of view and his or her peripheral field of view. An additional, intriguing factor is that the B-pillars of the signaling vehicles appear to pose an impediment to the ability of the drivers to detect the blind-zone vehicle through peripheral or even direct vision. In the top two images, the head of the front-seat occupant in the signaling vehicle is obscured by the B-pillar, suggesting that a driver in the same scenario might have difficulty detecting an adjacent vehicle in the direction of the B-pillar. A similar situation seems likely in the other scenarios depicted in Figure 10. B-pillar obstruction may make the detection of an adjacent vehicle by a signaling driver about to make a lane change less likely, enhancing the potential safety benefit of MMTS in this scenario.

The images in Figure 10 were deliberately chosen to be those in the video that best illustrated the potential eccentricity advantages of the external mirrors as a location for a signal repeater. Reviewing the video showed clearly that the potential for benefit was directly related to the length of the signaling vehicle. Increasing the fore-aft distance between the rear-mounted signals and the mirror increases the area adjacent to the vehicle within which the rear signals are not visible but the mirror is.

Gathering data on the location of vehicle mirrors with respect to the rear of the vehicle was an important goal of the data collection conducted for this study. Table 1 shows that passenger car mirrors are an average of 284 cm from the rear of the vehicle. Light truck mirrors are an average of 332 cm forward of the vehicle rear, but the standard deviation is nearly double that for passenger cars (Table 2). Of the 34 light trucks measured for this study, three had lengths from the mirror to the rear of the vehicle of more than 4 m.

Dimensions were obtained from the vehicle measurement data for calculation of mirror eccentricities using equation 1 (see Section 2.2). As a reasonable approximation,  $w$  is taken to be the same for all potential signal locations. Based on vehicle widths in the mirror FOV dataset, and assuming 3.658-m lanes, the average lateral space between vehicles is 1.985 m or approximately 2 m for a population of vehicles that is 50 percent light trucks and 50 percent passenger cars. Using this value and the average distance of a driver's eyes from the right side of his or her own vehicle of 1.3 m (see Tables 3 and 4), a typical value of  $w$  is 3.3 m. The mean and standard deviation of  $G$  are given in Tables 1 and 2 for passenger cars and light trucks.

Taking  $x$  as zero gives eccentricities for the mirror that would be obtained when the viewing driver's eyes are directly adjacent to the rear of the signaling vehicle (and hence the rear-mounted signals may lie just outside of the viewing driver's peripheral vision). The average value of  $G$  for passenger cars is 2.84 m, giving an eccentricity for the mirror of  $\arctan(3.3/2.84) = 49$  degrees in this scenario. Using the average value of  $G$  for light trucks of 3.32 m, the average mirror eccentricity is 45 degrees. For a long truck or van with a  $G$  value of 4 m, the mirror eccentricity is 40 degrees when the eccentricity of the rear signal is 90 degrees.

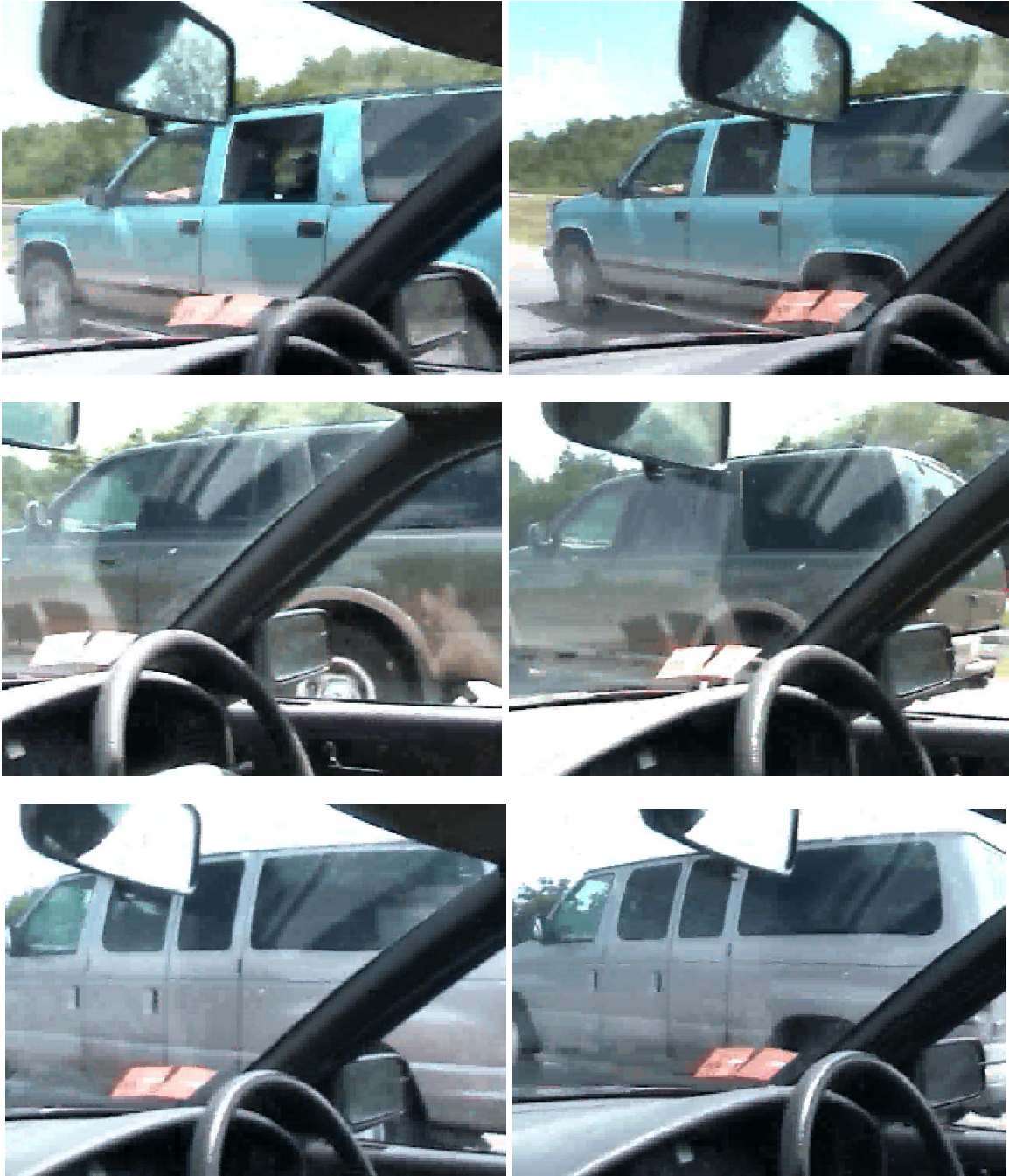


Figure 10. Illustration of adjacent-vehicle eccentricity differential between mirrors and rear signals for two SUVs and one full-size van viewed from a passenger car. For safety reasons, scenes were shot on video from the passenger seat and flipped horizontally to approximate the view of the driver to the right. The left frame was taken from the point when the rear signals were approximately adjacent to the driver. The right frame shows the rear signal obscured by the A-pillar. Note that in each case, the mirror is visible but the rear turn signal is not.

## DISCUSSION

Turn signals mounted on the external mirrors of passenger cars and light trucks may be more visible to drivers of adjacent vehicles than the standard signals mounted near the ends of the vehicles. The analysis in this report shows that the signals of vehicles that are minimally compliant with the turn-signal visibility requirements of FMVSS 108 will not be visible to the drivers of adjacent vehicles over a large range of potential lane-change/merge conflict scenarios. A mirror-mounted signal could substantially reduce the size of the zones in which turn signals are not visible.

The primary factors affecting the geometric visibility of turn signals are (1) the locations of the turn signals on the signaling vehicle, (2) the locations of these signals with respect to the viewing driver's field of view, and (3) obstruction of the viewing driver's field of view due to vehicle structures. The primary advantage of the external mirrors as signal mounting locations is that the mirrors are higher and further forward on the vehicle relative to the conventional rear and side-repeater signal locations. Using vehicle geometry data and driver eye locations, this report shows that signals mounted at the height of the exterior mirrors are more likely to be visible to adjacent drivers through the passenger door window than are the rear turn signals and side repeaters, which are nearly always lower than the mirrors. Simulations showed that the mirror of a signaling vehicle would be visible through the passenger door window 52 percent more often than a typical European side repeater.

The eccentricity analysis showed that the external mirror is much closer to the viewing driver's forward-directed line of sight than the rear turn signals in a typical blind-zone scenario. When the signaling vehicle is slightly forward of the viewing vehicle, the driver of the signaling vehicle may not detect an adjacent vehicle that lies wholly or partially within the zone that is not visible in the mirror or in peripheral vision. The eccentricity advantage in this scenario is particularly apparent with long vehicles, such as vans and pickup trucks. Video images obtained in road traffic showed that B-pillar obscuration of the signaling driver's peripheral vision may expand the blind area adjacent to the vehicle and increase the importance of turn signal visibility in the lane-change/merge scenario. The effects of B-pillar obscuration on drivers' awareness of adjacent vehicles should be explored in future research.



This report has been concerned only with the geometric visibility of turn signals, that is, whether there is an unobstructed line of sight between the signal and the viewing driver's eyes. Many other factors can be expected to affect the utility of MMTS. A primary concern is the conspicuity of signals in the periphery of a driver's vision. Does the difference in eccentricity between mirrors and rear-mounted signals documented in this report affect the likelihood that a person will detect a turn signal or the speed with which that signal will be detected? A future report will build on the geometric analysis reported here by addressing this conspicuity issue.

The analysis has shown that higher-mounted turn signals that are located further forward on the signaling vehicle are less likely to be obstructed by the viewing driver's vehicle, but the implications of these observations for crash avoidance have not been quantified. The key issues relate to driver behavior in incipient lane-change/merge (LCM) crashes. Are turn signals activated prior to a significant percentage of LCM crashes? If the signals are activated, does the LCM maneuver happen slowly enough, or late enough after the activation of the signal, that a viewing driver would have time to take evasive action?

There must be some benefit, as yet unquantified, in having a turn signal visible in the blind-zone, adjacent-vehicle scenario in which most LCM crashes are believed to occur. Current U.S. regulations do not require visibility in that scenario, and the analysis in this report shows that European side-repeaters are less visible than higher mirror-mounted signals when the vehicles are close together. The external mirror seems to be a nearly ideal location for mounting a turn signal that is intended to be visible when vehicles are close together in adjacent lanes.

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