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16. Abstract

This quasi-experiment investigated the effects on lane change crashes of nonplanar (spherical convex and multiradius) driver-side mirrors compared to planar mirrors. The analysis was based on 1,062 crashes reported from 1987 to 1998 to Finnish insurance companies, for vehicles with passenger-side spherical convex mirrors and one of three types of driver-side mirror (planar, spherical convex, or multiradius).

The results showed that the mean effect of nonplanar mirrors compared to planar mirrors was a statistically significant decrease of 22.9% in lane change crashes to the driver side. The effects of spherical convex and multiradius mirrors were not statistically different from each other. The nonplanar mirrors were beneficial especially for the high risk driver groups, as well as for the lane change situations and environmental conditions in which most lane change crashes take place in the U.S.

The present findings support the use of nonplanar driver-side mirrors. If drivers have problems with judgements of the speed and distance of approaching vehicles using nonplanar mirrors, the magnitude of this concern seems to be minimal compared to apparent benefits with regard to other mechanisms of lane change crashes.

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# CONTENTS

# INTRODUCTION

The potential advantages and disadvantages of various types of driver-side mirrors have been discussed for a long time. In summary, for a given mirror size, the blind zone with a nonplanar mirror is smaller than with a planar mirror. On the other hand, images in nonplanar mirrors are minified and, therefore, the estimation of distances and relative speeds of cars approaching from behind is more difficult. Planar mirrors are mirrors with unit magnification (i.e., flat). Nonplanar mirrors include both spherical convex mirrors, whose surfaces are portions of uniform spheres, and so-called aspheric mirrors which, in practice, have been designed to have a spherical inboard section and an outboard section that is progressively more curved (also referred to as multiradius mirrors).

The discussion of the tradeoff between the quality and quantity of field of views has been resolved in two ways. In Europe, driver-side mirrors can be either planar, spherical convex, or multiradius. In the U.S., on the other hand, only planar driver-side mirrors are allowed, because it has been argued that the distortions caused by nonplanar mirrors might result in unsafe behavior.

Several studies have been conducted to investigate various effects of exterior mirrors (for a review see Flannagan, 2000). Flannagan summarizes the results on subjective evaluations and human factors studies of the perceptual components of mirror use as follows. First, two studies have recently reported generally positive subjective evaluations of nonplanar mirrors by drivers in the U.S. (Flannagan and Flannagan, 1998) and the Netherlands (De Vos, Theeuwes, and Perel, 1999). Each of those studies is limited—the U.S. study because it involved primarily middle-aged males, and the Dutch study because it was a relatively small, preliminary part of a larger study. Second, the results of the extensive research on the effects of nonplanar mirrors on distance cues show that it seems unlikely that negative effects of distortion introduced by nonplanar mirrors can be completely ruled out. However, it also seems unlikely that the problems with distance perception are very severe. Several circumstances can be expected to decrease the potential negative effects of distance distortions. Drivers adapt to the images provided by nonplanar mirrors, becoming more accurate in their judgements with experience (e.g., Burger, Mulholland, Smith, and Sharkey, 1980; Flannagan, Sivak, and Traube, 1996), and drivers tend to rely on the planar interior mirror rather than the nonplanar mirror for judgement of distance and speed, if there is a planar interior mirror available (Mortimer, 1971).

It seems evident that it is difficult to design a set of human factors studies to cover all necessary aspects so that valid conclusions for the safety effects of nonplanar mirrors can be made. Therefore, crash studies have attempted to provide a comprehensive assessment of the tradeoffs involved in using nonplanar mirrors.

Luoma, Sivak, and Flannagan (1994) showed that the statistics on lane change crashes can be used as a useful measure, if both a mixture of driver-side mirror types and detailed crash records are available. The rationale for the use of lane change crashes is that, in lane change maneuvers, information about traffic behind the vehicle is particularly important. Therefore, lane change crashes are, perhaps, the type of crash most likely to be influenced by the driver's use of exterior mirrors. Because crashes are typically multicausal, however, lane change crashes cannot necessarily be attributed to the improper design of rearview mirrors alone.

Although there have not been any formal experiments in which crash rates have been measured, there have been two quasi-experimental studies of crash data from countries that allow both planar and nonplanar mirrors on the driver side (Luoma, Sivak, and Flannagan, 1994; Schumann, Sivak, and Flannagan, 1996). The two studies were similar in design. Specifically, they focused on lane change crashes to the driver side, using lane change crashes to the passenger side (on which all the vehicles involved had spherical convex mirrors) as a control for exposure. Luoma et al. (1994) examined 407 Finnish crashes. Because at that time in Finland only some midsize cars were equipped with the multiradius driver-side mirrors, only similar vehicles in terms of size were included in the analysis. The main results showed that, compared to planar mirrors, multiradius and spherical convex mirrors were associated with a 22% decrease in crashes. However, the statistical strength of the data was low: the 95% confidence interval for the effect of nonplanar mirrors ranged from a 51% decrease to a 25% increase in crashes.

Schumann et al. (1996) examined 3,038 crashes in Great Britain and found a nonsignificant tendency for spherical convex mirrors to lead to fewer lane change crashes than planar mirrors. However, this tendency was confined to the largest tested vehicles (i.e., midsize cars), and to drivers in the two extreme age groups (17-24 years of age and over 54 years of age).

The present study replicated the study of Luoma et al. (1994) with an expanded database. The crash data of this study covered 12 years, while the prior study included only 6 years. In addition, new analyses concerning different driver groups and crash characteristics were also included in the present study. The main analyses focused on the comparison of the effects of nonplanar and planar mirrors, because it was assumed that the difference in fields of view between those mirror types is much greater than the difference between multiradius and spherical convex mirrors.

# METHOD

## Crash data

The data included lane change crashes in Finland between 1987 and 1998 that were reported to the Finnish insurance companies. The database includes all road crashes that led to indemnities on the basis of a mandatory, third party, liability insurance of motor vehicles. The database covers about 70% of all traffic crashes and about 80% of injury crashes (Road and Waterways Administration, 1988). The most frequent crash types that are not included are pedestrian and bicyclist crashes, and single-vehicle crashes without injuries (Road and Waterways Administration, 1988; Finnish Motor Insurers' Centre, 1993). However, those crashes were not of interest in this study.

## Mirror data

Information on exterior mirrors was obtained primarily by a mail survey (to Finnish car importers) conducted by Luoma et al. (1994) that provided information by make, model, and model year for driver-side and passenger-side exterior mirrors concerning (1) type, (2) radius, if applicable, and (3) area. This information was supplemented with a survey among Finnish car dealers.

All models included in the analysis were equipped with spherical convex passenger-side mirrors, and either multiradius, spherical convex, or planar driver-side mirrors. If there were mirror design changes during a model year, that model was excluded for that year. The final set included information on the following midsize cars (with a wheelbase of 245-285 cm):

*Audi* 80, 90 (1988-92), 100, 200 (1984-92)
*BMW* 300, 500 (1984-92)
*Citroen* CX (1987-88)
*Honda* Accord (1985-92)
*Mazda* 626 (1989-90)
*Opel* Ascona (1984-88), Omega (1986-92), Record (1984-87), Vectra (1988-92)
*Renault* 21 (1987-91)
*Saab* 900 (1984-92), 9000 (1985-92)
*Toyota* Camry, Carina II (1984-92)
*Volvo* 200, 700 (1984-92)

## Data analysis

The analysis was based on a comparison of the frequencies of lane change crashes to the driver side for vehicles equipped with different types of driver-side mirrors, while the frequencies of lane change crashes to the passenger side were used as controls. Because the passenger-side mirrors were of the same type on all vehicles, crashes to the passenger side should provide an index of exposure. Thus, the effect of the type of the driver-side mirror was calculated from crash frequencies using Formula

$$E = 100 \times \left( \frac{\frac{D_1}{P_1}}{\frac{D_2}{P_2}} - 1 \right) \tag{1}$$

where

$E$ = effect (%) of the driver-side mirror of Type 1 compared to the driver-side mirror of Type 2

$D_1$ = number of crashes to the driver side for cars with the driver-side mirror Type 1

$P_1$ = number of crashes to the passenger side for cars with the driver-side mirror Type 1

$D_2$ = number of crashes to the driver side for cars with the driver-side mirror Type 2

$P_2$ = number of crashes to the passenger side for cars with the driver-side mirror Type 2

# RESULTS

## Crashes

Data consisted of lane change crashes in which a car with a spherical convex passenger-side mirror had changed lanes. The original data set included 1,271 crashes. However, only crashes with the lane changing driver fully at fault (88.1% of all cases), and with no drunk driver involvement (94.4% of all cases), were selected for further analyses. Consequently, the final data set included 1,062 crashes. Of those, 49.0% involved a lane change to the driver side and 51.0% a lane change to the passenger side.

## Mirrors

Vehicles with spherical convex mirrors on the passenger side were classified into three categories, according to the type of the driver-side mirror. Mirror dimensions were similar for each side. Table 1 summarizes the mirror data.

Table 1
Mirrors by vehicle group.

| Vehicle group | Driver-side mirror/ Passenger-side mirror | Radius of the driver-side mirror (mm) | Radius of the passenger-side mirror (mm) Δ |
|---|---|---|---|
| 1 | Multiradius/ Spherical convex | 2,000 and 140-800* | 2,000 |
| 2 | Spherical convex/ Spherical convex | 1,400-2,000Δ | 1,400-2,000 |
| 3 | Planar/ Spherical convex | ∞ | 1,400-2,500 |

* Radius of the progressively reducing part.

Δ Radius information covers only 58% of models.

**Effects of the type of driver-side mirror on crashes**

The number of lane change crashes to each side for the three mirror types is given in Figure 1. Compared to the number of lane change crashes to the passenger side, the number of the crashes to the driver side was lowest for the multiradius mirror, followed by the spherical convex mirror, and the planar mirror.

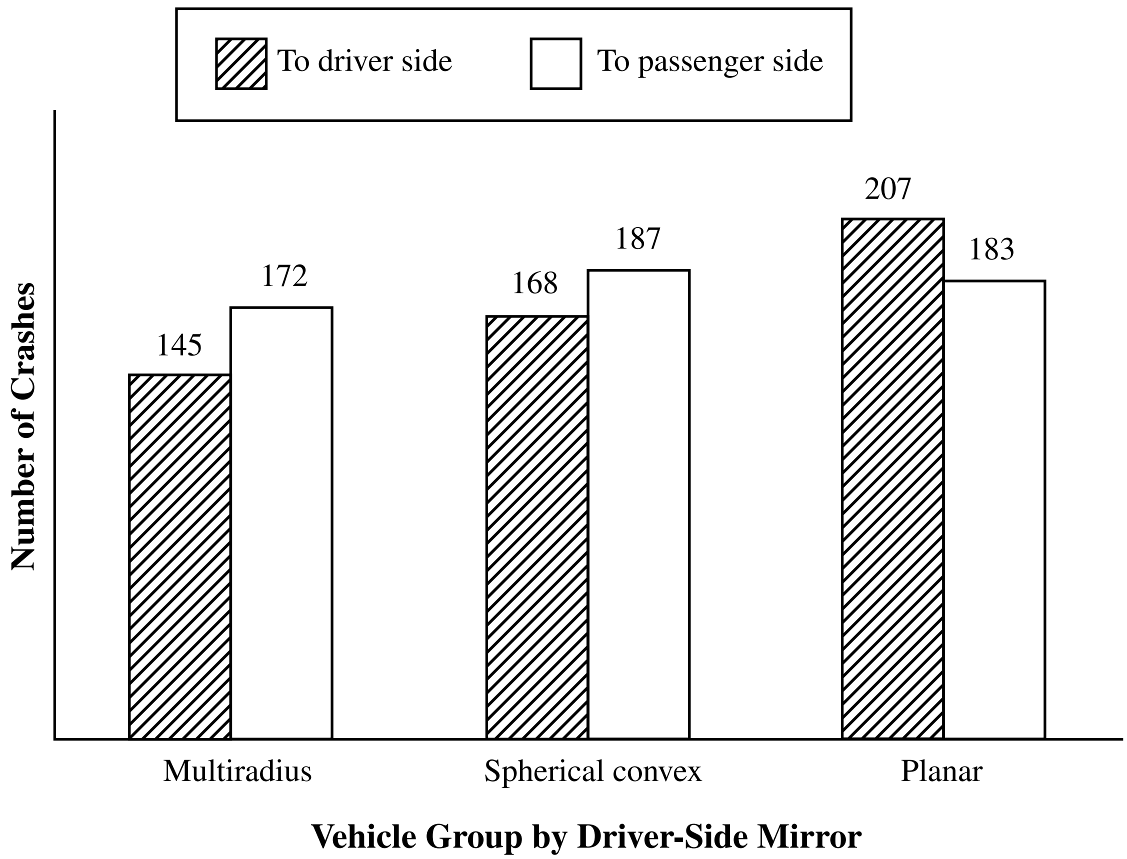


Figure 1. Frequency of lane change crashes by type of driver-side mirror.

Figure 2 shows the effectiveness measures for different driver-side mirror comparisons using Formula (1), along with the 95% confidence intervals (Agresti, 1990). The mean effect of nonplanar (spherical convex and multiradius) mirrors compared to planar mirrors was a 22.9% decrease, $\chi^2(1) = 4.17$, $p = .041$. The effects of spherical convex and multiradius mirrors were not statistically different from each other. The difference in the frequency of lane change crashes was marginally not statistically significant for multiradius mirrors compared to planar mirrors, $\chi^2(1) = 3.76$, $p = .052$, with a mean effect of a 25.5% decrease. The effect of spherical convex mirrors compared to planar mirrors (with a mean decrease of 20.6%) was not statistically significant.

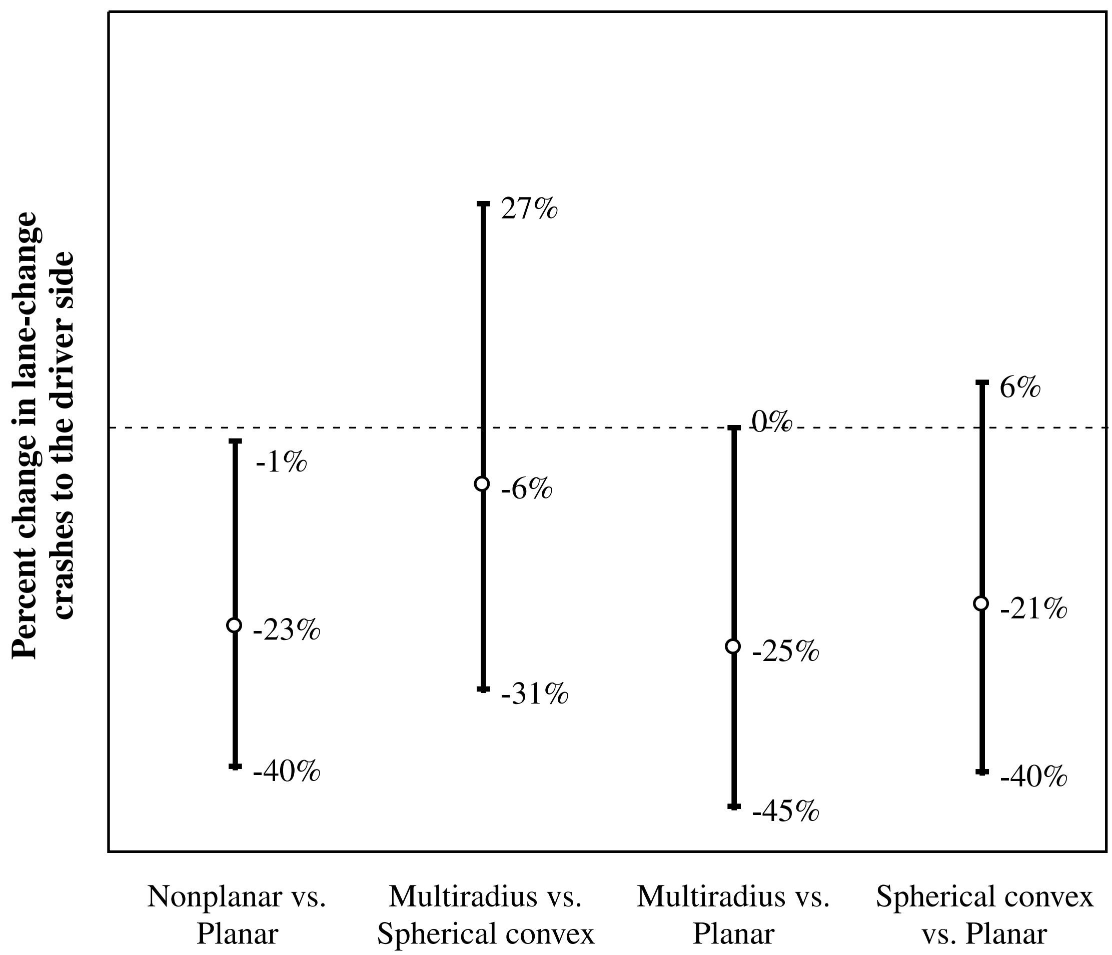


Figure 2. Effectiveness measures for (a) nonplanar versus planar, (b) multiradius versus spherical convex, (c) multiradius versus planar, and (d) spherical convex versus planar driver-side mirrors (mean and 95% confidence interval).

**Effectiveness of nonplanar mirrors by driver characteristics, pre-crash speed, and environmental conditions**

This section of the report presents the mean effectiveness measures for nonplanar versus planar driver-side mirrors by driver characteristics, relative pre-crash speeds of the vehicles involved, and environmental conditions. In addition, the corresponding frequencies of lane change crashes in the U.S. (Wang and Knipling, 1994) are presented in order to compare how the mirror effectiveness relates to crash frequencies.

**Age.** Figure 3 shows the effectiveness of nonplanar driver-side mirrors for five age groups.[1] There was a statistically significant decrease in driver-side crashes for the youngest age group (18-24 years; 45% decrease; $\chi^2(1) = 4.09$, $p = .043$) and a tendency in the same direction for the oldest age group (55+ years; 50% decrease; $\chi^2(1) = 3.75$, $p = .053$). Table 2 shows that there is quite a similar trend over age groups in the overall involvement in lane change crashes per vehicle miles traveled.

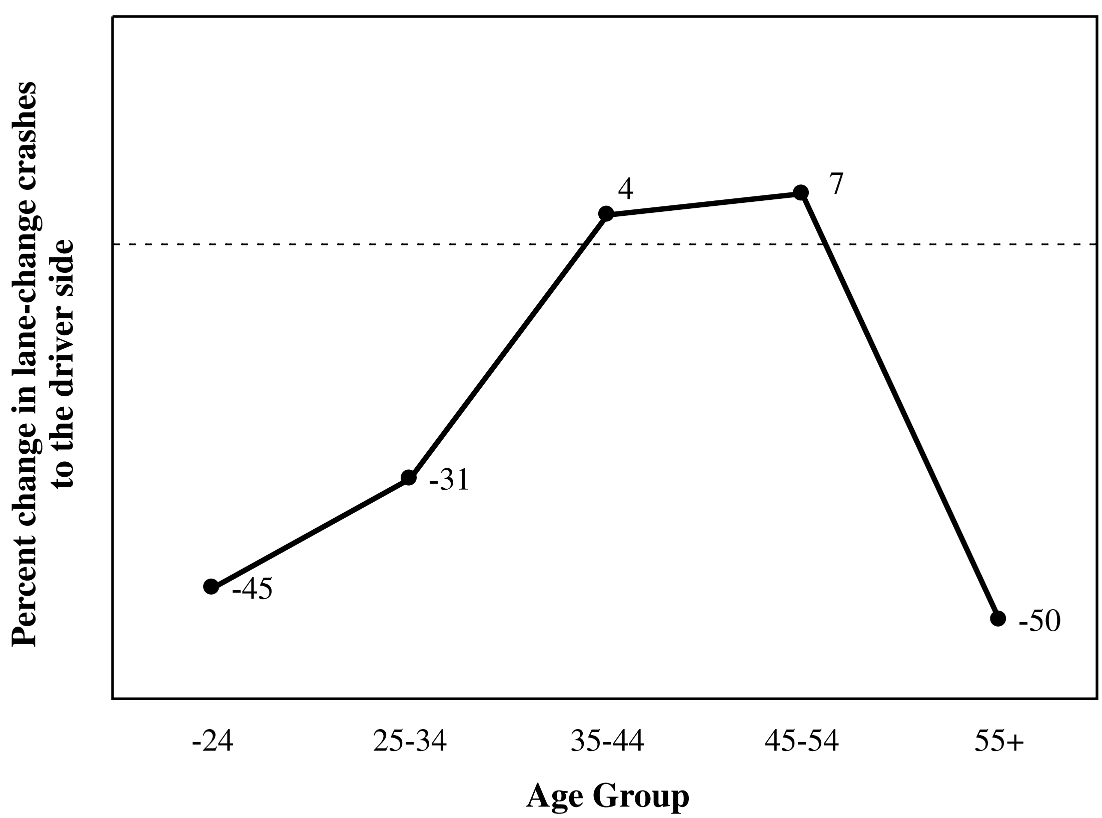


Figure 3. Effectiveness measures for five age groups of nonplanar versus planar driver-side mirrors, with respect to the frequency of lane change crashes to the driver side. (The number of cases in each age group ranged between 165 and 243).

[1] There were too few cases in the oldest age group (n = 167) for any finer age classification.

Table 2
Lane change crash involvement rate by driver age. (Adapted from Wang and Knipling, 1994.)

| Driver's age | Crash rate per 100 million vehicle miles traveled |
|---|---|
| 15-19 | 30.7 |
| 20-24 | 14.8 |
| 25-54 | 8.5 |
| 55-64 | 9.8 |
| 65-74 | 14.1 |
| 75+ | 17.9 |

**Gender.** Table 3 shows that the benefits of nonplanar mirrors were confined to male drivers (31% decrease; $\chi^2(1) = 6.35$, $p = .012$). The crash data of Wang and Knipling (1994) indicate that, as the drivers of the lane changing vehicles, males have a slightly higher involvement rate (11.5) per vehicle miles traveled than do females (9.6).

**Relative pre-crash speed.**[2] Nonplanar mirrors were most effective when both vehicles had been traveling at approximately the same speed (46% decrease; $\chi^2(1) = 7.76$, $p = .005$) (see Table 3). In addition, there was a tendency in the same direction if the vehicle in the adjacent lane drove faster than the lane changing vehicle (35% decrease; $\chi^2(1) = 1.69$, $p = .194$). According to the crash data of Wang and Knipling, 63.2% of the vehicles in the adjacent lane traveled at a speed within 5 mph of the lane changing vehicles, while 19.4% traveled faster and 17.3% traveled slower than the lane changing vehicle.

**Area.** The benefits of nonplanar mirrors appeared to be confined to urban areas (23% decrease; $\chi^2(1) = 3.86$, $p = .049$) (see Table 3). The crash data of Wang and Knipling indicate that 83.9% of lane change crashes of passenger vehicles in the U.S. occur in urban areas and 16.1% in rural areas.

**Light conditions**. Nonplanar mirrors were effective in daylight (28% decrease; $\chi^2(1) = 4.98$, $p = .026$) but no significant mirror effect was found for conditions with reduced visibility (Table 3). Also, most of the lane change crashes of passenger vehicles happen in daylight (74.6%), while 25.4% happen in dark, dark but lighted, or dawn/dusk conditions (Wang and Knipling, 1994).

**Road surface conditions**. Table 3 shows that the greatest effectiveness of nonplanar mirrors was found for dry road surface conditions (37% decrease; $\chi^2(1) = 7.12$, $p = .008$), in which 80.3% of lane change crashes of passenger vehicles occur (Wang and Knipling, 1994).

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[2] There were a considerable number of unknown cases for pre-crash speed in both databases—approximately 40% in the Finnish database and 70% in Wang and Knipling (1994).

Table 3
Effectiveness of nonplanar driver-side mirrors for different groups based on five background variables, with respect to the frequency of crashes to the driver side.

| Variable | Effectiveness (%) | Number of crashes |
|---|---|---|
| Gender | | |
| Male | -31 | 819 |
| Female | +8 | 243 |
| Pre-crash speed of the vehicle in the adjacent lane compared to the speed of the lane changing vehicle* | | |
| Higher | -35 | 178 |
| The same | -46 | 355 |
| Lower | +6 | 72 |
| Area | | |
| Urban | -23 | 962 |
| Rural | +2 | 100 |
| Light conditions | | |
| Daylight | -28 | 772 |
| Twilight, dark, or dark but lighted | -11 | 266 |
| Road surface conditions | | |
| Dry | -37 | 581 |
| Wet, snowy, or icy | -6 | 455 |

* Pre-crash speeds were classified in increments of 10 km/h.

# DISCUSSION

This study investigated the effects of nonplanar driver-side mirrors on lane change crashes. Specifically, the analysis compared the frequencies of lane change crashes to the driver side for vehicle groups equipped with different types of driver-side mirrors, while the frequencies of lane change crashes to the passenger side were used as controls for exposure.

The main results showed that the mean effect of nonplanar mirrors compared to planar mirrors was a statistically significant decrease of 22.9% in lane change crashes to the driver side. A more detailed analysis showed that the mean effect of multiradius mirrors compared to planar mirrors was a marginally not significant decrease of 25.5%. The effect of spherical convex mirrors compared to planar mirrors was a statistically not significant decrease of 20.6%.

The obtained magnitudes of the mirror effects were similar to those reported in previous studies. Specifically, Luoma et al. (1994) found a decrease of 22.0% for nonplanar versus planar mirrors, and Schumann et al. (1996) found a decrease of 17.9% for spherical convex versus planar mirrors for midsize vehicles. Furthermore, the results are consistent with the results of a simulation experiment of Helmers, Flannagan, Sivak, Owens, Battle, and Sato (1992), which evaluated the effects of planar, spherical convex, and multiradius driver-side mirrors on drivers' response times for detection of cars at short distances behind in the adjacent lane. The shortest response times were for multiradius mirrors, followed by spherical convex, and planar mirrors.

The results concerning mirror effectiveness by driver characteristics showed that, overall, nonplanar mirrors were effective for the highest risk groups in the U.S. Specifically, the nonplanar mirrors were beneficial for the youngest and oldest driver groups, and for males. Schumann et al. found a similar trend for age and provided the following hypotheses why these age groups have problems in turning their head to check for vehicles in the blind zone: (1) The youngest drivers might be careless in performing this task, or might not have enough experience with the blind zones; and (2) the oldest drivers are more likely to have problems in turning their heads due to their reduced mobility. In addition, lane change situations are rather demanding if the driver is expected to observe the traffic in the adjacent lane, and there is another vehicle traveling in front. Both age groups might have problems performing these concurrent tasks, the young drivers because of their overall inexperience with driving, and the old drivers because of more general problems with divided-attention tasks. The present results also suggest that the benefits of nonplanar mirrors were confined to males. Although no specific behavioral data are available, one might assume, based on their higher overall rate of lane change crashes (Wang and Knipling, 1994), that males tend to fail to check the blind zone more frequently than do females.

Nonplanar mirrors were found most effective in situations with the smallest difference in pre-crash speeds, or when the vehicle in the adjacent lane was traveling faster than the lane changing vehicle. These situations correspond to 83% of lane change crashes in the U.S. (Wang and Knipling, 1994). These results suggest that nonplanar mirrors are most effective in situations with the highest crash frequency. In addition, these are the only situations in which the driver needs to monitor the area behind the car; it is not the case if the vehicle in the adjacent lane is traveling substantially slower than the lane changing vehicle. Importantly, these findings do not provide any evidence that nonplanar mirrors cause misjudgments of the speed and distance of approaching vehicles of such magnitudes that they would reduce overall safety.

The benefits of nonplanar mirrors appeared to be confined to urban areas. (In the U.S., 84% of lane change crashes of passenger vehicles occur in urban areas.) However, nonplanar mirrors did not provide any benefits in rural areas, where speed distribution is wider. This finding might imply that, especially in rural areas, there could be crashes caused by misjudgment of the speed and distance of approaching vehicles using nonplanar mirrors. Unfortunately, the present data do not allow us to evaluate the interaction between relative pre-crash speed and urban/rural area. On the other hand, given the infrequency of lane change crashes in rural areas, and the effectiveness of nonplanar mirrors when the vehicle in the adjacent lane is traveling faster than the lane changing vehicle, the magnitude of this concern seems to be minimal compared to apparent benefits with regard to other mechanisms of lane change crashes.

Nonplanar mirrors were most effective in daylight and when the road surface was dry. Interestingly, most lane change crashes by passenger vehicles happen in these conditions (75% and 80%, respectively). Although no behavioral data on the use of driver-side mirrors by light conditions are available, it may be that during the night the detection of a vehicle in the adjacent lane depends less on mirror type, because other visual cues are available. Specifically, if the vehicle in the adjacent lane is in the blind zone of a planar mirror, the detection of that vehicle is easier in the dark than in the daylight. This is because of the lighted pavement in front of the vehicle that may be visible by peripheral vision to the driver of the lane changing vehicle. In the case of the effects of road surface conditions, it is possible that the exterior mirrors are more difficult to use effectively in inclement weather, because there is more likely water or snow on the mirror surface.

Although the present results do offer evidence for beneficial effects of nonplanar driver-side mirrors, the data have their own limitations. First, crash data do not provide any information concerning the actual use of mirrors before lane changes. Such information would be of great interest in understanding various aspects of driver information processing and mirror use (e.g., aiming of mirrors). Second, only midsize cars were included in the analysis, because only this vehicle class included cars equipped with the multiradius driver-side mirrors that were of major interest. Third, there may also be other crash types that are affected by the driver-side mirror type. Flannagan (2000) and Flannagan and Sivak (1996) suggested that rear-end crashes could also provide useful information, because in those crashes a following driver's vision is typically diverted from the direction of travel, and the length of such diversion might depend on the mirror type.

# CONCLUSIONS

The present findings support the use of nonplanar driver-side mirrors. Nonplanar mirrors were beneficial especially for the high risk driver groups, as well as for the lane change situations and environmental conditions in which most lane change crashes take place in the U.S. To some degree, the benefits of nonplanar mirrors appeared to be confined to these driver groups and circumstances. A tendency indicating that nonplanar mirrors provided no benefits in rural areas might imply that drivers have some problems with judgements of speed and distance of approaching vehicles using nonplanar mirrors. However, given the infrequency of lane change crashes in rural areas, and the effectiveness of nonplanar mirrors when the vehicle in the adjacent lane is traveling faster than the lane changing vehicle, the magnitude of this concern seems to be minimal compared to apparent benefits with regard to other mechanisms of lane change crashes.

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