Eye Glance Behavior of Van and Passenger Car Drivers During Lane Change Decision Phase

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Eye Glance Behavior of Van and Passenger Car Drivers During Lane Change Decision Phase

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Data are presented on the eye glance behavior of passenger car and van drivers before the start of discretionary lane changes. Thirty-nine volunteers ranging from 20 to 60 years of age served as either van drivers (*N* = 19) or passenger car drivers (*N* = 20) in the study. Each driver used an instrumented vehicle and was accompanied by a ride-along observer in daylight and dry pavement conditions. The test route included driving on both public highways at 55 mph or more and city roads at 25 to 35 mph. A total of 549 lane changes (290 for vans, 259 for passenger cars) were analyzed in terms of driver eye glance behavior 10 s before the lane change start. Results indicated that for left-to-right lane changes, the probability of a glance to the center mirror was substantially higher than the probability of a glance to the right side mirror. For right-to-left lane changes, the probability of a glance to the center mirror was substantially less than that for rightward lane changes, and the probability of a glance to the left side mirror was appreciably higher than that for right side mirror use in rightward lane changes. These results held for both van and passenger car drivers. Except for a slightly higher probability of over-the-shoulder glances on city roads, these results hold for both highway and city street driving. These data should be factored into the design of lane change warning system displays and mirror systems.

A lane change may be defined as a deliberate and substantial shift in the lateral position of a vehicle with the intent to cross a lane boundary to enter an adjacent lane. A lane change crash occurs when a driver attempts to change lanes and strikes or is struck by a vehicle in the adjacent lane. Lane change crashes are estimated to account for approximately 4% to 10% of all police-reported crashes (*1*, *2*). Of all lane change crashes, the majority occur during daylight or on dark but lighted roadways, on dry pavement, and with relatively few attempts at an evasive maneuver. Collectively, these factors are taken as indications that drivers are unaware of the crash hazard. Furthermore, an estimated 78% of crashes (excluding those when the vehicle drifts out of the lane, which are not considered deliberate maneuvers) involve situations in which the two involved vehicles were laterally overlapped for some period of time before collision. These lane change crashes are termed proximity crashes in some reports (*3*). Alleviation of even a portion of such crashes may have substantial benefits in terms of crash-caused delays, property damage costs, and injuries.

A lane change can be modeled, to a first approximation, in terms of a decision phase and an execution phase. The decision phase is the time interval from when the driver desires to change lanes until the steering input that initiates the lane change execution phase. During the decision phase, the driver nominally seeks out information (primarily through visual checks of mirrors and by head turns) about whether to proceed or postpone the lane change execution itself. The execution phase is defined as the interval from the initial steering input until the vehicle is stabilized in the destination lane (for a successful lane change), or until the vehicle returns to the original lane (for a successful abortive maneuver), or until a crash occurs. There have been some attempts to model the execution phase by using simple kinematic models, for example, in the study by Chovan et al. (*3*). Much less attention has been devoted to modeling the decision phase of the lane change maneuver. The current study is intended to lend insights into the decision phase.

Intelligent transportation system (ITS) technologies are becoming available to help alleviate such crashes. Lane change warning system technologies use sensors, signal processing, and driver displays to provide the driver with alerts or warnings of objects sensed in adjacent lanes proximal to the host vehicle. The development of lane change technologies depends, at least in part, on an understanding of driver behavior and performance during lane change maneuvers (*4*). In particular, a key aspect of driver behavior while driving is allocation of vision. An understanding of how drivers glance to the road ahead, use mirrors, and execute head turns is considered by some to be important in developing an effective driver interface that promotes safety-relevant visual sampling behaviors and is compatible with driver experience and preferences.

Prior research has investigated driver eye glance behavior during the driving task (*5*–*8*). That research provides some insights into the nature of eye glance behavior in general and mirror sampling in particular. Individual differences among drivers and the directionality of lane change can have a significant impact on mirror sampling behavior. Recent research (*9*–*12*) has expanded an understanding of driver behavior by examining driver behavior before and during naturalistic lane changes.

The current paper is based on a previously unpublished report (*13*) that predates the most recent work. It is presented here to provide a public record of independent data collected with a different method to further an understanding of lane change behavior by comparing vehicles (van versus passenger car) and lane change direction across routes composed of both highways with a speed limit of 55+ mph and roads with limits of 25 to 35 mph. Moving beyond the emphasis on

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glance duration, this study seeks to consider frequency of glances and pattern of glances across specified locations in the driver's visual field.

METHOD

Nineteen volunteers from the Transportation Research Center, Inc. (TRC), in East Liberty, Ohio, participated in the data collection effort by driving an instrumented 1991 Plymouth Voyager van. They included eight men and 11 women, ranging from approximately 20 up to 55 or 60 years of age. The sample of opportunity included two technicians and two research engineers assigned to support the NHTSA Vehicle Research and Test Center. The remaining volunteers were TRC test drivers with varying levels of experience at the job. All individuals participated in the data collection run as part of a work day and received no other compensation for their participation.

A second group, of 20 volunteers, from TRC participated in the data collection by driving an instrumented 1994 Chevrolet Lumina passenger car. The passenger car group was a sample of opportunity that included 10 men and 10 women and spanned approximately the same age range as the van drivers. All test participants in the passenger car group were different from the test participants who participated in the van group.

Both vehicles were instrumented to capture video at 30 Hz. Event markers indicated roughly the start and end of a lane change maneuver in a data stream (triggered by a ride-along observer using a switch). Vehicle lane position at the start and end of the lane change (vehicle longitudinal centerline with respect to lane center) was captured with downward-looking cameras. Steering wheel position, travel speed, turn signal activation, and lateral accelerations were captured before and during the lane change. Driver eye glance behavior was captured by means of a face camera in time-stamped VHS video (operated at 30 Hz) and coded to predefined locations in the visual scene (e.g., left side mirror, road ahead, center mirror), including head turns.

The procedure involved observation and collection of data from multiple lane change maneuvers performed by each test participant in the instrumented van or passenger car. The lane change crash type is one that occurs largely in ideal circumstances (dry pavement, daylight). For this reason, as well as for safety considerations, it was deemed advisable to conduct data collection only under conditions of dry pavement and daylight conditions on open roadways. A route was chosen that allowed travel and data collection over four-lane divided and four-lane undivided highways (posted speed 55 mph) and city streets (posted speed 25 to 35 mph). The same ride-along observer was present at all times in the van and in the passenger car. The observer's duties were to operate equipment, provide requests to the driver to change lanes as needed, and to look out for hazardous conditions.

The ride-along observer informed the volunteer test participant that the purpose of the data collection session was to collect data on the ability of the instrumentation to accurately record vehicle position. The driver was informed that lane changes were needed to check the lane tracking subsystem. The driver was told that he or she was responsible for maintaining safe control of the test vehicle at all times. The driver was also asked to change lanes as he or she normally would. If, in the ride-along observer's opinion, the test participant was not making sufficient lane changes in a given segment of the data collection run, the driver was reminded to do so from time to time by the ride-along observer. No instructions were given regarding mirror sampling or turn signal use.

The lane change decision phase was operationally defined for this study as the 10 s before the start of the lane change execution phase, which was determined by research engineer review of driver steering inputs and lane tracker indications, aided by review of video of the driving situation and the presence of an event indicator that a lane change had in fact taken place. Driver eye glance data were manually reduced from the 30-frames-per-second VHS video of the driver's face and head. From the videotape, several measures were derived.

Link analysis (*14*) was used to analyze driver eye-scanning behavior during the 10 s before the start of lane change execution. The link analysis provides the probability of a glance to a given location (from any other location) as well as the probability of a glance transition between two different locations. It should be noted that in the link diagrams presented here, the values indicate the probability of a glance to a given location, not the proportion of glance time. There may be many short glances to a specific location, yet the total time is less than that spent at another location, so the two measures are not the same. The link analysis provides some indication of the nature of mirror use and head-turning behavior during the lane change decision phase.

Percentages were also calculated in this study in terms of the proportion of lane changes with at least one glance to a given location. This measure is of interest because it may provide information on optimizing the display location of the lane change warning system.

RESULTS

A total of 290 lane changes executed by the 19 van test participants were analyzed for inclusion in this paper. This number represents a total of 1,796 glances and 1,506 transitions. At the lowest level of analysis, lane changes are characterized as left-to-right lane changes or right-to-left lane changes, executed either on highways at 55+ mph or on city roads at 25 to 35 mph.

A total of 259 lane changes executed by the 20 passenger car test participants were analyzed for inclusion. This number represents a total of 1,368 glances and 1,105 transitions. At the lowest level of analysis, lane changes are characterized as left-to-right lane changes or right-to-left lane changes, executed either on highways at speeds of 55+ mph or on city roads at 25 to 35 mph.

Link Analysis of Driver Eye-Scanning Behavior

The link diagrams for the van group and for the passenger car group are included in Figures 1 and 2, respectively. The circles are labeled by the location they represent; numbers within a circle represent the probability of a glance to that location during the 10 s before the lane change start. The transition probabilities between two locations are represented by a line segment joining them, annotated with the transition probability value. All link probabilities were calculated as relative frequencies. That is, each probability is calculated as the proportion defined by the ratio of number of events of a particular type divided by the total number of events of all types. It should be noted that for improved legibility, probability values were rounded to two decimal places. As a result, transition lines or circles for proportions less than 0.005 are not included in the diagrams.

For left-to-right van lane changes on highways (Figure 1*a*) and right-to-left van lane changes on highways (Figure 1*b*), the two diagrams differ relatively little in the probability of a glance to the road scene ahead. However, substantial differences are apparent between the two diagrams in the glance probabilities associated with mirror

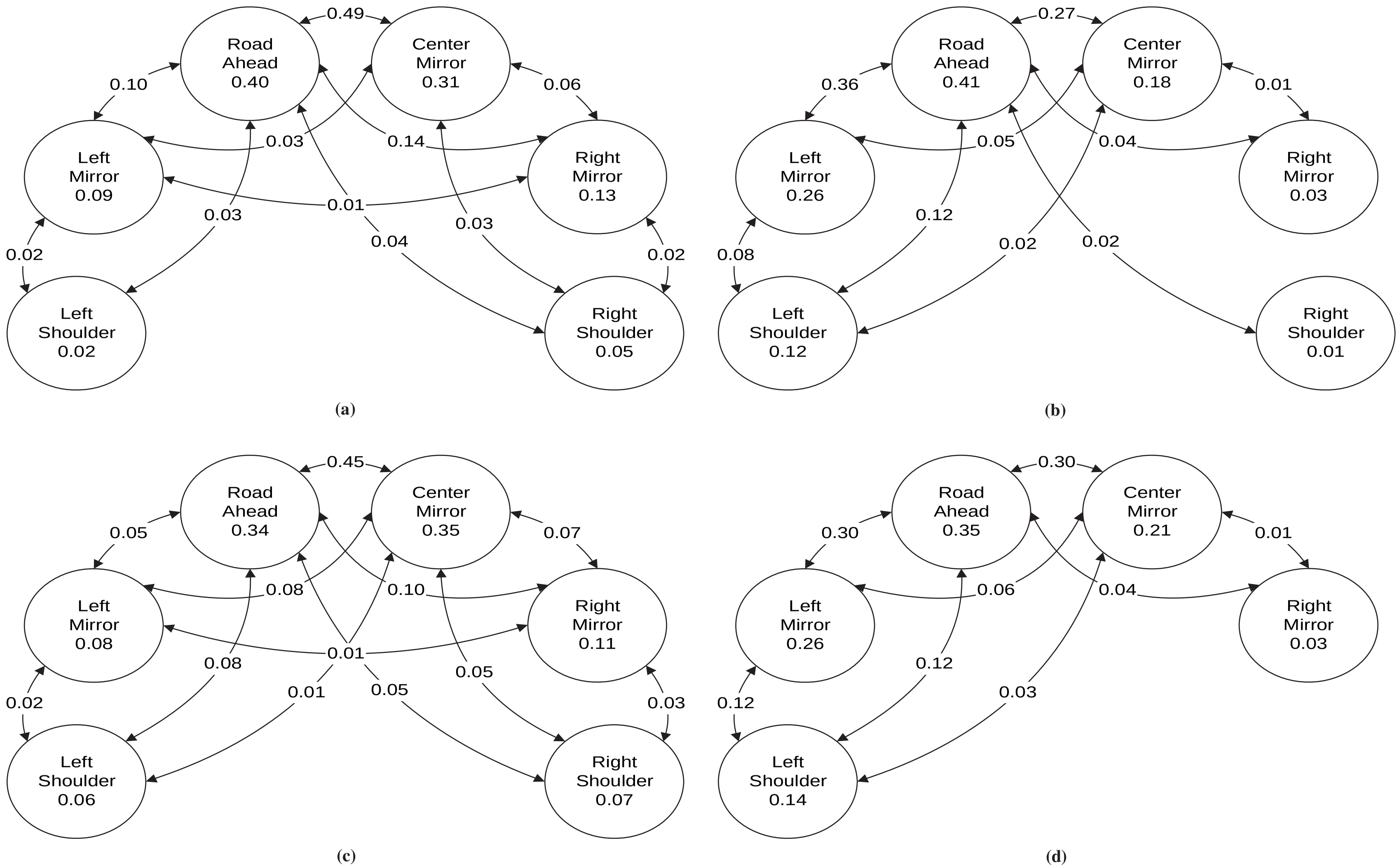

FIGURE 1 Link diagrams for eye glance behavior observed during lane changes on four-lane highways executed in van: (*a*) left to right, 55+ mph; (*b*) right to left, 55+ mph; (*c*) left to right, 25 to 35 mph; and (*d*) right to left, 25 to 35 mph.

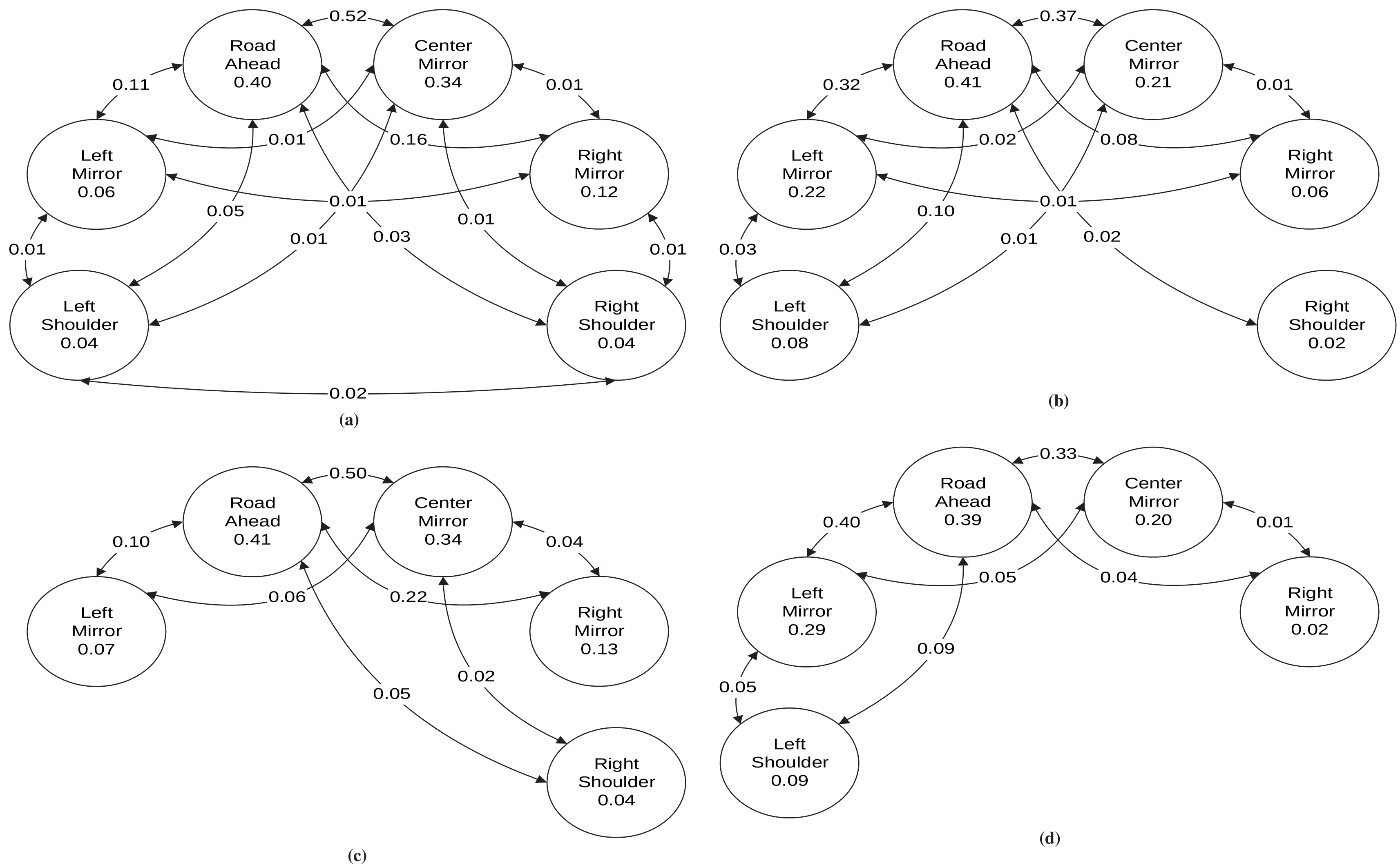

FIGURE 2 Link diagrams for eye glance behavior observed during lane changes on four-lane highways executed in Lumina passenger car: (*a*) left to right, 55+ mph; (*b*) right to left, 55+ mph; (*c*) left to right, 25 to 35 mph; and (*d*) right to left, 25 to 35 mph.

use. When moving to the right, drivers depended most heavily on the center mirror, as shown by the relatively high transition probability between road ahead and center mirror locations and by the relatively high glance probability associated with the center mirror. Relative to a leftward lane change, the link diagrams also indicate that the drivers were substantially less likely to sample the right mirror location and less likely still to make a right shoulder (direct) glance.

A right-to-left lane change (Figure 1*b*) presents a somewhat different picture. Here the glance probability to the center mirror is substantially less than that in the rightward lane change and the left mirror glance probability is appreciably higher than is right mirror use in the rightward lane change. Furthermore, left shoulder (direct) glance probability is over twice that for a right shoulder (direct) glance in the rightward maneuver, perhaps indicative of less trust in the mirror information in this maneuver.

For the link diagrams associated with lane changes in a van executed over 25- to 35-mph roads, the probabilities of glances to the road ahead are somewhat lower than those for the highway data but again differ very little between right-to-left and left-to-right lane changes. More striking is the similarity of the link diagrams across 25- to 35-mph roads and 55+ mph highways. Glance probabilities to mirrors differ very little. Slightly higher glance probabilities over the right shoulder or left shoulder can plausibly be explained by the greater traffic density that was present in the 25- to 35-mph roads (city streets). This explanation may also clarify the reduction in glance probability to the road ahead; that is, there was a relatively greater need to visually sample around the vehicle for objects and events.

Figure 2 contains a similar layout of link diagrams for those lane changes observed in the passenger car. The pattern of results is strikingly similar to that for the van data, with a few exceptions. For example, the difference in glance probability to the road ahead for 25- to 35-mph roads versus 55+ mph highways found in the van data is not present in the passenger car data. Another difference is that the passenger car drivers were somewhat less likely to glance over the left shoulder in a right-to-left lane change than were van drivers (0.08 and 0.12, respectively, for 55+ mph highway maneuvers, 0.09 and 0.14, respectively, for 25- to 35-mph road maneuvers). These differences may be due to the relatively greater visibility (or impression of visibility) afforded by the passenger car as opposed to the van or perhaps by the greater familiarity of drivers with passenger cars as opposed to vans. Beyond these exceptions, however, the overall pattern of driver eye scan patterns during the 10 s before lane change start did not substantially differ between van drivers and passenger car drivers for the test participants and vehicles used in this study.

Glances to Different Locations and Lane Changes with at Least One Glance to Given Location

Existing analysis of the lane change crash problem suggests that driver unawareness of the lane change crash hazard is the principal causal or contributing factor. What distinguishes an uneventful lane change from a crash, then, is the inopportune presence of a principal other vehicle when the single-vehicle driver is not aware of or expecting it. This, in turn, suggests that naturalistic driving studies [e.g., that by Olsen (*9*)] will be useful to characterize driver behavior and lane change performance with which lane change warning system must be compatible. Such studies are best conducted in on-the-road observational studies with instrumented vehicles or nonobtrusive methods such as video surveillance (e.g., to examine turn signal use) or more sophisticated systems such as the System for Assessing the Vehicle Motion Environment (SAVME), which can record the trajectories of vehicles as they pass through the sensor field of view. Laboratory or simulator studies are less applicable for such work.

Table 1 presents one set of findings from the study. It should be noted that for both van and passenger car data, the percentage of lane changes in which side and center mirrors were used differs for leftward versus rightward lane changes. The left side mirror is used much more in leftward lane changes (between 65% and 85% in the study) than is the right mirror in rightward lane changes (between 36% and 52%), regardless of vehicle type. In contrast, the center mirror is used relatively more in rightward lane changes (between 82% and 92%) than in leftward lane changes (between 56% and 67%). This finding suggests that if visual displays for lane change warning systems are to be compatible with driver eye-scanning behavior before a lane change, both center and side mirror locations should be considered. It is notable that the percentages of lane changes accompanied by at least one glance to either the center or appropriate side mirrors range from over 97% to approximately 84%. Also notable is that glances to the road ahead were virtually omnipresent, suggesting that a forward-positioned visual display (e.g., a head-up display), appropriately designed for spatial compatibility, would be worth investigation. A better understanding of the differences between van and passenger car applications and the highway (55+ mph posted travel speeds) and city streets (25- to 35-mph posted travel speeds) awaits further research.

Table 2 presents another view of the driver eye glance behavior 10 s before lane change start. "Check" is used to signify the percentage of the *N* lane changes made in a given vehicle to a given direction with either at least one center mirror or one appropriate side mirror glance (or both). The term "FullCheck" signifies the percentage of *N* lane changes made with at least one glance to the center mirror or appropriate side mirror or a head turn in that direction (or some combination of these). The following salient points can be made. On highways (i.e., 55+ mph roadways), van driving was associated with a higher percentage of checks and full checks as compared with passenger car driving. On 25- to 35-mph roads, this trend was less consistent. The percentage of checks or full checks to the left was higher than that to the right for van driving, whereas the reverse was true for passenger car driving. The reasons for this finding are unknown. Finally, although the percentage of lane changes with checks or full checks approached 98% in some conditions, mirror checks or head turns were not universally made during the 10 s before lane change start. Presumably, lane changes made without checking at all were done on the basis of information acquired earlier and the expectation that the situation had not changed significantly.

The interpretation of the measures under discussion must be carefully made. The fact that the road ahead is virtually always sampled at least once does not necessarily support the conclusion that dashboard-mounted or head-up-mounted lane change warning displays are appropriate from a human factors standpoint. The finding must be tempered by the need to manage driver workload in the direction of the forward view, by the need to promote stimulus-response compatibility, and by the need to minimize driver nuisance effects. However, the finding does suggest that center mirror displays, especially if they can be perceived within the driver's road ahead glance, may be one component of an effective lane change warning placement strategy.

DISCUSSION OF RESULTS

The findings reported in this study provide previously unpublished data on driver eye glance behavior during the decision phase of a lane change maneuver. The results complement more recent research and

TABLE 1 Eye Glance Percentages for Discretionary Lane Changes 10 s Before Lane-Change Start

	Lane Changes from Right to Left		Lane Changes from Left to Right	
Van data				
	$N = 130$		$N = 75$	
Lane changes for 4-lane 55+ mph	Left shoulder	56.2%	Left shoulder	14.7%
	Left mirror	80.8%	Left mirror	38.7%
	Road ahead	96.9%	Road ahead	100.0%
	Center mirror	65.4%	Center mirror	92.0%
	Right mirror	13.1%	Right mirror	48.0%
	Right shoulder	6.2%	Right shoulder	21.3%
	Left or center mirrors[a]	97.7%	Right or center mirrors[a]	97.3%
	$N = 54$		$N = 31$	
Lane changes for 4-lane 25–35 mph	Left shoulder	63.0%	Left shoulder	22.6%
	Left mirror	85.2%	Left mirror	41.9%
	Road ahead	98.1%	Road ahead	100.0%
	Center mirror	66.7%	Center mirror	83.9%
	Right mirror	13.0%	Right mirror	38.7%
	Right shoulder	3.7%	Right shoulder	25.8%
	Left or center mirrors	96.3%	Right or center mirrors	83.9%
Passenger car data				
	$N = 105$		$N = 78$	
Lane changes for 4-lane 55+ mph	Left shoulder	28.6%	Left shoulder	17.9%
	Left mirror	64.8%	Left mirror	28.2%
	Road ahead	95.2%	Road ahead	96.2%
	Center mirror	56.2%	Center mirror	82.1%
	Right mirror	19.0%	Right mirror	35.9%
	Right shoulder	5.7%	Right shoulder	12.8%
	Left or center mirrors	86.7%	Right or center mirrors	88.5%
	$N = 51$		$N = 25$	
Lane changes for 4-lane 25–35 mph	Left shoulder	25.5%	Left shoulder	4.0%
	Left mirror	80.4%	Left mirror	28.0%
	Road ahead	100.0%	Road ahead	100.0%
	Center mirror	56.9%	Center mirror	92.0%
	Right mirror	7.8%	Right mirror	52.0%
	Right shoulder	2.0%	Right shoulder	20.0%
	Left or center mirrors	90.2%	Right or center mirrors	96.0%

Percentages in the table refer to the percentage of *N* lane changes in each condition with at least one glance in the direction indicated. *N* refers to the total number of lane changes observed in that condition.
[a]"Left or center mirrors" refers to the percentage of *N* lane changes with at least one glance to the left mirror or center mirror (or both). A similar interpretation applies to "Right or center mirrors" entries.

TABLE 2 Lane Changes with Glance to Center or Appropriate Side Mirror and Lane Changes with Glance to Mirror or Head Turn, by Road Type and Lane Change Direction

	Van Data				Passenger Car Data			
Road Type	Leftward Lane Change[a]		Rightward Lane Change[b]		Leftward Lane Change		Rightward Lane Change	
Lane changes for 4-lane 55+ mph roads	Check:	97.69%	Check:	97.33%	Check:	86.67%	Check:	88.46%
	FullCheck:	97.69%	FullCheck:	97.33%	FullCheck:	88.57%	FullCheck:	89.74%
		$N = 130$		$N = 75$		$N = 105$		$N = 78$
Lane changes for 4-lane 25–35 mph roads	Check:	96.30%	Check:	83.87%	Check:	90.20%	Check:	96.00%
	FullCheck:	96.30%	FullCheck:	87.10%	FullCheck:	90.20%	FullCheck:	96.00%
		$N = 54$		$N = 31$		$N = 51$		$N = 25$

In each cell, *N* indicates the total number of lane changes made in that condition. Percentages given in the table are with respect to that *N*.
[a]For leftward lane changes, "Check" signifies the percentage of *N* lane changes made with at least one glance to the center mirror or left side mirror (or both). "FullCheck" for leftward lane changes signifies the percentage of *N* lane changes made with at least one glance to the center mirror or left side mirror or leftward head turn (or some combination of these).
[b]For rightward lane changes, "Check" signifies the percentage of *N* lane changes made with at least one glance to the center mirror or right side mirror (or both). "FullCheck" for rightward lane changes signifies the percentage of *N* lane changes made with at least one glance to the center mirror or right side mirror or rightward head turn (or some combination of these).

indicate similar outcomes. The link analysis results are more or less consistent with those reported by other researchers. This similarity provides a degree of validation between findings collected approximately a decade apart with a different sample of test participants and with different test methodology. There appear to be differences in the eye glance behavior of van and passenger car drivers sufficient to consider them separately in further studies of lane change warning systems. The impacts of road type are also noticeable, suggesting that varied driving conditions should be made a part of future on-road studies of lane change warning systems.

The findings of this study are relevant to the design of lane change collision avoidance systems and the evaluation of such systems (*15, 16*). These results are consistent with findings from more recent work conducted in a naturalistic setting (*10, 12*). With such data, visual displays may be placed in locations compatible with normal eye glance behavior during the lane change decision phase. This placement would increase the likelihood that such displays will be noticed by the driver. Blind spot or lane change warning systems are either already on or are coming onto the market that make use of visual displays in the side mirrors. The results of this study suggest that center mirror displays also deserve consideration for such applications.

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