SECTION 4. DISCUSSION

INTRODUCTION

The objectives of the experiment were to determine whether: (1) driving behavior is affected when the driver has access to a SSGCS and to a CWS, (2) driving performance is affected by reductions in visibility, and (3) driving performance is affected by variations in traffic density. Driving-performance data were obtained from 52 drivers: 32 drove with both the SSGCS and CWS, and 20 were controls. The analyses of the data focused on the following experimental questions:

- *Does driving performance change with the use of the SSGCS and CWS?*
- *Is driving performance affected by the age of the driver?*
- *Does driving performance change when the visibility level is reduced?*
- *Does driving performance vary with traffic density?*

There were three operational modes for the intelligent vehicle systems. Each individual participant decided if, when, and for how long each of these modes would be used. Data were collected throughout the 35-min journey, and partitioned according to the choices the driver made about system use. Then, the data analysis focused on the following:

- Driving-performance data that were collected while the driver was using the SSGCS.
- Driving-performance data that were collected while the driver was using the CWS only (i.e., data that were obtained when the CWS was activated and the SSGCS was disengaged).
- Driving-performance data that were collected when both the SSGCS and the CWS were disengaged, but were obtained after the driver had activated the SSGCS at least once.

The analysis was divided into six sections, as is this discussion.

CROSS-EXPERIMENTAL COMPARISON OF THE PERFORMANCE OF CONTROL-GROUP DRIVERS

The driving performance of the drivers in the control group in the current experiment was compared with the driving performance of drivers in the control group in the previous study in this series by Bloomfield, Levitan, Grant, Brown, and Hankey.[8] The performance of the controls in the two experiments was directly compared using 95-percent confidence intervals and the following five driving measures: (a) steering instability, (b) the number of steering oscillations/min, (c) average velocity, (d) velocity instability, and (e) the number velocity fluctuations/min. With each driving measure, there was a large overlap in the confidence intervals for the two sets of data—a result consistent with the view that the driving performance of the control-group drivers in the previous experiment and in the current experiment was essentially the same.

DRIVING WHILE USING THE SSGCS

The performance of drivers who were using the SSGCS was compared with that of the control-group drivers. When the SSGCS was activated, it controlled the steering, the speed of the driver's car, and the distance between the driver's car and the vehicle ahead; the drivers selected the speed of the simulator car and the gap between it and the vehicle directly ahead. Because of this, only the following limited set of comparisons could be made.

Average Velocity. When the average velocity of drivers in the control group was compared with that of drivers in the experimental group while the SSGCS was activated, it was found that using the SSGCS had no effect on the average velocity.

Minimum Following Distance vs. Minimum Gap Setting. The minimum following distance for drivers in the control group was compared with the minimum gap set by drivers in the experimental group. In the two poorest visibility conditions, with the 200-m (656-ft) and 100-m (328-ft) fog, the minimum following distance was shorter for the control-group drivers than the minimum gap set by the experimental-group drivers. In addition, for younger drivers when the visibility was clear, the minimum following distance was shorter for drivers in the control group than the minimum gap set by drivers in the experimental group. It was only for older drivers, when the visibility was clear, that this result was reversed. In this case, the minimum following distance was longer for drivers in the control group than the minimum gap set by drivers in the experimental group. However, it should be noted that, in this case, the minimum gap set by drivers in the experimental group was still relatively large—2.2 s.

Average Actual Gap. The average actual gap of drivers in the control group was compared with both the average actual gap of drivers in the experimental group and with the average gap set by the latter. When the SSGCS was activated, the average actual gap was longer for drivers in the experimental group (3.2 s) than it was for drivers in the control group (2.8 s).

Conclusions. When the driver was using the SSGCS, there was no noticeable effect on the speed at which the driver traveled; however, the driver's car tended to be further behind the vehicle ahead than it was for the control-group drivers who did not have access to the SSGCS.

DRIVING WHILE USING ONLY THE CWS

Unlike the SSGCS, the CWS did not take control of any driving functions; when it was the only system activated, it issued a warning if the driver approached the vehicle ahead too quickly. Driving-performance data obtained from drivers in the experimental group while they were using the CWS alone and from drivers in the control group were compared using the full range of lane-keeping, speed-control, and following-distance measures.

Lane-Keeping Performance. When the experimental-group drivers were using only the CWS, their steering instability was 0.24 m (0.79 ft)—less than the 0.28-m (0.93-ft) steering instability of the control-group drivers. The experimental-group drivers also had more steering oscillations (18.0/min) than the control-group drivers (11.6/min). The experimental-group drivers reduced their steering instability while increasing the number of steering oscillations. They were steering more precisely than the control-group drivers, making more frequent steering correction movements that were much smaller in amplitude than those made by the control-group drivers.

Average Velocity. When the experimental-group drivers were using only the CWS, their average velocity was 2.54 km/h (1.16 mi/h) greater than the controls when the visibility was clear, 2.81 km/h (1.75 mi/h) greater than the controls when the visibility was 200 m (656 ft), and 4.75 km/h (2.95 mi/h) greater than the controls when the visibility was 100 m (328 ft).

Speed Control. When the experimental-group drivers were using only the CWS, their velocity instability was 2.4 km/h (1.5 mi/h), less than the 4.9 km/h (3.0 mi/h) velocity instability of the control-group drivers. They also had many more velocity fluctuations (13.6/min) than the controls (only 2.9/min). The experimental-group drivers reduced their velocity instability while increasing the number of velocity fluctuations. They were controlling the speed more precisely than the control-group drivers, making more frequent speed corrections of much smaller amplitude than those made by the control-group drivers.

Following Distance. When the minimum following distance and the average actual gap of the experimental-group drivers were compared with the minimum following distance and the average actual gap of the control-group drivers, no evidence was found to indicate that group had any effect on either measure.

Conclusions. When the driver was using the CWS alone, the driver controlled both the speed and the steering more precisely than the control-group drivers. It is worth adding a cautionary note. These improvements in performance may be short-lived; they may have occurred only because at those times that the driver decided to use the CWS alone, he/she was very likely to have been paying much more attention than normal to the task of driving. When using the CWS alone, the speed at which the driver traveled was greater than that of the control group drivers. This effect was particularly noticeable in the 100-m (328-ft) fog. Here, it is worth adding an ameliorative note. This more aggressive driving may have occurred because, in some instances, when the driver was using the CWS alone, he/she was likely to have been driving faster than normal specifically because he/she was testing the CWS, as he/she had been invited to when recruited and when given instructions for this experiment. Use of the CWS alone had no noticeable effect on the following-distance measures.

DRIVING WHEN THE SSGCS AND CWS WERE DISENGAGED

Using the SSGCS or CWS did have an effect on some aspects of driving. Now, the possible effect of having used such systems on the driver's subsequent driving behavior is examined. The driving performance of experimental-group drivers, when both intelligent systems were disengaged but after the SSGCS had been activated at least once, was compared with the driving performance of the control-group drivers. The comparison was conducted using the full range of lane-keeping, speed-control, and following-distance measures.

Lane Keeping. When the first lane-keeping measure was used to compare the performance of the drivers in the experimental group—after the driver had activated the SSGCS at least once, but when both the SSGCS and the CWS were disengaged—with the performance of the control-group drivers, the results were mixed. There was more steering instability for the experimental-group drivers in two combinations of conditions: for older drivers when the visibility was 200 m (656 ft), and for younger drivers when the visibility was 100 m (328 ft). And, there was less steering instability for the experimental-group drivers in the remaining four combinations of conditions: for older drivers when the visibility was clear and when it was 100 m (328 ft), and for younger drivers when the visibility was clear and when it was 200 m (656 ft). In contrast, when the second lane-keeping measure was used to compare the drivers in the experimental group with those in the control group, the experimental-group drivers had more steering oscillations (20.5/min) than the control-group drivers (11.6/min). In this case, the experimental-group drivers increased the number of steering oscillations without changing steering instability. They were making more frequent steering correction movements than the control-group drivers, without changing the steering instability

Average Velocity. The drivers in the experimental group—after the driver had activated the SSGCS at least once, but when both the SSGCS and the CWS were disengaged—had a higher velocity than the drivers in the control group in two cases: with high-density traffic in clear or 100-m (328-ft) visibility. And, the experimental-group drivers had a lower average velocity in four cases: with high-density traffic in 200-m (656-ft) visibility, and with low-density traffic in all three visibility levels.

Speed control. The velocity instability of the experimental-group drivers was 1.9 km/h (1.2 mi/h), less than the 4.9 km/h (3.0 mi/h) velocity instability of the control-group drivers. In addition, the experimental-group drivers had many more velocity fluctuations (13.8/min) than the controls (only 2.9/min). The experimental-group drivers reduced their velocity instability while increasing the number of velocity fluctuations. They were controlling the speed more precisely than the control-group drivers, making more frequent speed corrections of much smaller amplitude than those made by the control-group drivers.

Following Distance. There was no evidence that there was any difference in the minimum following distance of the drivers in the experimental group and in the control group. However, there were differences in the average gap between the two groups. The older drivers in the experimental group had a larger average actual gap than the older drivers in the control group when the visibility was 200 m (656 ft) and 100 m (328 ft), and the younger drivers in the experimental group had a larger average actual gap than the younger drivers in the control group when the visibility was clear. In contrast, older drivers in the experimental group had a smaller average actual gap than older drivers in the control group when the visibility was clear, and younger drivers in the experimental group had a smaller average actual gap than younger drivers in the control group when the visibility was 200 m (656 ft) and 100 m (328 ft).

Conclusion. When the driving performance of the experimental-group drivers—with both intelligent systems disengaged but after the SSGCS had been activated at least once—was compared with the driving performance of the control-group drivers, the results fell into three categories. For three driving-performance measures, steering instability, average velocity, and average actual gap, the results were mixed, with effects in both directions. For one measure, the minimum following distance, there was no noticeable difference in the performance of the drivers in the experimental group and those in the control group. And finally, for the remaining three driving-performance measures, steering oscillations, velocity instability, and the number of velocity fluctuations, there were clear performance differences. The experimental-group drivers had more steering oscillations—they made steering correction movements more frequently than the control-group drivers, but without changing their steering instability. They also reduced their velocity instability while increasing the number of velocity fluctuations. They were controlling the speed of the vehicle more precisely than the control-group drivers, making more frequent speed corrections of much smaller amplitude than those made by the control-group drivers. It should be noted that these changes in driving performance may be short-lived, and may have occurred in this experiment because, as the driver had to decide whether, and when, to use the SSGCS and CWS, he/she may have been paying much more attention than normal to the task of driving.

THE LANE-CHANGING BEHAVIOR OF DRIVERS WITH INTELLIGENT VEHICLE SYSTEMS

As visibility decreased, the average number of lane changes apparently increased for the experimental group while staying approximately constant for the control group. It is to be noted that, when the experimental group had the collision warning system on alone, although both groups reduced their average velocities as visibility decreased, the experimental group's did not decrease as rapidly. Perhaps the two effects are correlated in that the experimental group changed lanes more frequently in the service of maintaining a higher average velocity. It is also to be noted, however, that average velocities were relatively low throughout the experiment: at 10-km (6.2-mi) visibility, average velocities were less than 84 km/h (about 52 mi/h) for both groups; at 100-m (328-ft) visibility, average velocities were about 70 km/h (about 43 mi/h) or less for both groups.

Regarding age, the older drivers maintained a relatively constant average number of lane changes across visibility levels, but the younger drivers apparently increased their average number of lane changes as visibility decreased. It is tempting to conclude that the younger drivers were more aggressive than the older drivers, but the average velocities do not support aggressiveness as a mediator: Both groups decreased their average velocities as visibility decreased, and the decrease was more rapid for the younger drivers. In addition, although the fastest average velocity at any visibility level was for the younger drivers at 10-km (6.2-mi) visibility, it was still less than 87 km/h (54 mi/h), while the posted speed limit was 88.6 km/h (55 mi/h). It is not clear what the explanation is for the interaction between age and visibility level on average number of lane changes.

IMPLICATIONS FOR THE AHS

- The fact that use of the SSGCS, which was essentially an intelligent cruise control system plus a lane-keeping capability, had no obvious effect on average velocity or minimum following distance/gap setting may bode well for the AHS. If this outcome is replicated, it will mean that drivers can get the benefits of such automation (e.g., a less stressful trip, better fuel efficiency, reduced pollutants in the air) without any obvious negative effects (such as higher speeds and shorter gaps).
- While the collision warning system was on alone, on the other hand, lane keeping (as steering instability) and speed maintenance (as velocity instability) were both better for the experimental group than for the control group. Both effects were also seen—"carried over to?"—when both automation systems were disengaged after the SSGCS had been on at least once. Though these appear to be positive effects, they may in fact not be. First, the performance differences may not have had any practical significance: lane keeping is typically adequate for the great majority of drivers (as it was in this experiment), and overall speed was generally quite low, ranging from about 66 km/h (41 mi/h) to 84 km/h (52.2 mi/h). Second, and perhaps more important, it may be that the experimental drivers' better performance was at the expense of situation awareness: Because they were paying more attention to staying in their lane and holding a constant speed, they may have been paying less attention to the more global situation around them regarding potential obstacles and the like. The fact that lane keeping was poorer (steering instability was higher) for both the experimental and control groups in high-density traffic than in low-density traffic lends some support to this notion: In high-density traffic, attending to the more global situation was more important because of the presence of more vehicles, and thus drivers were less able to attend to their lane-keeping behavior. (Of course, this does not explain the incremental effect of having the collision warning system on.) At any rate, the hypothesis that improved driving behavior along some dimensions comes at the expense of poorer performance along other dimensions deserves careful study.

- When the collision warning system was on alone, there was also an interaction between group and visibility level on average velocity: Although both groups reduced their speeds as the visibility decreased, the difference between the groups increased as visibility decreased. At 10-km (6.2-mi) visibility, the experimental group drove an average of 2.5 km/h (1.6 mi/h) faster than the control group, while at 100-m (328-ft) visibility they drove an average of 4.8 km/h (3.0 mi/h) faster. Though the absolute differences are not great, the trend is not a good one. It is as if the driver believed that the warning would compensate for his/her increased (relative) speed, and this seems a potentially dangerous game to play.
- There was an apparent increase in the number of lane changes for the experimental group as the visibility decreased, and this occurred either when the collision warning system (CWS) was on alone or when neither system was on (the data did not differentiate between these possibilities). As has been discussed above, when the experimental group was using the collision warning system, drivers did not reduce their speed as much as did those in the control group when the visibility decreased. Thus, the increase in the number of lane changes may be another reflection of the experimental-group drivers' using the CWS as a basis for driving faster than drivers who did not have the system available.
- Use of the collision warning system led to some driver behavior that merits further investigation before such a system could be recommended for actual use.
- On the questionnaire, drivers indicated they would use either automated system if it were available on their real vehicles, and that neither system would affect their speed or inter-vehicle gap. These attitudes are positive preliminary indications that such automation may be favorably received.