Behavioral Aspects of Automatic Vehicle Guidance

Relationship Between Headway and Driver Comfort

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Automation of road traffic has the potential to greatly improve the performance of traffic systems. The acceptance of automated driving may play an important role in the feasibility of automated vehicle guidance (AVG), comparable to automated highway systems (AHS). Because decreasing headways could mean a large increase in road capacity, a study was conducted concerning the acceptability of short headways in an automated traffic system. In one part of a driving simulation experiment, subjects gave ratings on comfort regarding the headway in an automated lane; in another part of the experiment, subjects were allowed to adjust the headway setpoint to a comfortable level. Subjects also rated the comfort level when driving under manual control in a number of traffic conditions. Results showed that to equal the comfort level that people experience daily in dense traffic on the freeway network in rush hours, the AVG headway should be no less than 0.86 sec. If a comfort level that people experience daily during incident situations (not uncommon in unstable traffic flow) would be acceptable, the AVG headway could be as short as 0.29 sec. The AVG headways as set by the subjects correspond to the values observed in normal traffic (on average 1.1 sec).

Automation of road traffic has the potential to greatly improve the performance of the traffic system. In the not-too-distant future, systems that support or automate parts of the driving task will appear on the market. Eventually, fully automated driving systems on parts of the road network may become possible. Worldwide, a growing effort is dedicated to developing automated vehicle guidance (AVG) systems. In the United States, a precursor system analysis (PSA) on automated highway systems (AHS) was initiated, and the National Automated Highway Systems Consortium (NAHSC) was formed. In Europe the first prototypes of fully automatic vehicles were developed within the framework of PROMETHEUS. The Dutch Ministry of Transport, Public Works, and Water Management has identified AVG as one technology for which research and assessment should be actively supported (*1*).

Based on a survey of candidate configurations for the implementation of AVG, Verwey (*2*) has proposed a number of human factors-related research items. The main issue identified is the man-machine interaction, which involves transferring control between the driver and the automated system, monitoring the driver and preparing the driver to take over manual control, the effect of prolonged automated driving on behavior in nonautomated driving, and the acceptance of automated driving. One aspect determining acceptance—headway—is addressed here.

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With AVG, small headways as well as very accurate lateral vehicle control could be technically feasible. In this way more vehicles can pass over a narrower stretch of road. However, the limits for maximum use of the infrastructure are set not only by technical feasibility, but also by acceptance by the road users. As shorter headways may result in the most dramatic increase in road capacity, this study investigates the acceptability of various headways and distances in automated traffic. One of the questions to be answered is whether comfort decreases with decreasing distance or, alternatively, whether comfort only decreases to a certain minimum, after which comfort increases again. In other words, is there some point at which very short headways might be considered as comfortable as very long headways? A possible reason for such an effect would be the realization that when a collision occurs between vehicles traveling at a following distance near zero, the impact speed between those vehicles will be very low and thus the collision energy will be very low. When comfort is plotted against headway, this effect would result in a U-shaped curve.

Drivers' responses to decreasing vehicle separations during transition into the automated lane were investigated in a driving simulator by Bloomfield et al. (*3*). In this experiment, each subject started as the lead vehicle of a platoon of automated vehicles. The headway to the platoon ahead was fixed at between 2 and 7.5 seconds. After some time a second vehicle entered the automated lane ahead of the simulator vehicle. This second vehicle accelerated until its speed matched the AVG speed, during which period the distance to the simulator vehicle decreased. Subjects were asked to indicate their comfort level by pushing or pulling a lever. The AVG speed, the distance between platoons, and the time at which the second vehicle entered the automated lane were varied. The results showed that subjects generally considered driving in the lead of a platoon with relatively large between-platoon headway (2 to 7.5 seconds) as comfortable. When a vehicle entered the automated lane in front of the subjects, the comfort level tended to become negative (in 71.6 percent of the trials). There was no comparison to comfort levels experienced in normal traffic.

The present study investigated the acceptability of short headways in an automated traffic system and compared these to comfort levels experienced in normal driving. This study focused on the headways within a platoon (for a detailed description see ref. *4*).

Two parts the experiment consisted of complementary methods to assess the relationship between headways and acceptability. In one part, subjects gave a comfort rating about a fixed headway condition in which they were driving; in the other part, subjects were allowed to adjust the headway setpoint.

As smoothness and accuracy of the automated control could have an impact on the confidence people have in an AVG system, and thus the level of comfort, the control algorithm was varied in the experiment. Since the consequences of a collision increase with increasing driving speed, and this might be realized by subjects, the speed factor was also varied.

Before and after each AVG session, subjects drove the simulator under manual control on a stretch of freeway as in normal traffic. The objective of the manual-control session was to get a reference point to which the comfort rating under AVG conditions could be compared. These manual-control sessions also give an indication of the effects of prolonged AVG driving on manual driving behavior. In the manual control sessions, subjects rated the comfort level in a number of traffic conditions. The comfort level in free driving without surrounding vehicles should be considered the optimal level of driving comfort, as it is today. The comfort level in dense traffic as accepted by drivers in current day-to-day traffic could be considered a sufficient level for an AVG system as well. The comfort level as experienced in a conflict situation, which is not uncommon in unstable traffic flow, could set the lower limit for the comfort level that could be accepted in AVG.

METHOD

Experimental Conditions

The experiment consisted of three parts: manually controlled driving, AVG driving with fixed headways, and AVG driving with adjustable headways.

During the manual control sessions traffic conditions were presented in the following order: free driving, driving in dense traffic, a conflict situation, and, finally, driving in dense traffic again. In all conditions, subjective ratings were registered.

In the AVG comfort rating part of the experiment, fixed car-following conditions were offered to the subjects. In this condition, subjects were asked to give a subjective rating concerning the traffic situation on a seven-point scale. The conditions of driving speed [80, 105, and 130 kph (50, 65, and 81 mph)] headway (0.01, 0.05, 0.1, 0.25, 0.5, 1.0, 1.5, and 3.0 seconds), and swiftness of the approach of the platoon in front (slow, swift) were varied.

In the headway adjustment part of the experiment, subjects were free to adjust the headway maintained by the AVG system to a comfortable level. Subjects could move their vehicle closer or farther away from the lead vehicle until it reached a headway they found comfortable. To determine whether subjects considered very short and long headways equally comfortable, it was necessary to have subjects adjust the headway initially, starting both very close and far from the vehicle ahead. This approach also allows the detection of a possible hysteresis in a headway acceptance. The initial position from which the subjects were allowed to adjust the headway was either 0.01 second or 3 seconds. Again in this part of the experiment, the driving speed was varied (80, 105, and 130 kph). To investigate the influence of inaccuracy in headway control that may occur in a realistic AVG system, the variability of the headways was varied on two levels (high, low). Each condition occurred twice in this part of the experiment.

Apparatus

The experiment was carried out in the TNO driving simulator—a fixed-base interactive driving simulator with a mock-up of a passenger car. Computer-generated images were projected on a cylindrical screen with a horizontal visual angle of 120 degrees.

A three-lane freeway was modeled in the simulator. In the right and middle lane, traffic moved under normal manual control. The left lane was a dedicated AVG lane with the following characteristics:

- It had a brown road surface, instead of the dark grey color of normal asphalt.
- Double road markers were located between the AVG lane and the manual-control lanes. These markers had a 9-3 pattern [the lines were 9 m (10 yd) long, while the gap between the lines was 3 m (3.3 yd),]
- The AVG lane was 3 m (3.3 yd) wide, the normal lanes were 3.6 m (4 yd) wide].
- Overhead matrix signs above the AVG lane showed a dedicated lane symbol (diamond shape) with a capital A (automatic) inside.

Figure 1 illustrates the AVG traffic environment when driving at a large headway. In all conditions a speed limit of 100 kph (62 mph) was shown on matrix signs above the manual-control lanes. Within the simulator mock-up, the status of the AVG system was indicated by means of green lamps on the dashboard. A red lamp on the dashboard indicated that something had to be done, either to give a subjective rating or to adjust the headway to a comfortable level.

In the comfort-rating session, subjects gave a rating of the current driving situation by means of a button board. This board was mounted to the right side of the steering wheel at an easy reaching distance from the subject. There were seven buttons: three green ones on the right side, three red ones on the left side, and a half-green/half-red button in the middle. The left side of the scale was marked “very uncomfortable”; the right side of the scale was marked “very comfortable.”

In the headway adjustment sessions, subjects were able to adjust the headway by means of a tumble switch to the right of the driver. Pressing this forward reduced the headway, while pressing it backward increased the headway. Subjects could adjust the headway continuously between 0.01 and 3.0 sec.

When the vehicle was driven in the AVG lane, the system automatically took control (*5*). After moving into the automated lane, the subject saw a complete platoon of cars in the distance. After a few seconds the platoon was slowed until it reached a specific headway

FIGURE 1 AVG driving at a headway of 3 sec.

relative to the simulator vehicle. As soon as a particular condition was completed, the platoon moved away to the manual control lanes and a new platoon moved in front of the simulator vehicle. The procedure of a platoon moving in front of the simulator vehicle until moving away again is referred to as a trial.

Subjects

Of the sixteen subjects who participated in the simulator experiment, nine were male, seven female. Subjects were selected on the basis of the following criteria: between 21 and 45 years old, had been a licensed driver for more than 3 years, and drove more than 10 000 km (6,210 mi) per year. Subjects were paid for their participation.

Procedure

Each subject participated in 2 half-day sessions on separate days; 1 session for comfort ratings and 1 for headway adjustment. Two subjects participated in alternating sessions of 20 min. Before each session, subjects read a written instruction, which was repeated verbally when the subjects were seated in the simulator. The AVG system and the freeway were explained. Subjects were warned that traffic jams and breakdowns of the AVG system might occur. Subjects were told to give a comfort rating with respect to the separation of the preceding vehicles and how this was established.

In the AVG sessions, subjects started in the right lane. They were instructed to speed up in the right lane and steer into the AVG lane, after which the control of the vehicle was automatically taken over by the system. Subjects were allowed to take their hands and feet off the controls because even in breakdown situations the system was always in full control (i.e., subjects could not intervene).

For the manual control sessions, subjects were instructed to stay in the right lane; in dense traffic they were allowed to pass other vehicles in the left lane. Furthermore, subjects were instructed to choose their speed and headway as they would normally do, for example, when driving to work. Subjects were told about the speed limit of 100 kph (62 mph). In the manual control session, drivers started on an empty road; after 5 km (3 mi) of free driving, subjects were prompted to give a subjective rating of the driving condition. Later they encountered slow-moving traffic that speeded up after the subject had joined behind. For the next 5 km subjects drove in dense traffic conditions, after which a subjective rating was asked. At the beginning of the last 5 km, a conflict situation occurred; the preceding vehicle suddenly decelerated at a rate of 6 m/sec^2. Shortly after, subjects gave their ratings and traffic started moving again. Finally, a comfort rating in dense traffic was given again from 5 km on.

In the comfort rating session each subject drove six experimental runs of about 20 min. Each run consisted of all eight headway conditions. The order of the headways was balanced. The speeds were blocked: during a run the speed was kept constant. The order of the speeds was balanced between subjects. A control algorithm determined the rate at which the platoon closed in on the subject before the simulator vehicle was locked into the platoon. This condition was pseudo-randomly attributed in such a way that all conditions occurred once.

To increase the validity of the experiment, in each run a catch trial was added randomly to show subjects that during automatic control the systems could break down. In a catch trial the AVG platoon suddenly came to a halt. After a catch trial, a dummy trial was done to smooth out the effect of this sudden experience. In total, a run consisted of 10 trials.

Subjects were explicitly instructed to consider both the approach and the steady-state following situation in their judgment. The comfort ratings were given after 1 min of steady-state following.

In the headway adjustment session, eight experimental conditions were given in one run. During a run the speed was constant. The order of the speed levels was balanced between subjects. In one-half of the trials, the subject started adjusting the headway from a very close starting point (0.01 sec headway); in the other one-half, the starting point was very far (3 sec headway) from the preceding AVG vehicle. In one-half of the trials, the AVG system controlled the headway very accurately, resulting in a very low headway variability. In the other one-half of the trials, the accuracy was low, with a corresponding high variability of the headway. The order of the starting position and the order of the headway variability were balanced. Also in these runs, catch trials were added, followed by a dummy trial.

Experimental runs were preceded by a full practice run of 20 min.

RESULTS

Comfort Ratings

An analysis of variance (ANOVA) was performed on the Z-transformed comfort ratings in AVG with approach (swift, slow), speed [80, 105, and 130 kph (50, 65, 81 mph)] and headway (0.01, 0.05, 0.1, 0.25, 0.5, 1.0, 1.5, and 3.0 sec) as main factors. Only the factor headway showed a main effect [$F(7,105) = 65.8$, $p < 0.001$]. The effects of speed and approach were not significant (respectively [$F(2,30) = 3.01$, n.s.] and [$F(1,15) = 1.71$, n.s]). As Bloomfield et al. (*3*) reported a difference in driver response between males and females, the comfort rating (without Z-transformation) was analyzed with the gender factor. Gender was not significant and did not interact with any other factor.

Figure 2 shows the Z-transformation of the comfort ratings as a function of the headway for all three speeds. The relationship between headway and comfort rating shows no sign of a tendency toward increased comfort at very short headways. This indicates that the hypothesis of people accepting very short headways as still comfortable (e.g., due to low impact) does not apply for the current AVG configuration. Although subjects were explicitly instructed to consider both the approach and the steady-state following situation in their judgment, the comfort rating given after one minute of steady-state following showed no effect on the swiftness of the approach.

An ANOVA was performed on the comfort rating in manually controlled traffic (Z-transformation with the parameters of the AVG ratings) with run order (before the first AVG session, after the first AVG session, before the second AVG session, and after the second AVG session) and traffic situation (free driving, dense traffic, conflict situation, and dense traffic after the conflict situation) as factors. A main effect of the traffic situation was found [$F(3,45) = 26.2$, $p < 0.001$]. No main effect of run order was found [$F(3,45) = 0.34$, n.s.]. Figure 3 gives the average comfort ratings for the four traffic situations.

Figure 4 presents the average comfort levels as a function of headway as found in AVG. The horizontal lines indicate the comfort ratings in the manual control sessions. The points of intersection between the comfort levels in manually controlled traffic and the AVG comfort curve were determined. The comfort rating of manual control driving in dense traffic corresponds to a headway of

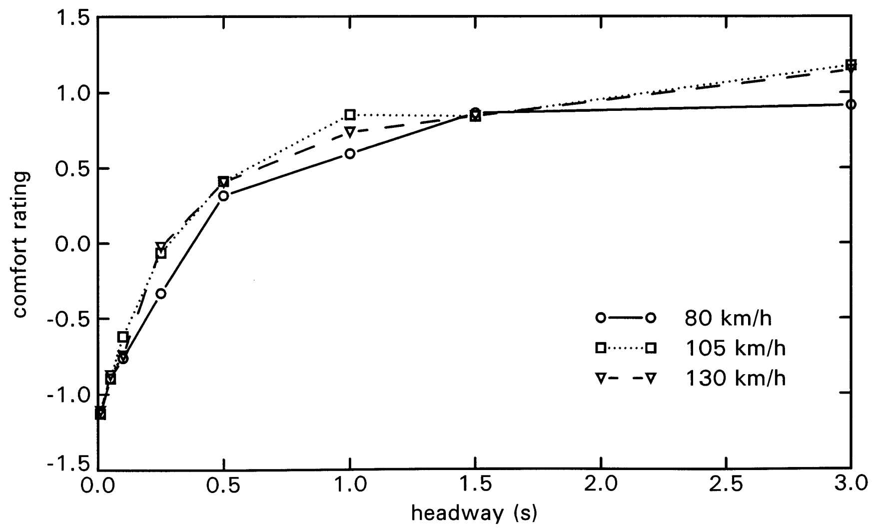

FIGURE 2 Comfort rating (Z-transform) as a function of the time headway for three speed levels—80, 105, 130 kph (50, 65, and 81 mph).

0.86 seconds in automated traffic, while the comfort rating just after the conflict situation in manually controlled traffic corresponds to a headway of 0.29 sec in the automated mode. For large headways the comfort rating in AVG seems to asymptomatically approach the comfort level of free driving in manually controlled traffic.

Preferred Headways

The headway setpoints resulting from the headway adjustment sessions (preferred headway) were analyzed in an ANOVA with speed factors [80, 105, and 130 kph (50, 65, and 81 mph)], initial position (close, distant), and variability (low, high). A main effect of the initial position was found [$F(1,15) = 19.4$, $p < 0.001$]. Furthermore, there was a tendency toward longer preferred headways in the high variability condition [$F(1,15) = 3.41$, $p < 0.1$] Speed had no effect on the preferred headway [$F(2,30) = 0.963$, n.s.]. In a separate analysis the gender factor (male, female) was taken into account. Neither a main effect of gender was found, nor any significant interactions with other factors.

Figure 5 shows the difference in preferred headway for the two initial positions and for both high and low headway variability. Starting at a very short headway, subjects choose an average comfortable headway of 0.70 sec, whereas when starting at a long headway subjects only closed in on the preceding vehicle to a headway of 1.46 sec; there is clearly a hysteresis in the preferred headway. On average a headway of 1.1 sec was adopted.

Figure 6 shows the preferred headway as a function of speed. This confirms that subjects do have a notion of time-headway (instead of just distance) to control a comfortable situation. When the headway is transformed into a following distance, an ANOVA confirms significant effect of driving speed [$F(2,30) = 18.6$, $p < 0.001$].

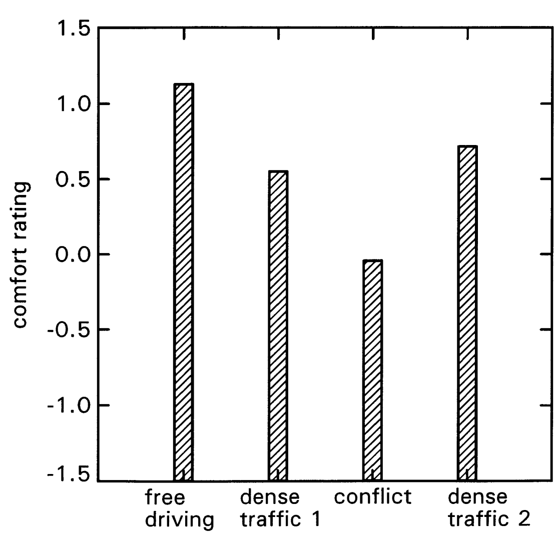

FIGURE 3 Comfort ratings during manual control driving.

Free Driving Speed

To get a first impression of whether prolonged AVG driving affects normal manual driving, the speed choice in the free-driving situation of the manual control sessions was analyzed taking into account the run order factor (before the first AVG session, after the first AVG session, before the second AVG session, and after the second AVG session). This showed an increase of driving speed after the AVG sessions [$F(3,45) = 5.38$, $p < 0.01$], as illustrated in Figure 7.

CONCLUSIONS

On the basis of the results of the present study, recommendations can be derived for the design headway of a comfortable AVG system. In order to equal the comfort level in dense traffic as experienced daily on the freeway network in rush hours, the AVG

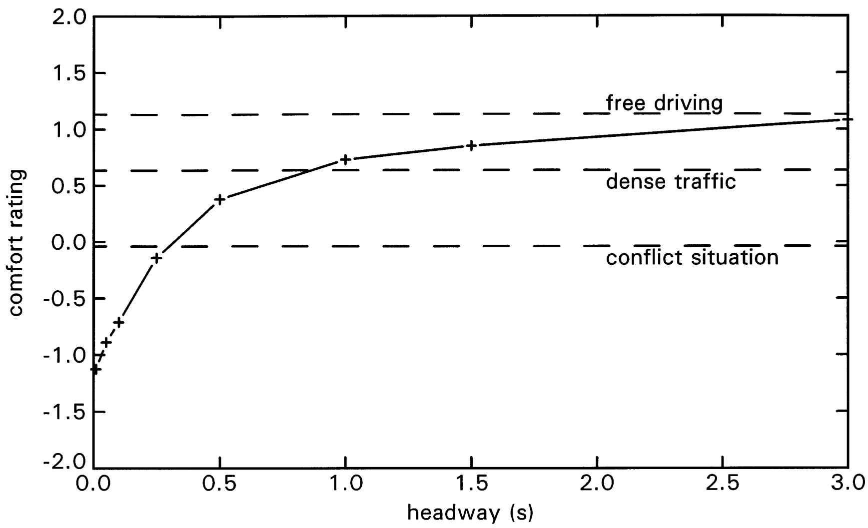

FIGURE 4 Comfort ratings in both automated traffic and in manual control driving.

headway should be no less than 0.86 sec. If it is accepted that the comfort level that occurs in incident situations would already suffice, the AVG headway could be 0.29 sec. For the final acceptance, other factors may also play a role, i.e., costs of an AVG system, whether there are other compensating comfort aspects such as being able to work or to relax during an AVG journey, reduced travel times, or how long a certain condition is maintained (a relatively low comfort level may be acceptable at bottlenecks in the road network). Furthermore, the discomfort as experienced at short headways may decrease after some time when people get used to the situation.

The results of this study should mainly be seen as preliminary. In the experimental setting, subjects are asked to be consciously aware of comfort; in a natural setting they would not. On the other hand, the threat in real traffic will be higher than in the protected setting of a driving simulator. This study, however, shows that when an AVG system is designed, aiming at a considerable increase of road capacity through short headways, the aspect of driver comfort should be carefully taken into account.

Driver comfort at very short headways did not increase in this experiment (a U-shape of the comfort-versus-headway curve). When the hypothesis that at short headways the chance of a collision is high but the collision energy is low is reconsidered, it might be possible that, given a normal vehicle, even a collision with low-impact speed is undesirable, i.e., it results in a bump and light damage to the vehicle. For this reason a different result may be found if the short distance is realized by means of a mechanical coupling or when a collision buffer is mounted at the front of the vehicle.

The results of the headway adjustment trials seem to correspond to the values observed in normal traffic. Starting at a very short headway the average comfortable headway was 0.70 sec, while when starting at a long headway, the preferred headway was 1.46 sec. On average, a headway of 1.1 sec was adopted. In an overview given by van der Horst (*6*), a wide range of average headways is

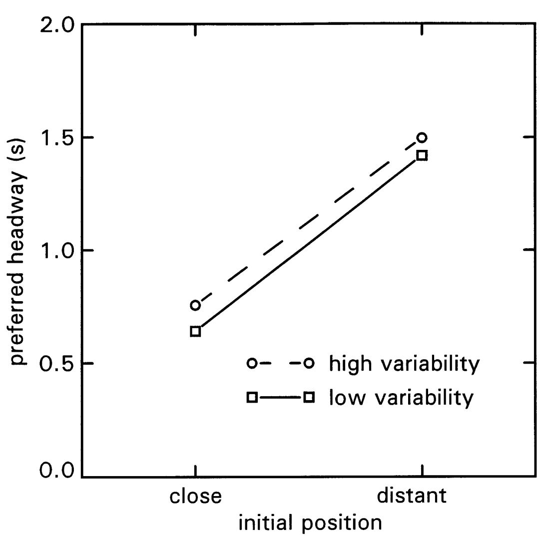

FIGURE 5 Preferred headway for close and distant initial position and at high and low headway variability.

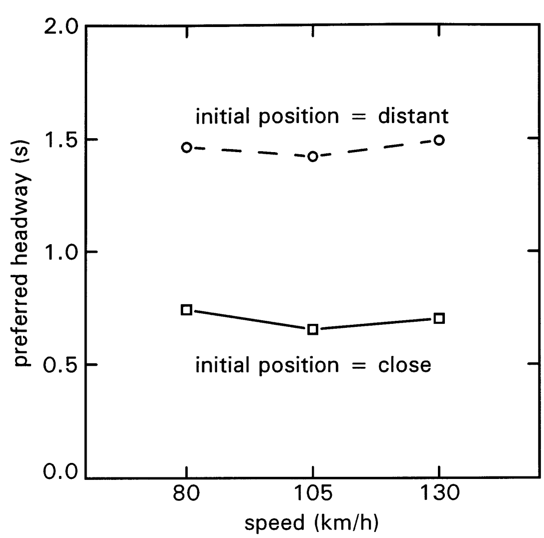

FIGURE 6 Preferred headway as a function of driving speed for both a distant initial position and a close initial position.

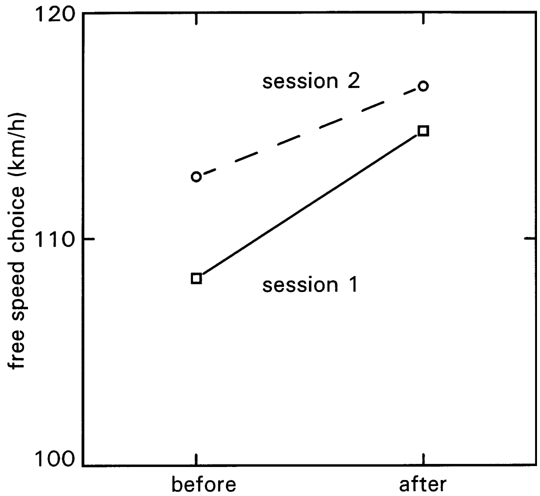

FIGURE 7 Free driving speed choice in the manual control sessions before and after the first and the second AVG session.

reported: when close following was encouraged (subject driving an instrumented vehicle), an average headway as low as 0.46 sec was found, while spot observations on a freeway showed average headways in the right lane of 2 sec. In an experiment in which an instrumented vehicle moved closely in front of another vehicle, the headway of the following vehicle was restored to only 0.81 sec, while the headway was 1.41 sec on average before the vehicle cut in front (*7*). The results in the latter experiment are quite similar to the results of the two initial position conditions in the AVG experiment.

Whether the increased free driving speed at the end of the experimental sessions was influenced simply by driving a simulator for some time or whether this effect was caused by driving in automated traffic cannot be determined from the present experiment, as no control group drove during the same period in manually controlled traffic. Although the average speed in the automated sessions was 105 kph (65 mph) the experience of driving 130 kph (81 mph) in one out of three runs may inspire subjects to adopt a higher speed afterward in the manual control runs. The effect of prolonged AVG driving on the choice of speed and headway in subsequent manual control driving should be investigated in a separate experiment.

In addition to the results of Bloomfield et al. (*3*) on driver response to between-platoon headways (2 to 7.5 sec), this study gave the comfort levels of within-platoon headways (0.01 to 3 sec). The approach of the present study not only allowed a comparison of different AVG situations, it also provided a comparison to driving under manual control in normal traffic. Contrary to the results reported by Bloomfield et al., no effect of gender was found in the present study.

ACKNOWLEDGMENT

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