EFFECTS OF CARBON MONOXIDE INTOXICATION ON DRIVING TASKS

Thomas H. Rockwell, The Ohio State University; and
Francis W. Weir*, General Motors Corporation

Although a great deal is known about the human physiological response to acute carbon monoxide poisoning, considerable controversy exists over the possible psychophysical and behavioral response to carbon monoxide exposures that produce carboxyhemoglobin (COHb) levels less than 20 percent. Because a variety of carbon monoxide exposure conditions can produce equivalent COHb levels, the major emphasis of this study is the effects of specific COHb levels. This study was designed to investigate the possible effects of CO on driving-related performance. The scope of the investigation included, first, laboratory and field measurements of COHb in human subjects. Next, the relation of the various levels of COHb to physiological performance, simple and complex psychomotor skills, and driving performance was studied. The complex laboratory tasks related to driving included pursuit tracking, choice reaction time, and dual tasks (wherein both pursuit tracking and choice reaction time tests were performed simultaneously). The driving performance studies investigated vehicle dynamics such as velocity and spacing during car following; operator control movements such as steering wheel, gas pedal, and brake pedal applications; and perceptual measures, such as driver's visual search and scan patterns measured with the Ohio State University eye-movement camera technique. This paper is limited to results of the road studies only.

•THE FIRST-YEAR EFFORT was designed to screen those factors and tasks that are affected by a 20 percent COHb level. Those tests that demonstrated changes at 20 percent COHb were incorporated into the second-year efforts with COHb levels of nominally 7 and 14 percent. The effects of 7 and 14 percent COHb levels on driving are the focus of this paper. To accomplish the research required that a method be developed to produce desired COHb levels in the subjects. Support personnel were trained to monitor carbon monoxide in air and blood in order to standardize methods. One important goal was maintenance of COHb levels outside the laboratory during test sessions.

Subject safety was of utmost concern. Initially, only the subjects were unaware of the carbon monoxide exposure conditions. Later, when lower COHb levels were possible, experimenter biases were eliminated by having only the medical monitor and the research chemist aware of CO concentrations in the testing.

The overall experimental design strategy for the research allowed the subjects to serve as their own controls. This required that there be no transfer effects across COHb levels and test periods. It further required that there be small differential subject effects by COHb treatment. Tests were counterbalanced to guard against biases due to learning or fatigue.

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*Mr. Weir was with The Ohio State University when this research was conducted.

EFFECTS OF CARBON MONOXIDE ON HUMANS

Several investigations have indicated that the central nervous system is impaired at COHb levels as low as 3 to 5 percent (3, 18, 21, 31). Other investigators have not confirmed these findings (24, 32). Readers interested in the toxicological basis of CO uptake and the physiological response to CO intoxication are referred to the 1970 HEW report on air quality criteria for CO and to Coburn (12).

It is now widely accepted (5, 25) that COHb competes with oxyhemoglobin (O_2Hb) at the cellular level, creating symptoms associated with anemic hypoxia. Consequently, it is not surprising that some of the behavioral effects that have been observed with CO intoxication are similar to those manifested by those exposed to reduced partial pressures of atmospheric oxygen sufficient to produce hypoxia.

Research indicates that human vision is one of the first systems to be affected in hypoxic conditions, including CO intoxication. While summarizing earlier experiments, Halperin and coworkers (16) reported an increase in visual threshold at COHb concentrations as low as 4 to 5 percent. Lilienthal and Fugitt (20) observed that subjects exposed simultaneously to CO and a reduced oxygen environment exhibited decreased critical flicker fusion frequencies, i.e., the frequency at which a flickering light appeared to be a steady glow. More recently, Hosko (17) detected differences in the visual evoked response (VER) of subjects whose COHb levels were approximately 22 percent. At lower COHb levels, no differential VER effects have been detected. The author suggested that the changes observed in the VER represented the direct cortical response to activity in the scotopic (rod) visual system.

Stewart et al. (32) used a battery of psychomotor tests to study several groups of subjects intoxicated to 31.8 percent COHb. At lower levels of CO intoxication, no significant differences in performance were apparent between control and CO conditions.

This research suggested that performance deterioration at low levels of COHb increased as the extent of use of higher mental processes and the visual system in the task increases. It is suggested that the mental processes responsible for psychomotor performance are affected by CO but that simple tasks such as those often studied are not sufficiently sensitive to the subtle effects of low-level CO intoxication to show significant deterioration in task performance.

Effects on Driving

Ramsey (27) investigated the effects of inhaled traffic exhaust on the performance of a simple reaction time task. Subjects drove in rush-hour traffic for 90 minutes in an average CO atmosphere of 38.1 ppm. Reaction time of the exposed group was compared with that of a control group that did not participate in the driving task, and driving performance before and after exposure was compared. Results indicated that the reaction time of the exposed group was significantly higher than that of the control group.

Rockwell and Ray (28) studied the effects of 20 percent COHb intoxication on three drivers in normal city traffic. Several aspects of driving were affected by CO inhalation. The mean driving responses were not generally affected, but the variance of many of the performance measures increased significantly, indicating that their driving performance was more erratic than that of the control group.

It is suggested that under loaded conditions, when the operator must time-share between different independent tasks, CO reduces the operator's ability to perform several tasks simultaneously. In effect, CO intoxication reduces the "channel capacity" of the operator's information processing system. This reduced capacity, not evident in simple tasks, should be manifested in the time-sharing situation by decreased performance either on particular tasks or a combination of time-shared tasks. These ideas were supported by Safford (30) and by Attwood (2), who used laboratory dual-task studies and road studies with subjects at 20 percent COHb.

Allen (1) hypothesized that CO acts in part to destroy visual acuity, visual motor coordination, and perceptual alertness. He pointed out that any compensable visual irregularity becomes progressively less compensable under the influence of CO. This idea lends itself to the concept of spare visual capacity. Allen also suggested that persons with measurable levels of COHb are more asthenopic and have more binocular and accommodative problems than persons not exposed to CO. This suggests that fixation times for persons exposed to carbon monoxide might be increased.

Eye Movements and Driving

Lack of available information on normal driver vision is partially due to lack of equipment and techniques to measure the visual behavior of persons in other than fixed laboratories. One exception to this is the eye-movement camera developed by the Systems Research Group (29). The device enables accurate determination of the eye-movement behavior of the driver and provides information on the driver's visual sampling behavior. The eye-movement equipment is quite adaptable and can be used under many driving conditions. Several studies have been conducted with this apparatus; some of the studies are described below.

In a study to determine the effects of low alcohol concentrations on driver eye movements, Belt (4) found a significant increase in the amount of time drivers spent fixating in a 3- by 3-deg area of the driving scene (measured in subtended visual angle). This indicated a "spatial narrowing," which Belt hypothesized was due to blurring or blunting of the peripheral stimuli forcing the driver to use only central vision. Belt also observed that, under 0.08 percent BAL, drivers were able to maintain "good lateral control" of their vehicles but exhibited narrowed compensatory eye fixation patterns; however, when subjects reverted to the eye-movement pattern typical of the normal driver, lateral control performance was degraded. Belt found no differences in "temporal" measures of eye movements that could be related to alcohol concentrations.

Mourant (23) found that novices driving at 70 mph exhibited frequent pursuit eye movements similar to those of the experienced subjects tested by Kaluger and Smith (19) after 12 hours of driving and sleep deprivation on the night before the test. The experienced drivers tested by Mourant, however, did not make any pursuit eye movements. Novice drivers also made fewer horizontal and vertical eye movements than experienced drivers did.

Secondary Task Techniques and Driving

Considerable research has been conducted recently by using secondary task techniques to evaluate the effects of drugs and alcohol on human performance. Moskowitz suggested that deterioration of performance on secondary (or dual) tasks might be a sensitive method, i.e., when subjects performed two simultaneous tasks or time-shared between primary and secondary tasks. Because most driving in traffic involves secondary tasks, this approach to measuring effects of CO on human performance seems to offer considerable potential.

One successful application of a secondary task procedure in a simulated driving condition was reported. Subjects operating a driving simulator were required to respond to colored lights presented adjacent to the driver's central line of sight. The secondary task was sensitive to performance deterioration at low levels of alcohol intoxication.

Different types of secondary tasks have been used several times to measure aspects of driving performance. Brown and various coworkers (6, 7, 8, 9) suggested that the driver can be thought of as a communications channel with a greater capacity for dealing with information than is usually required. Brown also stated that, unless a way to measure the driver's spare capacity is developed, any investigation is unlikely to differentiate between "concentrated effort and relaxed, over-learned skill" (6).

It was the hypothesis of this research that human information processing ability is reduced by elevated COHb levels. The reduction was assumed to be minute because only when the driver is faced with processing demands that tax the system near its capacity is the effect of low COHb levels apparent.

CARBON MONOXIDE: ADMINISTRATION, CONTROL, AND MEASUREMENT

Carbon monoxide was administered to subjects by two methods. All subjects were first exposed to air or CO in a dynamic flow chamber for 1.5 to 2.0 hours to produce the desired COHb level. During certain experiments, subjects remained in the chamber and continued to receive CO at a concentration sufficient to maintain the desired COHb level. For experiments involving driving and for certain laboratory experiments, subjects were periodically "refreshed" with CO from a pressure cylinder to maintain the desired COHb level.

Several safety devices were incorporated into the exposure facility to ensure subject safety. A high-limit pressure transducer was installed in the CO delivery system to monitor the absolute flow of CO from the storage cylinder to the chamber intake system. A second pressure transducer was installed in the chamber influent duct to measure the differential pressure between the duct and the laboratory. This differential pressure was directly related to the chamber air flow rate.

Carboxyhemoglobin Refreshing Technique

Subjects were administered either air or a mixture of air and CO (1,000 ppm) by mask through a demand regulator from a pressure cylinder. The quantity of gas administered was measured by passing all expired air through a Parkinson-Cowan dry gas meter.

Subjects were "refreshed" at intervals of 30 to 45 minutes to maintain specified COHb levels. Calculations for quantity of gas to be administered were based on the interval since last administration based on the Coburn formula (11). Figure 1 shows the experimental sequence.

Carboxyhemoglobin Analyses

Blood from all subjects was routinely taken for chemical analyses of COHb. For most samples, capillary blood from a pricked finger was collected in heparinized microhematocrit tubes. Approximately 0.04 ml of blood was adequate for each analysis. Blood from the cephalic vein was withdrawn from selected subjects for comparison of venous and capillary samples.

The spectrophotometric method of Commins and Lawther (14) was evaluated for COHb determination. For this study, the method was modified as follows:

1. A self-calibration method was used, as suggested by Buchwald (33), and
2. Absorption was measured at both the bases and the peak in the Soret band to overcome the error associated with the reproducibility of wavelength in the spectrophotometer.

Research Design

Basically, the tasks were numbered and are described as follows:

1. Car following at an average speed of 50 mph; test driver used normal search and scan patterns;
2. Car following at an average speed of 50 mph; test driver closed his eyes whenever possible;
3. Open-road driving at target speed of 50 mph; test driver used normal search and scan patterns;
4. Open-road driving at target speed of 50 mph; test driver had vision occluded;
5. Open-road driving at target speed of 30 mph; test driver used normal search and scan patterns;
6. Open-road driving at target speed of 30 mph; test driver had vision occluded; and
7. Leapfrog passing.

All tasks were performed in an instrumented 1971 Chrysler sedan driven in low-density traffic on limited-access highways. Tasks 1 through 6 used eye-movement recording techniques to permit analysis of driver search and scan patterns.

In the voluntary occlusion tests, the driver shut his eyes as long as possible during the task and opened them long enough to ensure control of the vehicle. Of interest in these spare visual capacity studies were the mean and variance of open and closed time and where the driver sampled for information after the closed period.

Figure 1. Experimental exposure to CO.

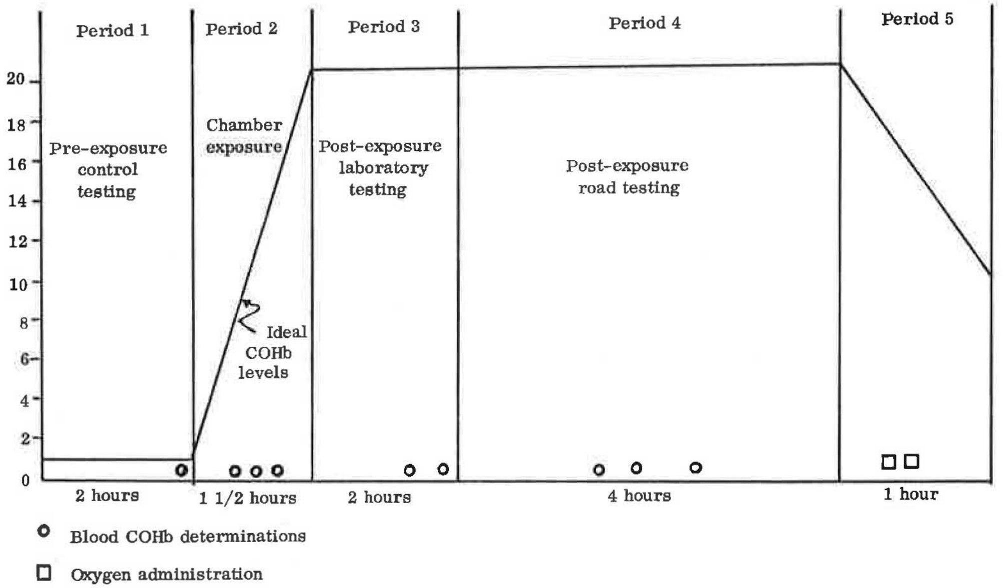
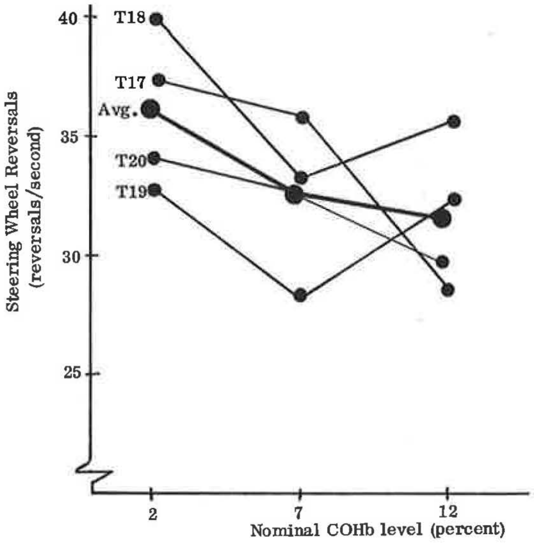


Table 1. Primary response variables.

Variable	Symbol	Tasks
Mean velocity	V BAR	All
Velocity standard deviation	S_V	All
Mean headway	H BAR	1 and 2
Headway standard deviation	S_H	1 and 2
Relative velocity standard deviation	S_{RV}	1 and 2
Gas pedal deflection rate	G	All
Brake pedal activation rate	B	All
Steering wheel reversal rate	SWRR	All
Mean look time		All
Look time standard deviation		All
Percentage of total time looking at target areas[a]		All
Mean occlusion time		2, 4, and 6
Occlusion time standard deviation		2, 4, and 6
Percentage of total time occluded		2, 4, and 6

[a]A look is defined as an aggregation of consecutive fixations in a specified target area, e.g., speedometer, lead car, mirror, etc.

Figure 2. Steering wheel reversals for 50-mph tasks.



The primary response or dependent variables of importance to each task are given in Table 1.

Subjects

Subjects were selected from a group of volunteers who responded to a series of newspaper advertisements soliciting healthy males, over age 21, who were licensed drivers. Candidates completed the Cornell Medical Health Index Questionnaire and a habit inventory form. Prospects who had uneventful medical histories and who were professed nonsmokers were selected for further screening.

Prospects selected from the above group were administered standard tests for visual acuity and color blindness. They were given a complete physical examination by a physician before final acceptance.

RESULTS

Vehicle Status Measures

In those tasks in which the driver elected his own velocity no practical effects of COHb levels were observed. (A statistically significant trend of +2 mph due to elevated COHb levels was found.) Velocity standard deviation was not affected by COHb levels. Mean elected headways in car following were reduced by about 15 feet (from 100 to 85 feet) during normal driving. Relative velocity effects and headway variance effects were minimal.

Control Movements

Control movements as exhibited by gas pedal and brake pedal activation and steering wheel reversals showed little effect due to COHb level. Gas pedal reversals showed a trend upward with COHb level, but none of the differences was statistically significant. Brake pedal applications in perturbated car following also failed to show effects due to COHb level.

Steering wheel reversals reflected COHb effects as well as the subject's effect normally found in driving research. There was also evidence of subject-CO interaction effects. Figure 2 shows a reduction in steering activity with elevated COHb levels.

Visual Measures

The percentage of time drivers closed their eyes decreased with elevated COHb levels, and the average closed time was also reduced. In normal vision driving, the percentage of fixations in the central forward viewing area (percent STR) increased with elevated COHb levels. This lends support to the notion of perceptual narrowing under the stress imposed by elevated COHb levels. This is supported by less mirror use under elevated COHb levels. These effects, while practically significant, are not statistically significant because of large residual error. Figure 3 shows a comparison of dual task (car following) and open-road driving. The mean forward look time increases markedly for elevated COHb levels in car following as compared to open-road driving.

Perceptual Uncertainty

Examination of the occluded 50-mph task for a sample of six subjects at both control (1.5 to 2.0 percent COHb) and 6 to 8 percent COHb reveals an interesting phenomenon. If the mean look time is divided by the percentage of closed time and multiplied by 1,000, the result reflects perceptual confidence or the lack of it. This measure is large when mean look time is long (suggesting visual inefficiency), when the percentage of closed time is small (suggesting uncertainty about car path direction), or when the two are combined. The converse of these factors produces less perceptual uncertainty. Data for six subjects are shown in Figure 4 for both the control and the 6 to 8 percent COHb level. Note that in each case there is greater perceptual uncertainty

Figure 3. Mean straight looks for normal vision driving tasks.

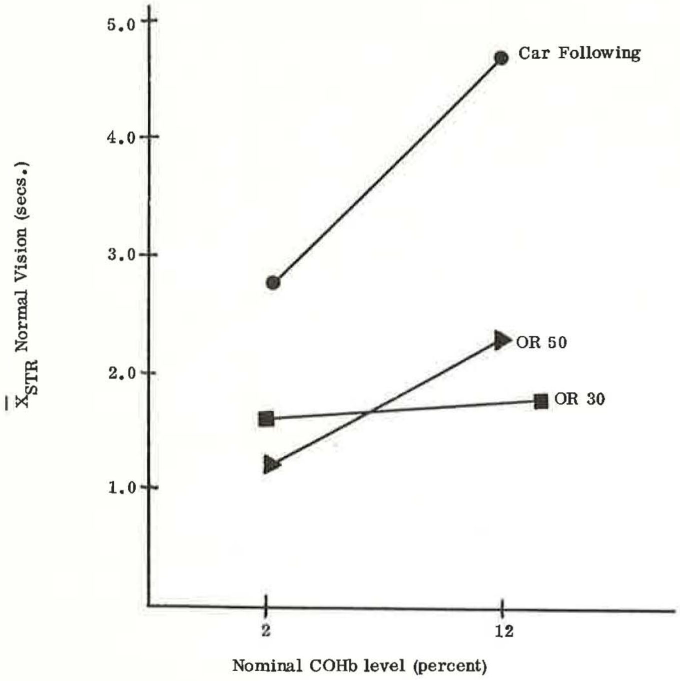
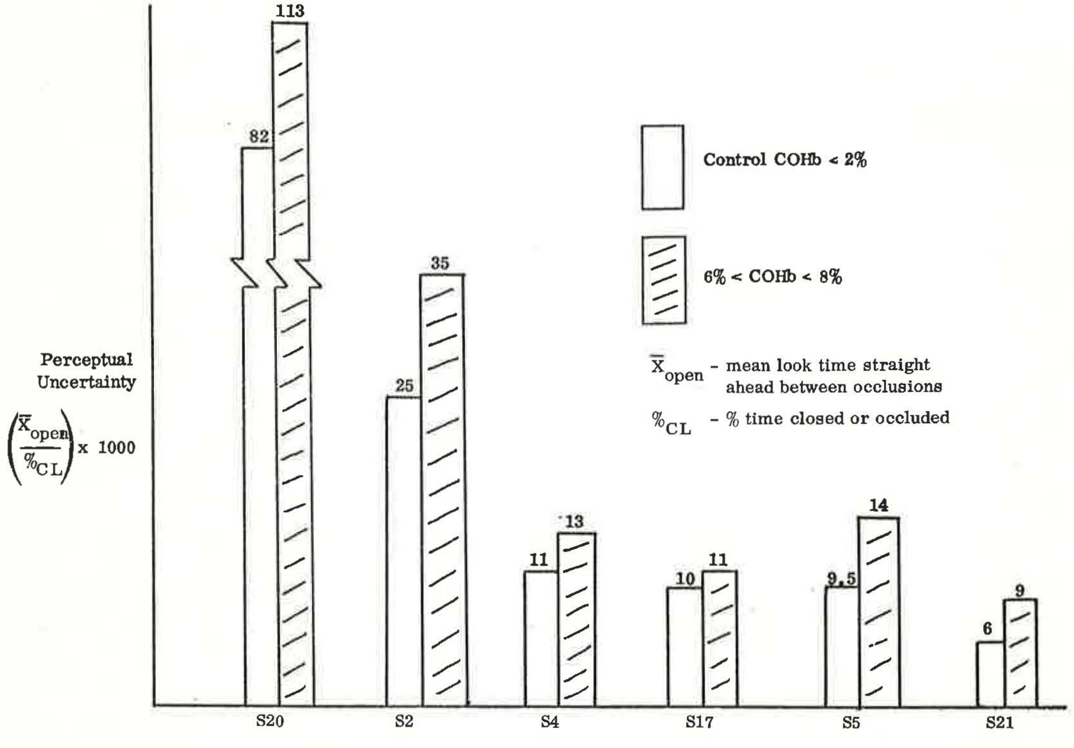


Figure 4. Perceptual uncertainties for selected subjects.



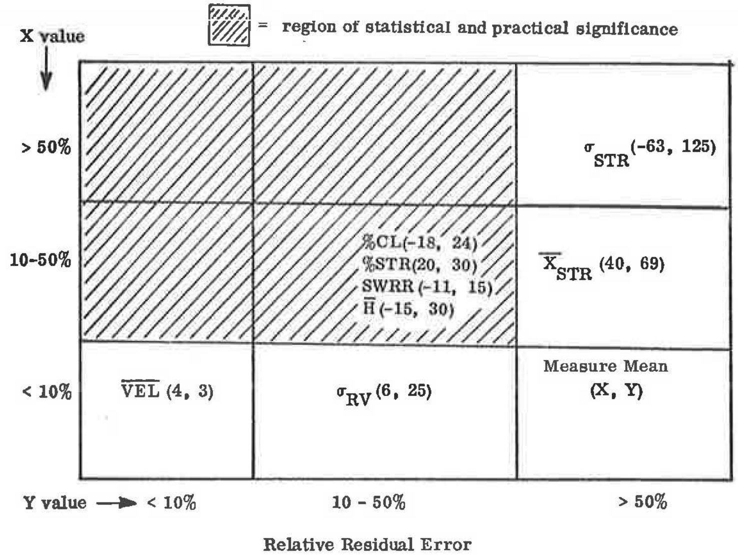


Figure 5. Illustrative results for all tasks.

$$X = \frac{12\%\ \text{COHb mean} - 2\%\ \text{COHb mean}}{2\%\ \text{COHb mean}} \times 100$$

$$Y = \frac{\sigma_E}{2\%\ \text{COHb mean}} \times 100$$

$\%_{CL}$ = % time eyes closed

σ_{STR} = STD deviation looks straight ahead

σ_{RV} = Relative Velocity STD deviation

$\overline{X}_{STR}$ = mean look time straight ahead

$\%_{STR}$ = % of look time straight ahead

SWRR = steering wheel reversal rate

$\overline{H}$ = mean headway

$\overline{VEL}$ = mean velocity

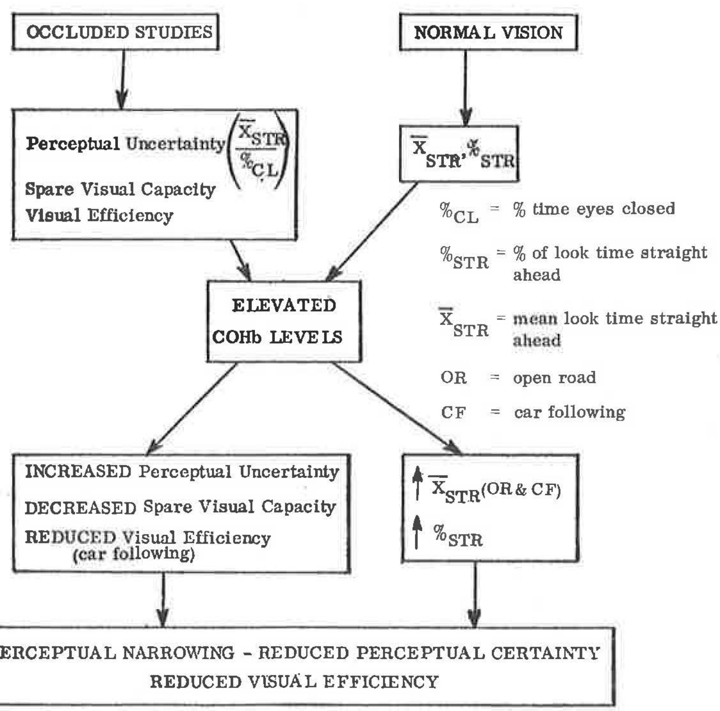


Figure 6. Trends in perceptual measures.

for elevated COHb levels. The magnitude of the increase is apparently related to the initial control level. That individual subjects react differently to this unique task designed to spare visual capacity is not surprising. What is significant is that all subjects showed greater uncertainty at elevated COHb levels.

The results of the leapfrog passing task largely supported the results of the analyses of tasks 1 through 6. Examination of the data showed that COHb levels of nominally 12 percent were associated with

1. Slightly lower average speeds and higher variation in speeds over the 20 trials and
2. Reductions in the number of looks at mirrors both prior to and during the average pass.

CONCLUSION AND DISCUSSION

This research found no obvious performance deterioration in driving at COHb levels of 12 to 14 percent. This is consistent with the findings of Safford (30), who conducted tests at 20 percent COHb levels. However, as has been discussed, there are subtle performance changes, especially in visual measures in more demanding driving situations, e.g., car following and visual occlusion tasks.

In terms of sensitivity to carbon monoxide, it was expected that vehicle status measures would be least sensitive, driver control next, and perceptual measures most sensitive, and this was, in fact, found in the data. Inherent variability associated with performance also increased from the vehicle measures to the perceptual measures. At the same time, safety relevance of performance decrement is probably more related to perceptual measures than vehicle measures because perceptual failures are usually the initiating factors in the accident chain.

Figure 5 shows some results over all tasks and clearly illustrates the dilemma of the analyses. The relative change at 2 to 12 percent COHb in mean values of performance measures is plotted against the residual error relative to the base line (2 percent COHb) mean. It should be noted that regions of both strong statistical and practical significance were actually not found in the research. Were there to be any statistical significance in this figure, the residual error would probably be less than 50 percent and typically about 30 percent of the mean value of the performance measure. This figure is interesting on two grounds. It should be noted that, as anticipated, vehicle measures showed minor changes in mean values and were also the variables with the smallest residual error. In the middle cells we find the control movements, and, in the cells involving more than 50 percent change in mean value due to COHb levels, we find perceptual measures. These perceptual measures are associated with large residual error and, hence, the inability to test these measures for statistical significance. These large residual errors stem from both intrasubject variability and subject-CO interaction.

This analysis suggests some trends in driver performance at elevated COHb levels. In general, the largest differences occurred in perceptual measures and the smallest in the vehicle measures (except for car-following spacing). The literature supports the findings with the visual measures (e.g., dark-light adaptation and night vision deteriorate under elevated COHb levels). Further, the preliminary laboratory studies demonstrated that central information processing might be the basis of any performance degradation. Current work of Moskowitz on the effect of marijuana and the work of Finkleman (15) on noise suggest that operator capacity to time-share between two tasks is affected by both the external and the internal stress mechanisms. Often performance degradation not found in any single measure will develop from secondary task loading (as found in driving tasks).

Figure 6 shows the trends in perceptual measures with elevated COHb levels. Occlusion studies permit us to study perceptual uncertainty, spare visual capacity, visual efficiency, and risk (of the time the subject would operate without information). Normal vision tests permit us to find the average amount of time spent in looks directly ahead and the percentage of time the subject concentrates on the roadway environment ahead of the car. In addition, intersignal sampling intervals in car following can also be extracted from normal vision studies. At elevated COHb levels, we find an increase in perceptual uncertainty, a decrease in the spare visual capacity of the subjects (as measured by percentage of closed time), and reduced visual efficiency in the occluded car-following tasks. In the normal vision tests, we find that increased levels of COHb result in increases in both open-road and car-following mean straight ahead look time, again suggesting reduced visual efficiency, and increases in percentage of time spent looking at the road directly ahead. COHb apparently affects mean straight ahead look time more in car-following tasks than in open-road driving. These combined effects suggest a form of perceptual narrowing on the part of the subject, a reduced visual efficiency. It might be noted that, in each of these instances, the data of Safford (30) at 20 percent COHb support these findings.

When the vehicle dynamics and driver control measures were examined as a function of elevated COHb levels, it was found that steering wheel reversal rates decreased with elevated COHb levels. If CO acts in the same way as driving fatigue, this result would be consistent with the work of Platt (26) and others who have examined operator control movements as a function of driving time.

In terms of car-following performance (as measured by headway and relative velocity), there was a decrease in maintained headway at elevated COHb levels. This fairly consistent reduction of headway under elevated COHb appears to be an anomaly not easily explained in terms of perceptual measures described earlier. The driver's perceptual narrowing mentioned earlier may suggest that, when he overconcentrates his vision on the lead car, he misses other cues to provide spacing information. This would explain changes in headway but not necessarily the fact that the changes were negative.

Because headway refers to elected spacing in car following, the observed reduced headways may have their locus not in perception but in risk acceptance whereby elevated COHb levels serve to relax driving inhibitions. In any event, reduced headways, lack of mirror sampling, increased perceptual uncertainty, and reduced visual efficiency (visually loaded tasks) are indicative of decreased safety in car following.

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