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CONTENTS

FOREWORD

Studies of four of the factors that can influence a driver's ability to control his vehicle are treated in the reports included in this RECORD. The effects of alcohol, occluded vision, carbon monoxide, and aerodynamic disturbance by large vehicles were considered, and the findings will be useful to human factors specialists, safety professionals, enforcement agencies, and researchers in the driver performance field.

Weir, Hoh, and Teper show that adjacent passenger vehicles can be significantly disturbed by airflow around large vehicles. Their experimental results show that factors such as vehicle size and shape, wind, speeds, and relative speeds can cause adjacent cars to exceed normal lane boundaries despite driver corrective action. They suggest several ways in which these effects might be minimized. They further report no important effects when large vehicles are widened from 96 to 102 inches.

Rockwell and Weir investigated the possible effects of carbon monoxide exposure, as related to carboxyhemoglobin levels of less than 20 percent, on driving-related performance. As anticipated, they confirmed that vehicle status and driver control measures were less affected than perceptual measures but suggest that degradation in the latter might well have greater relevance to safety than would the vehicle factors. In particular, elevated COHb levels produced reduced headways, lack of mirror sampling, increased perceptual uncertainty, and reduced visual efficiency, all of which can be detrimental to safety in visually loaded tasks.

Zwahlen and Balasubramanian did theoretical and field studies of automobile path deviations while drivers attempted to steer along a straight path with their vision occluded. Vehicle displacements under these conditions were found to be smaller than displacements when drivers had no steering control and were also smaller at higher speeds. A discussion by Weir generally supports the work and suggests ways to extend the usefulness of any later experiments.

The influence of the Fairfax County alcohol safety action project on the blood alcohol concentrations of drivers at night is discussed by Smith. Data were taken before and 9 months after the start of the project. Significantly higher percentages of drinking drivers were found in the after survey, with a slight reduction (not statistically significant) in BAC above 0.10 percent. An index of accident probability that revealed dramatic reductions in accident probability for late night hours on weekends was calculated; these reductions are no doubt beneficial to safety.

DRIVER-VEHICLE CONTROL AND PERFORMANCE IN THE PRESENCE OF AERODYNAMIC DISTURBANCES FROM LARGE VEHICLES

David H. Weir, Roger H. Hoh, and Gary L. Teper, Systems Technology, Inc., Hawthorne, California

The airflow around a large truck or bus on the highway can disturb an adjacent automobile and degrade its performance under certain conditions. Procedures for investigating the effects of such disturbances on driver-vehicle systems have been developed. Equations of motion define the lateral-directional dynamics of the vehicle, and multiloop describing functions model the driver's steering response to perceptual cues. The aerodynamic forces and moments can be determined from scale model experiments. The analytical and experimental results show that the following factors can have an influence on driver-vehicle performance in such situations: vehicle handling and aerodynamic properties, driver skill and alertness, ambient wind, configuration and shape of large vehicle, vehicle separation and clearance, and vehicle speeds and relative speeds. In some cases, the disturbance can be large enough to cause the automobile to exceed nominal lane boundaries, despite corrective driver steering control. Investigations showed no important effects on the performance of nominal driver-vehicle systems due solely to the small change in disturbance caused by increasing bus or truck width from 96 to 102 in. Driver-vehicle performance in disturbance situations can be improved in the following general ways: change vehicle shapes to reduce disturbance sensitivity, increase separation between vehicles, increase relative speed of the overtaking car, reduce large vehicle speed, improve car handling and driver skill, and design highway geometry and structures to minimize ambient crosswinds.

•AERODYNAMIC DISTURBANCES on the highway can cause degraded driver-vehicle performance and corresponding reductions in safety. Procedures for investigating the effect of such disturbances on the driver-vehicle system have been developed. Analytical and experimental results are shown in this paper for the disturbance situation caused by car operation in close proximity to a large bus or truck.

This paper illustrates the application of control engineering techniques to the understanding of a specific highway disturbance problem and provides an overview of the results. Some of the technical details needed to fully understand the analyses are presented in summary form. An attempt has been made to present the results and implications in more familiar terms.

DISTURBANCE SITUATION

The airflow around a large vehicle on the roadway can cause an aerodynamic disturbance to adjacent automobiles. The geometry of this disturbance is shown in Figure 1. The car (disturbed vehicle) is shown on the left of the truck or bus, either overtaking it or being overtaken by it. Positive lateral path deviations (y_1) move the car

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toward the right (and toward the truck or bus). The driver's task is to stay in the center of his lane and avoid drifts in lane position. To accomplish this, he makes steering corrections, based on perceived motions of his vehicle, to minimize the lateral deviations caused by the disturbance. A convenient performance measure is the peak lateral deviation from the lane centerline due to the disturbance ($\hat{y}_l$).

The truck or bus creates a turbulent wake that propagates downwind. A positive relative crosswind is one that causes the wake from the truck or bus to blow away from the lane the car is in, and conversely. The crosswind angle (ψ_w) is measured relative to a sensor on the moving truck or bus, and it reflects a combination of the ambient wind (relative to the ground) and vehicle motion. Zero crosswind refers to the case with no relative crosswind angle, although a headwind or tailwind may be present. Because the vehicles are symmetrical, the results are equally applicable to the case with the car on the right. If the vehicles are traveling along their respective lane centerlines, the vehicle centerline separation equals the lane width.

DRIVER-VEHICLE MODEL

Nomenclature

The nomenclature used in the driver-vehicle response and performance model follows:

C_n = nondimensional aerodynamic yaw moment coefficient,
C_y = nondimensional aerodynamic side force coefficient,
e = base of Naperian logarithm,
$j = \sqrt{-1}$,
K_m = gain margin of driver-vehicle closed-loop system,
K_{p_y} = driver gain for lateral deviation control,
r = heading rate of disturbed vehicle,
T_L = driver lead equalization (anticipation) time constant,
U_B = bus forward velocity along roadway,
U_C = disturbed vehicle velocity along roadway,
U_T = truck forward velocity along roadway,
v = lateral velocity in body fixed coordinates of disturbed vehicle,
WV = incident wind as measured by vector vane on disturbed vehicle,
x_B = longitudinal position of center of gravity of disturbed vehicle relative to front of bus,
x_T = longitudinal position of center of gravity of disturbed vehicle relative to front of truck,
y_B = centerline separation of disturbed vehicle and bus,
y_l = lateral deviation of disturbed vehicle relative to lane centerline,
$\hat{y}_l$ = peak lateral deviation of disturbed vehicle from lane centerline,
y_T = centerline separation of disturbed vehicle and truck,
Y_c = transfer function for disturbed vehicle response to steer input,
Y_c' = effective transfer function for vehicle response to steer input, in the presence of some driver closed-loop control activity,
Y_p = describing function for driver steering control response,
Y_{p_y} = driver describing function for lateral deviation control,
Y_{p_ψ} = driver describing function for heading control,
Y_{v_g} = lateral acceleration of the disturbed vehicle due to a 1 ft/sec crosswind,
δ_w = steer angle input at front wheels of disturbed vehicle,
σ = real part of Laplace transform complex variable,
τ = effective driver time delay in closed-loop steering task,
τ_o = effective driver time delay with no disturbance input,
φ = sprung mass (body) roll angle of disturbed vehicle,
φ_m = phase margin of closed-loop system,
ψ = heading angle of disturbed vehicle relative to lane centerline,
ψ_w = relative angle between centerline of moving truck or bus and incident wind,
ω = frequency,

ω_c = driver crossover frequency (or response gain) for steering control actions,
ω_{c_y} = driver crossover frequency for lateral deviation control, and
ω_{c_ψ} = driver crossover frequency for heading control.

The dynamic model for driver-vehicle response and performance is based on an empirical theory of manual control that takes into account

1. Guidance and control requirements related to stability and path following and
2. Driver requirements related to human characteristics.

The driver responds to stimuli from the full visual field. The current driver control model is based on human response data obtained in a variety of vehicular control tasks, including driving. The basic manual control theory is presented elsewhere (1, 2). Specializations to driver control have been described in detail (3, 4) and are reviewed briefly below.

The dynamics of the disturbed vehicle are a major task variable. The lateral-directional properties pertinent to steering control were modeled by using linear equations in three degrees of freedom: lateral velocity, heading rate, and body roll angle. The equations of vehicle motion and steer angle response functions were quantified by using chassis and tire data and were verified in full-scale tests.

Driver Describing Function

Driver closed-loop steering response can be modeled by describing functions with parameters that depend on the system and situation, rules that tell how to adjust the parameters, and an additive remnant.

Remnant is the part of the driver control output that is not linearly correlated with the input, and it can be modeled as a random noise added to that output. Its main source seems to be nonstationary behavior. Some evidence of remnant is seen in the steer angle and heading rate of the full-scale data shown subsequently. Generally, it can be neglected when differences in performance due to changes in the vehicle geometry, disturbance situation, and so on are analyzed.

The rationale of driver equalization can be expressed most simply by using an approximate crossover model (1), which states that the driver adjusts his describing function in each loop such that the open-loop function, made up of the effective vehicle dynamics and the driver, in the vicinity of the gain crossover frequency for that loop has the following approximate form:

$$Y_p Y_c \doteq \frac{\omega_c e^{-j\omega\tau}}{j\omega} \qquad (1)$$

The crossover frequency in Eq. 1 is a key parameter. It corresponds to the "bandwidth" of the closed-loop driver-vehicle system, and its magnitude determines the quality of control and system responsiveness. The crossover frequency is adjusted by the driver for a given situation based on the vehicle's handling properties, the driver's skill level, and the nature of the inputs and the perceptual situation. The time delay in Eq. 1 includes neuromuscular dynamics as well as any high-frequency vehicle lags. In multiloop situations the controlled-element dynamics will include the effects of all the inner loops closed. Experimental values of the parameters in Eq. 1 and the basic adjustment rules have been discussed by others (1-4).

Driver-Vehicle System Structure

Multiloop control involving more than one feedback stimulus is needed to satisfy the guidance, control, and driver requirements. The system shown in Figure 2 is representative of the steering control task of interest and the example cars used in the study. This system has a primary feedback loop of vehicle heading angle plus an outer loop of lateral deviation. These feedback cues are operated on by the driver describing functions to produce steer angle corrections.

Y_p and Y_c (Fig. 2) account for the effective driver-vehicle response properties.

Figure 1. Typical large vehicle-car disturbance situation.

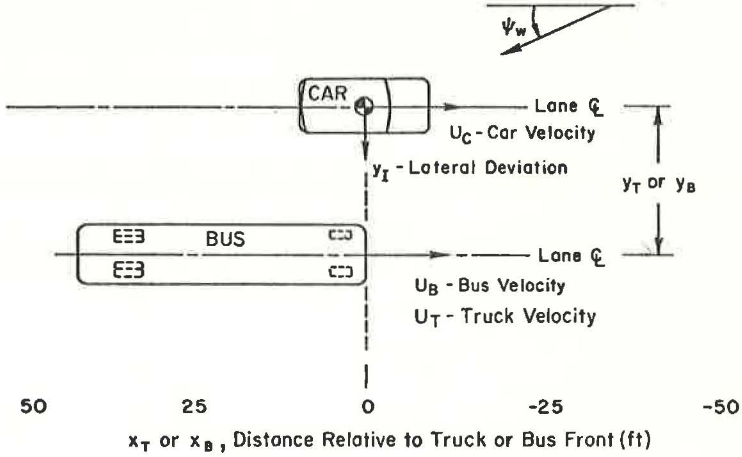


Figure 2. Representative driver-vehicle system.

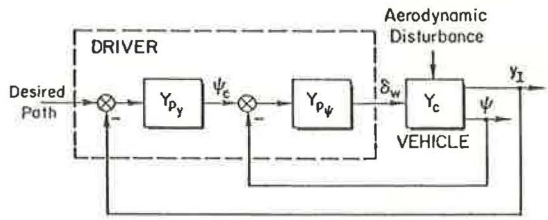


Figure 3. Driver-vehicle heading control.

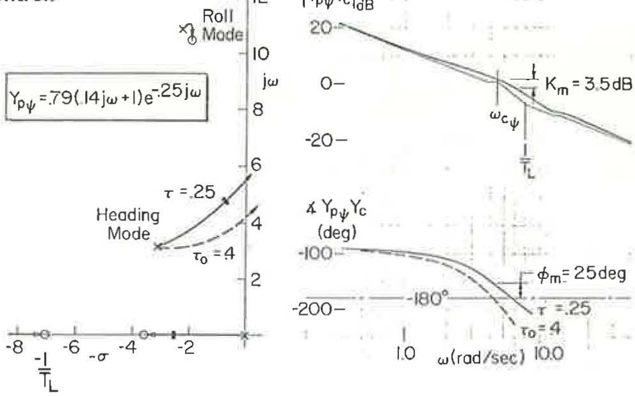
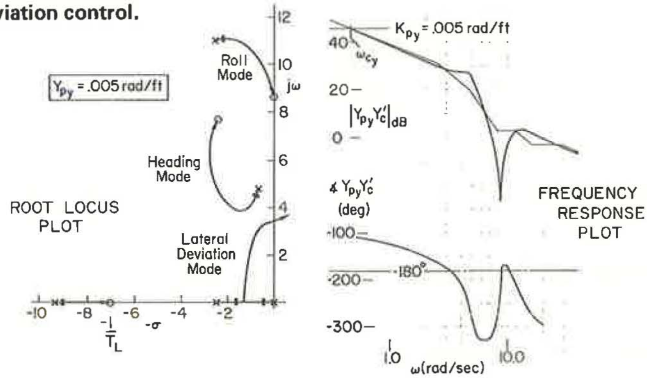


Figure 4. Driver-vehicle lateral deviation control.



However, they are not necessarily an exact analog of the system details. For example, driver perceptual activity may involve some attention to other cues such as heading rate and lateral acceleration, but the net effects of these feedbacks (if present) are embodied in Y_{p_ψ} and Y_{p_y}. Similarly, higher order dynamic properties of the vehicle are reflected in the three-degree-of-freedom model for the range of frequencies and amplitudes important to driver control in gust regulation tasks.

Driver-Vehicle Response

The procedures and models outlined have been used to estimate the response and performance of driver-vehicle systems in the presence of aerodynamic disturbances (5, 6). Example results for a full-sized 1972 station wagon are summarized below.

Heading Control—The driver-vehicle response properties for the heading loop are shown in Figure 3. The heading and roll modes identified on the root locus refer to the roots of the vehicle characteristic equation. A Pade approximation is used for the driver time delay, $e^{-\tau j\omega}$. Driver lead equalization of 0.14 sec is used in Figure 3 to offset the midfrequency lag in the vehicle's heading angle response. The $\omega_c/j\omega$ slope (20 dB/decade) of the amplitude ratio of the frequency response plot shows that this driver lead allows $Y_{p_\psi}Y_c$ to satisfy the form of Eq. 1. For this value of T_L and with no disturbance input, the driver delay is about 0.35 to 0.4 sec, and the corresponding (zero phase margin) crossover frequency, ω_{c_0}, is about 4.2 rad/sec. The presence of a gust disturbance increases driver neuromuscular tension and reduces the closed-loop time delay to about 0.25 sec, giving the stability margins shown on the frequency response plot.

Lateral Deviation Control—Closing the heading loop results in an open outer loop effective controlled element, which is combined with Y_{p_y}. Again applying the crossover model gives the driver-vehicle frequency response properties for lateral deviation control shown in Figure 4, and the broad region of $\omega_c/j\omega$-like amplitude ratio, which will allow the driver to use proportional control ($Y_{p_y} = K_{p_y}$).

Selection of the outer loop crossover frequency in Figure 4 involves several factors. Within limits, higher crossover frequencies give wider driver-vehicle system bandwidths, which improve performance. The penalty associated with this is an increase in driver work load. If the crossover frequency becomes too high, performance will deteriorate because of reduced path damping and stability margins. For some vehicle handling dynamics, the quality of the response becomes poor for crossover frequencies well below the stability limits, as a result of undesirable interaction between the heading and roll modes.

These considerations and subsequent full-scale correlations lead to the estimate $\omega_{c_y} = 0.46$ rad/sec for the station wagon, which corresponds to $Y_{p_y} = 0.005$ rad/ft. For this relatively low gain the lateral deviation and heading mode roots are well separated as shown in Figure 4. This gives relatively simple response qualities, dominated by the lateral deviation mode. If ω_{c_y} were increased, the closed-loop roots of the lateral deviation and heading modes would approach each other, and the driver would find the resulting fourth-order response undesirable. Vehicles that are more gust-sensitive require higher crossover frequencies to maintain a given range of performance, but this factor does not override these response quality considerations for the station wagon.

AERODYNAMIC DISTURBANCE DATA

The aerodynamic disturbances shown in Figure 2 were quantified for various truck or bus shapes by using wind tunnel experiments and 1:10 scale models. The forces and moments of the disturbed car were measured for various relative crosswind angles, centerline separations, and longitudinal positions. Details of the scale model experiments are given by Heffley (7).

Example C_n and C_y disturbance coefficients are shown in Figure 5a for a full-sized station wagon in the presence of a 54-ft semitrailer. Data are shown for zero crosswind and three centerline separations. The principal disturbance in this case results from the flow around the bluff front of the truck. Intercity bus data have a similar appearance for the zero crosswind case.

Figure 5. Typical aerodynamic disturbance data for station wagon disturbed by (a) truck under zero crosswind and (b) truck or bus under negative crosswind.

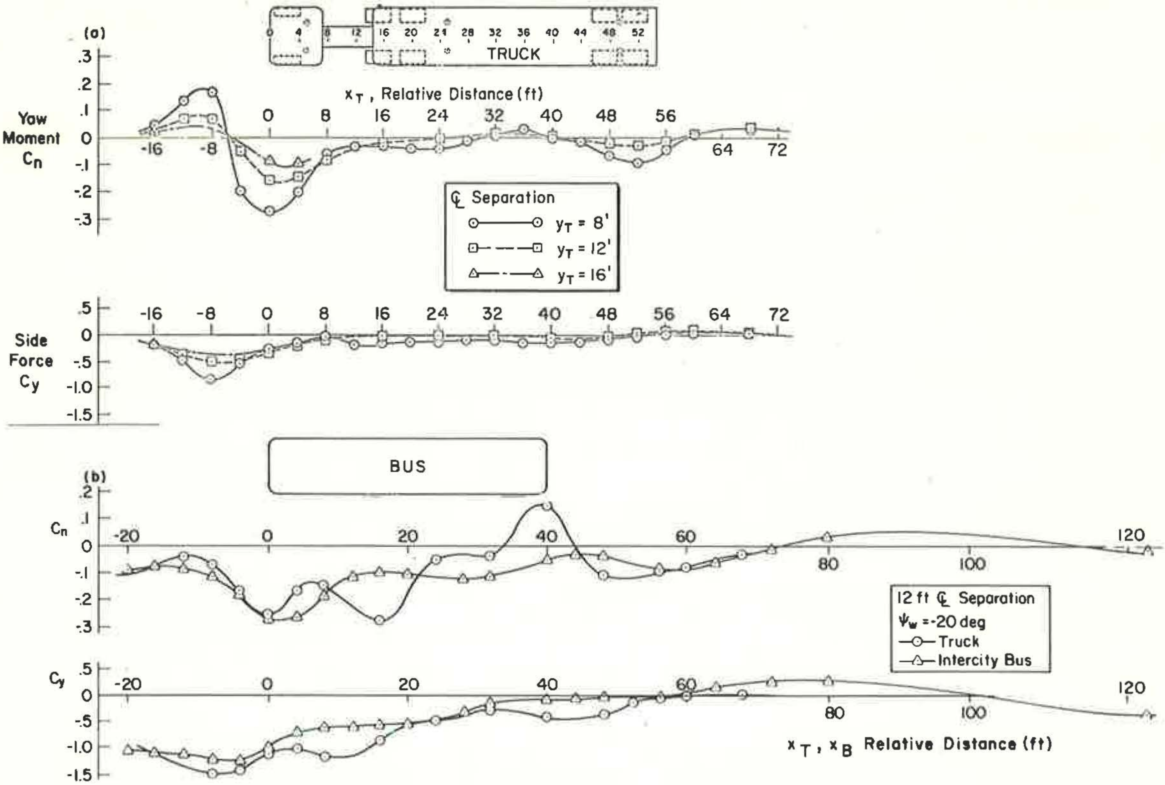
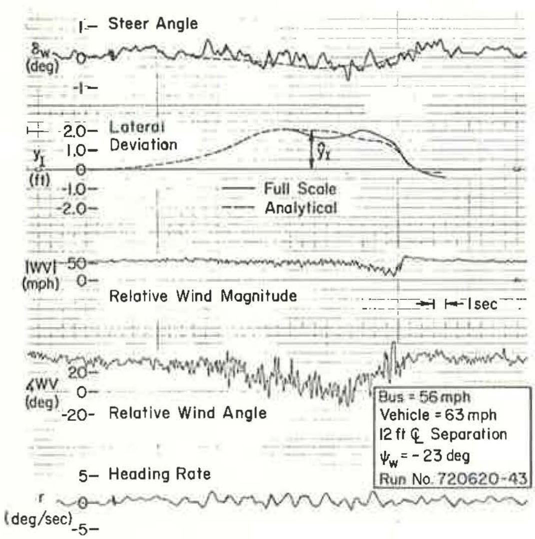


Figure 6. Comparison of results for station wagon.



Crosswind disturbance data are shown in Figure 5b, wherein the disturbed vehicle passes along the lee side of the bus. In this case the main disturbance is large and of lower frequency than the zero crosswind situation, and it results from the bus shadowing the relative crosswind. The data in Figure 5b also show differences between truck and bus shape. Variations in centerline separation have less effect on the disturbance magnitude with a crosswind than they do with zero crosswind. Additional aerodynamic data for vehicle disturbance situations are given by Heffley (7) and Brown (8).

PERFORMANCE ESTIMATES

Driver-vehicle response and performance estimates were simulated digitally by using the models and data discussed to obtain time responses for various disturbance situations. Simultaneous full-scale tests with instrumented vehicles were used to confirm the analytical and model results. An example comparison of analytical and full-scale results is shown in Figure 6. The aerodynamic disturbance shown was caused by the station wagon passing an intercity bus at a relative speed of 7 mph in the presence of a strong crosswind. In Figure 6, δ_w is the front-wheel steer angle, r is the heading rate, and $|WV|$ and $\measuredangle WV$ are the magnitude and angle of the wind relative to the moving car. The results show good agreement, particularly in terms of the overall y_l. The higher frequency (3 to 10 rad/sec) oscillations in the δ_w and r data can be modeled by the remnant. This comparison supports the choice of outer loop crossover frequency shown in Figure 4:

$$\omega_{c_y} \doteq 0.46 \text{ rad/sec}$$

Similar analyses and experiments have been done with other vehicles (5, 6). Of the vehicles tested, cars towing trailers were most susceptible to the disturbance inputs. Vans show low stability margins and high crossover frequencies, just the opposite of the station wagon; these differences depend on the aerodynamic and handling properties. For American sedans of conventional design, the results show outer loop crossover frequencies of about 1 rad/sec and phase margins of about 60 deg. These values give good path stability and overall performance, simple response qualities, and relative insensitivity to changes in driver gain.

The driver-vehicle performance estimates used subsequently are based on a reasonably skilled and alert driver attempting to maintain a constant path in the lane. This level of control activity and performance is sufficient for studying the effects of changing other parameters such as truck or bus width and ambient wind, and the results of these comparisons are insensitive to fairly wide variations in driver skill and attentiveness. In an absolute sense, however, the performance values shown could improve somewhat with a very skilled driver and degrade substantially if the driver were inexperienced or distracted.

RESULTS AND IMPLICATIONS

In general, there are several ways to improve driver-vehicle performance in disturbance situations. Changing vehicle shapes reduces the magnitude of the aerodynamic disturbance. Increasing the distance between vehicles is invariably beneficial. Increasing the speed of the passing car helps by reducing exposure time and increasing the frequency content of the disturbance (which results in greater attenuation by the car's inertia). If the truck or bus passes the car, reduction in the speed of either vehicle is generally helpful. Better car-handling dynamics and driver skill improve performance. Reducing the vehicle airspeeds and wake effects is helpful, and this will occur with no headwind (or a tailwind) and when the crosswind (if present) is such that the truck or bus wake is not blowing across the path of the car.

Disturbed Vehicle Properties

The differences in aerodynamic properties of the disturbed vehicle generally correspond to truck or bus disturbance inputs. The peak values of the aerodynamic disturbance tend to correlate with the peak lateral deviations of the driver-vehicle system, particularly with zero crosswind. With a strong crosswind this is not always the case. In general, the basic aerodynamic data give some insight into potential disturbance problems, but it is essential to consider the driver-vehicle-disturbance situation to make performance comparisons.

These effects are shown in Figure 7. The aerodynamic properties of the disturbed vehicle are shown in terms of Y_{v_g} (Fig. 7b). Large low-density vehicles (such as a pickup truck-camper or a utility van) are more gust-sensitive than conventional sedans. Driver-vehicle performance of these vehicles in the presence of a bus disturbance with strong negative crosswind is shown in Figure 7a. The differences in performance generally follow the trend of the gust sensitivities, with the exception of the station wagon and station wagon towing trailer. These perform poorly because of their aerodynamic and handling properties.

Relative Wind

The direction and magnitude of the ambient wind relative to the moving vehicles are significant parameters in vehicle disturbance situations, and there are two basic conditions:

1. Zero crosswind in which the flow about the front of the truck or bus pushes the vehicle away (also representative of vehicle passing upwind of a truck or bus in a crosswind) and
2. Negative crosswind (disturbed vehicle downwind) in which the wake alongside and to the rear of the truck or bus "pulls" the two vehicles together.

The variations in performance with relative wind for two nominal disturbance situations are shown in Figure 8. Both positive (toward bus) and negative (away from bus) peak deviations are shown. Positive crosswind (car upwind from bus) results differ little from zero crosswind. For negative relative crosswind angles and magnitudes greater than about 5 deg, the performance decreases sharply because of the large-amplitude, low-frequency disturbance caused by the shadowing effect of the bus. Results for the semitrailer have a similar form, although the negative crosswind performance degradation transition occurs at $\psi_w \doteq -10$ deg because of the differences in shape and configuration between bus and truck.

Headwinds intensify and tailwinds reduce the effects shown in Figure 8. Because negative crosswinds cause much larger lateral deviations for most types of disturbed vehicles, procedures to alleviate this problem are needed where steady crosswinds are commonly encountered. These procedures could include selecting right-of-way and basic highway geometry to avoid the crosswinds, erecting appropriate fences or other wind barriers, reducing speed limits, increasing separation between vehicles, posting driver warnings, and restricting disturbance-sensitive vehicles.

Bus and Vehicle Speed

Varying the speeds of both the car and the truck or bus has a substantial effect on performance. This is shown in Figure 8 with two speed combinations: car 60/bus 50 and car 70/bus 65. The 70/65 case results in substantially larger path deviations by the car. At higher speeds the dynamic pressure increases, and this amplifies the level of the disturbing forces and moments. At lower relative speeds the disturbance lasts longer and changes more slowly, which tends to disturb the car more despite corrective driver steering. At higher speeds the car's handling dynamics change, it responds more gradually to driver steering corrections, and this reduces performance.

All of the results discussed thus far are for the bus (or truck) and the disturbed vehicle traveling in the same direction (Fig. 1). Oncoming vehicles present a case in which the relative speed is very high. This generally causes the disturbance to have a very short duration and results in a relatively small lateral deviation of the driver-vehicle system. The median on most modern highways increases separation and reduces the disturbance due to oncoming vehicles.

Figure 7. Effect of disturbed vehicle properties on gust sensitivity and performance.

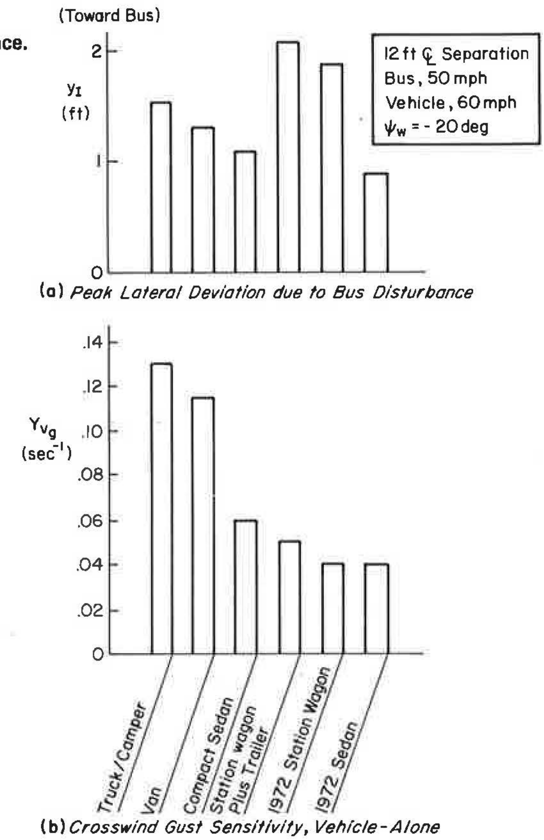
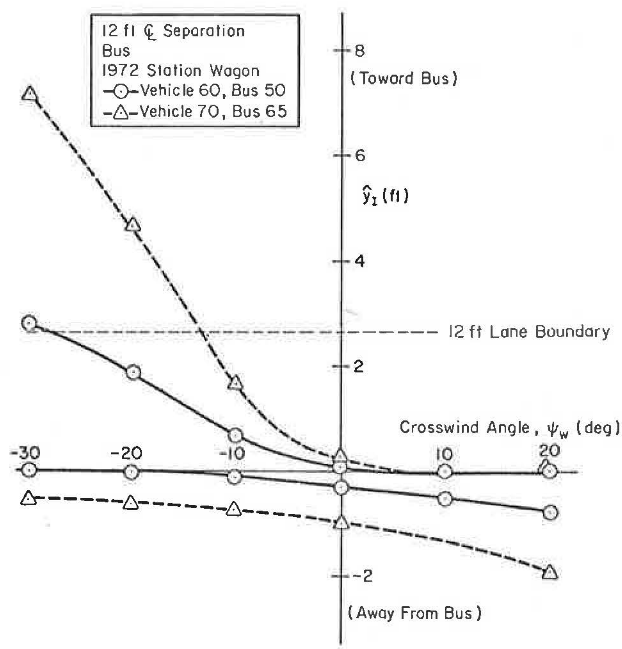


Figure 8. Effect of crosswind angle of driver-vehicle lane keeping performance.



Vehicle Lateral Separation

The effect on path performance of changing lateral separation is most pronounced in the zero crosswind case, where it is proportional to the change in the peak side-force disturbance (Fig. 5a). This is shown in Figure 9 for 0 and -20 deg relative crosswind angles and two vehicle-bus speed combinations. With a negative crosswind (Fig. 9b), the peak lateral deviation is toward the bus, and the disturbance is larger than with zero crosswind (Fig. 8); but the effect on performance of changing lateral separation is relatively small. For zero crosswind (Fig. 9a), the peak deviation is away from the bus and the percentage change in $\hat{y}_1$ with changing separation is larger. Nevertheless, for nominal driver-vehicle characteristics and the car 60/bus 50 speed case, the peak lateral deviation is less than 0.5 ft even at the smallest separations. Similar results obtain with truck-induced disturbances.

Truck or Bus Width and Shape

Although large vehicle widths are limited by statute, we investigated the consequences of increasing this width. Increasing truck or bus width by about 6 percent showed no important effect on the disturbance or the driver-vehicle performance. This was borne out by full-scale highway studies (9) that showed no significant difference in passing vehicle behavior when the bus was widened from 96 to 102 in.

Specifically, the effect of increasing truck or bus width was small but measurable for the zero crosswind case (Fig. 10a), whereas for the negative crosswind case the effect was much less (Fig. 10b). With zero crosswind, increasing bus width from 96 to 102 in. under nominal conditions (without changing shape) increases the magnitude of the peak lateral deviation of the driver-station wagon from 0.30 to 0.35 ft. Analysis showed that about one-half of this difference was due to the 3-in. reduction in side clearance, and the remainder resulted from the increased flow disturbance at the front of the bus. Preliminary studies in which the nose of the bus was streamlined suggest that this might offset the small increase in disturbance caused by a 6-in. increase in bus width.

Small variations (±6 inches) in the underbody clearance of the bus (between the wheels) have a small effect in a negative crosswind and essentially no effect otherwise. Increasing the clearance by 6 in. reduces the lateral deviation due to the disturbance by a small percentage, whereas a similar decrease causes a slight degradation in performance of the disturbed vehicle. On the other hand, large reductions in the underbody clearance of the truck (e.g., from 4 ft to 2 ft) substantially degraded adjacent driver-vehicle path performance in the negative crosswind case, because of the increased shadowing effect. The bus showed less sensitivity to changes in underbody clearance because its clearance is smaller than the truck's initially.

Reductions in the length of the gap (e.g., from 8 to 3 ft) between the tractor and semitrailer had little effect on adjacent vehicle performance, even in the negative crosswind case.

Implications for Highway Operations

An alerted driver can minimize the effects of aerodynamic disturbances. However, because the disturbance varies greatly with the conditions, a driver cannot always predict a large disturbance when overtaking a truck or bus and must compensate for path errors as they develop. Suitable warning signs in windy areas, training, and publicity are all potentially useful.

The full-scale experiments showed increased driver stress associated with the truck or bus disturbance input. This can improve driver steering performance, but the driver may reduce his attention to other aspects of the driving task. Hence, other driver tasks, such as reading signs and monitoring cross traffic, should be minimized on stretches of highway that characteristically present disturbance situations.

The results also suggest guidelines for the truck or bus driver. He should move away from passing vehicles and other traffic when there are no vehicles or pedestrians on the shoulder. He should be alert for a passing car that may experience difficulty.

Figure 9. Effect of bus-vehicle separation on driver-vehicle lane keeping performance.

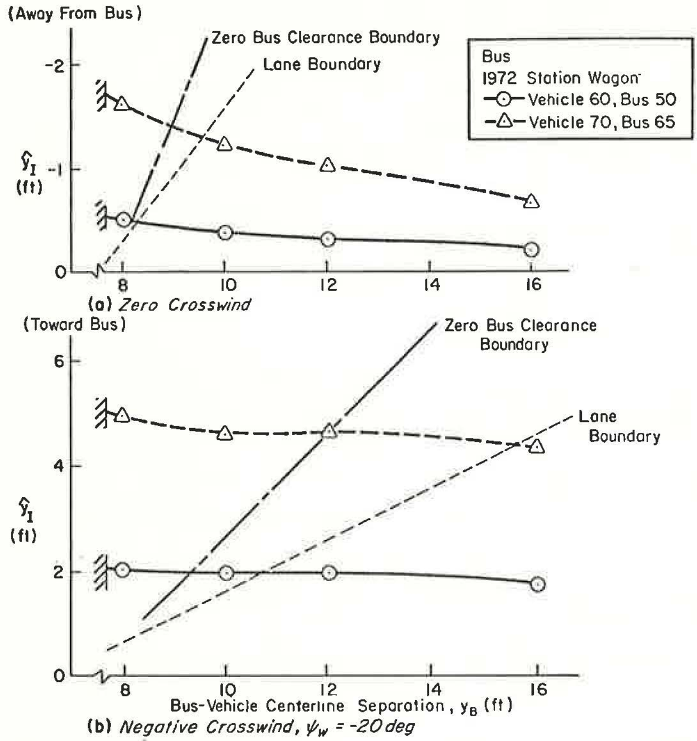
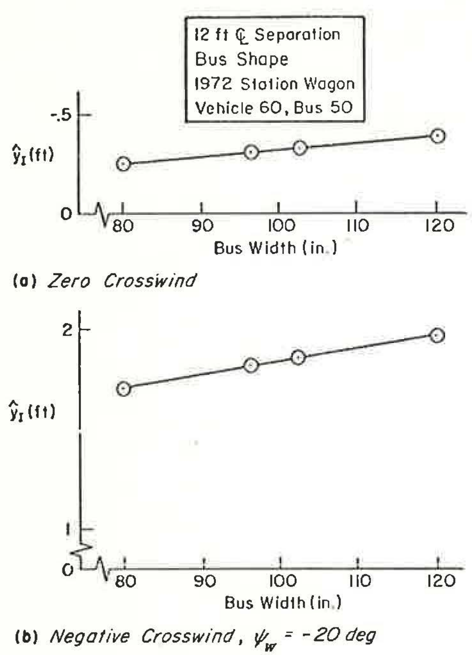


Figure 10. Effect of bus width on driver-vehicle performance.



Similarly, he should recognize that, when his vehicle overtakes a slower car, it may cause an unexpected disturbance to that vehicle and its driver. The results show that this situation is most critical when the truck or bus overtakes a car towing a trailer.

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EFFECTS OF CARBON MONOXIDE INTOXICATION ON DRIVING TASKS

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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.

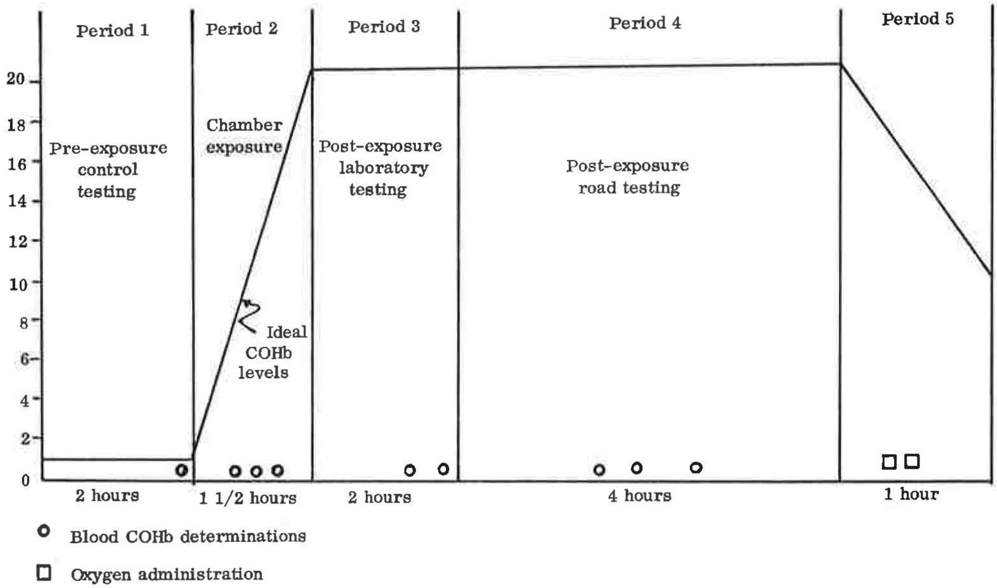
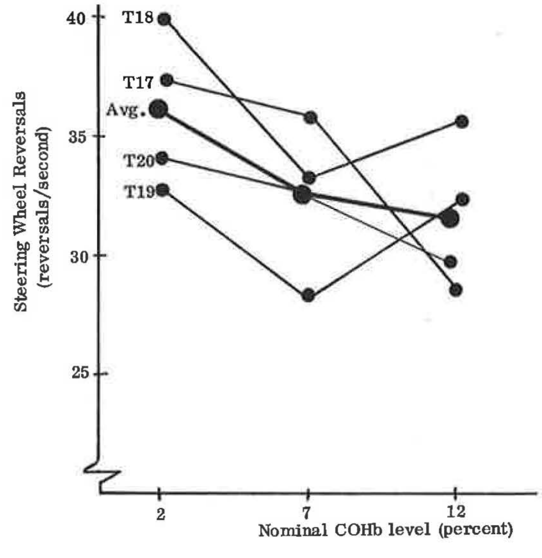


Table 1. Primary response variables.

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.

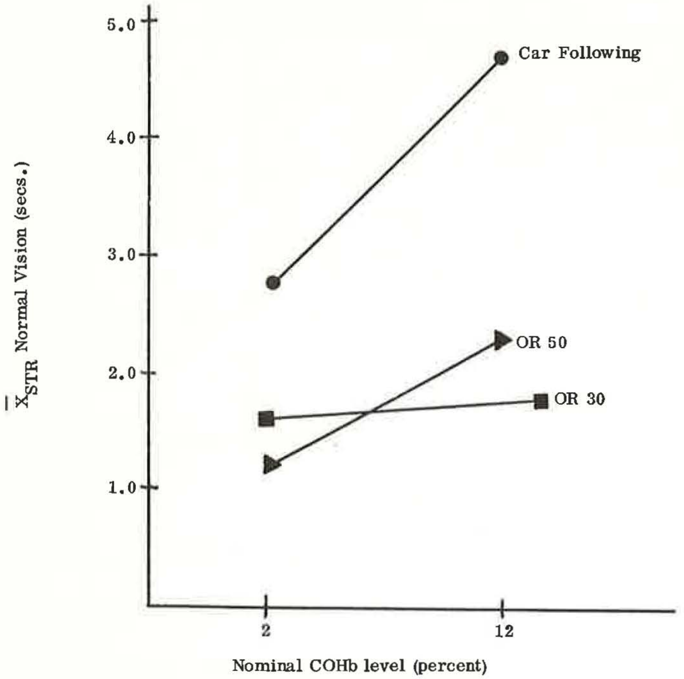


Figure 4. Perceptual uncertainties for selected subjects.

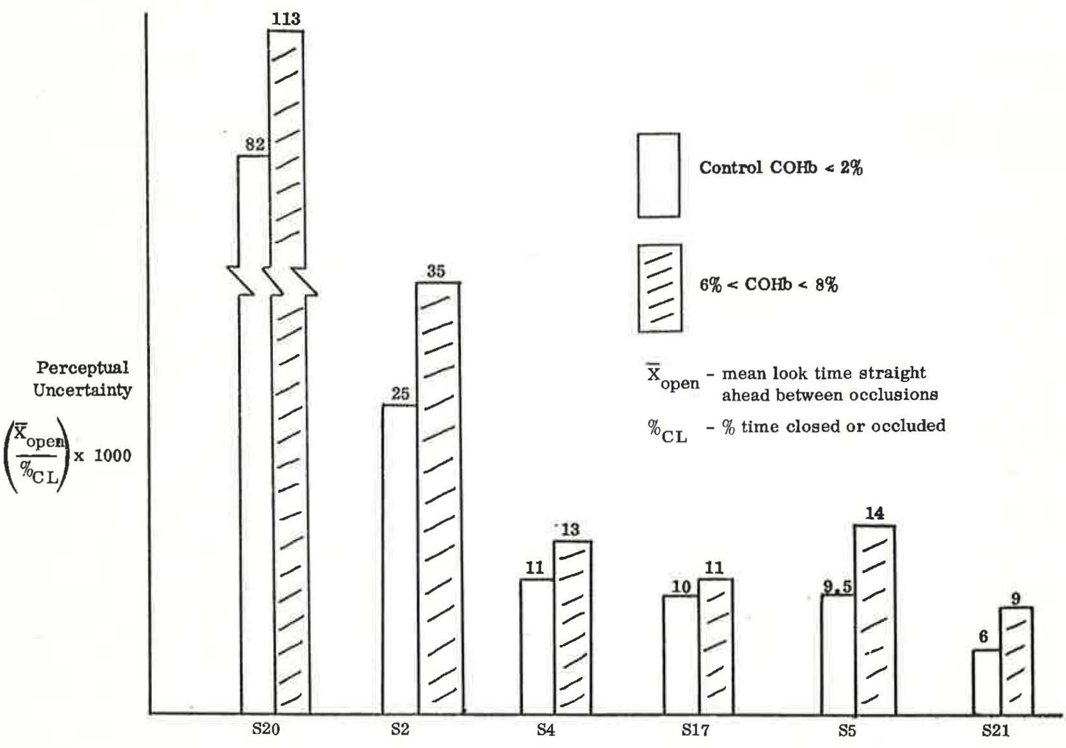
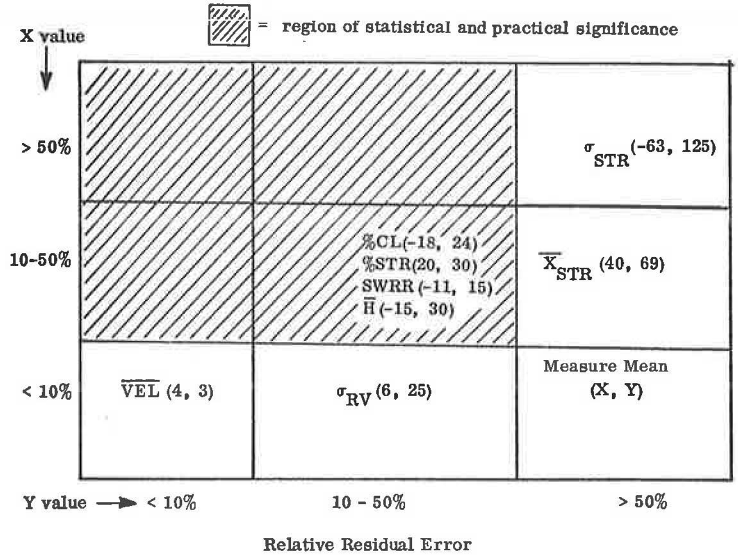


Figure 5. Illustrative results for all tasks.



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

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

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

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

SWRR = steering wheel reversal rate

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

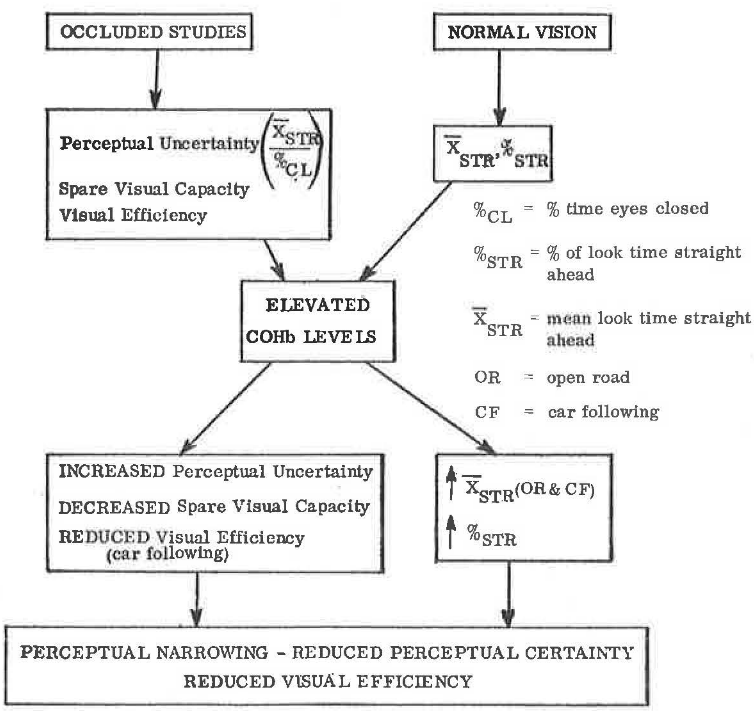
σ_{STR} = STD deviation looks straight ahead

σ_{RV} = Relative Velocity STD deviation

$\bar{H}$ = 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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A THEORETICAL AND EXPERIMENTAL INVESTIGATION OF AUTOMOBILE PATH DEVIATIONS WHEN DRIVER STEERS WITH NO VISUAL INPUT

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Theoretical and experimental investigations were conducted of automobile path deviations when a driver is attempting to steer his vehicle along a straight path with his vision occluded. A three-factor (car, subject, speed), two-level field experiment was carried out to test for main and interaction effects. Another field experiment was carried out to determine the effects of no steering control. In both experiments, the vehicle path deviations from the theoretical straight path were measured over several hundred feet and were used as the dependent variable. Both experiments were conducted on a flat airport runway under daylight and no-wind conditions. The experimental results indicate no significant car or subject effects but a highly significant speed effect and a significant car-subject interaction. Specifically, the standard deviations of the vehicle displacements from the theoretical straight path are considerably smaller at the higher speed for a given distance traveled under occluded vision. Further, the standard deviations of vehicle displacements for a given distance traveled are considerably larger for the no steering control condition than for the steering control condition with no visual input. The experimentally obtained data seem in basic agreement with the theoretical path deviation model. Based on the experimental data, the distribution of vehicle displacements for a given distance traveled under no visual input could be reasonably approximated by a normal distribution.

•AN UNCERTAINTY MODEL in which the driver is treated as an information processing device has been developed (4, 5). The analyses were based on steady-state driving in which the driver's vision was intermittently occluded, and on the assumption that a driver's uncertainty between two consecutive looks stems from (a) the loss of relevant road information ahead of him because he forgot or it became obsolete and (b) his uncertainty about the vehicle's lateral position on the road because of random disturbances in the orientation of the vehicle. This study, discussed in more detail elsewhere (1), deals only with vehicle position uncertainty and demonstrates that the functional relationship as derived (4, 5) cannot be supported by experimental evidence. A new functional relationship that is in better agreement with the experimental data is developed in this study. Theoretical studies dealing with driver steering control have been conducted by a number of authors (6) and are the background for the theoretical development of the new functional relationship.

THEORETICAL DEVELOPMENT

Review

As pointed out, this study deals only with lateral vehicle position uncertainty, which was derived (4, 5) as

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$$U_n(T) \propto V^2 \times T^{3/2} \quad (1)$$

where

$U_n(T)$ = uncertainty about the lateral position of the vehicle due to disturbances in the orientation of the vehicle for an occlusion time T in bits per second,
V = vehicle velocity in miles per second (km/s), and
T = occlusion time in seconds.

In developing Eq. 1, the researchers (4, 5) assumed that the uncertainty about the lateral position of the vehicle was proportional to the expected value of the root mean square displacement of the vehicle from the centerline of the lane, at time T. Hence, Eq. 1 can be rewritten as

$$\sigma_y \propto V^2 \times T^{3/2} \quad (2)$$

where σ_y = standard deviation of vehicle displacement from the centerline of the lane in inches (cm).

Therefore, point σ_y, rather than $U_n(T)$, will be used in this study. The functional relationship given by Eq. 2 implies that, for a given speed, σ_y increases with an increase in T. This agrees with what is observed in practice. To point out a further consequence of this functional relationship, we will compute the σ_y corresponding to the same distance of travel under occlusion and make comparisons at a low speed of 11 mph (18 km/h) and a high speed of 46 mph (74 km/h). To aid this comparison, we rewrite Eq. 2 as an equality.

$$\sigma_y = k \times D^2/T^{1/2} \quad (3)$$

where

D = distance traveled in feet (meters) at a constant velocity V during the occlusion time T,
V = D/T, and
k = a constant of proportionality that has been arbitrarily set at 0.0004 (0.011) to match an experimental estimate of standard deviation for 46 mph (74 km/h) at 210 feet (64 m).

Figure 1 shows the theoretically computed standard deviations of the lateral vehicle path displacements for the low speed and high speed obtained from Eq. 3 as a function of the distance traveled under occlusion. Figure 1 shows that, if a driver travels 200 feet (61 m) under occlusion at a constant speed, σ_y will be less for a low speed than for a high speed; i.e., the vehicle path variation will be greater at higher speeds than at lower speeds for the same distance traveled. This result clearly does not agree with the experimental evidence presented in this study.

Development of a New Functional Relationship

Let the position and orientation of the vehicle at time t seconds after the time occlusion started be as shown in Figure 2. It is assumed that the difference between the path angle and the heading angle on a straight road is negligible. Let y(t) be the lateral displacement of the vehicle after t seconds of occlusion. Then y(t) is the lateral velocity. Let V be the constant velocity and $\theta(t)$ be the heading angle of the vehicle with respect to the theoretical straight path. The lateral component of V can be expressed as $V \times \sin\theta(t)$. For small angles of $\theta(t)$, $\sin\theta(t) \simeq \theta(t)$. Hence,

$$\dot{y}(t) = V \times \theta(t) \quad (4)$$

$$\ddot{y}(t) = V \times \dot{\theta}(t) \tag{5}$$

The theory of driver steering control has been studied extensively by Weir and McRuer (6), who suggest three types of controls: heading angle, path angle, and lateral deviation. With visual feedback, lateral deviation control is the poorest of all. But during occlusion, when information on the path angle and heading angle does not exist, the lateral deviation model explains the possible steering control behavior of the drivers. In the lateral deviation control two types of information input exist. One is the actual deviation that the driver sees and the second is the lateral acceleration that he feels. For the situation considered here, the first type of input does not exist, and the lateral path change (2) is the double integral of the yaw velocity (rate of change of heading angle) response with an added minor effect, which is the integral of the side-slip velocity due to side-slip angle. If the difference between the path angle and the heading angle is considered negligible, then the lateral acceleration is assumed to be directly proportional to the rate of change of heading angle. Thus in the following theoretical development we will assume that the rate of change of heading angle is the only input for the driver-vehicle system and is characterized by Eq. 5. It should be noted that this assumption is very different from the assumption made by others (4, 5) that the rate of change of heading angle is related to the distance traveled, i.e., $\partial\theta/\partial x(t)$. Based on the literature the assumption made in this study seems to be more reasonable and justifiable. From Eq. 5 it follows that

$$y(t) = V \times \int_t \left\{ \int_t \dot{\theta}(t)\, dt \right\} dt \tag{6}$$

Figure 3a shows the combined driver-vehicle system having $\dot{\theta}(t)$ as the input and y(t) as the output. The system is assumed to be linear in that the system function operates on the input to give the output in the frequency domain. The system basically consists of two integrators (Fig. 3b). The system function is given by

$$H(s) = \frac{V(1 - e^{-sT})^2}{s^2} \tag{7}$$

To develop the model for y(t), we make certain assumptions about $\dot{\theta}(t)$ and y(t). $\dot{\theta}(t)$ is assumed to be a continuous Gaussian random process with the properties of ergodicity and white noise. The Gaussian assumption implies that $\dot{\theta}(t)$ has a normal distribution with mean zero and some variance. The white noise assumption implies that the process $\dot{\theta}(t)$ has a constant spectral density over the entire frequency range (Fig. 4a). It is also assumed that the system is sensitive to frequencies in the range of 0 to w_1 rad/sec only and that beyond this range the spectral density is zero. Within the range 0 to w_1, the spectral density G_θ is constant (Fig. 4b). The ergodic assumption states that the time average of $\dot{\theta}(t)$ is equal to its ensemble average. The output y(t) is assumed to be normally distributed with zero mean and some variance and also to have ergodic properties.

By definition the power density spectrum of y(t) denoted by G_y is equal to the product of the power density spectrum of $\dot{\theta}(t)$ and the square of the magnitude of the system function.

$$G_y = G_\theta \left| H(jw) \right|^2 \tag{8}$$

By the property of conjugate complex numbers,

$$\left| H(jw) \right|^2 = \frac{V^2}{W^2}(1 - e^{-JWT})^2 \times (1 - e^{+JWT})^2$$

Figure 1. Theoretically computed standard deviations of the vehicle path displacements when driver's vision is occluded.

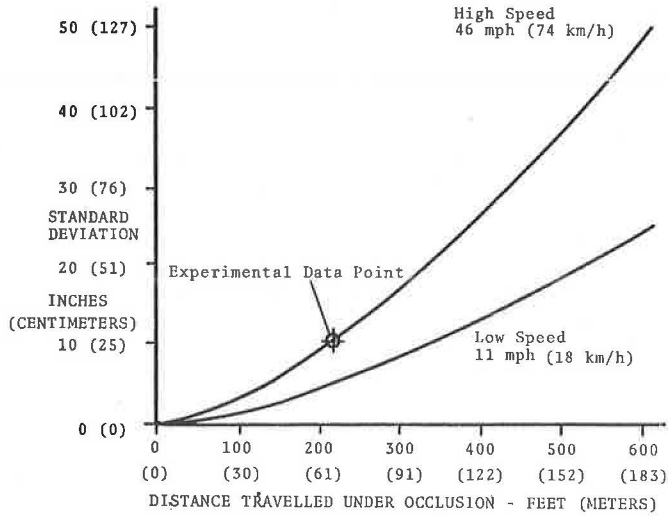


Figure 2. Vehicle position and heading angle after t seconds of occlusion.

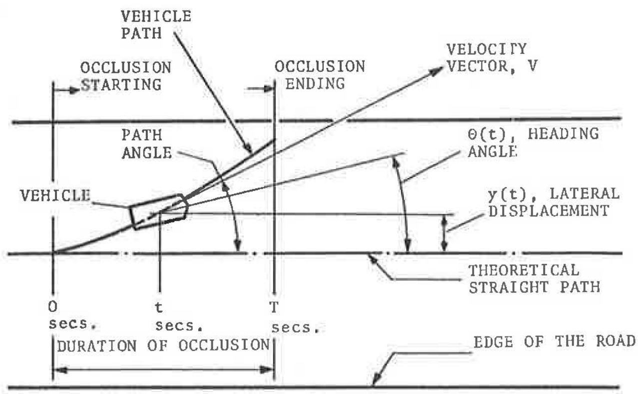


Figure 3. Combined driver-vehicle system.

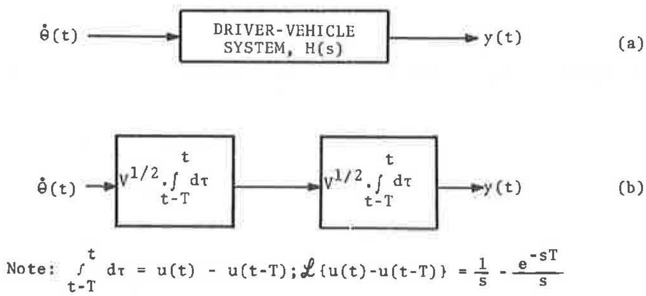
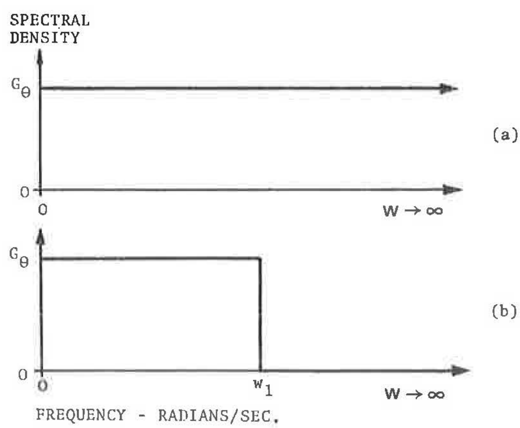


Figure 4. Spectral density of $\dot{\theta}(t)$.



Therefore,

$$G_y = G_\theta \frac{V^2}{w^4} (6 - 8 \cos wT + 2 \cos 2wT)$$

$$= \frac{4G_\theta V^2}{w^4} (1 - \cos wT)^2 \tag{9}$$

The average power of y(t), denoted by $\overline{y^2(t)}$, is the integral of G_y over the entire frequency range in rad/sec.

$$\overline{y^2(t)} = 4V^2 G_\theta \int_0^{w_1} \frac{(1 - \cos wT)^2}{w^4} dw \tag{10}$$

Substituting w = (z/T) in Eq. 10 and extending the upper limit of the integral to infinity give the average power as

$$\overline{y^2(t)} = 4V^2 G_\theta \int_0^{\infty} \frac{(1 - \cos z)^2 \times T^4}{z^4 T} dz$$

$$= 4V^2 T^3 G_\theta \int_0^{\infty} \frac{(1 - \cos z)^2}{z^4} dz \tag{11}$$

The integral in Eq. 11 is a constant. Hence,

$$\overline{y^2(t)} = kV^2T^3 \tag{12}$$

where k is a constant of proportionality. Because y(t) is assumed to ergodic, its time average of the second moment should be equal to its ensemble average of the second moment. Therefore,

$$\overline{y^2(t)} = E(y_T^2)$$

$$= E\left[(y - \bar{y})^2\right] \text{since } \bar{y} = 0$$

$$= \left[\sigma_{y_T}\right]^2 \tag{13}$$

Therefore, Eq. 12 can be written as

$$\left[\sigma_{y_T}\right]^2 = kV^2T^3 \tag{14}$$

$$\sigma_{y_T} = kVT^{3/2} \tag{15}$$

where k is a constant of proportionality. Because V is constant it can be substituted by D/T where D is the distance traveled during T. Thus

$$\sigma_{y_T} = kDT^{1/2} \tag{16}$$

Equation 16 represents the new functional relationship describing the behavior of the driver-vehicle system under conditions of no visual input. Figure 5 shows the implications of the new functional relationship for the same speeds used in Figure 1. The value of k in Eq. 16 was arbitrarily set at 0.025 (0.683) to match an experimental estimated standard deviation for 46 mph (74 km/h) at 210 feet (64 m). The new theoretical functional relationship leads to the following conclusions:

1. The standard deviation for the lateral vehicle displacements increases as the occlusion time increases, and
2. For the same distance traveled, the standard deviation will be smaller at a high speed than at a low speed.

Although the first conclusion is in agreement with the results from the previous functional relationship, the second is opposite. This can be observed by comparing the reversed locations of the two curves in Figures 5 and 1.

EXPERIMENTAL INVESTIGATION

The experimental investigation had two major objectives. First, the effect of vehicle speed on the standard deviation of lateral vehicle displacements was investigated for different travel distances under steering with no visual input to compare the predicted standard deviations with the previous functional relationship and with the functional relationship derived in this study. Second, an experimental investigation was also needed to determine whether the driver exercised any steering control while steering without visual input and whether the lateral vehicle displacements at different travel distances under steering with no visual input could be assumed to come from normally distributed populations.

Subjects

The subjects were 23-year-old graduate students who had driven approximately 20,000 miles (32 000 km). Both subjects had no physical handicaps, participated in the experiment voluntarily, and were not paid.

Experimental Arrangement and Procedure

The experiments were conducted on a concrete airport runway. The two cars used were a 1965 Volkswagen two-door sedan and a 1971 AMC Ambassador. To determine the vehicle path on the runway, we attached a marking device at the center of the rear bumper of the vehicles. It was a cylindrical device filled with a colored liquid that was released by a spring-operated valve at the nozzle. When the vehicle was in motion, the experimenter inside the car operated the valve by means of a cable. The deviation of this liquid trace from the centerline of the runway was measured at intervals of 15 feet (accuracy of $\pm\frac{1}{2}$ inch or 1 cm).

Basically the first experiment was a two-level, three-factor (car, subject, speed) factorial design with four replications and complete randomization of the eight observations in each replication. The car factor was qualitative and fixed, whereas the subject factor was qualitative and random. The speed was quantitative and fixed at 10 and 40 mph (16 and 64 km/h).

The first experiment consisted of 32 runs, all in the same direction, on the same day, during daylight, and with relatively no wind conditions. During each run the subject drove the car at a specified speed and oriented the car centerline as closely as possible to the runway centerline. On reaching a reference cross line, the experimenter instructed the subject to close his eyes and continue steering as straight as possible along the centerline of the runway. The run was terminated either because of too large a deviation toward the edge of the runway or after a distance of 500 feet (152 m). A stopwatch with 0.01-minute accuracy was used to measure the occlusion period.

The second experiment was carried out with one subject only and the AMC car. A total of 60 runs were made at a speed of 30 mph (48 km/h). Of the 60 runs, 47 were with steering control and no visual input and 13 were with no steering control. The experimental arrangement and equipment and the procedure for conducting the experiment and measuring the vehicle path deviations were basically the same as those used in the first experiment except that, when the subject had no steering control, he was not asked to close his eyes. Instead, he was asked to take his hands off the steering wheel until the run was completed.

Figure 5. Theoretically computed standard deviations of the vehicle path displacements when driver's vision is occluded based on the new functional relationship.

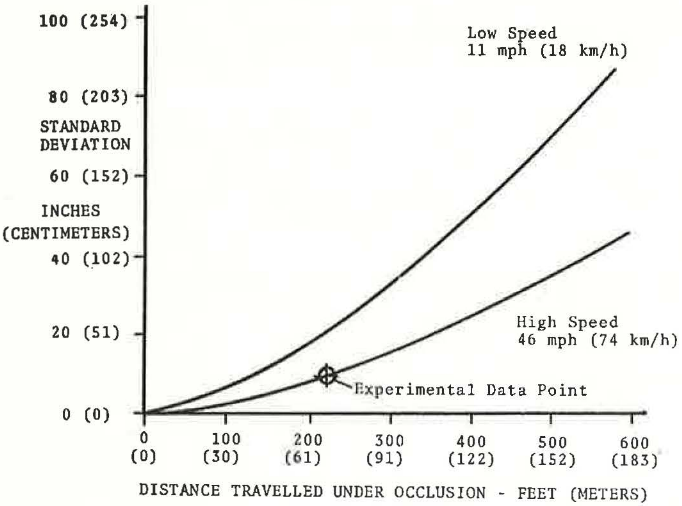
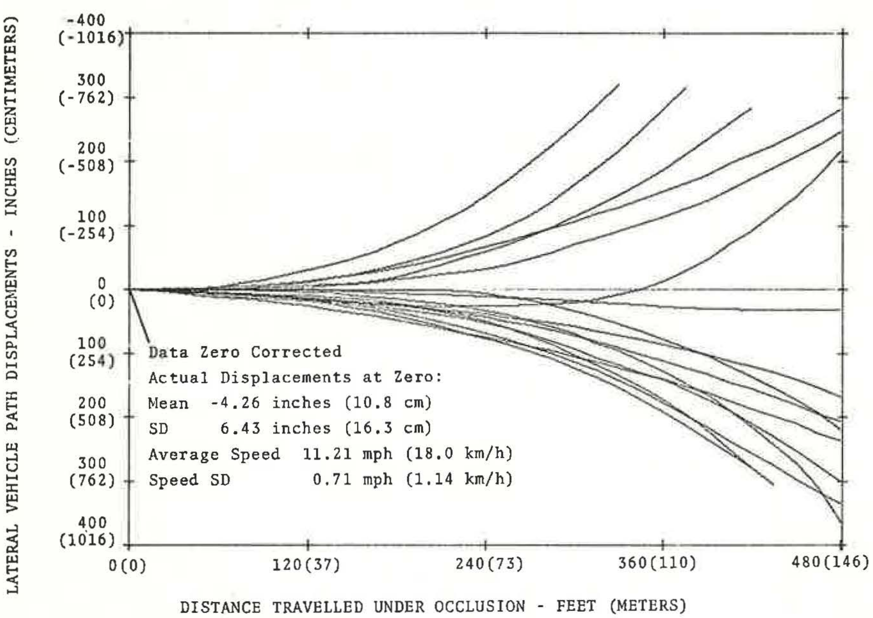


Figure 6. Vehicle paths of low-speed runs in experiment 1.



RESULTS

The vehicle paths for the two speed conditions in experiment 1 are shown in Figures 6 and 7. These data were zero corrected; i.e., the vehicle's lateral deviation from the centerline at the start of each occlusion run was subtracted from the measurements made at 15-foot (4.6-m) intervals. A cursory examination of Figures 6 and 7 reveals that the pattern of the vehicle paths is considerably wider at the low speed than at the high speed.

We used the zero-corrected vehicle path deviations to perform full-model analyses of variance of all 32 occlusion runs at 15-foot (4.6-m) intervals from 15 to 330 feet (4.6 to 101 m). These analyses showed that the car-speed and subject-speed interactions were not significant, and hence a revised model, without these two interactions, was formulated. Based on the ANOVA the speed effect was significant ($p < 0.05$) for all distances investigated beyond 75 feet (22.8 m). Further, the car-subject interaction was not insignificant. Hence, the standard deviations of vehicle displacements were computed from the zero-corrected path deviations for each 15-foot (4.6-m) interval for each of the car-subject-speed combinations. Figure 8 shows these standard deviations of the vehicle displacements as a function of the occlusion distance. The curves plotted in Figure 8 show that, for each car-subject combination, the standard deviation of the vehicle displacements is greater for the low-speed condition than for the high-speed condition. Hence the previously made observation from Figures 6 and 7 about the vehicle path patterns for the two instructed speeds is confirmed. Further, a comparison of Figures 5 and 8 shows that the functional relationships of the theoretical and the experimental curves are very similar.

The average speed for each of the 32 occlusion runs was computed by dividing the distance traveled by the corresponding time. These speeds were from 0 to 12 percent higher than the instructed speeds, and the relative speed variation, or the coefficient of variation, was between 6 and 8 percent within each speed-subject combination.

The vehicle path measurements for each 15-foot (4.6-m) interval from the second experiment were again zero corrected and also angle corrected; i.e., the heading angle of the vehicle at the start of occlusion was determined and used as the theoretical straight line. The standard deviations of vehicle displacements as a function of the distance traveled for zero- and angle-corrected path deviations for the no steering and the no visual input conditions are shown in Figure 9. The standard deviations for the angle-corrected data are somewhat smaller than for the zero-corrected data. However, the standard deviations for the no steering conditions are larger with both corrections than with the no visual input condition. The variances of the vehicle path displacements for the no steering and the steering with no visual input conditions were used to form F-ratios at every 15-foot (4.6-m) interval. For distances greater than 100 feet (30.5 m), these F-ratios were significant at the 0.01 level indicating that the variability in the path deviations with the two conditions is different.

The zero- and angle-corrected path deviations from the 47 runs with steering and no visual input were tested for normality at 15-foot (4.6-m) intervals beginning at the start of occlusion. Kolmogorov-Smirnov tests indicated that, for the investigated occlusion distance range of 0 to 450 feet (137 m), the observed maximum absolute differences for both zero- and angle-corrected path deviations were in most cases well below the allowable difference value of 0.21 for a sample size of 47 and a 0.05 significance level. The absolute differences were somewhat smaller for the angle-corrected path deviation data. These results indicate that the lateral vehicle displacements along the occlusion path can be reasonably assumed to come from normally distributed populations.

CONCLUSIONS

A new functional relationship describing the behavior of the driver-vehicle system under conditions of steering with no visual input was developed. According to this new relationship, the standard deviation for the vehicle path displacements at a given distance will be smaller at a high speed than a low speed at the same distance, which is opposite to what the functional relationship derived previously (4, 5) suggests. The results of the new functional relationship are well supported by the results of the first experiment.

Figure 7. Vehicle paths of high-speed runs in experiment 1.

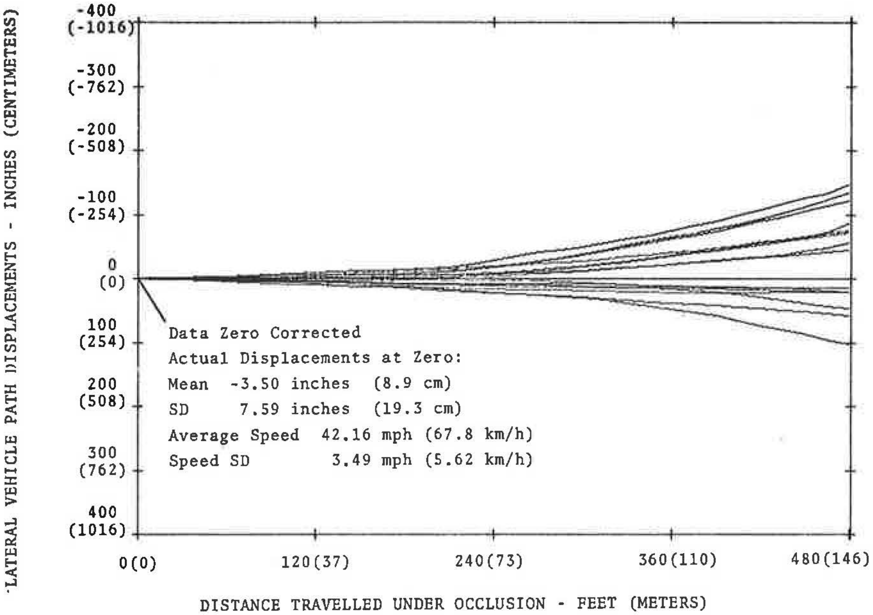


Figure 8. Standard deviations of vehicle displacements as a function of the occlusion distance for zero-corrected data for all car-subject-speed combinations.

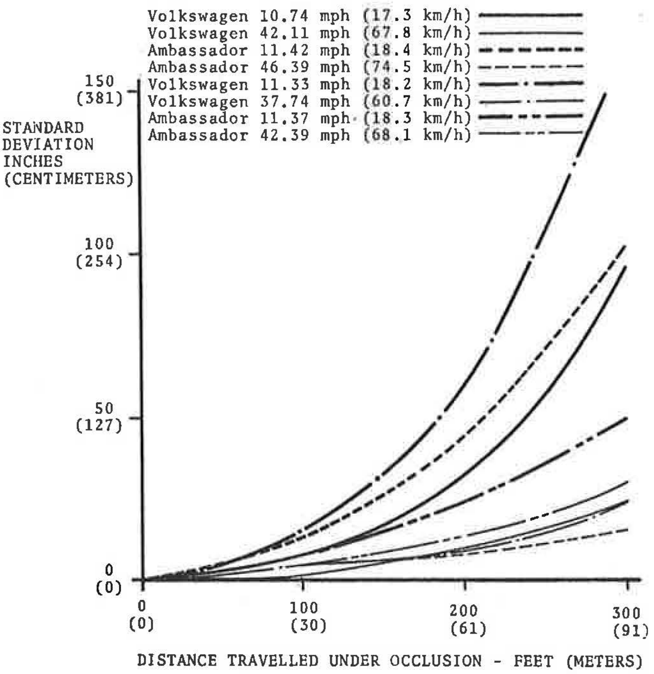


Figure 9. Standard deviations of vehicle displacements as a function of the occlusion distance for zero- and angle-corrected data for the no steering and steering with no visual input conditions.

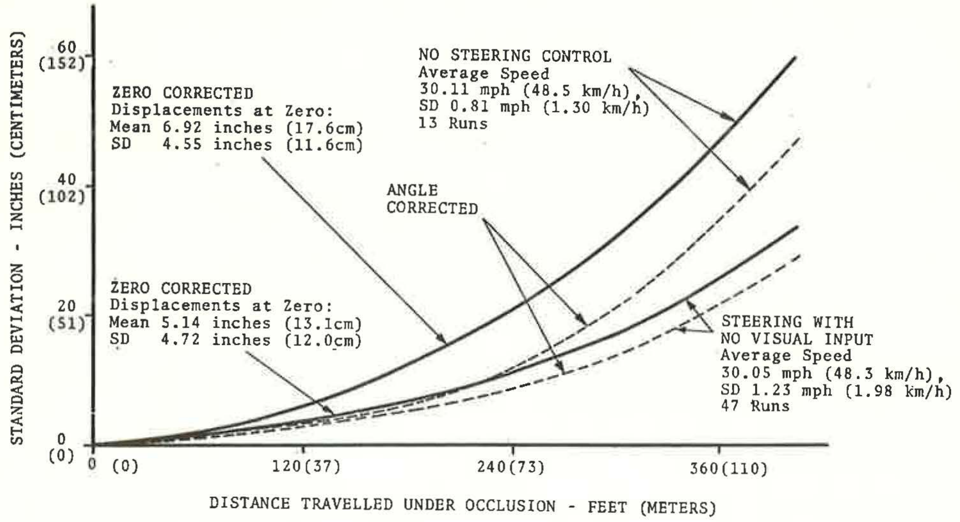
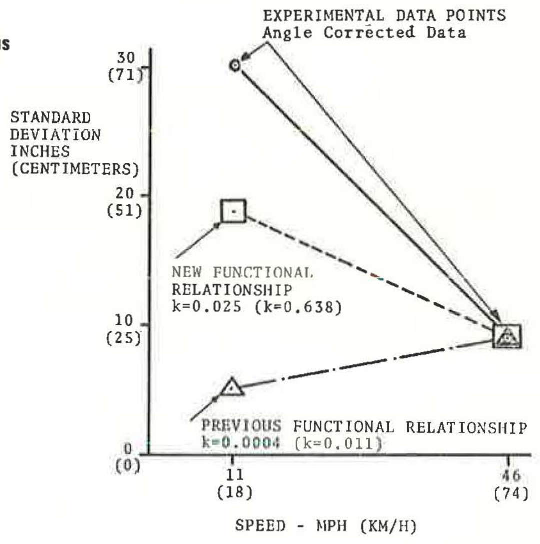


Figure 10. Standard deviation of vehicle path displacements at 210 feet (64 m) versus speed based on the two functional relationships and experimental data.



Analysis of the data in experiment 1 indicated that vehicle speed has a significant effect on the vehicle path displacements when the driver steers during occlusion. For any distance traveled the path variability about the intended straight path as indicated by the standard deviation of the lateral vehicle path displacements was significantly higher at the low speed than at the higher speed. Figure 10 shows the standard deviations at 210 feet (64 m) based on both functional relationships and on the angle-corrected data of the Ambassador driven at low and high speeds in experiment 1. The constants of proportionality used in both functional relationships were arbitrarily fixed so that the standard deviations obtained were equal to the standard deviation for one subject driving at the high speed. The new functional relationship shown in Figure 10 depicts the behavior of the driver-vehicle system under steering with no visual input much better. Another important result obtained by the analyses of variance of experiment 1 data is the relatively large effect of the car-subject interaction. Figure 8 showed that for each car-subject combination the standard deviation was always smaller for the higher speed than for the low speed; therefore, the speed effect conclusion is not affected.

What cues does the driver respond to when steering with no visual input, and why is there better lateral control at higher speeds than at lower speeds at a given distance traveled? In the first part of this study it was mentioned that the concept of lateral acceleration control may be assumed to exist under occlusion. It is an established fact in vehicular dynamics that the lateral accelerative forces are higher at high speeds than at low speeds. It is reasonable to assume that the driver is able to sense these higher lateral forces relatively efficiently. This means that the sensing of cues in the form of lateral forces related to vehicle displacement and the driver's responding to these cues are better at higher speeds than at lower speeds. Figure 10 shows that the standard deviation obtained by the new functional relationship for the low speed is considerably below the actual standard deviation obtained. This could be because the new functional relationship has an implied assumption that the driver's response is proportional to the lateral forces, whereas in practice the driver is sensitive to lateral forces only beyond a certain threshold value. This characteristic of human behavior has been clearly demonstrated in test-driver technique studies (3). It is left to future research to include a correction factor for a human threshold for lateral acceleration in the new theoretical model.

Based on the results of the second experiment, we may conclude that the vehicle path variability is significantly less when the driver steers with no visual input than when he has no steering control. This indicates that the driver does exercise some positive lateral control through steering even when he does not get the normally available cues such as heading angle, path angle, and lateral displacement. In addition, we may also conclude that the lateral vehicle path displacements at a given distance traveled with occluded vision are normally distributed. This result indicates the inherent nature of the vehicle path displacement data and is helpful in the selection of the appropriate statistical tests for analysis of lateral vehicle path displacement data.

This study has demonstrated that the vehicle position uncertainty component as derived (4, 5) cannot be supported by experimental evidence and is thus incorrect. The new model derived is in better agreement with the experimental data. The authors did not determine how much error this incorrect vehicle position uncertainty component introduces into the uncertainty model advanced by others (4, 5) nor in the estimates and conclusions derived from it because there is a high probability that the results of a pending experimental investigation will show that the uncertainty component can also not be validated experimentally.

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DISCUSSION

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The authors have provided an enlightening treatment of a relatively complex subject. Automobile handling and driver control are contributing factors in accidents, and quantification and clarification of the underlying parameters can be of potential benefit. The following comments relate mainly to clarification and interpretation; their basic approach, which combines analytical modeling and experimental verification, has yielded useful results.

The authors' model for the driver-vehicle system (Fig. 3) is a relatively simple one. It assumes that the primary perceptual cue for steering control is a lateral acceleration component due to heading rate times forward speed. Although this approximation for lateral acceleration can be reasonably good for nominal lane keeping in a straight line, the neglect of other lateral acceleration components (such as side-slip rate) may be important when the model is extended to large-amplitude maneuvers or limit-of-performance situations. Further, the lateral acceleration approximation used applies to motions of the vehicle mass center. If the driver is located ahead of (or behind) the vehicle mass center, an additional acceleration component that is the product of the moment arm from the mass center and the heading angle acceleration arises. This latter term can become significant if the displacement from the mass center is on the order of 1 or 2 feet (0.3 or 0.6 m) or more. This can occur, for example, in the case of a rear-engine automobile or with utility vehicle configurations such as vans where the driver is seated near the front. Rolling and pitching accelerations can also cause similar effects. Including these acceleration terms in the linear dynamic model of the vehicle is relatively straightforward, and this might be a useful step in extensions of the present work.

As the authors note, the driver can obtain the lateral acceleration cue from proprioceptive or tactile sensors. The cue can also be sensed vestibularly via the semicircular canals (heading rate) or from the otoliths (lagged linear acceleration). As noted above, the nature of the acceleration will vary depending on the sensor location within the vehicle and, hence, the point within the driver's body at which the acceleration is sensed. Furthermore, these several sensors can have different dynamic properties and thresholds, and it might be of interest to take such factors into account in any future studies of this particular driving situation.

The simple driver-vehicle model form shown in Figure 3 implies that the driver's steering response is proportional to the sensed lateral acceleration error when the driver is attempting to maintain a straight line. The data and theory of manual control indicate that a more complete model for this situation would include a driver time delay of a fraction of a second as well as some driver lag equalization or "smoothing" of his response. The driver would provide this equalization to obtain better low-frequency lateral placement control, while at the same time suppressing his response to relatively high-frequency disturbances and vehicle heading motions. The subjects in the experiments described may in fact have been using these more characteristic forms of steering control. Because the vehicle trajectory data shown provide only an overall response measure it would be difficult to distinguish the detailed form of the driver's response and adaptation, given only those data. Nevertheless, these driver processing factors could be taken into account in a more detailed analysis of this driving task.

The authors are to be commended for their ingenuity in obtaining the lateral placement and trajectory measures. These kinds of measures have always plagued experimenters, and their use of direct pavement markings seems to have worked well in this case.

When the results of experiment 1 are reviewed, it would be helpful to know what the specific instructions to the subjects were prior to the runs, inasmuch as the nature of the instructions may have influenced the form of control behavior the drivers adopted. Similarly, experiment 2 might have had a somewhat different outcome had the subjects been instructed to hold the steering wheel fixed in a centered position rather than releasing the steering wheel as was apparently the case. With the steering wheel free the directional dynamics of the vehicle change, because of the steering subsystem dynamics and the tire-aligning torques, whereas with the steering wheel held fixed the vehicle dynamics are the same as when the driver is providing active control of steer angle (position) as in experiment 1.

The results appear to confirm the authors' analytical interpretation of vehicle performance under these conditions, and they seem to provide a better explanation of the data than does the Senders' Hypothesis. Further experiments in this area could use the more detailed human operator response models available that take into account the effect of perceptual thresholds, for example, as suggested by the authors.

AUTHORS' CLOSURE

We wish to thank Weir for his comments, which indicate that the problem of driver steering control under the conditions discussed in this paper could be modeled by considering a number of vehicle and human variables giving explicit consideration to every one of them. Weir pointed out that the model could be extended by giving special consideration to side-slip rate, the position of the driver from the vehicle mass center, and also human operator lag.

Almost all the improvements suggested earlier have been incorporated in a number of earlier studies related to either vehicle dynamics or driver-vehicle system. The main reason for considering a simple model in this study was its sufficiency to carry out study objectives. The aim was to investigate the functional relationship that is frequently referred to and used in a number of human information processing studies (4, 5). Hence, a macroscopic approach was taken to consider the changes that take place because of changes in the driver-vehicle system as a stochastic process with the random input $\dot{\theta}(t)$. We feel that our experimental results are due to driver behavior at different speeds because the experimental design and procedures used kept the effects of variables other than driver behavior to a minimum or balanced them under different levels of experimental factors.

When this study is extended, the first step will be to incorporate the self-aligning torque and a time lag for the human operator into the present relationship. The driver could use lateral acceleration as a cue at high speeds and the feel of steering as a cue at low speeds.

TRENDS IN BLOOD ALCOHOL CONCENTRATION LEVELS OF NIGHT DRIVERS

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As part of the Fairfax alcohol safety action project (ASAP), two roadside surveys have been conducted in Fairfax, Virginia. A base-line survey was conducted in January 1972 prior to the start of ASAP operations in February 1972, and a second survey was conducted in October 1972. The ASAP concept recognizes the major role that alcohol plays in fatal and serious highway crashes, and the project consists of countermeasures designed to identify drunken drivers, remove them from the road, and refer them to proper educational or rehabilitation programs. The ultimate objective of the ASAP is to reduce the number of accidents caused by the drinking driver. The purpose of the roadside surveys of randomly selected drivers is to provide a secondary measure of the project's effectiveness in reducing the incidence of driving under the influence of alcohol. This paper compares the blood alcohol concentrations of drivers in the base-line survey with those during the second survey.

•THE FAIRFAX alcohol safety action project (ASAP) was initiated in January 1972 as one of a number of 3-year, federally funded demonstration projects designed to implement and evaluate comprehensive community alcohol countermeasures to the problem of drunken driving. The ultimate objective of the Fairfax ASAP is to reduce the number of crashes that result in fatalities, personal injuries, and property damage by reducing the incidence of drunken driving. Drunken drivers account for a disproportionately large share of serious and fatal accidents. If the ASAP is successful in affecting the normal driving patterns of drunken drivers so that they drive less under the influence, it follows that the number of alcohol-related accidents will be reduced.

The purpose of conducting roadside surveys at night is to provide a secondary measure of the project's effectiveness in reducing the incidence of drunken driving. The base-line roadside survey was conducted before the ASAP countermeasures were implemented. Base-line survey results were established as the base against which changes in drinking habits as indicated in the subsequent yearly surveys could be measured. The second survey was conducted after 9 months of ASAP operations. Because the ASAP countermeasures were operative for only 9 months before the second roadside survey, there may not have been enough time for ASAP to have had a measurable impact. Therefore, any trends identified or conclusions drawn from the comparison of the first two surveys are tentative.

METHODOLOGY

The basic survey procedures were patterned after the procedures outlined in a report by Perrine (1) of the University of Vermont. The two primary functions of the roadside surveys as stated in Perrine's report are "to provide data for describing the basic problem in terms of identification and specification of assumedly relevant parameters, and to provide data for evaluating the results of any changes in circumstances surrounding the basic problem, whether they are the result of unplanned natural events, on the one hand, or controlled premeditated countermeasures, on the other."

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Sampling Frequency

There will be a total of four roadside surveys during the Fairfax ASAP. The first survey was conducted each night from January 5 through the early morning hours of January 16, 1972. The base-line survey had to be conducted in January because comparative data had to be collected before implementation of the enforcement countermeasure on February 1, 1972, and when the five cooperating police agencies in the area could be of assistance. The second survey was conducted in October 1972, and the two subsequent surveys are scheduled for the month of October. October was selected for the surveys so that the annual changes in BAC levels would reflect fewer seasonal variations in drinking patterns. In addition, the survey results would be available in time for analysis and inclusion in the annual evaluation report. In a more practical vein, the weather in October is more conducive to taking an outdoor survey.

Sample Size and Day of the Week

U.S. Department of Transportation guidelines specify a minimum sample size of 640. The guidelines also suggest that the samples be taken on Friday and Saturday nights. However, ASAP surveys conducted throughout the week in North Carolina and Michigan produced positive readings of 22.2 and 19.0 percent compared with the positive reading of 42.0 percent reported by the Oregon ASAP conducted only on Fridays and Saturdays; therefore, both test periods were considered important. Testing during both periods would reveal those periods that showed the greatest number of drunken drivers so that police patrols could be increased appropriately. Thus, both the base-line and second surveys were conducted on weekends and weeknights. With minimum sample sizes of 640 for both weeknights and weekends (Friday, Saturday), a total of three sets of statistics on the levels of drinking by night drivers can be measured on weekends, on weeknights, and in the aggregate.

Hour of Day

Sampling hours for the drinking driver patterns in Fairfax were 7 p.m. to 3 a.m. This 8-hour period was divided into three 2-hour-20-minute periods in which the interviews were conducted and 1 hour for travel between sites. The time periods were 7:00 to 9:20 p.m. (site 1), 9:50 p.m. to 12:10 a.m. (site 2), and 12:40 to 3:00 a.m. (site 3). Using three time frames instead of the four suggested by the U.S. DOT guidelines allowed us to increase the amount of interview time by reducing the travel time between sites by 33 percent.

Site Selection

The locations for survey sites were roughly proportioned among the five participating police jurisdictions on the basis of their resident populations and the number of police officers. This achieved representative sampling of the various driving conditions in Fairfax and involved all of the police departments from the very beginning of the ASAP. After asking the police departments for a list of sites that conformed to the U.S. DOT guidelines, a staff member of the Virginia Highway Research Council reviewed this list. Sites were selected that seemed to be a representative mixture of rural and urban areas in Fairfax dispersed throughout the county. The final selection of sampling sites was based on keeping travel time between sites under 25 minutes. Thus the driving population was sampled randomly within the constraints of travel time and research design.

Questionnaire and Equipment

The standard U.S. Department of Transportation questionnaire for roadside surveys was used. This questionnaire consisted of questions on the respondent's place of residence, driving habits, drinking habits, drinking attitudes and knowledge, and demographic data and, most importantly, the BAC reading on the breath test.

The breath-testing device for the base-line survey was the Intoximeter-Mark II.

Both the Intoximeter and the HALT breath-testing machine were used on the second survey.

Administrative Procedure

The five participating police departments provided the necessary patrolmen for traffic control. The coordinators were staff members of the Safety Section of the Virginia Highway Research Council. The interviewers and data recorders were provided under a subcontract, and the breath-test operators were ASAP lab technicians provided by Fairfax County.

The coordinators selected the vehicles to be stopped by the policemen, designating the first eligible vehicle whenever a vacancy existed within the mobile vans used for interviews. The policemen simply directed the motorist out of the line of traffic and over to the coordinators. The coordinators requested the motorist's cooperation in the survey. After securing a motorist's cooperation, the coordinator led the driver to one of the two interview vans where he was greeted by a lab technician, who immediately administered the breath test. Then the driver was given the questionnaire, and, by the time the questionnaire was finished, his BAC reading had been calculated and was recorded on the questionnaire. The coordinator thanked the motorist for his cooperation, and he was allowed to proceed on his way if his BAC reading was under 0.10 percent. Those drivers whose BAC was 0.10 percent or greater were given the options of being driven by a sober passenger when available, by a member of the local Jaycees, or by volunteers from the military. Subjects who were only slightly above 0.10 percent were given the option of remaining at the site until their BAC dropped below 0.10 percent upon retesting.

DISCUSSION OF FINDINGS

Summaries of the BAC results are given in Table 1. Comparisons of BACs from the base-line and the second surveys were made from these data.

Total Sample

Comparison of the distribution of BACs for the total sample gave a chi-square value of 18.845. This surpassed the value of 13.277, which is used to establish significance at the 99 percent confidence level for four degrees of freedom. Thus the two distributions were found to be significantly different at the 99 percent confidence level.

After the distributions were found to be significantly different, they were tested to determine in what ways they were different. The percentages of positive BACs were 29.2 for the base-line survey and 35.9 for the second survey. These two percentages were compared and found to be significantly different at the 99 percent confidence level. It can be concluded that there was a greater percentage of positive BAC readings on the second survey than on the base-line survey.

The percentages of BACs above 0.10 percent were 4.2 for the base-line survey and 4.1 for the second survey. These two percentages were not found to be significantly different at even the 20 percent confidence level.

Weeknight Sample

Comparison of BAC distributions for weeknights yielded a chi-square value of 15.822, and the two distributions were found to be significantly different at the 99 percent confidence level.

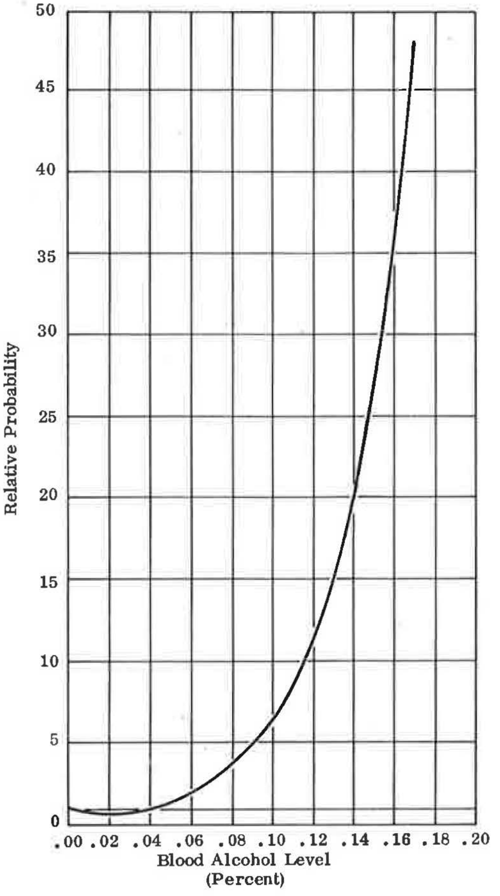
The percentages of positive BACs on weeknights were 25.8 on the base-line survey and 31.6 on the second survey. These two percentages were compared and found to be significantly different at the 99 percent confidence level. It can be concluded that there was a greater percentage of positive BAC readings in the second survey than in the base-line survey.

The percentages of BACs above 0.10 percent were 3.4 for the base-line survey and 4.5 for the second survey. These two percentages were not significantly different at the 95 percent confidence level, so no conclusions can be drawn concerning the difference.

Table 1. BAC levels in roadside surveys.

Sample	BAC Category	Base-Line Survey Number	Base-Line Survey Percent	Second Survey Number	Second Survey Percent
Total	Negative	1,116	70.8	966	64.1
	01 to 04	293	18.6	356	23.6
	05 to 09	101	6.4	123	8.2
	10 to 14	43	2.7	46	3.0
	15 or more	24	1.5	17	1.1
Weeknight	Negative	622	74.2	571	68.4
	01 to 04	139	16.6	169	20.2
	05 to 09	49	5.8	58	6.9
	10 to 14	20	2.4	28	3.4
	15 or more	8	1.0	9	1.1
Weekend	Negative	494	66.9	395	58.7
	01 to 04	154	20.8	187	27.8
	05 to 09	52	7.0	65	9.6
	10 to 14	23	3.1	18	2.7
	15 or more	16	2.2	8	1.2

Figure 1. Relative probability of causing an accident (2).



Weekend Sample

Comparison of the BAC distributions for weekends gave a chi-square value of 7.219. Thus the weekend distributions were not significantly different at the 95 percent confidence level, although they were significant at the 80 percent level.

The percentages of positive BACs were 33.1 for the base-line survey and 42.3 for the second survey. These percentages were found to be significantly different at the 99 percent confidence level. It can be concluded that a greater percentage of drivers had positive BACs on the second survey than on the base-line survey.

The percentages of BACs above 0.10 percent were 5.3 for the base-line survey and 3.9 for the second survey. These percentages were not significantly different at the 95 percent confidence level, so no conclusions can be drawn concerning the difference.

INDEX OF ACCIDENT PROBABILITY

The traditional chi-square method for comparing BAC distributions has been used quite often to compare the drinking patterns in one state with those in another or to compare drinking patterns within a state over a period of time. The analysis presented shows that there was a greater percentage of drinking drivers on the second survey than on the first, but the percentages of drivers who were drunk were not found to be significantly different. However, there is one important fact missing from the previous analysis. Drunken drivers represent only about 4 percent of the driver population, yet they account for 50 percent of all highway fatalities. This disproportionate representation of the drunken driver is not taken into account by a chi-square analysis inasmuch as this analysis assigns an equal value to every category. The method of analysis suggested proposes to include the vital "risk factor" by using the probability of causing an accident (Fig. 1) as developed by Borkenstein in his study of drinking drivers (2). An index of accident probability (IAP) was calculated by multiplying the percentage of drivers in each BAC category by the risk index of that category and then summing the products. In addition to simply comparing the BAC levels, we can compare the relative probabilities of an accident from one survey to another and from one time period to another.

The risks assigned to the BAC levels are as follows:

BAC Category	Risk Index
Negative	1
01 to 04	1
05 to 09	3
10 to 14	12
15 or more	27

Total Sample Comparison

The IAP for the total sample in the base-line survey was 1.815, and that for the second survey was 1.780 (Table 2). This represents a decrease of 1.9 percent in accident probability from the base-line survey even though the previous analysis determined that there were more drivers who had been drinking.

Weeknight Sample Comparison

The IAP for weeknights of the base-line survey was 1.640, whereas that on the second survey was 1.798. This represents an increase of 9.6 percent in the relative accident probability for the weeknight periods.

Weekend Sample Comparison

The IAP for weekends of the base-line survey was 2.053 compared with 1.801 for the second survey. This represents a decrease of 12.3 percent in the relative risk of accidents on weekends from the base-line survey. Although the relative risk of accidents on weekends was reduced by 12.3 percent, it was still higher on weekends than on weeknights as reflected in the IAPs of 1.801 and 1.798 during the second survey.

Table 2. Index of accident probability applied to base-line and second surveys.

Sample	BAC Category	Risk Index	Base-Line Survey Percentage	Base-Line Survey Value	Second Survey Percentage	Second Survey Value
Total	0	1	0.708	0.708	0.641	0.641
	01 to 04	1	0.186	0.186	0.236	0.236
	05 to 09	3	0.064	0.192	0.082	0.246
	10 to 14	12	0.027	0.324	0.030	0.360
	15 or more	27	0.015	0.405	0.011	0.297
		IAP		1.815		1.780
Weeknight	0	1	0.742	0.742	0.684	0.684
	01 to 04	1	0.166	0.166	0.202	0.202
	05 to 09	3	0.058	0.174	0.069	0.207
	10 to 14	12	0.024	0.288	0.034	0.408
	15 or more	27	0.010	0.270	0.011	0.297
		IAP		1.640		1.798
Weekend	0	1	0.669	0.669	0.587	0.587
	01 to 04	1	0.208	0.208	0.278	0.278
	05 to 09	3	0.070	0.210	0.096	0.288
	10 to 14	12	0.031	0.372	0.027	0.324
	15 or more	27	0.022	0.594	0.012	0.324
		IAP		2.053		1.801

Table 3. IAP for total sample by time period.

Time Period	BAC Category	Risk Index	Base-Line Survey Percentage	Base-Line Survey Value	Second Survey Percentage	Second Survey Value
7:00 to 9:20 p.m.	0	1	0.809	0.809	0.694	0.694
	01 to 04	1	0.142	0.142	0.230	0.230
	05 to 09	3	0.033	0.099	0.052	0.156
	10 to 14	12	0.010	0.120	0.018	0.216
	15 or more	27	0.006	0.162	0.006	0.162
		IAP		1.332		1.458
9:50 p.m. to 12:10 a.m.	0	1	0.715	0.715	0.697	0.697
	01 to 04	1	0.194	0.194	0.219	0.219
	05 to 09	3	0.065	0.195	0.059	0.177
	10 to 14	12	0.019	0.228	0.019	0.228
	15 or more	27	0.007	0.189	0.005	0.135
		IAP		1.521		1.456
12:40 to 3:00 a.m.	0	1	0.488	0.488	0.496	0.496
	01 to 04	1	0.262	0.262	0.267	0.267
	05 to 09	3	0.126	0.378	0.148	0.444
	10 to 14	12	0.077	0.924	0.062	0.744
	15 or more	27	0.047	1.269	0.026	0.702
		IAP		3.321		2.653

Table 4. IAP for weeknight sample by time period.

Time Period	BAC Category	Risk Index	Base-Line Survey Percentage	Base-Line Survey Value	Second Survey Percentage	Second Survey Value
7:00 to 9:20 p.m.	0	1	0.817	0.817	0.767	0.767
	01 to 04	1	0.129	0.129	0.178	0.178
	05 to 09	3	0.034	0.102	0.031	0.093
	10 to 14	12	0.010	0.120	0.021	0.252
	15 or more	27	0.010	0.270	0.003	0.081
		IAP		1.438		1.371
9:50 p.m. to 12:10 a.m.	0	1	0.727	0.727	0.700	0.700
	01 to 04	1	0.191	0.191	0.216	0.216
	05 to 09	3	0.063	0.189	0.057	0.171
	10 to 14	12	0.016	0.192	0.021	0.252
	15 or more	27	0.003	0.081	0.006	0.162
		IAP		1.380		1.501
12:40 to 3:00 a.m.	0	1	0.532	0.532	0.543	0.543
	01 to 04	1	0.226	0.226	0.214	0.214
	05 to 09	3	0.129	0.387	0.143	0.429
	10 to 14	12	0.089	1.068	0.071	0.852
	15 or more	27	0.024	0.648	0.029	0.783
		IAP		2.861		2.821

INDEX OF ACCIDENT PROBABILITY BY TIME PERIOD

The distributions of BACs were found to be significantly different from one time period to another, for there were more people drinking and more drunken drivers in the sample at the latest time period, 12:40 to 3:00 a.m. The test periods were examined by assigning them IAPs so that the relative risks of accidents could be compared from one time period to another.

Total Sample Comparison

The IAP for 7:00 to 9:20 p.m. was a very low one of 1.332 during the base-line survey compared with 1.458 for the second survey (Table 3). This represents an increase of 9.5 percent from the base-line survey, but it is still a relatively low IAP.

The IAPs for the time period of 9:50 p.m. to 12:10 a.m. were 1.521 for the base-line survey and 1.456 for the second survey. This represents a 4.3 percent decrease from the base-line survey.

The IAPs for 12:40 to 3:00 a.m. were 3.321 for the base-line survey and 2.653 for the second survey. This represents a decrease of 20.1 percent from the base-line survey, but this time period still ranked as the most dangerous. This decrease could reflect the impact of the ASAP police patrolling during the time period.

Weeknight Sample Comparison

IAPs for 7:00 to 9:20 p.m. on weeknights were 1.438 for the base-line survey and 1.371 for the second survey (Table 4). This represents a 4.7 percent decrease from the base-line survey and is a relatively low IAP.

The IAPs for 9:50 p.m. to 12:10 a.m. on weeknights were 1.380 for the base-line survey and 1.501 for the second survey. This represents an increase of 8.8 percent from the base-line survey.

IAPs for 12:40 to 3:00 a.m. on weeknights were 2.861 for the base-line survey and 2.821 for the second survey. There was very little change from the base-line survey for this time period on weeknights: a decrease of only 1.4 percent. Such a slight reduction might indicate that more ASAP police patrols should be scheduled for this time period on weeknights rather than for earlier hours.

Weekend Sample Comparison

IAPs for 7:00 to 9:20 p.m. on weekends were a very low one of 1.183 for the base-line survey and 1.574 for the second survey (Table 5). This increase of 33.1 percent was large on a percentage basis, but the IAP of 1.574 was still relatively low when compared with those of other time periods.

IAPs for 9:50 p.m. to 12:10 a.m. on weekends were 1.705 for the base-line survey and 1.408 for the second survey. This represents a decrease of 17.4 percent from the base-line survey and might indicate that the ASAP police patrols do affect weekend drinking and driving patterns in Fairfax.

The IAP for 12:40 to 3:00 a.m. on weekends was 3.580 for the base-line survey, and that for the second survey was 2.513. This is a decrease of 29.8 percent from the base-line survey and seems to indicate that the ASAP police patrol has effected modification in weekend drinking and driving patterns in Fairfax.

CONCLUSIONS

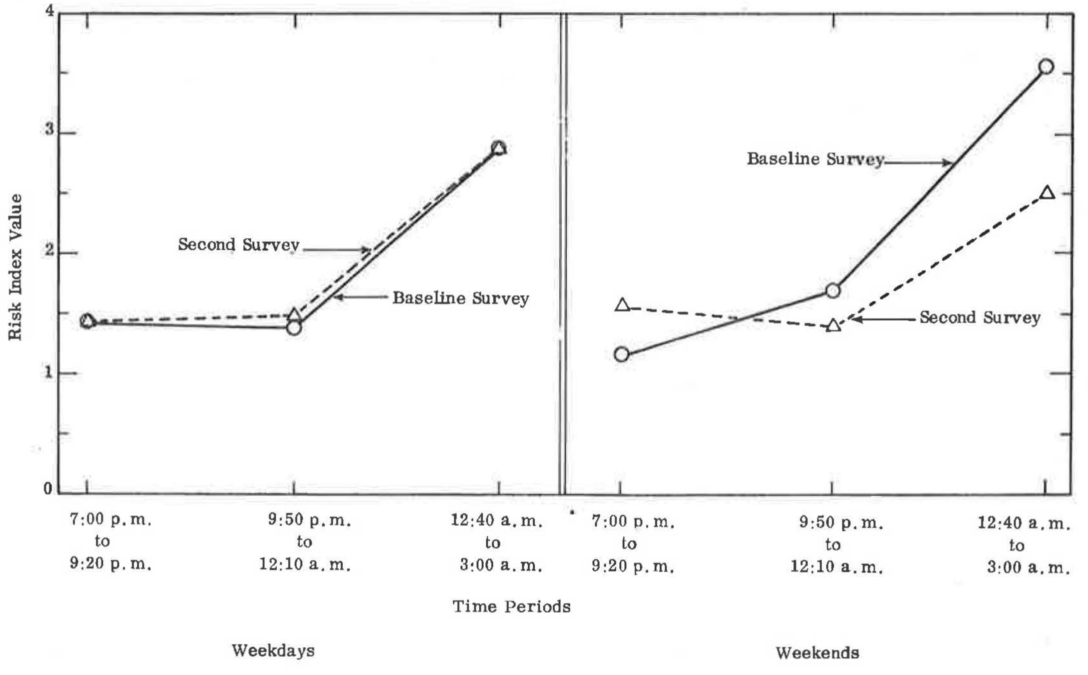
An IAP was calculated for each time period for both weekends and weeknights for both the base-line survey and the second survey. These indexes are shown in Figure 2. The purpose of calculating an index of accident probability was to augment the analysis of BAC levels by comparing the relative risks of accidents associated with the various BAC levels.

From an examination of the graphs in Figure 2, it is apparent that there was very little difference between the surveys in the probabilities of accident occurrence on weeknights. The graphs show that on weeknights the risk of an accident among the drivers

Table 5. IAP for weekend sample by time period.

Time Period	BAC Category	Risk Index	Base-Line Survey Percentage	Base-Line Survey Value	Second Survey Percentage	Second Survey Value
7:00 to 9:20 p.m.	0	1	0.797	0.797	0.594	0.594
	01 to 04	1	0.161	0.161	0.302	0.302
	05 to 09	3	0.031	0.093	0.080	0.240
	10 to 14	12	0.011	0.132	0.014	0.168
	15 or more	27	0.000	0.000	0.010	0.270
		IAP		1.183		1.574
9:50 p.m. to 12:10 a.m.	0	1	0.700	0.700	0.694	0.694
	01 to 04	1	0.198	0.198	0.222	0.222
	05 to 09	3	0.068	0.204	0.064	0.192
	10 to 04	12	0.021	0.252	0.016	0.192
	15 or more	27	0.013	0.351	0.004	0.108
		IAP		1.705		1.408
12:40 to 3:00 a.m.	0	1	0.463	0.463	0.450	0.450
	01 to 04	1	0.282	0.282	0.320	0.320
	05 to 09	3	0.125	0.375	0.153	0.459
	10 to 14	12	0.070	0.840	0.053	0.636
	15 or more	27	0.060	1.620	0.024	0.648
		IAP		3.580		2.513

Figure 2. Index of accident probability.



on the road was about twice as great from 12:40 to 3:00 a.m. as it was for the two earlier time periods. This relative risk measurement did not attempt to take into account differences in traffic volume, but dealt only with the drivers who were operating their vehicles during the given time periods.

The graphs do depict a change in weekend drinking and driving patterns between the two surveys. Both the 9:50 p.m. to 12:10 a.m. and the 12:40 to 3:00 a.m. time periods show a reduction in the IAP from the base-line survey; the more dramatic reduction occurred in the latter time period. This reduction in the IAP on weekends might be a result of the impact of the Fairfax ASAP. In the least, it certainly shows encouraging signs that the late-night ASAP patrols were successfully affecting the normal drinking and driving patterns with the result that the probability of accidents was dramatically reduced.

There is still progress to be made, especially from 12:40 to 3:00 a.m. on weeknights, but it is encouraging to note that, although a significantly greater percentage of drivers were drinking on the second survey, they were drinking in moderation such that the relative risk of accidents actually was reduced. This phenomenon will be carefully monitored throughout the course of the project as a means of determining whether ASAP is successfully reaching the high-risk drivers and removing them from the road to rehabilitate them and reduce their risks to themselves and others.

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