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

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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_l) 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 ($\hat{y}_1$).

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_1 = lateral deviation of disturbed vehicle relative to lane centerline,
$\hat{y}_1$ = 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:

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

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.

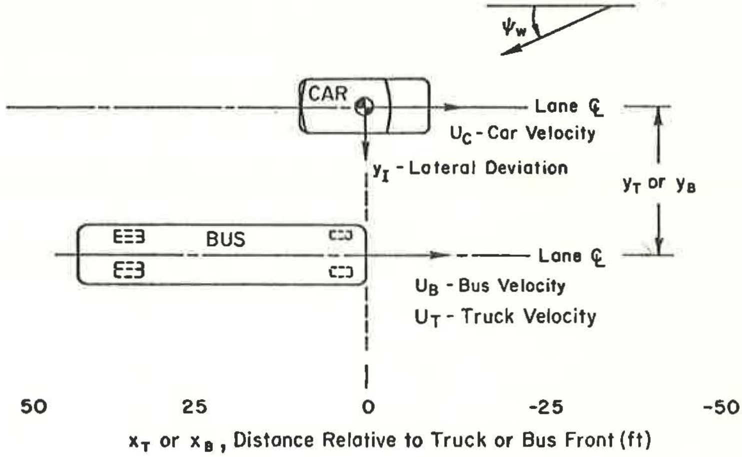


Figure 2. Representative driver-vehicle system.

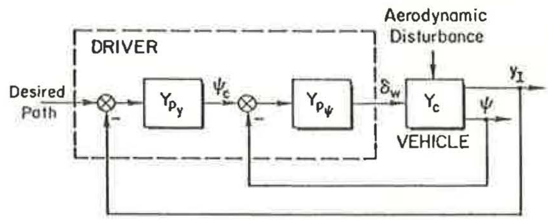


Figure 3. Driver-vehicle heading control.

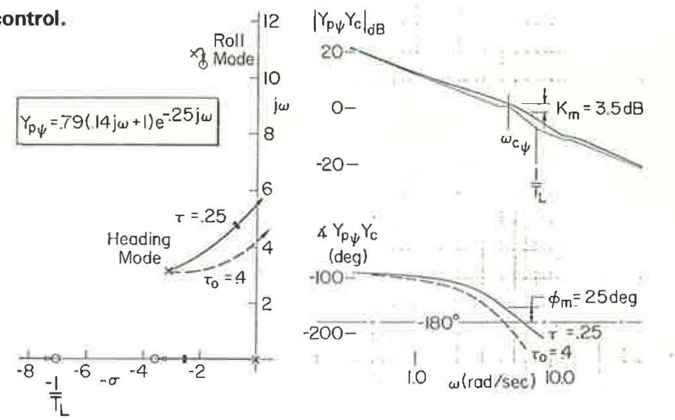
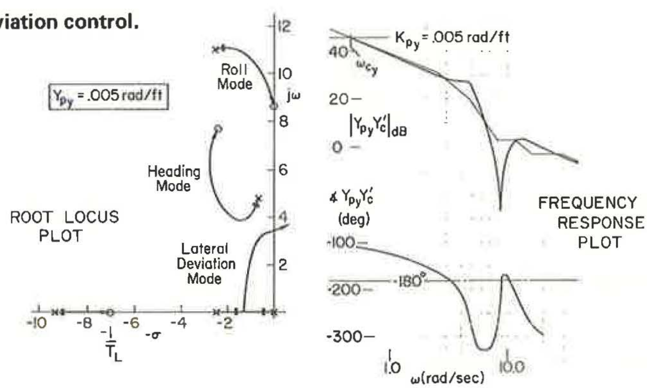


Figure 4. Driver-vehicle lateral deviation control.



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.

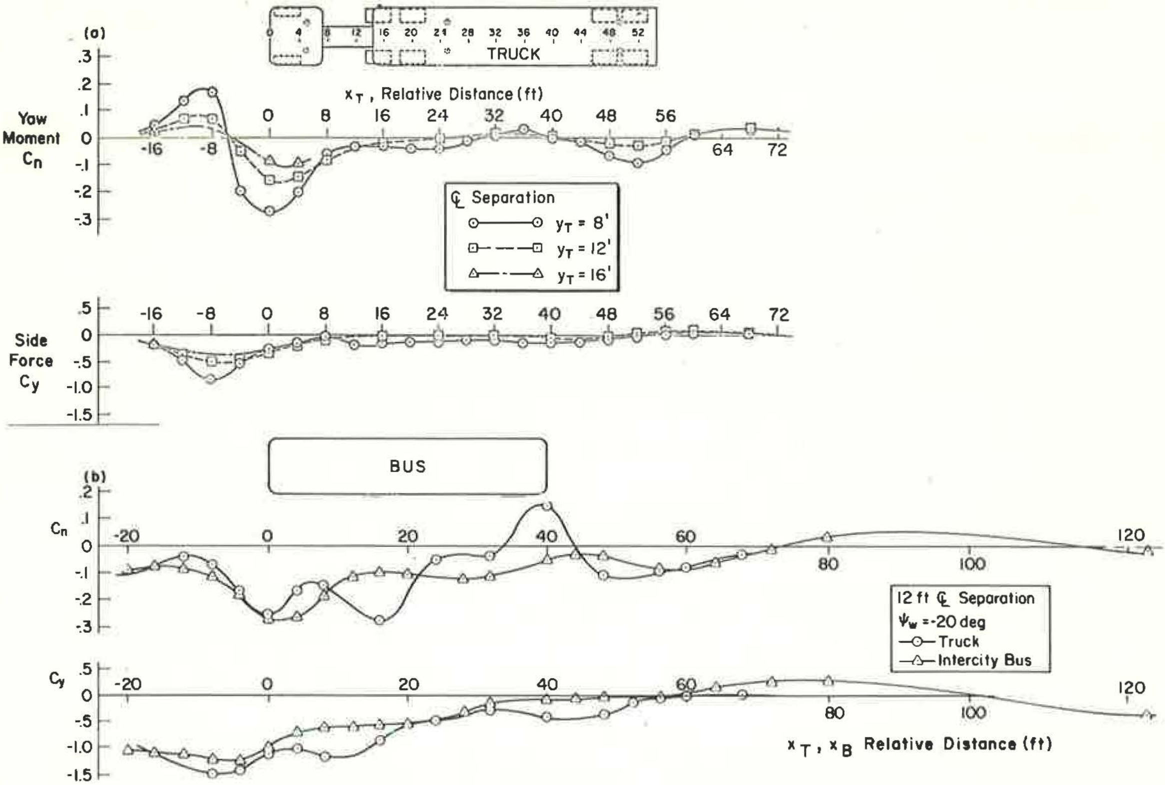
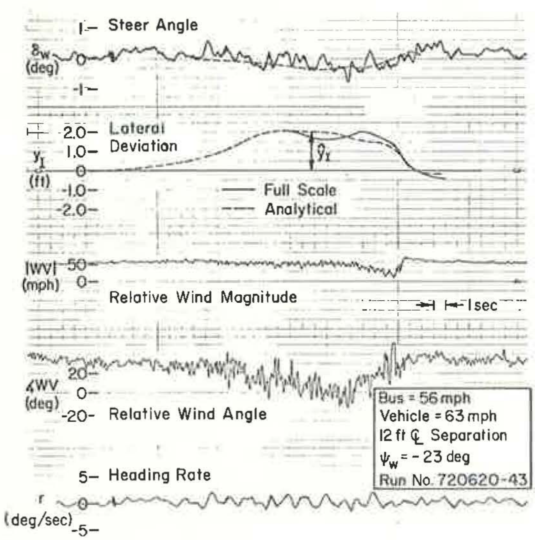


Figure 6. Comparison of results for station wagon.



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.

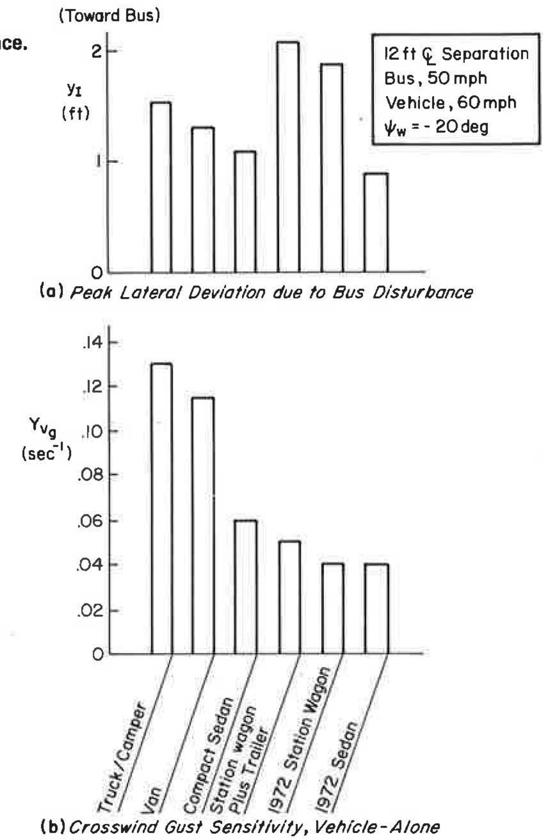
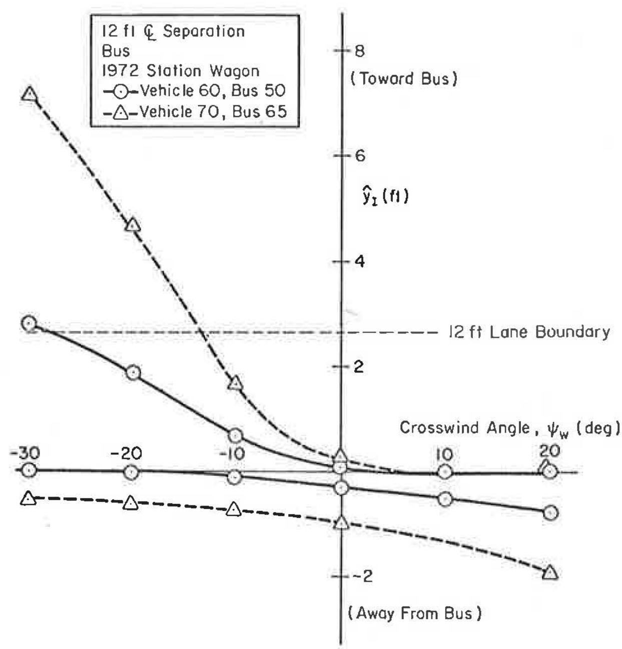


Figure 8. Effect of crosswind angle of driver-vehicle lane keeping performance.



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.

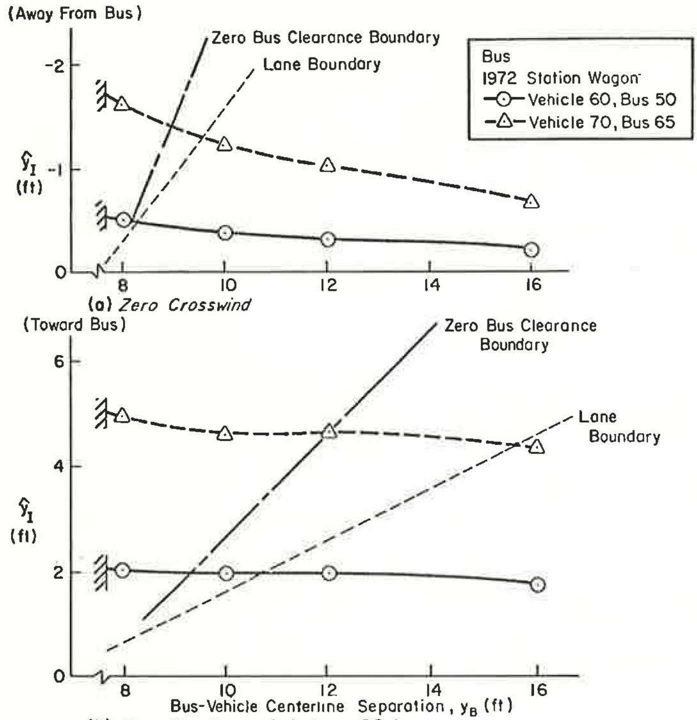
Implications for Highway Operations

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.

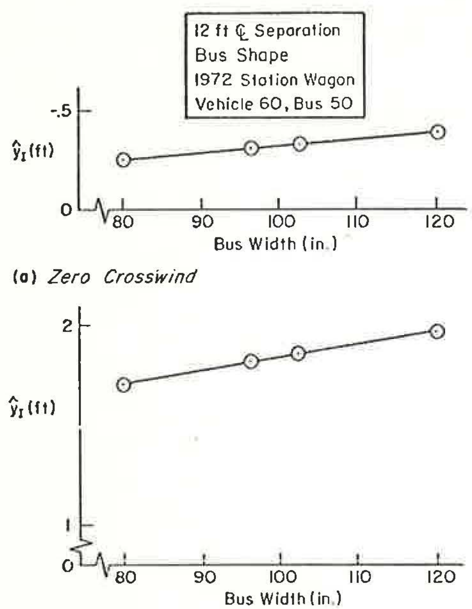
Figure 9. Effect of bus-vehicle separation on driver-vehicle lane keeping performance.



(a) *Zero Crosswind*

(b) *Negative Crosswind*, ψ_w = -20 *deg*

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



(a) *Zero Crosswind*

(b) *Negative Crosswind*, ψ_w = -20 *deg*

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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