THE INTERACTION OF AERODYNAMIC PROPERTIES AND STEERING SYSTEM CHARACTERISTICS ON PASSENGER CAR HANDLING

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SUMMARY

A computer-based analysis of the crosswind handling performance of a nominal driver-vehicle system is presented. Modifications to the baseline vehicle's aerodynamics, chassis, and steering system properties are utilized in evaluating the influence of such changes on the crosswind handling of the baseline vehicle. A candidate crosswind handling measure, derived from summary results of simulated driving under random crosswind conditions, is offered as one possible method for evaluating improvements or degradations in crosswind handling performance. At high speeds, aerodynamic and tire properties are seen to most strongly affect the crosswind handling evaluation. Steering system compliance was identified as the most influential steering system property affecting the candidate crosswind handling index.

1. INTRODUCTION

This paper examines the influence of vehicle aerodynamic properties and steering system characteristics on the handling qualities of a conventional passenger car. Evaluations are performed for both open-loop and closed-loop driving scenarios. The study is based upon results predicted by a newly-developed aerodynamic/handling model of a passenger car [1] in conjunction with high speed test data specifically collected for its development and validation [2]. The paper reports on results of a simulation study examining the interaction between aerodynamic properties, steering system characteristics, and handling, by focusing on system responses to crosswind disturbances. Constant crosswind gusts and random-varying crosswind inputs of low to moderate magnitudes are used as the two primary wind environments in the computer analysis. Several different aerodynamic, chassis, and steering system configurations are examined.

Recent studies [3, 4, 5, 6] which have examined vehicle-aerodynamic-driver interactions have had mixed results in trying to identify strong causal relationships between driver subjective ratings of handling and preferred aerodynamic and chassis properties. A major difficulty in identifying such strong linkages has usually been related to typical variations in driver opinion ratings and/or insufficient excitation of the driver-vehicle system from external aerodynamic inputs [5]. The latter reason has usually been related to 1) too short of an excitation period when utilizing wind fans, or, 2) relatively small aerodynamic forces experienced during prolonged driving tests in natural wind conditions. Of these studies, one indicated that driver preferences correlate strongly with more rearward locations of the aerodynamic center of pressure [3]. Others have noted that reduced vehicle yaw motions and driver steering activity are strongly related to positive driver subjective ratings [4, 6].

A computer-based analysis by Ufflemann in 1985 [7] suggested possibilities for relating crosswind sensitivity to handling and aerodynamic properties of vehicles by utilizing the RMS value of required steering wheel velocity for a simulated driver in a random crosswind as a method for identifying and evaluating possible driver preferences. The terms "passive" and "active" wind behavior used by Ufflemann are also employed in this paper to describe the vehicle-alone (open-loop) and driver-controlled (closed-loop) system responses during aerodynamic excitation. The approach of these and other researchers of addressing vehicle crosswind evaluations from the viewpoint of the total driver-vehicle system, as opposed to a vehicle-alone phenomenon, is further endorsed within this paper and by the thrust of the research program supporting it.

2. VEHICLE/STEERING-SYSTEM/AERODYNAMICS/DRIVER SYSTEM

Figure 1 shows a block diagram outlining the principal components of the crosswind driver/vehicle system included in this study.

Vehicle Model. The vehicle model is characterized by five degrees of freedom for the sprung mass, constant forward speed, and massless suspension/wheel assemblies. Tire and suspension compliances are also included. Tire lateral force is treated as largely linear except for cornering stiffness dependency on vertical load. The basic dynamics of the vehicle are very similar to that developed by Segel [8]. High speed test data, collected during the course of the on-going aerodynamic crosswind stability research program at UMTRI [2], was used to validate the baseline model behavior through direct comparisons with model predictions. Test track handling measurements and aerodynamic wind tunnel measurements of the same passenger car, in two different aerodynamic configurations, have been conducted previously at nominal speeds of 100 mph. A stable platform and a variety of transducers were used to measure all body motions, steering wheel/front wheel rotations, and additional steering system functions such as power boost pressures and pitman arm motion.

Aerodynamics. The aerodynamics of the vehicle include the three conventional forces (drag, side force, and lift) and the three corresponding moments about each body axis. Each force and moment is characterized by a constant coefficient and a linear variation with respect to the aerodynamic sideslip angle. The nominal aerodynamics represented in the computer model were based upon aerodynamic measurements performed by Chrysler at the Lockheed wind tunnel.

Driver Characteristics. An existing driver steering control model [9, 10] was extended within this study to provide for generation of steering wheel torque, T_{SW}, seen in Figure 1. This served as the primary steering control input during the simulated closed-loop driving scenarios involving random crosswind disturbances.

Steering System. A simplified second order dynamic steering system model augments the aforementioned sprung mass dynamics and relates steering wheel torque and displacement to front wheel motion. See Figure 2. Properties of the steering system include: compliance, friction, steering wheel inertia, lash, and power steering boost characteristics. Much of the steering system model is patterned after that originally proposed by Segel [8, 11]. The treatment here does not include the high frequency front wheel dynamics but does include a power steering boost torque approximation. The power steering boost is treated as a driver-assisting torque linearly proportional to the sum of the front tire aligning torques.

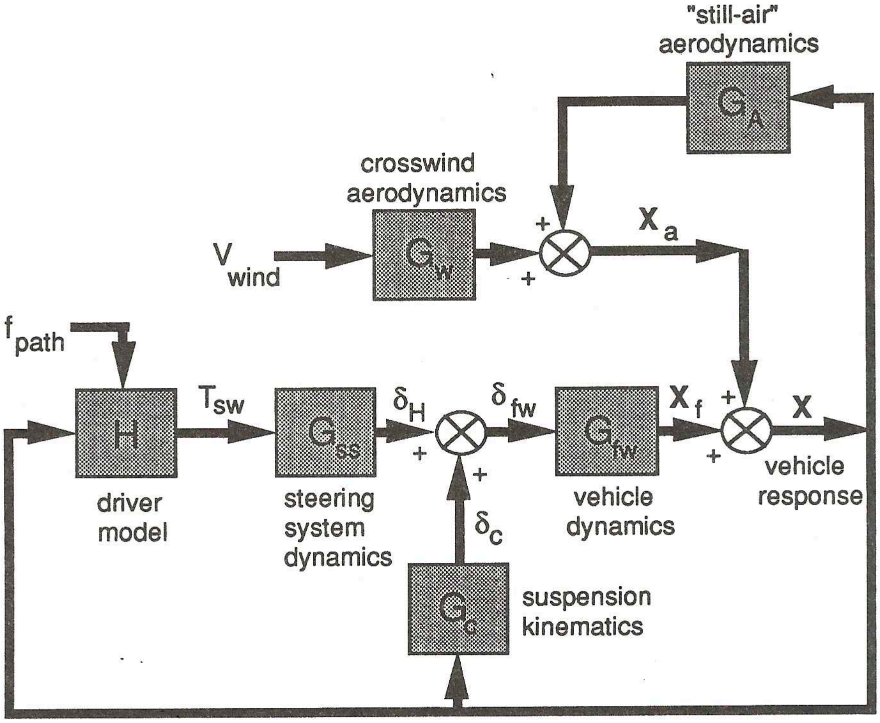

Figure 1. Chrysler/UMTRI Crosswind Vehicle Model.

Figure 3 shows an example comparison for the steering system model and test data collected at 100 mph during which low frequency sinusoidal-like steering torque inputs were applied by a test driver for purposes of validating the baseline vehicle model and its steering system properties. This type of steering input is similar to that proposed by Norman [12] as part of an on-center handling test procedure (normally conducted at 100 kmh) for evaluating basic properties of the steering system and associated vehicle responses.

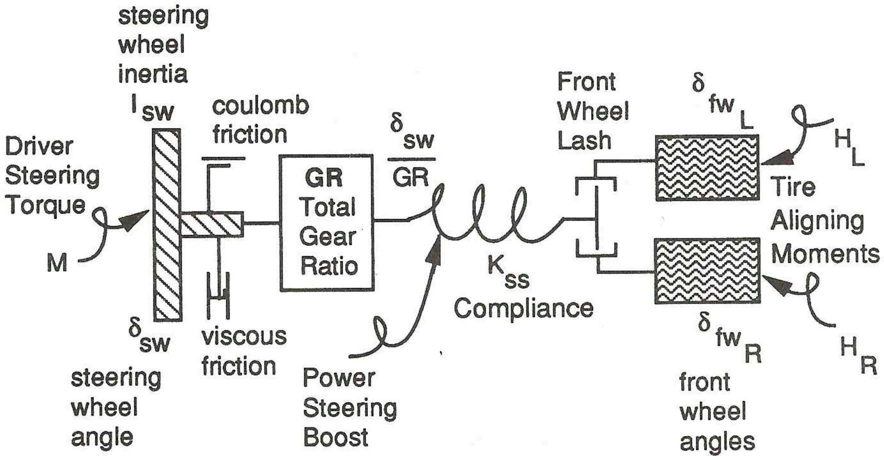

Figure 2. Simplified Steering System Model.

3. SIMULATED CROSSWIND MANEUVERS

Two basic maneuvers were used to study the response of the simulated system responding to crosswind conditions. The first maneuver was an open-loop, fixed-steering wheel maneuver in the presence of a constant crosswind and constituted the "test" of the passive crosswind behavior of the vehicle without the driver. The second maneuver, serving to evaluate the active crosswind behavior, involved the driver model and required extended steering regulation in the presence of a randomly-varying crosswind. All simulations were conducted at speeds of 100 mph.

Step Gust. The fixed steering wheel test used to evaluate the passive wind behavior is shown in Figure 4. The vehicle starts in a still-wind condition, encounters the constant 25 mph crosswind after 1 second, and then reaches a steady-state turning condition after several seconds. The resulting steady-state yaw rate response was used to evaluate the passive wind performance.

Random Crosswind Maneuver. The active crosswind behavior of the total system, including the driver, was evaluated using a straight-line driving scenario in the presence of a random crosswind over a time interval of 25 seconds. Figure 5 shows a plot of the power spectral density of the simulated crosswind as a function of frequency. The simulated crosswind was based upon wind characteristics measured previously in the research project using a special wind measurement transducer developed by Chrysler and mounted on the baseline test vehicle.

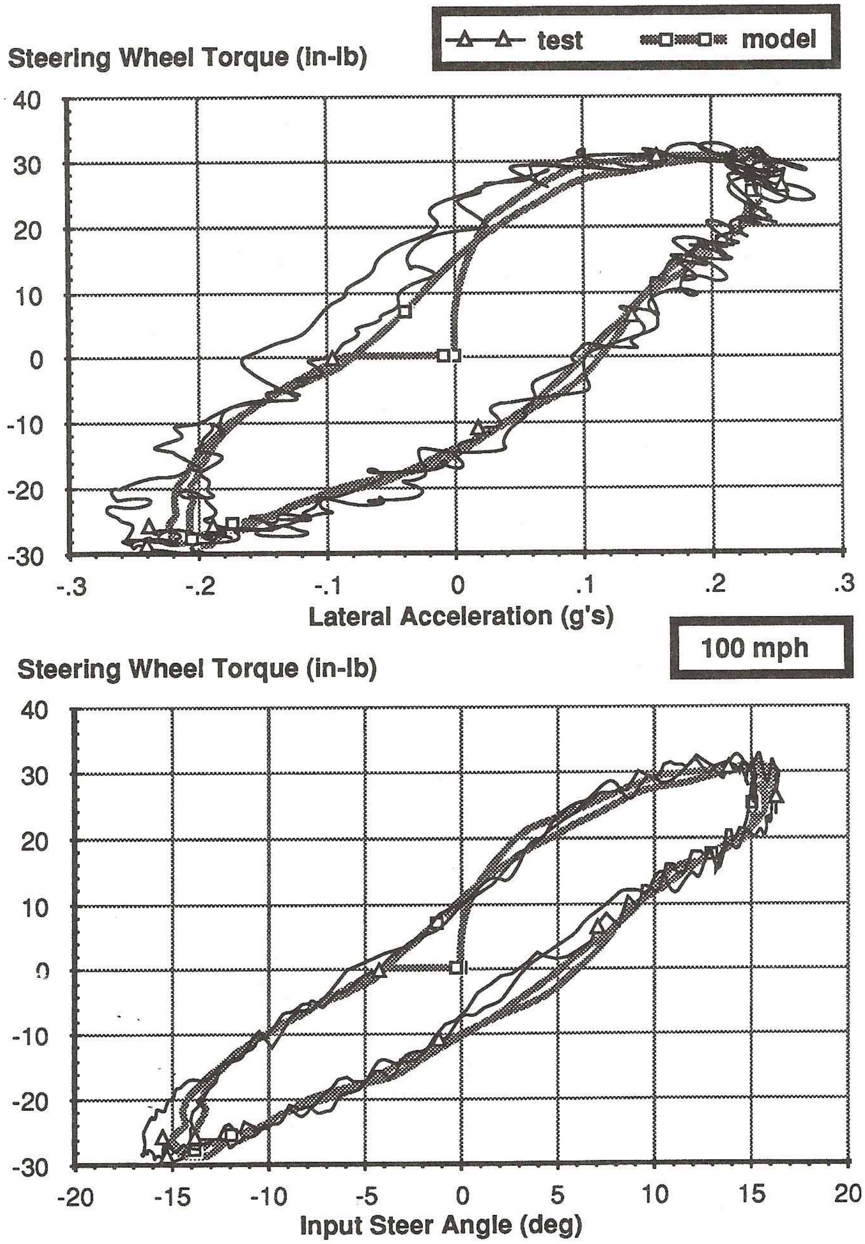

Figure 3. Steering System Characteristics.

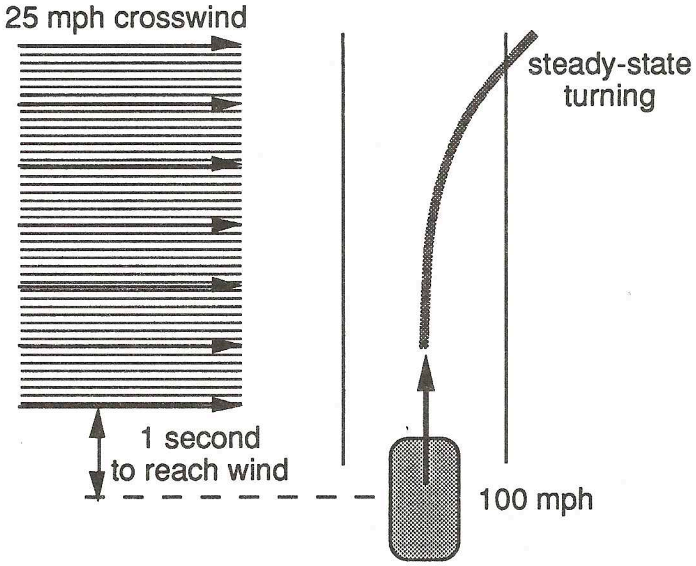

Figure 4. Fixed Steering Wheel Simulated Test.

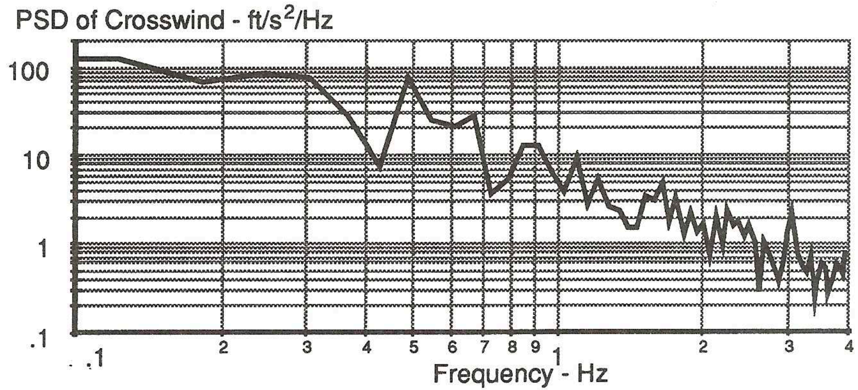

Figure 5. Power Spectral Density of Simulated Crosswind.

4. PARAMETER VARIATIONS EXAMINED

Three basic categories of parameter variations are considered and include: a) aerodynamic properties, b) steering system characteristics, and c) chassis modifications. All of these appear as parameter variations in subsequent figures. It should be noted that for the passive wind behavior maneuver, not involving the driver or dynamical properties of the steering system (e.g., steering wheel inertia), the number of parameter variations examined is reduced accordingly.

The principal parameters describing the baseline vehicle configuration in this study are given below in Table 1:

vehicle weight: 3160 lb
yaw inertia: 18000 in-lb-sec^2
c.g. to rear axle: 60 in
aero side force coefficient: 0.035
front tire $C\alpha$: 278 lb/deg
steering stiffness: 1500 in-lb/deg
steering viscs damp: 0.44 in-lb-s/deg
power steer boost coef: 0.55

wheelbase: 97 in
c.g. to front axle: 37 in
c.g. to aero CP: 15 in
aero yaw coefficient: 0.009
rear tire $C\alpha$: 217 lb/deg
steer coul fric: +/- 3 in-lb
steer inertia: 0.4 in-lb-s^2
overall gear ratio: 16.9

Table 1. Baseline Vehicle Parameters

Aerodynamic Variations. The primary aerodynamic alteration of the baseline vehicle was to move the center of pressure "CP" 1) rearward to the neutral steer point "nsp" of the baseline vehicle, and 2) forward to the front axle location through variation of the aerodynamic yaw moment coefficient. The nominal baseline location of the CP was about 25% of the wheelbase aft of the front axle. The other major variation was to increase the aerodynamic side force coefficient and yaw moment simultaneously by 50% (or, equivalently, the lateral cross-sectional aerodynamic area by 50%).

Steering System. Numerous alterations to the steering system were examined, primarily because of the number of parameters involved and also because of the emphasis of this particular study. These included: a) increases in steering system stiffness by factors of 2 and 10, b) introduction of +/- 0.2 deg of front wheel lash, c) removal of all coulomb friction, d) increasing the viscous damping by 50%, e) doubling of the steering wheel inertia, f) doubling of the mechanical trail of the front wheels, g) increasing the overall gear ratio by 50%, and h) decreasing the power boost by 50%.

Chassis. The principal chassis variation was to reduce all or some of the tire cornering stiffnesses ($C\alpha$) by 25%. A roll stiffness reduction of 50% was the other primary chassis variation examined. A speed reduction of 20% (to 80 mph) is also included in this category.

Driver Characteristics. The baseline driver model was characterized by a maximum preview time parameter of 1.5 seconds and a transport time delay parameter of 0.25 seconds. These parameter values have been used frequently in previous studies to represent realistic driver steering control properties of human operators in normal steering maneuvers.

5. RESULTS

Passive Crosswind Behavior. Results of the fixed-steer simulation runs for a constant 25 mph crosswind are seen in Figure 6. The ordinate variable is simply the steady-state yaw rate during each run normalized by the magnitude of the aerodynamic slip angle produced by the constant crosswind (14.3 degrees except for the one run conducted at 80 mph.) The first three variations correspond to large variations in the vehicle aerodynamics (fore/aft location of the CP and area) and produce, not unexpectedly, correspondingly large variations in the steady turning response of the vehicle. Locating the CP at the neutral steer point of the vehicle is seen to result in no steady turning response. The next three variations correspond to moderate reductions in tire cornering stiffnesses and likewise result in significant variations from the nominal baseline response. The roll stiffness modification has little effect while the lower speed (80 mph) run lowers the turning response by about 20%. The wheel lash modification which introduced +/- 0.2 degrees of lash at the front wheels is seen to reduce the turning response. The last two runs, related to reduced steering system compliance, indicate only a small increase in the passive, fixed-steer turning response.

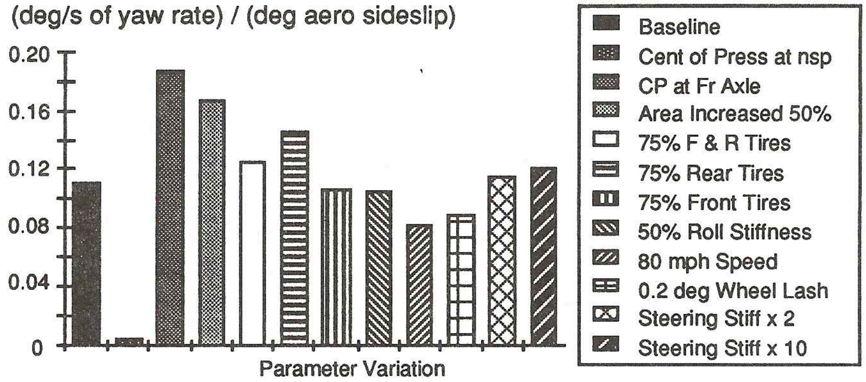

Figure 6. Passive Crosswind Sensitivity.

Referring to Figure 7, it can be shown [13], that the computer predictions seen in Figure 6 are explained by a simple formula which relates the steady turning response of a vehicle to an external side force (aerodynamic or otherwise). This expression is given by,

$$r / F_a = [m\, U]^{-1} (c + d) / (c + \zeta) \qquad (1)$$

where,

r	is the steady-state yaw rate
F_a	is the applied aerodynamic side-force
m	is the vehicle mass
U	is the vehicle speed
c	is the distance from the nsp to the mass center
d	is the distance from the mass center to the CP
ζ	distance proportional to the tire yaw damping moment about the nsp and equal to: $(a + b)^2 C_f C_r / [(C_f + C_r)\, m\, U^2]$, (small at high speeds, per Fig. 7)
C_f	is total front tire cornering stiffness
C_r	is total rear tire cornering stiffness
a, b	mass center to axle distances

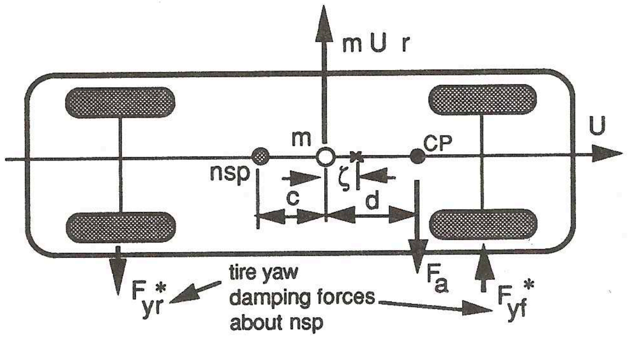

Figure 7. Static Turning Equilibrium in a Constant Crosswind.

and is seen to express the turning response induced by the aerodynamic side-force as a ratio of two moment arms. The moment arms (c+d) and ($c + \zeta$) are associated with the aerodynamic side force, F_a, and the inertial force, mUr, acting with respect to the neutral steer point. Consequently, aerodynamic variations which move the CP forward or rearward alter the value of the moment arm, d, in equation (1). If d = -c, the yaw rate is predicted to be zero as confirmed in the second computer run of Figure 6. Likewise, fore/aft movements of the neutral steer point due to alteration of the tire cornering stiffnesses, affect the moment arm, c, in equation (1) and will produce increased or decreased yaw rate responses depending upon the relative magnitudes of the d and ζ moment arms. Similar, though smaller movements of the nsp are achieved by changes to the steering system stiffness. Wheel lash acts as a force-dependent "softening" mechanism at the front wheels, effectively moving the nsp rearward.

Active Crosswind Behavior. Results of regulating the vehicle in a random crosswind through use of the closed-loop steering control model [9] are presented next. RMS values of steering wheel angle, steering wheel torque, vehicle yaw rate, and required driver steering power are seen in Figures 8 - 11. Additional parameter variations, related to and affecting the dynamic characteristics of the steering system, are included in these results. The legend of Figure 8 applies to each of the subsequent figures. The average steering wheel power expenditure seen in Figure 11 was calculated by integrating the cumulative area inside the steering wheel torque - steering wheel angle relationship (as seen previously in Figure 3) over the duration of the maneuver, and normalizing by the time of the calculation (approx 25 sec). The average steering wheel power expenditure by the driver is seen to provide a more discriminatory measure of driver steering control requirements introduced by the particular parameter variations, as opposed to steering wheel angle or steering wheel torque.

As with the passive fixed-steer maneuver, the results for the active random crosswind maneuver indicate that the greatest leverage over crosswind behavior is obtained through aerodynamic and tire force modifications. Movement of the CP rearward is a powerful mechanism for achieving reduced responses for both the vehicle yaw motion and the driver steering activity. In fairness, it should be recognized that the degree of CP movement presented here is somewhat exaggerated and impractical for most passenger cars. However, even if CP variations one-half the magnitude those examined here are considered (and achievable in many body styles), the influence of the aerodynamics is still a strong influence at this speed. Furthermore, as forward speed increases, the aerodynamic influences increase even more in strength relative to the other chassis and steering system modifications. By the same token, at speeds considerably below 100 mph, these same aerodynamic influences are quickly diminished relative to the other vehicle modifications. Consequently, speed, as might be expected, is seen to play an important role here in determining the relative level of tradeoffs achievable between aerodynamic modifications and chassis or steering system changes.

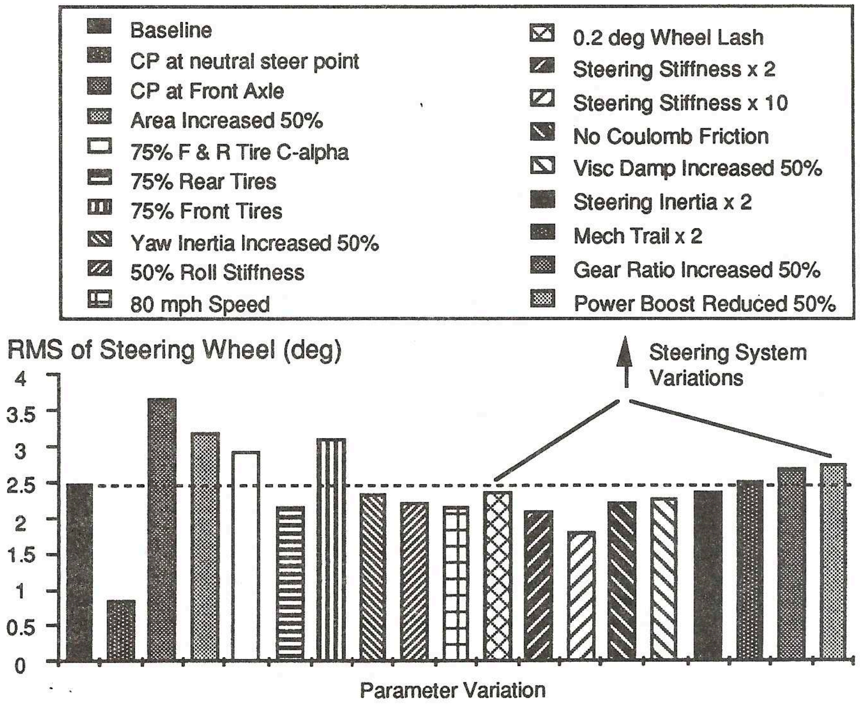

Figure 8. Active Crosswind Sensitivity.

In order to evaluate these results in terms of "crosswind handling," one possible measure for the crosswind handling performance of a vehicle is suggested in Figure 12. This candidate measure reflects the effects of the random crosswind on both the driver and the vehicle. The vehicle response is represented in this measure by the RMS value of yaw rate (Figure 10) obtained in the random crosswind

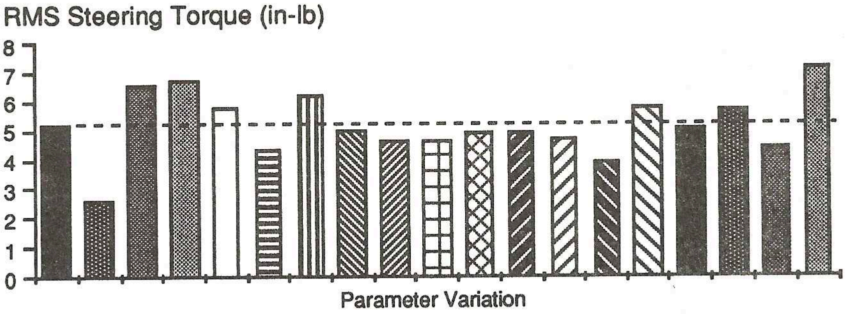

Figure 9. Active Crosswind Sensitivity.

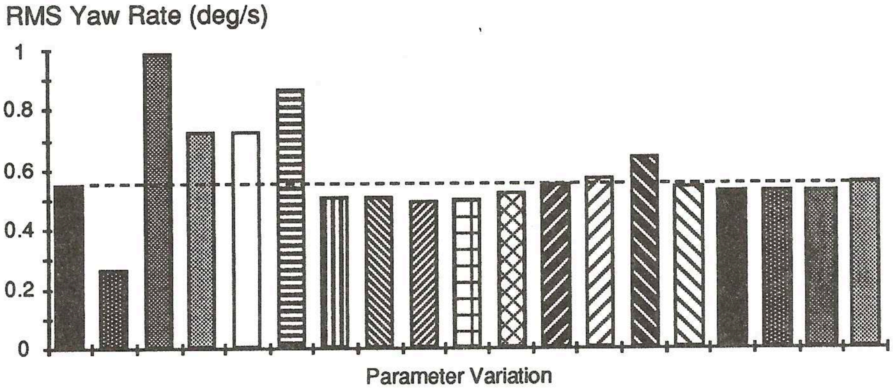

Figure 10. Active Crosswind Sensitivity.

maneuver. The driver energy expenditure per unit time is included in the same measure by the average steering power calculation from Figure 11. The results (see Figure 12) are normalized by the baseline vehicle response and formulated so that a value of 0 for this measure represents the baseline vehicle. A value of 1 represents an undisturbed vehicle with no dynamic steering requirement (ideal). Negative values represent decreased handling attributes relative to the baseline vehicle for this candidate index.

CONCLUSIONS

The results of this study indicate a number of interesting points. First, the relatively high degree of correlation between the passive crosswind response of the vehicle alone (Figure 6) and its active crosswind counterpart of Figure 10, suggests that a number of vehicle-based crosswind sensitivity properties can be evaluated through use of fixed-steer tests and be expected to have similar responses in closed-

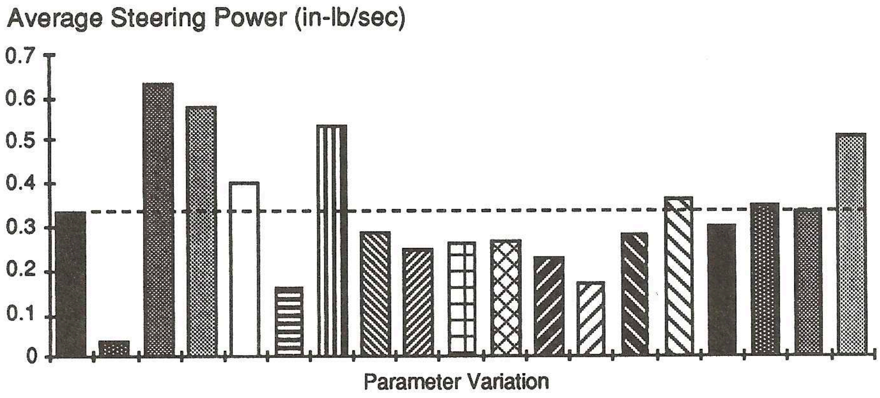

Figure 11. Active Crosswind Sensitivity.

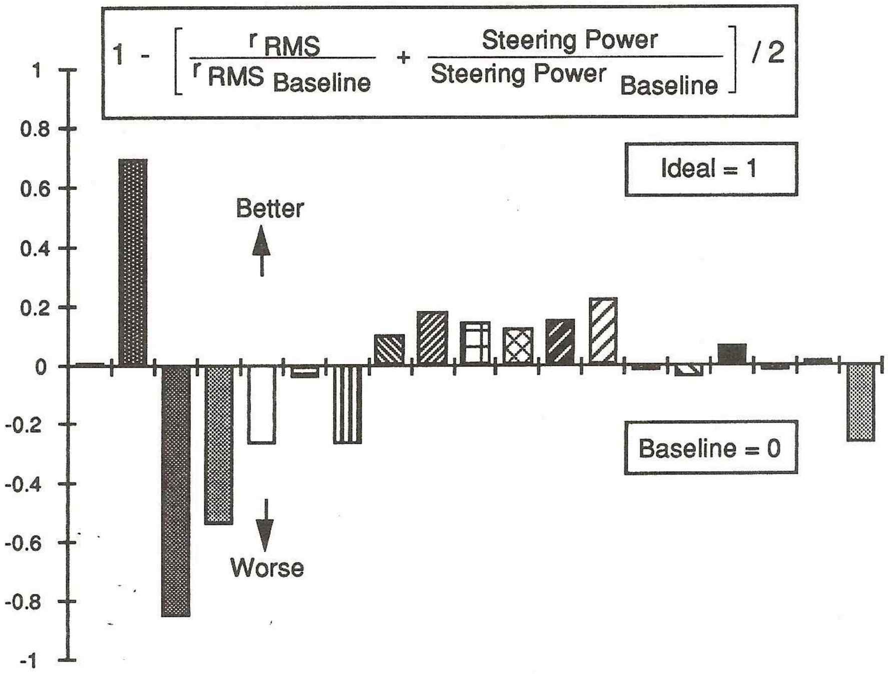

Figure 12. Example Handling Measure for Evaluating Active Crosswind Sensitivity.

loop tests involving drivers. However, this type of vehicle-alone measure is far from the total picture and is insufficient for evaluating such vehicle modifications as they relate to the crosswind sensitivity of the total driver-vehicle system. Instead, an incorporation of such vehicle-alone measures of vehicle response *with* driver steering-workload requirements is needed to more accurately account for the degree of driver steering effort necessary for achieving a specific level of vehicle directional control during realistic crosswind conditions. One candidate crosswind handling measure aimed at the concept of representing both the vehicle yaw response and the corresponding driver steering requirement within the same measure was presented in Figure 12.

Not surprisingly, the findings presented here suggest that at high speeds, aerodynamic and tire properties are the most influential factors in affecting a vehicle's handling in natural crosswinds. The steering system characteristic most influential in affecting crosswind handling was found to be torsional compliance. A stiffer steering system is identified as improving the crosswind performance primarily by lowering the steering power requirement of the driver. The other principal steering system property found to affect the crosswind handling performance was the power boost. Degradations in crosswind handling are associated with reduced power boost because of the increased steering torque requirement for the driver. Steering system friction, mechanical trail, and gear ratio alterations were seen to have little influence on the candidate crosswind handling measure. A modest improvement in crosswind handling, deriving primarily from an observed reduction in required driver steering power, was indicated for an increased steering wheel inertia.

Lastly, front wheel lash is seen here as being interestingly associated with a small improvement in crosswind handling due to small reductions in yaw rate and steering power. Because of the lateral pre-loading of the vehicle (and the opposing tire steering forces) by the DC component of the wind, the lash is not being regularly encountered in this particular driving maneuver. This would not be the case for a strictly on-center driving scenario in which aerodynamic and lateral tire steering force reversals would be occurring regularly. A purely on-center scenario would require the lash to be fully traversed in a continual manner by the driver in order to "access" and generate the required steering control forces of opposite polarity, thereby leading to increased steering activity by the driver and a decreased handling rating.

When considering tradeoffs in crosswind handling performance between aerodynamics and steering system properties, it is apparent that the greatest "leverage" is available through aerodynamic modifications at high speeds. As speed is reduced, the tradeoff issues are more equalized between aerodynamics and steering system properties. At higher speeds, tire properties are likely to be the most influential tradeoff mechanism in compensating for aerodynamic modifications.

Lastly, it should be noted that a follow-on set of crosswind handling tests, to be conducted with a variety of test drivers, will help to further clarify results from this work by relating these and other findings to subjective evaluations of vehicle configurations similar to those examined here. A subsequent paper will report on those results.

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