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Static Stability and Control of the Automobile Utilizing the Moment Method

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ABSTRACT

Some three and a half years ago the present authors described a new method for analyzing automobile stability and control (see SAE Paper No. 760712, "The Static Directional Stability and Control of the Automobile," October 1976). The present paper is an extension of the earlier work with particular emphasis upon its application, interpretation, and general utility for evaluating automobile stability and controllability. Specific applications of the technique to production vehicles will be used for illustration. The usefulness of the method for mapping out the total maneuvering performance in the nonlinear and limit handling as well as in the linear range will be examined. Such items as off-trim operation, a maneuvering diagram, tangent speed, and the determination of the transient response from the Moment Method diagrams will be discussed, as will the possibility of developing a universal diagram based on a force/moment presentation for the vehicle. A conclusion that this method offers distinct advantages in analyzing car stability and control, including front drive problems, is reached.

A NEW APPROACH to the evaluation of the lateral-directional stability and control characteristics of automobiles was introduced four years ago in SAE Paper No. 760712 (1).* Since that time, the method has been used in a series of studies involving applications to vehicle design which has confirmed its usefulness for the analysis of specific maneuvers as well as its generality in dealing with overall maneuvering performance. In the course of these studies the technique has been further extended and much progress has been made in the interpretation of the graphical presentations which are a feature of the Moment Method (as the technique is now called). These advances have been facilitated by the development of a new digital computer simulation program which, with a print/plot routine, enables the rapid production of the diagrams upon changes in vehicle configuration and operating conditions.

The objective of the present contribution is to bring the subject up to date and reaffirm the potentialities of this approach to the stability and control of the automobile. More detailed coverage in the present paper will be focused on its application to vehicle design and its capability to provide a measure of transient response, along with some discussion of current thinking on the significance and utility of the Force-Moment

*Numbers in parentheses designate References at end of paper.

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diagram. Although the Moment Method has been viewed as a quasi steady-state technique, it was recognized that the transient response must depend upon information inherent in the diagrams. A technique has now been developed for extracting a transient response time. This constitutes a major forward step toward the objective of providing the designer with a comprehensive, nonlinear tool for the analysis and synthesis of automobile stability and control characteristics.

GENERAL BACKGROUND

An attempt was made in Ref. 1 to orient the Moment Method relative to such commonly-used concepts and techniques of automobile stability and control analysis as understeer gradient, response and control gains, response times, the neutral steer line and static margin, Critical and Characteristic Speeds, Cornering Compliance, etc. Although these traditional approaches may be expanded by operating point perturbation techniques, they are essentially mathematical or experimental data linearizations. Conceptually, these ways of viewing stability and control can all be derived from the derivative representation of the linearized theory of (2). In the normal maneuvering range, (less than 0.3 g), linearization is justified in many instances, and experience indicates that satisfactory characteristics in this range may carry over to somewhat higher lateral accelerations. Thus the stability and control design of American cars has been largely that of meeting empirically established requirements in the linear range, the process being in part facilitated by the use of the Cornering Compliance "budget" for the contributions of the various under/oversteer factors from the front and rear wheel pairs. Additionally, vehicles are normally tested on the skid pad over the full trimmed steady-state operating range and the results interpreted in under/oversteer terms. For special operating problems, resort is had to nonlinear dynamic computer simulations of various levels of sophistication.

There are a number of basic limitations to the techniques noted above, some of which are becoming apparent with the introduction of front wheel drive with efforts to improve active safety and the achievement of optimum ride/handling compromise on the new small cars. These limitations are reflected in the insufficiency of these traditional design tools to:

(a) Deal with problems involving changes in trim (for example, torque steer),

(b) Characterize, and quantitize, the behavior at max lateral (breakaway),

(c) Handle the important so-called "mid-range" (say 0.35 - 0.65 g lateral acceleration) where inadvertent and emergency operation takes place,

(d) Investigate operational situations involving steady combined longitudinal and lateral accelerations, that is, accelerating or braking in a turn.

These limitations arise from the fact that neither the available steady-state or dynamic techniques give a detailed knowledge of the force and moment producing capability of the automobile over the full nonlinear range of the control and operational variables. Experience with other man-carrying vehicles indicates that this knowledge (for conditions of steady velocity and acceleration) is required for the comprehensive design and understanding of maneuvering behavior. It may be supplemented with various derived measures, such as the response times, but the variation of the forces and moments with path and control geometry is fundamental. This fact has long been recognized in the design of aircraft, ships, and submarines by the provision of wind tunnels and towing basins; it is similarly common practice to measure the component forces and moments for the pneumatic tire, as an entity, on a tire tester. Likewise, when interest centers on the effect of aerodynamics on automobile stability, the aerodynamic forces and moments are measured in a wind tunnel over the full range of independent variables.

Largely for historical reasons, the notion of analyzing the overall force and moment capability of the automobile has been long delayed, receiving its first formal expression in (1) and the earlier work upon which the Moment Method is based.

Conceptually, it is possible to visualize a facility, analogous in principle to a wind tunnel or a tire tester, for measuring the so-called external forces and moments which exist on an automobile. Because of the near impossibility of producing scale model tires, such a facility would have to be designed for full-scale vehicles. Additionally, the automobile, unlike aircraft and submarines, is subjected to two significant sets of forces - those arising from tire/road interaction and from aerodynamics. The impracticality of devising a simulated roadway unit mountable in a full-scale wind tunnel for constrained force and moment measurements has led to the development of the computer simulation. This program will accept complete nonlinear tire force/moment data, comprehensive chassis parameter data, and aerodynamic force/moment data, as available.
To insure that the individual tire loads correspond to real life, the simulation places no constraints

upon the vertical, rolling, and pitching degrees-of-freedom. An effective longitudinal constraint in the program simulates road-load or steady acceleration or braking. The program permits the vehicle to be untrimmed or trimmed in the lateral degree of freedom, the latter corresponding to the situation in which the tire and aerodynamic forces equilibrate the centrifugal force and the vehicle is constrained in path. An effective constraint on the yaw degree of freedom (and on the lateral degree of freedom for the untrimmed case) enable the calculation of the yawing moment (and the lateral force) for the full range of combinations of vehicle attitude to the path (β) and steer angle (δ).

The significance of these calculations may be appreciated by noting their inclusiveness in terms of both traditional and new information. Thus, when the calculated yawing moment is zero and the lateral degree of freedom trimmed in road load conditions, the results correspond to the conventional "constant throttle" skid pad test. When the lateral degree of freedom is untrimmed with other conditions as above, the results are those of the "constant radius" test. However, when the yawing moment is not equal to zero, an unbalanced moment exists which is available for angularly accelerating (or maneuvering) the vehicle. It is this ability of the method to define maneuvering capability over the full operational envelope which sets it apart from traditional steady-state techniques.

The application of the Moment Method to specific vehicle design has indicated how valuable it is to have a graphical portrayal of the maneuvering envelope in a format which depicts the full range of trim conditions, the stability associated with the departure from any trim, the available control, and limit behavior. The conventional practice of examing performance at discrete values of the lateral acceleration, usually in the linear range, is extremely limiting and far too gross for studying the subtleties and nuances of control. Compared to the Moment Method the conventional technique can give only a marginal, and frequently misleading feel, for total operational suitability.

The directional stability and control of the automobile depends in the last analysis upon the magnitudes of the lateral forces at the front and rear wheel pairs and their relative phasing. These in turn depend upon the detailed shape of the tire carpet plots, the effect of driving/braking traction on the tire characteristics, the geometric and compliance chassis parameters, and the load transfers associated with longitudinal and lateral accelerations. The only real hope for understanding and tuning the configuration lies in an ability to trace the build-up of the elementary forces and moments in the system.

Experience with the Moment Method has also led to a reappraisal of traditional concepts and their interpretation. The oldest and most widely used concept in automobile control technology is that of understeer which derives from the conventional constant radius skid pad test wherein the steer angle to maintain steady-state trim at various lateral accelerations is recorded. Since the Ackermann steer angle is constant in this test, the understeer gradient (3) is the rate of change of steering wheel angle with respect to change in steady-state lateral acceleration, at a given trim. The value of such a steer characteristic must stem from its precise and reliable relationship with such fundamentals of motion behavior as trim, control, and stability which are expressable in an absolute sense and are well understood across the vehicle sciences. Since the test from which the understeer gradient is defined is one purely of determining a series of steady-state trim points, the notion of trim is contained in understeer. The element of control is likewise present since the changes in trim are associated with changes in control position. Finally, there is an increase of stability as a steeper gradient requires a larger control motion for achieving the change of trim. Thus, all of the fundamental concepts of motion behavior are involved in understeer but in an ambiguous fashion.

The notion of stability, so heavily associated with understeer, is based on the assumption that the control moment equilibrates the stability moment in steady-state, and hence may be used as a measure of it. This assumption has some validity in the linear range of the tire cornering force but beyond that there is no way of determining whether the variation of understeer gradient is the result of a change in the directional stability or the control moment. Thus, the understeer gradient at the higher lateral accelerations is not an assured measure of behavior. The Moment Method uses an absolute measure of stability, namely, the yawing moment required to produce a unit change in lateral acceleration (for the trimmed path case) or lateral force (for the untrimmed path). These slopes are taken along the constant steer angle line at the appropriate trim, emphasizing the fact that stability has no meaning except as a departure from a pre-established equilibrium state. Unlike the understeer gradient, the stability slope on the Moment Diagram (defined as the Stability Index) includes the so-called path curvature stiffness (1), a real component of the restoring moment. Recent experience with the

Moment Method using specific car and tire data indicates that situations may occur in which the understeer gradient is increasing while the absolute stability as indicated by the Stability Index is decreasing. As an aside, regions of conditional stability or instability may show up on the Moment Diagram which would not be detected in an analysis of discrete operating points.

Dealing as it does at the fundamental force level, as opposed to derived or abstract concepts, the Moment Method has no difficulty in treating vehicle behavior under limiting conditions. In fact, it offers a precise quantitative picture of breakaway (skid or plow).

RECENT DEVELOPMENTS IN FORCE-MOMENT ANALYSIS

The initial graphical presentation utilized with the Moment Method was a plot of the steady-state vehicle yawing moment against the trimmed lateral acceleration ($A_y = Y/W = V^2/gR$) for a range of vehicle slip angles, β, and steer angles, δ. Yawing moments other than zero (referred to as unbalanced yawing moments) are available for angularly accelerating the vehicle. Since the plot is drawn for a given speed (and vehicle configuration), the trimmed lateral accelerations establish various path curvatures. This diagram has considerable utility for analyzing the stability and control in many driving situations in which the vehicle is essentially in lateral force trim.

It was subsequently realized that the lateral trim constraint limited the generality of the Moment Method technique and attention was then directed to the characteristics of a performance envelope of the vehicle in a set of force-moment coordinates, yielding an F-M[1] diagram (or in terms of coefficients, a C_y-C_n diagram). The development of the F-M diagram for the linear two-degree-of-freedom vehicle was given in (1).

The lateral force and yawing moment arising from the tire-road interaction are basic to the maneuvering and control of the automobile. Thus, the lateral force enables the establishment of a path curvature while an unbalanced lateral force is required for a change in path curvature. The yawing moment through its control of attitude is the principal determinant of the lateral force and its variation.

It should be noted that the F-M representation has also seen use with other vehicles, notably aircraft where it is common practice to plot yawing moment versus lateral force and pitching moment versus lift force from measured wind tunnel data (for untrimmed values of the variables).

In addition to defining the maneuvering potential of the vehicle, the F-M diagram may be thought of as a "signature" or fundamental characterization of the vehicle type. For example, submarines and airships have a typical shape of diagram as a result of their ability to produce large moments (couples) in the presence of small forces. Different classes of land vehicles also produce F-M diagrams of unique generic shapes. Thus to meet its maneuvering requirements, the typical race car develops large lateral forces and relatively small yawing moments.

For the reasons noted above, there has been considerable incentive to continue the development of the F-M representation beyond the results reported in (1). A brief summary of the current level of development is given below.

The F-M diagram may be constructed for various path radii. There are reasons, however, which suggest that the infinite radius diagram is the most fundamental characterization of the vehicle relative to maneuvering. As noted in (1), the $\delta = \ell/R$ locus is the $\delta = 0$ line for infinite radius or straight-running conditions and it is also the curve of $\delta = 0$ for infinite velocity. Furthermore, the infinite radius diagram is directly applicable to maneuvers which are initiated from a straight path, a common practice in vehicle testing. For such maneuvers, movement up the β line establishes the initial conditions. Although path radius is of less significance at aircraft operating speeds, wind tunnel tests are always performed for the infinite radius condition. It is also interesting to note that the MIRA constrained vehicle testing technique (4) is confined to a straight path.

However, the F-M diagram for infinite radius is easily convertible to other radii - a process which is simpler than the conversion to other speeds for the N-A_y diagram. The F-M plot may, as noted in Ref. 1, be converted to an N-A_y diagram for a particular speed. The conversion techniques are more analytically straightforward for the linear regions of the diagram.

A relatively new use for the Moment Method approach is that of "maneuver plotting" in which particular maneuvers are graphed on the diagrams in terms of the variations in δ, β, etc. Such plots permit a visualization of the various control possibilities for changing trim and the quasi-static history of the motion variables consequent to

[1] M is here used as referring to "moment" in general. Specifically the moment of interest is the yawing moment, N.

specific control action. Because of the lack of constraint in the lateral force coordinate, the F-M diagram is generally more suitable for maneuver plotting than N-A_y. It can be shown that the "Bergman Turn" (5) in which a steady turn is established in one direction after which the control is reversed, can be graphed conveniently on the F-M diagram.

It has been pointed out under General Background that inherent in the Moment Method is the information required for the computation of a transient response time. The F-M diagram proves to be suitable for step-wise transient response calculations.

An attribute of the F-M approach which can be particularly helpful when working with vehicle design problems, is the clean separation of effects arising from the front and rear wheel pairs. Thus, questions are always present as to which end of the vehicle is responsible for a given behavior and are improvements most logically effected on the front or rear. This property of the F-M diagram is apparent from the separation of the basic front and rear axle construction lines whose slopes are $(M/F)_{Front} = a$, and $(M/F)_{Rear} = b$. Starting from these lines, the boundaries of the diagram are established by front and rear tire force saturation, while the internal δ and β arrays are deduced from the nonsaturated tire characteristics and the steering kinematics - all modified by the so-called "add-ons" which take into account suspension compliance effects, roll steer, and roll camber. Because of the straightforward constructural aspects of the F-M diagram, the effect of changes in the variables is more easily seen. For example, path curvature rotates the diagram in a calculable way.

The technology of automobile handling has been almost totally confined to the analysis of specific vehicle/tire configurations. The number and complexity of parameters governing the chassis and tires is such that synthesis is seldom attempted, much less in the nonlinear range. The manner in which the F-M diagram is built up with its separation of front and rear end effects, and the graphical aspects of the Moment Method in general, have suggested the possibility of an approach to synthesis. Two considerations appear favorable: First, as pointed out in Ref. 1 and reiterated in the present paper, the Moment Method diagrams are more than a limited abstract representation of the vehicle - they are, in fact, in the nature of a "portrait" of the maneuvering capability of the vehicle over the full linear and nonlinear range of operation. With sufficient experience with this method it will be possible to specify satisfactory and desirable maneuvering diagrams for different classes of vehicles. Thus the objectives for synthesis can become available. Second, each of the chassis and tire parameters contribute to the detail of the Moment Method diagram in a specific way. Thus, a given parameter may affect the boundary of the diagram or the slope, spacing, or curvature of the internal lines. When these effects are fully understood it will be possible to rationally alter the vehicle/tire configuration to achieve a desired handling portrait. Progress to date along these lines has been encouraging, particularly since the various parameters appear to affect the diagrams in unique ways. The evidence is that the F-M diagram is most suitable for synthesis.

A typical performance diagram in the F-M format is shown in Fig. 1. It illustrates the features which were discussed above. It reflects the stability of the vehicle over the entire performance range at specific operating conditions; it shows the basic front and rear end construction (performance) lines and the convenient separation of their effects along β angle loci; and it depicts the initial maneuvering moment available for changing path, which leads to its utility for characterizing a response time parameter. This latter point, and other interpretations to be made from such diagrams, will be discussed next.

TRANSIENT RESPONSE PARAMETER - The previous discussion has illustrated how the forces and moments produced by the tires are combined with the physical characteristics of the vehicle to give an overall performance portrait. It has been shown that the fundamental force-moment relationships yield a fixed array of steer-sideslip angle lines within the diagram. This backdrop, in the F-M (or CN-CY diagram), can be thought of as translating without rotation as the vehicle comes to a new trim condition. In effect, the lines are simply re-identified for finite radius operation - the $\beta = 0$ line becomes $\beta = + b/R$ and the $\delta = 0$ line becomes $\delta = + \ell/R$. For a more complete discussion of this pattern shift, the reader is referred to the earlier paper (1). Three points are worth reiterating:

(a) The lines on the infinite radius force-moment diagram reflect vehicle capability - there are no constraints on how this capability is utilized.

(b) A non-zero moment is a maneuvering moment; with fixed controls, the vehicle will seek a different operating point, which is a new trim.

(c) The application of a step-like steering angle change on the diagram generates appropriate initial conditions for a change in trim.

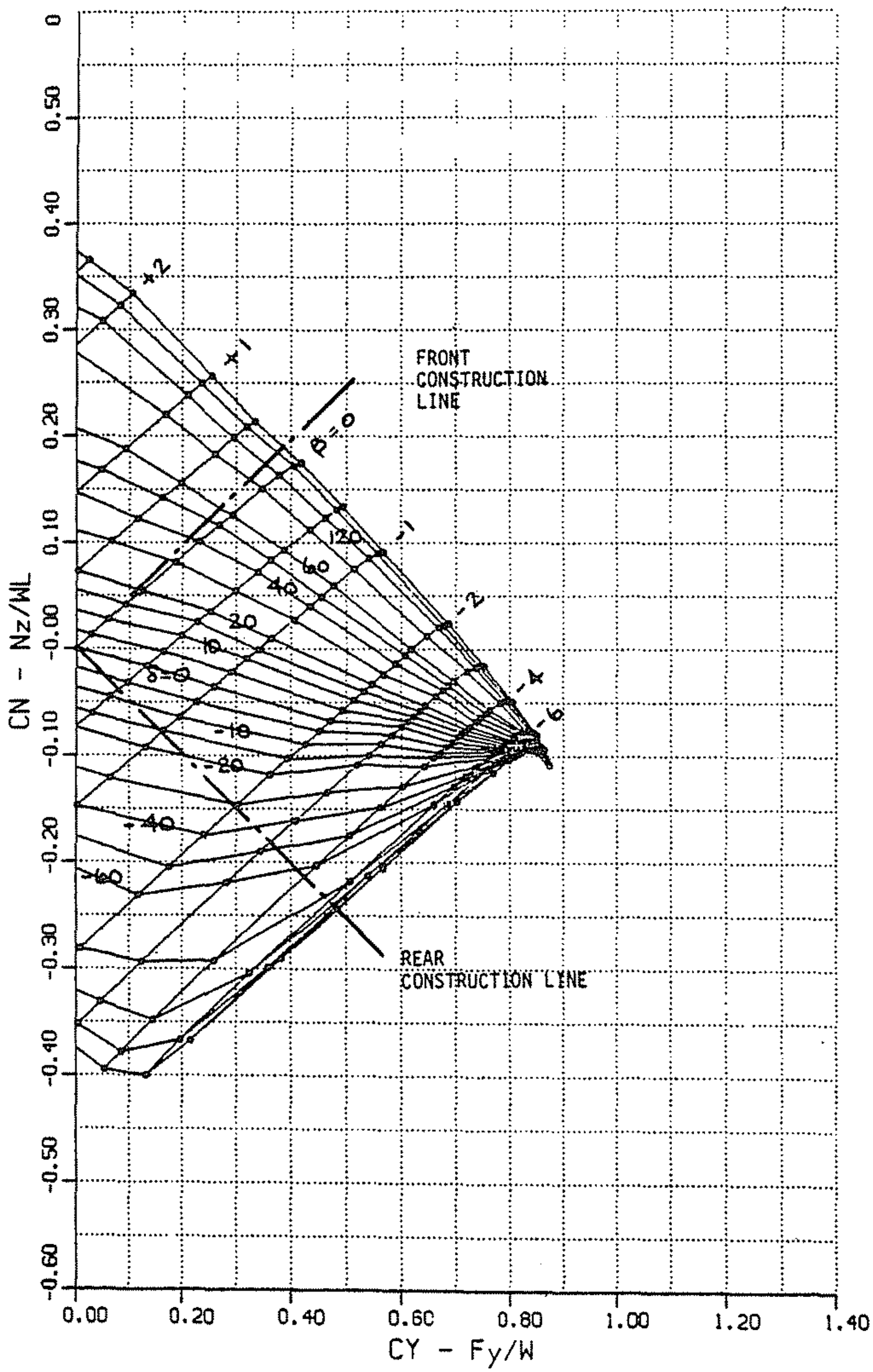

Fig. 1 - Force-moment

These observations are the foundation blocks on which the application of the Moment Method concept to transient performance evaluation is based.

It has been traditional in vehicle dynamics studies to attempt to characterize transient response with a single response time parameter. This parameter may be related to either the lateral acceleration or yaw rate response; it has been evaluated as the time to reach 63%, 90%, or 95% of steady-state value; it has been defined with respect to peak value of the response; and, it has been related to properties of the frequency response phase plot (3, 6, and 7). In effect, there has been no general acceptance of a single definition even though there is wide recognition that some measure of time-to-respond is an important handling consideration. The only reason we make this point here is that the Moment Method provides yet another reference; it is based on evaluation of the initially available maneuvering moment.

In our earlier studies, it was found that a reasonable approximation to a yaw rate-related response could be computed from the expression:

$$\tau = \frac{k^2}{\ell V \sigma}$$

where τ = response time (secs)

σ = Stability Index

k = yaw radius of gyration

ℓ = wheelbase

V = velocity

In effect, the initially available yawing moment is simply related to the yaw moment of inertia to obtain a time term which is equivalent to the time constant of a linear first order system. Here, the value of σ is read from the CN-AY diagram and the other parameters are assumed to be known.

The limitations of this representation are associated with the force balance constraint of the CN-AY analysis. Thus, a similar expression (that is, one still based on the initial maneuvering moment derived from a step input of steering) was sought from the more universal F-M diagram. Reexamination of Fig. 1 will illustrate the approach. The pre-control operating point is at the origin of the plot. With application of a steering command, the locus of the transient response is along the $\beta = 0$ line to the value of the applied steering angle and then along a descending line to a steady-state trim point that is determined by speed. This slope of this "response line" can be expressed as:

$$m = \frac{a\,[1 + KV^2]}{1 - V^2 \dfrac{Ka}{\sigma \ell}}$$

where a = slope of β lines

K = spacing of δ lines

σ = slope of δ lines

While the locus of this line has several interesting possibilities for improving understanding of the transient (for example, the definition of the transient contributions of the three moment-producing factors) it serves only as an intermediate step in obtaining a value for the response time parameter. With additional manipulation of the terms, this parameter can be expressed as:

$$\tau = \frac{k^2\,(1 - \frac{a}{m})}{aV}$$

where k = radius of gyration

a = slope of β lines × wheelbase

m = slope of response line

This expression can then be used to compute values for the response time parameter at any desired speed. Thus, a <u>single</u> infinite-radius F-M diagram provides <u>complete</u> information for calculating a measure of the transient response at all operating conditions.

APPLICATION TO VEHICLE DESIGN/ANALYSIS - In the last year or so, the method has been used in a series of studies for real car development and evaluation. These investigations have been concerned with a wide variety of tire and suspension design options for two different baseline vehicles. Over 100 performance diagrams have been generated to illustrate the effects of a wide variety of design modifications - weight and weight distribution changes, tire performance characteristics, suspension compliance influences - and of operating conditions on the stability and controllability of the vehicle. A few examples of these diagrams are included here to illustrate the application of the technique. For the purposes of the discussions which follow, it is necessary to define the configuration and the operating conditions only with respect to steering ratio (approximately 17:1), wheelbase (as used here, 8 ft), load distribution (about 50/50) and speed (60 mph).

Fig. 2 is a performance plot for this selected configuration operating at road load conditions (zero longitudinal acceleration). For the values given above, the Ackermann angle gradient is 32 deg/g (measured at the steering wheel) and the front and rear path stiffness parameters are approximately 0.94 and 0.96 deg/g (measured at the road wheels).

Observations about the vehicle performance which can be made from this diagram are:

(a) A maximum trim lateral acceleration of about 0.75 g is achievable.

(b) Control sensitivity is about 1.5 g/100 deg of steering wheel in the normal operating region (AY $\leq$ 0.3 g).

(c) For maneuvering in the neighborhood of 0.5 g, the control sensitivity is about 0.5 g/100 deg.

(d) The sideslip sensitivity over the operating range is about 4 deg/g (increasing slightly at high lateral acceleration). This implies a rear compliance value of about 3 deg/g.

(e) The understeer gradient is about 2 deg/g in the normal operating range. In the region around 0.5 g, the gradient is approximately 3 deg/g.

(f) The vehicle plows at its limit. That is, with the maximum forces available from both ends of the car (the apex of the diagram), the unbalanced maneuvering moment is negative.

(g) The vehicle is stable over the complete operating range. The value of the Stability Index is approximately -0.22 at low lateral acceleration and about -0.50 near the trim limit.

(h) The front compliance is computed to be about 5 deg/g in the linear operating region. It is approximately 6 deg/g in the neighborhood of 0.5 g. In conjunction with the value determined for the rear cornering compliance of 3 deg/g, understeer gradients of 2 and 3 deg/g can be computed.

For this same vehicle configuration, operation with closed throttle is depicted in Fig. 3. The effect of the forward load transfer for this condition is apparent in the diagram. The unbalanced yaw moment at the diagram apex is reduced; maximum trimmed lateral acceleration is increased; the internal lines of the diagram are shifted; and the stability is somewhat altered - all with respect to the previous diagram. Observations similar to those listed for Fig. 2 can again be made and nominal values for the various performance parameters can be obtained. The key point, however, in using the method for design evaluation is the shift of operating points from the road load condition. Clearly, the vehicle is still stable over the range, which continues to pertain to the 60 mph initial speed. There is, nevertheless, a movement of the trim operating points for given steer angles toward higher acceleration. The shift is barely perceptable at low lateral acceleration values but more pronounced at the higher values. For example, at road load conditions, a steer angle of 60 deg produces trim at about 0.59 g. With dropped throttle, trim for this steer angle occurs at about 0.63 g. Associated values for the Stability Index are -0.19 and -0.45, respectively.

The simulation program is also capable of generating diagrams for braked conditions. Fig. 4 illustrates a run of this type. It is for a different vehicle than that of the previous figures, and no valid basis for comparison should be inferred. In this case, vehicle speed is 80 mph and nominal deceleration is about 0.50 g. The vehicle is seen to be directionally stable over the lateral acceleration range, which has a trim limit of about 0.54 g whereas the limit was about 0.7 g for road load conditions with this car (that is, the diagram size is much reduced). Note also the maneuvering limitations imposed at higher lateral accelerations.

CONTINUING DEVELOPMENT OF THE METHOD - The fundamental F-M approach is currently receiving priority. Additional effort is being applied to investigation of the basic similarities/differences in the Stability Index and understeer gradient parameters over the whole maneuvering envelope. Refinement of the method for design synthesis has been undertaken. A few comments on this last point are included here.

In the course of generating over 100 performance envelope diagrams, it has been observed that each design change influences the pattern of the diagram in a specific way. For example, a change in rear lateral force compliance shifts

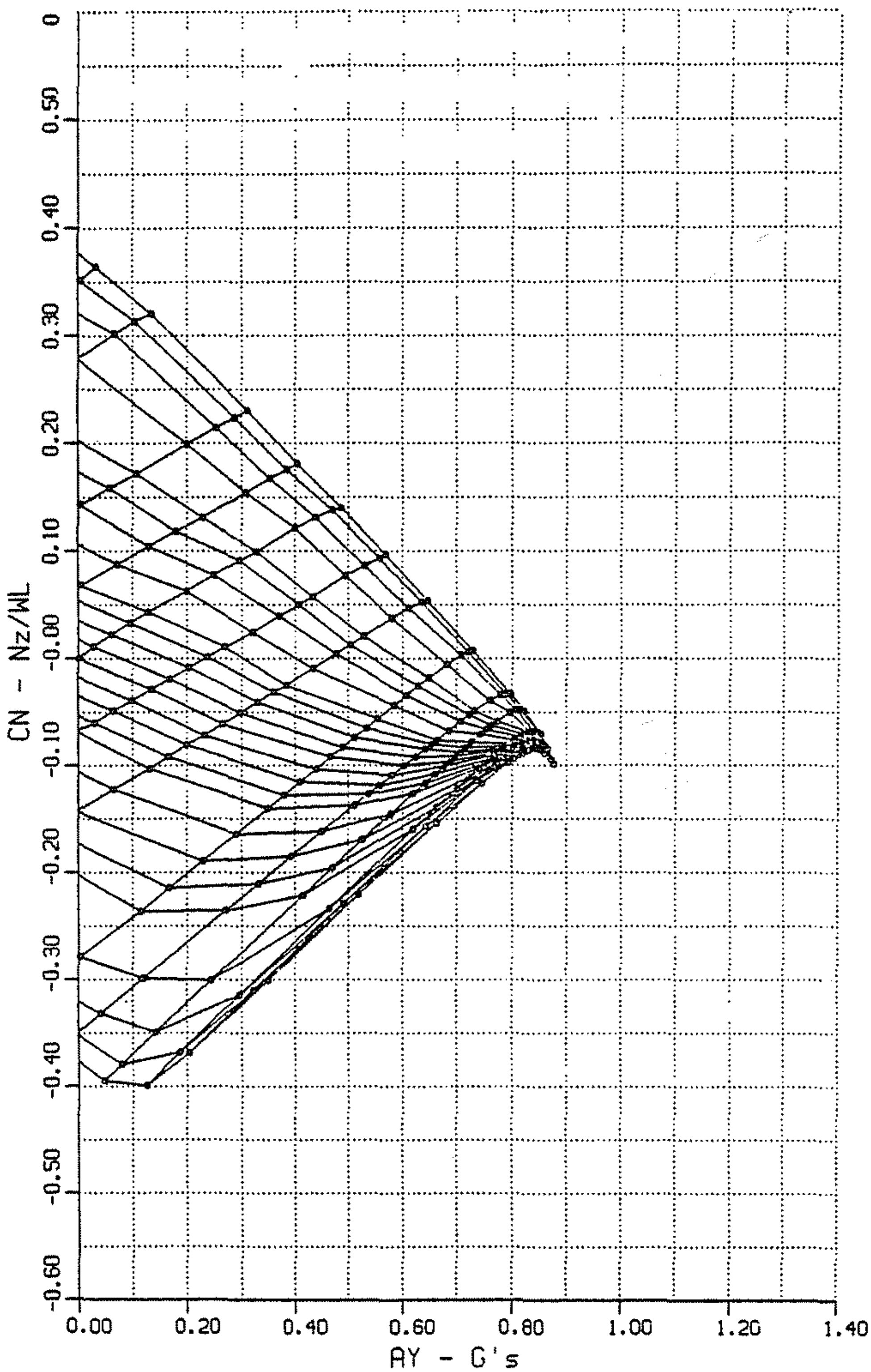

Fig. 2 - Road load

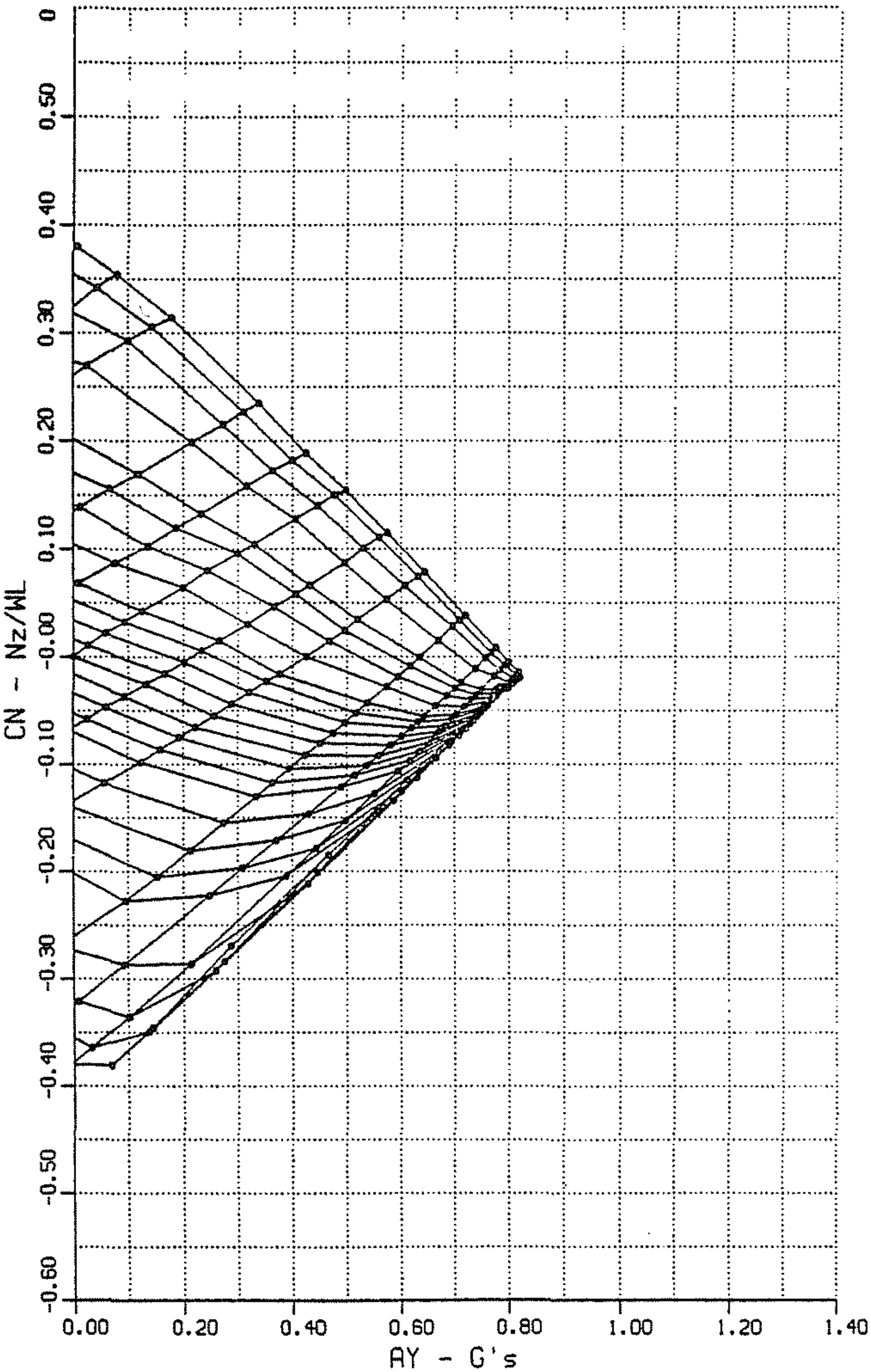

Fig. 3 - Closed throttle

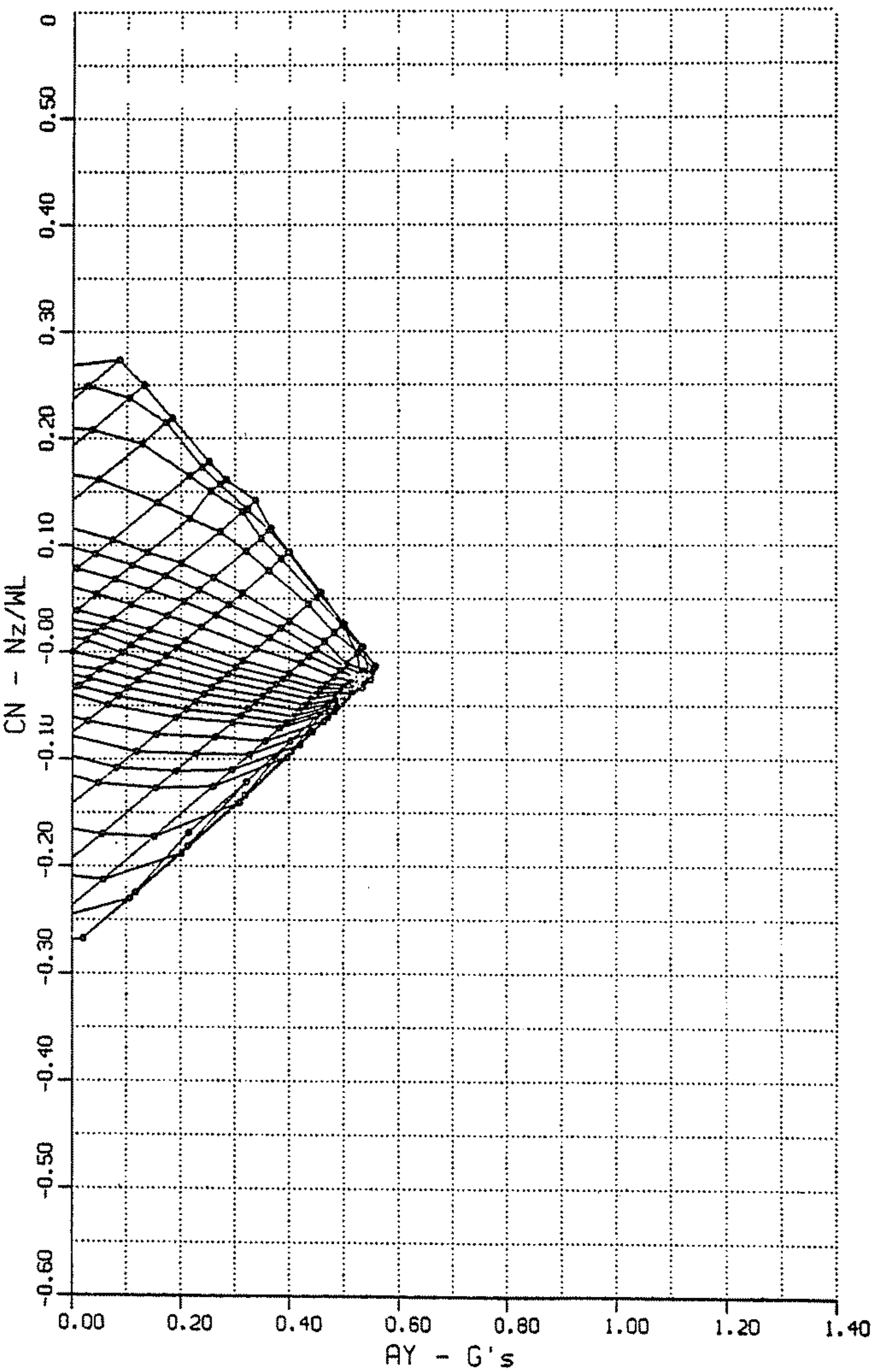

Fig. 4 - Braking

the sideslip (β) lines parallel to their original alignment but does not affect the limit envelope of the diagram. The steering angle (δ) lines reflect this shift by rotation. A change in, say, front roll steer, however, is manifested in the diagram by changes in the steering angle lines only, without any effect on the orientation of the sideslip lines. Other design modifications similarly have their own identifiable signatures in the diagram.

It has not been practical to incorporate detailed discussions of each design characteristic and its influence on the line patterns of the diagram in this paper. Such discussions would require the inclusion of a large number of specially prepared diagrams and a convenient means for comparing the internal line patterns. Nevertheless, several significant observations pertaining to the utilization of the method in vehicle design synthesis can be identified:

(a) It is convenient to separate the compliance terms into two categories - effective slip angle influences and geometric steer effects. As tne words indicate, the former includes the design characteristics which result in an actual change in required slip angle for operation at a given condition; it includes tire performance properties (cornering stiffness as function of normal load, inclination angle and camber thrust), and load distribution. The second category involves characteristics which affect merely the orientation of the road wheels with respect to the chassis. It consists of the physical compliance effects - roll steer and lateral force and aligning torque influences on wheel position. Only the first set, the effective slip angle terms, can be used to modify the envelope (limiting behavior) of the diagram.

(b) Design modifications made at front and rear are distinguishable from each other. Sideslip angle requirements are determined solely by rear end terms. Both front and rear changes affect steer angle requirements.

(c) Special modifications, such as changes in anti-roll bar size affecting distribution of the roll couple, can be evaluated.

CONCLUDING REMARKS

Recent developments in the Moment Method have taken place in a number of areas as briefly noted below:

(a) Inclusion of longitudinal acceleration capability in the computer simulation.

(b) Application of the method to problems of vehicle design, including trim changes.

(c) Development of a method for calculating a transient response time from the Moment Method presentation.

(d) The plotting and analysis of specific maneuvers on the Moment Method diagrams.

(e) The identification of characteristic changes in the diagrams consequent to changes in individual design parameters and the use of the method for vehicle handling synthesis.

Finally, there is an increasing recognition of the basic importance of the Force-Moment (or in coefficients, C_y-C_n) diagram which was discussed but not featured in (1). This diagram for infinite path radius represents a measure of the absolute stability inherent in the vehicle.

ACKNOWLEDGEMENTS

Contributions to the development of the Moment Method have been made by many people over a period of several years and it is not practical to include a complete listing here. The authors do wish to recognize, however, contributions to the phase of development reported herein. In particular, the support of Chevrolet Engineering personnel is acknowledged. In addition, the work of Messrs. Dennis T. Kunkel and David J. Segal (both formerly of Calspan) and Ms. Nancy W. Robinson of Calspan on various aspects of the simulation development is gratefully recognized.

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