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SURFACE VEHICLE STANDARD

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MEASUREMENT OF VEHICLE AND SUSPENSION PARAMETERS FOR DIRECTIONAL CONTROL STUDIES—RATIONALE

Foreword—While the theoretical fundamentals of primary ride had been established by Rowell [1][1] in 1922, the first guidelines for static deflections and dynamic index were provided in 1934 by Olley [2].

Olley also provided the first measurements of directional control performance through his concept of understeer and oversteer. Meanwhile, Lutz [3] was using one-tenth scale models to study directional control. Early theoretical studies of directional control were generally simplified, such as those of Huber [4] and Riekert and Schunk [5] in 1940. The first dynamic transition test was reported by Stonex [6] in 1941, using an optical method to determine the path of the vehicle. In 1953, Fonda [7] developed a more complete linear model by using stability derivative notation from aircraft practice, and Schilling [8] calculated transient response.

Early measurement of vehicle and suspension characteristics was typically straightforward, sometimes crude; Olley used pairs of jacks and scales to measure ride and roll rates and a cable driven rotary scale to measure axle steer, for example. A 1938 work by Kamm and Schmid [9] includes illustrations of the test equipment used to measure spring rates, Coulomb friction, shock absorber characteristics, steering system compliance, center of gravity location, and pitch moment of inertia. These early measurements, even if sufficiently accurate, appear to have been quite labor intensive and time consuming.

Facilities for convenient, systematic measurement of vehicle and suspension parameters are apparently relatively recent, such as those described by Nedley and Wilson [10], Ellis and Sharp [11], Basso [12], Winkler [13], and Bell, et. al. [14,15]. Other researchers [16,17,18] have addressed other aspects of vehicle and suspension parameter measurement and characterization.

1. Scope—This SAE Information Report presents the background and rationale for SAE J1574-1.

The motor vehicle industry is working toward a more complete understanding of the factors affecting the motions of vehicles on the roadway, by using a variety of techniques that predict responses to road and operator inputs. The capability to predict responses is desirable so that vehicles can be designed for optimum safety and utility. In addition to the force and moment properties of the pneumatic tires, a number of vehicle and suspension parameters affect the response of the vehicle; these include weight, center-of-gravity location, moments of inertia, suspension ride and roll rates, suspension kinematic and compliance properties, and shock absorber characteristics. These parameters must be quantified in order to predict vehicle responses.

1. Numbers in parenthesis designate references at the end of report.

Measurement of most of these parameters will be limited to determining their values in the linear range for use in directional control simulations. The limitation to linear range characteristics primarily reflects current measurement practice, to which SAE J1574-1 is directed. In the case of mass and inertia properties, this limitation clearly does not apply. For those to which it does apply, it is not felt to be a serious limitation since most of the measurement techniques can be extended beyond the linear range through appropriate increases in steering or suspension displacement or loading. Use of the measured parameters in simulations is assumed as the most frequent use. However, this does not seem to limit their use to simulations. Vehicle and suspension characteristics appropriate for simulation can equally well be used for vehicle and suspension characterization and comparison, suspension development and optimization, and processing of road test data.

As noted in SAE J1574-1, vehicles addressed will be limited to passenger cars, light trucks, and on-highway recreational and commercial vehicles with two or more axles of approximately the same wheel track. This excludes bicycles, motorcycles, tricycles, and vehicles intended primarily for off-highway use. This limitation is largely a recognition of the types of vehicles historically measured for ride and directional control simulation, since SAE J1574-1 has been written to document the current state-of-the-art rather than to expand it. Additionally, inclusion of these other vehicles might well require measurement of other chassis characteristics to properly simulate their dynamic characteristics. The measurement of these additional characteristics may not be supported by widespread experimental practice.

1.1 Assumptions and Limitations—The focus of SAE J1574-1 is consolidation and documention of the best existing technology. The intent is to avoid introducing unproven and unestablished practices.

The assumptions related to the methods of suspension characterization (static characteristics, phenomenological descriptions, characterization for linear range maneuvers, and use of superposition) stem largely from established practice, with established validity. All of these suspension characterization methods are widely, though not exclusively, used and have given valid simulated responses of steady-state and dynamic vehicle characteristics. This is not to say that other approaches are not also valid.

The limitations associated with types of simulations addressed also stem primarily from the limitations of existing practice, which has generally focused on the simulation of fixed control directional control properties in the linear range. While simulation of free control vehicle responses is not uncommon in the automotive industry, its inclusion in SAE J1574-1 would require the measurement of steering system component masses and inertias. Such measurements are not common practice.

The limitations associated with vehicle characteristics addressed deserve brief discussion. Suspension side view kinematic properties are not addressed since they are not required for constant speed directional control simulation. This is also true of rotational inertias of wheels, tires, brakes, and driveline components as well as steer and camber compliances resulting from longitudinal force. The measurement of steer and camber compliances resulting from overturning and rolling resistance moment is omitted since these compliances normally have small effects on vehicle directional control characteristics. (Rolling resistance moment generally has negligible effects on steer and camber deflections.) Finally, the measurement of the remaining variables (kingpin and caster offsets, ride and roll damping, and fifth wheel characteristics) is omitted due to the absence of standard industry practice. Ride and roll damping are usually calculated from shock absorber damping constants and suspension kinematic characteristics. These calculations will be discussed in Section 10.

1.2 Characteristics Measured—No discussion in addition to that of SAE J1574-1.

1.3 Nature of Measurements—SAE J1574-1 gives an overview of the types of measurements required for each class of variable measured. This discussion will generally be repeated in much more detail in the first two paragraphs of each section. This more detailed discussion will include minimum accuracy requirements, based on simulation requirements or the capabilities of current experimental practice. In some cases, simulation requirements are not particularly stringent and accuracy requirements may more realistically be indicated by experimental practice. With this in mind, a brief, general discussion of accuracy requirements may be helpful here, with a more specific discussion for each variable given in this Information Report for each section.

In those cases where the data are used solely for vehicle subjective development, the measurements may normally be made to 5% accuracy, especially if chassis parameter changes significantly larger than this are being made. This assumes that just noticeable subjective differences in response characteristics are about 10%, thus necessitating chassis parameter changes of at least 10%, preferably more.

Vehicle and suspension parameter data may also be used as inputs for mathematical models that calculate vehicle responses. The sensitivity of the response to errors in the input data varies with the vehicle being simulated, with its tire characteristics, and the characteristic in question, thus making it difficult to generalize about accuracy requirements. With regard to stability and control calculations, it may be observed that the understeer gradient is the summation of numerous effects, such as weight distribution, roll camber, roll steer, lateral force deflection steer, and aligning torque deflection steer. A 1% error in measurement of any one quantity is likely to alter the understeer gradient by 1% or less. Only when inaccuracies accumulate in the same direction is it possible for a significant error in the simulated response to result. Transient properties, such as lateral acceleration response time or yaw velocity response time, can be expected to have sensitivities similar to those for the understeer gradient. Accuracy requirements for simulation thus depend on the desired accuracy of the simulation and on whether one assumes that errors will accumulate in one direction or not.

As a final note on the nature of the measurements, the measurement of suspension kinematic and elastic characteristics with tires mounted should be briefly discussed. As noted in SAE J1574-1 for this section, common practice is to leave wheels and tires mounted during all measurements. While this may introduce small errors in some measurements, it is treated here as the primary mode of measurement, because of its widespread use and relatively small effect on accuracy. However, other methods, which might omit or bypass the tire are not excluded if the additional accuracy is desired. Paragraph 9.2.2 of this document covers this subject in more depth.

1.4 Use of Recommended Practice and Information Report—No discussion in addition to that of SAE J1574-1.

2. References

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein.

1. H. S. Rowell, "Principles of Vehicle Suspension," The Institution of Automobile Engineers, Proceedings, vol. XVII (1922-23), part II, pp 445-541.
2. M. Olley, "Independent Wheel SuspensionæIts Whys and Wherefores," SAE Transactions, vol. 29 (1934), pp 73-81.
3. O. Lutz, "Grundlagen fur Modellversuche an Fahrzeugen (Fundamentals of Vehicle Research using Models)," ATZ 37 (1934), pp 211-212.
4. L. Huber, "Die Fahrtrichtungsstabilitat des schnellfahrenden Kraftwagens (Directional Stability of High-speed Vehicles)," Deutsche Kraftfahrtforschung, vol. 44 (1940), no. 1, p. 23.
5. P. Riekert and T. E. Schunk, "Zur Fahrmechanik des Gummibereiften Kraftfahrzeugs (On the Mechanics of Rubber-tired Vehicles)," Ingenieur Archiv, vol. 11 (1940), p 210.

6. K. A. Stonex, "Car Control Factors and Their Measurement," SAE Transactions, vol. 48 (March 1941), pp 81-93.
7. A. G. Fonda, "Development of the Lateral Equations of Motion for an Automobile," Cornell Aeronautical Laboratories Flight Research Memorandum No.181, 1953.
8. R. Schilling, "Directional Control of Automobiles," Industrial Mathematics Society Paper, Detroit, Michigan, 1953.
9. W. Kamm and C. Schmid, “Das Versuchs—und Messwesen and dam Gabiet des Krafthahrzaugs (Experimental and Measurement Techniques in the Automotive Field),” Springer, Berlin, 1938.
10. A. L. Nedley and W. J. Wilson, “A New Laboratory Facility for Measuring Vehicle Parameters Affecting Understeer and Brake Steer,” SAE Paper No. 720473.
11. J. R. Ellis and R. S. Sharp, "Measurement of Vehicle Characteristics for Ride and Handling," The Institution of Mechanical Engineers, Proceedings, vol. 182, part 3B (1967-68), pp 71-81.
12. G. L. Basso, “A Methodology for Measurement of Vehicle Parameters Used in Dynamic Studies,” National Research Council Canada No. 13497, Mechanical Engineering Report MS-134, Ottawa, July, 1973.
13. C. B. Winkler, “Measurement of Inertial Properties and Suspension Parameters of Heavy Highway Vehicles,” SAE Paper No. 730182.
14. S. C. Bell, S. C. Burns, J. R. Ellis, and W. R. Garrott, “The Design of a Suspension Parameter Measurement Device,” SAE Paper No. 870576.
15. S. C. Bell, J. R. Ellis, W. R. Garrott, and Y. C. Liao, “Suspension Testing Using the Suspension Parameter Measurement Device,” SAE Paper No. 870577.
16. M. B. Goran and G. W. Hurlong, Jr., “Determining Vehicle Inertial Properties for Simulation Studies,” Bendix Technical Journal, Spring 1973.
17. D. B. January, “Steering Geometry and Caster Measurement,” SAE Paper No.850219.
18. W. A. Cobb, R. L. Leffert, and P. M. Riede, Jr., “Typical Vehicle Parameters for Dynamics Studies Revised for the 1980's,” SAE Paper No. 840561.

3. Vehicle Description and Preparation

3.1 General Vehicle Description—The vehicle description forms presented in SAE J1574-1 are designed to give a fairly complete vehicle description for three basic reasons. First, the vehicle description enables more meaningful interpretation of test results through documentation of vehicle content. This becomes important when time, unfamiliarity, or multiple vehicle changes make human memory fallible. Second, such identification would be required if the test data were part of subsequent litigation. Finally, although not the primary purpose, the vehicle description process may identify aspects of the vehicle which make it unsuitable for the intended tests, such as incorrect or out of specification parts.

3.2 Specific Measurements—The intent of the vehicle description form is to define and describe the vehicle prior to testing. Unfortunately, this process depends on certain measurements made in subsequent sections, as discussed in SAE J1574-1. Excluding this interdependence, it should be possible to complete the vehicle description form before proceeding to subsequent sections.

3.3 Vehicle Preparation—The purpose of vehicle preparation is to ensure that the vehicle represents design intent, or a predetermined out-of-specification condition, is safe for the intended tests, is sufficiently clean for part identification and measurement, and is ballasted to proper tire normal forces or suspension trim heights. Ballasting often results in undesired suspension trim heights, for the correct tire normal forces, or vice versa. The discrepancy should be small if the vehicle, including springs, represents design intent. Generally, proper tire loading is more important for directional control performance than proper suspension trim heights. But for the measurements addressed in SAE J1574-1, suspension trim heights are generally more important than tire normal forces. This is true for the measurement of vehicle geometric characteristics, center of mass positions, and suspension and steering kinematic properties. Proper tire normal forces are more important in the measurement of vehicle mass and moments and products of inertia.

4. Measurement of Dimensional and Geometric Characteristics

4.1 Variables Measured—No discussion in addition to that of SAE J1574-1.

4.2 Apparatus

4.2.1 GENERAL PERFORMANCE REQUIREMENTS—No discussion in addition to that of SAE J1574-1.

4.2.2 GENERAL CONFIGURATIONS—Table 3 of SAE J1574-1 lists a number of typical transducers used in making the measurements listed. The reader should be reminded that this list of "typical" transducers is provided for reference but should not be limiting. Many methods or special tools can be used on most of the measurements. For instance, an adjustable trammel bar, or set of these, may be more useful than a steel tape for many of the linear dimensions. Measurement methods and transducers should be determined by types of vehicle measured, frequency of measurements, and cost.

4.2.3 PERFORMANCE REQUIREMENTS—The accuracy requirement for each measurement covered by Table 3 is determined by its role in:

a. Defining the test vehicle
b. Simulating its dynamic performance
c. Chassis development, or
d. Processing road test data

In general, accuracy reflecting the accuracy of available, cost-effective transducers and good mechanical measurement practice exceeds the requirements of any of these uses. While these values of accuracy are seemingly more stringent than required, other sources of error in simulation and vehicle testing require that those associated with vehicle definition be minimized. This allows effort to be directed at minimizing the other sources of error. For this reason, the accuracy requirements shown in Table 3 generally reflect available transducer accuracy and good measurement practice.

The accuracy requirements in Table 3 are stated as a percentage of actual reading. This criterion ceases to be meaningful when the required accuracy is less than the accuracy of available transducers, which can occur with variables whose values can be near zero. In this case, an alternate, absolute accuracy is given to be used as the accuracy criterion near zero. It should be used when larger than the accuracy determined by the percentage accuracy times the actual reading.

4.3 Test Procedures

4.3.1 VEHICLE PREPARATION—No discussion in addition to that of SAE J1574-1J1574-1.

4.3.2 TEST PROCEDURES

4.3.2.1 Measurement of Linear Dimensions—Many of the measurements of linear dimensions outlined in SAE J1574-1 include averaging values on opposites sides of the car. This reflects the existence of lateral asymmetries in most dimensions of a vehicle. These are generally small but can occasionally be significant. Thus, measuring values on both sides allow a check of the magnitude of the asymmetry and averaging allows a truer representation of the vehicle's dimensions. However, in certain instances the magnitude of the asymmetry may be desired (in vehicle development, for instance) and averaging may not be appropriate. In addition, side-to-side asymmetries sometimes represent a special design asymmetry (wheelbase, on certain vehicles) which should be documented. In these special cases, the needs of a particular laboratory or circumstance should take precedence.

SAE J1574-1 specifies ballasting the vehicle to curb suspension trim heights, measured either between the suspension and sprung mass or between the sprung mass and ground. The former is preferred and both are discussed further here.

Suspension trim height can be defined in various ways and measured with different techniques to different levels of accuracy. The simplest, and least precise approach is to measure the vertical distance between the wheel center and an arbitrarily defined point on the body fender lip. This is usually done with a steel tape. Its disadvantage is in not uniquely defining suspension trim exclusive of body position relative to suspension attachment points. Further, the wheel lip reference is often arbitrary and may be difficult to reproduce at a later date. A more precise and repeatable method is to measure relative heights between some point(s) on the suspension and/or a point on an adjacent frame member. (Such points are often a ball joint seat, axle centerline, control arm pivot bolt, or frame "kick-up" above axle centerline.) These measurements are more difficult and require that the test vehicle be on an accurate horizontal reference, usually a steel bed plate. Vertical measurements should be made between reference points and the bed plate. Subtraction defines their relative height.

The measurement of wheel track, between centers of tire contact, can be complicated by the existence of camber and toe-in. It is customary to measure wheel track above the road plane at the tire tread centerline at front and rear. These dimensions should be averaged to correct for toe-in. In addition, there should be an additional correction made for camber, normally measured on a wheel alignment facility. This is also discussed in 8.2.2 of SAE J1574-1.

4.3.2.2 Measurement of Wheel Alignment—No discussion in addition to that of SAE J1574-1.

4.3.2.3 Measurement of Tire Pressure—No discussion in addition to that of SAE J1574-1.

4.4 Calibration Procedures—No discussion in addition to that of SAE J1574-1.

5. Measurement of Vehicle and Component Weights

5.1 Variables Measured—Total vehicle weight, front and rear unsprung weights, sprung weight, and individual tire normal forces are measured. The total vehicle weight is the weight of the complete vehicle conforming to specified conditions, including appropriate quantities of coolant, fuel, and lubricant. The unsprung weight is all weight which is not carried by the suspension system, but is supported directly by the tire or wheel, and considered to move with it. Portions of the weight of the suspension members are also included. (See 5.3.2.2 for a further discussion of this issue.) The sprung weight is the total weight minus the total of unsprung weights.

Since the sprung weight is the difference between total and unsprung weights, it is not necessary to measure all three. It is customary to measure total and unsprung weights and determine the sprung weight from their difference.

Some applications may not require the measurement of unsprung weight, such as the simulation of a nonrolling "bicycle" model. If such is the case, it should be avoided, due to the difficulty of disassembling the vehicle suspensions.

The need to measure individual tire normal forces stems from the need to determine the vehicle horizontal center of gravity position, discussed in the next section. To measure the vehicle's longitudinal center of gravity position, only the "axle loads" (sum of tire normal forces on an axle) are required, assuming the wheelbases are the same on each side. (This symmetry usually exists, at least nominally, for most vehicles.) Given the axle loads and the wheelbase, the solution of a statics problem provides the longitudinal center of gravity position. Similarly, to measure the vehicle's lateral center of gravity position, only the sum of tire normal forces on each side of the vehicle would be required, if the wheel tracks were the same. But, this is generally not true and individual tire normal forces are required. Because of this, the need to measure individual tire normal forces will be assumed in SAE J1574-1. The accuracy requirements for these measurements will be determined by the accuracy requirements set for the measurement of total vehicle weight and center of gravity position, not by accuracy requirements for the measurement of tire normal forces, per se. This will be discussed further in 5.2.3 of this section.

5.2 Apparatus

5.2.1 GENERAL PERFORMANCE REQUIREMENTS—No discussion in addition to that of SAE J1574-1.

5.2.2 GENERAL CONFIGURATIONS—Due to the general need to measure individual tire normal forces, one or more scales capable of measuring each tire normal force are required. In certain cases, this may not be required. If a given laboratory does not need to measure center of gravity horizontal position, a single scale to measure total vehicle weight and sprung or unsprung weights would suffice. Similarly, a single scale to measure axle load or the sum of tire normal forces on one side of the vehicle could be used to measure horizontal center of gravity position, if the vehicle symmetry conditions discussed in 5.1 were met.

5.2.3 PERFORMANCE REQUIREMENTS—Table 5 in SAE J1574-1 gives accuracy requirements for the measurement of tire normal forces, sprung and unsprung weights, scale level, and scale planarity. The purpose of this discussion is to explain these requirements by developing the theory related to them. Since a few of the accuracy requirements are vehicle dependent, the availability of the theory will allow the user to set his/her own accuracy requirements which are consistent with those of Table 5.

It is assumed in this discussion that individual tire normal forces are to be used primarily to calculate total vehicle weight, longitudinal weight distribution (center of gravity position), and lateral weight distribution (center of gravity position). They may also be used as input to four-wheeled directional control simulations, in which case their importance depends on tire force and moment nonlinearities. Since SAE J1574-1 is limited to directional control simulation in the linear range, these effects will be assumed small. Therefore, this discussion will focus on errors in the measurement of tire normal forces which ultimately affect apparent total weight and horizontal center of gravity position. (Longitudinal and lateral weight distribution will be used as indications of the effect of measurement error on the determination of horizontal center of gravity position.) The errors discussed are: scale error, side view scale slope, front view scale slope, and scale planarity. Errors introduced by inaccuracies in these variables are assumed to superimpose and will therefore be discussed separately. Derivations will assume a four-wheeled vehicle.

The following variable names will be used:

θ_y side view slope of plane of scale(s)
θ_x front view slope of plane of scale(s)
a horizontal distance from total vehicle center of gravity to front wheel centerline
b horizontal distance from total vehicle center of gravity to rear wheel centerline
c horizontal distance from vehicle lateral plane of symmetry to total vehicle center of gravity (assumed positive to the right)
e scale error, measurement error divided by true value
h height of one tire center of tire contact above plane of others
H height of total vehicle center of gravity above ground
k_f front roll stiffness, including tire effects
k_r rear roll stiffness, including tire effects
k_θ effective stiffness of roll stiffnesses in series
L wheelbase
P_1 left front tire normal force
P_2 right front tire normal force
P_3 left rear tire normal force
P_4 right rear tire normal force
T_f front wheel track
T_r rear wheel track
W total vehicle weight
W_f front axle load
W_r rear axle load
WD_x longitudinal weight distribution
WD_y lateral weight distribution
apparent value of variable resulting from effects of error(s)

The effect of scale error is easiest to address by first defining its effect on the measurement of an individual tire normal force. Using the previous definition of e (see Equations 1 and 2),

$$e = (P_i' - P_i) / P_i \tag{Eq. 1}$$

and,

$$P_i' = (1 + e)P_i \tag{Eq. 2}$$

The worst-case effect of scale error in the measurement of total vehicle weight would be four scales with errors in the same direction, or one scale with the same error. In this case, the apparent total weight would be as shown in Equation 3:

$$\begin{aligned} W' &= (1+e)P_1 + (1+e)P_2 + (1+e)P_3 + (1+e)P_4 \\ &= (1+e)W \end{aligned} \tag{Eq. 3}$$

The apparent total weight depends only on scale error and total vehicle weight and is independent of vehicle center of gravity position or other design attributes.

The worst-case effect of scale error in the measurement of longitudinal weight distribution would be having front scales with errors in one direction and rear scales with errors in the opposite direction. In this case (see Equations 4 to 6),

$$W_f' = (1 + e)W_f \qquad \text{(Eq. 4)}$$

$$W_r' = (1 - e)W_r \qquad \text{(Eq. 5)}$$

$$\begin{aligned} WD_x' &= (1 + e)W_f / ((1 + e)W_f + (1 - e)W_r) \\ &= W_f / (W_f + (1 - e)W_r / (1 + e)) \end{aligned} \qquad \text{(Eq. 6)}$$

The apparent longitudinal weight distribution depends on the scale error and the vehicle's true weight distribution. For a vehicle with 50/50 weight distribution, a 5% scale error in the directions assumed will indicate a weight distribution of 52.5% front. This sensitivity is roughly, but not exactly, the same for different true weight distributions.

The worst-case effect of scale error in the measurement of lateral weight distribution would be having scales on one side of the vehicle with errors in one direction and scales on the other side with errors in the opposite direction. In this case, the governing equations are the same as those for the longitudinal analysis, with the substitution of tire normal forces on one side of the vehicle for axle loads. If the wheel tracks are the same, then the lateral weight distribution corresponds to lateral offset of the center of gravity. If the wheel tracks are not the same, this correspondence no longer holds exactly. For most passenger cars, wheel tracks are usually nearly equal and the previous sensitivity of weight distribution to scale error is applicable. If the wheel tracks are significantly different, then the lateral weight distribution is not a true indication of the center of gravity lateral position. The apparent offset of the center of gravity is determined from apparent individual tire normal forces and the solution of a statics problem:

$$c' = [(P_2 - P_1)(T_f / 2) + (P_4 - P_3)(T_r / 2)] / (P_1 + P_2 + P_3 + P_4) \qquad \text{(Eq. 7)}$$

Scale side view slope can also produce errors in the measurement of total weight and longitudinal weight distribution. This results from the fact that the weight vector acting at the vehicle total center of gravity is not perpendicular to the plane of the scales. Its component normal to the plane of the scales is Wcosqy and its longitudinal component is Wsinqx. These effects result in the following apparent axle loads (assuming insignificant sprung mass pitch resulting from the scale slope and a slope which raises the rear of the vehicle above the front) (see Equations 8 and 9):

$$W_f' = W \cos\theta_y b / L + W \sin\theta_y H / L \qquad \text{(Eq. 8)}$$

$$W_r' = W \cos\theta_y a / L - W \sin\theta_y H / L \qquad \text{(Eq. 9)}$$

The apparent total weight is the sum of these loads. The apparent longitudinal weight distribution is as shown in Equation 10:

(Eq. 10)

$$WD_x' = W_f'/(W_f' + W_r')$$

Scale front view slope can produce similar errors in the measurement of total weight and lateral weight distribution. As before, suspension deflections are assumed to be insignificant and the slope is assumed to raise the left side of the vehicle. Lateral load transfer will be assumed to be distributed according to the longitudinal weight distribution. This is related to the assumption of insignificant suspension deflection, due to Coulomb friction. In this case, suspension roll center heights and roll stiffness distribution do not come into play and the assumption of load transfer distribution equalling the weight distribution is justifiable. The apparent individual tire normal forces are as shown in Equations 11 to 14:

(Eq. 11)

$$P_1' = Wb\cos\theta_x / (2L) - WbH\sin\theta_x / (LT_f)$$

(Eq. 12)

$$P_2' = Wb\cos\theta_x / (2L) + WbH\sin\theta_x / (LT_f)$$

(Eq. 13)

$$P_3' = Wa\cos\theta_x / (2L) - WaH\sin\theta_x / (LT_r)$$

(Eq. 14)

$$P_4' = Wa\cos\theta_x / (2L) + WaH\sin\theta_x / (LT_r)$$

The apparent total weight is the sum of these values. The apparent longitudinal weight distribution is shown in Equation 15:

(Eq. 15)

$$WD_x' = (P_1' + P_2') / (P_1' + P_2' + P_3' + P_4')$$

The apparent lateral weight distribution (again ignoring wheel track differences) is shown in Equation 16:

(Eq. 16)

$$WD_y' = (P_2' + P_4') / (P_1' + P_2' + P_3' + P_4')$$

The last source of error to be discussed is lack of scale planarity. Since scale slope errors have already been addressed, it will be assumed that tire normal forces are being measured by four scales, three of which are level and coplanar. The fourth will be assumed to be higher by an amount h. Assuming that the front axle has the out-of-plane scale, the centers of tire contact are displaced in roll by h/Tf, using small angle approximations. In this displacement mode, with the vehicle in static equilibrium, the suspension roll stiffnesses (including tires) are in series and carry equal and opposite moments. Therefore, knowledge of the magnitude of this moment will allow determination of the load transfer across each axle and the individual tire normal forces. The tire normal force at the out-of-plane (higher) scale and diagonal to it will be higher than that for coplanar scales.

The series spring rate of the two suspensions is shown in Equation 17:

(Eq. 17)

$$k_\theta = k_f k_r / (k_f + k_r)$$

The moment carried by each suspension is the product of this effective stiffness and the imposed roll displacement due to the scale height h is shown in Equation 18:

(Eq. 18)

$$M = k_\theta h / T$$

The load transfer across the front suspension is this moment divided by the wheel track is shown in Equation 19:

(Eq. 19)

$$\begin{aligned} P_f &= M / T_f \\ &= k_f k_r h / [T_f 2(k_f + k_r)] \end{aligned}$$

The load transfer across the rear axle arises from the same moment and imposed roll angle (at the front) but may be carried across a different wheel track as shown in Equation 20:

(Eq. 20)

$$P_r = k_f k_r h / [T_r 2(k_f + k_r)]$$

Therefore, the apparent individual tire normal forces are shown in Equations 21 to 24:

(Eq. 21)

$$P_1' = Wb / 2L + k_f k_r h / [T_f 2(k_f + k_r)]$$

(Eq. 22)

$$P_2' = Wb / 2L - k_f k_r h / [T_f 2(k_f + k_r)]$$

(Eq. 23)

$$P_3' = Wa / 2L - k_f k_r h / [T_r 2(k_f + k_r)$$

(Eq. 24)

$$P_4' = Wa / 2L + k_f k_r h / [T_r 2(k_f + k_r)]$$

The equations developed previously should allow the reader to calculate acceptable values of scale level and planarity, for a given vehicle, such that the accuracy requirements of Table 5 of SAE J1574-1 are met. The absolute accuracy requirements for scale level and planarity shown in Table 5 of SAE J1574-1 are given so that such calculations are not required. Table 5 gives some insight into these requirements, using the previous equations, and based on the characteristics of a small front-wheel-drive passenger car.

TABLE 5—SCALE ERROR, LEVEL, AND PLANARITY CONTRIBUTIONS TO TOTAL ERROR

Variable	Total Error		Error Sources Scale	Error Sources SV Slope	Error Sources FV Slope	Error Sources Planarity
total vehicle weight	0.2%	max error:	0.20%	0.0005	0.0005	
		sensitivity:	1.00%/%	0.002%/deg	0.002%/deg	
		max source:	0.20%	0.25 deg	0.25 deg	
long. weight distribution	0.2%	max error:	0.10%	0.10%		
		sensitivity:	0.50%/%	0.50%/deg		
		max source:	0.20%	0.20 deg		
lat. weight distribution	0.2%	max error:	0.10%		0.10%	
		sensitivity:	0.50%/%		0.50%/deg	neg.
		max source:	0.20%		0.20 deg	
front tire normal force	1.0%	max error:	0.20%	0.10%	0.20%	0.50%
		sensitivity:	1.00%/%	0.50%/deg	1.20%/deg	0.20%/mm
		max source:	0.20%	0.20 deg	0.17 deg	2.50 mm
rear tire normal force	1.0%	max error:	0.20%	0.20%	0.20%	0.40%
		sensitivity:	1.00%/%	1.00%/deg	1.20%/deg	0.20%/mm
		max source:	0.20%	0.20 deg	0.17 deg	2.00 mm

Notes
1 The "max error" is the maximum error permitted for a given error source. The sum of these values equals the "total error" shown for each variable.
2 The "sensitivity" is the measured error, in percent, for the variable per unit of error at the source. Values are approximate for the vehicle studied.
3 The "max source" is the maximum error at the source such that the "max error" is not exceeded for the "sensitivity" shown. The "max source" is the "max error" divided by the "sensitivity."
4 No entry indicates no influence of an error source on the variable. Planarity can influence indicated lateral weight distribution for unequal wheel tracks. For most vehicles, these are roughly equal and the sensitivity is negligible, although not zero.
5 The "max source" angles for scale slope on total weight do not equal the "max error" divided by the "sensitivity," due to the nonlinear nature of the source and resultant error.

Table 5 shows the rationale for the maximum values of scale slope and planarity error in Table 5a of SAE J1574-1 based on an assumed scale error of 0.2%. The allowable scale slope and planarity errors (0.2 degree, 0.2 degree, and 2.0 or 5.0 mm) are small enough to allow measurement of total weight and weight distribution to the accuracy stated. Wheel track differences up to 25% have small effects on the error sensitivities.

Use of the equations developed previously for individual tire normal forces allows further determination of the vehicle horizontal center of gravity position, discussed in Section 6. The accuracy stated for total weight and longitudinal weight distribution will allow the simulation of understeer to within about 0.05 degree/g, based on sensitivity studies not included here. The total error shown for lateral weight distribution is chosen to minimize errors in the determination of center of gravity height, discussed in Section 6, and vehicle inertia, discussed in Section 7.

The allowable scale slope and planarity errors of 0.2 degree, 0.2 degree, and 2.0 or 5.0 mm will also allow for the measurement of individual tire normal forces to the stated accuracy of 1.0%. This accuracy, along with determination of total weight, longitudinal weight distribution, and lateral weight distribution to within 0.2%, is considered sufficient for directional control simulation and vehicle description. Measurement of individual tire normal forces to greater accuracy is considered optional. If this is done, the sensitivities shown for individual tire normal forces should be used as guidelines or recalculated for the test vehicle in question.

In this discussion, the determination of longitudinal and lateral weight distribution to given levels of accuracy have been used as indications of the ability to determine horizontal center of gravity position to certain levels of accuracy. In the longitudinal direction this is true, given wheelbase symmetry. In the lateral direction the relationship between (lateral) weight distribution and center of gravity position is complicated by wheel track inequality. Use of the equations developed previously with the example vehicle shows that the lateral weight distribution does give a good indication of center of gravity lateral position, even with a rear wheel track 25% smaller than the front. In all cases, determination of center of gravity lateral position from the lateral weight distribution and average wheel track agreed very closely with the exact value, calculated from individual tire normal forces and wheel tracks.

5.3 Test Procedures

5.3.1 VEHICLE PREPARATION—The vehicle is ballasted to appropriate axle loads for the proper determination of total weight and center of gravity horizontal position. Suspension trim is uncontrolled since scale level error is small (less than 1.0 degree) and any suspension trim error would produce only a sine error on apparent center of gravity horizontal position.

5.3.2 TEST PROCEDURES

5.3.2.1 *Measurement of Total Vehicle Weight*—No discussion in addition to that of SAE J1574-1.

5.3.2.2 *Measurement of Vehicle Component Weights*—The unsprung weight is all weight which is not carried by the suspension system, but is supported directly by the tire or wheel, and considered to move with it. Portions of the weight of the suspension members are also included. The following components are considered to be directly supported by the tire or wheel and move with it:

a. Axles (solid axle suspension)
b. Backing plates
c. Brake assembly(s)
d. Differential
e. Drums/rotors
f. Front and rear solid axle
g. Outboard universal joints
h. Stabilizer bar (mounted to unsprung mass)
i. Steering knuckles
j. Stub axles
k. Tires
l. Wheels
m. Wheel bearings

Suspension members connecting the unsprung and sprung masses function as both, and their mass must be proportioned accordingly. The complexity of correctly determining appropriate factors for each of the various components prohibits such discussion as part of SAE J1574-1. A generally accepted approximation is to assign 50% of the weight to the unsprung, and 50% to the sprung weight of the vehicle. This method is suggested unless specific or more representative information is available. The following components should be so divided:

a. Control arms
b. Drive shafts/axle shafts (independent suspension)
c. Panhard rod/track bar
d. Shock absorbers
e. Springs
f. Stabilizer bars (mounted to sprung mass)
g. Suspension links
h. Tie rods

5.4 Data Processing and Presentation

5.4.1 DETERMINATION OF TOTAL VEHICLE WEIGHT—No discussion in addition to that of SAE J1574-1.

5.4.2 DETERMINATION OF UNSPRUNG WEIGHTS—No discussion in addition to that of SAE J1574-1.

5.4.3 DETERMINATION OF VEHICLE SPRUNG WEIGHT—No discussion in addition to that of SAE J1574-1.

5.5 Calibration Procedures

5.5.1 CALIBRATION OF WEIGHT SCALES—No discussion in addition to that of SAE J1574-1.

6. Measurement of Center of Gravity Positions

6.1 Variables Measured—Direct determination of the unsprung cg locations presents a time-consuming job which, depending on intended use and available information, may not be required. Reasonable estimates of these locations can often be made with the unsprung component weights measured in Section 5 (or with weights from spare suspension components) and with component cg locations from layout drawings. Determination of effective unsprung mass center of gravity position should rely on the 50/50 rule and be based on established principles of mechanics. If the unsprung cg positions are measured directly, rather than estimated, then the procedures of SAE J1574-1 should be followed.

6.2 Apparatus

6.2.1 GENERAL PERFORMANCE REQUIREMENTS—No discussion in addition to that of SAE J1574-1.

6.2.2 GENERAL CONFIGURATIONS—No discussion in addition to that of SAE J1574-1.

6.2.3 PERFORMANCE REQUIREMENTS—Both the data reduction techniques of 6.4.1, of SAE J1574-1, and the error analysis which follows require the basic equations covering the mechanics of the tilt table center of gravity height test method. Only one fundamental equation covers this statics problem, but its rearrangement results in a more useful relationship for cg height determination. This is derived as follows, with rearrangement, so that both the data reduction and error analysis are more easily understood.

Figure 1 shows simple diagrams of the geometry of the tilt table and vehicle center of gravity, both before and after tilt has occurred. The following variable names are used:

θ table tilt angle
H vehicle center of gravity height above road plane and table pivot axis (assumed coincident)
M table restoring moment
W vehicle weight
Y lateral offset of vehicle center of gravity relative to pivot axis, at zero tilt angle
Y_{SH} lateral shift of vehicle center of gravity due to tilt angle

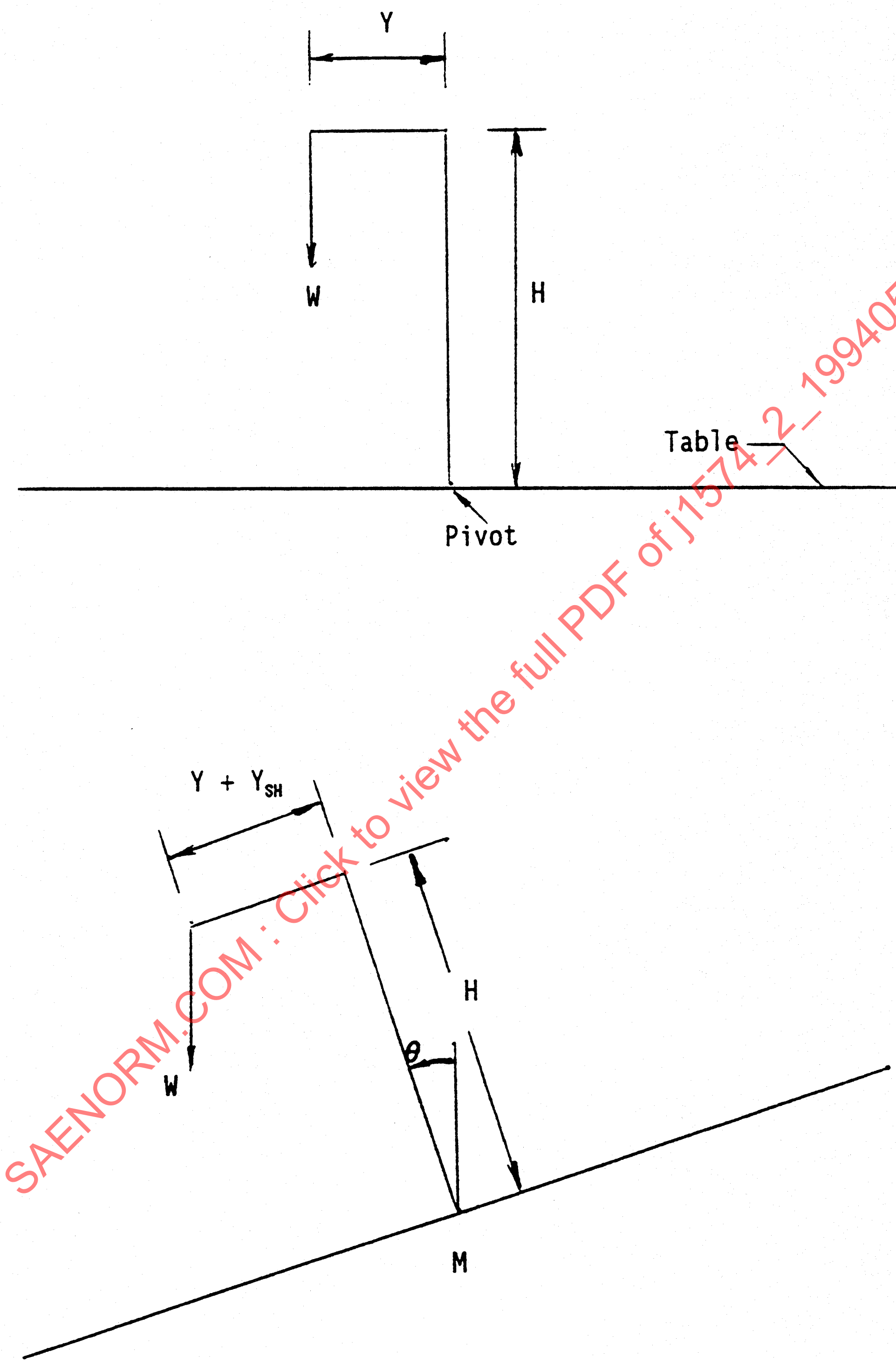

FIGURE 1—CENTER OF GRAVITY HEIGHT TEST GEOMETRY

The governing relationship for this test method is the static equilibrium equation for the vehicle and table at a nonzero tilt angle. To write this, the moment arm of the weight vector relative to the pivot axis is required. This is the sum of the vertical projections of the moment arms ($Y + Y_{SH}$) and H. This sum is $(Y + YSH)\cos\theta + H\sin\theta$. Thus, the equation for the restoring moment is shown in Equation 25:

(Eq. 25)

$$M = W[(Y + Y_{SH})\cos\theta + H\sin\theta]$$

This can be rearranged to Equation 26:

(Eq. 26)

$$M/(W\cos\theta) - Y_{SH} = H\tan\theta + Y$$

This will yield an expression for H if the derivative with respect to $\tan\theta$ is taken. In doing this, it is important to note that Y is a constant but that Y_{SH} depends on θ and $\tan\theta$. As a result (see Equation 27):

(Eq. 27)

$$H = d[M/(W\cos\theta) - Y_{SH}]/d\tan\theta$$

Equation 27 shows a relationship of the form y = mx + b, where $y = M/(W\cos\theta) - Y_{SH,}$ m = H, $x = \tan\theta$, and b = Y. The derivative form simply isolates the cg height, H, and defines its value in terms of the other variables, excluding Y, whose derivative with respect to $\tan\theta$ is zero. Equation 27, in y = mx + b form, is the most useful with experimental data. It can be used with linear regression techniques to determine the value of H, if data is taken at a number of different tilt angles. This is the conceptual approach described in SAE J1574-1.

These relationships also allow an error analysis to be performed to determine the accuracy required in the knowledge of M, W, θ, and Y_{SH}, for a desired accuracy in the value of H. This can be accomplished by forming the variables $M/(W\cos\theta) - Y_{SH}$ and $\tan\theta$, with and without fixed errors introduced for M, W, θ, and Y_{SH}. The results of such an analysis, for a small FWD passenger car, are shown in Table 7. This forms the rationale for the accuracy requirements of Table 7 of SAE J1574-1. It follows the format of Table 5 of the Information Report of Section 5.

TABLE 7—RESTORING MOMENT, VEHICLE WEIGHT, TILT ANGLE, AND LATERAL SHIFT CONTRIBUTIONS TO TOTAL ERROR

Variable	Total Error		Error Sources Moment	Error Sources Weight	Error Sources Angle	Error Sources Lat. Shift
total vehicle cg height	0.5%	Max error:	0.20%	0.20%	0.10%	0.02 %
		sensitivity:	1.00%/%	1.00%/%	1.00%/%	0.002%/%
		max source:	0.20%	0.20%	0.10%	10.00 %

Notes
1 The "max error" is the maximum error permitted for a given error source. The sum of these values equals the "total error" shown for each variable.
2 The "sensitivity" is the measured error, in percent, for the variable per unit of error at the source. Values are approximate for the vehicle studied.
3 The "max source" is the maximum error at the source such that the "max error" is not exceeded for the "sensitivity" shown. The "max source" is the "max error" divided by the "sensitivity."

Note that all of the "max source" values in Table 7 are expressed in percent since all of the values for moment, weight, angle, and lateral shift are nonzero for a tilted table. In this case, it is appropriate to express the error sources ("max source" values) as percentages of the variable itself. As a result, all of the sensitivities carry the units %/%. This is not possible if the associated variable can be zero, which was the case in Table 5 for slope and planarity errors.

Table 7 does not include the initial lateral position of the vehicle cg, Y, since its value is not required to determine the cg height, using the equation form derived previously.

The sensitivity study shows that the sensitivities to measurement error for restoring moment, total weight, and tilt angle are all about 1%/%, while that for lateral shift is much less, at 0.002%/%. The "max source" values depend on the total measurement error established as acceptable and a rational allocation of errors to each of the error sources. The maximum error ("max source") established for total vehicle weight, from Table 5a of SAE J1574-1 is 0.2%. Therefore, the maximum error in the measurement of cg height, due to this error, must be 0.2% (0.2% error source times 1.0%/% sensitivity). Since the total measurement error must be greater than this, due to additional contributions from the other three sources, its value can be established at any value above 0.2%. The 0.5% value shown is arbitrarily chosen in this context. The "max error" values of 0.2% for moment and 0.1% for angle are arbitrarily chosen to make up the balance of the 0.5% total error, ignoring the small contribution of lateral shift measurement error. Since the sensitivities for moment and angle measurement are 1.0%/%, the "max source" values for these error sources are the same as the "max error" values. The "max source" value of 10% for lateral-shift measurement is arbitrary, resulting in a negligible 0.02% total contribution for this error source.

This sensitivity study is based on the measurement of restoring moment for generality. If restoring moment is measured by measuring a force acting through moment arm(s), then the measurement accuracy for both the force and the moment arm(s) must not exceed that cited for the measurement of restoring moment.

6.3 Test Procedures

6.3.1 VEHICLE PREPARATION—The vehicle is tested at curb loading to eliminate center of gravity movement when the vehicle is tilted on the cg height tilt table. Such movement occurs as a result of the movement of simulated passengers or cargo held with compliant restraint systems. Since it is difficult to design very light, rigid restraint systems, or systems with a specified compliance, testing consistency is improved by testing the vehicle at curb loading. Other loading conditions should be simulated using measured positions and (local) center of gravity positions of passengers and cargo. This approach eliminates restraint compliance effects on total vehicle cg position, or allows it to be defined in a known manner. The approach also requires independent measurements of passenger and cargo cg positions, seat vertical compliance, and suspension ride rates, at the least, and are not covered by SAE J1574-1.

The recommendation to completely fill or empty the fuel tank is also intended to eliminate unknown mass shifts due to fluid movement, both static and dynamic. Completely filling the tank should minimize this effect to an acceptable level but, if there is evidence that fuel movement or sloshing remains, the tank should be completely drained before the center of gravity height measurements begin. The curb less fuel center of gravity height should be corrected for the (normal) fuel load using the weight of fuel and dimensions of the fuel tank.

6.3.2 TEST PROCEDURES

6.3.2.1 Measurement of Total Vehicle Center of Gravity Position—No discussion in addition to that of SAE J1574-1.

6.3.2.2 Measurement of Unsprung Center of Gravity Positions—No discussion in addition to that of SAE J1574-1.

6.4 Data Processing and Presentation

6.4.1 DETERMINATION OF TOTAL VEHICLE CENTER OF GRAVITY POSITION—No discussion in addition to that of SAE J1574-1.

6.4.2 DETERMINATION OF UNSPRUNG CENTER OF GRAVITY POSITIONS—No discussion in addition to that of SAE J1574-1.

6.4.3 DETERMINATION OF VEHICLE SPRUNG CENTER OF GRAVITY POSITION—No discussion in addition to that of SAE J1574-1.

6.5 Calibration Procedures

6.5.1 WEIGHT SCALES—No discussion in addition to that of SAE J1574-1.

6.5.2 RESTORING MOMENT TRANSDUCER—No discussion in addition to that of SAE J1574-1.

6.5.3 TILT TABLE OR PLATFORM—No discussion in addition to that of SAE J1574-1.

6.5.4 PRECISION PROTRACTOR—No discussion in addition to that of SAE J1574-1.

6.5.5 DIAL INDICATOR DISPLACEMENT DEVICES—No discussion in addition to that of SAE J1574-1.

7. Measurement of Moments and Products of Inertia

7.1 Variables Measured—No discussion in addition to that of SAE J1574-1.

7.2 Apparatus

7.2.1 GENERAL PERFORMANCE REQUIREMENTS—No discussion in addition to that of SAE J1574-1.

7.2.2 GENERAL CONFIGURATIONS—No discussion in addition to that of SAE J1574-1.

7.2.3 PERFORMANCE REQUIREMENTS—The measurement accuracy required for moments and products of inertia depends on the sensitivity of vehicle response parameters to errors in values for the vehicle inertial characteristics. This can be determined through simulation by simulating a reference case and test cases with errors introduced in the inertial characteristics. Such a study, using yaw velocity and roll angle 90% response times (time to reach 90% of steady-state value), shows the following sensitivities for a passenger car:

a. Total vehicle yaw inertia on yaw velocity response time: 1.0%/%
b. Sprung mass roll-yaw product on yaw velocity response time: 0.0%/%
c. Sprung mass roll inertia on roll angle response time: 0.5%/%

These values can be used with an allowable error for the response parameter to establish allowable measurement errors. Using the first of these (the most sensitive), an allowable error of 2.0% in the determination of yaw velocity response time would require that yaw moment of inertia be determined to within 2.0%. This arbitrary criterion is applied to the determination of total vehicle yaw moment of inertia, and thereby extended to both sprung and unsprung mass yaw moments of inertia. For reasons of consistency, this same allowable error is applied to the measurement of all moments of inertia. Due to the low sensitivity of yaw velocity response time to sprung mass product of inertia, a less stringent criterion of 5.0% is established for the measurement of products of inertia.

These allowable error criteria allow allocation of measurement error to the directly measured variables of period and restoring spring rate, for moment of inertia, and reaction moment and roll acceleration, for product of inertia. This allocation is shown in Table 9, with arbitrary allocation to the two error sources for each type of inertia. The "sensitivity" shown is that for the sensitivity of calculated inertia to an error in input to the governing data reduction equation. In the case of moment of inertia, calculated inertia is proportional to the square of measured period, thus giving this measurement a sensitivity of about 2.0%/%. (A 1.0% error in the determination of period will result in about a 2.0% error in calculated moment of inertia.) The other three sensitivities are about 1.0%/%.

Table 9 shows allowable error allocations for the measurement of the primary variables used in the calculation of each type of inertia. Since some of these may depend on other measurements (linear spring rate and moment arm, in the case of restoring spring rate), they reflect the aggregate error allowed for that "lumped" error source. The experimenter must ensure that all measurements made, which contribute to the measurement of period, restoring spring rate, reaction moment, and roll acceleration, are consistent with the allowable errors of Table 9.

TABLE 9—PERIOD, SPRING RATE, REACTION MOMENT, AND ROLL ACCELERATION CONTRIBUTIONS TO TOTAL ERROR

Variable	Total Error		Error Sources	Error Sources
			Period	**Spring Rate**
total vehicle moment of inertia	2.0%	max error: sensitivity: max source:	1.0% 2.0%/% 0.5%	1.0% 1.0%/% 1.0%
sprung mass moment of inertia	2.0%	max error: sensitivity: max source:	1.0% 2.0%/% 0.5%	1.0% 1.0%/% 1.0%
			Reaction Moment	**Roll Acceleration**
total vehicle product of inertia	5.0%	max error: sensitivity: max source:	2.5% 1.0%/% 2.5%	2.5% 1.0%/% 2.5%
sprung mass product of inertia	5.0%	max error: sensitivity: max source:	2.5% 1.0%/% 2.5%	2.5% 1.0%/% 2.5%

Notes
1 The "max error" is the maximum error permitted for a given error source. The sum of these values equals the "total error" shown for each variable.
2 The "sensitivity" is the measured error, in percent, for the variable per unit of error at the source.
3 The "max source" is the maximum error at the source such that the "max error" is not exceeded for the "sensitivity" shown. The "max source" is the "max error" divided by the "sensitivity."

Note that all of the "max source" values in Table 9 are expressed in percent since all of the values for period, spring rate, (maximum) reaction moment, and (maximum) roll acceleration are nonzero. In this case, it is appropriate to express the error sources ("max source" values) as percentages of the variable itself. As a result, all of the sensitivities carry the units %/%.

7.3 Test Procedures

7.3.1 VEHICLE PREPARATION—In all of these tests, the vehicle should have been tested with an empty fuel tank. Since fuel can represent a significant contribution to total vehicle mass, its absence results in inertia values which do not correspond to those for the vehicle at curb condition (with fuel). Common practice is to measure the location and shape of the fuel tank and add in its effect using standard inertia formulas for this distributed mass. It is also common practice to similarly add the inertial effects of passengers and cargo, to avoid the experimental complications of simulated passengers or cargo which may shift during the inertia tests. This requires knowledge of the inertial characteristics of a passenger, relative to the seat "H point," not covered in SAE J1574-1.

7.3.2 TEST PROCEDURES—No discussion in addition to that of SAE J1574-1.

7.3.2.1 Measurement of Total Vehicle and Unsprung Mass Pitch and Roll Moments and Roll-Yaw Products of Inertia—No discussion in addition to that of SAE J1574-1.

7.3.2.2 Measurement of Total Vehicle and Unsprung Mass Yaw Moments of Inertia—No discussion in addition to that of SAE J1574-1.

7.4 Data Processing and Presentation

7.4.1 DETERMINATION OF TOTAL VEHICLE AND UNSPRUNG MASS PITCH AND ROLL MOMENTS AND ROLL-YAW PRODUCTS OF INERTIA—No discussion in addition to that of SAE J1574-1.

7.4.2 DETERMINATION OF TOTAL VEHICLE AND UNSPRUNG MASS YAW MOMENTS OF INERTIA—No discussion in addition to that of SAE J1574-1.

7.5 Calibration Procedures—No discussion in addition to that of SAE J1574-1.

8. Measurement of Suspension Kinematic Characteristics

8.1 Variable Measured—No discussion in addition to that of SAE J1574-1.

8.2 Apparatus

8.2.1 GENERAL PERFORMANCE REQUIREMENTS—No discussion in addition to that of SAE J1574-1.

8.2.2 GENERAL CONFIGURATIONS—A basic displacement mechanism(s) is required; it must be capable of providing relative vertical motion between the ground plane (tire contact patch) and the sprung mass of the vehicle. This motion can be accomplished by either of the following methods:

a. Rigidly fixing the ground (tire contact patch) plane and rotating (roll) or vertically translating (ride) the sprung mass about it. (Care must be exercised in utilizing this method so that the sprung mass is displaced in only planar rotation or planar translation.)
b. Rigidly fixing the sprung mass of the vehicle and rotating/translating the ground plane about it. An advantage to this method is that it is possible to actuate individual wheels/axles in rotation or translation.

The displacement mechanism should be able to cycle the suspension system(s) through its total available ride travel and at a minimum of ±5 degrees of roll motion. It should be capable of adjusting the vehicle trim condition to reflect any changes experienced during actual vehicle operation (from curb to gross vehicle weight).

The reaction mechanism for the suspension forces generated by the ride/roll motions of the vehicle must be sufficiently rigid so as to minimize any deflections which could be misinterpreted as suspension or wheel motion. (See Section 9, paragraph 9.2.2 for a more in-depth discussion of this issue.)

Tire pad tables for each wheel position are required to provide for the rotational freedom about the steering axis and lateral and fore and aft displacement of the tire patch with respect to the vehicle sprung mass. This is to be accomplished with a minimum of frictional restraint.

A steering constraint mechanism is necessary to rigidly fix the sprung mass components of the steering system (steering wheel, column, steering gear) to prevent any undesired or extraneous steering inputs during test measurements. A device to apply the vehicle service brakes is necessary for those test procedures requiring the road wheels to be locked during measurements.

8.2.3 PERFORMANCE REQUIREMENTS—As in other sections of this document, this paragraph is devoted to the rationale for the accuracy requirements shown in Tables 11a and 11b of SAE J1574-1. This is addressed in Table 11 which shows allowable errors for the variables discussed in SAE J1574-1, as well as allocations for contributions to that error. Aside from overall steering ratio, only roll-related coefficients were studied, with the associated ride coefficient errors based on those of the roll coefficients. Notes on interpreting the table follow it.

The "total error" values shown in the second column of the table are based on sensitivity studies performed with a vehicle dynamics simulation of a small FWD passenger car. Total allowable errors for variables which affect understeer are based on a criterion of affecting understeer by less than 0.05 degree/g. For most variables, which apply to both front and rear suspension, the criterion was an effect of less than 0.025 degree/g, thereby splitting the 0.05 degree/g error equally between suspensions. The roll camber calculations are based on a worst case of a bias tire. For overall steering ratio, the 0.05 degree/g criterion is based on a test data reduction case, in which steering sensitivity is known and understeer is to be determined.

Other variables do not affect understeer significantly. The roll caster total allowable error is based on the criterion of calculating kingpin torque gradient to within 0.1%. The roll center height total allowable error is based on the criterion of less than 0.05 degree/g error in roll gradient from both suspensions, again split equally front and rear. The shock absorber travel ratio total allowable error is approximate, based on a criterion of less than 5.0% error in roll angle overshoot, half of which is assumed to come from errors in measuring travel ratio and the other half from measuring shock absorber damping coefficients. The total allowable error for suspension roll is arbitrary, but chosen within the context of consistency in Table 11.

Two final notes should help in the interpretation of Table 11. First, since all of the variables are determined by calculating a ratio, an error in the numerator of 1.0% will cause an error of 1.0% in the quotient and a similar error in the denominator will cause an error in the quotient of nearly 1.0%. Therefore, all of the "sensitivity" values shown express this relationship and have a value of 1.0%/%. Second, the "max source" for half (wheel) track of 0.2% is used, as established in Section 4 of SAE J1574-1.

TABLE 11—VARIOUS CONTRIBUTIONS TO TOTAL ERROR

Variable	Total Error		Error Sources	Error Sources	Error Sources
			HW Steer	**RW Steer**	
overall steering ratio	1.5%	max error:	0.5%	1.0%	
		sensitivity:	1.0%/%	1.0%/%	
		max source:	0.5%	1.0%	
			Camber	**Susp. Roll**	
roll camber coefficient	2.0%	max error:	1.0%	1.0%	
		sensitivity:	1.0%/%	1.0%/%	
		max source:	1.0%	1.0%	
			Caster	**Susp. Roll**	
roll caster coefficient	10.0%	max error:	9.0%	1.0%	
		sensitivity:	1.0%/%	1.0%/%	
		max source:	9.0%	1.0%	
			Half Track	**Lat. Disp.**	**Vert. Disp.**
roll center height (disp.)	2.5%	max error:	0.2%	1.5%	0.8%
		sensitivity:	1.0%/%	1.0%/%	1.0%/%
		max source:	0.2%	1.5%	0.8%
			Half Track	**Lat. Force**	**Vert. Force**
roll center height (equil.)	2.5%	max error:	0.2%	1.0%	1.3%
		sensitivity:	1.0%/%	1.0%/%	1.0%/%
		max source:	0.2%	1.0%	1.3%
			Steer	**Susp. Roll**	
roll steer coefficient	2.0%	max error:	1.0%	1.0%	
		sensitivity:	1.0%/%	1.0%/%	
		max source:	1.0%	1.0%	
			Shock Disp.	**Wheel Center Disp.**	
shock-absorber travel ratio in roll	5.0%	max error:	4.0%	1.0%	
		sensitivity:	1.0%/%	1.0%/%	
		max source:	4.0%	1.0%	
			Half Track	**Wheel Center Disp.**	
suspension roll	1.0%	max error:	0.2%	0.8%	
		sensitivity:	1.0%/%	1.0%/%	
		max source:	0.2%	0.8%	

Notes
1 The "max error" is the maximum error permitted for a given error source. The sum of these values equals the "total error" shown for each variable.
2 The "sensitivity" is the measured error, in percent, for the variable per unit of error at the source. Values are approximate for the vehicle studied.
3 The "max source" is the maximum error at the source such that the "max error" is not exceeded for the "sensitivity" shown. The "max source" is the "max error" divided by the "sensitivity."

Note that all of the "max source" values in Table 11 are expressed in percent since all of the values represent displacements (linear and angular) or force changes relative to some datum and will always be nonzero. In this case, it is appropriate to express the error sources ("max source" values) as percentages of the variable itself. As a result, all of the sensitivities carry the units %/%.

8.3 Test Procedures

8.3.1 VEHICLE PREPARATION—No discussion in addition to that of SAE J1574-1.

8.3.2 TEST PROCEDURES

8.3.2.1 *Measurement of Overall Steering Ratio*—No discussion in addition to that of SAE J1574-1.

8.3.2.2 *Measurement of Front and Rear Ride Camber Coefficients*—No discussion in addition to that of SAE J1574-1.

8.3.2.3 *Measurement of Ride Caster Coefficient*—No discussion in addition to that of SAE J1574-1.

8.3.2.4 *Measurement of Front and Rear Shock-Absorber Travel Ratios in Ride*—No discussion in addition to that of SAE J1574-1.

8.3.2.5 *Measurement of Front and Rear Ride Steer Coefficients*—No discussion in addition to that of SAE J1574-1.

8.3.2.6 *Measurement of Front and Rear Roll Camber Coefficients*—No discussion in addition to that of SAE J1574-1.

8.3.2.7 *Measurement of Roll Caster Coefficient*—No discussion in addition to that of SAE J1574-1.

8.3.2.8 *Measurement of Front and Rear Suspension Roll Center Heights*—No discussion in addition to that of SAE J1574-1.

8.3.2.9 *Measurement of Front and Rear Shock-Absorber Travel Ratios in Roll*—No discussion in addition to that of SAE J1574-1.

8.3.2.10 *Measurement of Front and Rear Roll Steer Coefficients*—No discussion in addition to that of SAE J1574-1.

8.4 Data Processing and Presentation—In general, these test procedures will produce data in the form of hysteresis loops describing the relationship of the dependent variable to the independent variable. This hysteresis can be produced by friction and/or lash in the suspension or steering system. Such hysteresis loops complicate the data reduction process of determining slopes at a given operating point. Methods of determining such slopes are discussed in some detail in 9.4. No single method is recommended as the best, since there is no generally accepted industry practice for determining such slopes in the presence of hysteresis.

8.4.1 DETERMINATION OF OVERALL STEERING RATIO—No discussion in addition to that of SAE J1574-1.

8.4.2 DETERMINATION OF FRONT AND REAR RIDE CAMBER COEFFICIENTS—No discussion in addition to that of SAE J1574-1.

8.4.3 DETERMINATION OF RIDE CASTER COEFFICIENT—No discussion in addition to that of SAE J1574-1.

8.4.4 DETERMINATION OF FRONT AND REAR SHOCK-ABSORBER TRAVEL RATIOS IN RIDE—No discussion in addition to that of SAE J1574-1.

8.4.5 DETERMINATION OF FRONT AND REAR RIDE STEER COEFFICIENTS—No discussion in addition to that of SAE J1574-1.

8.4.6 DETERMINATION OF FRONT AND REAR ROLL CAMBER COEFFICIENTS—No discussion in addition to that of SAE J1574-1.

8.4.7 DETERMINATION OF ROLL CASTER COEFFICIENT—No discussion in addition to that of SAE J1574-1.

8.4.8 DETERMINATION OF FRONT AND REAR SUSPENSION ROLL CENTER HEIGHTS—No discussion in addition to that of SAE J1574-1.

8.4.9 DETERMINATION OF FRONT AND REAR SHOCK-ABSORBER TRAVEL RATIOS IN ROLL—No discussion in addition to that of SAE J1574-1.

8.4.10 DETERMINATION OF FRONT AND REAR ROLL STEER COEFFICIENTS—No discussion in addition to that of SAE J1574-1.

8.5 Calibration Procedures—No discussion in addition to that of SAE J1574-1.

8.5.1 LINEAR DISPLACEMENT TRANSDUCERS—No discussion in addition to that of SAE J1574-1.

8.5.2 ANGULAR DISPLACEMENT TRANSDUCERS—No discussion in addition to that of SAE J1574-1.

8.5.3 FORCE TRANSDUCERS—No discussion in addition to that of SAE J1574-1.

9. Measurement of Suspension Elastic and Coulomb Friction Characteristics

9.1 Variables Measured—Section 9 of SAE J1574-1 describes measurement procedures for determining all of the suspension compliance and Coulomb friction characteristics which have a major influence on the vehicle's wheel position as regards linear regime, yaw, and roll plane performance of the vehicle. As a general approach, and in order to comply with broadly used vehicle modeling techniques, measurement procedures described generally identify tire forces and moments, as defined by SAE, as the motivating, independent variables of the experiments. Further, suspension or wheel motions, defined in the SAE vehicle-coordinate system, are considered to be the dependent variables of the experiments. Thus the procedures are designed to measure suspension compliance, specifically excluding the contributions of tire compliances from the measurement.

It is recognized that in specific instances, it may be of value to the investigator to define alternate independent and dependent variables. For example, aligning moment about the kingpin of a steering suspension may be a desirable independent variable.

9.2 Apparatus—There are a number of points of interest regarding the apparatus described in 9.2 of SAE J1574-1 which deserve further discussion.

9.2.1 GENERAL PERFORMANCE REQUIREMENTS—It was noted in 9.2 of SAE J1574-1 that "force, moment, and deflection measurements should be conducted continuously during quasi-static motions" of the suspension. "Alternatively, displacement may be generated in a stepwise manner over time with measurements conducted during quiescent periods. In this case, however, special care must be taken to prevent the abatement of the applied forces and moments during quiescent periods." The force/deflection characteristics of vehicle suspensions may include significant levels of Coulomb friction as well as compliance properties. It is the presence of Coulomb friction which, in the second case, may lead to experimental difficulty.

Figure 2 displays a hysteretic force/deflection relationship representative of many vehicle suspension properties. Such a relationship might be determined from measurements made during an experiment employing continuous motion. Figure 3 displays the force/deflection behavior of the same suspension during a hypothesized experiment employing stepwise displacement of the suspension. In this experiment, at each quiescent period in the increasing portion of the loading cycle, the motivating mechanism relaxes through a very small displacement prior to the recording of each data point (indicated by the x's). Because of Coulomb friction, however, the slight decline in displacement results in a significant drop in force. Thus the data taken are not truly representative of the force/deflection characteristics of the suspension.

Accordingly, in measuring force/deflection characteristics in which Coulomb friction may be present, the investigator should take great care to prevent abatement of applied forces if a stepwise procedure is used.

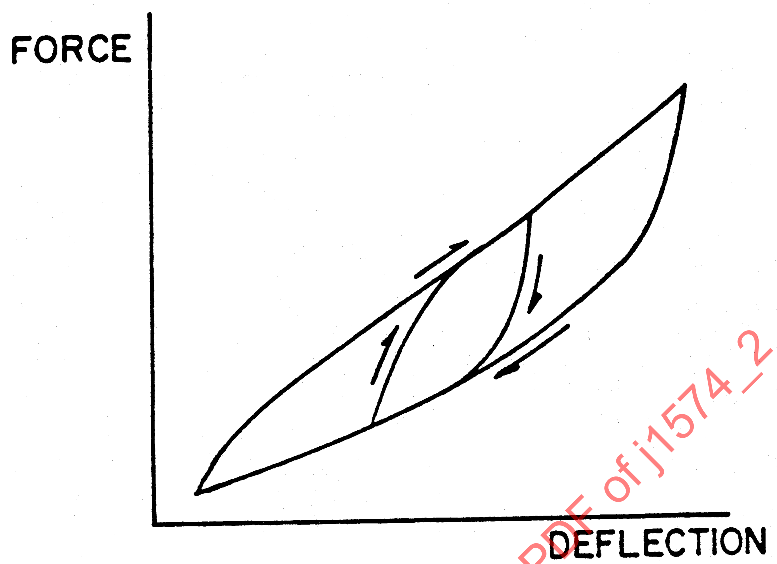

FIGURE 2—SUSPENSION LOAD/DEFLECTION RELATIONSHIP FOR CONTINUOUS DISPLACEMENT

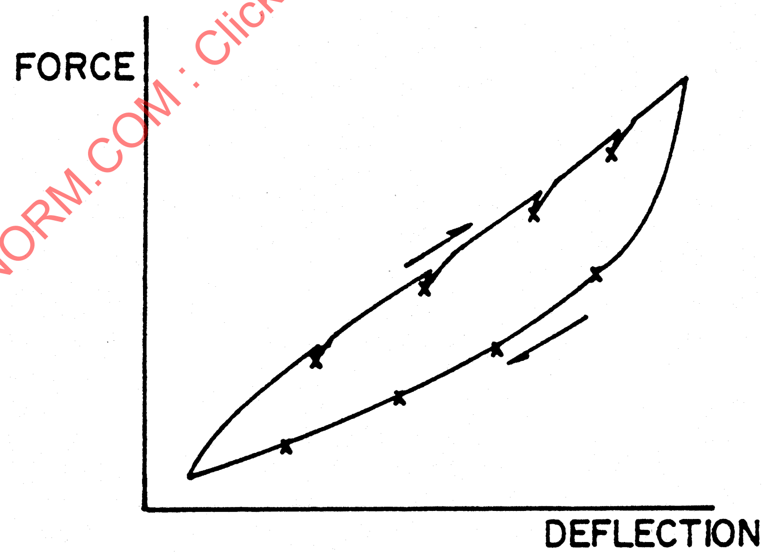

FIGURE 3—SUSPENSION LOAD/DEFLECTION RELATIONSHIP FOR STEPWISE DISPLACEMENT

9.2.2 GENERAL CONFIGURATIONS—In 9.2.1 of SAE J1574-1 it is stated that "machine configurations which allow for testing of suspensions with tires installed in their normal manner" are recommended by the standard, but that to overcome certain deficiencies of this approach, specialized spindle support features are also acceptable. Simply stated, a standard tire is a most convenient "fixture" by which to apply tire forces and moments to the suspension. Further, leaving the tire installed, rather than mounting special fixtures, may simplify test setup resulting in a more efficient test procedure. Unfortunately, using the tire as the "fixture" by which to apply forces and moments to the suspension does not allow fully independent control of all test conditions and variables. For example, the tire-rolling radius defines the position of the tire shear plane relative to the vehicle and its suspension. Rolling radius is, however, a function of the individual tire, inflation pressure, and the tire-loading condition. Thus, to the extent that rolling radius, and other geometric characteristics of the tire, are variable, the geometry of the suspension-loading condition is variable. Further, when a tire is used to apply suspension loads, overturning moment becomes a dependent, rather than independent, variable, being a function of the individual tire, inflation pressure, the applied vertical and lateral forces, and tire-camber angle. For solid axle suspensions, tire overturning moment can generally be considered as but one portion of the total roll moment applied to the suspension. For independent suspensions, however, it stands as a conceptually independent input, which unfortunately cannot be independently controlled if the input "fixture" is a tire resting on the ground plane.

Accordingly, the investigator should be aware that the results obtained by the methods described in SAE J1574-1 may be, in part, dependent on the particular tire fitted during testing. Although the influence of the tire may be expected to be relatively small, tests with a variety of tires installed and/or analytical evaluations should be conducted to determine this influence and its effect on the test accuracy desired.

As an alternative, special spindle support fixtures, allowing independent control of rolling radius and overturning moment (along with vertical and lateral force and aligning moment) may be employed. Such fixtures, while alleviating the aforementioned conceptual difficulties, may impose significant increases in equipment complexity and cost and cause a decrease in testing efficiency.

At the outset of 9.2.2 of SAE J1574-1, it is indicated that "there are two reasonable, alternative, general configurations for suspension compliance measurement devices" and that these are:

a. Devices in which the vehicle body/frame is held fixed and the suspension is exercised by a moving ground plane and
b. Devices in which the ground plane is fixed and the suspension is exercised by moving the vehicle body/frame.

In either of the previous cases, the "proper" method of applying forces (be they reactive forces or motivating forces) to the body/frame does not yield to straightforward definition.

The body/frame is, itself, a compliant element and consequently, can have a contributory effect on measured "suspension" compliances, depending on the nature and location of body/frame-to-test-fixture attachment points. In some cases, it may be the purpose of the investigator to isolate and measure suspension compliances only. Conversely, it may be reasonable to include the effects of body/frame compliance in "suspension" measurements since these compliances exist in the vehicle in normal operation and may contribute to significant displacement parameters, e.g., road-wheel steer angle. In this case, however, it must be realized that the inevitable point-wise loading which a test fixture will apply to the body/frame will produce deflection patterns somewhat in variance with those produced under the distributed, inertial force loading generated in vehicle use.

Trucks and highway trailers deserve special consideration with respect to the issue of body/frame compliance. The frame rail configuration of such vehicles generally yields high levels of body/frame complianceæsufficiently high that these compliances may have as strong an effect on certain aspects of ride and handling performance as do suspension compliances. Further, the wide variety of bodies which may be mounted on a given chassis and the equally wide variety of loading configurations may strongly affect body/frame compliances and their resulting effect on performance.

As a consequence of the previous issues, it is suggested that:

a. If it is the purpose of the investigator to isolate and measure only suspension compliances, the body/frame attachment hardware should rigidly locate all members to which suspension elements are mounted as near to the suspension-mounting points as practicable.
b. For passenger cars, if it is the intention of the investigator to include body/frame compliance effects, then the passenger section of the vehicle should be rigidly located through a minimum of four attachment points located approximately at the four (plan view) corners of that section. This recommendation should be tempered by the engineering judgment of the investigator based on his understanding of the structure of the specific test vehicle.
c. For trucks and trailers of conventional frame-rail construction, it is suggested that Item (a) be followed and individual attention be given to the effects of body/frame compliance.

Paragraph 9.2.2 of SAE J1574-1 also indicates that a suspension compliance measurement facility should be capable of independent application of tire-lateral force and aligning moment at each of the wheel positions of the subject suspension. The application of either load is to be accompanied by effectively zero levels of:

a. Other tire shear forces and moments and
b. Suspension vertical and roll displacements

Note that Item (a) implies a high degree of precision in establishing the line of action of the lateral force through the tire contact center. Maintenance of constant vertical wheel position (Item (b)) throughout the loading process, in general, requires control of the vertical displacement actuator via feedback of the vertical wheel displacement signals. If such a control function is not available, an optional approach is as follows: Having established the nominal vertical displacement condition, maintain the relative position of the simulated ground plane and the vehicle body/frame constant during the experiment. In this case, tire deflections will allow small vertical and/or roll displacements of the suspension. Measure and record vertical and roll displacement data during the cyclical loading in order that this data, in conjunction with suspension kinematic characteristics (Section 8) can be used to compensate the steer angle data collected during the experiment. That is, vertical and roll displacements are to be used with ride and roll steer coefficients to predict the level of wheel steer generated by these kinematic effects. This level of steer is then to be subtracted from the measured steer angles of this experiment prior to determining the lateral force steer coefficient.

Finally, 9.2.2 of SAE J1574-1 states that a suspension-compliance measurement facility should be capable of measuring tire normal force, lateral force, aligning moment, and overturning moment at each wheel position of the subject suspension. Due to the influence of tire and suspension compliances, the strict maintenance of the proper orientation of both the applied loads and the load-transducer systems may be difficult to accomplish. While it is straightforward to orient the normal force axis perpendicularly to the ground plane, the maintenance of the lateral force axis through the contact center and in a direction perpendicular to the line of intersection of the wheel plane and ground plane may be difficult. Two options appear reasonable with respect to both force and moment application and measurement, viz.:

In the initial zero lateral force and zero aligning moment condition, the force and moment application system and the measurement system axes should be oriented coincidentally with the SAE tire axis system. Thereafter:

a. These systems may remain fixed in the ground plane segment whose motion induces aligning moment and/or lateral force, or
b. These systems should remain fixed in the ground plane as referenced to the line of intersection of the ground plane and the vehicle plane of symmetry.

Either option produces errors in the orientation of the force and moment reference axis system relative to the SAE tire axis system under deflected conditions. For example, under conditions of applied aligning moment, because of tire compliances the force reference system of option (a) will rotate in the ground plane through a larger angle than will the SAE tire axis system. Conversely, the reference system of option (b) will not, by definition, rotate at all. In either case, induced errors for linear range measurements should be small.

In general, the shear-load actuation system requires a low-friction planar bearing parallel to the ground plane in order to support tire normal loads. This bearing may represent a path-to-ground for shear loads which is parallel to the shear-load transducers, as well as being a source of unwanted longitudinal shear loads. Therefore, the bearing should have a maximum friction coefficient under operational conditions of 0.001.

9.2.3 PERFORMANCE REQUIREMENTS—As in other sections of this document, this paragraph is devoted to the rationale for the accuracy requirements shown in Tables 13a and 13b, of SAE J1574-1. This is addressed in Table 13 which shows allowable errors for the variables discussed in SAE J1574-1, as well as allocations for contributions to that error.

Four of the variables listed (two steer and two camber coefficients) directly affect total vehicle understeer. For these variables, the "total error" values shown in the second column are based on sensitivity studies performed with a vehicle dynamics simulation of a small FWD passenger car and are consistent with an understeer error contribution of less than 0.025 degree/g (per axle) for that coefficient. Acceptable errors for the camber coefficients are based on a worst case of a bias tire. The acceptable error for ride rate is consistent with the determination of sprung mass ride frequency to within 2.5%. That for roll rate is consistent with the determination of roll gradient to within 5%. The acceptable errors for Coulomb friction match those for ride and roll rate since they are determined from the ride and roll rate load deflection curves. The acceptable error for lateral force deflection coefficient is arbitrary.

As in Table 11, all of the sensitivities have values of 1.0%/%. This reflects the fact that an error of 1% in any of the "max source" variables (such as aligning moment) will result in an error of 1% in the variable being computed (such as aligning moment steer coefficient). All of the "max source" errors are expressed as a percentage of a measured variable which is normally nonzero. Possible exceptions to this are camber angle, in the measurement of aligning moment camber coefficient, and steer angle, in the measurement of lateral force steer coefficient. These possibilities are addressed by the inclusion of absolute error limits in Tables 13a and 13b of SAE J1574-1.

9.3 Test Procedures—The test procedures which were described in SAE J1574-1 assume that the resulting parameters are intended for use in linear vehicle models. Therefore, the procedures are generally defined to determine the rate (or gain) of the relationship of interest about the nominal operating point, i.e., nominal axle load (9.3.1), zero roll angle, zero tire shear loads, and for steerable suspensions, zero steer angle. According to the simplest theory, such gains may be determined by exercising the suspension through infinitesimal ranges about the operating point. In fact, the presence of Coulomb friction-related hysteresis requires testing through finite ranges as do limitations of instrumentation. These procedures recommend exercising the suspension to the estimated possible extremes of what is normally considered the linear range. These procedures allow the experimenter to evaluate the appropriateness of the linear assumption. They also generally ensure that gain and hysteresis effects may be clearly distinguished. It is also recommended that the test suspension be exercised over smaller ranges as may be appropriate to the intended application of the data. Recommendations for choosing such ranges are given in 9.4 herein.

TABLE 13—VARIOUS CONTRIBUTIONS TO TOTAL ERROR

Variable	Total Error		Error Sources	Error Sources
			Camber	**Aligning Moment**
aligning moment camber coeff.	10.0%	max error:	5.0%	5.0%
		sensitivity:	1.0%/%	1.0%/%
		max source:	5.0%	5.0%
			Steer	**Aligning Moment**
aligning moment steer coeff.	5.0%	max error:	2.5%	2.5%
		sensitivity:	1.0%/%	1.0%/%
		max source:	2.5%	2.5%
			Camber	**Lateral Force**
lateral force camber coeff.	5.0%	max error:	2.5%	2.5%
		sensitivity:	1.0%/%	1.0%/%
		max source:	2.5%	2.5%
			Lat. Disp.	**Lateral Force**
lateral force deflection coefficient	5.0%	max error:	2.5%	2.5%
		sensitivity:	1.0%/%	1.0%/%
		max source:	2.5%	2.5
			Steer	**Lateral Force**
lateral force steer coeff.	5.0%	max error:	2.5%	2.5%
		sensitivity:	1.0%/%	1.0%/%
		max source:	2.5%	2.5%
			Vert. Force	**Wheel Ctr. Displacement**
Coulomb friction in ride	5.0%	max error:	2.5%	2.5%
		sensitivity:	1.0%/%	1.0%/%
		max source:	2.5%	2.5%
			Vert. Force	**Wheel Ctr. Displacement**
ride rate	5.0%	max error:	2.5%	2.5%
		sensitivity:	1.0%/%	1.0%/%
		max source:	2.5%	2.5%
			Roll Moment	**Roll Displacement**
Coulomb friction in roll	5.0%	max error:	2.5%	2.5%
		sensitivity:	1.0%/%	1.0%/%
		max source:	2.5%	2.5%
			Roll Moment	**Roll Displacement**
roll rate	5.0%	max error:	2.5%	2.5%
		sensitivity:	1.0%/%	1.0%/%
		max source	2.5%	2.5%

Notes

1 The "max error" is the maximum error permitted for a given error source. The sum of these values equals the "total error" shown for each variable.

2 The "sensitivity" is the measured error, in percent, for the variable per unit of error at the source. Values are approximate for the vehicle studied.

3 The "max source" is the maximum error at the source such that the "max error" is not exceeded for the "sensitivity" shown. The "max source" is the "max error" divided by the "sensitivity."

The linearity assumption also implies the validity of superposition, i.e., the absence of cross-coupling effects of the independent variables on the dependent variables. The procedures are structured accordingly. Further, certain dependent variable-independent variable relationships are assumed. For example, with respect to steer angle related compliances, it is assumed that vehicle models to which measured parameters will be applied have a general form as shown in Equation 28:

$$\delta_i = f(\delta_{sw}, \phi, F_{yi}, M_{zi}, \ldots) \quad \text{(Eq. 28)}$$

where

δ_i = Steer angle of the wheels of axle i
δ_{sw} = Steering-wheel angle (assuming i is a steerable axle)
ϕ = Vehicle roll angle
F_{yi} = Tire lateral force on the wheels of axle i
M_{zi} = Tire aligning moment on the wheels of axle i

Or in linearized form as shown in Equation 29:

$$\delta_i = \delta_{sw} + (\partial\delta_i / \partial\phi)d\phi + (\partial\delta_i / \partial F_{yi})dF_{yi} + (\partial\delta_i / \partial M_{zi})dM_{zi} + \ldots \quad \text{(Eq. 29)}$$

where the purpose of these procedures is to determine the partial derivatives.

For example, the aligning-moment steer-test procedure is intended to produce a direct measurement of ¹di/¹Mzi through a measurement of the relationship of di and Mzi. To do so, of course, requires that this relationship be determined under conditions in which the other independent variables (dsw, f, Fyi) are constant. The following procedures imply linearized models of particular forms, by describing variables to be measured (the dependent variable and the independent variable corresponding to the partial derivatives of interest) and the other independent variables to be held constant. The experimenter should determine that the implied model forms correspond to those in which his measurements are to be employed. If they do not, the procedures should be altered or expanded accordingly.

9.3.1 VEHICLE PREPARATION—No discussion in addition to that of SAE J1574-1.

9.3.2 TEST PROCEDURES—No discussion in addition to that of SAE J1574-1.

9.3.2.1 Measurement of Aligning-Moment Camber Coefficients—No discussion in addition to that of SAE J1574-1.

9.3.2.2 Measurement of Aligning-Moment Steer Coefficients—No discussion in addition to that of SAE J1574-1.

9.3.2.3 Measurement of Lateral-Force Camber Coefficients—No discussion in addition to that of SAE J1574-1.

9.3.2.4 Measurement of Lateral-Force Compliance Coefficients—No discussion in addition to that of SAE J1574-1.

9.3.2.5 Measurement of Lateral-Force Steer Coefficients—No discussion in addition to that of SAE J1574-1.

9.3.2.6 Measurement of Ride Rate—No discussion in addition to that of SAE J1574.1.