Acceptability of Shock Absorbers for Road Roughness Measuring Trailers

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The accuracy of the response-type road roughness meters depends primarily on how the dynamic characteristics of the test vehicles adhere to prescribed standards. The standards for shock absorbers used in roughness-measuring vehicles as defined by ASTM are discussed in this paper. A new acceptability criterion is proposed that assures a higher overall accuracy of the measuring system and at the same time allows for larger deviations of the shock absorber parameters from the standard values. The method allows for verifying the acceptability of shock absorbers mounted in road roughness measuring vehicles. The effects of typical nonlinearities in shock absorber characteristics are also presented.

Road roughness is evaluated in most states on the basis of the dynamic response of a vehicle of specified parameters subjected to the road profile. For the accuracy of the measurements it is essential that the dynamic characteristics of the test vehicle adhere strictly to prescribed standards. ASTM is developing such standards for cars and trailers used in measuring road roughness. A car is represented by a quarter-car or a half-car simulation model, which is specified in a proposed ASTM standard *(1)*. A trailer is represented by a half-trailer simulation model of the same structure as the quarter-car model but of different parameters *(2)*, which are also given in the proposed standard *(1)*. The standard models are useful in calibrating actual test vehicles.

The characteristics of the actual vehicles used in measuring road roughness never exactly match the characteristics of the standard model. The deviations between the actual and standard model parameters cause measurement errors. In this paper the effects of two parameters of roughness-measuring trailers—shock absorber damping coefficient and hysteresis in axle-body displacement transducer—are investigated. A relatively simple procedure is presented that allows for verification of the acceptability of trailer shock absorbers. Although the acceptability criterion formulated by ASTM *(2)* is discussed, a modified criterion is recommended.

HALF-TRAILER MODEL

The main characteristics of the trailers used in simulating vehicle response to road roughness are specified in the new ASTM standard *(2)*. The trailers are two-wheeled, single-axle vehicles that are towed on highways at typical traffic speeds while the relative movement between the axle and body is transduced and recorded as an indication of road roughness.

The structure of the trailer simulation half-trailer model is shown in Figure 1, and its frequency response is plotted in Figure 2. The values of the parameters used in the two standard vehicle models are given in Table 1.

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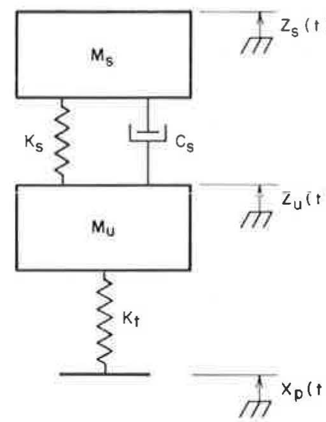

FIGURE 1 Half-trailer model.

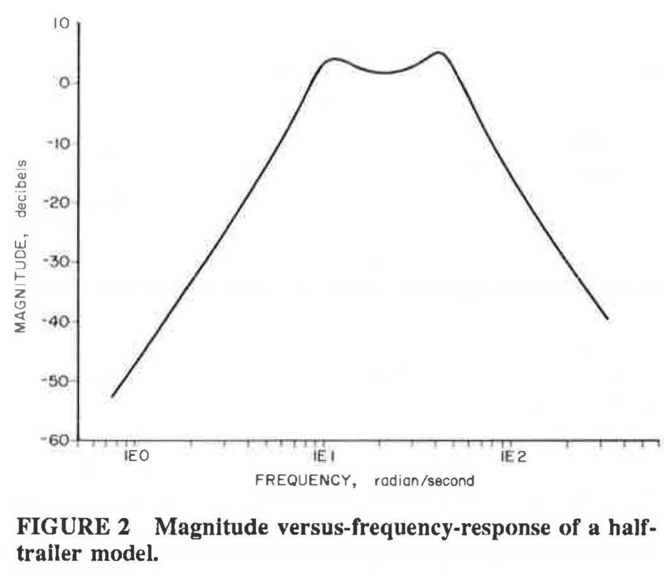

FIGURE 2 Magnitude versus-frequency-response of a half-trailer model.

TABLE 1 PARAMETER VALUES FOR THE STANDARD QUARTER-CAR AND HALF-TRAILER MODELS

Model	k_s/M_s (sec^{-2})	k_T/M_s (sec^{-2})	M_u/M_s	C_s/M_s (sec^{-1})
Quarter-car	62.3	653	0.15	6.0
Half-trailer	125.0	622	0.26	8.0

The motion of the half-trailer model is governed by the following differential equations:

$$\ddot{z}_s = -\frac{C_s}{M_s}\dot{z}_s - \frac{k_s}{M_s}z_s + \frac{C_s}{M_s}\dot{z}_u + \frac{k_s}{M_s}z_u \tag{1}$$

$$\ddot{z}_u = -\frac{C_s}{M_u}\dot{z}_u - \frac{k_t + k_s}{M_u}z_u + \frac{C_s}{M_u}\dot{z}_s + \frac{k_s}{M_u}z_s + \frac{k_t}{M_u}x_p \tag{2}$$

The main output variable from the model is an axle-body displacement (for suspension travel) $\Delta_z(t)$:

$$\Delta_z(t) = z_s(t) - z_u(t) \tag{3}$$

The normalized absolute value of the suspension travel accumulated over a period of time t_f yields a measure of road roughness *ST*, which is defined as

$$ST = \frac{1}{L}\int_0^{t_f} |\dot{\Delta}_z(t)|\, dt \tag{4a}$$

or in a discrete form

$$ST = \frac{1}{L}\sum_{k=1}^{N} |\Delta_z(k) - \Delta_z(k-1)| \tag{4b}$$

The trailer suspension travel is measured by a displacement transducer that introduces a measuring error due to hysteresis in its input-output characteristics. As a result, the signal $\hat{\Delta}_z(t)$ produced by the transducer differs from the actual axle-body displacement, as shown in Figure 3. Figure 4 shows a simplified block diagram of the entire measuring system. In order to investigate the performance of the trailer-based measuring system, the computer program CARTRA has been developed at the Pennsylvania Transportation Institute. The program allows for simulation of the half-trailer model given by Equations 1 and 2, together with the assumption that the displacement transducer has a nonlinear characteristic with hysteresis of width 2δ. The program calculates an accumulated suspension travel of the half-trailer model subjected to an arbitrary road profile, which is measured by the displacement transducer with hysteresis in the input-output characteristic. Again, for consistency with the quarter-car model analysis, the same road profile as that used in verifying the acceptability of the quarter-car parameters introduced by Gillespie et al. *(3)* is used as the input. The profile, called the ABAB pattern, is shown in Figure 5. According to Gillespie et al. *(3)*, this profile has the spectral properties of an average bituminous road at 50 mph when the profile is actually traversed at 15 mph. The same test conditions as specified in Gillespie et al. *(3)* were used in the computer simulation. The velocity of the trailer was 15 mph, and the period of integration of the suspension travel was equal to the time it takes to traverse the profile plus 1 sec for the transient motion of the trailer to cease. Although many states have found that these ABAB bumps do not provide good calibrations, the bumps provide a good basis for comparisons with simulations. Alternative methods are also given for actual calibration.

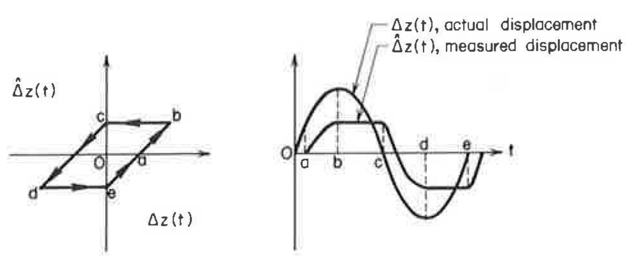

FIGURE 3 Transducer hysteresis and its effect on measured displacement.

FIGURE 4 Block diagram of a trailer-based system.

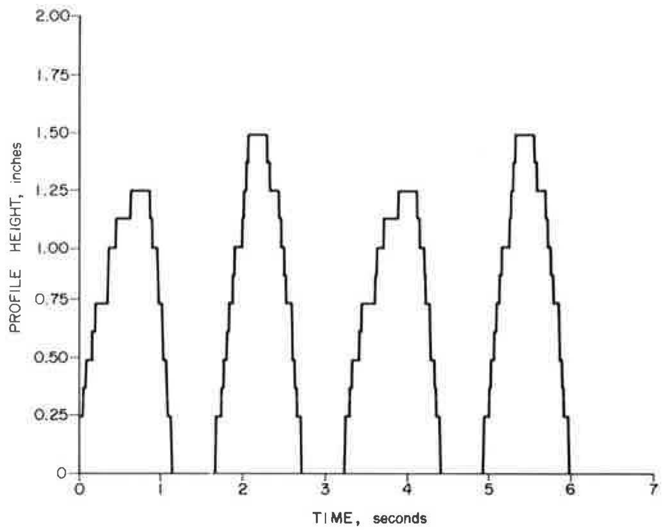

FIGURE 5 ABAB calibration surface profile.

The results of computer simulation of the half-trailer system subjected to the conditions just described are shown in Figure 6. The parameters that are of greatest concern in determining the acceptability of a road roughness measuring system—the relative damping coefficient of the shock absorber $\gamma = C_s/M_s$ and the transducer hysteresis δ—were varied over the ranges 5 to 13 sec^{-1} and 0 to 1.27 mm (0.05 in.), respectively.

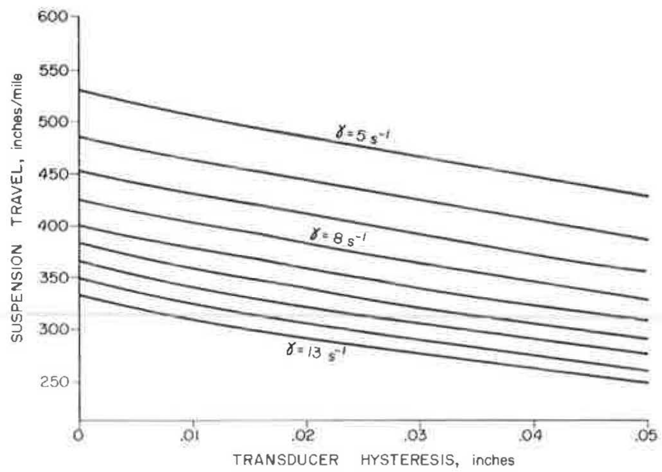

FIGURE 6 Computer simulation of suspension travel versus transducer hysteresis for different damping coefficients.

Effect of Shock Absorber Nonlinearities

In the trailer simulation program used to generate suspension travel data, a linear model of the trailer given by Equations 1 and 2 was used. Actual shock absorber characteristics are nonlinear and concern over how these nonlinearities affect the trailer performance is justified. The confidence with which the results obtained for a linear model can be applied to actual trailers are certainly affected by the shock absorber nonlinearities.

In order to investigate the problem, a nonlinear force-versus-velocity characteristic for a typical shock absorber was incorporated in the trailer simulation program. Figure 7 shows the characteristics of a shock absorber installed in a 1967 midsized Chevrolet; the force-velocity relationship is indeed strongly nonlinear. In addition, the shock absorber exhibits much greater damping in extension than it does in compression, as is shown by different slopes of the two dashed straight lines representing linear approximations for the positive and negative applied velocities.

The results of the computer simulation for a trailer with linear and nonlinear shock characteristics are shown in Figure 8. The dashed line represents the accumulated suspension travel of the trailer with the nonlinear shock absorber. The solid line indicates the results obtained using the linear trailer model with relative shock absorber damping $\gamma = 3.58$, which is the value that yields a suspension travel versus hysteresis characteristic closest to that of the nonlinear characteristic. A good agreement between the nonlinear and linear model performance can be observed from Figure 8. The following explanation is offered for this observation. The ABAB profile contains a broad spectrum of frequencies and a large range of amplitudes. The response of the nonlinear trailer model is integrated over the length of the profile and normalized with respect to the unit length. The mathematical operations of integration and division by the integration range yield an average value of the integrated variable, the trailer suspension travel in this case. All the partial responses of the trailer to all the components of the ABAB profile are averaged out. On the other hand, the linearized characteristic of the shock absorber represents an average damping coefficient of the nonlinear shock absorber. If the amplitudes contained in the road profile are equally distributed, averaging of the damping characteristic and averaging of the trailer response yield similar results. Therefore, the effect of shock absorber nonlinearity is negligible. Considerable care should, however, be exercised if profiles other than ABAB are used. If the distribution of amplitudes of different frequency components in the road profile is not uniform, the process of averaging the trailer response is disturbed, and significant discrepancies may occur between the linear and nonlinear cases. This possibility should be taken into consideration when a new road surface is selected for the calibration of road roughness measuring systems.

Another source of nonlinear effects in shock absorber performance is variation in air temperature, which causes changes in the temperature and thus in the viscosity of the shock absorber fluid. In a study by Croteau (private communication), the analysis of 300 pairs of roughness and temperature data collected on five different pavements indicates that a 10°F change in air temperature causes a measurement error of about 3 in./mi. In

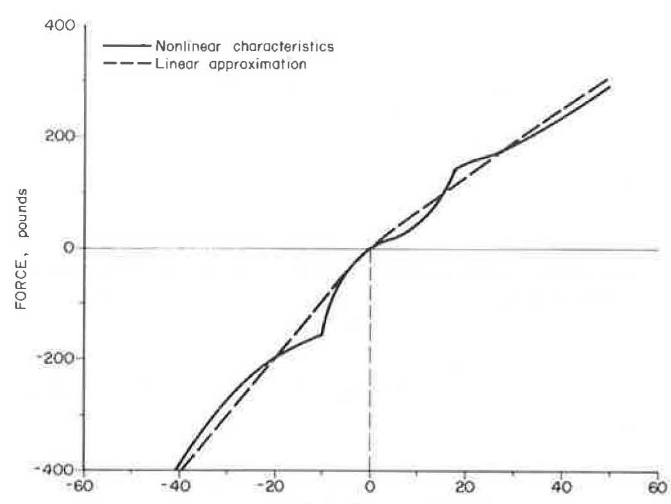

FIGURE 7 Nonlinear shock absorber characteristic.

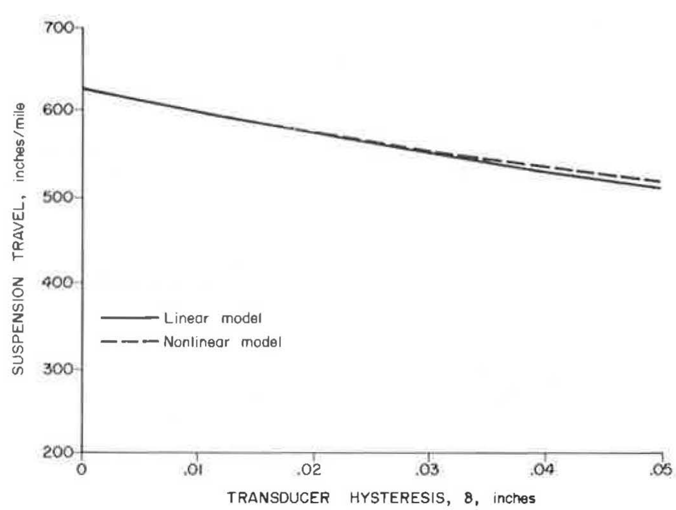

FIGURE 8 Effect of nonlinear shock absorber characteristics.

conjunction with this study, temperature correction equations are currently being developed.

Shock Absorber Acceptability Criterion

The accuracy of road roughness measurements obtained with a trailer system is dependent primarily on the extent to which the actual trailer parameters agree with the parameters of the standard model given in Table 1. The measuring error is also affected by the hysteresis of the axle-body displacement transducer. The proposed ASTM standard establishes the following limits for the deviations of the relative shock absorber damping coefficient γ, and for the hysteresis of the displacement transducer δ:

$$5.5 \text{ sec}^{-1} \leq \gamma \leq 13.0 \text{ sec}^{-1} \quad \text{(5a)}$$

and

$$0 \leq \delta \leq 0.05 \text{ in. (1.27 mm)} \quad \text{(5b)}$$

The limiting values of the relative damping coefficient were selected so that the values of the accumulated suspension travel generated by the half-trailer models with $\gamma = 5.5$ and 13.0 sec^{-1} towed over the ABAB surface differ by ±20 percent, respectively, from the accumulated suspension travel obtained with the standard model ($\gamma = 8.0$) towed over the same surface. The 20 percent deviations occur for $\delta = 0$ in the displacement transducer. The maximum acceptable value for hysteresis, $\delta = 0.05$ in. (1.27 mm), also causes a 20 percent deviation in the accumulated suspension travel value when the relative shock absorber damping coefficient is equal to its standard value $\gamma = 8.0 \text{ sec}^{-1}$. The dashed area in Figure 9 represents the acceptable combinations of the relative damping coefficient γ and the transducer hysteresis δ. The acceptability criterion can also be stated in a more general form as follows: a trailer is considered acceptable if the normalized suspension travel measured while the trailer is towed over the ABAB surface lies within the acceptable area marked in Figure 9. This is the equivalent of the requirements for a car presented in *NCHRP Report 228 (3)*.

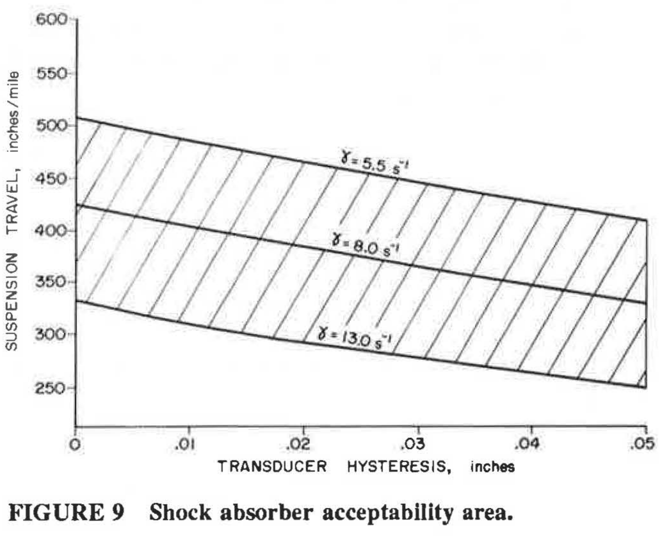

FIGURE 9 Shock absorber acceptability area.

The acceptability criterion raises doubts whether indeed one can distinguish good or acceptable trailers from bad or unacceptable ones. The measuring error of a trailer having relative damping coefficient γ and transducer hysteresis δ, towed over the ABAB surface, can be calculated as

$$\varepsilon(\gamma, \delta) = \frac{|ST(\gamma, \delta) - ST(8.0, 0.0)|}{ST(8.0, 0.0)} \times 100 \text{ percent} \quad (6)$$

The limits for the shock absorber damping γ and transducer hysteresis δ given by Equation 5 were established separately for the two parameters. In actual measurements, the error is determined by a combined effect of the deviations of γ and δ from their reference values. To illustrate this effect, the measuring error defined by Equation 6 was plotted versus hysteresis for several values of shock absorber damping coefficient. Figure 10 shows that the error is zero even in instances where both

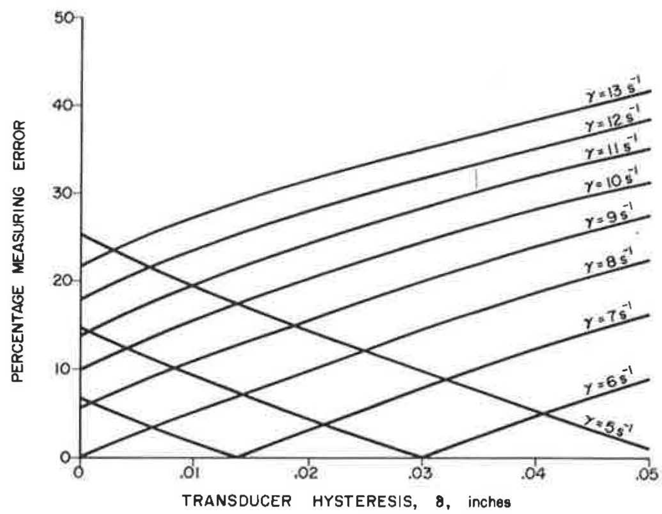

FIGURE 10 Measuring error curves for different values of system parameters.

parameters do not have the values prescribed by the standard. In fact, for each value of relative damping coefficient γ less than 8.0 sec^{-1} there is a nonzero value of transducer hysteresis δ for which the error is zero. This effect is caused by the two error components, one from the damping coefficient and the other from the transducer hysteresis, that cancel each other. Physically, this fact can be explained by noting that if a softer shock absorber is used, $\gamma < 8.0 \text{ sec}^{-1}$, the trailer suspension overreacts, producing larger values of accumulated suspension travel, which can be partially or even totally compensated by a loss of motion in increased hysteresis of the axle-body motion transducer. For harder shock absorbers, the two error components always add up, contributing to the increased value of the overall measuring error. It can therefore be concluded that, in general, softer shocks are more likely than harder shocks to produce accurate results. This conclusion must not be extended too far to prevent drastic nonlinear effects such as hitting shock absorber end limits from interfering in the measuring process.

The ASTM acceptability criterion for road roughness measuring trailers establishes limits on shock absorber damping and transducer hysteresis, neglecting the effect of interaction between γ and δ. In its present form, the criterion is cause-oriented and not result-oriented. To illustrate the consequences of such a formulation of the acceptability criterion, consider two systems. In the first system, the hysteresis $\delta = 0.05$ in. (1.27 mm) is within the acceptable limits, and the damping coefficient $\gamma = 5.0$ sec^{-1} is outside the acceptable limit. Therefore, according to the criterion, the trailer is unacceptable. From Figure 10, the measuring error for this unacceptable trailer is less than 2 percent. On the other hand, a trailer with a transducer hysteresis $\delta = 0.04$ in. and damping coefficient $\gamma = 13.0$ sec^{-1} is acceptable according to the proposed criterion. The measuring error of this trailer on the ABAB surface is about 38 percent (Figure 10).

It is proposed that the acceptability criterion be based on the measuring error of the trailer rather than on deviations of the trailer parameters from the standard values. A trailer acceptability would then be decided solely on the basis of the difference between the accumulated suspension travel when the trailer is towed over the ABAB surface and the suspension travel generated by the standard half-trailer model. Figure 11 shows the acceptable area as determined by a 20 percent maximum acceptable difference between the suspension travel values. According to this acceptability criterion, the transducer hysteresis must be less than 0.05 in. (1.27 mm), but an acceptable value of damping coefficient depends on the actual value of the hysteresis

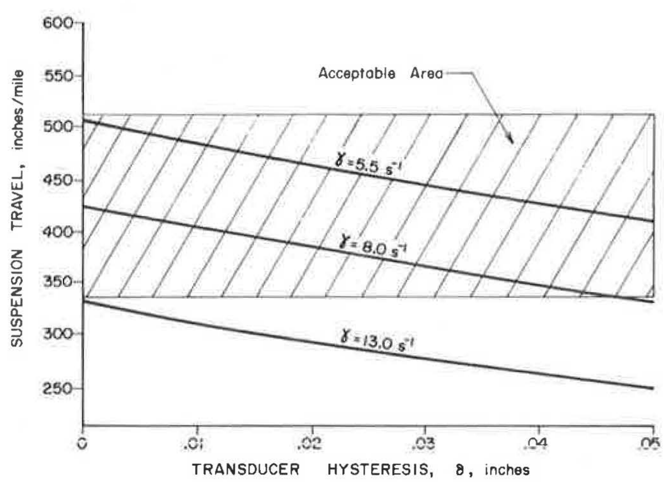

FIGURE 11 Modified acceptability criterion.

$$\gamma_{min}(\delta) \le \gamma \le \gamma_{max}(\delta)$$

The two limiting curves $\gamma_{min}(\delta)$ and $\gamma_{max}(\delta)$ are plotted in Figure 12. The following regression equations have been developed for the limiting curves:

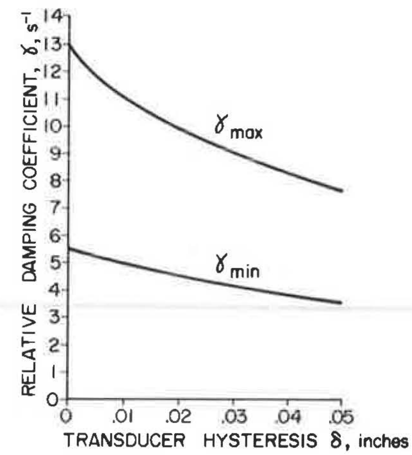

FIGURE 12 Minimum and maximum relative damping coefficients for the modified acceptability criterion.

$$\gamma_{min} = 5.49 - 55.4\delta + 341\delta^2 \quad (7)$$

$$\gamma_{max} = 12.8 - 159\delta + 1{,}078\delta^2 \quad (8)$$

Verification of Shock Absorber Acceptability

A practical procedure to be employed in the verification of trailer acceptability in terms of the ASTM standard depends on whether the ABAB calibration surface is available or not. Both situations will now be considered. The procedure is the same, regardless of which of the two acceptability criteria discussed in the previous section is used.

The first step in the verification procedure involves a determination of the transducer hysteresis. This step is the same, regardless of what calibration surface is used. If the hysteresis δ_a is acceptable, that is, less than 0.05 in. (1.27 mm), the corresponding maximum and minimum values of the accumulated suspension travel ST_{max} and ST_{min} are found from Figure 9, where

$$ST_{max}(\delta_a) = ST(\delta_a)\,|_{\gamma = 5.5} \quad (9)$$

and

$$ST_{min}(\delta_a) = ST(\delta_a)\,|_{\gamma = 13.0} \quad (10)$$

If the ABAB surface is available, the trailer is towed over it and the generated suspension travel is measured. The trailer is considered acceptable if the measured accumulated suspension travel falls between the minimum and maximum values corresponding to the transducer hysteresis. Mathematically, the acceptability condition can be presented as

$$ST_{min}(\delta_a) \le ST(\delta_a) \le ST_{max}(\delta_a) \quad (11)$$

This procedure is illustrated in Figure 13.

For most users of road roughness measuring trailers, the ABAB surface is not readily available. It is therefore desirable that the proposed ASTM acceptability criterion be applied to other surfaces.

The following procedure is proposed for verification of shock absorber acceptability on a user-selected pavement surface.

1. Select a road section subject to some regimen and obtain profile data for it.

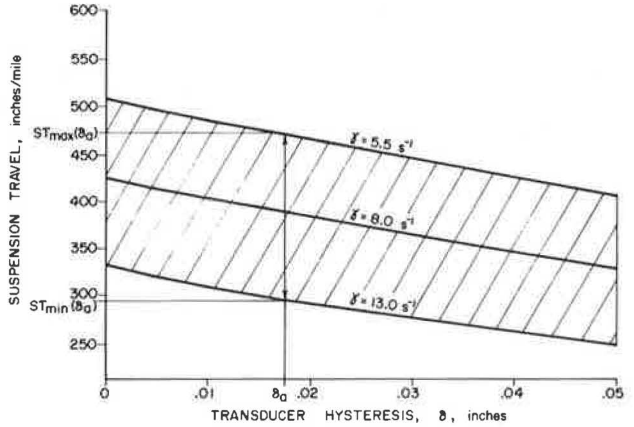

FIGURE 13 Verification of shock absorber acceptability.

2. Determine hysteresis δ_a in the axle-body displacement transducer.
3. Simulate a half-trailer model subjected to the road profile obtained in Step 1 with transducer hysteresis δ_a for two values of damping coefficient, γ_{min} and γ_{max}. Record the accumulated suspension travel values obtained for the limiting values of the damping coefficient, $ST_{min}(\delta_a)$ and $ST_{max}(\delta_a)$.
4. Tow the trailer over the selected road test section and measure the generated suspension travel $ST(\delta_a)$. The trailer, and in particular its shock absorbers, will be considered acceptable if the acceptability condition is satisfied, that is, if

$$ST_{min}\ (\delta_a) \leq ST(\delta_a) \leq ST_{max}\ (\delta_a)$$

In order to employ this procedure, a profile of the selected road test section must be provided. Also, a computer program will be necessary in Step 4 to simulate a half-trailer model.

To illustrate the procedure, a complete shock absorber acceptability area was developed for the Pavement Roughness Research Facility of the Pennsylvania Transportation Institute (PTI) *(4)*. The results are shown in Figure 14. The PTI profile is composed of 11 sinusoidal sections of different amplitude and wavelength. The amplitudes and wavelengths in the 11 sections were selected to approximate a white noise frequency spectrum when the profile is traversed three times at 30, 60, and 90 ft/sec. When the results obtained with the ABAB and with the PTI surfaces are compared, some interesting observations can be made. First, the level of roughness of the PTI surface is considerably higher. In fact, the PTI surface is much rougher than most actual road surfaces. This causes the ABAB curves to decline faster with increased hysteresis, because the effect of hysteresis is more visible at the lower level of surface roughness. The relative effect of the shock absorber damping coefficient is most pronounced on the ABAB surface. The sensitivity of the accumulated suspension travel to changes in the damping coefficient can be defined as

$$\frac{(ST|_{\gamma = 5.5}) - (ST|_{\gamma = 13.0})}{ST|_{\gamma = 8.0}} \times 100 \text{ percent}$$

which is equal to 40 percent for the ABAB surface and 30 percent for the PTI profile.

These observations should be taken into consideration when a road section is to be selected for testing shock absorbers. The test surface should be sufficiently rough to ensure the required sensitivity of the measuring system. From the results obtained on both the ABAB and the PTI surfaces, the normalized accumulated suspension travel will change by about 20 percent when the value of the damping coefficient changes from its standard value, $\gamma = 8.0\ sec^{-1}$, to the maximum or minimum admissible value, $\gamma = 13$ or $\gamma = 5.5\ sec^{-1}$, respectively. The higher the level of roughness, the better the resolution of the measurements obtained with a trailer. In addition, the road roughness should be fairly uniformly distributed along the length of the selected section. If a selected road has only a few severe bumps that contribute to high average roughness, the results of the measurements may be disturbed by nonlinearities in the trailer suspension.

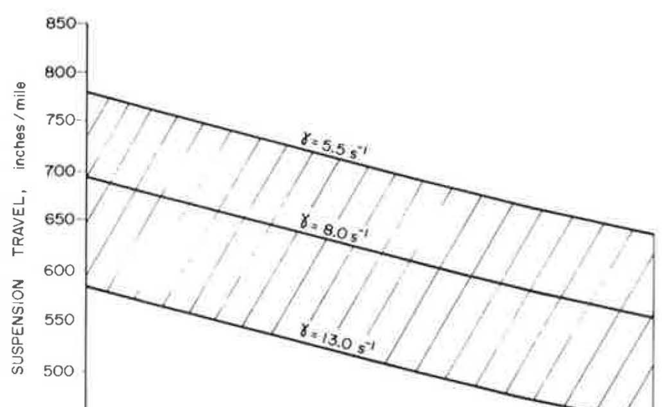

FIGURE 14 Acceptability area for the PTI Pavement Roughness Research Facility.

CONCLUSION

A procedure for verifying the acceptability of shock absorbers for use in road roughness measuring trailers has been presented. The testing procedure is simple and can be conducted on any road section for which the profile data have been acquired. It is desirable that the test surface have a high level of roughness uniformly distributed along its length. A computer simulation program is also necessary to calculate maximum and minimum acceptable values of the trailer suspension travel produced when the trailer is towed over the test surface. The ASTM acceptability criterion should be modified to address the problem of the accuracy of the entire trailer. In its present form, the criterion determines the acceptable limits of the shock absorber damping coefficient, which constitutes but one element of the trailer. The accuracy of the trailer does not depend exclusively on its shock absorber nor on any other single component of the system, but is a result of interaction among all the trailer elements. A new modified criterion has been proposed, based on the relative measurement error rather than on the values of selected trailer parameters.

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